

TECHNEAU WA5.3

Optimization of water treatment: Enhanced coagulation and ozonation-biofiltration

Summary report on performance assessment tools and optimization



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Colophon

Title

Optimization of water treatment: Enhanced
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Summary report on performance assessment tools
and optimization

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Executive Summary

This report is a summary of the water treatment performance optimization activities and achievements obtained within TECHNEAU WA5.3: Operation of water treatment facilities - Optimization efforts and modeling of unit processes.

The water treatment facilities studied include enhanced coagulation (EC) as well as ozonation-biofiltration (OBF) processes. The applied water quality and treatment performance assessment/diagnostic tools include NOM fractionation, BDOC column analysis, EEM, SEC as well as full-scale implementations of the TECHNEAU enhanced coagulation optimization roadmap. The performance of the water treatment processes has been evaluated mainly with respect to water quality, safety and sustainability, including treated water quality, bio-stability, corrosion control, resources used (coagulation chemicals) and waste (sludge) produced.

The results show that there is a great potential for improvements and savings of resources and costs at existing enhanced coagulation as well as ozonation-biofiltration facilities. The applied optimization procedures and diagnostic tools (NOM-fractionation, BDOC, EEM) may not only help in understanding treatment performance and operation requirements, they can also provide new design recommendations, in specific for ozonation-biofiltration processes. In addition, these tools provide valuable links between raw water characteristics and treatment on one side, and between treatment and distribution on the other side. A good correlation (R^2 0.85) was found between BDOC and the hydrophilic NOM fractions.

In addition to the optimization activities, diagnostic tools and results reported here, additional results can be found in previous WA 5.3 deliveries (D5.3.1A, 5.3.1B, 5.3.2A) and in the report from the TECHNEAU Case Bergen (D7.11.3B) where four enhanced coagulation (EC) and two ozonation-biofiltration (OBF) facilities were used as sites for full-scale demonstration activities.

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1. Background and introduction

1.1 Safe and sustainable operation of existing facilities

30-50 % of the known waterborne disease outbreaks are due to failures in water treatment, and treatment barrier efficiency and stability are critically dependent on good operation performance.

We also know that implementation of safer and more sustainable water treatment technologies takes time. Thus, in order to obtain significant improvements in safety and sustainability levels in the water supply sector within a reasonable time scale, one has to address the operation performance of the **existing** water supply systems as the first step. This is the main goal of TECHNEAU WP5.3, and some major reasons for this approach are given below:

- 1) Most water treatment plant (WTPs) are already built - and these facilities will still be in operation for decades to come
- 2) Operation performance assessments, optimisation efforts with respect to safety **and** sustainability, and identification of best operation practices has not yet been adequately performed and implemented
- 3) Because NOM controls most water treatment processes and significantly affect chemical and biological processes in the distribution system, improved knowledge of NOM fraction concentrations and seasonal variability, NOM nature, as well as NOM biodegradability and treatability is imperative
- 4) Sub-optimum operation is widespread and is responsible for some 30-50 % of known waterborne disease outbreaks
- 5) Full-scale optimisation efforts have revealed significant unexploited operation optimisation potentials and benefits, in terms of improved water quality, improved safety/treatment barrier efficiency, increased sustainability/less use of resources (chemicals and energy), less waste production, and less operational costs
- 6) Conventional benchmarking activities have traditionally compared operation performance of similar, but different facilities/sites. In this respect, the TECHNEAU operation optimization procedure (roadmap) represents an alternative way of benchmarking where the current operation performance is compared to the optimum performance/best operation practice identified by full-scale optimization efforts. Thus the optimization potentials of the specific facility are clearly identified. In addition, the full-scale optimization efforts at specific sites allow an internal benchmark to be established

where the comparisons and results are not heavily influenced and disturbed by site-specific raw water quality, treatment characteristics and operator skills. For the facilities, this specific information is more useful and directly applicable in order to achieve the main goals: safer and more sustainable operations.

2. Techneau optimization test sites

The water quality and process performance tools applied in Techneau WP5.3 include advanced water quality analyses, process performance assessments and optimization trials at the following sites/test facilities:

1. **Daugava WTP.** This is a treatment facility in Riga, Latvia that abstracts raw water from the River Daugava. The treatment process scheme includes preozonation, coagulation, flocculation, sedimentation, filtration, main ozonation, biofiltration, and chlorination.
2. **Daugava pilot.** This is an biofiltration pilot plant located at Daugava WTP. Treated water from Daugava WTP taken after the main ozonation step is used as raw water in the biofiltration pilot.
3. **VIVA pilot, Trondheim WTP.** This is a treatment pilot plant with three treatment trains in parallel:
 - i. Alkaline filtration through crushed CaCO_3 with pre-addition of CO_2 for corrosion control, i.e. the current treatment scheme that is used as a reference (The full-scale VIVA WTP also has UV for disinfection. Raw water is abstracted from Lake Jonsvatnet)
 - ii. Ozonation and subsequent biofiltration in an alkaline filter with crushed CaCO_3 and pre-addition of CO_2 for integrated ozonation-biofiltration and corrosion control
 - iii. Enhanced coagulation (Al or Fe) and contact filtration in a 3-M filter with anthracite, sand and alkaline material with crushed CaCO_3 and pre-addition of CO_2 for integrated enhanced coagulation and corrosion control
4. **Svartediket (SVD), Jordalsvatnet (JOR), Sædalen (SAE), and Kismul (KIS) WTPs.** These are four enhanced coagulation facilities in Bergen. The treatment process scheme includes alkaline filtration or addition of fine-graded CaCO_3 slurry for corrosion control, enhanced coagulation (Fe or Al), 2-M or 3-M filtration with anthracite and sand, and anthracite, sand and crushed CaCO_3 , respectively, and finally UV for disinfection at all facilities.
5. **SUND (SUN) and AUSTEVOLL (AUS) WTPs.** These are two ozonation-biofiltration facilities located in municipalities close to Bergen. The treatment process scheme includes microscreening (AUS only) ozonation, biofiltration through layers of activated carbon, sand and alkaline media, and UV for disinfection.

Please see deliverable D7.11.3B on TECHNEAU Case Bergen (Eikebrokk 2011) for a more detailed description of the approach and results from the full-scale demonstration of the TECHNEAU optimization procedures and assessment/diagnostic tools at the facilities presented within numbers 4 and 5 above.

Treatment flow sheets for the full-scale and pilot scale facilities are shown in Figure 1, 2 and 3.

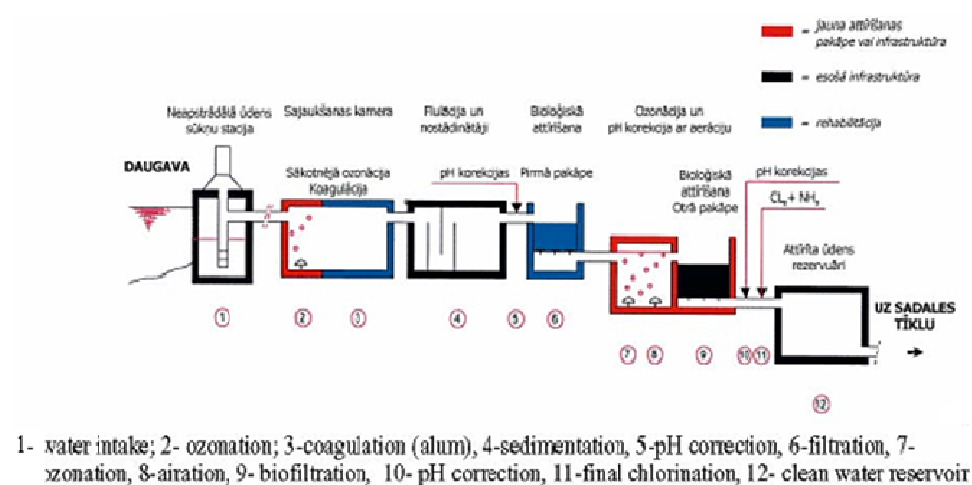


Figure 1. Process scheme of the Daugava WTPs

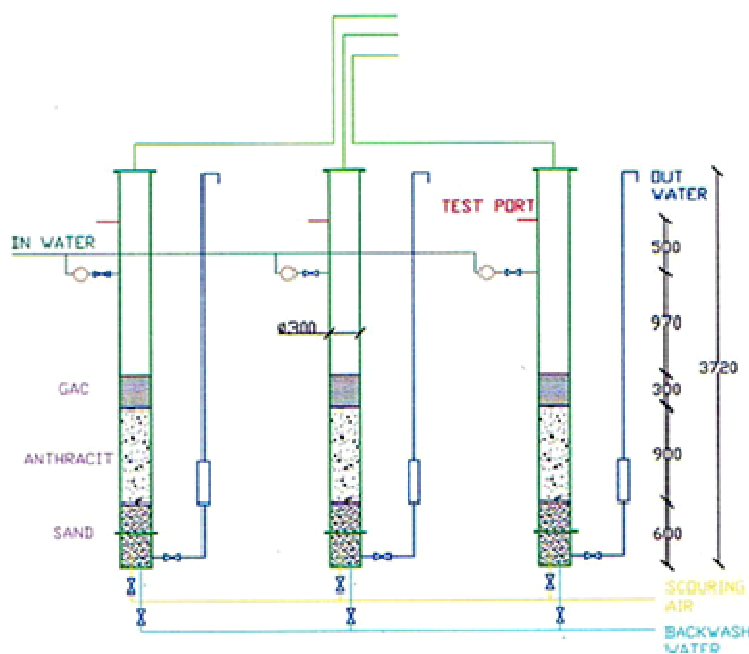


Figure 2. Process scheme of the Daugava Biofiltration pilot plant

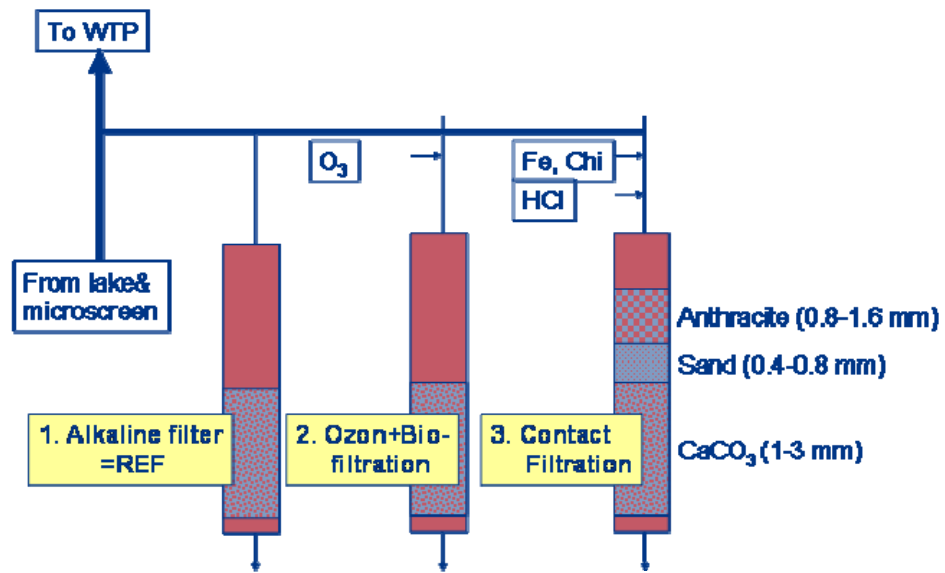


Figure 3. Process scheme of the VIVA Trondheim pilot

3. Techneau optimization tools

3.1 Enhanced coagulation optimization roadmap

For the enhanced coagulation-filtration facilities subject to this study, an operation optimization procedure was implemented according to the Techneau enhanced coagulation optimization roadmap (Eikebrokk et al. 2006; 2007; 2010):

1. Mapping of operation performance status. This includes comparison of current operation performance and applied process conditions (e.g. coagulant doses, coagulation pH, etc) to known experiences and model predictions
2. Water quality and NOM characterization (Diagnostic tools). This includes water quality and variability characterisation, e.g. rapid NOM fractionation, excitation-emission fluorescence matrix measurements (EEM), biodegradability testing (BDOC), ATP-measurements, flow cytometry measurements/total bacteria counts, zeta potential measurements in coagulated water, etc.
3. Optimization trials (Curative tools). This includes planning and performance of full-scale experimental trials including water sampling and analysis, with systematic variation of coagulant dose and pH – in incremental steps – in order not to compromise produced water quality
4. Identification of optimization potentials and possible benefits. Optimization potentials and benefits are identified on the basis of the results from steps 1-3.
5. Implementation of selected operation conditions. This is done on the basis of an overall assessment of advantages and disadvantages – for the treatment plant as well as the distribution system.

Full-scale optimization trials, NOM and BDOC analyses to be reported here includes activities at VIVA pilot (both enhanced coagulation and ozonation-biofiltration), at SVD and JOR WTPs in Bergen (enhanced coagulation), at Daugava WTP (conventional coagulation and ozonation-biofiltration), and at Daugava pilot in Riga (biofiltration).

For the ozonation-biofiltration facilities, studies on DOC/BOM degradation and degradation rates have been conducted at Daugava Pilot, and at SUN and AUS WTPs. NOM fractions and BDOC have been analysed in samples taken at different seasons, and adaptations to the treatment process have also been made in order to reduce regrowth/heterotrophic plate counts in the non-chlorinated distribution systems (AUS WTP).

3.2 Diagnostic tools

NOM fractionation and BDOC analyses of raw and treated water were performed in several sampling rounds in order to identify process performance efficiency and seasonal variability in raw and treated water qualities. The NOM fractionation and BDOC experimental set-ups are presented in Figure 4 and 5 below. More details can be found in other TECHNEAU reports and WA 5 deliverables (Eikebrokk et al., 2006; 2007).

3.2.1 Rapid NOM fractionation

The applied rapid NOM-fractionation and column-based BDOC set-ups are shortly presented below (Figures 4 and 6, respectively).

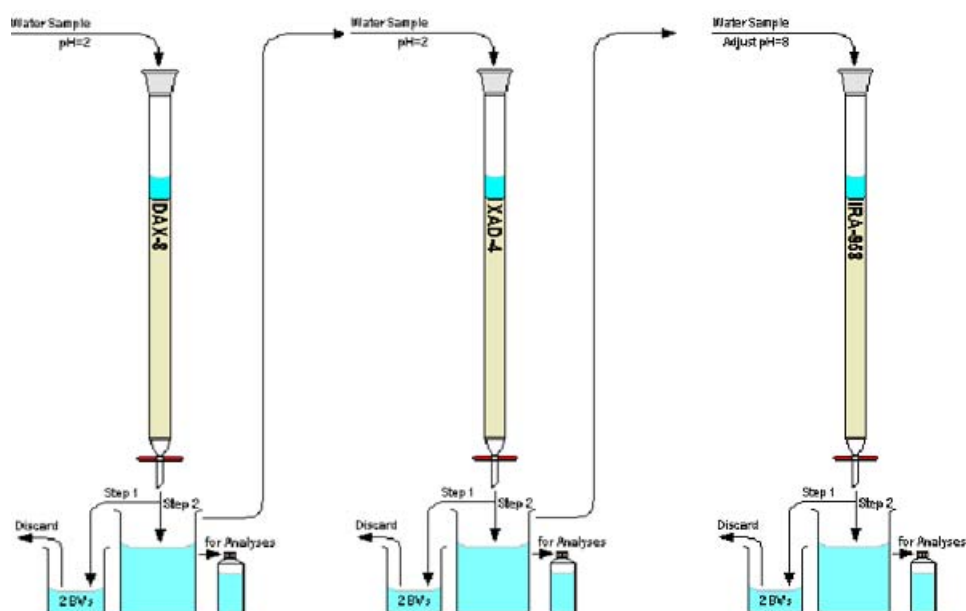


Figure 4. Rapid NOM-fractionation set-up (Fabris et al. 2008)

The rapid NOM fractionation procedure allows identification of four fractions of NOM/DOC based on subtractions of the DOC concentrations of subsequent resin effluents:

- 1) Very hydrophobic acids, VHA (adsorbed by DAX-8)
- 2) Slightly hydrophobic acids, SHA (adsorbed by XAD-4)
- 3) Charged hydrophilic substances, CHA (bound to the anion exchange resin IRA-958)
- 4) Neutral hydrophilic substances, NEU (passed through all columns).

In order to illustrate the kind of information provided, Figure 5 shows a typical example of the distribution of NOM fraction concentrations in Norwegian lake waters (labelled "Raw"). NOM fraction concentrations are presented for raw water samples, outlet water samples from different treatment steps as well as distributed water samples for two of the enhanced coagulation and ozonation-biofiltration facilities involved in TECHNEAU WA5 and WA7 (Case Bergen) activities.

The dominating hydrophobic VHA fraction and to some extent also the SHA fraction in the raw water is composed of high-molecular, biostable humic substances of allochthonous origin. These fractions are supposed to be responsible for most of the colour and UV-absorbance present in the water, due to their aromatic nature with significant amounts of double bonds. Furthermore, these fractions are supposed to determine the coagulant dose requirements and are amendable to removal by coagulation. The hydrophilic substances on the other hand are more biodegradable, low-molecular weight fractions that are supposed to be responsible for biological growth/regrowth, biofilm formation, fouling of membranes, etc. These substances, in specific the NEU fractions, are resistant to removal by coagulation. Ozonation processes are capable of splitting the double bounds and transferring hydrophobic NOM fraction into hydrophilic ones, i.e. VHA to CHA, as shown in Figure 5.

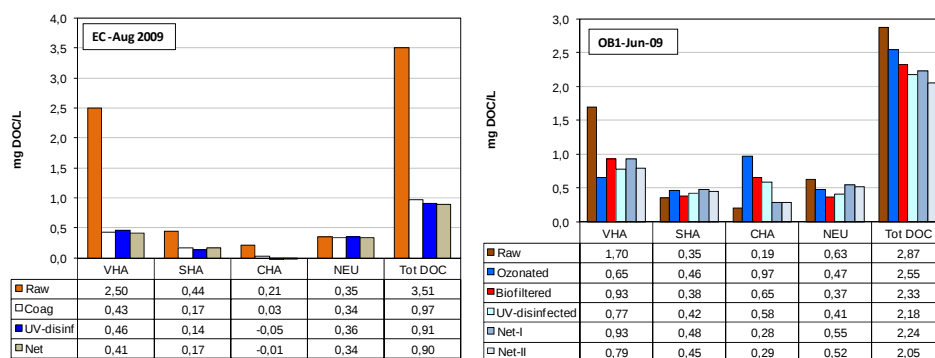


Figure 5. Comparison of NOM fractionation results from the EC (Aug-09 samples) and OB1 (Jun-09) facilities.

Figure 5 also shows that coagulation is capable of removing significant amounts of DOC. This is not the case for the ozonation-biofiltration facility where DOC removal is only slight. It should also be pointed out that the CHA fractions are almost completely removed by enhanced coagulation. In the ozonation-biofiltration facility however, the ozonation step is transferring significant amounts of VHA into CHA, thus significantly increasing the CHA fraction concentration relative to the raw water. In spite of the fact that the biofilter is capable

of removing some of the CHA, significant amounts of remaining CHA (0.6 mg/L) are fed into the distribution system and further degraded there.

Typically, the VHA and SHA fractions of DOC include the humic and fulvic substances, the CHA fractions include the low molecular fatty acids, and the NEU fractions include the polysaccharides. The hydrophobic fractions (VHA and SHA) are often associated with good treatability by coagulation and high reactivity (DBPFP). Due to the high colour and UV-absorbance levels, control of these fractions is also important in relation to design and operation of UV-disinfection processes. The hydrophilic fractions (CHA and NEU) on the other hand, may be associated with high biofilm formation and membrane fouling potentials. Thus, both NOM fractions amenable and recalcitrant to removal by coagulation can be identified on the basis of seasonal NOM fractionation analyses, and predictions on obtainable removal efficiencies can be made.

The specific UV-adsorption (SUVA, i.e. UV-absorbance/DOC) correlates well to the aromatic content of NOM. According to Edzwald and Tobiasson (1999) coagulation is controlled by NOM (and not by turbidity or some other parameters) when the specific UV-absorption (SUVA) is 4 or greater. In this SUVA-range NOM is dominated by high-molecular weight aquatic humic substances with high hydrophobicity. DOC removals are normally 50 % or greater in this range. For SUVA-values in the range of 2-4, coagulation is also influenced by NOM. Only for SUVA values below 2, the corresponding NOM dominated by low molecular weight, non-humic and hydrophilic substances have little influence on coagulation. In this SUVA range, the obtainable DOC removals are normally poor, 25 % or lower.

3.2.2 BDOC columns-in-series

In order to assess biodegradability, several methods have been used. Biodegradable organic carbon (BDOC) represents the fraction of DOC that can be used as energy and carbon source by microorganisms, and this fraction was traditionally calculated as the difference between the initial DOC of a water sample and the minimum DOC observed after inoculation with heterotrophic, environmental bacteria in batch reactors for typically 28 days at 20 °C (Servais et al. 1987).

Later, continuous bioreactors with immobilized biofilm on carriers like sand or glass beads were used (Lucena et al. 1990; Ribas et al. 1991; Volk et al. 1997). Due to the higher biomass in the continuous bioreactors with carriers, the test period can be significantly reduced,

and BDOC determination can usually be performed within 3 hours by this rapid method (Lucena et al. 1990). In order to identify also degradation kinetics, samples are taken out and analyzed for DOC (BDOC) at certain time intervals (i.e. empty bed contact times, EBCT).

Contrary to the parallel bioreactor set-up used by Lucena et al. (1990), a novel set-up of six bioreactors in series was used by SINTEF in this study (Figure 6). Each of the six glass columns (H = 29 cm, Ø = 2.5 cm, Chromaflex, USA) were filled with 200 g of glass carrier beads (Ø = 6 mm, surface area = 3.76 cm²/g). The water samples were continuously pumped upwards through the columns by a peristaltic pump (REGLO Analog tubing pump ISM 828, Ismatec, Switzerland). The empty bed volume of each column is 147 mL, while the real volume after subtracting the volume of the glass beads is about 70 mL.

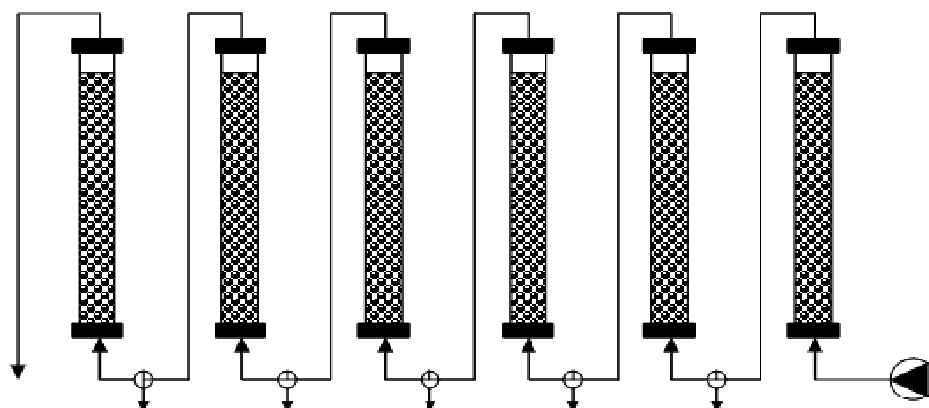


Figure 6. The six BDOC columns-in-series set-up used by SINTEF (Eikebrokk et al., 2010)

The columns were originally inoculated by pumping a mixture of raw water and effluent water from the ozonation-biofiltration pilot plant at VIVA through the columns. Later, the feed water was changed to ozonated water from the pilot plant at VIVA. When columns were not in use for BDOC testing, the biological activity was maintained by recirculation of ozonated water (VIVA pilot) from a 5 liter sample beaker through the columns and then back to the beaker. The water was changed at a few days' intervals. In this mode, the columns were operated as two columns in series (three parallel lines) to maintain as high a biological activity in the columns. The columns were operated at room temperature and were covered with black plastic to prevent algal growth.

During the BDOC test, the columns were operated as six columns in series (two columns in series were used by RTU at Daugava WTP). A three-way valve configuration allowed effluent water sampling from each column. The water sample flow was adjusted to 1.63 mL/min, i.e. an EBCT of 1.5 hrs in each column. This flow was chosen for practical reasons and from experience with the actual DOC degradation rates of the tested NOM water samples. The sample flow can be adjusted according to the DOC degradation rates of the actual sample. The 4-liter sample bottles will normally provide enough sample volume for rapid NOM fractionation as well as BDOC testing. With this approach, the resulting EBCTs (i.e. 9 hours in total) were considered reasonable. Besides, it is possible to run one water sample during a normal work day. Test samples from water facilities were sent to SINTEF in 4-liter fluorinated high-density polyethylene bottles (Nalgene), and pre-filtered through a 0.45 μm membrane filter. If a sample could not be analyzed immediately, it was frozen. Feeding of the test water into the columns was started in the afternoon and the pumping through the columns continued overnight before DOC sampling was carried out, thus providing about 17 hrs of acclimation time before sampling. This is around four times the actual retention time in the columns. A longer acclimation time will increase the required sample volume and the total test time.

After acclimation, water sampling was started from the last column. As soon as enough sample volume was collected (one hour), the flow was redirected from the previous (i.e. second-last) column into a new sample beaker. This procedure continued until effluent samples from all six columns was collected. In addition, inlet (raw) and outlet samples were taken. The sample beaker was weighted before and after sampling to verify a correct flow rate. The collected (7) samples were filtered through 0.45 μm membrane filters before dissolved organic carbon (DOC) analysis (Teledyne Tekmar TOC Fusion analyzer). All values were then compared to the DOC of the inlet (raw) water sample, and the difference in DOC between the inlet sample and the effluent sample from the actual column constitutes the biodegraded DOC according to the EBCT after that specific column.

The difference in DOC between the inlet sample and the effluent sample from the last column (i.e. EBCT of 9 hrs) gives the final BDOC, while the results from the intermediate samples (i.e. EBCTs with 1.5 hrs intervals) indicate the biodegradation kinetics of the sample.

Figure 7 shows a typical example from an ozonation-biofiltration facility treating raw water with a moderate DOC level (2.5-3.5 mg/L). The figure shows the BDOC-curves in samples taken from inlet (raw

water), ozonated water, biofiltered water, UV-disinfected water, as well as two samples from the distribution system. It can be seen that the curves level off at a final BDOC level after some 3 hours. From the very low BDOC levels in the raw water, significant amounts (0.6 mg/L) of BDOC are formed during ozonation. This is only partially removed during biofiltration, thus leaving some remaining 0.25 mg/L BDOC to enter the distribution system. Contrary to the situation at the ozonation-biofiltration facility, the low BDOC levels are maintained and even further reduced during treatment at the enhanced coagulation facility.

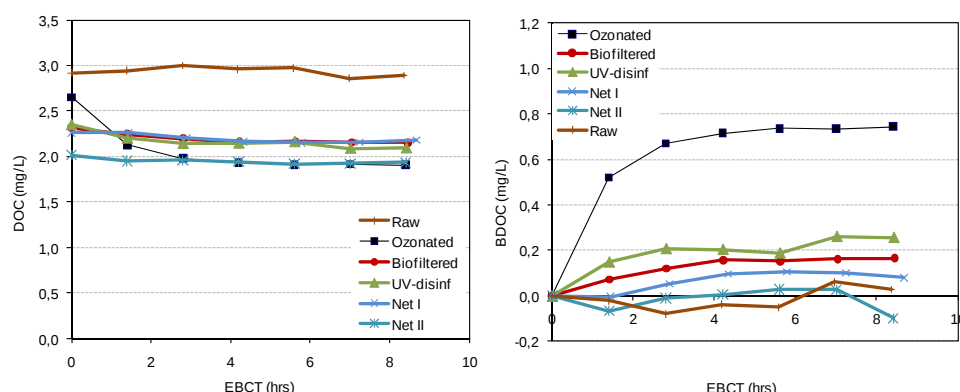


Figure 7. Example of DOC and BDOC profiles in water samples taken during treatment (ozonation, biofiltration, UV-disinfection) and distribution (Eikebrokk et al., 2010)

3.2.3 EEM and SEC-DOC analyses

As a supplement to NOM-fractionation and BDOC analyses as performed by SINTEF and RTU, UNESCO IHE Delft (S. Sharma) performed measurements of fluorescence excitation-emission matrixes (EEM) and size-exclusion chromatography with dissolved organic carbon detection (SEC-DOC) in samples from VIVA pilot, from the enhanced coagulation facilities in Bergen, and from the ozonation-biofiltration facility in Austevoll. Samples were prepared by 0.45 µm pre-filtration and shipped by air to Delft in prewashed nalgene bottles on ice.

EEM allows one to track humic-like NOM, effectively removed during coagulation, and protein-like NOM, amenable to removal by biofiltration. SEC-DOC allows one to track biopolymers, potentially removable by biofiltration, low molecular weight acids, significantly removable by biofiltration, and humic substances, effectively removed by coagulation. Both EEM and SEC-DOC can provide quantitative as well as qualitative information.

The fluorescence excitation-emission matrixes (EEM) were measured using a Horiba Jobin Yvon FluoroMax-3 spectrofluorometer. Normally three clearly visible peaks were present: (1) humic/fulvic-like, (2) humic-like and (3) protein-like substances, as illustrated in Figure 8 below for raw water (left) and coagulated water samples (right) from the VIVA pilot. It appears from Figure 8 that coagulation effectively removes the humic/fulvic-like material (peak No. 1) and also the humic-like material (peak No. 2). The protein-like material however (peak No. 3) is not removed.

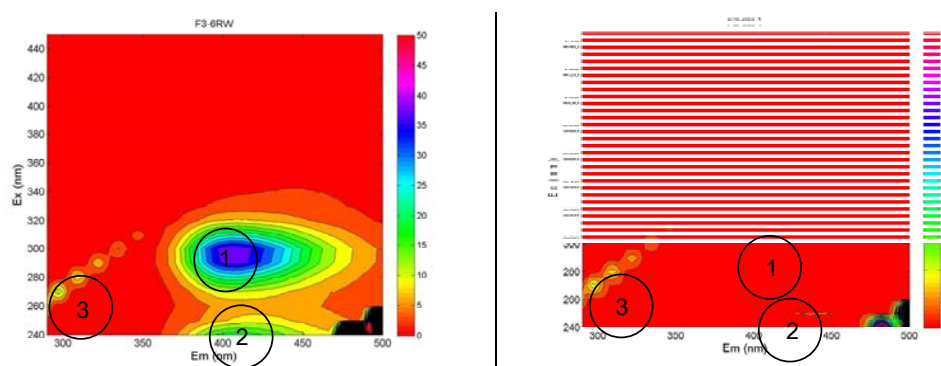


Figure 8. Examples of EEM in raw water (left) and coagulated (right) water samples from VIVA, Trondheim with three clearly visible peaks: (1) humic/fulvic-like, (2) humic-like and (3) protein-like substances

As an illustrating example, SEC-DC chromatograms for raw water, treated (coagulated), and ozonated-biofiltered water samples from VIVA are presented in Figure 9 below. Separate chromatograms were obtained with UV210, Dissolved carbon, Fluorescence and UV254 detectors to characterize different fractions/sizes of the organic matter.

3.3 Treatment performance assessments and optimization trials

In addition to the main diagnostic tools presented above, the Techneau coagulation optimization roadmap includes treatment operation performance assessments and full-scale optimization trials. It is a major objective of the optimization trials that the step-wise changes in operation conditions are small enough to allow for normal operation without significantly compromising treated water quality during the tests. It is also of vital importance that resources are allocated and that the operators themselves are heavily involved in running the plant, in water sampling and in discussing and following-up of the results. The knowledge gained during these tests is normally highly appreciated by the operators.

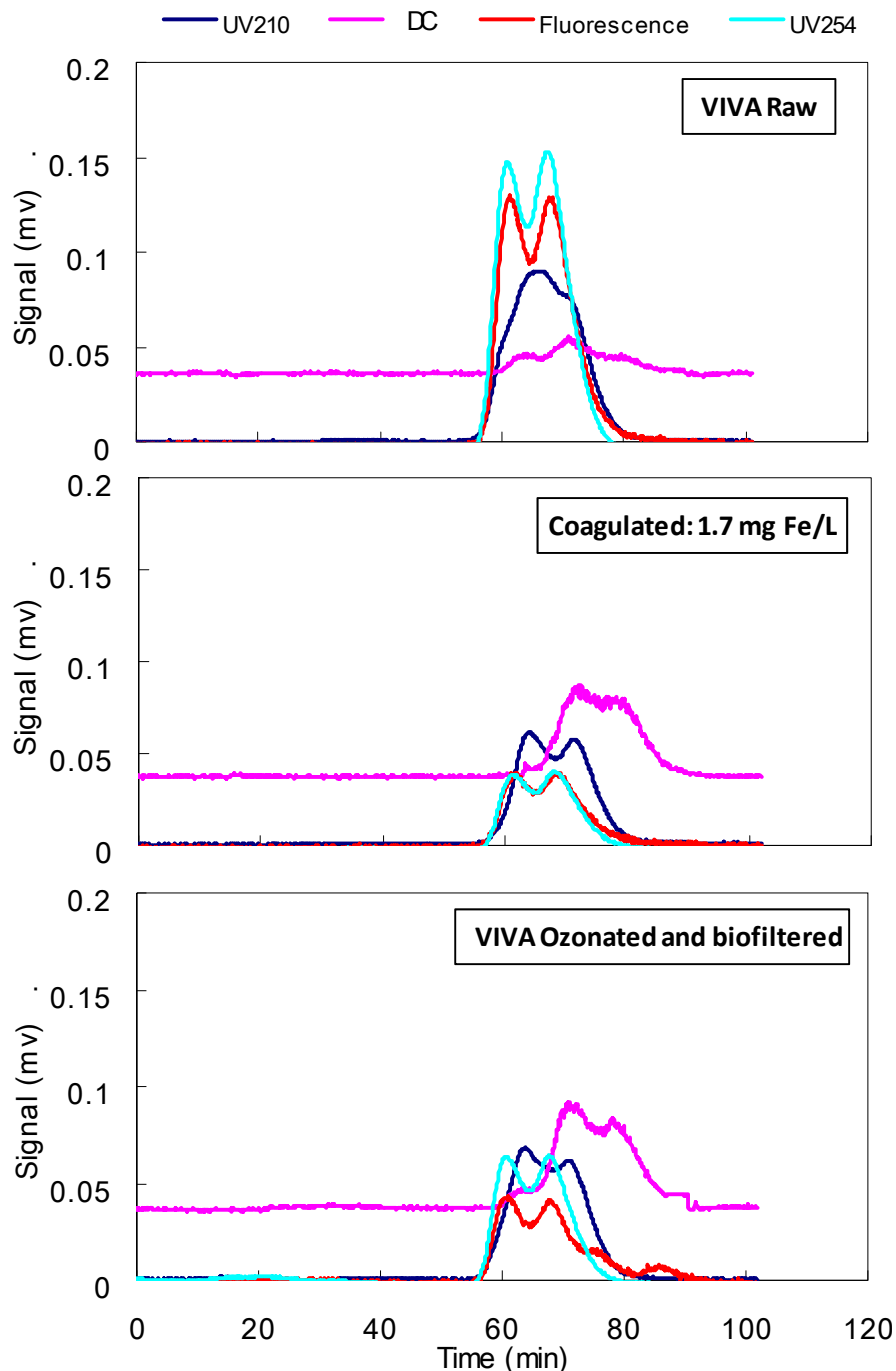


Figure 9. Examples of SEC-DC in raw water (upper) and coagulated (lower) water samples from VIVA, Trondheim

3.3.1 Coagulation barrier indicator values

The Norwegian regulations are based on the EU's Drinking Water Directive. In addition, the Norwegian regulations require: 1) approval of all water supply systems by the Norwegian Food Control

Authorities, and 2) the presence of at least two (hygienic) safety barriers. These requirements apply to all water supply systems supplying more than 50 people or 20 households.

The Norwegian regulations and guidelines also define hygienic barriers as specific log-reduction requirements (2-3 log reductions) depending of the type of microorganism. In addition, a set of treatment-specific barrier indicators are presented. For coagulation, the barrier indicators and the current indicator values are presented in Table 1.

Table 1. Norwegian guidelines on coagulation barrier indicator values (Norwegian Food Control Authorities, 2001)

Indicator/parameter	Value	Comments
Coagulant residual (mg Me/L)	< 0.15	When Al- or Fe coagulants are used
Colour (mg Pt/L)	< 10	< 5 when Al or Fe coagulants are used
Total organic carbon (mg TOC/L)	< 3	
Turbidity (NTU)	< 0.2	To be measured on-line from each filter unit
Particle count 2-400 µm (1/mL)	< 500	To be measured on-line from each filter unit

4. Process performance at Daugava WTP

Daugava Water Treatment Plant (WTP) is the largest plant in Latvia supplying about 50% of the drinking water for Riga city (100.000 m³ per day). The plant abstracts water from River Daugava (from the reservoir of Riga Hydroelectric Power Station). Upstream the intake several villages and cities are located (in Russia, Belarusia and Latvia) therefore the raw water is influenced by wastewater discharges. To reduce the pollution risk of the drinking water in 2001 the treatment process was upgraded with two stage ozonation. Consequently, Daugava WTP is using preozonation (1-3 mg/l), chemical coagulation with alum, rapid filtration, main ozonation (2-8 mg/L), biologically active carbon (BAC) filtration and final chlorination.

Today NOM removal is only moderately effective in the surface water treatment plant (WTP) Daugava of Riga city (Latvia) compared to other reported (Wang et al., 2002). In this research NOM was characterized before and after each treatment step and the results were used to determine how different processes influence NOM removal. Several diagnostic tools were used for monitoring of NOM and NOM removal: TOC and DOC analysis for the quantification of organic carbon in raw and treated water samples; BDOC determination (Ribas et al., 1991) for characterisation of biological stability of raw and treated water; RF technique (Chow et al., 2004) for characterisation of NOM physical properties; FT-IR analysis for qualitative (functionality) characterisation of NOM; LC-OCD analysis for size characterisation of NOM. The objective of the present study was to determine the character and chemical composition of NOM and water quality changes with respect to NOM, in drinking water treatment plants (in Latvia).

The results showed that large and intermediate molecular size fractions predominate in the raw (surface) water and pre-ozonated water in WTP which confirms the results from previous studies (Nissinen et al., 2001; Tihomirova et al., 2010; Tihomirova and Juhna, 2008; Rubulis et al., 2008). Large molecules, mainly humic substances, were removed much better during the coagulation and filtration processes (MC-RSF) compared to smaller molecules. Bacteria within the BDOC column system utilize the degradable organic carbon and produce CHA or LMA fractions (Rubulis et al., 2008). The second ozonation can improve BDOC removal efficacy. According to analysis, aromatic compounds decreased after coagulation and filtration and aliphatic groups slightly increased or did not change after ozonation and biofiltration. The conventional water treatment in Daugava WPT is not effective

regarding the polysaccharide removal. The remaining TOC/DOC concentration levels after treatment are significant, producing high amounts of THMs upon chlorination.

TOC is a good method for the determination of the total NOM concentration. To characterize NOM fraction it is however necessary to apply other method such as rapid fractionation technique (RF). This method is quick and sensitive for the different type of molecules found in water samples. The information about NOM composition in each treatment train step and molecular size distribution is useful for improving treatment processes to enhance biological stability of drinking water and to reduce the generation of contaminants.

4.1 Optimization trials (Daugava WTP)

4.1.1 Coagulation

The total humic substances (VHA and SHA) removal determined with the rapid NOM fractionation method (Chow et al., 2004) was moderately effective (60%) during coagulation. Therefore this method in combination with enhanced coagulation (high coagulant doses and strict pH-control) can be applicable for the optimization of VHA and SHA fraction removal from humic rich raw waters.

The rapid NOM fractionation method was used to determine the optimal conditions for removal of NOM with respect to coagulation dose, pH, turbidity and residual aluminium concentration in tests performed at Daugava WTP. Additional tasks in this study were to evaluate the effect of pre-ozonation on coagulation efficacy, and to determine the amount of sludge produced in the coagulation process.

Based on the results obtained the optimal conditions for the the coagulation process at Daugava WTP in Riga, Latvia were - pH 6, alum dose of 15 mg/L, with a ratio between alum dose and TOC of 0.8. At these conditions the total removal of NOM measured as TOC was 62% (57 % determined as SUVA) and 64 % (61 % determined as SUVA) in raw water and preozonated water, respectively. The results (Table 2) show that the preozonation improved turbidity removal (a decrease from 7.2 ± 1.9 NTU in RW to 2.6 ± 0.2 NTU in OZ samples), and that preozonation was not beneficial with respect to the NOM removal obtained during the subsequent coagulation process.

Table 2. Analytical results of raw water (RW) and preozonated water (OZ) samples in the study period at the Daugava WTP (adapted from Tihomirova et al., 2010).

Parameter	Treatment train	
	RW	OZ
TOC $\pm$ sd, mg/L	18.1 $\pm$ 2.3	15.9 $\pm$ 0.8
DOC $\pm$ sd, mg/L	16.4 $\pm$ 0.6	15.1 $\pm$ 0.6
UV254 $\pm$ sd, cm-1	2.373 $\pm$ 0.028	2.146 $\pm$ 0.021
UV410 $\pm$ sd, cm-1	0.239 $\pm$ 0.014	0.189 $\pm$ 0.003
pH $\pm$ sd	7.31 $\pm$ 0.07	7.33 $\pm$ 0.08
Conductivity $\pm$ sd, μ S/cm	409 $\pm$ 47	411 $\pm$ 3
Turbidity $\pm$ sd, NTU	7.2 $\pm$ 1.9	2.6 $\pm$ 0.2
Red-Ox $\pm$ sd, mV	759 $\pm$ 91	844 $\pm$ 49
Temperature $\pm$ sd, $^{\circ}$ C	19.5 $\pm$ 1.6	20.0 $\pm$ 1.0

As shown in Figures 10 and 11, the analyses of water samples taken after pre-ozonation, coagulation, sedimentation and rapid filtration (RF) showed that the best DOC removal (70 %) was achieved at pH 6 and an alum dose of 15 mg Al/l in the raw water. With preozonated water the best DOC removal (67 %) was observed at pH 6 and alum dose of 20 mg Al/l, i.e. the efficacy of NOM removal in these tests was 7-10 % higher than usually achieved after preozonation at the full-scale WTP.

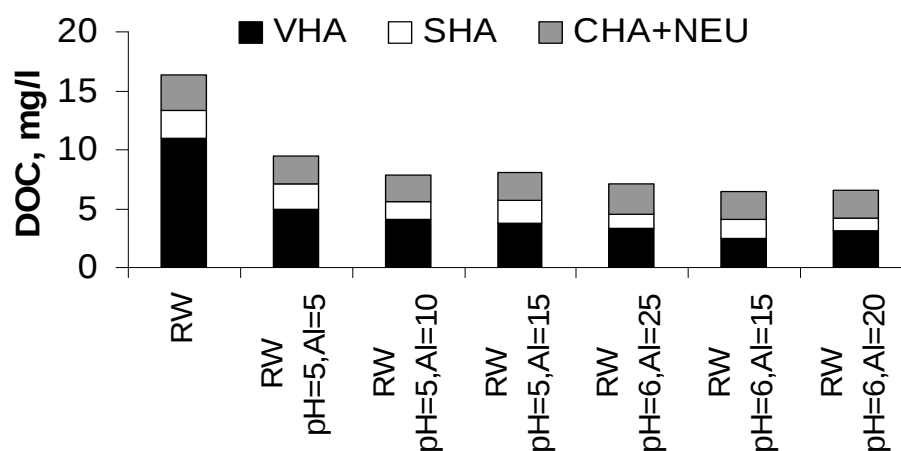


Figure 10. Changes in NOM fraction concentrations (average values from 3 experiments) during coagulation optimization experiments (jar-test) on raw (inlet) water (RW) using different coagulation pH and alum doses. Average results from 3 runs (adapted from Tihomirova et al., 2009)

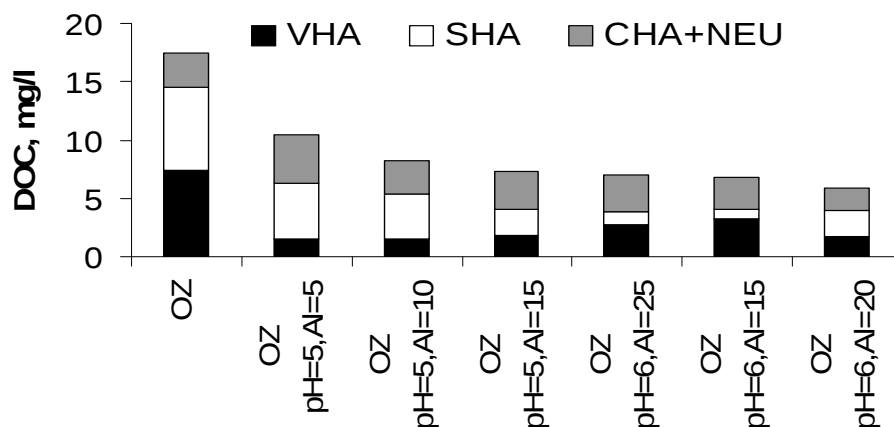


Figure 11. Changes in NOM fraction concentrations (average values from 3 experiments) during coagulation optimization experiments (jar-test) on preozonated water (OZ) using different coagulation pH and alum doses. Average results from 3 runs (adapted from Tihomirova et al., 2009)

VHA fraction removal increased from 67 % to 78 % at an alum dose of 15 mg Al/l and pH 6 in raw water (RW), and to 80 % at alum dose 5 mg Al/l and pH 5 in the preozonated water (OZ). No decrease in the NEU and CHA fraction concentrations was detected. The minimal NPOC values were reached at pH 6 and alum dose 20 mg Al/l for RW and OZ samples (4.50 ± 1.10 mg/l and 4.25 ± 0.18 mg/l respectively).

The minimal concentrations of residual aluminium were 0.032 mg/l in coagulated RW samples and 0.050 mg/l in treated OZ samples at pH 6 and alum dose 15 mg Al/l (Figure 12). Data on total residual aluminium is not available. This is however a very important parameter to control because of the fact that residual metal coagulant concentration may determine the overall coagulant dose requirements (Eikebrokk, 1996; 1999).

Given the very high and variable DOC levels in the Daugava River water, stable and efficient NOM removal is a challenge at Daugava WTP. Residual DOC and THMs formed after chlorination may be a challenge with respect to compliance with EU regulations. Further process optimization, in the coagulation as well as in the ozonation-biofiltration treatment steps can provide significant benefits at this plant.

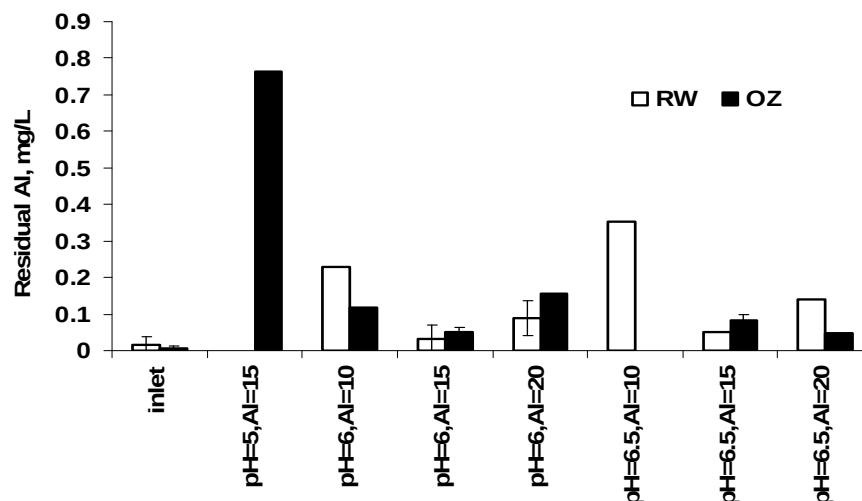


Figure 12. Concentration of residual dissolved aluminum in RW and OZ water samples after Jar test at different pH and alum dose. Legends: inlet – samples RW and OZ before Jar test. (adapted from Tihomirova et al., 2010).

4.1.2 Ozonation-Biofiltration

The results of this study showed that total organic matter removal was 7% only during BAC filtration. The biological stability of water samples as determined with a BDOC column system (Ribas et al., 1991) decreased by 15% during BAC filtration. The results published by Tihomirova et al. (2010) showed that BDOC is a portion of the NEU fraction (the easily degradable organic carbon) which can be utilized by microorganisms at the same time producing the CHA or LMA fractions. In colder period of the year the CHA were transformed into NEU within the BAC filters rather than removed, thus indicating that biological degradation was not efficient. In warm season of the year a portion of NEU fraction was slightly removed within BAC. One possible reason is that due to slow degradation rates it is mostly the rapidly degradable BDOC that is removed in the biofilter, which are usually designed for empty bed contact times (EBCT) of less than 30 minutes. The slowly degradable substances are however not removed (Yavich et al. 2004). If the rate of BDOC removal is not known, the necessary EBCT cannot be adequately determined. Thus, knowledge about degradation rates of BDOC is important in order to design and optimize biofiltration processes for drinking water production. The aim of this study was to estimate the degradation rate of BDOC in water samples from humic rich raw waters.

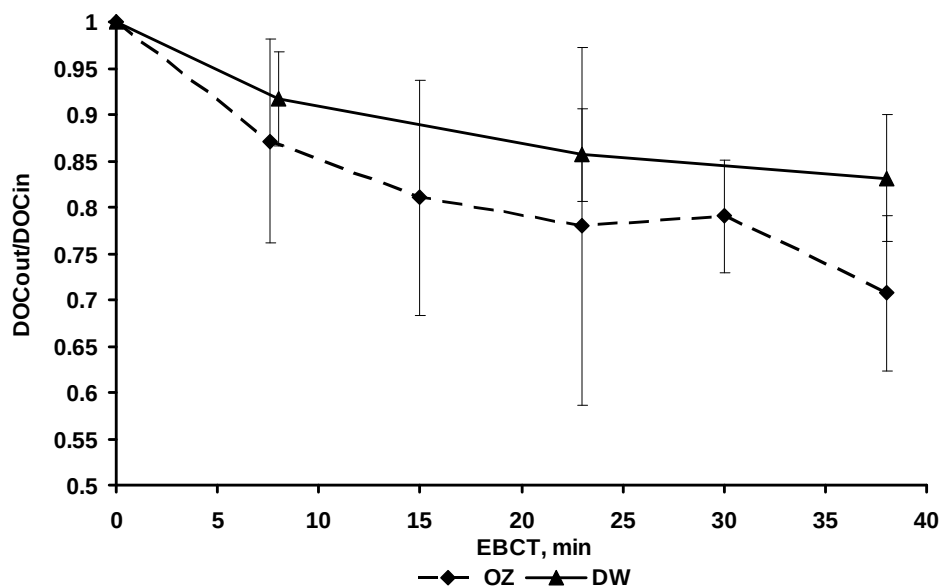
This study has demonstrated the applicability of a modified BDOC columns-in-series analysis for the assessment of ozonation-biofiltration treatment performance assessments on waters with high and low NOM concentrations (Daugava and Norway WTPs), respectively. The BDOC-

analysis developed within the EU-project TECHNEAU (Eikebrokk et al. 2007) yields rapid information not only on final BDOC-levels but also on the degradation kinetics. First order kinetic equation was applicable ($R^2 > 0.8$) to the observed BDOC removal rates in this study. The study demonstrates that biodegradation rates in humic rich waters can be increased by using oxidants (ozonation, chlorination).

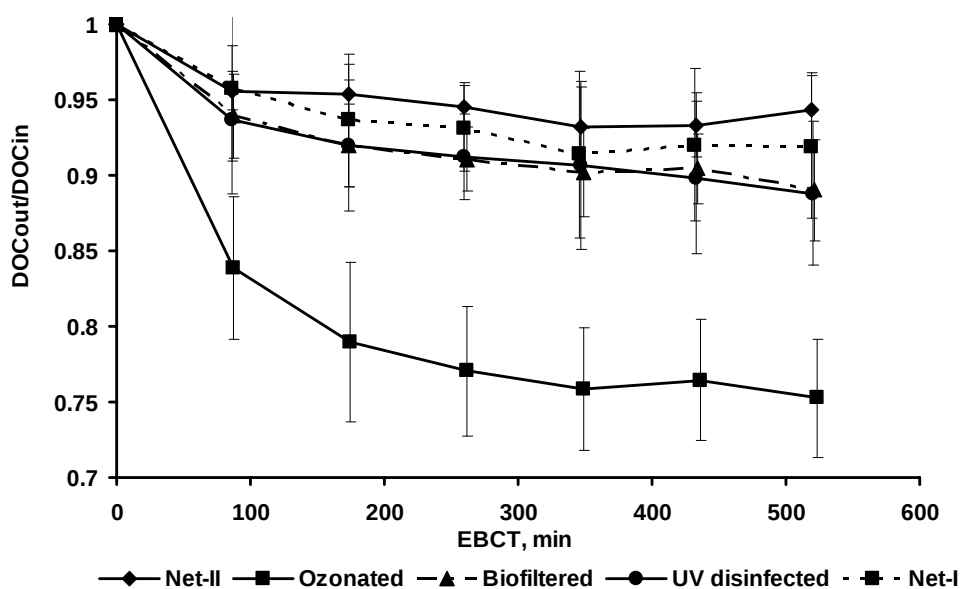
Ozonation significantly increased the biodegradation rates at both the Latvian and the Norwegian WTPs (Figure 13). The biodegradation rates of ozonated water samples from SUN WTP in Norway were high ($0.14 \times 10^{-2} \text{ min}^{-1}$) compared to the rates of samples taken after biofiltration and after UV disinfection, i.e. $0.05 \times 10^{-2} \text{ min}^{-1}$ (Figure 10 B).

The obtained degradation rates of BDOC in Daugava water samples after preozonation and after biofiltration were low, about 0.16×10^{-2} and $0.10 \times 10^{-2} \text{ min}^{-1}$ (Figure 10 A). The degradation rates after ozonation and in the drinking water after chlorination at WTP were higher, 1.40×10^{-2} and $0.65 \times 10^{-2} \text{ min}^{-1}$. The biodegradation rates obtained from samples taken at different places of the distribution network in Riga ranged from 0.24×10^{-2} to $3.15 \times 10^{-2} \text{ min}^{-1}$. In the distribution network supplied by OBF treated water in Norway the biodegradation rates of water samples were 0.04×10^{-2} and $0.02 \times 10^{-2} \text{ min}^{-1}$, i.e. significantly lower than those in Riga.

A strong correlation ($r=0.81$) between the BDOC results and the biodegradation rate constants was found in this study (Figure 14). Only modest correlations were found between DOC and biodegradation rate ($r=0.53$) and between DOC and BDOC values ($r=0.68$).



A



B

Figure 13. Average DOC changes versus EBCT. Legends: (A) water samples from Daugava WTP after ozonation (OZ, $n=10$) and after chlorination, i.e. drinking water sample (DW, $n=12$); (B) water samples from SUN WTP after ozonation (OZ), biofiltration (BAC), UV disinfection (UV) and from network I (Net - I) and network II (Net - II), $n=3$).

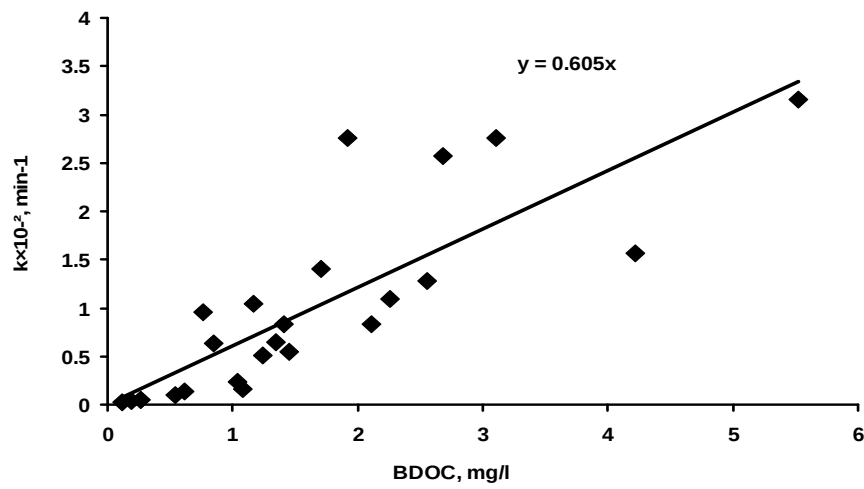


Figure 14. Correlation between BDOC and the biodegradation rate constant under this study.

5. Optimization studies at VIVA pilot, Trondheim WTP

The process scheme of the VIVA pilot at Trondheim WTP, Norway was shown in Figure 3. The pilot contains three parallel process trains: 1) alkaline filtration, 2) ozonation-biofiltration, and 3) enhanced coagulation-contact filtration. In the first experimental stages, an iron-based coagulant (PIX) is applied in the enhanced coagulation studies. This is due to the fact that this coagulant works well at low pH conditions (i.e. pH 4-5), which is ideal for a rapid dissolution (i.e. low contact time requirements) of the calcium carbonate filter material (for the purpose of corrosion control). Later, chitosan and/or alum coagulants may be candidates for further testing.

5.1 Dominating NOM fractions

The fractionation results indicate that the NOM in raw water at VIVA WTP is dominated by the hydrophobic humic fractions (75-80 % VHA and SHA). Due to the large raw water source (Lake Jonsvatnet) with a theoretical detention time of close to 10 years, the seasonal variations are small, both in terms of TOC (2.5-3 mg/L), NOM fractions concentration and NOM fractions distribution. Due to the long detention times and the possible NOM bleaching effects, the SUVA levels are relatively low compared to most lakes in this part of Norway (3.4-3.6 L mg⁻¹ m⁻¹). From the SUVA levels, relatively good treatability by coagulation should be expected. The hydrophilic NEU fraction, that is not amendable to removal by coagulation, is relatively low, thus indicating a limited regrowth potential in this raw water. This is confirmed by the close-to-zero BDOC levels measured in this water.

The high percentage of the biostable VHA and SHA fractions (75-80 %) also indicates that ozonation is required in order to provide a good overall removal of DOC if biofiltration processes are used for treatment of this water.

5.2 Enhanced coagulation optimization studies at VIVA WTP

Initial optimization experiments were performed according to the enhanced coagulation optimization procedures described before. Results from the initial optimization trials (i.e. identification of enhanced coagulation profiles) are presented in the Figures 15-18 below. Raw water quality during the test period was in the range of 0.1-0.4 NTU; 13-15 mg Pt/L; 9.3-10.2 m⁻¹; 2.6-3.0 mg/L; and 3.1-3.8 Lm⁻¹mg⁻¹ for turbidity, colour, UV-abs, DOC and SUVA, respectively. The optimization tests were performed with a constant filtration rate of 10.2

m/h. Hydrochloric acid and CO₂ was used for pH and corrosion control purposes.

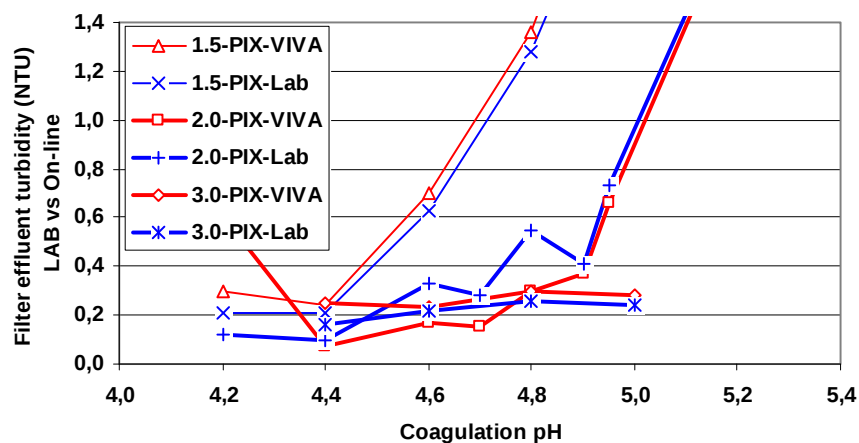


Figure 15. On-line (red) and lab-analysed (blue) filter effluent turbidity data obtained with different coagulation pH (4.2-5.2) and coagulant dosage levels (1.5-3 mg Fe/L as PIX113) during pilot-scale optimization trials at VIVA WTP, Trondheim Norway.

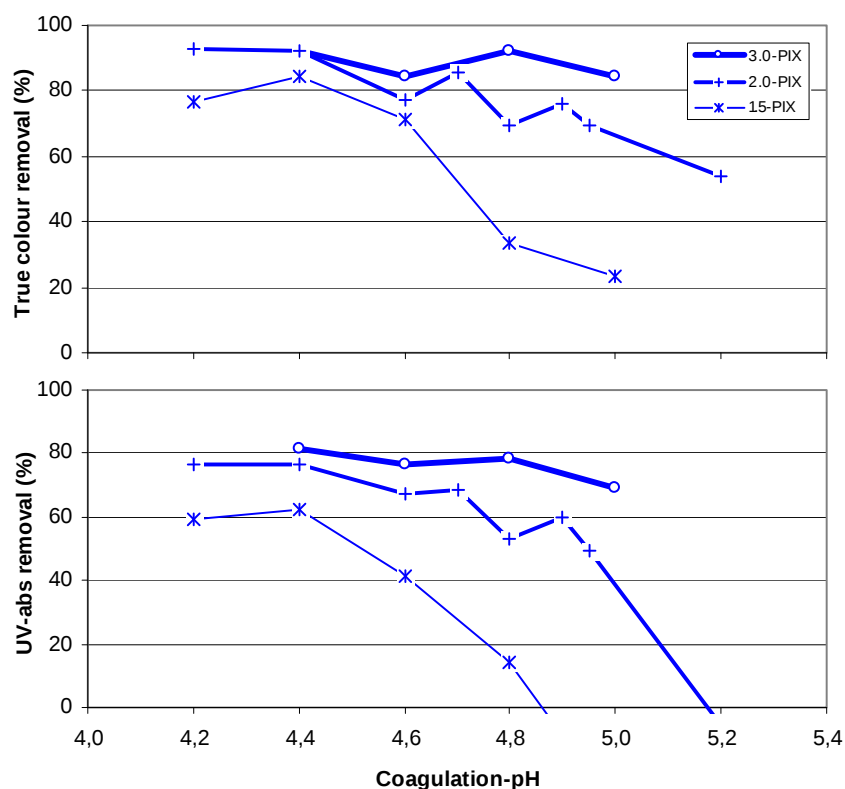


Figure 16. True colour (upper) and UV-abs removal efficiencies obtained with different coagulation pH and coagulant (Fe) dosage levels during pilot-scale optimization trials at VIVA WTP, Trondheim Norway.

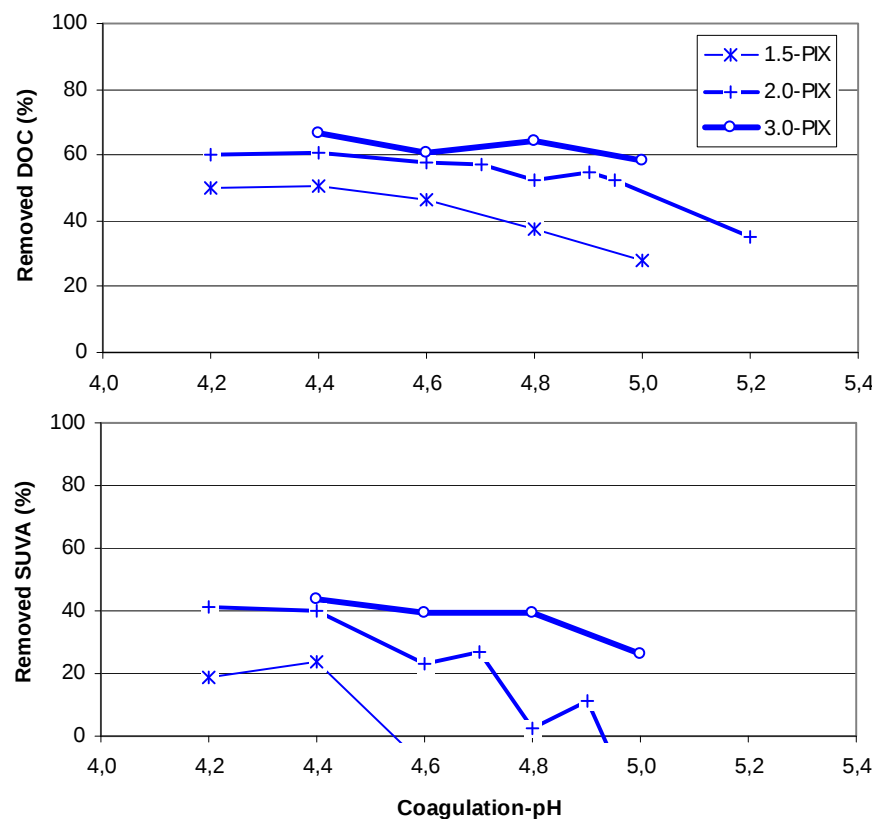


Figure 17. DOC (upper) and SUVA removal efficiencies obtained at different coagulation pH and coagulant (Fe) dosage levels during pilot-scale optimization trials at VIVA WTP, Trondheim Norway.

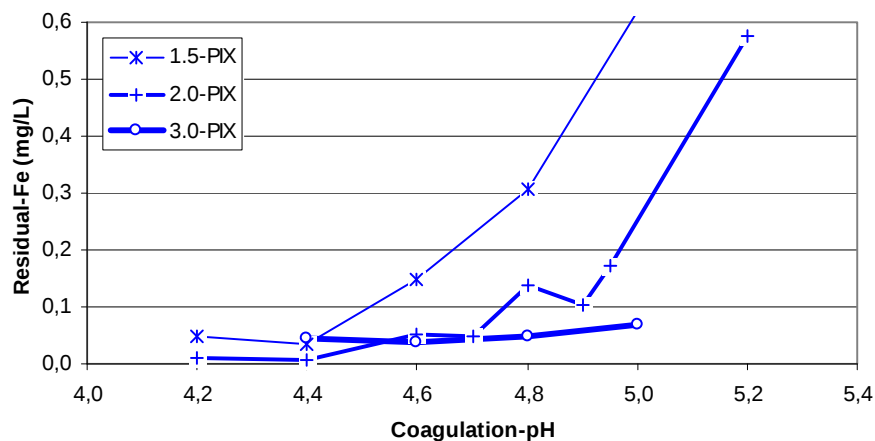


Figure 18. Residual Fe concentrations obtained at different coagulation pH and coagulant (Fe) dosage levels during pilot-scale optimization trials at VIVA WTP, Trondheim, Norway.

Based upon an overall evaluation of the optimization results obtained with the ferric coagulant (PIX-113) at the VIVA pilot, a coagulant dosage of 2.0 mg Fe/L and a pH of 4.4-4.5 were taken as the optimal coagulation conditions for this coagulant with this raw water. These optimal coagulation conditions were applied in a series of experiments designed to identify how NOM fractions removal was effected by differences in coagulant dose levels.

5.2.1 Effects of coagulant dose level on NOM fractions removal

Based on the results from the optimization experiments, a separate study was performed where coagulation pH was kept constant at an optimum level (pH 4.4) while the coagulant doses were varied within the range of 0.9-3 mg Fe/L. In addition to the analyses of conventional parameters as well as NOM-fraction and BDOC, additional samples from these experiments were analyzed by IHE-Delft with respect to EEM and SEC.

The results are presented in Figure 19-23 below. The results confirm that a dose of 2 mg Fe/L is close to optimum. It is evident from the data presented in Figure 16-20 that for the VIVA raw water the optimum coagulant dose level can be expressed as:

- Absolute dose: 2.0 mg Fe/L
- DOC-spec dose: 0.7 mg Fe/mg DOC
- Colour-spec dose: 0.15 mg Fe/mg Pt
- UV absorbance-spec dose: 0.2 mg Fe/m⁻¹

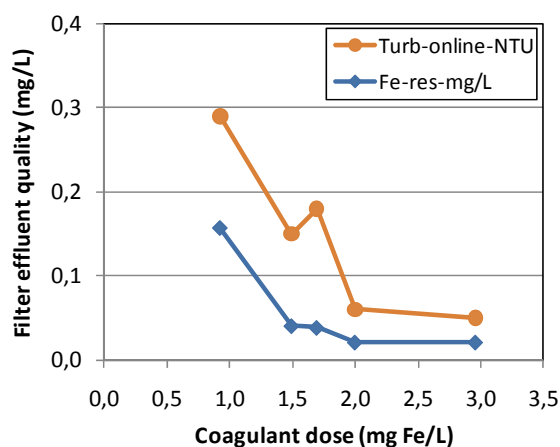


Figure 19. Filter effluent turbidity and Fe-coagulant residual levels during the EEM sampling experiments (Coagulation pH 4.4; filtration rate 10 m/h).

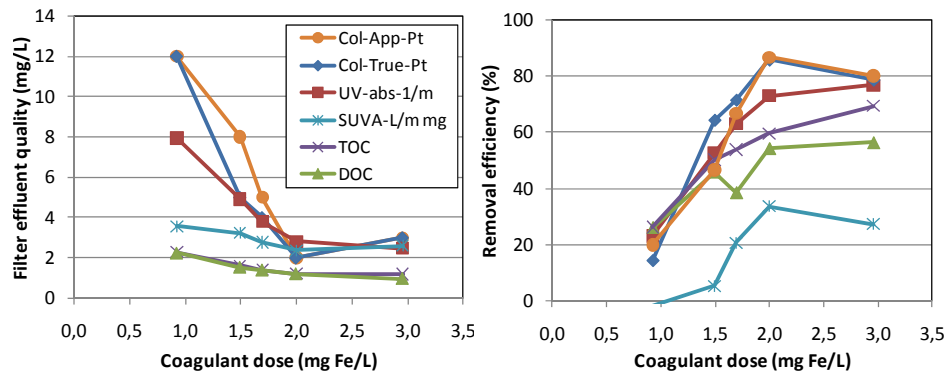


Figure 20 Filter effluent quality (mg/L) and removal efficiencies (%) obtained during the EEM sampling experiments

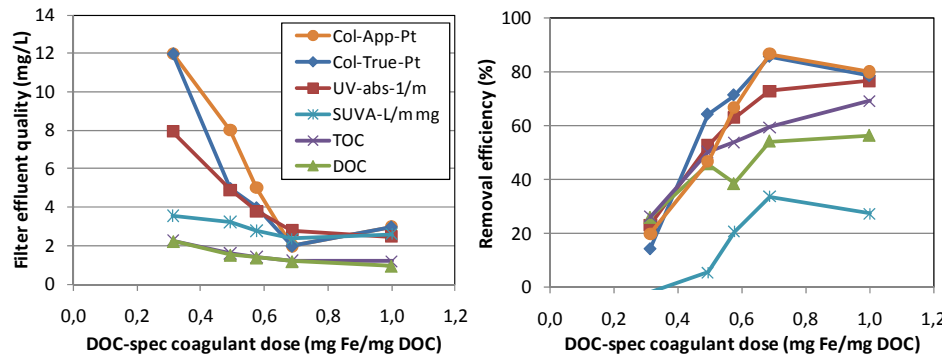


Figure 21 Filter effluent quality (mg/L) and removal efficiencies (%) at different DOC-specific coagulant dose levels

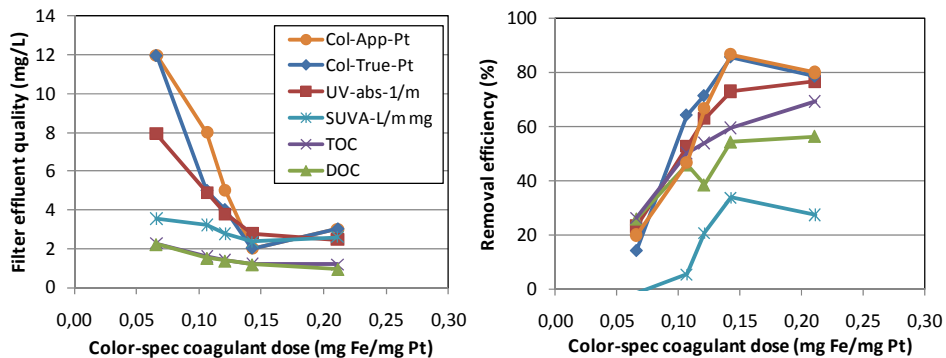


Figure 22 Filter effluent quality (mg/L) and removal efficiencies (%) at different colour-specific coagulant dose levels

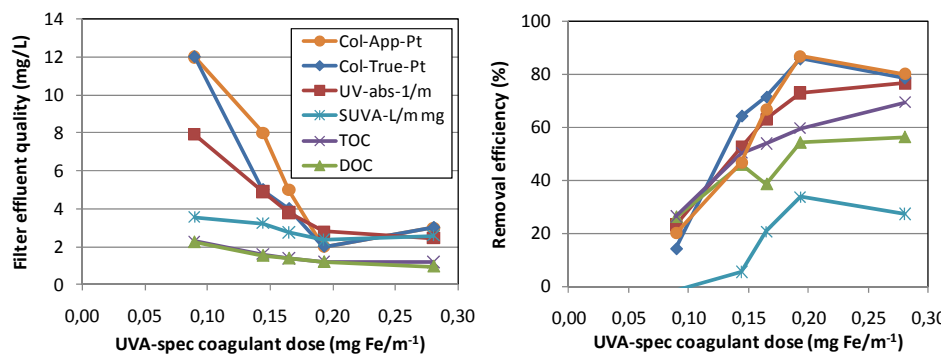


Figure 23 Filter effluent quality (mg/L) and removal efficiencies (%) at different UV absorbance-specific coagulant dose levels

5.2.2 NOM fraction removal

Prior to the presentation of the EEM and SEC results, the NOM fraction removal efficiencies shall be presented for the applied coagulant dose range of 0.9 to 3 mg Fe/L. This corresponds to raw water DOC-specific, colour-specific and UV-abs specific dosage levels of 0.3-0.99 mg Fe/mg DOC; 0.06-0.21 mg Fe/mg Pt, and 0.09-0.29 mg Fe/m-1, respectively.

Figure 24 summarizes the obtained removal efficiencies with respect to DOC and UV-absorbance during these runs, while in Figure 25 the NOM-fraction removal efficiencies are presented.

Figure 26 presents the remaining NOM fraction concentrations, and Figure 27 illustrates the remaining hydrophobic (VHA+SHA) and hydrophilic (fraction CHA+NEU) at different coagulant dose levels.

It appears from the results that the hydrophobic fractions (in specific the VHA) are effectively removed by enhanced coagulation. Also the hydrophilic CHA fraction is effectively removed, but since the CHA concentrations are low and the NEU fraction concentration increases somewhat during coagulation treatment, the overall hydrophilic NOM fractions removal efficiency is relatively insignificant.

BDOC concentration levels are close to zero in raw as well as coagulated water samples.

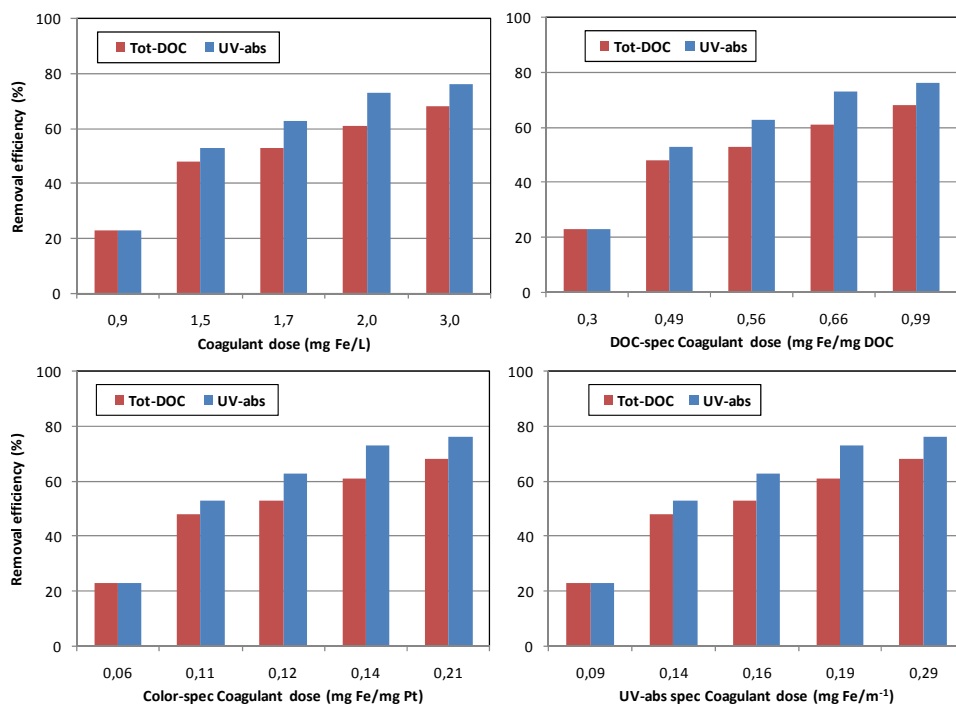


Figure 24 DOC and UV-absorbance removal efficiencies obtained at different coagulant doses (VIVA pilot; coagulation pH 4.4; filtration rate 10 m/h).

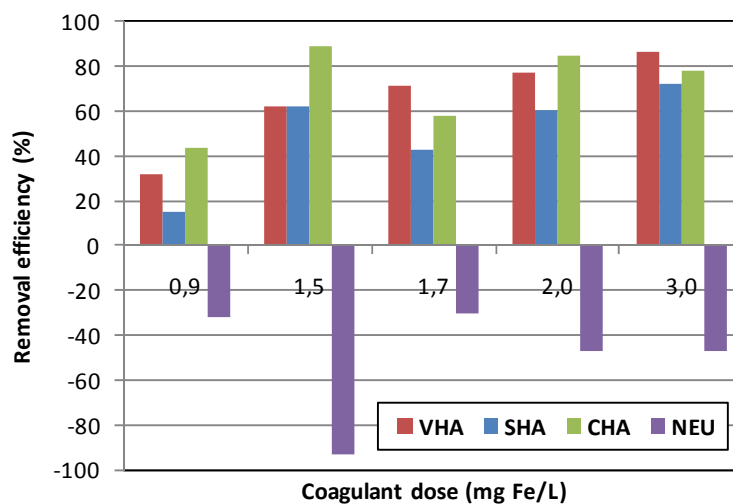


Figure 25 NOM fraction removal efficiencies obtained at different coagulant doses (VIVA pilot; coagulation pH 4.4; filtration rate 10 m/h).

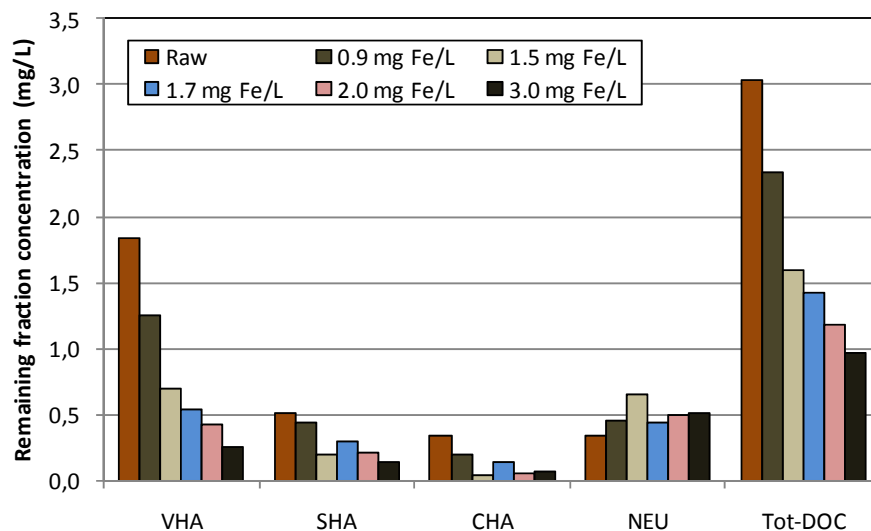


Figure 26 NOM fraction removal efficiencies obtained at different coagulant doses (VIVA pilot; coagulation pH 4.4; filtration rate 10 m/h).

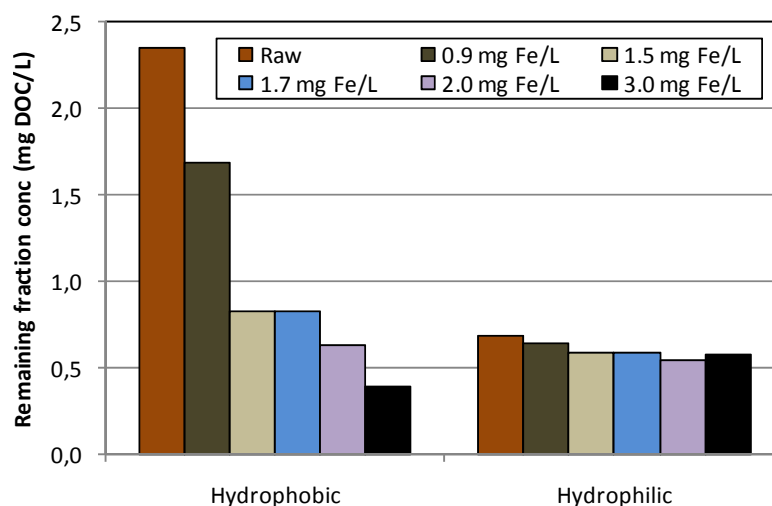


Figure 27 NOM fraction removal efficiencies obtained at different coagulant doses (VIVA pilot; coagulation pH 4.4; filtration rate 10 m/h).

5.3 Ozonation-biofiltration studies at VIVA pilot, Trondheim WTP

5.3.1 Ozonation-biofiltration pilot at VIVA

The ozonation-biofiltration pilot plant at VIVA (Figure 28) consists of an up-flow bubble contactor where ozone is dissolved into water and a reaction tank where dissolved ozone has time to react with water and where ozone degradation kinetics (and CT-values) can be studied. At the water flow used in these tests (0.2 L s^{-1}), the HRTs in the tanks are 2

min and 22 min, respectively (Table 3). In the biofilter, CaCO_3 is used as a filter media to study whether biofiltration and corrosion control can be achieved in the same filter. This would made upgrading of many Norwegian treatment plants with ozonation easier. The biofilter has been operated at filter velocity of 11 m h^{-1} and EBCT of 19 min based on original bed height. Due to gradual dissolution of CaCO_3 , the bed height has decreased during the study and therefore EBCT has become slightly reduced.

The experiments started in late 2007 to provide baseline results for further process optimisation. The average ozone dose has been 2.6 mg L^{-1} which equals a carbon based specific dose of $0.9 \text{ mg O}_3/\text{mg DOC}$ and a colour specific dose of $0.2 \text{ mg O}_3/\text{mg Pt}$. For comparison, occasional samples were taken also from the alkaline filter (with no preozonation).

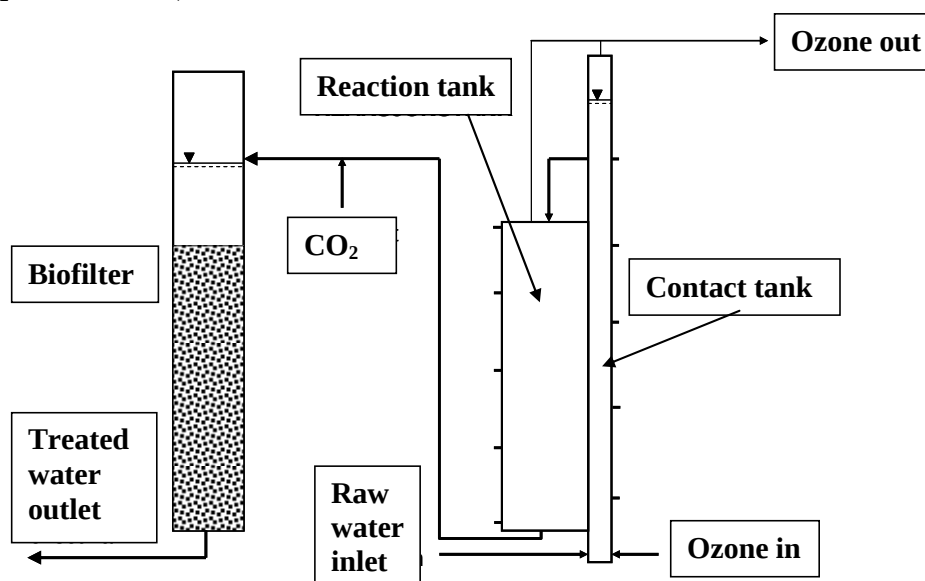


Figure 28. Process scheme – VIVA ozonation-biofiltration pilot.

Table 3. Design data for the ozonation-biofiltration pilot plant at VIVA

	Volume (m^3)	EBCT(min)
Contact tank	0,024	2,0
Reaction tank	0,26	22
Biofilter	0,23	19

5.3.2 Removal of colour, UV-abs and DOC during ozonation

The removal of colour and UV-absorbing matter is dependent on the applied ozone dose as shown in Figure 29. The obtained removal efficiencies are also compared to a model prediction (Ødegaard et al. 2006):

$$\frac{C}{C_0} = \frac{1}{1 + 20 \cdot D / C_0}$$

where C_0 = raw water colour (mg Pt/l),
 C = ozonated water colour (mg Pt/l)
 D = ozone dose (mg O_3 /l)

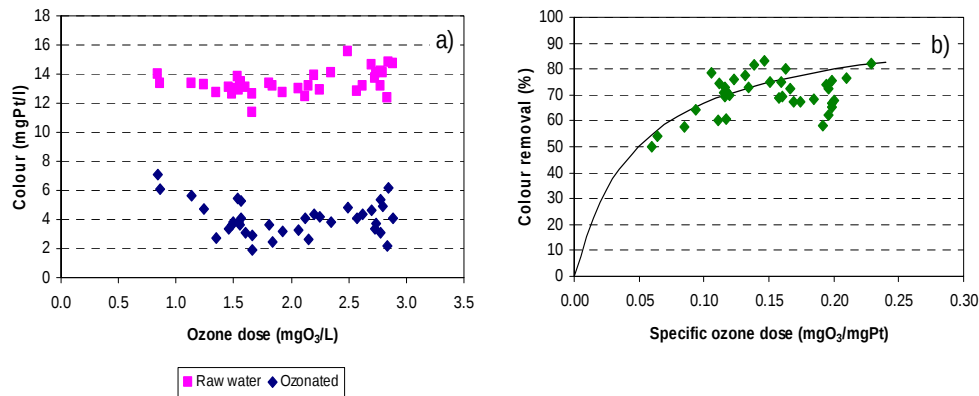


Figure 29. Colour levels in raw and ozonated VIVA water (a), and obtained versus model predicted (curve) colour removal colour (b)

The removal of UV-absorbing material follows the same pattern as colour. For DOC, however, the removal efficiency obtained by ozonation is low (< 10 %), as expected (Figure 30).

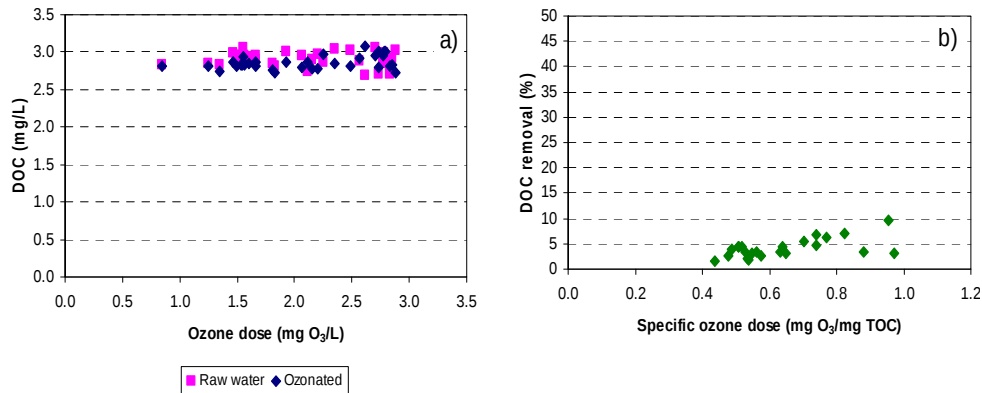
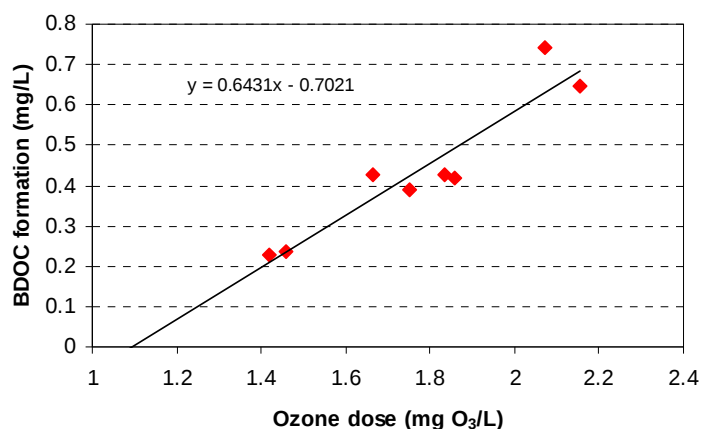


Figure 30. Removal of DOC during ozonation at VIVA pilot, Trondheim.

5.3.3 BDOC increase during ozonation

Figure 31 shows the increase in BDOC as a result of ozonation at different doses.



Figur 31. BDOC increase with increasing ozone dose at VIVA pilot

5.3.4 Biofiltration performance

Figure 32 shows the DOC removal during biofiltration calculated from raw water and from ozonated water concentrations. As a reference, the DOC removal during pure alkaline filtration (line 1 in the VIVA pilot) is shown as a reference.

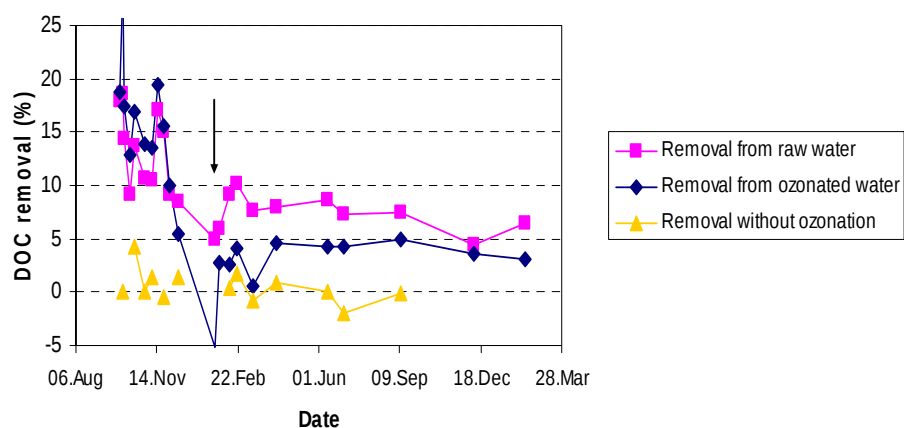


Figure 32. DOC removal during biofiltration at the VIVA pilot, calculated from raw water and from ozonated water concentrations. DOC removal during alkaline filtration is shown as a reference. (The arrow indicate the start of CO₂-dosing)

BDOC analyses on ozonated and on ozonated and biofiltered water samples are shown in Table 4. The BDOC removal obtained during biofiltration is low (10-33%) compared to literature data (40 til 70%) (Juhna and Melin, 2007). The remaining BDOC are considered high enough to sustain biological regrowth. Although good criteria are nor established, it is considered form literature data that levels below some 0.25 mg/L are required to avoid regrowth in cold water, non-chlorinated systems (Niquette et al., 2001).

Table 4. BDOC in ozonated and in ozonated and biofiltered samples from VIVA pilot

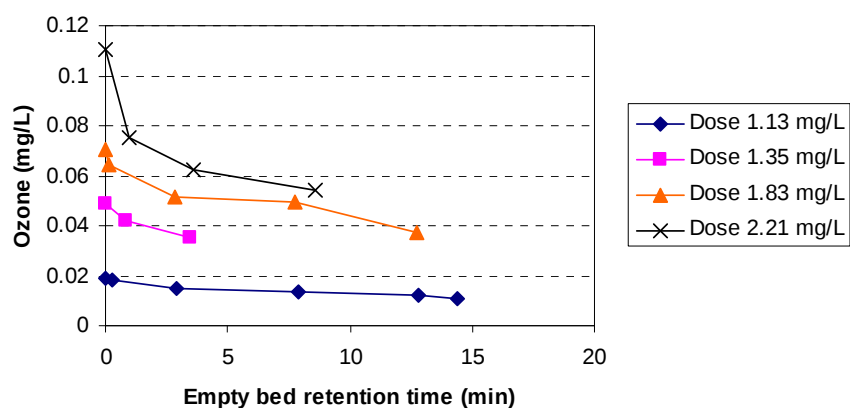
Date	Dose (mgO ₃ /L)	BDOC in ozonated water (mg/L)	BDOC i biofiltered water (mg/L)	BDOC removal (%)
10.4.2008	1.7	0,40	0,36	10
11.6.2008	2.2	0,65	0,51	22
30.6.2008	1.8	0,43	0,29	33

From the low removal efficiencies obtained during biofiltration, it was speculated if residual ozone was present in the biofilter influent, thus inhibiting the biological activity. However, presence of organic matter in the top sections of the biofilter should rapidly remove ozone residuals. It was also possible that CaCO₃ is not a good biofilter media because the dissolution of this material might prevent effective and stable biofilm establishment.

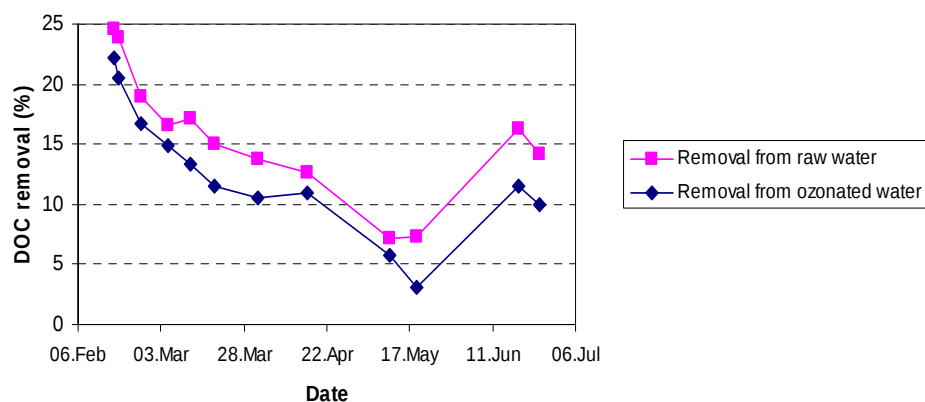
Analyses of water samples taken along the biofilter column showed smal amounts of ozone in the biofilter influent (Figure 33). It appears that ozone penetrates the top sections of the biofilter thus preventing biological activity and reducing the “effective” EBCT of the biofilter.

To prevent the negative effects of residual ozone and to secure effective and stable biofilm attachment, activated carbon (1 m) was introduced as the top layer of the biofilter unit (Feb 2009).

With the activated carbon in place, Figure 34 shows the obtained DOC removal efficiencies calculated from raw water and from ozonated water concentrations for the periode from February to July 2009. The applied ozone doses were in the range of 1.2-2.1 mg/L, i.e. 0.4-0.9 mg O₃/mg DOC during this time periode.



Figur 33. Residual ozone concentrations measured along the biofilter column at different ozone dosages. VIVA pilot.



Figur 34. DOC removal efficiencies at VIVA pilot with activated carbon as the new top layer in the biofilter.

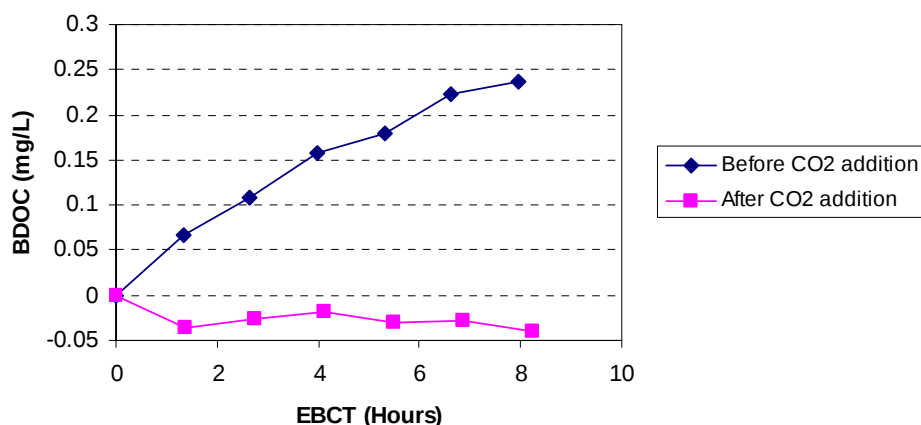
Two BDOC measurements (with SINTEF's 6 columns in series set-up) were performed after the inclusion of the activated carbon layer. The results are presented in Table 5. The results are more promising, with higher BDOC removal efficiencies obtained during biofiltration (31 in May and 51 % in June).

Table 5. BDOC in ozonated water and in ozonated and biofiltered (with activated carbon layer) water at VIVA pilot

Date	Dose (mg O ₃ /L)	BDOC in ozonated water (mg/L)	BDOC in biofiltered water (mg/L)	Removal (%)
18.5.2009	1.75	0.39	0.27	31
22.6.2009	1.83	0.74	0.36	51

At VIVA CO₂ is applied as part of the corrosion control process. A BDOC test was performed with ozonated water prior to and after CO₂ addition (Figure 35) in order to study if pH could be inhibitory. The pH in the two samples were pH 7.1 (without CO₂) and 5.6 (with CO₂). During the BDOC columns the pH levels increased to pH 7.3 and 6.2, respectively.

The results presented in Figure 35 indicate that CO₂-addition/low pH may inhibit the biofiltration process.



Figur 35. BDOC test of ozonated water at VIVA pilot prior to (pH 5.6-6.2) and after CO₂ addition (pH 7.1-7.3). Applied ozone dose: 1.5 mg/L, i.e. 0.6 mg O₃/mg DOC.

5.4 Advanced analyses

Ten water samples from the VIVA pilot plant in Trondheim, Norway were analyzed by UNESCO IHE Delft (S. Sharma) to characterize the organic matter present in raw water and their removal during different treatment processes.

The details of the samples were as follows:

- 1) Five inlet raw water and 5 treated water samples from the enhanced coagulation-alkaline filtration pilot, with varying Fe-coagulant doses in the 5 samples, i.e. 0.9, 1.5, 1.7, 2.0 and 3.0 mg Fe/L, respectively.
- 2) Two additional samples from the ozonation-biofiltration pilot:
 - i) after ozonation, and ii) after ozonation + biofiltration (same raw water as above)

For each samples the following parameters were measured:

- dissolved organic carbon (DOC)

- UV-absorbance (UVA254)
- Total nitrogen (TN)
- Fluorescence EEM
- Size Exclusion Chromatography – Dissolved Carbon (SEC- DC)

The results of these measurements and key findings are presented below, i.e. Table 6 for the raw water and Table 7 for the treated water samples.

Table 6. DOC, UV254, SUVA and T-N values in raw water samples (IHE-Delft)

	F3-6R	F3-7R	F3-8R	F3-9R	F3-10R	AVG	STDEV
DOC (mg/L)	3.05	2.97	2.96	3.07	3.08	3.03	0.06
UV-abs (1/m)	9.7	9.7	10.2	9.9	10.0	9.90	0.21
SUVA (L/mg-m)	3.2	3.3	3.4	3.2	3.3	3.3	0.1
T-N (mg/L)	0.30	0.28	0.28	0.30	0.29	0.31	0.28

Table 7. DOC, UV254, SUVA and T-N values in treated water (IHE-Delft)

	F3-6B	F3-7B	F3-8B	F3-9B	F3-10B	O3	O3+B
DOC (mg/L)	1.81	2.18	1.64	1.29	1.33	2.99	2.77
UV-abs (1/m)	3.1	7.0	3.1	1.9	2.5	4.3	3.9
SUVA (L/mg-m)	1.7	3.2	1.9	1.5	1.9	1.4	1.4
T-N (mg/L)	0.26	0.24	0.26	0.28	0.27	0.31	0.28

Main observations:

- Average DOC in raw water was 3.03 mg/L and average total-nitrogen is 0.29 mg/L
- DOC removal varied with the dose of coagulant. DOC removal for raw water samples number 6, 7, 8, 9 and 10 were 41%, 27%, 45%, 58% and 57% respectively
- As expected there was no DOC removal after ozonation, however there was significant change in SUVA values after ozonation (from 3.18 to 1.41)
- There was no change in total nitrogen after coagulation, ozonation or ozonation + biofiltration
- SUVA values were decreasing after coagulation, ozonation as well as ozonation+biofiltration indicating that there is preferential removal of humic (UV absorbing) organic matter

EEM

The fluorescence excitation-emission matrixes (EEM) of the 10 samples from the VIVA pilot in Trondheim are presented in Figure 36. In all the samples there were three clearly visible peaks: (i) humic/fulvic-like, (ii) humic-like and (iii) protein-like substances. Table 8 summarizes the intensities of different peaks in EEM spectra and fluorescence ratio (FR) for the samples.

Table 8. Intensities of different peaks in EEM spectra and Fluorescence ratio

	Humic like primary ① ¹	Humic like secondary ② ²	Protein like ③ ³	FR ⁴	REM
Raw F3-7	3.9924	5.9597	1.3133	0.90	
Raw F3-8	27.5555	7.4235	2.223	0.85	
Raw F3-6	40.3276	10.0230	1.3902	0.89	
Raw F3-10	3.8627	6.2895	3.7816	0.85	
Raw F3-9	15.7439	6.7195	2.7584	0.88	
F3-7 Coag	4.0275	4.2244	2.1803	0.90	0.9 Fe
F3-8 Coag	1.6715	1.6698	1.4572	0.80	1.5 Fe
F3-6 Coag	1.4225	2.4327	1.9858	0.82	1.7 Fe
F3-10Coag	1.1888	2.0947	1.6537	0.81	2.0 Fe
F3-9 Coag	1.0944	1.7444	1.6062	0.85	3.0 Fe
O ₃	1.5038	2.0127	3.4856	0.82	2mg O ₃ /L
O ₃ +Biof	1.7238	2.4301	3.4203	0.80	20 min EBCT

¹ Humic like primary (Excitation: 330-350nm, Emission: 420-480 nm) (Leenheer and Crowe, 2003)

² Humic like secondary (Excitation: 250-260 nm, Emission: 380-480 nm) (Leenheer and Crowe, 2003)

³ Protein like (Ex: 250-280 nm, Em: 280-350 nm) (Baker, 2001)

⁴ Ratio of FI (Ex=370 nm, Em=450 nm) to FI (Ex=370 nm, Em=500 nm) (FR > 1.8 : algae or bacteria based origin (i.e., autochthonous), FR < 1.5 : plant or soil based origin(i.e., allochthonous) suggests origin of DOC (Donahue et al., 1998; McKnight et al., 2001)

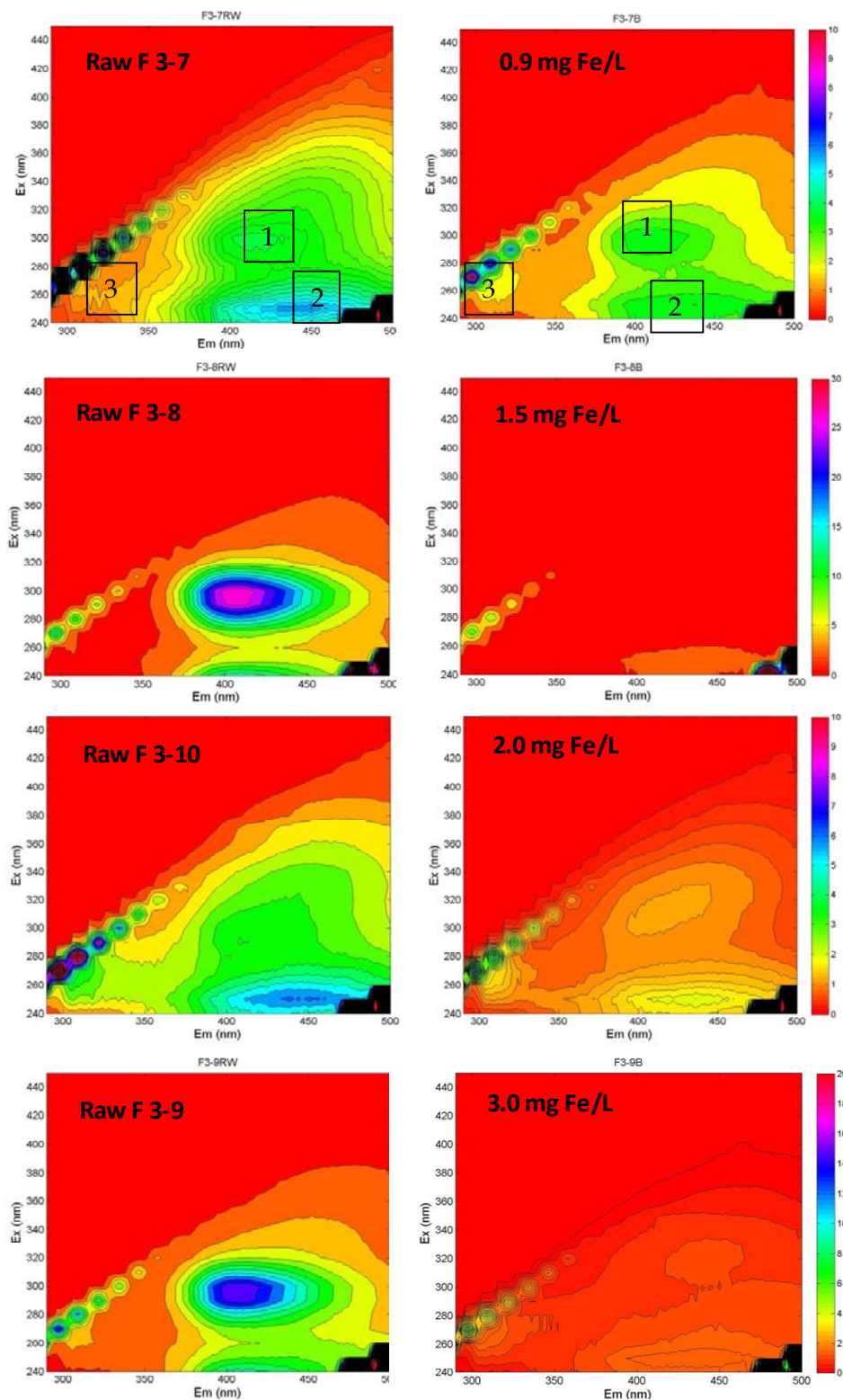


Figure 36. EEM in raw water (left) and coagulated (right) water samples (0.9-3 mg Fe/L) from VIVA, Trondheim

For comparison, the EEM for ozonated and for ozonated and biofiltered water from the VIVA pilot is presented in Figure 37. The ozonated and ozonated and biofiltered water samples contain far more NOM than the coagulated samples, both humic-like (peak 1), humic-like secondary (peak 2), and protein-like substances (peak 3).

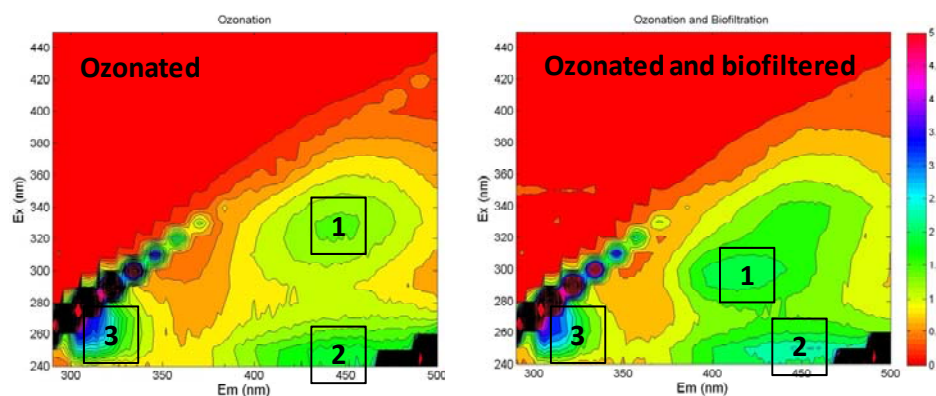


Figure 37. EEM in ozonated (left) and ozonated and biofiltered (right) water samples from VIVA, Trondheim

Main observations:

- Humic-like primary peaks were removed by 63 to 96% after coagulation
- Humic-like secondary peaks were removed by 30 to 82%
- No significant removal of protein like peaks after coagulation or ozonation
- The fluorescence ratio (FR) for all the samples were less than 1.5 indicating that organic matter present in water samples were of plant or soil based origin

SEC

The SEC-DC chromatograms for each of the raw and coagulated VIVA pilot sample are presented in Figure 38 below. For each separate chromatograms were obtained for UV210, Dissolved carbon, Fluorescence and UV254 to characterize different fractions/sizes of the organic matter.

For comparison, Figure 39 presents SEC results from raw water, coagulated water, and ozonated-biofiltered water samples.

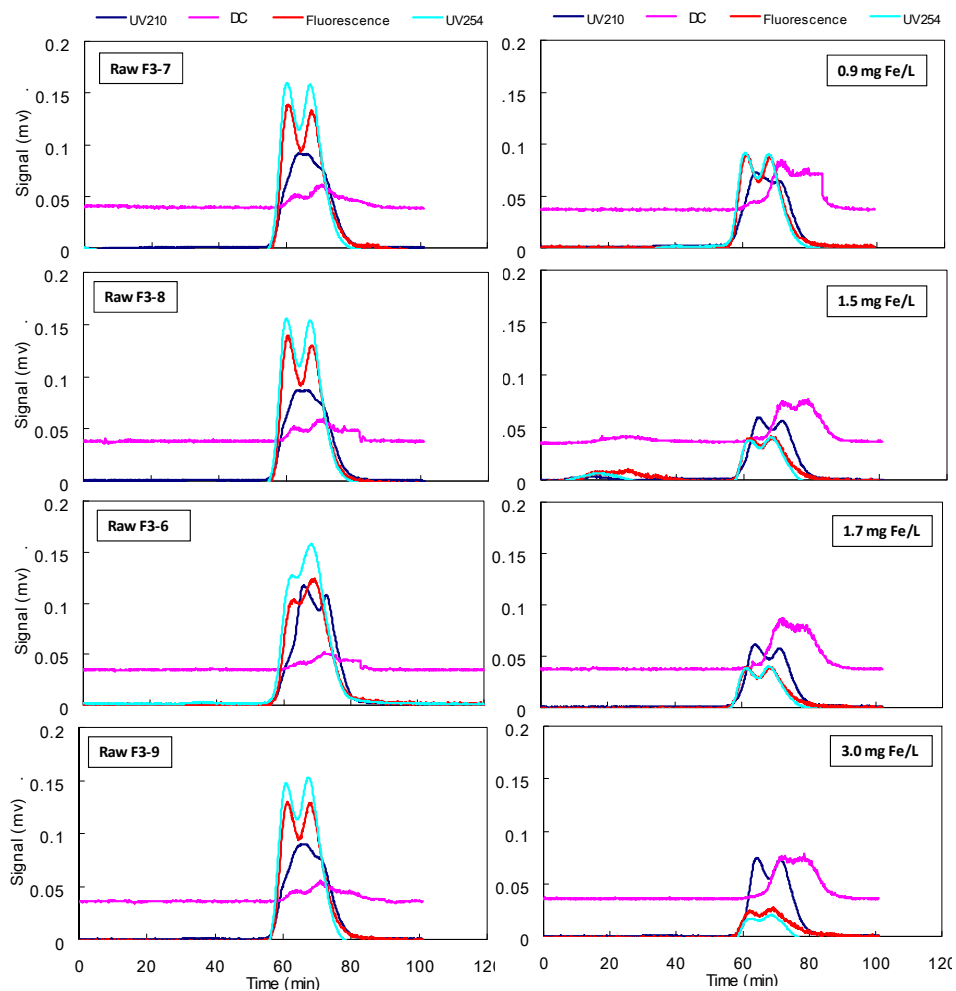


Figure 38. SEC-UV, SEC-DOC and SEC-fluorescence for raw water (left) and coagulated (0.9-3 mg Fe/L) water samples (right) from VIVA, Trondheim

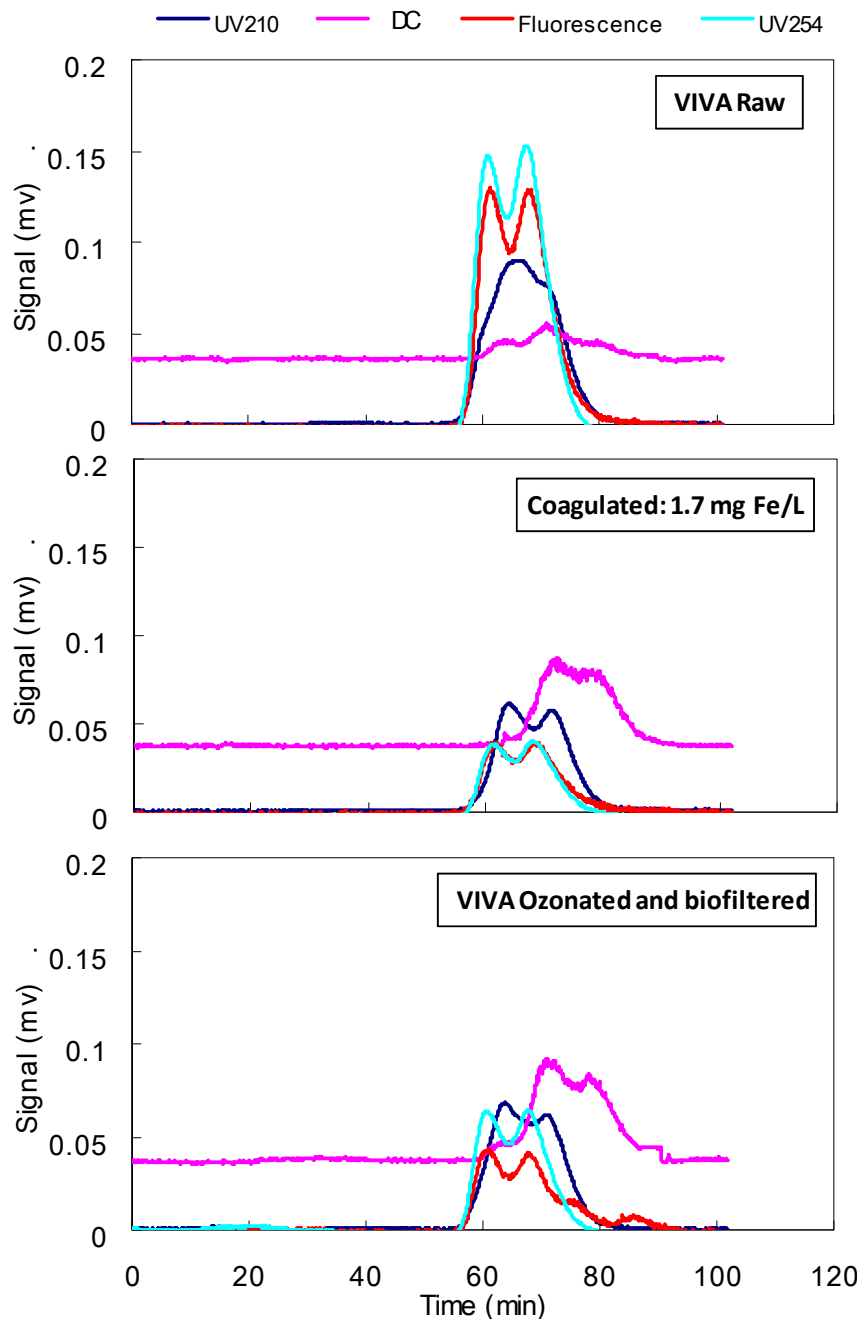


Figure 39. SEC-UV, SEC-DOC and SEC-fluorescence for raw water (top), ozonated water (middle), and coagulated water samples (bottom) from VIVA, Trondheim

Main observations:

- For majority of the samples intensity of UV210nm, Fluorescence (275nm, 450nm) and UV254nm was decreased after coagulation due to the reduction of humic in all samples.

- SEC-DC shows that coagulation removed more of high molecular weight substances.
- As shown earlier, DOC concentrations as well as humic like materials decreased with coagulation
- It is to be noted that the dissolved carbon signal in SEC-DC was increased after the addition of coagulants. This may be due to the addition of inorganic coagulants which were detected in dissolved carbon detector. After coagulation, the size of dissolved carbon peak was shifted from high molecular weight to lower molecular weight.

6. Studies at full-scale WTPs

Studies at full-scale WTPs were performed in Bergen, Norway (enhanced coagulation (EC) facilities) and in neighbouring municipalities (ozonation-biofiltration (OBF) facilities).

A summary of the main results are presented here, and more details can be found in the TECHNEAU Case Bergen deliverable D7.11.3B.

Compared to VIVA and the raw water from Lake Jonsvatnet in Trondheim, the lakes used as water sources in Bergen are smaller and have more seasonal quality variability. However, the SUVA levels are high (> 4.5) thus indicating good treatability by coagulation.

6.1 Enhanced coagulation

The WTPs in Bergen comply well ($> 99.5\%$) with the Norwegian water quality standards and the required barrier indicator levels (Table 9). As an illustration, Table 9 shows data on raw and treated water qualities and treatment performance for the four enhanced coagulation facilities in 2008.

Table 9. Raw and treated water quality data and coagulant dosage levels applied at the four EC facilities (2008).

2008	pH	Turbidity (NTU)	Color (Pt)	UV-abs (m ⁻¹)	Residual coagulant (µgMe/L)	Coagulant dose (mg/L)(µmol/mg Pt)
SVD-Raw	6.5±0.2	0.73±0.19	17±6			3.7±0.2 (Fe) 4.0±1.7
SVD-Treated	8.2±0.1	0.08±0.04	2±0	1.2±0.3	10±6	
SAE-Raw	5.2±0.2	0.53±0.09	24±5			2.5±0.0 (Al) 4.0±0.6
SAE-Treated	7.8±0.1	0.10±0.13	3±3	1.3±0.3	26±7	
JOR-Raw	6.6±0.2	0.54±0.17	19±4			3.9±0.1 (Fe) 3.7±0.5
JOR-Treated	8.1±0.2	0.08±0.04	2±4	1.5±0.4	11±5	
KIS-Raw	6.0±0.4	0.28±0.11	28±2			2.4±0.8 (Al) 3.1±0.9
KIS-Treated	7.4±0.2	0.08±0.03	3±1	2.7±0.3	21±12	

Three major conclusions can be drawn from the data in Table 9:

1. SVD WTP has the greatest variations in raw water quality over the year (2008) while KIS WTP has the least
2. In spite of this, SVD WTP applies a relatively stable coagulant dose level over the year, while KIS WTP has the greatest variability of the four facilities
3. The raw water colour-specific coagulant dose levels vary significantly over the year and between the WTPs (3.1-4.0 $\mu\text{mol}/\text{mg Pt}$, i.e. 0.17-0.22 mg Fe/mg Pt). This is also true for the UV-abs and DOC-specific coagulant doses.

The above treated water quality data indicate that the water safety and safety barrier efficiency is well maintained during the coagulation process. However, the data also indicate the existence of some overdosing of coagulants and thus some potential savings in the use of chemicals and energy. This impression is supported by a comparison of the applied coagulant doses to those predicted from EC models (Eikebrokk et al., 2007). Thus, the optimization trials were focused on the possibilities of reducing the amount of coagulants used. Reduced coagulant doses will in turn reduce the sludge load to the filter, reduce filter head loss and extend filter run times, reduce the backwash water consumption, reduce the energy requirements for pumping of backwash water, and reduce the operation costs. The possible benefits also include a safety element because the safety barrier efficiency and obtained log-reductions of pathogens are reduced during filter ripening. Thus extended filter run lengths imply less number of filter ripenings per unit time and thereby improved safety.

In addition, some potential improvements may be implemented with respect to process control. Since 2008, Bergen Water have put a lot of efforts in - and significantly improved - the adaptation of the coagulation conditions to the variations in raw water quality. In addition, a Delta UV-probe from S::can was installed at SVD WTP for on-line raw water quality measurements (e.g. colour, UV-absorbance, TOC, DOC, and turbidity). The probe readings were tested against laboratory data and a parallel on-line color monitor. For color and UV-absorbance, the probe readings agreed very well with laboratory data, while for parameters like turbidity and TOC/DOC some additional adjustments/recalibrations are needed. With a still increasing NOM content and more variability in the raw water quality (from climate change), the Delta UV probe is considered a valuable tool for the purpose of coagulation process control in the future.

6.1.1 Optimization results at SVD and JOR WTPs

Two of the four EC facilities in Bergen (i.e. SVD and JOR WTPs) have been subject to optimization trials according to the procedures within the TECHNEAU optimization roadmap.

The optimization trials were performed by adjusting the coagulation pH in a step-wise manner for each coagulant dose level. Normally 4-6 different pH levels were tested for each level of Fe-coagulant, with 3-5 levels of coagulant dosage. Following each change in coagulation pH/coagulant dosage, samples of raw, coagulated, and treated water were taken after sufficient time (normally 3-5 hrs) of operation for steady-state conditions to be achieved (i.e. after establishment of stable on-line filtered water turbidity readings). The filters were backwashed between every run. At both facilities, the prevailing “standard” operation conditions (i.e. the applied coagulation pH and Fe-coagulant dose) were used in the first round of optimization trials as a reference basis.

Table 10 shows that the treated water quality at SVD WTP was maintained well above the compliance and barrier indicator levels also during the optimization trials. Similar results were achieved at JOR WTP.

Table 10. Raw and treated water quality data measured at SVD WTP during the optimization trials in 2009.

SVD 2009	pH	Turbidity NTU	Colour mgPt/L	TOC mg/L	Ca mg/L	Alkalinity mmol/L	SUVA Lm ⁻¹ mg ⁻¹
Raw	6.1±0.1	0.57±0.09	31±2	3.5±0.2	1.4±0.3	0.02±0.01	4.5±0.2
Treated	8.0±0.2	0.05±0.01	2±1	0.8±0.1	29±7	1.11±0.23	0.7±0.2
N=36; Water temp 11.5±1.5 °C							

Figure 40 shows more in detail how some major treated water quality parameters (turbidity, UV-transmittance, residual Fe and TOC) responded to the step-wise reductions in applied coagulant dose levels and the coagulation-pH values applied, i.e. to variations within the ranges of 2.5-4.25 mg Fe/L and pH 3.2-4.8, respectively for SVD WTP.

For JOR WTP, the optimization results are shown in Figure 41. Variation in filtration rates within the range of 3-8 m/h did not significantly affect treated water quality.

It is evident that the given water quality parameters were not significantly affected of the imposed coagulant dose reductions. In addition, the results are not very sensitive to the variations in coagulation pH within the tested ranges. This is in part due to the

beneficial effects of the deep alkaline filter layer that has proven very effective in reducing Fe-coagulant residuals and to the efficient adsorbing capabilities of the metal hydroxide deposits within the contact filter bed.

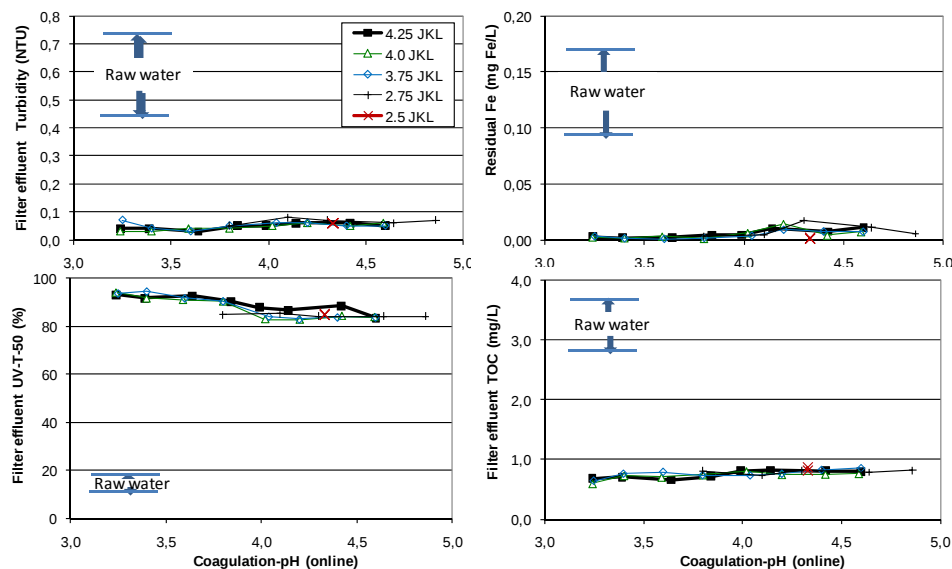


Figure 40. Range of raw water quality variability and treated water quality levels obtained at different coagulation pH and coagulant dose levels during the optimization trials at SVD WTP in 2009/10 (Eikebrokk et al., 2010).

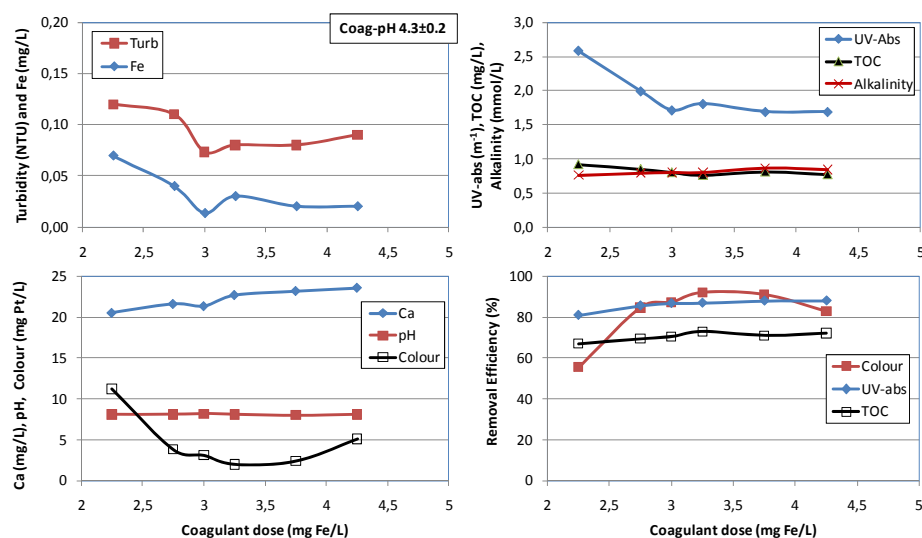


Figure 41. Effects of different coagulant dose levels on major filter effluent quality parameters (residual turbidity, Fe, colour, TOC, UV-absorbance), and the effects of coagulant doses on NOM removal efficiencies (colour, UV-abs and TOC) achieved during the optimization trials at JOR WTP in 2010.

The results presented in Figure 40 and 41 show that there is a potential for coagulant dose reductions of 35-40 % without compromising treated water quality, both at SVD WTP and at JOR WTP.

6.1.2 Sludge production and filter ripening

Figure 42 shows the effects of coagulant dose level on sludge production rates (as suspended dry solid), and on filter ripening time (i.e. until turbidity falls below 0.2 NTU). The increase in filter ripening time as a result of less coagulant dosage is more significant at SVD WTP compared with JOR WTP.

The significant reductions in sludge production that can be achieved further support the sustainable effects of reduced coagulant dosage. This also implies significant reductions in energy demand and CO₂ emissions during sludge processing and transport. When considering the overall reductions in the use of resources (chemicals, energy, diesel oil) and the corresponding reductions in GHG emissions, at the WTP as well as during manufacturing and transport, the possible reductions in costs, and societal and environmental impacts appear to be quite significant.

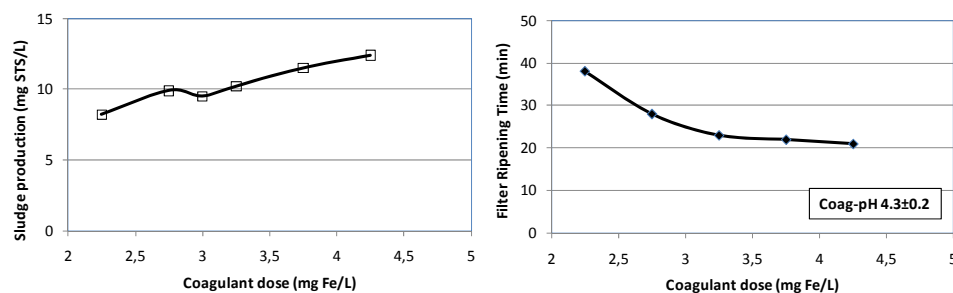


Figure 42. Effects of coagulant dose level on sludge production rates (left) and filter ripening times (right) during the optimization trials at JOR WTP in 2010.

6.2 Ozonation-biofiltration

The ozonation-biofiltration facilities studied here (SUN WTP and AUS WTP) produce water in compliance with the Norwegian and (EU) water quality standards. Compared to the enhanced coagulation facilities, problems related to biostability and microbial regrowth in the distribution system are more pronounced. SUN WTP has relatively good quality raw water that is considered well suited for ozonation-biofiltration treatment. The raw water at AUS WTP however, contains significantly more NOM and thus have a higher ozone demand to control colour and UV-absorbance at compliance levels. The seasonal variability in raw water quality is also larger at this facility, thus imposing greater challenges with respect to process control.

6.3 EC and OBF performance assessments

The diagnostic tools presented before can be applied to further assess the water treatment performance and optimization results presented above. In addition, they may provide informative links between treatment performance, raw water quality and seasonal variability, water treatability by various methods, as well as water quality deteriorating processes within the distribution system.

6.3.1 NOM fraction and BDOC concentration levels in raw water samples

Tables 11 and 12 present the overall NOM fraction concentrations, SUVA and BDOC data in raw water samples taken at different seasons at the four enhanced coagulation (EC) facilities, and at the two ozonation-biofiltration (OBF) facilities included in Techneau Case Bergen, respectively. Concentration levels (e.g. mg/L) as well as fractions of total DOC (%) are given. Due to the subtractions performed in the NOM fraction and BDOC calculations, small negative values may occur in a few cases because the TOC-monitor is operating within a range of ± 0.1 mg/L.

The data presented in Tables 11 and 12 show that although the average NOM (DOC) levels are higher at the OBF facilities, the NOM fraction distributions and the BDOC levels are quite similar. VHA is the dominating NOM fraction in the all raw waters (52-77 % of DOC). The CHA fraction is limited (0-14 % of DOC), while the SHA (9-20 % of DOC) and NEU (7-24 %) fractions are quite similar. The raw waters must be considered as biologically stable, with average BDOC levels below 0.14 mg/L (3 % of DOC).

Table 11. NOM fractions, SUVA and BDOC data in raw water samples from the EC facilities (June 2008-May 2010)

EC-facilities	DOC mg/L	VHA mg/L (%)	SHA mg/L (%)	CHA mg/L (%)	NEU mg/L (%)	SUVA L/m mg	BDOC mg/L (%)
AVG	2.73	1.87 (67)	0.35 (13)	0.14 (5)	0.37 (15)	4.9	0.08 (1)
STDEV	0.79	0.66 (7)	0.11 (3)	0.08 (3)	0.09 (4)	0.4	0.10 (3)
MAX	4.36	3.19 (77)	0.59 (20)	0.28 (14)	0.59 (24)	5.5	0.30 (7)
MIN	1.35	0.70 (52)	0.18 (9)	-0.03 (-1)	0.24 (10)	4.0	-0.06 (-2)
N	23	23	23	23	23	23	12
The calculations may results in small negative values due to the TOC-monitor accuracy of ± 0.1 mg/L							

Table 12. NOM fractions, SUVA and BDOC data in raw water samples from the OBF facilities (May 2008-Dec 2010)

OBF-facilities	DOC mg/L	VHA mg/L (%)	SHA mg/L (%)	CHA mg/L (%)	NEU mg/L (%)	SUVA L/m mg	BDOC mg/L (%)
AVG	4.95	3.50 (69)	0.61 (12)	0.32 (7)	0.52 (11)	4.4	0.14 (3)
STDEV	1.44	1.23 (6)	0.18 (1)	0.18 (4)	0.17 (5)	0.3	0.11 (2)
MAX	6.74	5.17 (77)	0.85 (15)	0.61 (12)	0.89 (22)	4.7	0.27 (5)
MIN	2.65	1.67 (59)	0.31 (11)	-0.04 (-1)	0.32 (7)	3.9	-0.04 (-2)
N	9	9	9	9	9	6	9
1) The calculations may results in small negative values due to the TOC-monitor accuracy of ± 0.1 mg/l							

To illustrate the seasonal variability in raw water quality, Figure 43 and 44 show the NOM fraction concentrations in all sampling rounds at SVD WTP as mg/L of DOC, and as fractions (%) of total DOC, respectively. At SVD WTP total DOC concentration levels vary significantly within the range of 1.3-3.8 mg/L, with VHA and the most dominating and CHA as the least dominating fraction.

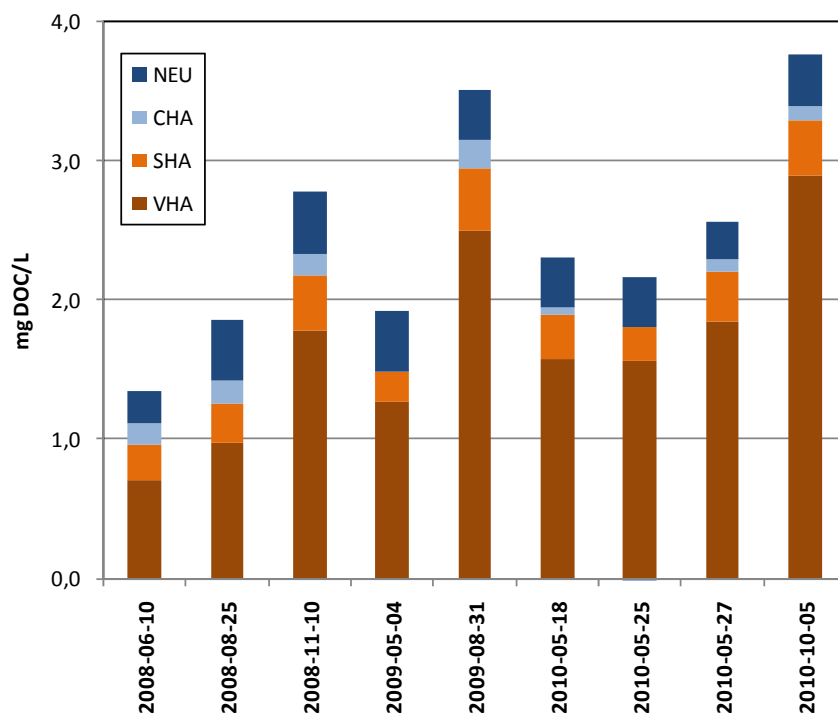


Figure 43. Seasonal variability in NOM fraction concentrations (mg/L) during 9 sampling rounds at SVD WTP (June 2008-Oct 2010)

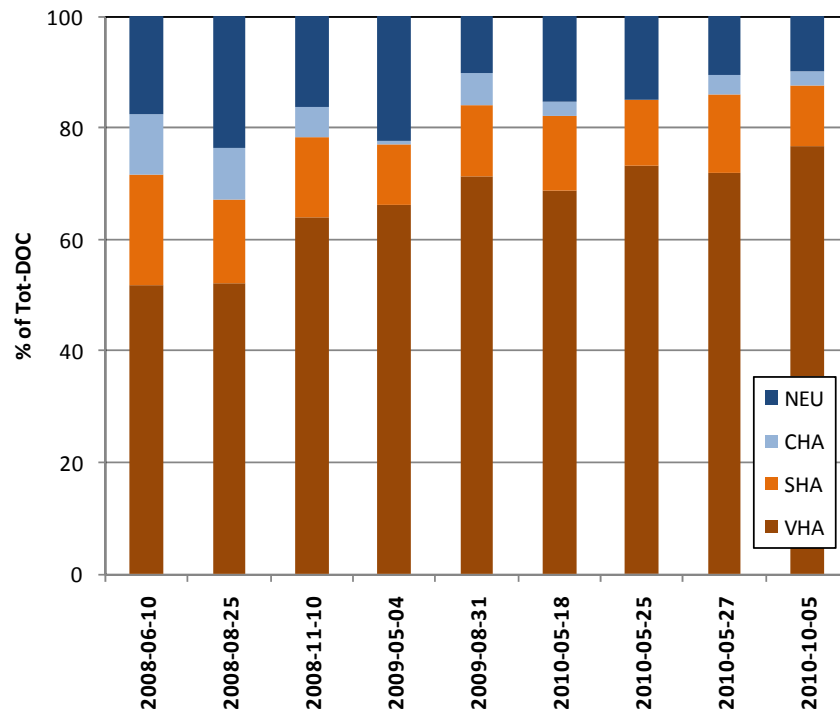
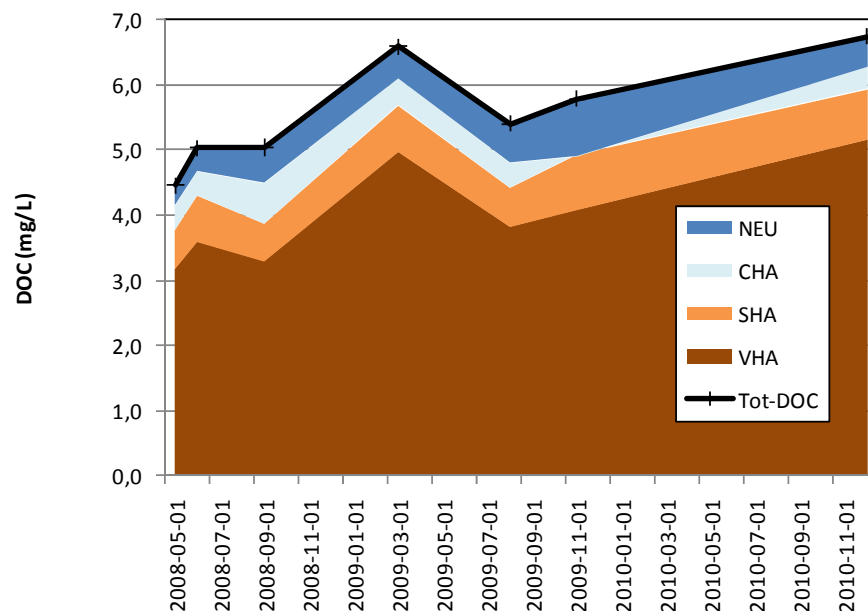


Figure 44. Seasonal variability in NOM fraction concentrations (as % of tot-DOC) during 9 sampling rounds at SVD WTP (June 2008-Oct 2010)

For AUS WTP, Figure 45 shows the NOM fraction and total DOC variability during 5 sampling rounds from May 2008 to December 2010. Again, VHA is the dominating NOM fraction. The total DOC levels are however higher at AUS WTP compared with the levels at the EC facilities.



	2008-05-06	2008-06-16	2008-09-29	2009-03-09	2009-08-31	2009-11-30	2010-12-06
NEU	0,32	0,36	0,55	0,50	0,60	0,89	0,47
CHA	0,36	0,36	0,61	0,40	0,37	-0,04	0,33
SHA	0,60	0,71	0,58	0,71	0,60	0,85	0,77
VHA	3,18	3,60	3,30	4,98	3,83	4,09	5,17
Tot-DOC	4,46	5,03	5,04	6,59	5,40	5,79	6,74

Figure 45. Seasonal variability in NOM fraction and total DOC concentrations (mg/L) during 7 sampling rounds at AUS WTP (May 2008-Dec 2010)

6.3.2 NOM fraction and BDOC concentration levels in treated water

Tables 13 and 14 present the overall NOM fraction concentrations, SUVA and BDOC data in treated water samples taken at different seasons at the four enhanced coagulation (EC) facilities, and at the two ozonation-biofiltration (OBF) facilities, respectively. The samples are taken prior to the UV-disinfection step. Concentration levels (e.g. mg/L) as well as fraction contributions to the total DOC (%) are given. Due to the subtractions performed in the NOM fraction and BDOC calculations, small negative values may occur in a few cases because the TOC-monitor is operating within a range of ± 0.1 mg/L.

The tables show that the relatively similar raw water distribution patterns have changed in a treatment-specific way. For EC, the VHA fraction contribution has now been reduced to levels of 0-59 % of DOC, and the NEU fraction contribution has increased significantly to levels

of 20-70 % of the remaining DOC. The SHA and CHA fractions contribute 0-40 % and 0-22 % of the remaining DOC, respectively. The EC treated waters appear even more biostable than the raw waters, with BDOC levels in the range of 0-0.13 mg/L (0-8 % of the remaining DOC). Both EC and OBF treated waters significantly reduce the SUVA levels, indicating loss of aromaticity and double bonds. Contrary to EC where the DOC removal is high (57-75 % with an average of 67 %), OBF is removing far less DOC (12-23 % with an average of 18 %).

After the OBF treatment, the VHA fraction is now reduced to levels of 36-43 % of the DOC remaining after treatment, while the CHA fraction has increased significantly to 27-31 %. The relative contribution to DOC from SHA (23-36 % of DOC) has increased somewhat, while the NEU (10-18 %) fractions contribution is relatively unchanged. The OBF treated waters appear less biostable than the raw waters, with BDOC levels in the range of 0.13-0.89 mg/L (7-18 % of the remaining DOC).

Table 13. NOM fractions, SUVA and BDOC data for treated (i.e. coagulated and filtered) water samples from the four EC facilities (June 2008-May 2010)

EC-facilities	DOC mg/L	VHA mg/L (%)	SHA mg/L (%)	CHA mg/L (%)	NEU mg/L (%)	SUVA L/m mg	BDOC mg/L (%)
AVG	0.98	0.42 (39)	0.17 (17)	0.04 (5)	0.34 (39)	2.1	0.05 (3)
STDEV	0.35	0.25 (17)	0.11 (9)	0.06 (8)	0.06 (13)	0.3	0.04 (3)
MAX	1.62	0.96 (59)	0.38 (40)	0.13 (22)	0.47 (70)	2.6	0.13 (8)
MIN	0.42	-0.03 (-7)	0.00 (0)	-0.07 (-11)	0.25 (20)	1.3	0.00 (0)
N	20	20	20	20	20	20	12

Table 14. NOM fractions, SUVA and BDOC data for treated (i.e. ozonated and biofiltered) water samples from the two OBF facilities (May 2008-Dec 2010)

OBF-facilities	DOC mg/L	VHA mg/L (%)	SHA mg/L (%)	CHA mg/L (%)	NEU mg/L (%)	SUVA L/m mg	BDOC mg/L (%)
AVG	4.12	1.61 (39)	0.81 (20)	1.17 (28)	0.54 (13)	2.2	0.58 (14)
STDEV	1.26	0.54 (3)	0.27 (3)	0.36 (1)	0.19 (3)	0.1	0.28 (4)
MAX	5.56	2.37 (43)	1.21 (23)	1.58 (31)	0.90 (18)	2.3	0.89 (18)
MIN	2.33	0.84 (36)	0.38 (36)	0.65 (27)	0.32 (10)	2.0	0.17 (7)
N	8	8	8	8	8	6	8

6.3.3 Overall removal efficiencies at EC and at OBF facilities

Tables 15 and 16 show the obtained NOM fraction, DOC, SUVA and BDOC removal efficiencies for the EC and OBF facilities, respectively.

NOM fraction removal efficiencies obtained by coagulation are 81 %, 53 %, 44 % and 12 % for the VHA, SHA, CHA and NEU fractions, respectively. The CHA fraction removal is very variable, from very high to very low, and the NEU fraction is not amenable to removal by coagulation. In spite of the fact that BDOC levels are low in raw water, the levels are reduced even further (53 %) during EC.

For the OBF facilities, average VHA fraction removal is 54 %. SHA fraction concentration increases by 35 %, and the NEU fraction concentration is almost unaffected (1 % reduced) by OBF. The CHA and BDOC levels, however, are significantly increased as a result of OBF treatment.

SUVA values are decreased by more than 50 % in both processes, while DOC is removed effectively by EC (67 %) and only moderate by OBF (18 %). The high DOC removal efficiencies obtained by the EC facilities are due to the high SUVA levels resulting from the dominance of aromatic, hydrophobic NOM fractions amenable to removal by coagulation.

Table 15. NOM fractions, DOC, SUVA and BDOC removal efficiencies obtained at the EC facilities (June 2008-May 2010)

EC-facilities	DOC %	VHA %	SHA %	CHA %	NEU %	SUVA %	BDOC %
AVG	67	81	53	44	12	57	53
STDEV	6	9	26	116	16	8	48
MAX	75	104	100	217	41	74	100
MIN	57	70	4	-300	-25	42	-33
N	19	19	19	19	19	19	8

Table 16. NOM fractions, DOC, SUVA and BDOC removal efficiencies obtained at the OBF facilities (May 2008-Dec 2010)

OBF-facilities	DOC %	VHA %	SHA %	CHA %	NEU %	SUVA %	BDOC %
AVG	18	54	-35	-362	1	51	-179
STDEV	3	5	27	396	23	5	515
MAX	23	59	6	-98	41	55	900
MIN	12	45	-70	-1320	-23	41	-1000
N	8	8	8	8	8	6	8

6.3.4 NOM fraction and BDOC profiles during treatment and distribution

In addition to the overall water quality and treatment performance data presented before, inspection of NOM-fraction and BDOC concentration profiles from different treatment steps during enhanced coagulation (EC) and OBF can provide additional information on treatment-specific issues. Typical NOM-fractionation and BDOC concentration profiles from an EC facility are shown in Figure 46. The profiles were very similar for all of the investigated EC facilities.

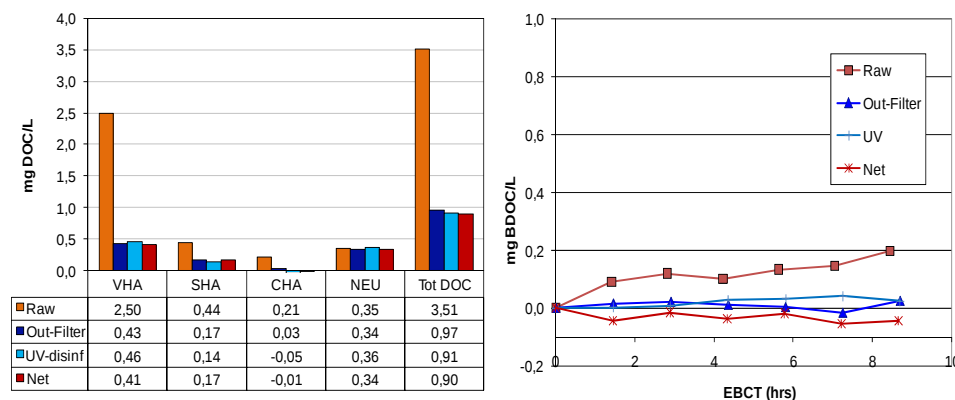


Figure 46. Typical NOM fraction and BDOC profiles in raw water, after enhanced coagulation-filtration, after UV disinfection (40 mJ/cm²), and in distributed (net) water at SVD WTP, Aug 2009 (Eikebrokk et al. 2010b)

Figures 47 and 48 show the concentration profiles from the OBF-1 and OBF-2 facilities, respectively. It appears from the results that the two OBF facilities show quite different concentration profiles. Since the treatment schemes and design of two OBF facilities are similar, the differences are related to differences in raw water quality and operation conditions, e.g. applied ozone doses.

To illustrate further, the raw water DOC concentration levels during the sampling events presented in Figures 47 and 48 were less than 3 mg/L at OBF-1 and more than 5 mg/L at OBF-2. This difference is also reflected in the ozone dosage level and correspondingly in the CHA and BDOC levels after treatment and during distribution.

The results presented in Figures 49 and 50 indicate that the OBF treatment performance is very sensitive to the raw water quality (NOM content) and to the applied ozon dose levels. In order to study these effects further, additional assessments of ozonated water samples and additional ozonation experiments were performed as described below.

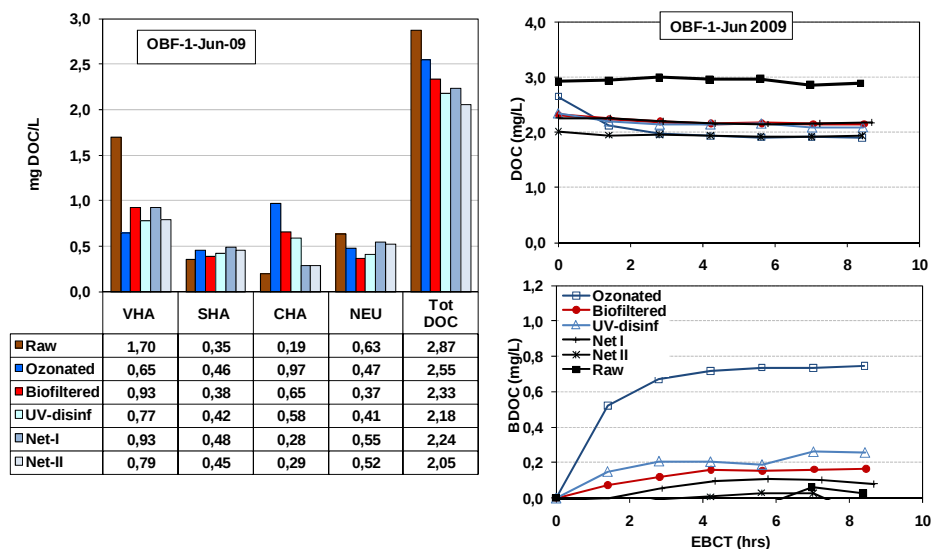


Figure 49. Typical NOM fraction and BDOC profiles for raw water, ozonated water, biofiltered water, UV disinfected water (40 mJ/cm²), and distributed (net) water at SUN WTP (low to moderate NOM content in raw water) (Eikebrokk et al., 2010b).

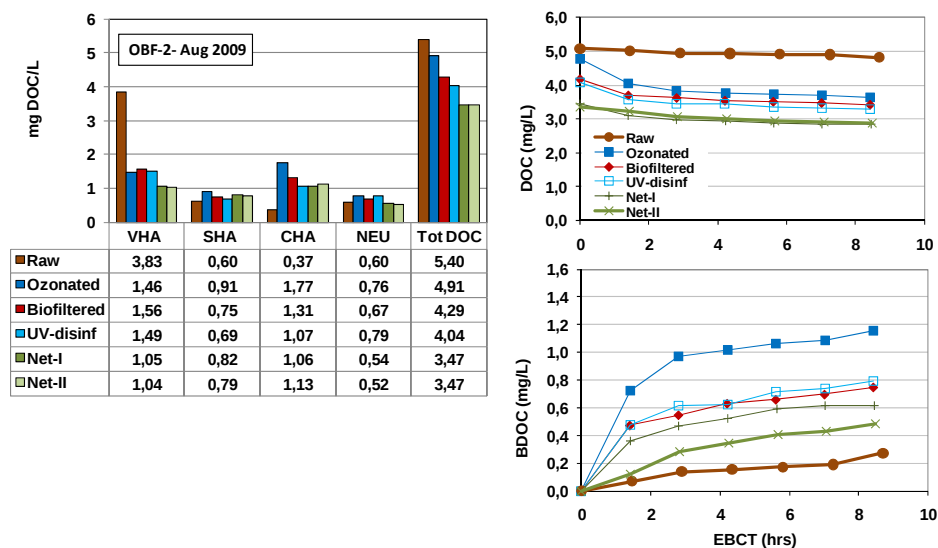


Figure 50. Typical NOM fraction and BDOC profiles for raw water, ozonated water, biofiltered water, UV disinfected water (40 mJ/cm²), and distributed (net) water at AUS WTP (high NOM content in raw water) (Eikebrokk et al. 2010b).

6.3.5 Effects of ozonation on NOM fraction concentration levels

In order to identify why ozonation-biofiltration treatment produces higher CHA and BDOC levels than enhanced coagulation, Table 17 shows the results of ozonated water samples, i.e. samples taken after the ozone contact tank, prior to the biofilter at the OBF facilities.

The data in Table 17 show that the VHA fraction concentration is significantly decreased, and that the CHA fraction concentration significantly increased as a result of ozonation.

Table 17. Summary data on NOM fractions, SUVA and BDOC in ozonated water samples from the OBF facilities (May 2008-Dec 2010)

OBF-facilities	DOC mg/L	VHA mg/L (%)	SHA mg/L (%)	CHA mg/L (%)	NEU mg/L (%)	SUVA L/m mg	BDOC mg/L (%)
AVG	4.72	1.50 (31)	0.92 (19)	1.64 (36)	0.66 (14)	1.7	1.03 (22)
STDEV	1.36	0.59 (6)	0.34 (2)	0.36 (6)	0.25 (4)	0.3	0.31 (4)
MAX	6.16	2.19 (40)	1.45 (24)	2.11 (51)	1.21 (22)	1.9	1.44 (29)
MIN	2.41	0.45 (19)	0.41 (17)	0.97 (29)	0.33 (10)	1.1	0.50 (15)
N	9	9	9	9	9	6	9

6.3.6 Studies on the effects of ozone dose levels

NOM fraction and BDOC concentration data for ozonated water are presented specific laboratory experiments were performed under controlled conditions. For a number of different ozone dose levels, NOM fraction and BDOC concentrations were measured in ozonated water samples (Eikebrokk, 2010c).

In order to study the effect of ozonation of NOM fraction distribution, Figure 51 shows the results from controlled laboratory experiments where raw water samples (2.4 mg DOC/L; pH 6.4) were ozonated at different dose levels prior to water quality analyses, including NOM fractionation and BDOC.

The results show a significant and close to linear transformation of VHA into CHA as a result of specific ozone doses in the range of 0-3 mg O₃/mg DOC. Only minor changes in DOC, SHA and NEU fraction concentrations were detected.

The effective reductions of the colour, UV-absorbance and SUVA levels (Figure 52) indicate a direct ozone reaction and specific attack on the

double bonds within the NOM molecules. Finally, Figure 53 shows how the ozone-induced transformation of VHA into CHA significantly increases the BDOC levels.

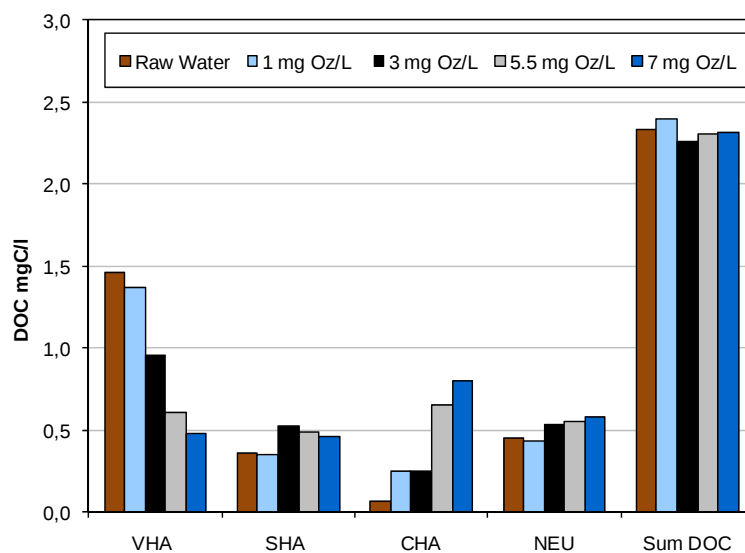


Figure 51. Effects of specific ozone dosage on NOM fraction concentrations (Raw water: DOC = 2.4 mg/L; pH 6.4) (Eikebrokk, 2010 - IHSS)

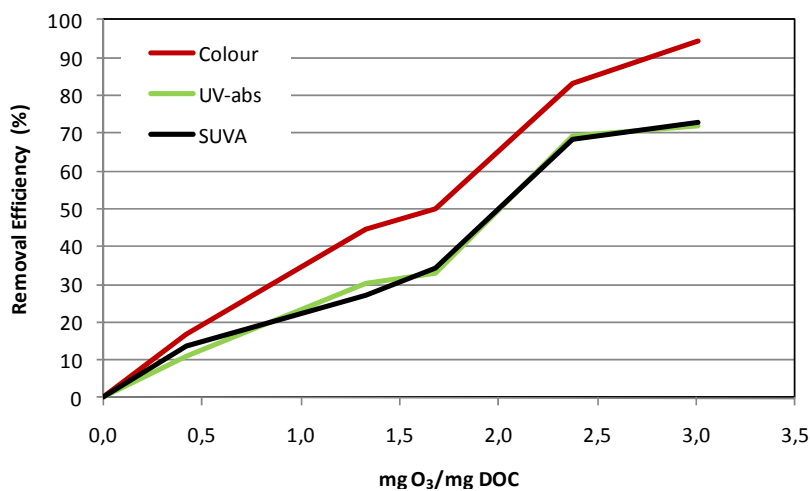


Figure 52. Effects of specific ozone dosage on colour, UV-absorbance and SUVA concentration levels in a raw water with colour 18 mg Pt/L; UV-abs 10.3 m⁻¹; SUVA 4.4 L m⁻¹ mg⁻¹; and pH 6.4 (Eikebrokk et al., 2010b)

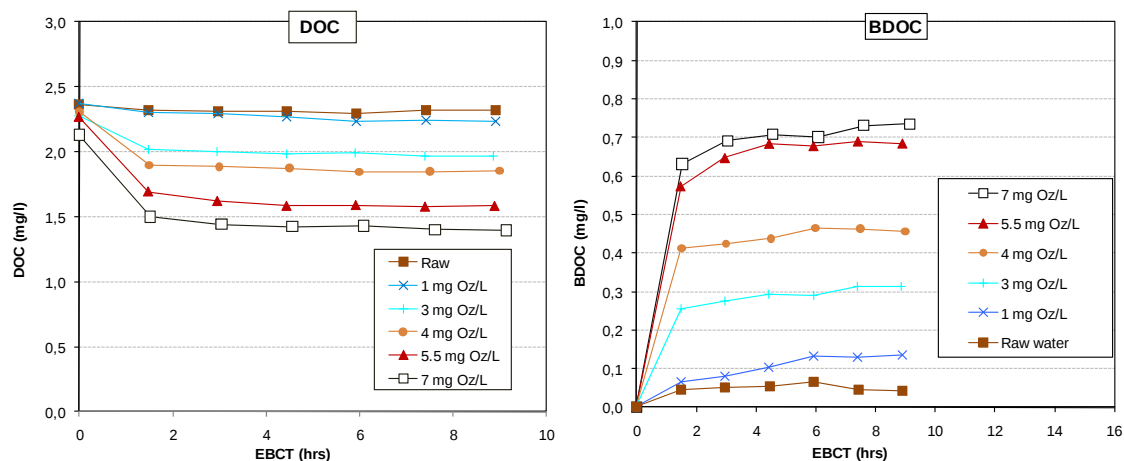


Figure 53. Effects of specific ozone dosage level on DOC and BDOC concentrations (Eikebrokk et al., 2010b).

6.4 Linking of biodegradability to hydrophilic NOM fractions

From analyses of raw and treated water analyses (different treatment steps) from 10 Norwegian water works, Figure 54 shows that BDOC correlates very well with the hydrophilic NOM fraction (CHA, NEU). BDOC was found to correlate equally well with the CHA fraction concentration in these water samples, while no correlation at all was found between DBOC and the hydrophobic NOM fractions (VHA, SHA). Thus control of the hydrophilic NOM fractions seems to be an important element in controlling regrowth and biofilm formation potentials, and valuable information on biostability can be found from rapid NOM fractionation analysis.

Furthermore, the data in Figure 54 also indicates that the enhanced coagulation facilities (only EC facilities in Bergen shown) are capable of maintaining the hydrophilic NOM fractions and the BDOC concentrations at very low levels. The low HPC levels and the marginal decrease in DOC and BDOC levels observed within the distribution system further are good indicators that EC treated waters are biologically stable. For OBF the HPCs are higher and the reductions in DOC and BDOC during distribution are more significant. Hence, the OBF treated waters within TECHNEAU case Bergen appear less biostable than the EC treated waters.

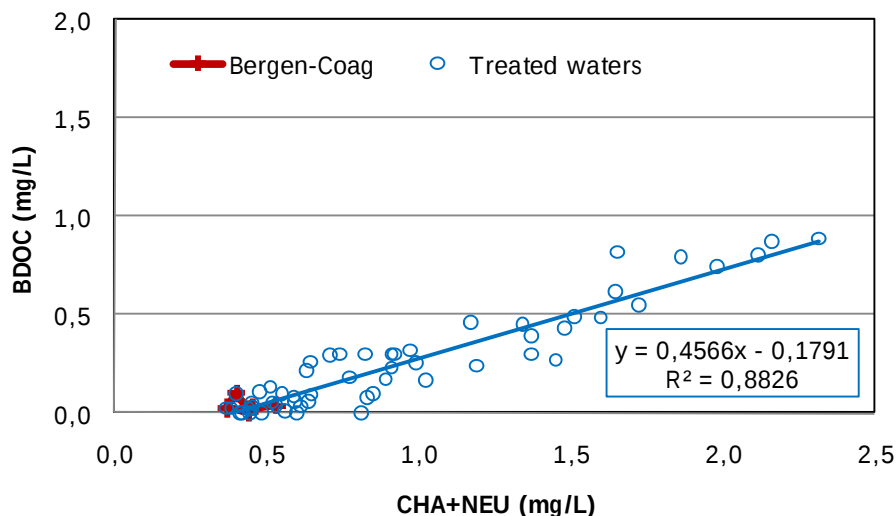


Figure 54. Correlation between hydrophilic NOM fractions (CHA, NEU) and BDOC concentrations found at 10 Norwegian water works with EC or OBF treatment processes (Eikebrokk et al., 2010).

6.5 EEM at enhanced coagulation facilities

Ten water samples were analyzed by UNESCO IHE-Delft (S. Sharma) to characterize the organic matter present in raw, treated, and distributed water. For each samples the following parameters were measured: (i) dissolved organic carbon (DOC), (ii) UVA_{254} and (iii) Fluorescence EEM. The results of these measurements are summarized in Table 18 below, and the obtained EEM are shown in Figure 55.

DOC concentrations of all pre-filtered samples were determined by the combustion method using a Shimadzu TOC- V_{CPN} organic carbon analyzer. UVA_{254} absorbance of each sample was measured in a 1 cm quartz cell using a Shimadzu UV-2501PC UV-VIS spectrophotometer. SUVA was determined by dividing the absorbance UVA_{254} by the corresponding DOC concentration. The fluorescence intensities were measured in a 1.0 cm quartz cell using a FluoroMax-3 spectrofluorometer (Horiba Jobin Yvon) at room temperature.

Table 18 Raw and treated water quality data (Bergen, Oct 2010)

Sample	DOC (mg/L)	UV- abs (1/cm)	SUVA (L/mg. m)	Fluorescence intensity (Raman peak)		
				Humic- like (1)	Humic-like (2)	Protein-like
1 KIS Raw	3.89	0.145	3.73	—	—	0.196
2 KIS T	1.56	0.028	1.79	0.143	0.092	0.093
3 SAE Raw	4.73	0.212	4.48	0.606	0.381	0.392
4 SAE T	1.77	0.036	2.03	0.192	0.123	0.099
5 JOR Raw	2.78	0.115	4.13	0.410	0.250	0.175
6 JOR T	0.87	0.017	1.95	0.019	—	0.042
7 SVD Raw	3.96	0.175	4.42	0.526	0.333	0.180
8 SVD T	0.94	0.018	1.91	0.016	—	0.046
9 Mølledvn	0.83	0.017	2.05	0.130	—	0.038
10 Wolfsgt	0.84	0.016	1.90	0.015	—	0.039

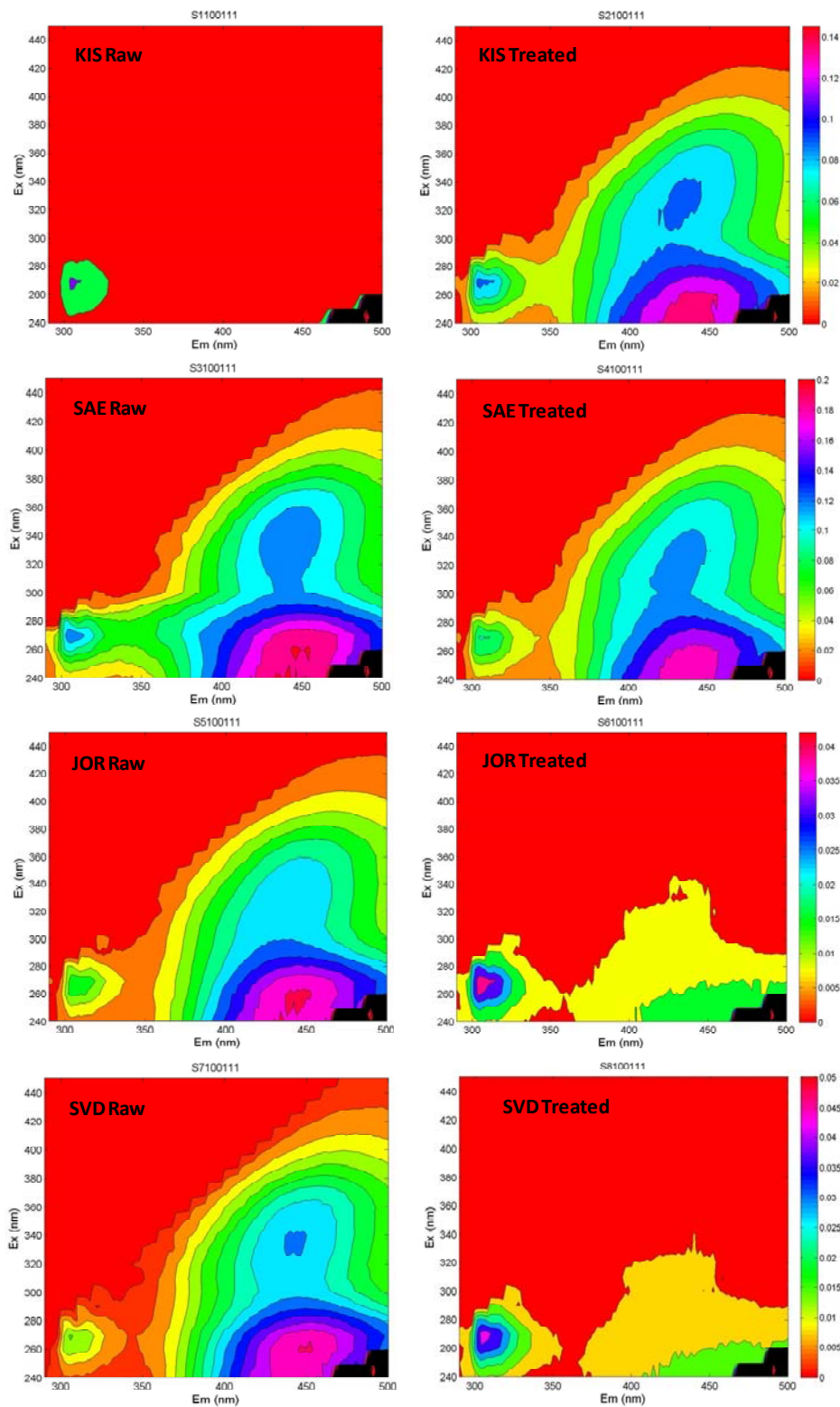


Figure 55. EEM in raw water (left) and in treated (right) water samples from the enhanced coagulation facilities in Bergen, Norway

Figure 56 shows the EEM in samples from the distribution system at SVD WTP in Bergen.

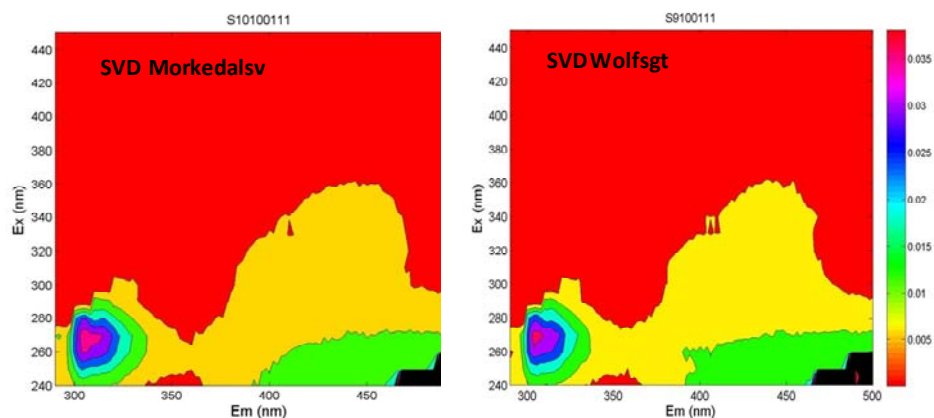


Figure 56. EEM in distributed water samples from SVD WTP in Bergen, Norway

6.6 EEM at ozonation-biofiltration facilities

Samples from Austevoll (AUS WTP) were taken in Dec 2010 from different treatment steps and from the distribution network: raw water, after ozone contact tank (ozonated), after biofilter (biofiltered), after UV-disinfection (UV-disinfected), and from the distribution system (Ausetvollhella, Kolbeinsvik and Storebø). The samples were analyzed by IHE-Delft, and the results are presented in Table 19.

Table 19 Results of analysis of samples (AUS WTP, Dec 2010)

Sample	DOC (mg/L)	UV-abs (1/cm)	SUVA (L/mg. m)	Fluorescence intensity (Raman peak)		
				Humic- like (1)	Humic- like (2)	Prot- like (3)
Raw	6.50	0.103	1.58	0.792	0.506	0.180
Ozonated	5.84	0.093	1.59	0.268	0.245	0.103
Biofiltered	5.16	0.103	2.00	0.366	0.249	0.154
UV- disinfected	5.09	0.277	5.44	0.378	0.299	0.111
Net Austevollh	4.52	0.093	2.06	0.340	0.229	0.100
Net Kolbeinsvik	4.47	0.09	2.01	0.302	0.255	0.110
Net Storebø	4.86	0.105	2.16	0.318	0.242	0.106

Like for the VIVA samples, clearly visible EEM peaks were present as illustrated in Figure 57 for a water sample taken from the distribution network at AUS WTP.

EEM results from raw water, ozonated water, biofiltered water, UV-disinfected water and distributed water samples from Austevoll WTP are presented in Figure 58.

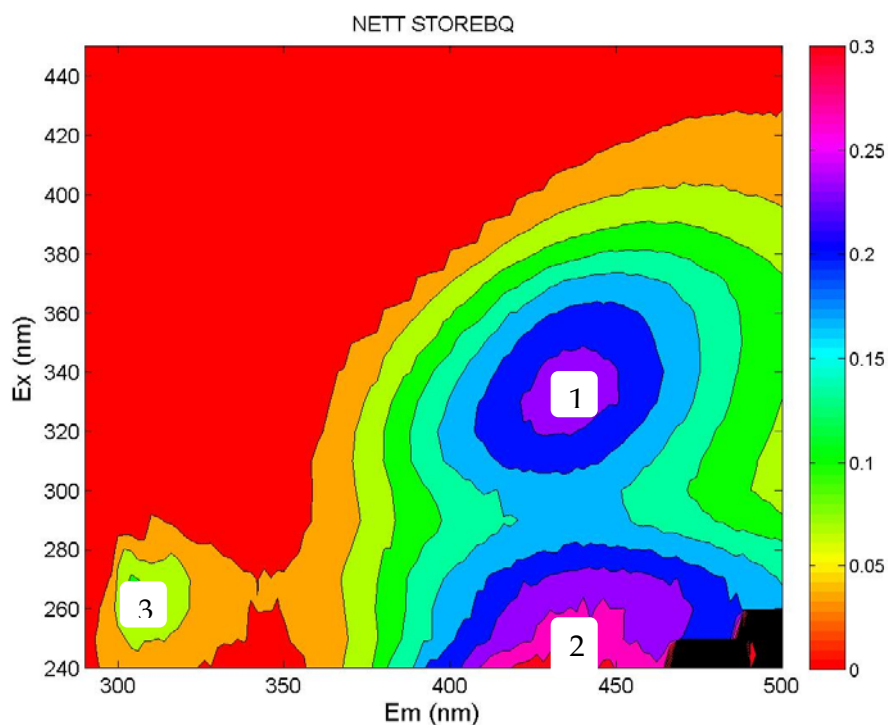


Figure 57 Typical F-EEM spectra showing (1) Humic-like (peak 1), (2) Humic-like (peak 2) and (3) Protein-like organic matter fractions/peaks (Sample: AUS, Net Storebø)

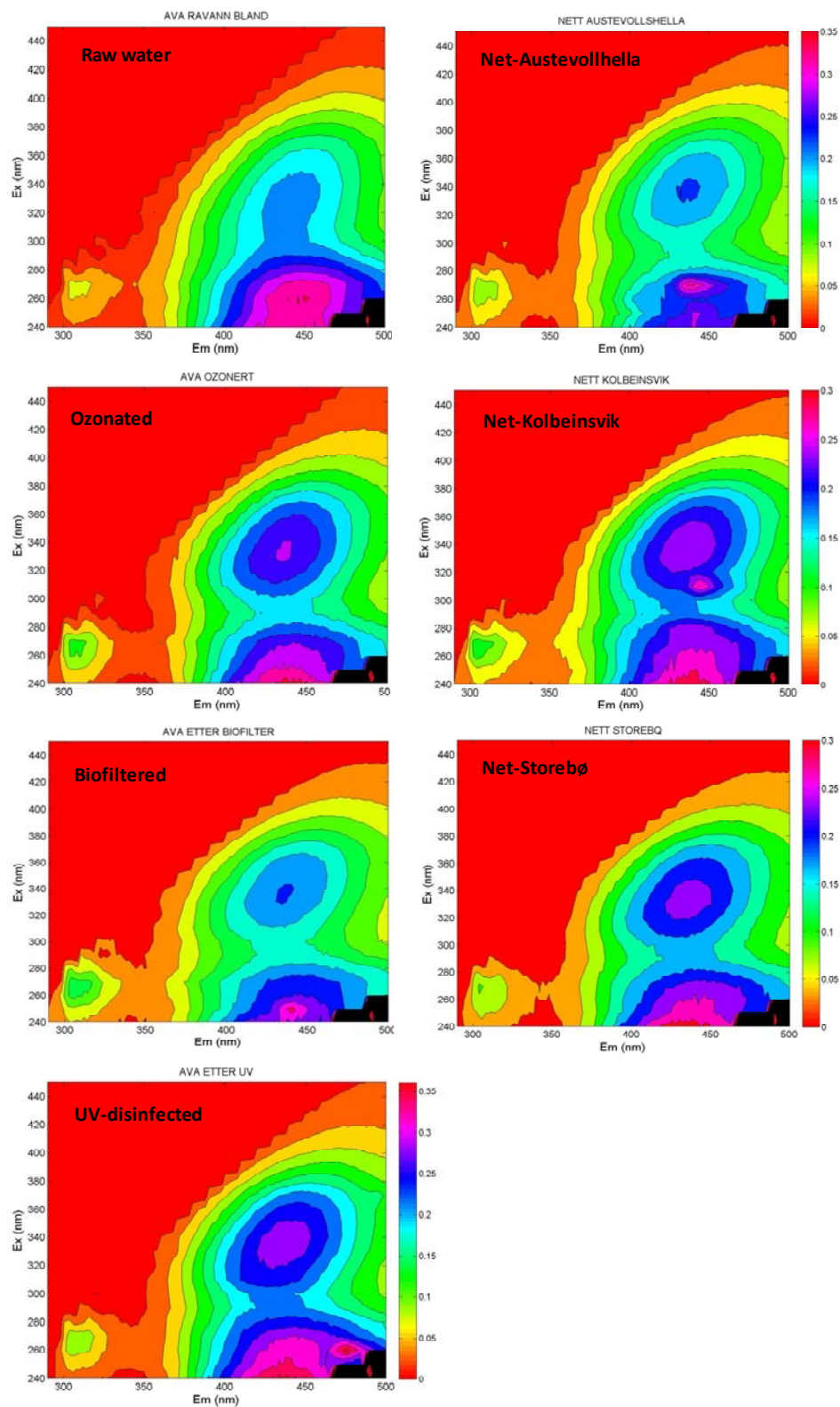


Figure 58. EEM in raw water, and in samples taken from different treatment steps and from distribution network at AUS WTP (Dec 2010)

7. Summary

From the results presented here, some summary remarks can be made:

- Significant potentials do exist for treatment performance optimization with respect to water quality, safety and sustainability at existing WTPs
- Optimization trials at two full-scale enhanced coagulation facilities reveal a potential reductions in coagulant demand of 35-40 % - without significantly compromising treated water quality
- The TECHNEAU coagulation optimization roadmap, including the water quality and treatment diagnostic tools like rapid NOM fractionation and BDOC analyses appear as valuable tools in performance assessments and optimization activities
- The Delta UV-probe provided on-line color and UV-absorbance data that was in good agreement with data from laboratory analyses and parallel color monitors. Thus in places where raw water quality and NOM composition vary significantly over the year, this sensor can be applied for the purpose of on-line process control
- More advanced water quality analysis like excitation-emission matrix (EEM) may give valuable additional information on water quality and treatment performance. The interpretation and the practical implications of EEM results may however still be a challenge
- The Norwegian raw waters studied here contained low to moderate levels of NOM (TOC < 3-7 mg/L). The DOC was dominated by the hydrophobic NOM fractions, in specific the VHA (allochtoneous humic) fraction. Correspondingly, the specific UV-absorption (SUVA) values are very high (4-5 L mg⁻¹ m⁻¹), indicating a high proportion of aromatic, coloured and UV-absorbing NOM fractions. The seasonal variability in NOM concentrations are significant, thereby imposing challenges with respect to process control. However, in spite of the seasonal and spatial DOC variability, the relative contribution from the different NOM fractions to the total DOC concentrations seems to remain relatively constant
- From this, the Norwegian raw waters are amendable to treatment by coagulation, and high NOM (TOC) removal efficiencies (> 60-70 %) can be predicted even at the low to moderate raw water concentration levels encountered. These predictions are supported by the treatment results presented
- The NEU fraction is not amendable to removal by coagulation. However, due to the low NEU concentrations normally

encountered in Norwegian raw water sources, this will only slightly affect the overall DOC removal efficiencies obtained by enhanced coagulation processes. The tested raw waters appear very biostable, with BDOC levels close to zero

- The Latvian raw water (River Daugava) however, contained high amounts of DOC (15-25 mg/L), with significant concentrations of hydrophilic NOM fractions (CHA, NEU). This indicates a high coagulant demand and increased biodegradability. Significant remaining optimization potentials seem to be present at Daugava WTP, both in the coagulation and ozonation-biofiltration treatment steps
- Ozonation of NOM laden waters seem to attack primarily the VHA fraction and the conjugated double bonds leading to substantial reductions in colour and UV-absorbance. Ozonation transforms VHA to CHA while the remaining NOM fractions remain relatively unaffected by ozone
- BDOC correlates very well with CHA. Thus ozonation significantly increases BDOC as well
- In ozonation-biofiltration processes, the biofilter should be capable of removing most of the CHA and thus the BDOC formed by ozonation. Otherwise, these substances may result in regrowth and biofilm formation in the distribution system.
- The raw water quality and NOM concentration levels of the two Norwegian full-scale OBF treatment facilities studied here are quite different. The treatment performance data clearly indicate that application of the OBF treatment process should be restricted to raw waters with low to moderate NOM content. Otherwise the ozone demand, the ozone dose levels and the corresponding CHA and BDOC concentration levels in treated water may be too high to control bacterial regrowth and biofilm formation during distribution.
- In order to control biostability, it is very important to control ozone dosages at limited levels to avoid excessive production of VHA and BDOC. Furthermore, it is important to design biofilters adequately with sufficient EBCT and to avoid any type of inhibition of the biological process to allow for a sufficient BDOC reduction during this treatment step.

7.1 Additional remarks

The results presented here demonstrate that NOM fractionation and BDOC analyses are valuable tools for assessing and diagnosing raw water quality and treatability, as well as water treatment process performance.

The results demonstrate that enhanced coagulation facilities is a good treatment process for typical Norwegian water sources with significant NOM content, low turbidity and low alkalinity and calcium levels. The dominance of the hydrophobic NOM fractions, the high aromatic nature and the high SUVA levels make these waters amendable to efficient treatment by enhanced coagulation. In addition, enhanced coagulation processes are capable of reducing the already low BDOC levels in the raw water to levels very close to zero in treated waters.

For ozonation-biofiltration facilities however, the situation is different. Like for the EC facilities, the raw water show high biostability with low BDOC levels. The BDOC levels in treated water however is more specific to the raw water quality and to the applied ozone dosage, with low to moderate BDOC levels where the raw water contains low to moderate levels of NOM and significantly higher levels where the OBF process is applied to raw waters with higher NOM levels and thus higher ozone demands. In order to avoid high BDOC levels including possible regrowth problems in distributed water from ozonation-biofiltration facilities the results show that it is imperative to: 1) control the ozone dosage levels in order to control the formation of easily biodegradable CHA at the lowest possible levels, and 2) design a biofilter with adequate capacity (EBCT) to oxidize the CHA formed by ozonation.

An implication of this is that application of ozonation-biofiltration processes should be restricted to raw waters with low to moderate NOM/VHA levels in order to avoid excessive ozone demands with high CHA production rates, increased BDOC concentration levels and corresponding regrowth problems.

More about distribution system optimization efforts and linking of treatment and distribution can be found in the Techneau Deliverable 7.11.3A.

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