Norwegian Water

Report

231 | 2018

NOMiNOR:

Natural Organic Matter in drinking waters within the Nordic Region

Aalto University

VIVAB
Vatten & Miljö i Väst AB

SLU Swedish University of Agricultural Sciences

I·V·A·R

NORRVATTEN

UiO : University of Oslo

bergen vann

SINTEF

Svenskt Vatten Utveckling

Lund University

HSY

SYDVATTEN

Cranfield University

NMBU Norwegian University of Life Sciences

Scottish Water
Trusted to serve Scotland

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Norsk Vann

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Norwegian Water Report

Extract
The NOMiNOR project has predicted the future level of natural organic matter (NOM) in ten Nordic and Scottish water sources by using selected models tools. The physiochemical characteristics of NOM is analyzed by both simple and easily available NOM diagnoses, and highly advance methods. The aim of the project has been to evaluate and test analytical methods that more easily can provide new valuable information – relevant to treatment process assessments, operation performance and optimization efforts. The results demonstrated that simple NOM diagnostics form a good basis for treatment performance assessments and identification of optimization potentials. Based on the results from water sample analyses and utility benchmarking, site-specific recommendations are provided on treatment performance, treatment peculiarities, as well as needs for additional treatment, optimization of treatment, and/or process control systems.

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Title
NOMiNOR: Natural Organic Matter in drinking waters within the Nordic Region

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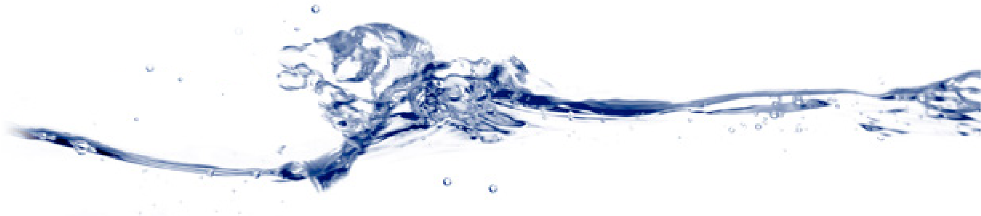
Natural Organic Matter (NOM); Temporal increase in NOM; Prediction of NOM trends; NOM characterization; NOM removal; Benchmarking; Treatment performance assessment; Treatment optimisation

Preface



The NOMiNOR project arise from a need of more knowledge about the connection between rising levels of natural organic matter in water sources, changes in NOM-quality and how to optimize the water treatment to meet this challenge. Focus throughout the project has been on practical tools and operational knowledge to be used by the water works. The project have provided valuable information for the selection of optimum future design and operations for water treatment works and stakeholders within the NOM-laden Nordic region.

The project have provided valuable information for the selection of optimum future design and operations for water treatment works and stakeholders within the NOM-laden Nordic region.

Project owner has been Norwegian Water BA. Partners in the project include Scottish Water (UK), Norrvatten (Sweden), IVAR IKS (Norway), Bergen Municipality (Norway), VIVAB (Sweden), Nedre Romerike Waterwork IKS (Norway), Helsinki Region Environmental Services Authority (Finland), Sydvatten (Sweden), SINTEF (research institute) , University of Oslo (UiO), Norwegian University of Life Sciences (NMBU) and Cranfield University (UCRAN).

Other Universities also involved in the NOMiNOR project include Swedish University of Agricultural Sciences (SLU), Lund University and Aalto University.

The project funding is a joint effort among the participating waterworks, and the Norwegian (Norsk Vann) and Swedish (Svenskt Vatten) Water Works Associations.

Overall project manager has been Kjetil Furuberg, Norwegian Water, and scientific project manager has been Bjørnar Eikebrokk, SINTEF.

To achieve the results which you can read about in this report, would not have been possible without a very dedicated group of person from the research institutes, universities and water works. Thank you for your efforts and willingness to share knowledge – to the best for water suppliers dealing with NOM.

Summary is found in chapter 7," Conclusions and recommendation". A shorter report from the project is also available in Norwegian (Norsk Vann rapport 230/2018 «NOMiNOR: Naturlig Organisk Materiale i Nordiske drikkevann - En sammendragsrapport»).

Hamar, 01.05.2018

Kjetil Furuberg	Bjørnar Eikebrokk
Norwegian Water	SINTEF

Content

ABBREVIATIONS AND DEFINITIONS

TOC – Total Organic Carbon

DOC – Dissolved Organic Carbon (0.45 ųm filtered)

NOM – Natural Organic Matter

DNOM – Dissolved Natural Organic Matter

BOM – Biodegradable Natural Organic Matter

BDOC - Biodegradable Organic Carbon

AOC - Assimilable Organic Carbon: The amount of organic carbon in a water sample that is converted to biomass by some specific types of bacteria. The amount of biomass produced from the water sample is related to amount of a known substrate (acetate) needed to produce an equivalent amount of biomass

HPHO, HPO – Hydrophobic NOM

VHA – Very Hydrophobic Acids

SHA – Slightly Hydrophobic Acids

HPHI, HPI – Hydrophilic NOM

CHA – Charged Hydrophilic Matter

NEU – Neutral Hydrophilic Matter

ATP – Adenosine Tri Phosphate: The energy carrier in all living cells

RSF - Rapid Sand Filter

2-M Filter – Dual media filter (normally anthracite and sand, or Filtralite and sand)

3-M Filter – Three media filter (normally antracite or Filtralite on top of sand, with a bottom layer of crushed calcium carbonate)

GAC - Granular Activated Carbon

NF - Nanofiltration

UF - Ultrafiltration

OBF - Ozonation and BioFiltration

1. BACKGROUND AND INTRODUCTION

Surface waters in Scotland and in southern Norway, Finland and Sweden have experienced significant increased concentrations and fluctuations of Natural Organic Matter (NOM) over the past decades. This increase is likely due to the combined effects of climate variation, reduced acid rain loading and increase in primary production/standing biomass. NOM concentration levels and its physiochemical properties vary significantly in space and time. The variations are site-specific and therefore unique to any raw water source. Surface waters are commonly used as raw water sources by waterworks for tap-water production in these countries. NOM in water affect colour, taste and odour, and increasing concentrations of NOM lead to increased demand for coagulants and disinfectants, and may thus also increase the levels of disinfection by-products (DBPs). NOM influences, furthermore, the stability and thereby the removal of inorganic particles and pathogens. Although not conceived to be toxic in itself, NOM carry micro-pollutants. NOM can also foul membranes, block activated carbon filtration pores and compete for adsorption sites. NOM influences corrosion and leads to regrowth and biofilm formation in the water distribution networks (Figure 1), including house installations. The increasing concentration and seasonal variability of NOM therefore represents a severe challenge for process control systems and for operation performance of water treatment and distribution systems.

Görvälnverket (Norrvatten) in Sweden can serve as an illustrating example of the significant treatment challenges arising from the increasing NOM levels faced at waterworks in the Nordic region. At this utility the strong increase in the NOM concentration level in the water source (Lake Mälaren) and the corresponding increase in DOC residuals after coagulation, caused a failure in the performance of the granulated activated carbon (GAC) filter. The GAC filter was intended to act as an adsorptive chemical barrier in case of petroleum spills and micropollutant contamination of the raw water source. In order to decrease the NOM load to the GAC filter, a nano filtration (NF) pilot plant was installed as an adequate and additional treatment step, thus reducing the high regeneration frequencies previously required in order to maintain GAC as an efficient barrier against chemicals and micro pollutants.

The physicochemical characteristics and concentration of NOM dictates the selection of optimum treatment technology, the treatment process design and the operation performance of treatment plants and distribution systems. NOM characterization/NOM-diagnosis are therefore valuable tools and prerequisites in order to adequately control NOM in tap water and avoid unwanted NOM-related effects. There is a repertoire of analytical techniques used to characterize NOM. Some of these methods are laborious and require advanced analytical equipment and are therefore less applicable for routine monitoring in the water plants – though these methods are valuable in science/academia in order to increase our understanding of NOM nature and fate during treatment and distribution. More readily applicable methods are typically less specific but may provide valuable proxies for treatment and distribution-relevant characteristics of NOM. A goal is therefore to understand better and thereby improve our interpretation of these common proxies. A major shortcoming in the humic matter science is poor inter laboratory precision as well as poor accuracy of the operationally defined analytical methods. This is partly due to differing sample handling and preparation as well as methodological differences in instrumentation settings.

The strategy of the NOMiNOR-project has been to apply the same set of relevant and easily applicable NOM characterizations methods (proxies) to a selection of water treatment works applying different treatment technologies and different unit process configurations in Scotland, Finland, Sweden and Norway. From this approach, the results have become more directly comparable, thus facilitating the exchange of knowledge and competence from one waterworks to the other. Selected samples have also been analysed using more sophisticated techniques rendering more specific information of the NOM.

Existing monitoring data of NOM concentration and quality from the involved water works have been compiled with deposition and climate data to assess the role of different factors governing temporal variation. Moreover, the differences in NOM characteristics in space and fluctuations in time have been related to reduction in acid rain and inter-annual as well as seasonal fluctuations in weather conditions, and to watershed characteristics. The decoupling of these pressures on the observed NOM changes has enabled the NOMiNOR-project to predict future trends in NOM amount and quality. The project will thereby provide valuable information for the selection of optimum future design and operations for water treatment works and stakeholders within the NOM-laden Nordic region.

The project funding is a joint effort among the participating waterworks, and the Norwegian (Norsk Vann) and Swedish (Svenskt Vatten) Water Works Associations.

2. MAIN OBJECTIVES AND PARTNERS

2.1. Objectives

The main objective of the NOMiNOR project has been to strengthen the conceptual understanding of the link between raw water NOM characteristics and NOM control and NOM removal. This is a prerequisite to improve water treatment and distribution performance.

A key factor in achieving this objective has been the need for increased levels of knowledge and competence on optimum NOM control during water treatment and distribution. In order to be able to learn from each other and fully utilize results and experiences, the same set of NOM-diagnostic tools (further described in Ch. 3) are applied for monitoring and comprehensive characterization of seasonal water samples collected during winter, spring, summer and autumn periods from water works in Sweden, Scotland, Finland and Norway.

The application of the same NOM characterization tools analysed using the same sample handling, treatment and analysis protocol allows direct comparisons between treatment results obtained at water works with different climate and source/watershed characteristics, different treatment technologies, and different disinfection policies (e.g. chlorine-based versus chlorine free distribution). Compilation of site-specific information regarding climate, vegetation, land use, geology and soil morphology in the watershed of the different raw waters is used for unravelling the governing factors for temporal and spatial differences between the amount and physicochemical characteristics of the NOM. This information is then related to treatment plant and distribution system characteristics as well as site-specific operation conditions included in the activities. Thus the results are contributing to valuable exchange of information, knowledge and competence among the participating waterworks as well as other stakeholders within the water industry.

Key questions addressed:

1) To what extent does climate change (temperature and runoff characteristics) explain changes in NOM levels and characteristics among different raw water sources, relative to other factors (changes in acid deposition and land use)?
2) Can a hydrological water balance approach improve our understanding on the great spatial variations in concentration and properties of NOM? Based on this knowledge is it possible to evaluate:
   a. How sensitive the different waterworks are to changes in weather conditions?
   b. Which weather conditions represent particular challenges to the waterworks with respect to NOM levels and properties?
3) Can the use of the suggested set of readily applicable NOM-characterization methods allow better predictions of: i) achieved and achievable (optimum) water quality and treatment results, and ii) challenges related to biological regrowth and biofilm formation, including interactions with - and NOM-adsorption to - metal hydroxide precipitates on the pipe walls?
   c. Can the applied NOM-characterization proxies form a basis for the development of safer water supply systems and more resource-efficient NOM removal processes, i.e. better adaptation of treatment and treatment conditions to raw water (NOM) characteristics, watershed and distribution system characteristics?
   d. Can the applied NOM-characterization proxies also contribute to a better understanding, and to improved operation of distribution systems, i.e. reduced corrosion, reduced biofilm formation/layers of precipitation, reduced sludge formation, and reduced need for pipeline flushings?
4) What NOM-fractions are removed/not removed by different treatment technologies, e.g. enhanced coagulation, NF, ozonation-biological filtration (OBF), GAC, etc?
   e. How are the bio-available NOM-fractions and the biological stability (BDOC) in distributed water affected by different treatment and disinfection technologies?
5) Can the results be used to improve the basis for optimized treatment process and treatment train selection, optimum system design, optimum operation and retrofitting/upgrading of existing systems also with respect to safer, more sustainable and more climate-robust water supply systems?
6) Can this project through the use of common analytical tools, and thus directly comparable results, contribute to increased exchange of knowledge between waterworks and stakeholders?
7) Can a set of NOM-characterization methods be implemented as ”standard” for the Nordic region?

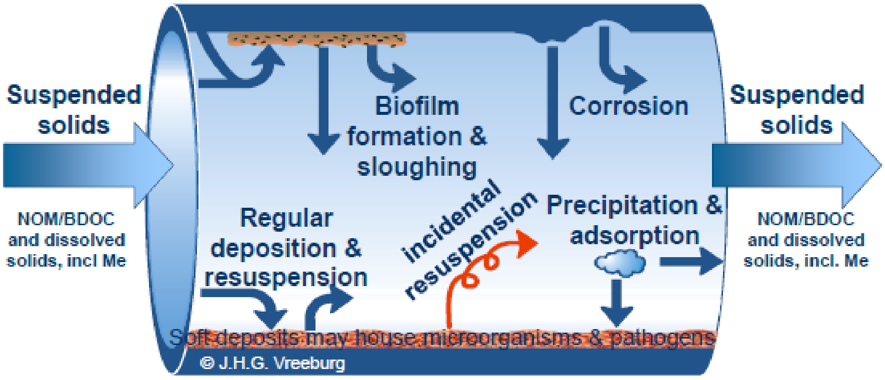


Figure 2-1 NOM-driven processes during distribution (Modified after Vreeburg et al., 2007)

2.2. NOMiNOR project partners

2.2.1. Water Utilities

Ten water treatment works (WTWs) were participating in NOMiNOR (in alphabetic order):

1) Bracadale WTW (Scottish Water, UK)
2) Burncrooks WTW (Scottish Water, UK)
3) Görvälnverket WTW (Norrvatten, Sweden)
4) IVAR Pilot WTW (Stavanger, Norway)
5) Jordalsvatnet WTW (Bergen, Norway)
6) Kärreberg WTW (VIVAB, Sweden)
7) Nedre Romerike Vannverk (NRV, Norway)
8) Port Charlotte WTW (Scottish Water, UK)
9) Pitkäkoski WTW, HSY (Helsinki Region Environmental Services Authority, Finland)
10) Ringsjöverket WTW (Sydvatten, Sweden)

2.2.2. Research Partners

The Research Institutes and Universities involved in the NOMiNOR project include SINTEF, University of Oslo (UiO), Norwegian University of Life Sciences (NMBU), Cranfield University (UCRAN), Swedish University of Agricultural Sciences (SLU), Lund University and Aalto University.

2.2.3. Partner Contacts

The main contact persons for the water works, research partners and water associations are presented below:

Water works/municipalities:

- IVAR (N) (Karl Olav Gjerstad)
- Bergen municipality (N) (Anna Walde, Paula Pellikainen)
- Nedre Romerike Waterworks (NRV) (N) (Marcus Rawcliffe)
- Norrvatten (S) (Per Ericsson, Kristina Dahlberg, Elin Lavonen)
- Sydvatten (S) (Britt-Marie Pott, Kenneth M. Persson)
- VIVAB (S) (Alexander Keucken)
- Scottish Water (UK) (Paul Weir)
- Helsinki Region Environmental Services Authority (FI) (Veli-Pekka Vuorilehto)

Research partners:

- SINTEF (Bjørnar Eikebrokk)
- NMBU (Ståle Haaland, Gunnhild Riise)
- UiO (Rolf D. Vogt, Ståle Haaland)
- Cranfield University, UCRAN (Peter Jarvis)
- SLU (Stephan Köhler)
- Lund University (Kenneth M. Persson)
- Aalto University (Riiku Vahala)

Water Associations:

- Norwegian Water/Norsk Vann (Kjetil Furuberg)
- Swedish Water/Svenskt Vatten (Gullvy Hedenberg/Daniel Hellström)

Figure 2-1. *The NOMiNOR team (Görvälnverket, Norrvatten, Sweden, Apr. 2017).*

3. MATERIALS AND METHODS

This Chapter contains descriptions of the materials and methods applied in the NOMiNOR projects, including project structure (Work Packages and Tasks), activities and responsibilities.

3.1. Water sampling and analyses

Water samples taken from 4-9 different sampling spots at each of the waterworks were analysed in four seasonal sampling rounds (winter, spring, summer, autumn).

1) Water sampling from the 10 participating water works in 4 different countries, i.e. Scotland, Sweden, Finland and Norway, with different types of water sources/watersheds, different treatment technologies, different disinfection technologies and disinfection policies, etc. Five generically similar sampling points were applied at each water works (i.e. No. 1: incoming raw water, No. 2-3: after different treatment steps, No. 4: after disinfection and clean water tank, and No. 5: from the distribution network).
2) Physicochemical characterization data of the water/NOM were compiled. These data included fast and applicable proxy methods and routine analytic data provided by the utilities themselves. In addition to this, SINTEF provided data on routine parameters including pH, colour, UV-absorbance, turbidity, TOC, DOC and SUVA, as well as hydrophobic and hydrophilic NOM fractions, NOM biodegradability (BDOC), microbial activity (ATP), elements and metals (e.g. P, Ca, Al, Fe, Mn, etc).
3) In addition, SINTEF and UCRAN provided comprehensive physicochemical analyses of a sub-set of water samples using sophisticated analytical techniques for more advanced NOM characterization (i.e. FT-ICR-MS; Conventional NOM-fractionation; Flow cytometry/total bacteria counts; Zeta potential; Fluorescence Excitation-Emission matrices (FEEM), High Performance Size Exclusion Chromatography (HPSEC) and disinfection by-product (DBP) formation potential).

For capacity reasons, the water sampling and analysis activity (rapid NOM-fractionation, biodegradability (BDOC), Adenosine triphosphate (ATP), etc) from the 10 waterworks was distributed over 2 years, i.e. 100 samples (4 seasons, 5 sampling spots, 5 water works) from the first 5 waterworks were analysed in 2014, and another 100 samples from the remaining 5 waterworks in 2015.

3.1.1. Simple NOM characterization

Rapid NOM fractionation and column-based BDOC measurements. The rapid NOM-fractionation and BDOC analyses provided by SINTEF (Figures 3-1 and 3-2) are rapid column-based methods implemented here as a part of the set of simple or "standard" NOM-characterization methods for the Nordic region to secure directly comparable results that can be easily implemented in practice. Both methods rely on sensitive and accurate DOC analysis, and the NOM fraction and BDOC concentrations are simply calculated from differences in DOC between inlet and outlet water samples. More information on the methods can be found in the documentation/reports from the EU-projects TECHNEAU (www.techneau.eu) and TRUST (www.trust-i.net). Specific UV-absorption (SUVA, i.e. A254nm/DOC), sVISa (A400nm/DOC) and SAR (A254nm/A400nm) were also included in the set of NOM-characterization proxies to be implemented as "standard methods" for the Nordic region.

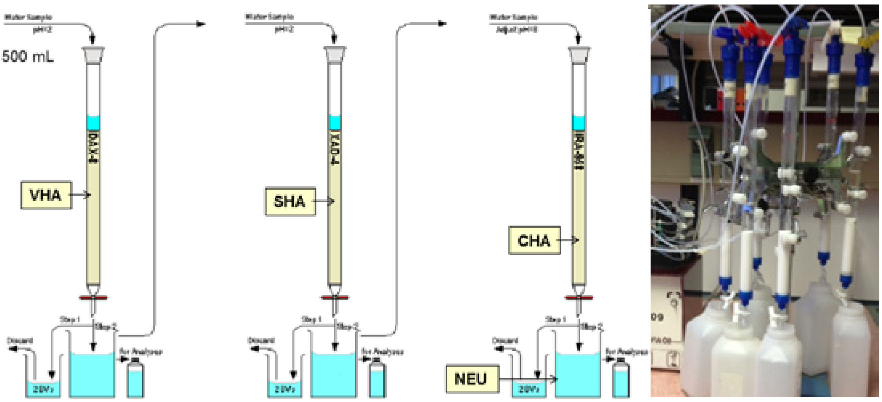


Figure 3-1. Rapid NOM fractionation set-up (from Chow et al., 2004)

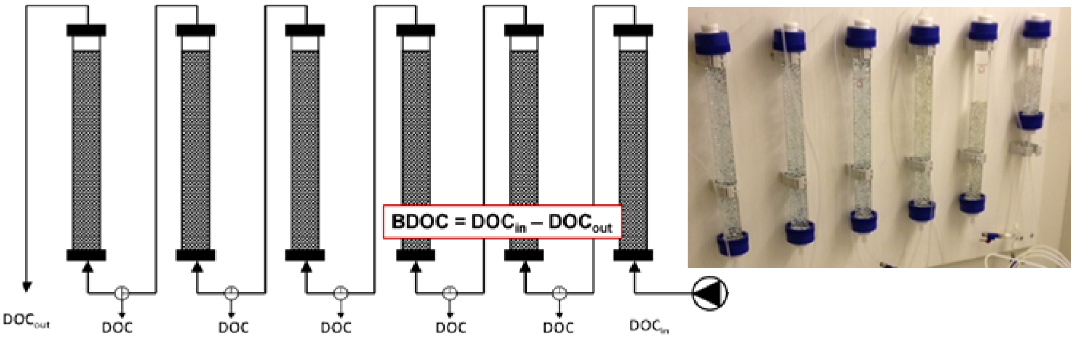


Figure 3-2. Column-based BDOC analytic set-up (Eikebrokk et al. 2007).

3.1.2. Advanced NOM characterization

The additional set of more advanced NOM physicochemical characteristics was determined on a sub-set of the samples using sophisticated instrumentation and analytical protocols. This includes Fourier transform ion cyclotron resonance mass spectrometer (FT-ICR-MS), zeta potential, molecular size distribution (HPSEC), Fluorescence Excitation Emission Matrix (FEEM), conventional NOM-fractionation (including DOC analysis of resin deposits/ eluates as well), disinfection by-products (DBPs), and flow cytometry/total bacteria counts.

NOM characterization by FT-ICR-MS (Fourier Transform Ion Cyclotron Resonance Mass Spectrometry). FT-ICR-MS is a novel mass spectrometric technique that is well suited for characterization of very complex mixtures of compounds due to its ultra-high-resolution performance that allows determination of the mass of individual compounds, without disturbance from the other compounds in the sample. FT-ICR-MS also performs a very accurate mass determination (<0.2 ppm), which allows calculation of the elemental formulas of the compounds. The elemental formula tells the number of carbon, hydrogen and oxygen (and other elements like chlorine, nitrogen and phosphorus) a molecule contain, and consequently to which compound class the molecules belong. In addition to molecular weight, and size distribution of molecules within complex samples, FT-ICR-MS provides information regarding the distribution of double bonds along the size distribution, i.e. the aromaticity of the molecules, which often is an important step in the characterization of unknown molecules.

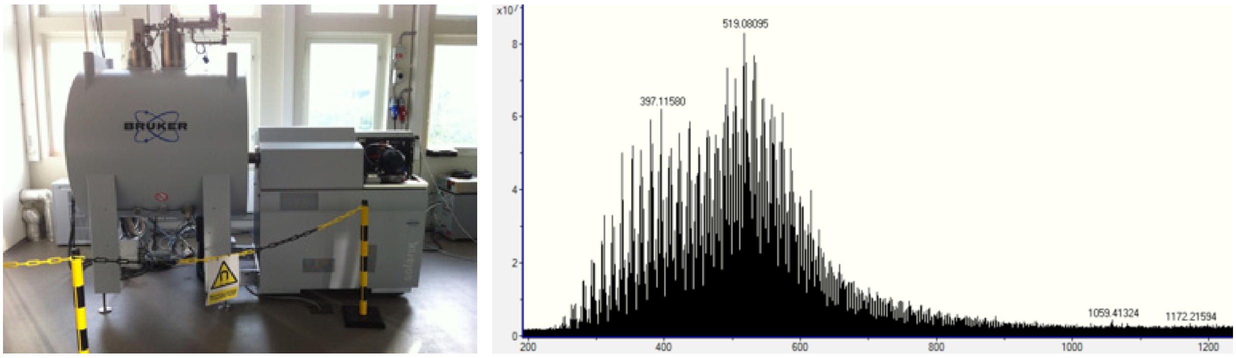


Figure 3-3 FT-ICR-MS instrument (left) and a typical NOM mass spectrum (right) showing a mass range from 200 to 1200 Dalton on the x-axis and response on the y-axis

The FT-ICR-MS instrumentation (Figure 3-3) has given a new insight into areas where the challenges with the complexity of the samples are the highest, examples besides from NOM chemistry are crude oil chemistry and metabolomics. FT-ICR-MS analysis generates very large sets of data, and the number of peaks in a mass spectrum can be more than 20 - 30 000. Mass spectra like the one showed above, give an indication of the size distribution, but for the comparison of different samples, Van Krevelen diagrams (Figure 3-4) are more informative.

Van Krevelen diagrams display elemental formula data in a 2-dimentional plot where the ratio of oxygen/carbon (O/C) is plotted along the x-axis and the ratio of hydrogen/carbon (H/C) is plotted along the y-axis. The Van

Krevelen diagram makes it possible to derive the compound classes from the location of the data points of the NOMs in the diagram. As will be shown in the results from the water treatment plants, the plots are especially valuable for the comparison of the effects of NOM composition from different water treatment processes.

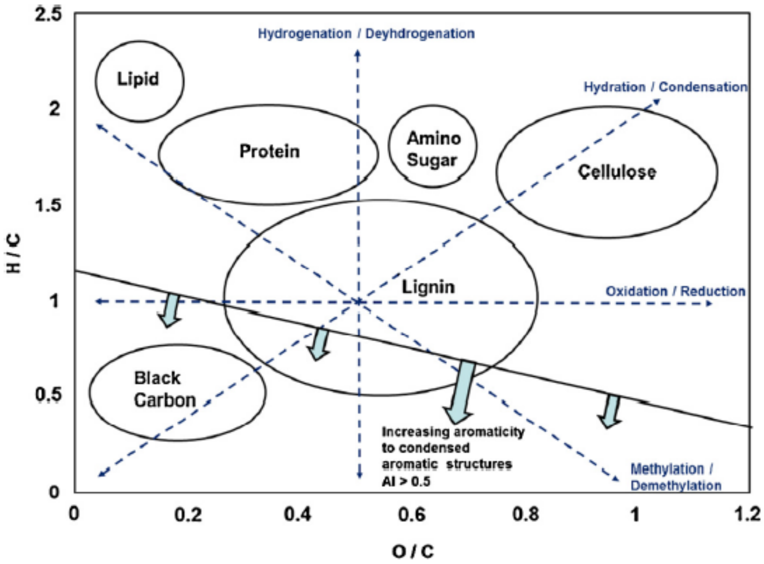


Figure 3-4 Schematic presentation of a Van Krevelen plot showing the plot locations for different classes of molecules. A large proportion of the NOM compounds will be located in the lignin type area. This is accordance with the literature (Andrilli et al 2013).

FT-ICR-MS: Modified sample preparation procedure

The sample preparation method was based on Dittmar et al 2008. The principle for the method is that NOM is extracted from water by solid phase extraction. The different steps of the methodology are shown below:

Sample: 500 mL water sample (stored at 4°C)
Filter by 0.22 µm
Acidify to pH 2 with HCl
Apply sample to Bond Elut PPL (200 mg) solid phase extraction (SPE) column
Elute SPE column with 1.5 mL methanol
Store at 4°C
Dilute 1:4 with water: methanol (50:50) before analysis
Infuse sample into FT-ICR-MS instrument (10 µL/min)
Capture spectra for ca. 10 min (approximately 300 spectra)
Ionization: Electrospray (ESI), negative mode

Slight modifications were made to increase the performance of the method.

For sample preparation and FT-ICR-MS methods, the following can be concluded:

A reproducible sample preparation procedure has been established
Stability of NOM samples have been confirmed by reanalysis
FT-ICR-MS methodology has been established
Reproducible MS data acquisition established (quality control samples)
Automated infusion has been established (reduced cost)
Data transformation and interpretation has been improved (reduced cost)

Conventional NOM Fractionation: Water samples were fractionated into their component hydrophobic and hydrophilic parts. The resins used were Amberlite XAD-7HP resin and Amberlite XAD-4 resin (Rohm & Haas, Germany). Amberlite XAD-7HP is an acrylic ester polymer. Amberlite XAD-4 is a styrene divinylbenzene polymer. These resins were prepared by Soxhlet extraction for 24 hours each with methanol, diethyl ether and methanol again to remove impurities. The resins were packed into glass columns and rinsed with DI water until the column effluent DOC was < 2 mg/L.

Two litres of each water sample were fractionated by XAD resin adsorption techniques into their hydrophobic (HPO) and transphilic (TPI) fractions using a method adapted from Malcolm & McCarthy (1992). The water samples were filtered to 0.45 µm and acidified to pH 2 using HCl. All of the acidified filtered water was put through the XAD-7HP/XAD-4 column pair. The XAD-7HP column was back eluted with 0.1 M sodium hydroxide (NaOH) to produce the HPO. The XAD-4 column was back eluted with 0.1 M NaOH to produce the TPI. The non-absorbed fraction was the hydrophilic fraction (HPI). Unlike the rapid fractionation method described before, the conventional fractionation method requires back-elution (NaOH) of the resins to produce the HPO and TPI fractions prior to DOC measurements.

Zeta potential: The zeta potential (electric surface charge of particles) was measured on unfiltered samples using a Zetasizer 2000 HSA (Malvern Instruments, Worcestershire, UK).

Flow cytometry (FCM): To measure the content of bacteria cells in the water samples a BD Accuri C6 flow cytometer equipped with a 488 nm solid-state laser (Becton Dickinson U.K. Ltd., Oxford, UK) was used for FCM analysis. Fluorescence staining was carried out adapting the protocol used by Hammes et al. To quantify total cell counts (TCCs), a 10,000× stock of SYBR Green I (SG) (S-7567; Life Technologies Ltd., Paisley, UK) was diluted with dimethyl sulphoxide (DMSO) (Fisher Scientific, Fair Law, NJ) to obtain a 100× working stock solution. 1 µL of this dye solution was added to sample volumes of 100 µL to obtain a 1× final SG concentration. For the quantification of intact cell concentrations (ICCs), a dye mixture was made of SG and Propidium Iodide (PI) (1 mg mL-1, corresponding to 1.5 mM; P3566; Life Technologies Ltd, Paisley, UK) at a ratio of 5:1. A 1.2 µL volume of this dye mixture was added to 100 µL of sample and 3 µM for SG and PI, respectively. The dye was aliquoted in round-bottom plastic plates followed by addition of 100 µL of bacteria. The mixture was subsequently incubated at 37 ºC for 13 minutes in a Grant-bio PHMP thermo-shaker (Grant Instruments Ltd, Cambridgeshire, UK) at 600 rpm. After incubation, samples were analysed using the FCM, at an excitation wavelength of 488 nm. All analyses were carried out in triplicate. Analyzed volumes were limited to 25 µl with the trigger set on FL-1 and fast flow rate settings corresponding to 35 µL/min and 16 µm core diameter. FL-1 limits 800 were excluded from analysis TCC and ICC signals were analysed on the FL3 (red fluorescence, 670 nm) vs FL1 (green fluorescence, 533 nm) density plot.

Fluorescence spectroscopy: Fluorescence excitation emission matrix spectra (FEEMS) were obtained using a Cary Eclipse Fluorescence Spectrophotometer (Varian, Surry, UK) and a 4 mL, 1 cm path length cuvette. Emission spectra were scanned from 300 to 500 nm at 0.5 nm increments and excitation spectra scanned from 250 to 400 nm with 5 nm increments (Baker, 2002). The slits for excitation and emission were 5 nm and the PMT voltage was set at 725V.

Disinfection by-products: To determine the potential of the water samples to form DBP, samples were chlorinated with excess chlorine and stored at 20 °C for 7 days in the dark. Samples were chlorinated at a dose that was five times greater than the DOC concentration. Samples were buffered at pH 7 to nullify any pH effects (adapted from procedure 5710 in 'Standard Methods for the Examination of Water and Wastewater' (APHA 1992). After seven days exposure to chlorine, samples were quenched using sodium sulphite (100 mg/L) and transferred into vials containing a buffer. The buffer was 1 % Sodium Phosphate dibasic (Na_2HPO_4) and 99 % Potassium Phosphate monobasic (KH_2PO_4). This buffer was added to avoid the transformation of other DBPs to THMs. THM4 (trichloromethane, dichlorobromomethane, dibromochloromethane and tribromomethane) were analysed using a modified form of USEPA Method 551.1. The total THM concentration was measured using gas chromatography (GC) with micro electron capture detection (µECD) (Agilent 6890).

3.2. Collection and compilation of data

In addition to the data from water sampling and analyses, data on watershed characteristics were collected along with available climate and deposition data as well as existing monitoring data from the waterworks. Data on the water chemical matrix, including major anions and cations, is required in order to interpret the NOM physicochemical data.

3.3. Assessments of watersheds, water quality and treatment

The effects of watershed characteristics, precipitation, acid rain, climate change, treatment performance, treatment optimization potentials, etc on NOM and NOM characteristics. The following issues were addressed:

Relative effect of reduction in acid rain vs. climate change on previous increase in NOM concentrations and changes in NOM characteristics
Explanatory factors and conceptually based processes governing the temporal and spatial differences in NOM increase and variability
Applicability of proxies describing the NOM in relation to treatment results
NOM fractions removed/not removed by the different treatment technologies
Treatment optimization potentials
Biostability and regrowth (distribution networks)
Benchmarking utilities (raw waters, treated waters, treatment operation performance)

From these assessments, conclusions were drawn regarding:

Likely future development in NOM concentrations and fluctuations in the raw water quality/water sources
Needs for improved treatment/additional treatment steps
A set of proxies for NOM properties to be used as “standard” methods for treatment process evaluations and process control in water works
Optimum treatment and optimum operations
Links between treatment performance and water/NOM quality during distribution

3.4. Partners and Work distribution

3.4.1. SINTEF

The research foundation SINTEF had a leading role in the NOMiNOR-project. In addition, SINTEF’s activities included:

Analysis of NOM-fractions, BDOC, ATP, and metals in 200 water samples
Identification and semi-quantification of specific NOM-/organic components by advanced FT-ICR-MS analysis (100 samples)
Preparation/presentation of results, linking NOM characteristics to treatment and distribution performance
Preparation of reports (site-specific reports to WTWs, status reports, final report)

3.4.2. NMBU, SLU, Cranfield, Lund, and Aalto Universities

NOMiNOR included university partners with main activities/responsibilities as presented below:

Norwegian University of Life Sciences (NMBU):
Characterized the watershed of the drinking water source with respect to geology, quaternary deposits, topography and vegetation types based on existing maps (GIS).

Used runoff characteristics in space and time to calibrate a water balance model for the different water courses. A gridded catchment approach was used to estimate contribution from different sub-catchments. Traditionally, this model was used for estimation of runoff of road salt (The Salt-smart project – Vegvesenet.no).
Linked variations in NOM to hydrology and changing weather conditions based on previous measurements on NOM and runoff data.
Analyzed major anions (SO_4^{2-}, Cl^- and NO_3-) in water samples

University of Oslo (UiO). UiO and NMBU shared a common Postdoc candidate (Ståle Haaland). In addition, the activities included:

Supplied NOM reference material with specific physicochemical characteristics
Compiled existing monitoring data from the water works with deposition and climate data for each watershed.
In cooperation with NMBU assessed the project data and submitted research papers on interpretation of proxies for NOM characteristics based on comparison using sophisticated analytical techniques.
Provided empirical and conceptual links between physiochemical quality of NOM and watershed and climate characteristics.
Discussed effect of acid rain vs. climate change on observed NOM changes.
Discussed explanatory factors and conceptually based processes governing the temporal and spatial differences in NOM increase and variability

Cranfield University (UCRAN) conducted NOM analysis of particle surface charge/zeta potential, molecular size distribution (HPSEC), fluorescence properties including humic-like, fulvic-like and protein-like NOM (FEEM), NOM-fractions (conventional fractionation), Disinfection by-products formation potential (DBPFPs), as well as Total bacteria counts (flow cytometry) on 40 samples.

Lund, SLU and Aalto Universities were involved in discussion of results, assessments and reporting (WP 3 and WP 5).

3.4.3. Waterworks

The responsibilities of the participating waterworks included:

Water sampling and sending of samples for analysis (to SINTEF, NMBU, UiO and UCRAN), provision of relevant monitoring data on NOM and data on water quality, operating conditions, etc.
Sharing knowledge and experience with the other participants in the project, in order to provide better capability at the waterworks to meet upcoming challenges related to NOM, and to ensure best possible performance of the water treatment processes.
Assessing benchmark results and optimization potentials

The water works were also part of the NOMiNOR reference committee and contributed with specific knowledge and competence at project meetings, etc.

3.4.4. Water associations

The Norwegian Water and Swedish Water Associations were part of the reference committee, and provided additional foundation of the NOMiNOR project. In addition, they provided information and dissemination of results to the stakeholders in the two countries. Norwegian Water (Kjetil Furuberg) was the project leader, with specific responsibilities for control of progress, economy, meetings and workshops, etc.

3.5. Work Packages

The NOMiNOR project was organized in 6 main activities/work packages (WPs) with sub-activities (Tasks) and responsible institutions/persons and deliverables as given below:

3.5.1. WP1 Water sampling and NOM-analyses

SINTEF (B. Eikebrokk) was responsible for WP1 that contained three tasks:

Task 1.1 (G. Thorvaldsen, SINTEF): Simple water quality and NOM analyses. Analyses of 200 water samples (100 in 2014 and 100 in 2015) from 5 sampling spots at all water works (WWs): 1) incoming raw water, 2-3) outlets from different treatment steps, 4) outlet from the clean water tank, and 5) from the distribution system. The samples were taken at 4 seasons: winter and summer (2014), spring and autumn (2015), and were analysed for the following parameters: Turbidity, pH, conductivity ¨VIS- (600 and 400 nm) and UV-absorbance (254 nm), TOC, DOC, total Al, Fe, Ca, Mg, Na, K concentrations, NOM-fractions (VHA, SHA, CHA and NEU), BDOC and ATP.

Task 1.2 (K. Zahlsen, SINTEF): Advanced NOM-analyses. FT-ICR-MS-based analysis for the identification and quantification of specific NOM/organic substances present in the water samples. 10 selected raw water and treated water samples, i.e. raw water and treated water samples from 5 WWs per year, was analysed in 2014 and 10 more samples in 2015 in order to detect differences in NOM, NOM-fraction concentration and composition prior to (raw water) and after treatment with different technologies. In addition, FT-ICR-MS analyses were conducted on 4 seasonal samples from two selected WWs in 2014 and two additional WWs in 2015 in order to identify seasonal variability in NOM composition in raw water as well as treated waters (incl. treatability assessments). 5 sampling spots was used: 1) incoming raw water, 2-3) outlets from different treatment steps, 4) outlet from the clean water tank, and 5) from the distribution system, i.e. 40 samples/analyses in 2014 and 40 in 2015.

Thus, for a total of 110 samples and analyses by FT-ICR-MS:

10 samples per year in 2014 and 2015, in order primarily to identify the effects on NOM and NOM fractions as well as NOM treatability by different treatment technologies
40 samples per year in 2014 and 2015, in order primarily to identify seasonal variability in raw and treated waters quality/NOM (different treatment technologies/treatment steps)
10 NOM reference samples

In fact, a lot more samples were analyzed by FT-ICR-MS during the NOMiNOR project.

Task 1.3 (P. Jarvis, UCRAN): Advanced NOM-analyses. Samples of raw water, coagulated water, treated water and distributed water from selected WWs were analysed for charge/zeta potential, MW-distribution (HPSEC), conventional NOM-fractionation into hydrophobic and hydrophilic –acids, -bases and -neutrals, total bacteria cell counts/flow cytometry, disinfection by-products (DBPs), and fluorescence/FEEM-analyses of humic-like, fulvic-like and protein-like NOM.

Importantly, and perhaps for the first time, links can be made between the results obtained by rapid and conventional fractionation procedures to determine whether these techniques tell us the different things or whether the rapid process can replace the conventional fractionation method.

UCRAN also looked at microbiological removal through the treatment train as well as DBPs, and linked that to NOM content/type and disinfection strategy. Microbial removal (log reductions) was measured by flow cytometry quite quickly and easily. The main concern here was the necessity for quite rapid shipment of water samples. The next day delivery promised by the transport provider, was not always achieved.

The measurement and data provided in WP1 enabled links to be made between the types of organic compounds removed by different treatment steps at the selected water treatment works. This included different coagulants, coagulation conditions as well as the applied solid-liquid separation processes. Through measurement of charge related parameters, supplementary indications of coagulation effectiveness were made. The results enabled a linking of treatment performance and the type of NOM being removed at the investigated water works. In addition, the data provided a good basis for treatment performance assessments, benchmarking among the utilities, and for identification of optimization potentials.

Results from WP1 were prepared and sent to the utilities/WTWs with presentation and discussion of their site-specific results, incl. practical implications.

3.5.2. WP2 Watershed and water chemistry

NMBU (Ståle Haaland) and UiO (Rolf David Vogt) were responsible for WP 2. WP2 included activities on characterization of watersheds, land-use, type and amount of vegetation, soil/geology, climatic conditions, precipitation patterns, hydrology, water chemistry, etc. UiO and UMB shared a post-doc candidate for this work.

UiO took on the main responsibility for the activities related to water/water chemistry, and NMBU for the mapping and characterization of the watersheds. Attempts were made to discern effects of acid rain from climate change, and to study processes governing NOM leaching.

WP 2 contained two tasks:

Task 2.1 Watershed characteristics (G. Riise and N.-O. Kitterød, NMBU): Watershed mapping (GIS) and water balance modelling. Linking of temporal variation in NOM to fluctuations in hydrology. Analysis of major anions, preparation of reports and publications.

Task 2.2 Water chemistry (R.D. Vogt, UiO): Water chemistry analysis of Al, Fe fractions or alkalinity (200 samples). Preparation of reports and publications.

WP2 deliverables included results, and reports/publications.

3.5.3. WP3 Results preparation, assessments and reporting

SINTEF (B. Eikebrokk) was responsible for WP3, along with UiO, NMBU and Cranfield.

This WP included overall assessments of results on NOM concentrations, NOM physicochemical properties as well as NOM treatability and NOM removal in relation to the specific watersheds/water sources, and water treatment/distribution systems characteristics, including biostability issues. Key elements were addressed, and site-specific assessments and recommendations were provided.

Lund University, SLU and Aalto University were involved as dialogue partners in results preparation, discussions, assessment and reporting.

WP3 deliverables included presentations, face-to-face meetings and reports to all utilities, including site-specific results and assessments on raw water/watershed, water treatment and distribution, etc. Possible recommendations towards safer and more sustainable/resource efficient operations were included. In addition, site-specific as well as overall summary/benchmark results were prepared and discussed at the meetings.

3.5.4. WP4 NOMiNOR-workshops

Under this WP, NOMiNOR project meetings and workshops were planned, prepared and arranged. Here the waterworks and the research partners met to present and discuss results, conclusions and recommendations. External stakeholders were invited to specific parts of the workshops as well.

WP4 deliverables included exchange of information, presentation and discussion of NOMiNOR results at a number of NOMiNOR meetings and workshops:

NRV, Norway (Nov 2013)
Bergen, Norway (Sep 2014
Islay, Scotland (March 2015)
Malmö, Sweden (Nov 2015)
Helsinki, Finland (Apr 2016)
Oslo, Norway (Nov 2016)
Stockholm, Sweden (Apr 2017)
Edinburg, Scotland (May 2017)

3.5.5. WP5 Final report with conclusions and recommendations

Responsible partners for the WP5 activities were SINTEF, along with UiO, NMBU and Cranfield.

This WP comprised the preparation of this final report with overall assessments, conclusions and recommendations. In the report similarities - and differences - between the NOMiNOR-waterworks are highlighted, including conditions related to: i) watershed, water sources and climate characteristics, ii) physiochemical characteristics of NOM, iii) water treatment and operation characteristics, iv) distribution system characteristics.

Based on these analyses and assessments, predictions were made with respect to future raw water quality/NOM content and corresponding operation challenges, need for water treatment upgrading/supplementary treatment steps, alternative modes of operation towards increased safety and sustainability, etc.

As part of this, we also expect that the NOMiNOR activities can help participating WWs in increasing their knowledge level with respect to their own water supply systems and all of its elements. In addition, we anticipate that the knowledge provided by this project will form a strengthened basis for meeting future challenges related to climate change effects and deteriorations in source water quality, including increasing NOM-concentrations and properties/reactivity, treatment capacity and capability, biological stability, etc.

Lund University, SLU and Aalto University were also involved as dialogue partners in evaluating and discussion in the preparation of this report.

WP5 deliverables included this final report (English version) with summary results, overall conclusions and recommendations. In addition, a comprehensive summary report is provided in Norwegian. Moreover, manuscripts for publication in international peer review scientific journals are prepared.

3.5.6. WP6 Project management (Norwegian Water/Norsk Vann)

This activity included overall project management and administrative work, including follow-up of budgets and economy, progress, meetings, etc. K. Furuberg at NV filled the position as the overall project manager, and B. Eikebrokk, SINTEF covered the scientific and technical aspects.

4. RESULTS AND DISCUSSIONS: Watershed and water source characteristics

4.1. Watershed and Water Source Characteristics

Introduction

Boreal and temperate lakes have had a distinct change in colour throughout the past few decades (Monteith et al 2007; Sobek et al. 2007). This recipient brownification is due to increased concentrations of allochthonous coloured natural organic matter (NOM), often in complexation with ferrous iron colloids (Forsberg & Petersen 1990; Weyhenmeyer et al. 2014; Kritzberg & Ekström 2012). Both iron, NOM and iron bound to NOM have strong abilities to absorb light in the blue PAR-area, intensifying the brownification process (Gjessing 1964; Kirk 1976; Shapiro 1957). In addition to the reduced anthropogenic acid rain deposition onto watershed soils (Krug & Frink 1983; Evans et al. 2006), climate change is also a strong driver for the increased levels of NOM. Moreover, the climate change along with increased levels of atmospheric CO_2, changes in land management and accumulated N-deposition has increased the amount of biomass (watershed greening) and thereby increased the leaching of NOM (watercourse browning) within boreal and temperate rivers and lakes (Larsen et al. 2011; Finstad et al. 2016).

Watersheds

Raw water sources in NOMiNOR are, at the WTW intake, either running (lotic) (Bracadale in Scotland, NRV in Norway, Ätran in Sweden) or still (lakes/reservoirs; lentic). Some of the watersheds are small headwaters that are fairly easy to assess, whereas others are large, high order and more complex watercourse systems consisting of several reservoirs, lakes or dams that are linked together and to some extent controlled by the WTWs (such as Burncrooks and IVAR). The watersheds range in size from a few square km to almost 40 000 km^2. The larger watershed systems, with moderate to larger raw water sources, often have a considerably slower watershed-recipient response. In NOMiNOR, both slow and rapid watershed-recipient response for raw water sources are thus included. Similarly, the NOM quality varies considerably between catchments (Picture 4-1; Figure 4-1).

Activities within watersheds for raw water sources are often restricted. However, larger watersheds might be markedly affected by human activities such as roads, buildings and a range of different point- and diffuse pollution sources as well as liming activities. Often, there are also excessive activities within the raw water source itself; such as fish- and bird life, boating, etc. Activities will modify the water chemistry, but the dynamics of NOM-concentrations within each watershed, are still very much controlled by a set of known regional drivers. These drivers are more or less universal among the NOMiNOR raw-water sources, though their significance in determining the amount and quality of NOM differ between the regions.

NOM drivers

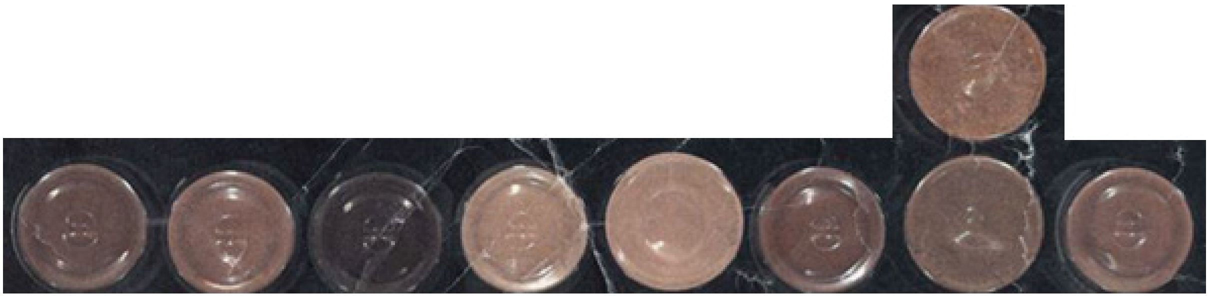
The different watersheds in NOMiNOR have a set of important drivers for NOM. Climate and rainfall quality are among the most important. The drivers are often the same amongst watersheds, but with different weights and impacts.

Temperature is a basic driver for NOM, through photosynthesis, plant growth, enzyme- and microbial activity. A range of different temperature vs NOM production connections (transfer functions) exists. In NOMiNOR, non-linear site-specific functions for temperature vs NOM production are used. The NOMiNOR watersheds, situated within the boreal and temperate domain, are following similar annual cycles with growing seasons in approximately May-September. However, there is one important categorical difference among the watersheds; those that drop below freezing point during winter and those that do not. In NOMiNOR, a few of the raw water sources rarely have air temperatures dropping below 0 °C. That makes it easier to model when using a temporal scale resolution finer than an annual basis, since winter hydrology can be excluded. Still, the trends in NOM in all of the watersheds are affected by an increase in air/soil temperature through increased production of organic matter and a subsequent degradation of organic matter.

Rainfall amounts will affect the NOM concentrations within the raw waters through source flushing, transport and dilution (Hongve et al 2003; Haaland et al. 2010; Figure 4-2). The NOMiNOR watersheds comprise a great range in amounts of annual rainfall. Average rainfall in the Stockholm area close to Mälaren, and in Finland close to Lake Päijänne, receives on average about 500-600 mm rainfall per year. In comparison, the westernmost watersheds in Norway and Scotland receive up to 3000 mm rainfall per year. However, the hydrological regimes (temporal annual rainfall distribution and snowmelt) within the NOMiNOR watersheds, are somewhat comparable. Increased rainfall amount and intensity leads to more sub-lateral water flow in shallow organic rich flow-paths. The NOM water passing through the watershed is thereby bypassing the sorption capacity of the deeper mineral soil. This leads commonly to increased levels of NOM with increased flow. On the other hand, some of the watersheds are rapidly diluted by incoming precipitation, such as in the watersheds with thin or sparse soils or peats in the southwest of Norway. Here, the watersheds also receive a considerable amount of precipitation. A further increase in rainfall in such regions tends to dilute the NOM concentration rather than increase it.

Some of the data-sets collected by the waterworks have more complete long-term data on colour than carbon (TOC, DOC). If colour is modelled, we have to take into account that iron can absorb light both at visible and UV regions. Iron might hence be regarded as a "driver" for colour (but not for NOM). From this, models for colour might have iron included as an (more or less) important driver.

Drivers that affect the ionic strength of the water will affect the electrostatic repulsion of NOM (Tipping & Hurley 1988). These drivers will thereby to some extent control the flocculation, coagulation and precipitation of NOM in the watershed and water sources. Differences between watersheds regarding drivers for NOM, can hence be reflected in the anionic composition of the raw water (Figure 4-1; Figure 4-3). Major inorganic anions in the NOMiNOR raw water sources are chloride, sulphate and bicarbonate. Chloride has its main source from the ocean (sea aerosols). Variations in sulphate is often a signature of acid rain, which was much more pronounced in some of the watersheds in the 1950s to early-2000s, peeking in the mid-1970s, and are less pronounced today (Monteith at al. 2007). Bicarbonate is mainly derived from the weathering of carbonate minerals. In watersheds with soils that contain carbonate minerals the bicarbonate is an important factor contributing to the soil solution total ionic strength and reducing solubility of NOM. The different drivers have different significance in governing the solubility of NOM at the different NOMiNOR watersheds. The relative importance of NOM drivers for the NOMiNOR watersheds, regarding both production, transport and solubility, are shown in Table 4-1.



Picture 4-1. Illustration of how different the appearance (quality) of NOM samples (freeze-dried) can be among different watersheds. The lower row represents autumn isolates (photographed in scintillating glasses) of NOM from eight different watersheds at Nordic/Boreal sites, comparable to the NOMiNOR sites. Watershed second from the right has also been sampled during spring (top row), visualizing a difference in NOM quality during the season. Isolates are taken from the NOMINIC-project (see Vogt 2001).

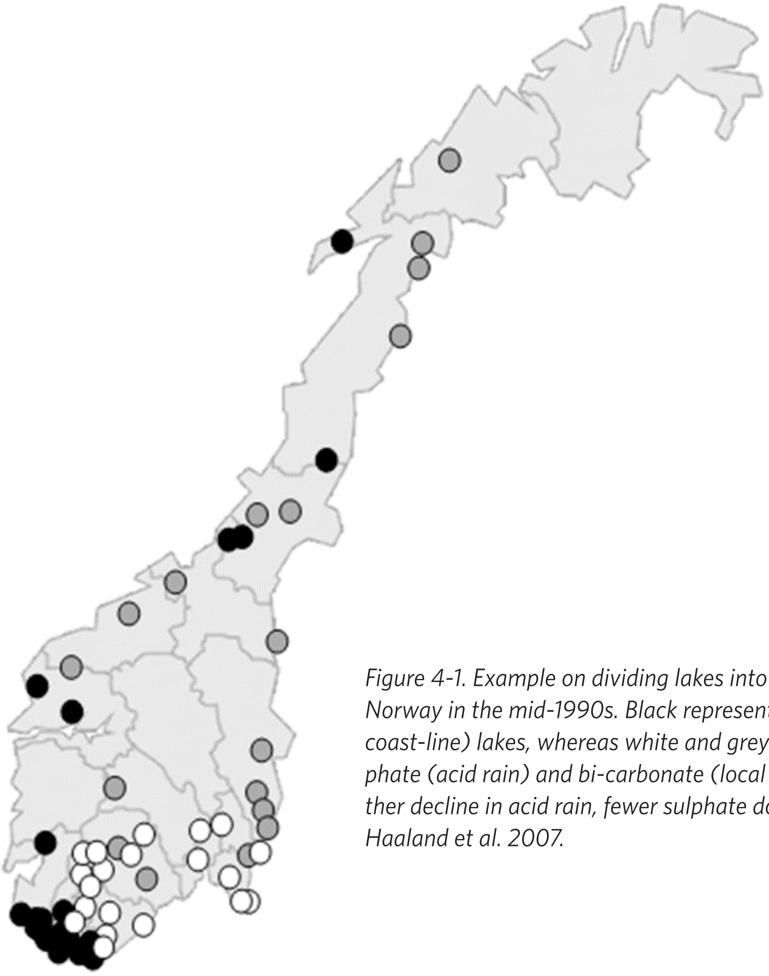


Figure 4-1. Example on dividing lakes into different anionic compositions in Norway in the mid-1990s. Black represents chloride dominated (close to the coast-line) lakes, whereas white and grey are lakes more dominated by sulphate (acid rain) and bi-carbonate (local geology), respectively. After a further decline in acid rain, fewer sulphate dominated lakes are left. After Haaland et al. 2007.

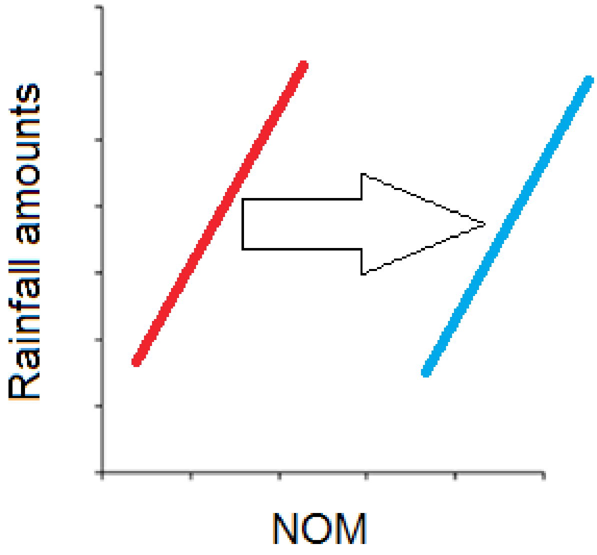


Figure 4-2. Generic model depicting rainfall amounts vs NOM-concentration derived from data from four raw water lake sources for the city of Oslo. Over the past few decades, we have been moving from the red line towards the blue line; more allochthonous NOM is now transported per mm of rainfall to these lakes. The sketch is derived from data published in Haaland et al. 2010.

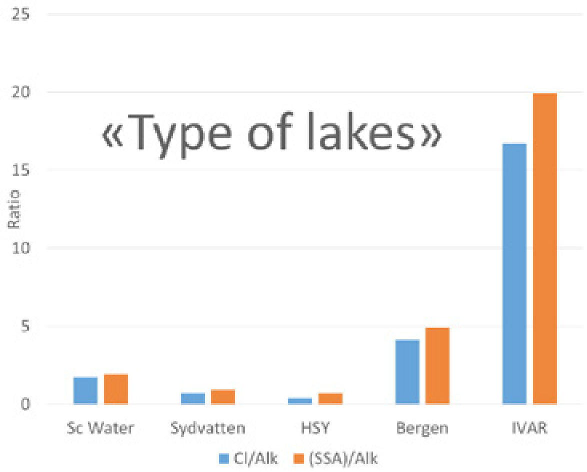
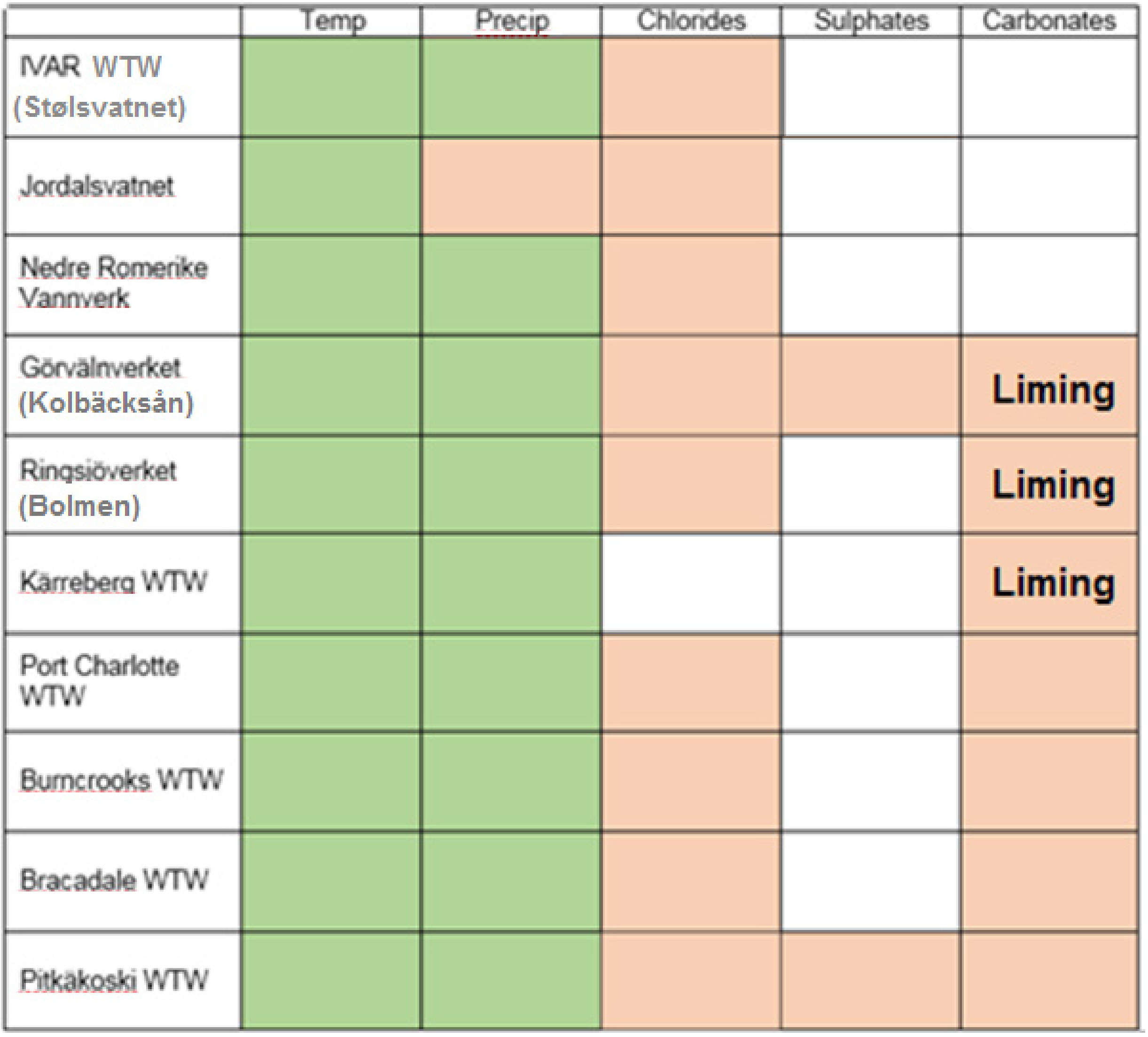


Figure 4-3. Raw water sources from NOMiNOR have different ionic composition, due to different atmospheric deposition and watershed soil characteristics. SAA = Strong Acid Anions (chlorides + sulphates + nitrates). Alk = alkalinity).

Table 4-1. The NOMiNOR watersheds and their different drivers for NOM. Green indicate a positive driver, whereas red indicate a negative driver. Temperature and precipitation are typical climatic drivers. Chloride is a proxy for sea-salt, sulphate for acid rain and carbonates for watershed inorganic buffer capacity.



	Temp	Precip	Chlorides	Sulphates	Carbonates
IVAR WTW (Stølsvatnet)	🟩	🟩	🟥		
Jordalsvatnet	🟩	🟥	🟥		
Nedre Romerike Vannverk	🟩	🟩	🟥		
Görvälnverket (Kolbäcksån)	🟩	🟩	🟥	🟥	🟥 **Liming**
Ringsjöverket (Bolmen)	🟩	🟩	🟥		🟥 **Liming**
Kärreberg WTW	🟩	🟩			🟥 **Liming**
Port Charlotte WTW	🟩	🟩	🟥		🟥
Burncrooks WTW	🟩	🟩	🟥		🟥
Bracadale WTW	🟩	🟩	🟥		🟥
Pitkäkoski WTW	🟩	🟩	🟥	🟥	🟥

4.1.1. Nedre Romerike WTW (NRV - Norway)

NRV is located in the lower parts of the largest watershed in Norway (Picture 4-2). The raw water source is Glomma, the longest river in Norway and the watershed covers almost 40 000 km^2.

Since Glomma, just upstream of the inlet at NRV, consist of two very large rivers, it is hard to model the NOM concentration (Figure 4-4). However, it is possible to locate NOM hotspots in the watershed using GIS (Figure 4-5). In the lower parts of the eastern watershed, the "e2" watershed, there are much higher concentrations of NOM than elsewhere in the watershed (Figure 4-6). This makes it easier to model. The area has been affected by acid rain and studies from similar watersheds similar to e2 near Oslo have been modelled regarding colour (Haaland et al. 2010). The raw water colour is also heavily influenced by precipitation amounts (Figure 4-7 and Figure 4-8).

There are no long-term trends in the NOM at this site. Important drivers for NOM are temperature, precipitation amounts and precipitation quality; dominated by sea-salt and at present to a lesser degree by sulphates from acid rain.

Picture 4-2. Two large rivers merge into Glomma just upstream of the intake to the NRV treatment plant in south-eastern Norway. Note the different water quality in the two rivers; darker water is seemingly entering from the east. Photo: inatur.no.

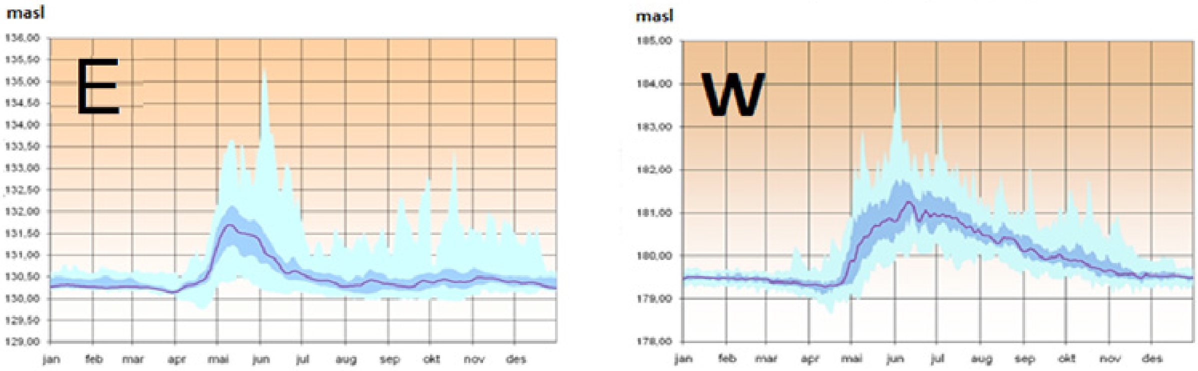


Figure 4-4. River discharge from the east river (E = e1 + e2; see figure 4-5) vs the west (W) river. The highest E (e1+e2) to W river water ratio is most likely to happen during autumn, when discharge peaks are driven by precipitation and not snowmelt. Mild winters could generate similar high e2:W water origin ratios. Data from NVE (The Norwegian Water Resources and Energy Directorate).

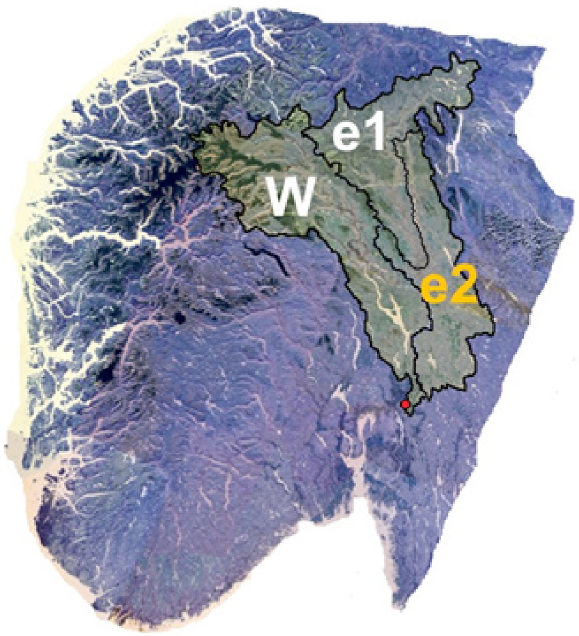


Figure 4-5. The most challenging watershed for NRV, regarding NOM, is the e2 (East 2) watershed. It is within e2 the highest concentrations of NOM are measured.

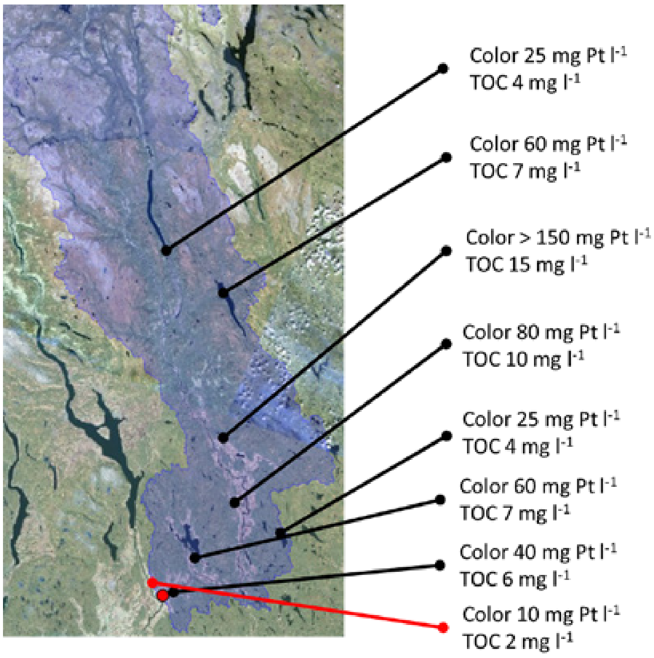


Figure 4-6. Measured concentrations of NOM within watershed e2 and in the lower parts of watershed W. Watershed W is draining the largest lake in Norway; Lake Mjösa.

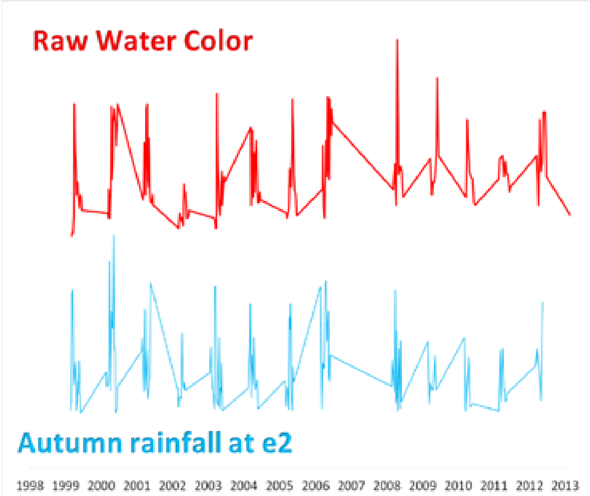


Figure 4-7. Plot (standardized scaling) of raw-water colour at NRV treatment plant (in red) over autumn precipitation onto the e2 watershed (in blue).

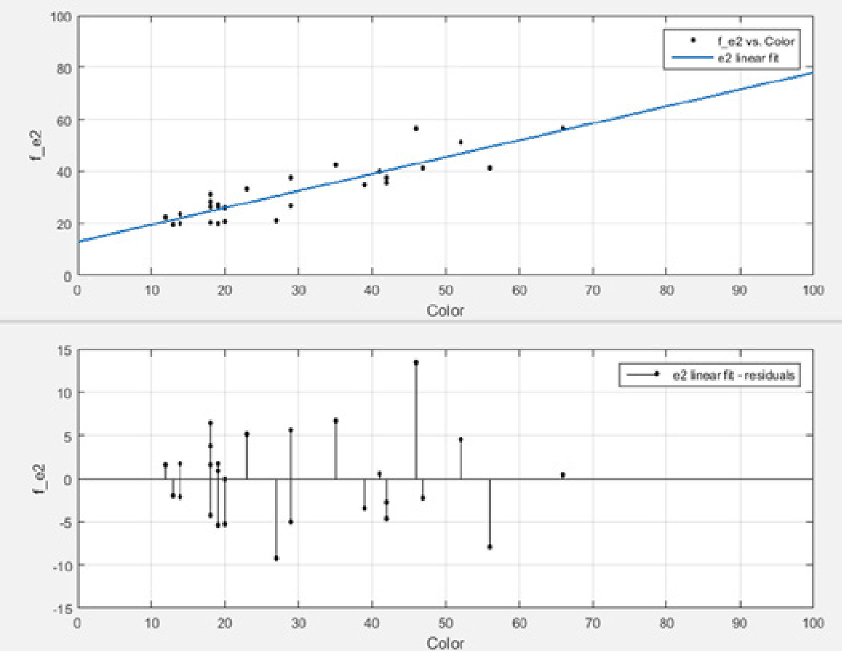


Figure 4-8. Precipitation and conductivity (sea-salt and acid rain) were the main drivers at e2. Precipitation, conductivity (sea-salt) and temperature will be the main drivers in the near future.

4.1.2. Burncrooks WTW (BUR - Scotland)

Burncrooks reservoir (Picture 4-3) includes a chain of connected reservoirs, and the watershed comprises scattered extensive forestry (as seen on a visit to the watershed in 2015). The main reservoir utilizes a vertical water mixing system that was installed to avoid anoxic conditions and release of manganese from the sediments. This has a major effect on the vertical circulation pattern; maintaining uniform conditions throughout the reservoir and eliminating vertical stratification and stagnation of "aged" bottom water (Gurney Environmental 2013).

Photo: Lairich Rig (2012)

Oblique aerial photograph (1952)

Photo: Gunnhild Riise (2015)

Picture 4-3. Burncrooks reservoir in Scotland.

There are large seasonal fluctuations but no long-term trends in the NOM concentration at the Burncrooks site. Maximum NOM concentrations during late autumn/early winter are generally well modelled using precipitation amounts only as an explanatory variable (Figure 4-9). This is likely due to relatively minor variations in sea-salt and air temperature during the years 2004-2016. Air temperature would probably have been more important if there had been a significant increase. The year 2009 and 2010 are not well predicted using precipitation amounts only. This is potentially due to stratification issues or sea-salt exposure from winter storms.

It is thus fair to postulate that important drivers for NOM are precipitation amount, temperature and precipitation quality; dominated by sea-salt. Carbonate from the watershed is also important.

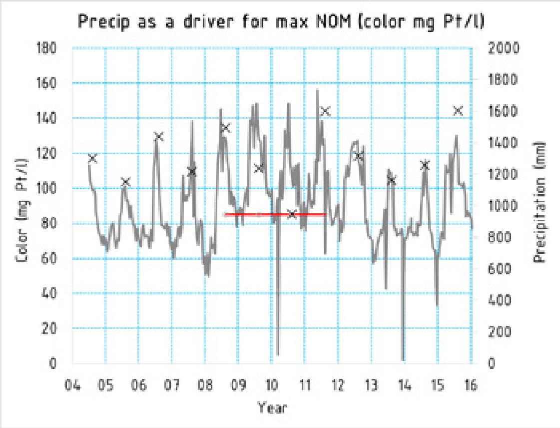


Figure 4-9. Maximum NOM (colour) concentrations (X) during late autumn, modelled by precipitation amounts at Burncrooks reservoir.

4.1.3. Pitkäkoski WTW (PIT- HSY), Finland

Lake Päijänne is the largest in terms of volume and the deepest lake (95 m) in Finland. Päijänne has a water retention time (TWRT) of 2.2 years, and a surface area of 1116 km^2. Mean depth of about 16 m (Picture 4-4). The lake has a very long and complex shore-line (Figure 4-10). The lake is situated 140 km from the sea, and is hence not strongly affected by sea-salt episodes. There has however, been a decline in both sulphate and chloride in the raw water over the past few decades Figure 4-11). This might be due to a decline in local anthropogenic pollution, such as from paper industry.

The colour of the water has increased more than 50 % since 2009. Important explanatory factors for trends and fluctuations in NOM concentrations are temperature, precipitation amounts and precipitation quality; dominated by chlorides and sulphate (possibly internal sources). Carbonate from the watershed is also important. The best long-term data for Lake Päijänne, regarding NOM, are colour measurements (Figure 4-12).


Photo: s-media

Picture 4-4. The beautiful Lake Päijänne in Finland.

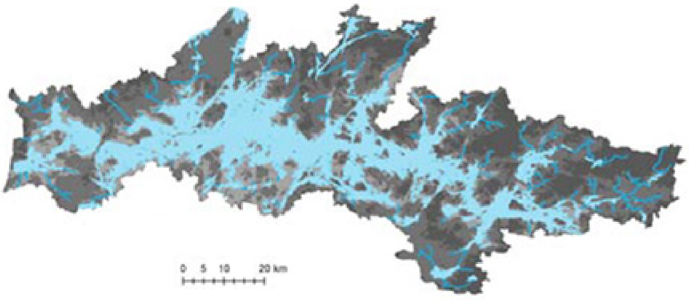


Figure 4-10. Lake Päijänne has a very long shoreline.

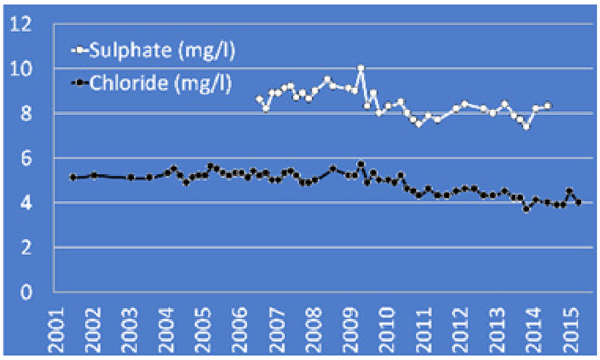


Figure 4-11. There has been a recent distinct decline in both chloride and sulphate in Päijänne. This might have been of an anthropogenic origin.

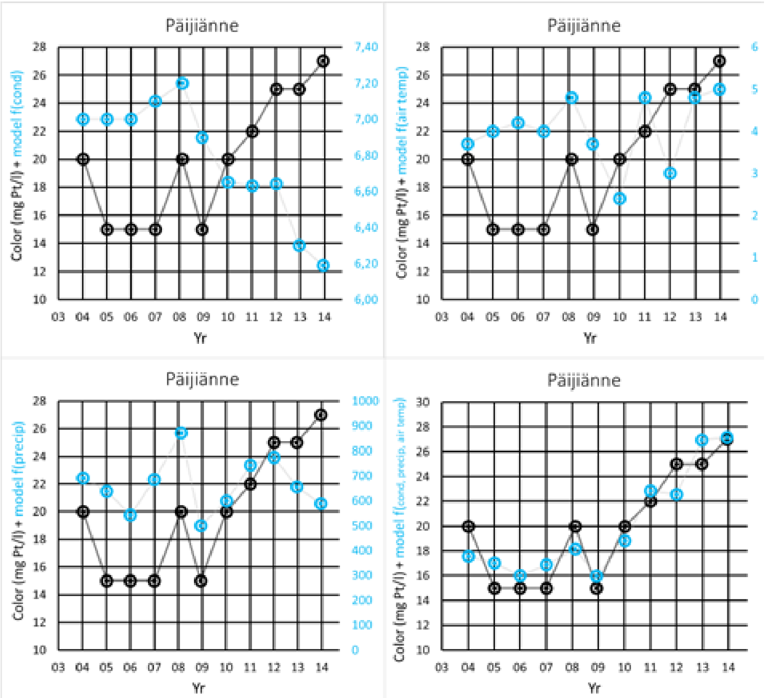


Figure 4-12. The colour in Lake Päijänne is well modelled using precipitation amounts, temperature and conductivity as inputs (lower right graph). Iron is presumably not an important factor for colour in this model.

4.1.4. Bracadale WTW (BRA - Scotland) & Port Charlotte WTW (PC - Scotland)

There are large seasonal fluctuations but no long-term trends in the NOM at these sites. Important drivers for NOM are temperature, precipitation amounts and precipitation quality; dominated by chlorides and to less extent sulphate. Carbonate from the watershed is very important, and the concentrations of iron and manganese are high. Variation in colour is still mainly due to annual variations in concentrations of NOM and to a lesser degree iron (Figure 4-15).

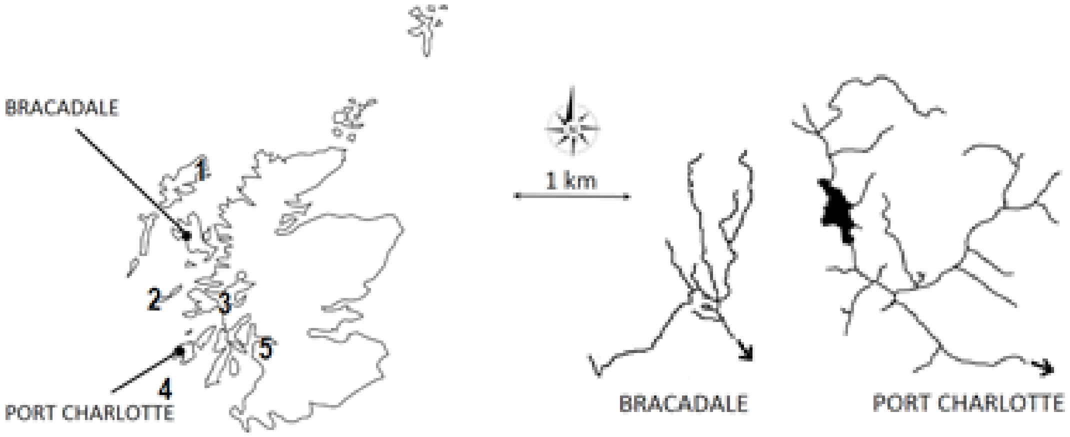


Figure 4-13. Locations and detailed watercourse patterns of Bracadale and Port Charlotte in Scotland. Meteorological stations (UK Met Office; historic station data) are shown with numbers 1-5 (left Figure); 1-Stornoway Airport, 2-Tiree, 3-Dunstaffnage, 4-Ballypatrick Forest (located in Northern Ireland), 5-Paisley. From Haaland et al. in prep.

At Bracadale and Port Charlotte, there are data on about weekly to bi-weekly scale for the chemistry. It is therefore possible to model NOM-dynamics at shorter time-steps. For climate (precipitation and air temperature) monthly data are used, since that is the finest resolution we have on climate scenarios provided by the UKCP09 (see more on scenarios and predictions in next chapter).

We are able to model colour development at both Bracadale and Port Charlotte with a satisfactory resolution (Figure 4-16 and Figure 4-17).

Picture 4-5. Sampling running waters at Bracadale, Scotland. This is not a very large raw water source, in fact the smallest within the NOMiNOR-project. The average annual rainfall, however, can be > 2500 mm yr-1 in this region.
Photo: Gunnhild Riise.

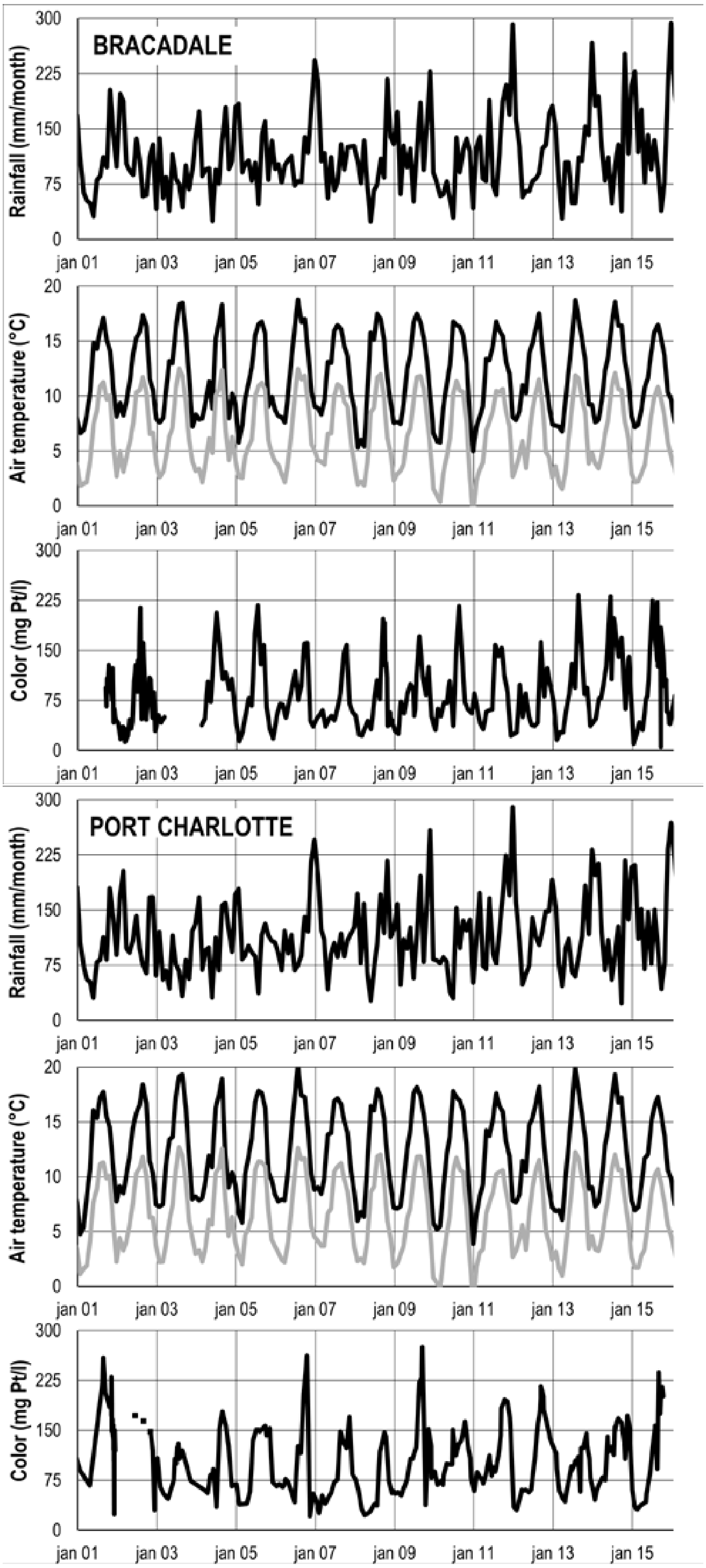


Figure 4-14. Precipitation, air temperature and colour measurements at Bracadale and Port Charlotte, years 2001-2015. Climate data provided from Met UK. Haaland et al in prep.

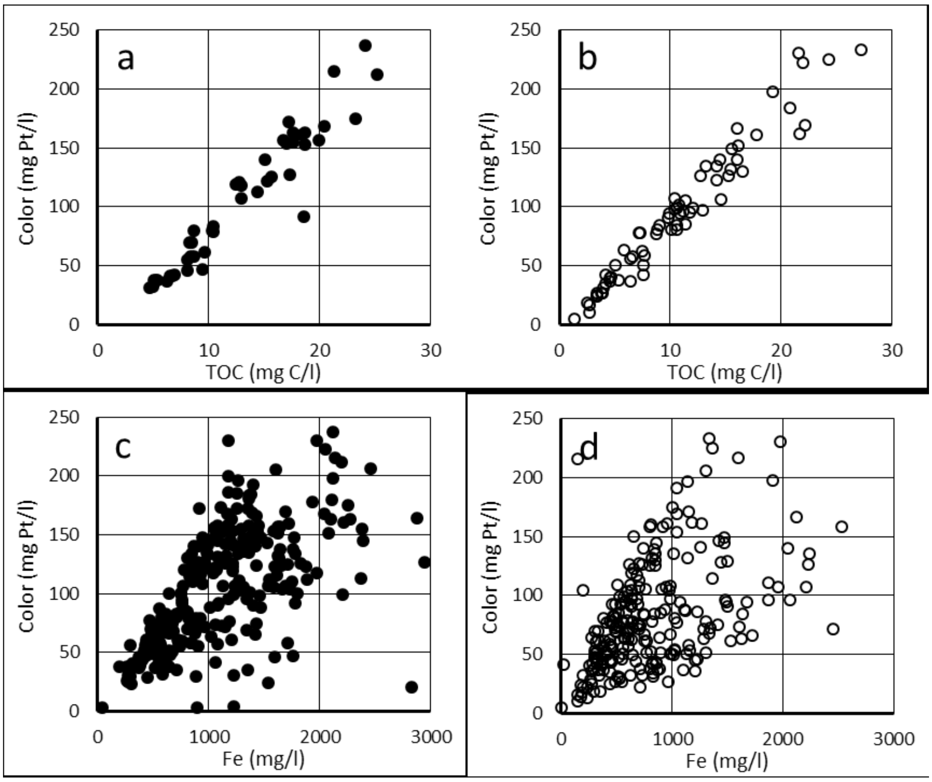


Figure 4-15. XY-plots for colour vs concentrations of total organic carbon (TOC) and iron (Fe) at Port Charlotte (filled circles; plot a and c) and Bracadale (open circles; plot b and d) for the period 2000-2015. TOC (na = 74 and nb = 106) is at these watersheds a stronger explanatory factor for colour than iron (nc = 169 and nd = 277). Linear trend regressions: r^2 = 0.90-0.95 for colour vs TOC; r^2 = 0.22-0.30 for colour vs Fe. Haaland et al. in prep.

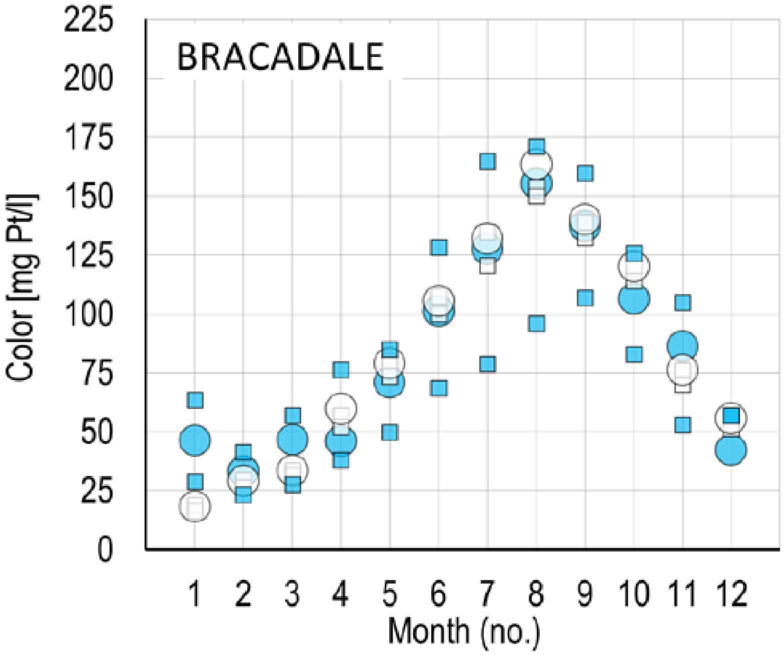


Figure 4-16. Measured colour (blue circles) and modelled colour (open circles) average for each month of the year, using input data from year 2001 to year 2016 at Port Charlotte (n = 201) and Bracadale (n = 201). Squares indicate 25th and 75th percentiles. Figures to the left are from the calibration, using data from 2001-2010. Figures to the right are test runs, using data from 2011-2016. Linear trend line regression (r^2), between measured and modelled averages over the whole data sampling period (2001-2016), are 0.91 for Port Charlotte and 0.95 for Bracadale (Haaland et al in prep.).

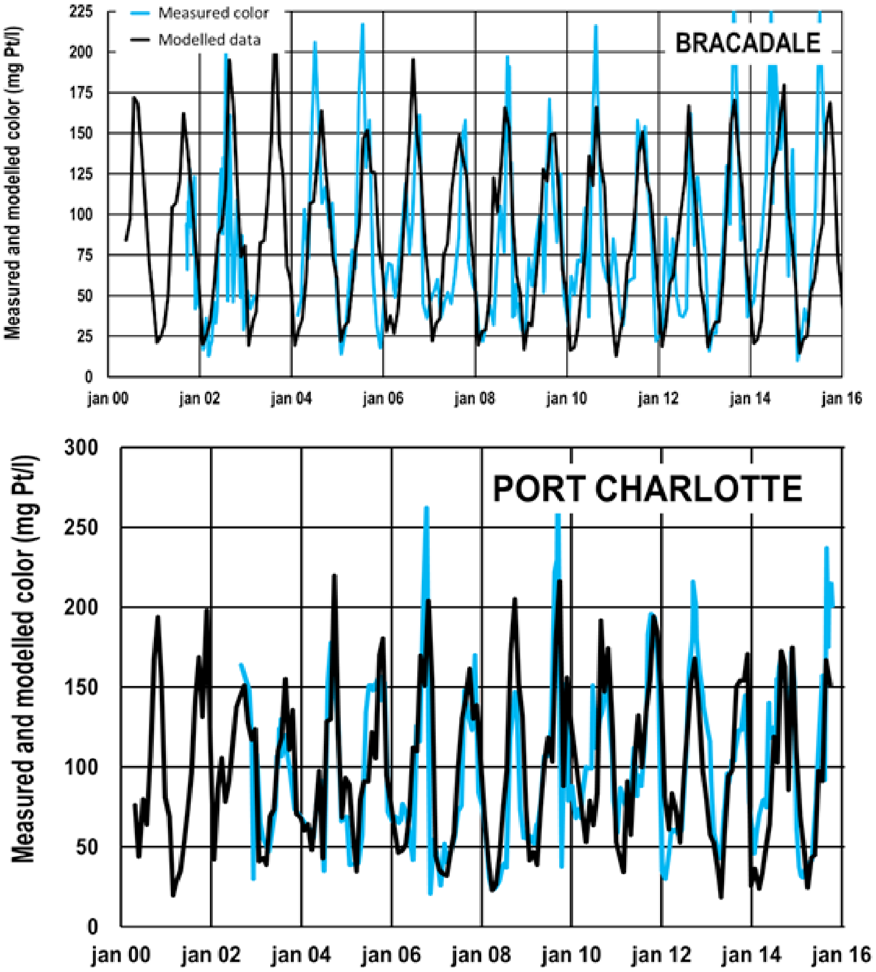


Figure 4-17. Model output (black lines) for colour at Bracadale and Port Charlotte, superimposed onto 15 years of weekly to bi-weekly measurements of colour concentrations (blue lines) provided by Scottish Water (Haaland et al. in prep.).

4.1.5. Jordalsvatnet WTW (JOR - Norway)

Jordalsvatnet water works is situated close to the city of Bergen, Southwest Norway (Picture 4-6 and Figure 4-18). The climate is temperate oceanic with an annual precipitation of > 2500 mm. 3000 mm per year is not uncommon. This is 5-6 times more than the driest watersheds in the NOMiNOR project.

The reservoir is about 50 m deep, has an annual influx of about 16 $\cdot 10^6$ m^3 and a theoretical WRT of about 9 months (Samdal et al. 1969). The raw water inlet is at 36-40 m. Even though the inlet is quite deep, there are yearly periods sensible to pollution (especially during spring- and autumn circulation).

There has been a strong increasing trend in NOM concentration in Jordalsvatnet. The important driver for NOM has been the decrease in acid rain deposition. Today it is temperature that is the most important NOM driver, while chloride from sea-salt is the most prominent input controlling the conductivity. During the acid rain period sulphate used to be an important anion, like many lakes at the southern parts of Norway (Figure 4-1 and Figure 4-19). Increased precipitation has here a diluting effect on NOM due to the thin soil cover in combination with the wet climate.

By using a comprehensive data-set from about 1100 lakes in Sweden, Wheyenmeyer et al. (2009) found that TOC concentrations increase with temperature in a non-linear way. The survey comprises a range of watersheds that overlaps fine with the NOMiNOR catchments, regarding the air-temperature. Since the NOM in Jordalsvatnet does not have a positive response to increases in precipitation amounts, we have instead used this non-linear transfer function of temperature in a RCA4.5 and RCA8.5 climate scenario for air temperature. We have not used the transfer function directly (as is), but as an analogue relative change when moving to higher temperatures, based on the actual TOC-concentrations at Jordalsvatnet. In addition, we have used a geospatial (GIS) approach to get a temperature distribution inside the Jordalsvatnet watershed. See the modelling- and GIS-results in the next chapter.

Picture 4-6. Jordalsvatnet close to Bergen is situated in a beautiful countryside. Photo Gunnhild Riise.

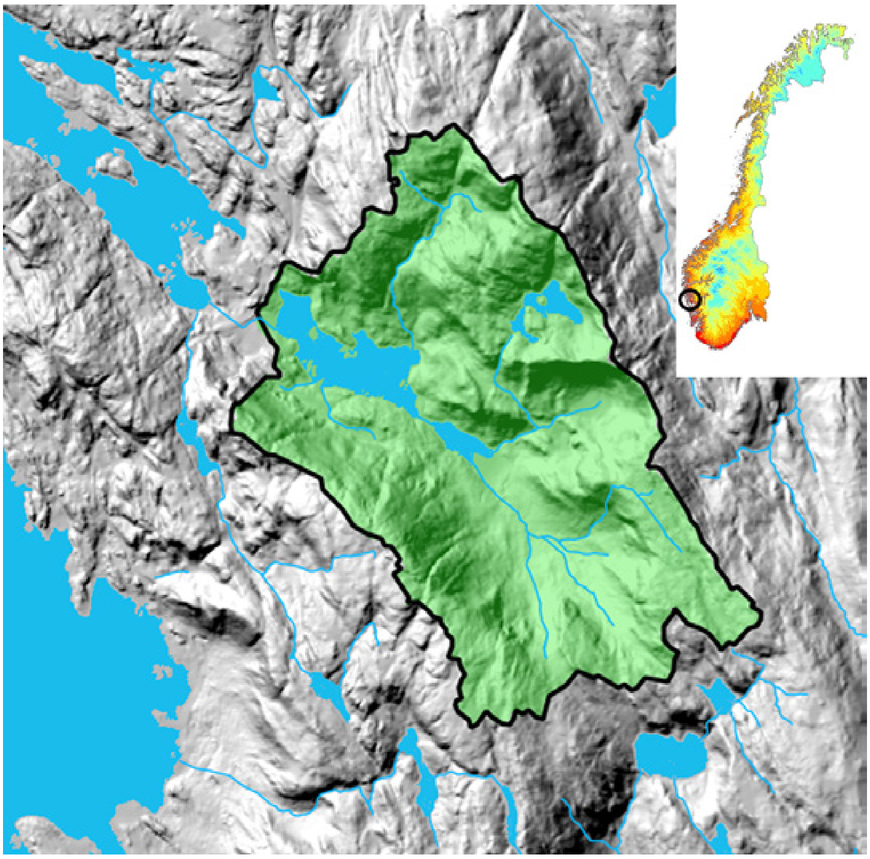


Figure 4-18. Watershed of Jordalsvatnet (Haaland et al. 2015).

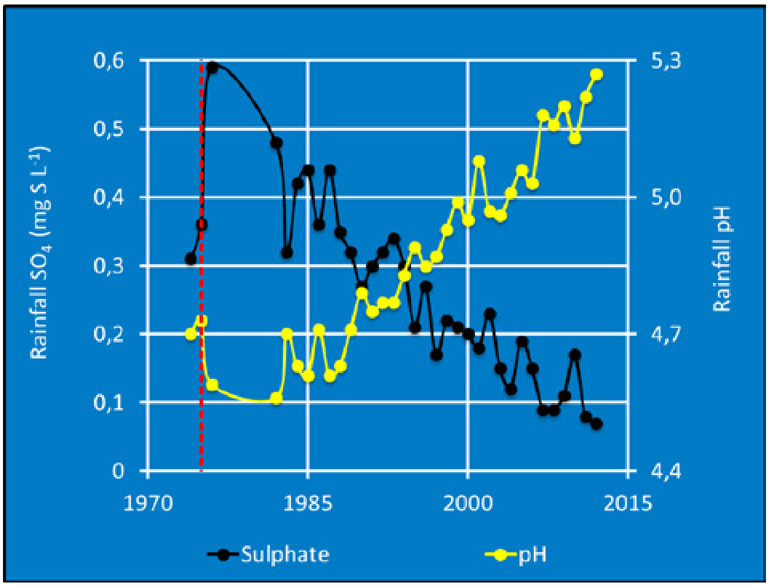


Figure 4-19. Long-term data at Jordalsvatnet shows a strong impact of acid rain. Acid rain is now declining and the colour is increasing (Haaland et al. 2015).

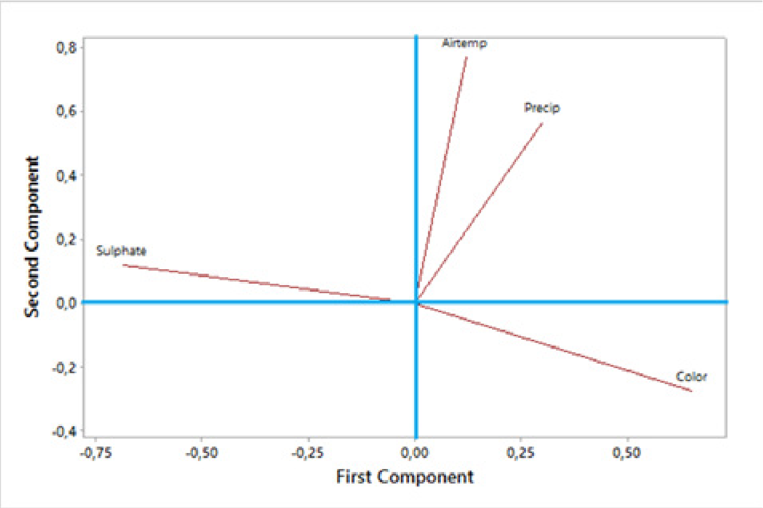


Figure 4-20. Principal Component Analysis (PCA) of the data from Jordalsvatnet using data from the period 1999-2006. Here pH is fairly low (4.8-5.3) and sulphate has a significant contribution to the ionic budget; SO_4 = 0.07-0.23 mg S/l. Colour is markedly suppressed by acid rain in this period.

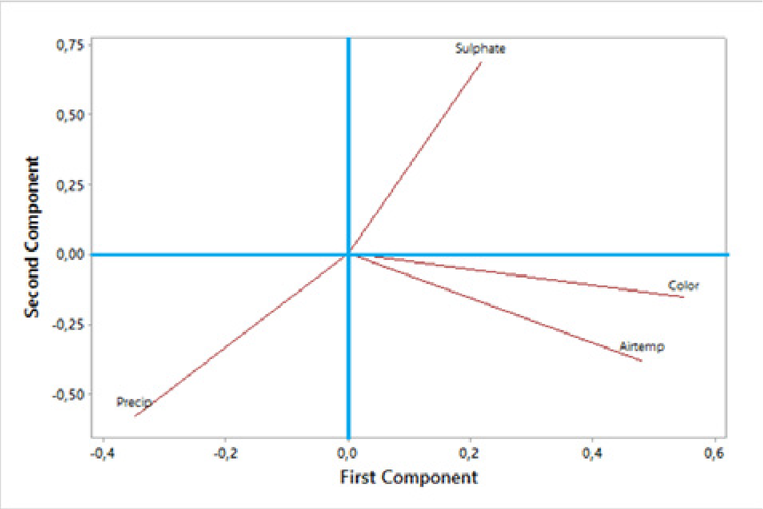


Figure 4-21. PCA analysis for Jordalsvatnet using data from the period 2007-2014. Here pH is fairly high (> 5.2) and sulphate has not a significant contribution to the ionic budget anymore; SO_4 = < 0.1 mg S/l. Colour is more related to suppressed climate; here air temperature.

4.1.6. IVAR WTW (IVAR – Norway)

Lake Stølsvatnet at IVAR WTW (Figure 4-22) is located 298 m a.s.l. and has a watershed of 20 km^2. There is a fairly complex network for the water flow between Lake Stølsvatnet and the other lakes. Stølsvatn has, in the comparison to other lakes and reservoirs within its region, quite high levels of colour (up to 24 mg Pt L^{-1}). Romsvatn, from which water is pumped into Stølsvatn, has less colour (about 5 mg Pt L^{-1}). Between years 2010-2015, operational dilution of NOM (colour) in Stølsvatn with water from Romsvatn has been somewhat constant. Over the same period, maximum colour concentrations in Stølsvatn is largely controlled by autumn precipitation (quantity and quality) (Figure 4-23).

Since 2011 there has been a decrease in the colour of Stølsvatn. Important drivers for NOM at Stølsvatnet is temperature, precipitation amounts and precipitation quality; dominated by chlorides.

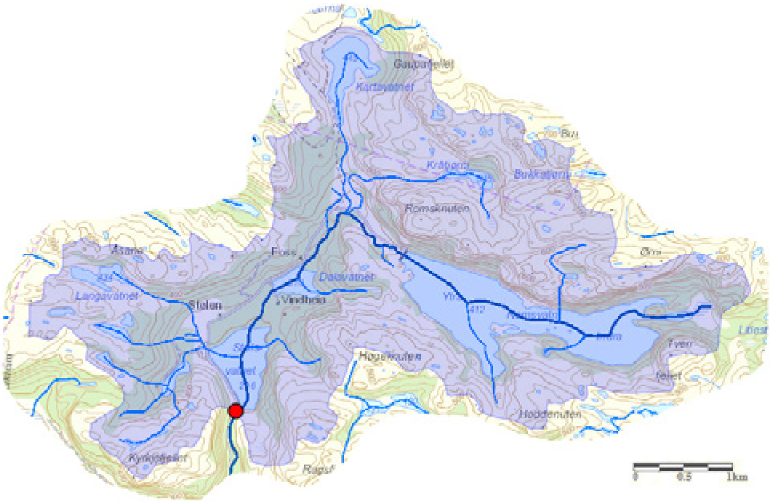


Figure 4-22. The watershed of Lake Stølsvatnet (the lake within the circle) at IVAR WTW. There is a network for moving of water inside the system; here illustrated for Stølsvatnet with arrows (not actual positions) from other water sources.

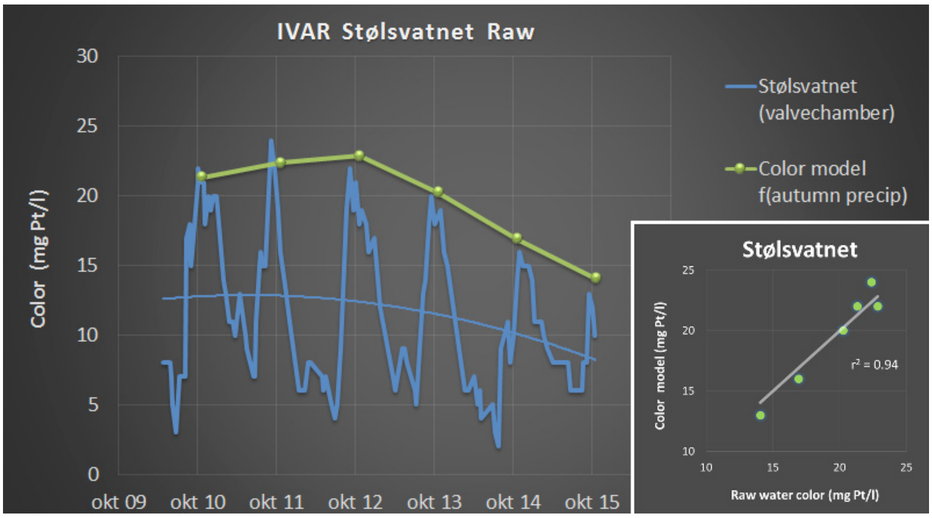


Figure 4-23. Modelled maximum colour concentration during autumn (green dots) at Støls-vatnet (valvechamber samples; blue line) over the period 2010-2015. Based on the 2010-2015 dataset the model is able to simulate the measured values with a linear correlation of $r^2 = 0.94$. Autumn precipitation (September; October) is a strong driver for the input of allochthonous NOM to Stølsvatnet.

4.1.7. Kärreberg WTW (KÄR - VIVAB, Sweden)

Ätran is, like Bracadale and Glomma, one of the running water systems in the NOMiNOR study (Picture 4-8). Water from this area is dominated by chlorides and sulphates, and also carbonates, in whereas the latter probably in some parts of the watersheds, also is added due to fish conservation (Figure 4-24). The system resembles both Bracadale and Port Charlotte in its chemistry, and has hence been modelled using a similar approach (Figure 4-25).

There is no clear long-term trend, though large seasonal fluctuation in NOM. Important drivers for NOM for River Ätran are temperature, precipitation amounts and precipitation quality. In addition; iron is an important driver for colour. Several lakes and rivers within the watercourse are limed; annually it is dosed about 6 million kg limestone flour at a cost of 3-4 million SEK in the river Ätran and its tributaries.

Picture 4-8. Since 1978, one of the world's most comprehensive liming projects is carried out in River Ätran and its tributaries. Thanks to this and to the intensive fishing conservation efforts, the wild strain of Atlantic salmon in River Ätran today is reproducing naturally. Photo: Gunnar Larsson (Wikimedia).

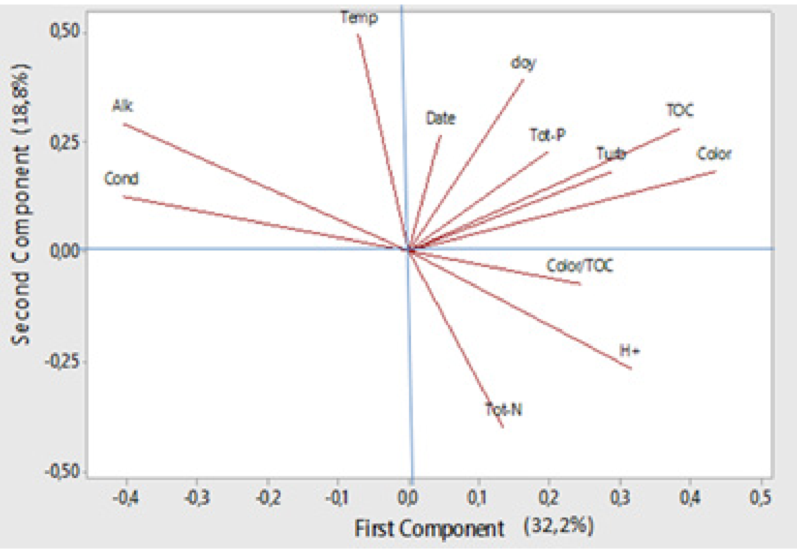


Figure 4-24. At Ätran, PC1 (78 samples) explains 32 % of the variance in the dataset. PC1 is defined by fluctuations in NOM and conductivity. Hydrology is hence important. Just as for Bracadale, bicarbonate is controlling the conductivity inside the river. However, here it is also added to the river in large amount by the fishing cultivators. PC2 explain 19 % of the variation in the dataset, and is defined by a seasonal fluctuation in temperature and also the decrease in Tot-N with time.

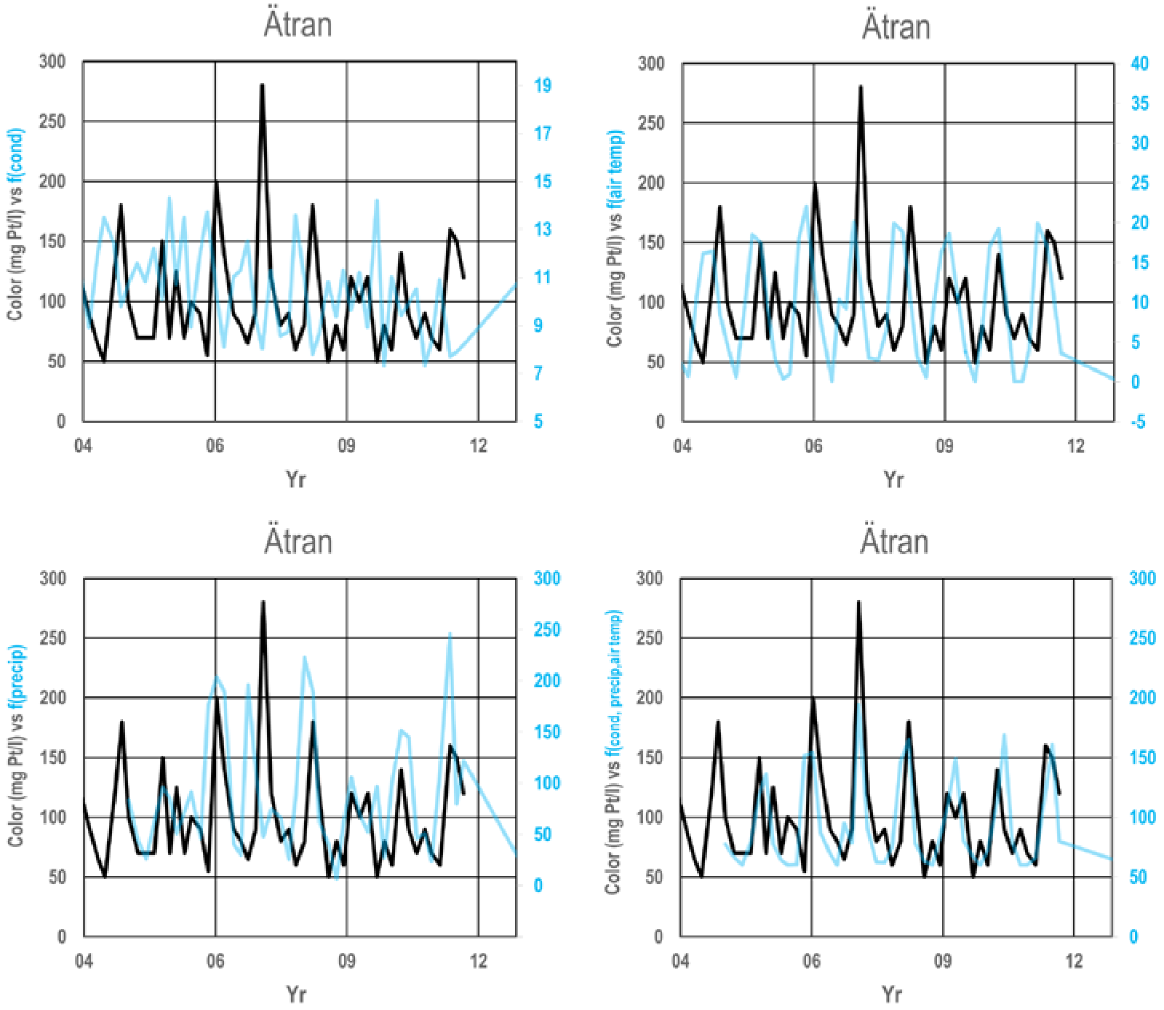


Figure 4-25. Model output (black lines) for colour at Ätran, superimposed onto quarterly measurements of colour concentrations (blue lines) provided by VIVAB.

4.1.8. Ringsjöverket WTW (Sydvatten, Sweden)

Lake Bolmen has an area of about 184 km^2, and is situated within a 1640 km^2 watershed used by Ringsjöverket WTW (Figure 4-26). Theoretical retention time is about 2.8 years. Maximum depth is 36 meters, and average lake depth is about 5.5 meters. From data series dating back to the 1970s, we can see that the colour had an increasing trend, which is strongly affected by the decrease in acid rain loading (Figure 4-27). The catchment is today extensively limed.

Important drivers for NOM in Bolmen are temperature, precipitation amounts and precipitation quality (sea-salts). The lake retention time is relatively long, and there is a recent stabilization of precipitation quality, i.e. post acid rain but still with liming activity. Annual precipitation amount as a single factor does not have a significant effect on year-to-year variations in colour in the lake at present. Temperature is expected to be the most important driver in the future (see next chapter).

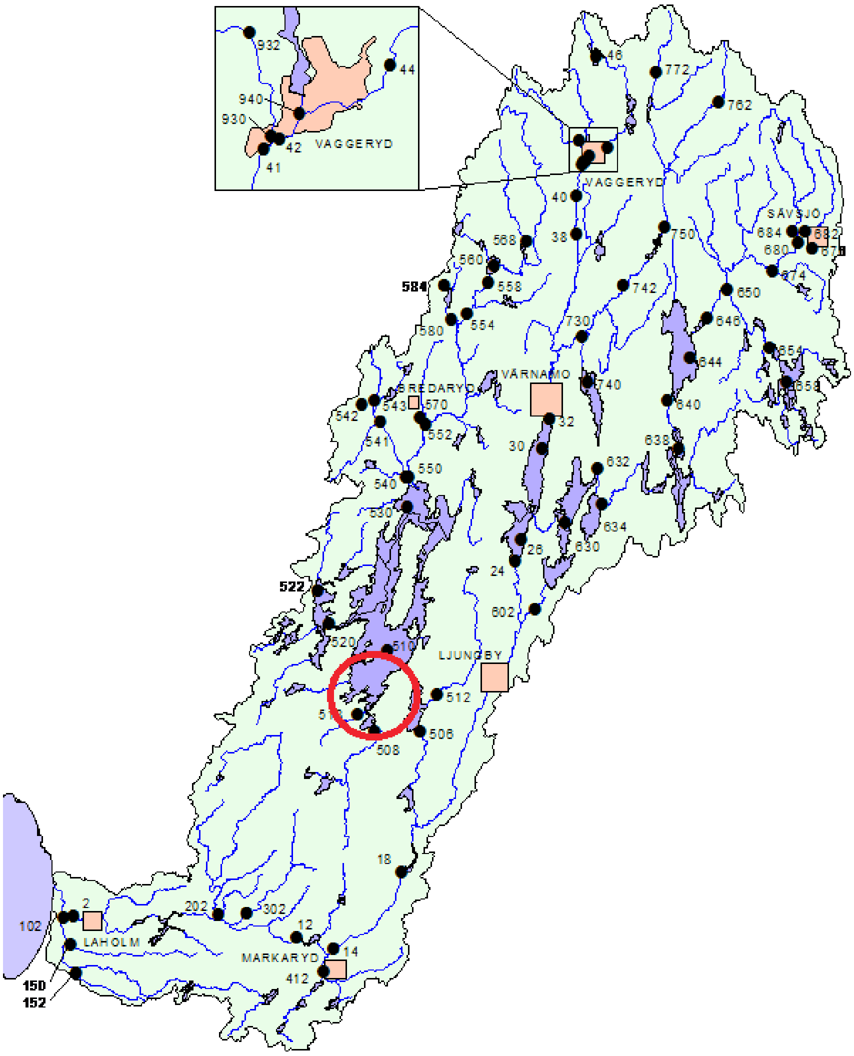


Figure 4-26. Map of the watershed and the raw water sources to Ringsjöverket, Sydvatten. Samples used in NOMiNOR are from Lake Bolmen, one of the larger lakes within the watershed (red circle). There is an extensive program for water quality samplings in the watershed (marked with black dots). Map provided by Sydvatten.

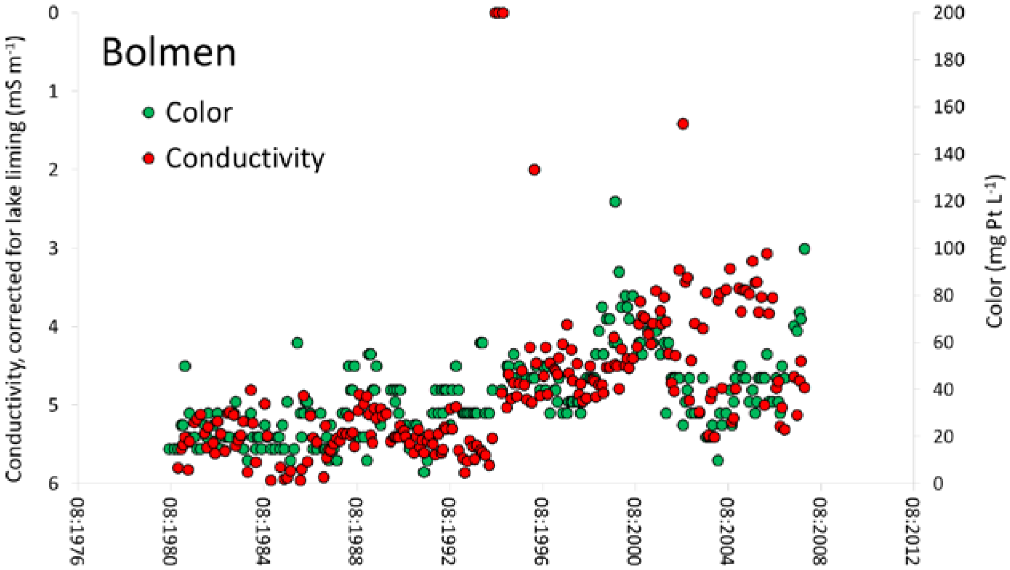


Figure 4-27. Acidification (acid rain) has previously been a strong driver for colour at Bolmen. The plot shows colour development (increase) and the similar but inverse conductivity development (decrease).

4.1.9. Görvälnverket WTW (Norrvatten, Sweden)

Kolbäcksån is one of the larger (200 km long; catchment size is 3120 km^2) tributaries to Lake Mälaren (the third largest lake in Sweden; total watershed of 22650 km^2). The Kolbäcksån is located in the North-West of the Mälaren catchment (Figure 4-28). The watershed of Kolbäcksån consists of several lakes, including Väsman, Barken and Åmänningen. The main lake dynamics needs to be taken into account when trying to model the NOM concentrations close to the river outlet at Lake Mälaren. This is because the water quality in the river will alter markedly between the circulation and stratification periods of the lakes. In NOMiNOR, when modelling NOM in Kolbäcksån, the river system was therefore divided temporally into four seasons; summer and winter for lake stratification periods, and spring and autumn during circulation. The water balance and the river discharge data were previously estimated by the hydrological HYPE-model for Sweden; S-HYPE. The S-HYPE-estimates tend to miss some of the high flow periods, but the data seems otherwise to be good and is used as a prerequisite for modelling the NOM-fluctuations inside the river.

There is no significant long-term trend in the NOM concentration. The TOC-fluctuation throughout the year is low. This causes an inferior precision by the TOC-analyzer compared to the spectrometric analysis as a proxy for NOM. The optic density measurements at λ420nm (OD_{420}) was thus used as input. Important drivers for NOM at Kolbäcksån are temperature, precipitation amounts and precipitation quality. Kolbäcksån is situated in an area consisting of bedrock and soils with quite poor buffer capacity. Due to this the lakes, rivers and also wetlands inside the watershed are extensively limed (Sonesten, 2009). A model output for NOM between years 2010-2013 is shown in Figure 4-29.

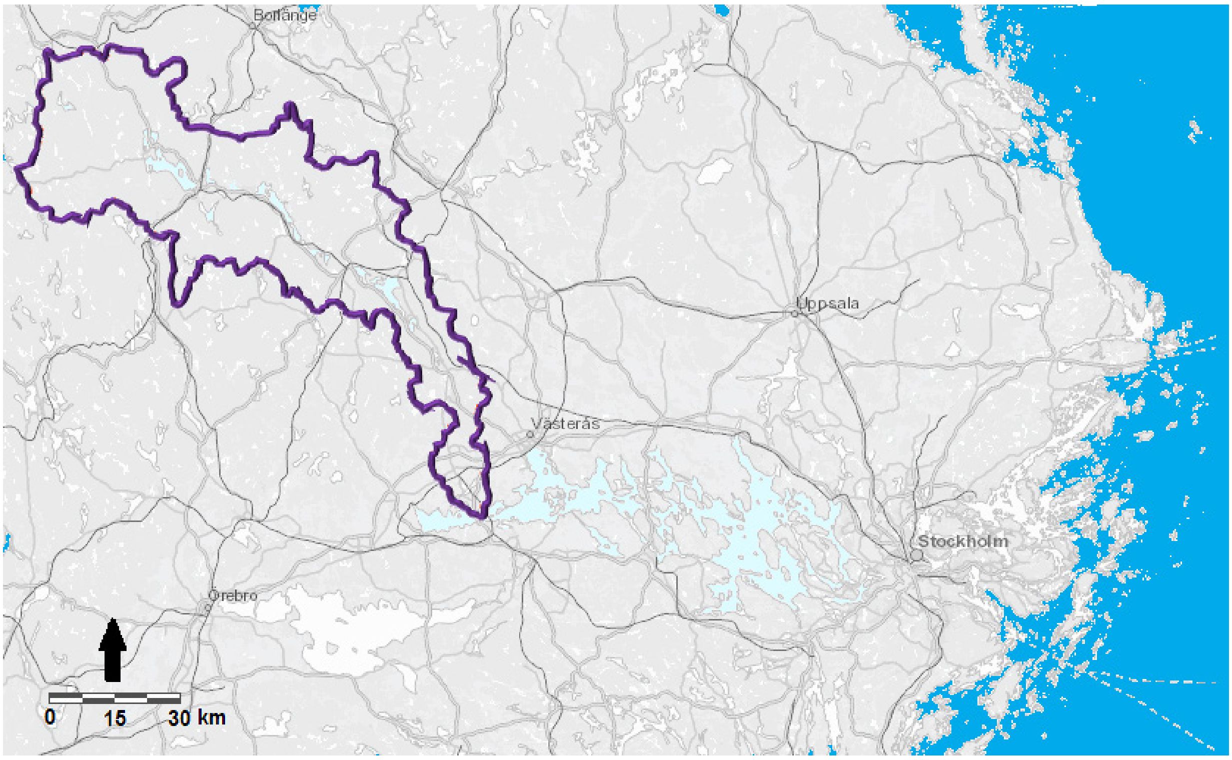


Figure 4-28. The watershed of Kolbäcksån, one of the major tributaries to Lake Mälaren (both shown in light blue). The watershed represents about 14 % of the total Mälaren catchment. There is an extensive sampling program for water quality in the watershed.

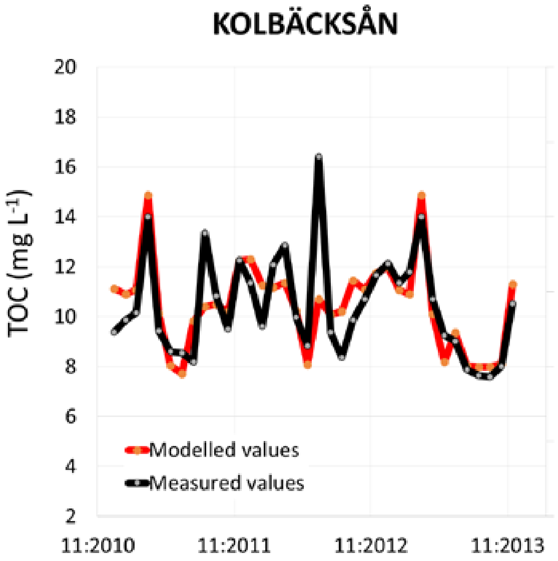


Figure 4-29. Model output for NOM over the period 2010-2013, at the lower end of the river close to Lake Mälaren. The river system was separated into four parts; summer and winter for lake stratification periods, and spring and autumn during circulation. Data output on river discharge derived from S-HYPE has been used. Model outputs are in red. NOTE: There are relatively small variations in the TOC-concentrations over the sampled period.

4.2. NOM predictions for the future

Climate scenarios

Changes in climate parameters due to global warming are important drivers for future changes in NOM concentrations. In NOMiNOR climate scenarios like the RCP4.5, with a radiative forcing increase of 4.5 W/m^2 compared to pre-industrial values, has been used for Norway (RegClim) and Finland (Finnish Meterological Institute). In Sweden, the H/B2 climate scenario has been used (SMHI/ Rossby Centre RCAO). See more on this in Beldring et al. (2016). For Scotland, Met UK has used the moderate A1B scenario, a scenario somewhat in-between the more recent AR5 and a bit more towards the RCP 6.0 scenario (see Figure 4-30), in their Met Office HadCM3 model based UKCP09 prediction. UKCP09 continues to provide a valid assessment of the UK climate and can still be used for adaptation planning (UK Met 2014). Here, we have used a moderate scenario, including an equal likelihood for the actual value to be less or more than the predicted value of air temperature and precipitation. All these scenarios generate somewhat moderate climate predictions.

Data selection

In NOMiNOR, large efforts and considerable determinations have been put into collecting relevant data on raw water quality. To have got this important database up and going has been a significant task, in which many patient individuals from the NOMiNOR WTWs have contributed. The extensive use of this database has been done with both pleasure and care.

The majority of the NOMiNOR raw water sources are reservoirs or lakes. They have often their raw water inlet below the thermocline as one of several hygienic barriers. A thermocline typically develops during the summer- and winter-season (Figure 4-31). For that reason, such raw water data are not similar to any other typical high-resolution lake monitoring dataset. Such lakes are most often sampled closer to the surface. The NOMiNOR raw water data, if sampled below the thermocline, will not promptly reflect changes in the watershed during summer and winter season. For this reason, only data from when we are confident that there is sufficient vertical mixing conditions were used – hence, only data from samples that were collected during late autumn were used in the assessment. These can be regarded as integrated samples, somewhat reflecting watershed changes throughout the past year. Autumn data is in this context also chosen over data derived during spring, since spring circulation often is weaker and also because we want to be as close as possible in time to the last growing season. An important aspect in the NOMiNOR project has been to carefully select the appropriate data from lentic raw waters (lakes, reservoirs) in a climate prediction context regarding NOM. This is a watershed process-understanding combined with limnology, and is a prerequisite for running statistics and creating proper NOM predictions. For lothic systems (rivers, streams), such vertical stratification is absent. Here, changes in the watershed activities are much more directly linked in time to changes in raw water quality. Smaller lothic systems also often have a more rapid response in this context, and smaller time steps can more effortlessly be included in a NOM model if such data is available.

Models

A prediction of NOM dynamics in lentic waters with short time steps (i.e. days) is not a trivial task. This is mainly due to the need of an understanding of in-lake processes, such as 3D circulation patterns and stratification, and the NOM dynamics inside a lake with a certain retention time, and then to link this to the NOM concentration of the raw water (at which the inlet often is below the thermocline). Hence, in the timeframe of the NOMiNOR project, we have used annual time steps on long-term data series, to depict inert-annual differences in circulating water bodies. This has been done for two main reasons: 1) An acceptable operational 3D model for the lakes included in NOMiNOR does not exist, and the task of implementing such models is outside the NOMiNOR reach, and 2) The long-term data series on raw waters, collected at water treatment plants, are often from inlets below the thermocline; hence, not all of the samples are temporally connected with in-situ changes affecting water quality in the epilimnion.

NOM dynamics within the watersheds are more easily predicted by models in small running water body systems. Having a good grip on the water balance (rainfall-runoff response) in a running water system, we are able to model quite rapid changes in NOM concentrations. A low parametric colour-model have been developed for both Bracadale and Port Charlotte. The results were also used in Ätran. The model setup is based on a best fit parameterization (classical Monte Carlo approach). The model was calibrated for monthly average colour concentrations, using a 15-years of weekly to bi-weekly data-series provided by Scottish Water and UK Met Office. Results are shown in Figure 4-17 and Figure 4-37.

For some of the modelling, a prediction of future temperature has partly been based on results from a Swedish study by Weyhenmeyer & Karlsson (2009), in which a nonlinear response function for NOM concentrations vs air temperature in boreal lakes has been carefully adapted to some lentic NOMiNOR raw water sources.

Digital terrain models (DTMs) were to be applied at all catchments; however, only some WTWs were able to gain access to DTMs in time. Hence, only a few watersheds were digitalized using this method. GIS incorporates spatial data information. Regarding NOM, spatial basic data of rainfall-surface runoff and air temperature would be interesting. For example, by using DTMs, precipitation falling onto Jordalsvatnet watershed above 400 m a.s.l. (Figure 4-3a), is shown to generate a very different spatial surface runoff pattern compared to similar amounts of rain falling at 50 m a.s.l. and above (Figure 4-33). In an NOM endmember context (analogous to Christophersen et al. (1992)), the runoff quality could be quite different for such two events. Surface runoff was here modelled using a D8 kinematic surface wave runoff algorithm (O'Callaghan & Mark, 1984; Johnson & Miller, 1997; Kitterød et al. 2013).

Spatial temperature distribution inside the Jordalsvatnet watershed (Figure 4-34) is likewise interesting for i.e. snow and ice cover, primary production and degradation processes, and can for Jordalsvatnet be obtained using available data from the Norwegian meteorological institute (DNMI). These data hasve been used for the Jordalsvatnet watershed, and has then been further downscaled to a 10x10 m grid network using a random point procedure coupled with Gaussian process regression statistics. The air temperature distribution was adjusted for m a.s.l. as described by Livingstone et al. (1999). Future temperature predictions have then been superimposed, where projections were taken from the average of 10 global climate models, using the IPCC scenario A2, and with a further downscaling using the average of 3 regional climate models (EU Prudence project).

Results from the coupling of NOM models with climate change predictions are shown in Figure 34-42. Only the actual (raw) result is shown (no error bars). There are uncertainties in such predictions, both within datasets, NOM-models and for the climate predictions. Results from different model approaches have however been checked up against each other, and also with results found in literature (if possible). Only small deviations have actually been found.

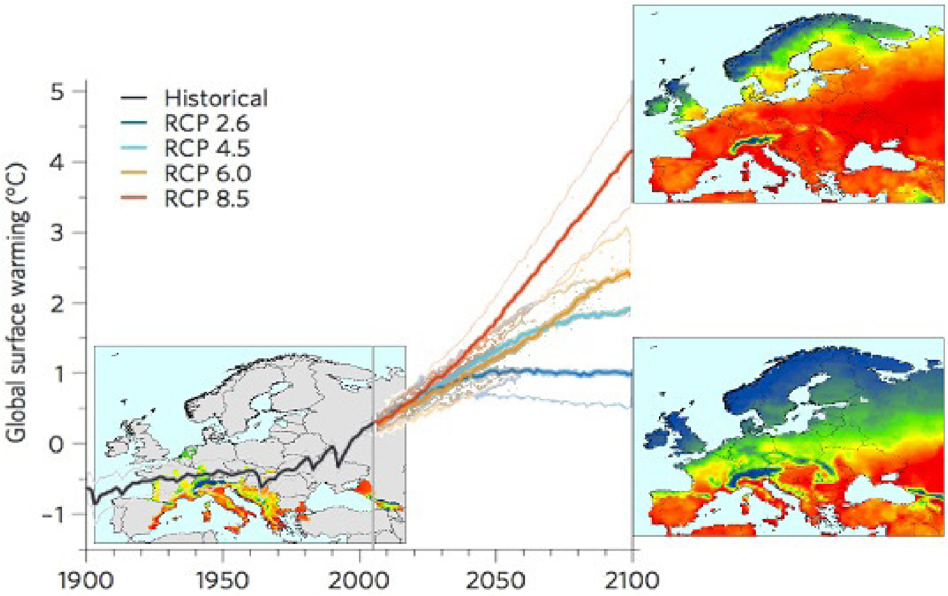


Figure 4-30. The latest generation of climate scenarios (RCPs – Representative Concentration Pathways) for greenhouse gas concentration trajectories at present and until year 2100, with a spatial distribution covering the NOMiNOR sites. The scenarios are adopted by the Intergovernmental Panel on Climate Change in their Fifth Assessment Report, AR5 (IPCC AR5, 2009).

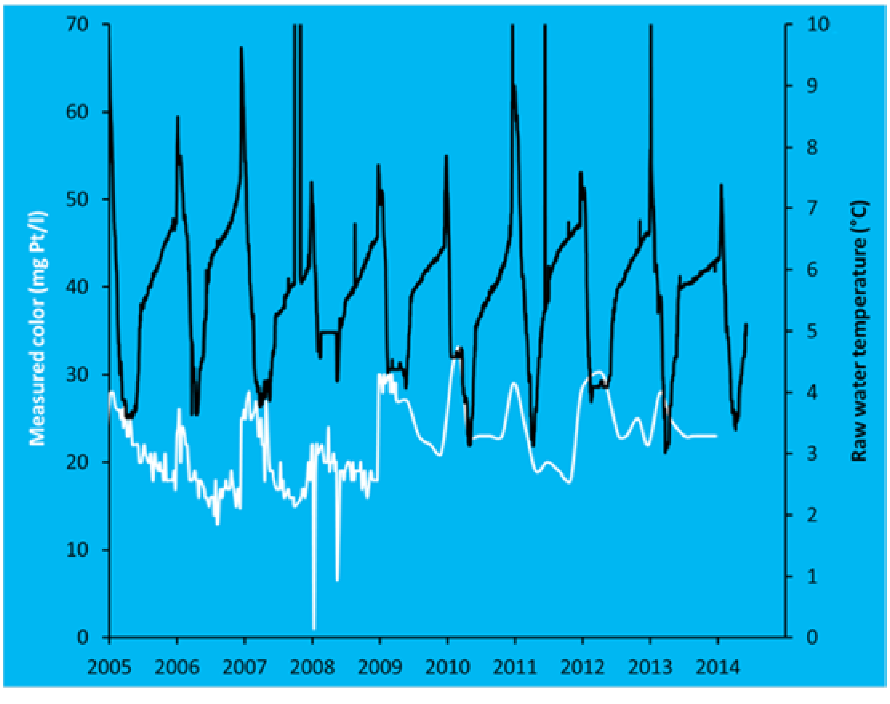


Figure 4-31. Variation in raw water colour with raw water temperature. The lake circulates twice a year; in spring and most pronounced in autumn. Samples collected from lakes to be used in the NOMiNOR project must be taken during lake circulation in autumn.

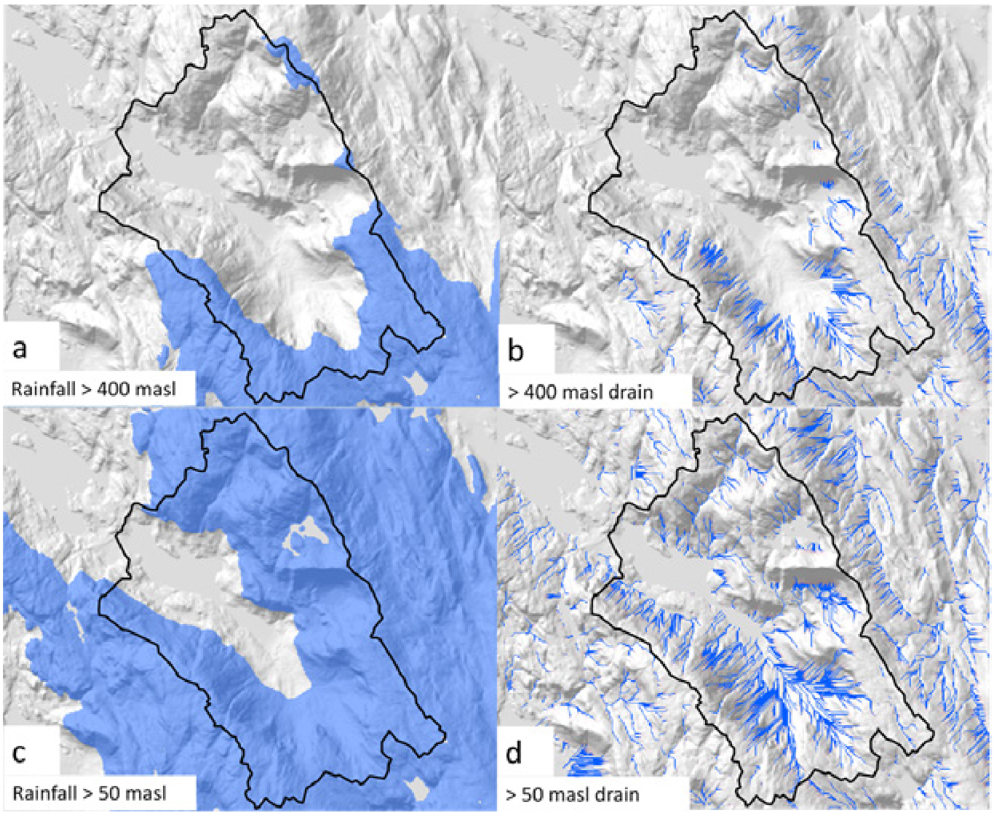


Figure 4-32. DTM GIS based watershed analysis. Rainfall-runoff at Jordalsvatnet (see text).

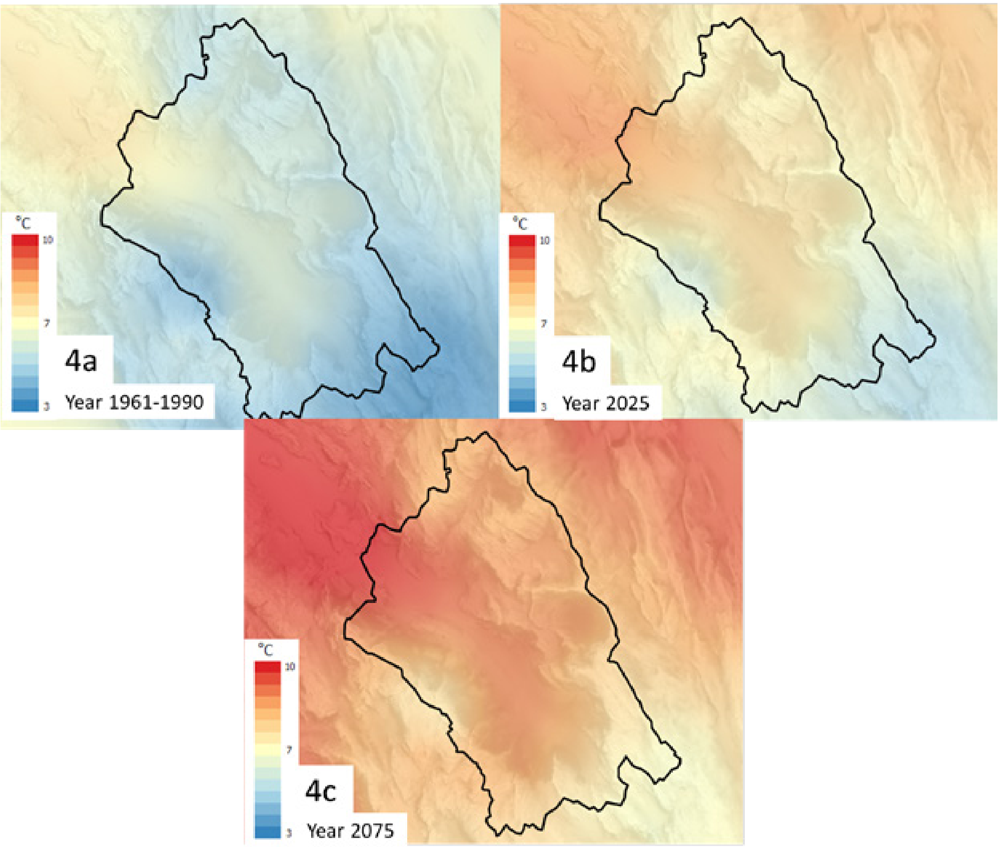


Figure 4-33. IPCC downscaled temperature distribution at Jordalsvatnet watershed, and a subsequent projected future increase in raw water colour due to the projected temperature increase.

4.2.1. Nedre Romerike WTW (NRV - Norway

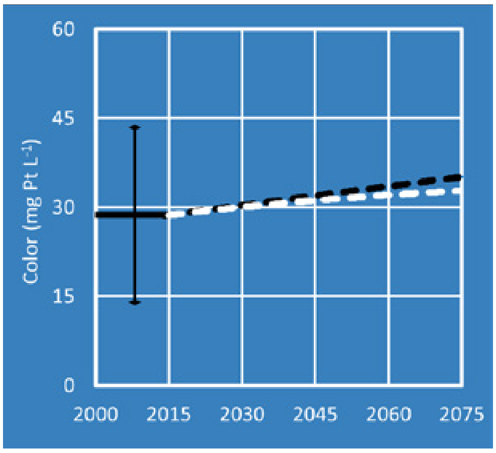


Figure 4-34. NOM prediction in River Glomma. The white dotted line represents RCP4.5. The black dotted line represents RCP8.5 (http://regclim.met.no/).

4.2.2. Burncrooks WTW (BUR - Scotland)

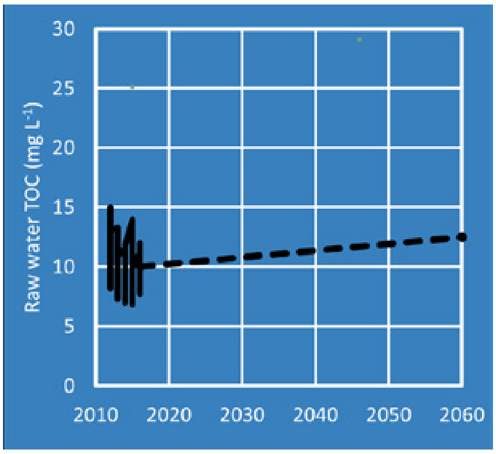


Figure 4-35. NOM prediction at Reservoir Burncrooks. A moderat UKCP09 scenario has been used (http://www.metoffice.gov.uk/).

4.2.3. Pitkäkoski WTW (PIT- HSY, Finland)

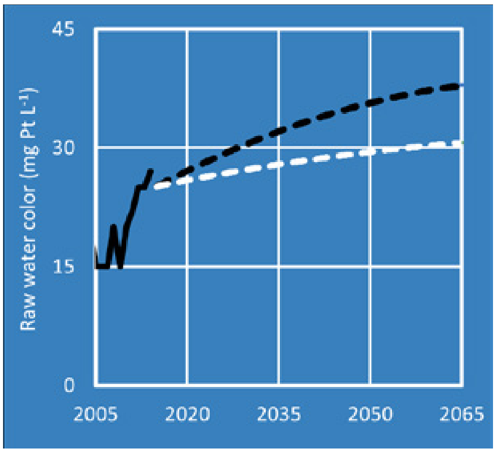


Figure 4-36. NOM prediction at Lake Päijänne. RCP4.5 has been used (Finnish Metrological Institute). The white dotted line represents that there will be no changes in input of anions compared to the present situation. The black line suggests a further change along the trends that we can see today.

4.2.4. Bracadale WTW (BRA - Scotland) & Port Charlotte WTW (PC - Scotland)

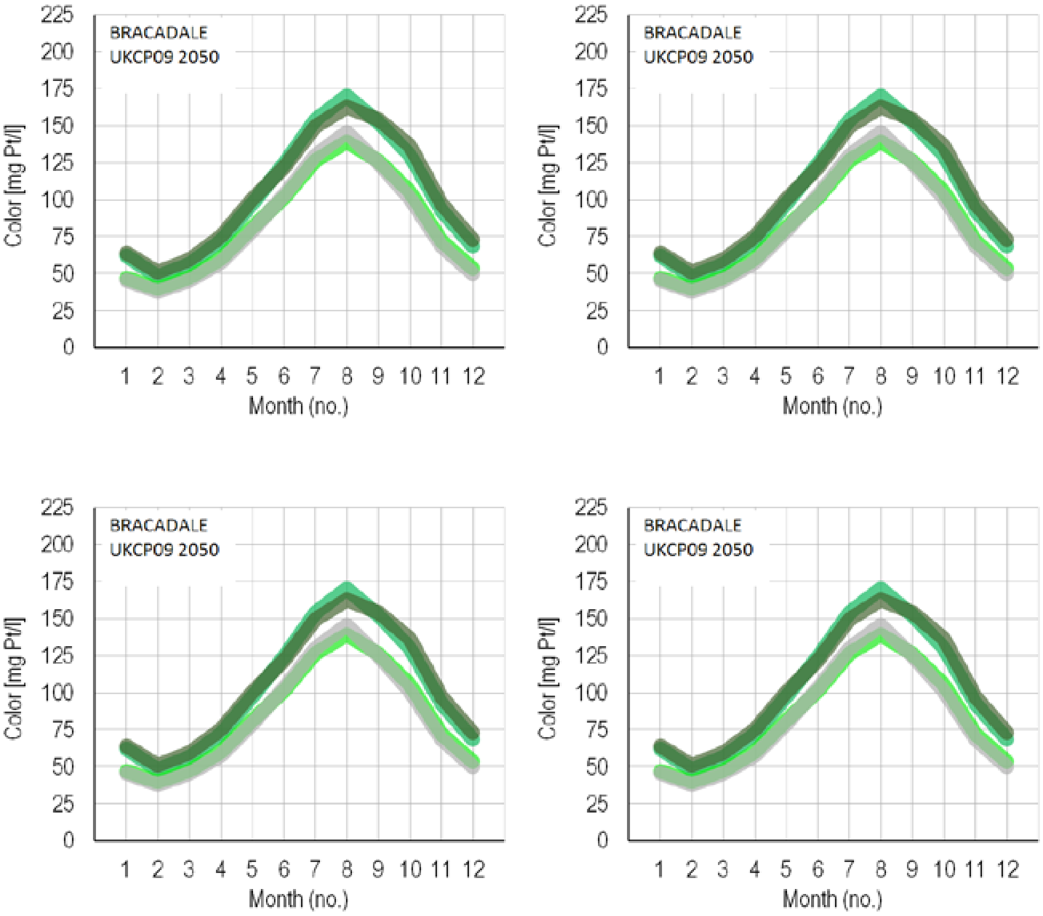


Figure 4-37. NOM predictions at Bracadale and Port Charlotte. A moderate UKCP09 has been used (http://www.metoffice.gov.uk/). Predictions for both year 2050 (left graphs) and year 2080 (right graphs) are shown. The grey lines are present state. Dark green represents the predicted NOM increases. The light and sage green lines, represents changes in precipitation and air temperature only, respectively.

4.2.5. Jordalsvatnet WTW (JOR - Norway)

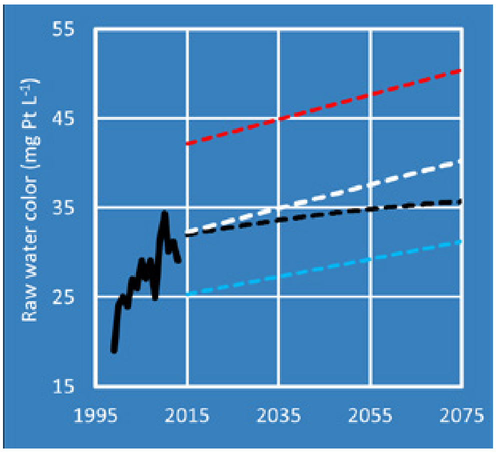


Figure 4-38. NOM prediction at Lake Jordalsvatnet. RCP4.5 and RCP8.5 has been used (http://regclim.met.no/). The white dotted line represents the RCP8.5 scenario. The black dotted line represents the RCP4.5 scenario. The blue and red line represents maximum temperatures within thewatershed (RCP 8.5), taken from the DTM-analysis.

4.2.6. IVAR WTW (IVAR – Norway)

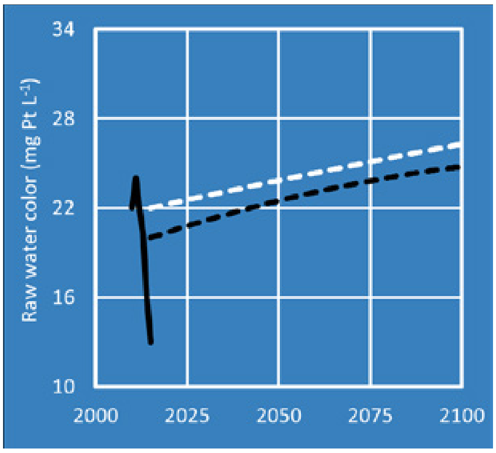


Figure 4-39. NOM prediction at Lake Stølsvatnet. RCP4.5 has been used (http://regclim.met.no/). Both the white and the black dotted line represent RCP4.5. The white line represents a development from about 22 mg Pt L^{-1} at present, whereas the black line represents a development from an average TOC value over the past few years.

4.2.7. Kärreberg WTW (KÄR - VIVAB, Sweden)

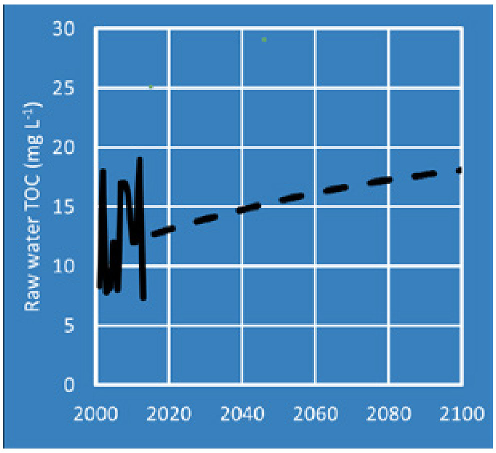


Figure 4-40. NOM prediction at River Ätran. The H/B2 climate scenario has been used (SMHI/Rossby Centre RCAO). In addition to this NOM prediction, a similar method that was used at Bracadale and Port Charlotte, was also partly adapted here – with very comparable results for the two approaches.

4.2.8. Ringsjöverket WTW (Sydvatten, Sweden)

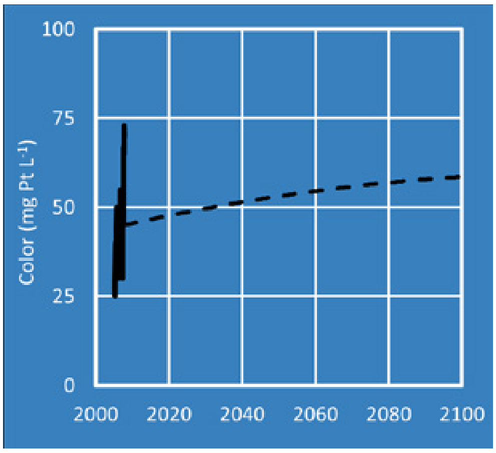


Figure 4-41. NOM prediction at Lake Bolmen. The H/B2 climate scenario has been used (SMHI/Rossby Centre RCAO).

4.2.9. Görvälnverket WTW (GÖR - Norrvatten, Sweden)

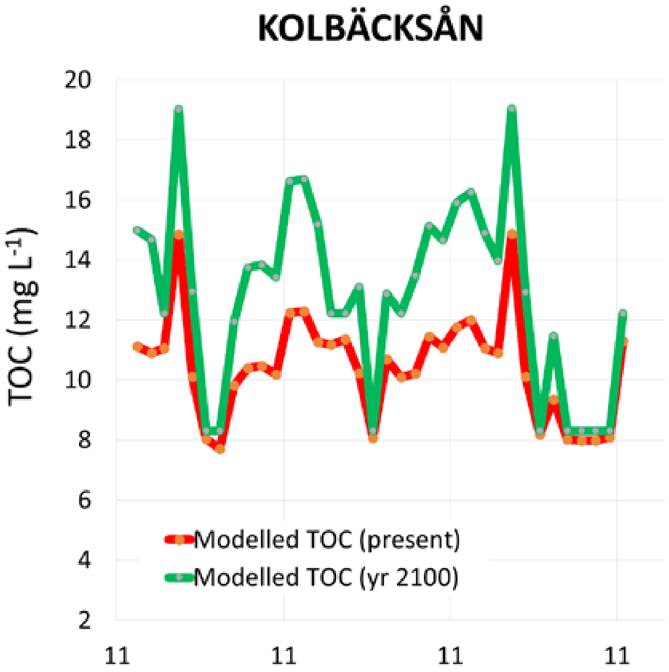


Figure 4-42. At River Kolbäcksån, we have predicted an increase in TOC-concentrations of about 20%, which is an increase from an average of 10.5 mg TOC L^{-1} at present to 12.9 mg TOC L^{-1} in year 2100. The results are comparable with modelling results obtained by Naden et al. (2010) in the same watershed. The lowest TOC values are recorded under low flow (throughout the whole year), which very often are paired with much higher conductivity values, and are also expected to be kept low in the future. X-axis indicates dates (month) for both present and year 2100. The H/B2 climate scenario has been used (SMHI/Rossby Centre RCAO).

5. RESULTS AND DISCUSSIONS: Water quality and treatment characteristics

The results and discussions presented in Chapter 5 are divided in two parts:

Part 1 (Chapters 5.1-5.10): Simple analysis of all water samples (SINTEF)

- Routine parameters (pH, turbidity, color, UV-absorbance, TOC, DOC, etc)
- Simple and practically applicable NOM analyses (rapid NOM fractionation, BDOC and ATP)
- ICP-MS-based analysis of elements (Al, Fe, Mn, Ca, etc)

Part 2 (Chapter 5.11): Advanced analyses of selected water samples (SINTEF and Cranfield University)

- FT-ICR-MS-based advanced NOM analysis (SINTEF)
- Supplementary advanced NOM analyses (Cranfield University), including fluorescence/FEEM, particle charge/zeta potential, particle size distribution/HPSEC, conventional NOM fractionation, total bacteria counts/Flow cytometry, etc)

The results from the utility-specific Part 1 analyses are presented one by one in Chapters 5.1-5.10, for the ten NOMiNOR utilities, respectively. The order of utility presentation is the same as in Chapter 4.

The results from Part 2 analyses are presented in Chapters 5.11.1 (SINTEF) and 5.11.2 (Cranfield University).

5.1. Nedre Romerike (NRV) WTW - Norway

The water treatment at NRV is enhanced coagulation (PAX18) with micronized marble ($CaCO_3$) for pH-control, polymer dosing prior to flocculation and sedimentation (Super pulsator), dual media filtration (anthracite and sand), GAC filtration, UV-disinfection, chlorination, and finally pH-adjustment for corrosion control. Figure 5-1-1 shows the flowsheet for the NRV treatment process along with the sampling spots used here.

Coagulation. The main water quality improvement takes place in the coagulation process step. Thus, the application of optimum coagulation conditions at all times are extremely important in order to obtain a good finished water quality and to maintain a safe and sustainable treatment process.

Between the four water sampling rounds at NRV, the coagulant dose and coagulation pH levels varied within the range of 2.3-3.8 mg Al/L (as PAX18), and pH 7.0-7.3, respectively. The DOC-specific dose varies in the range of 0.46-1.11 mg Al/mg DOC, i.e. 17-41 µmol Al/mg DOC.

The amount of DOC removed was in the range of 15-38 mg DOC per mmol of added Al. With constant NOM seasonal characteristics, e.g. a constant NOM fraction distribution over the year, a close to stoichiometric relationship is expected to exist between NOM content and coagulant dose requirement. However, at NRV the ratio between the maximum and minimum DOC-specific coagulant dosages is 2.4. This high value is taken as an indication of the existence of an unexploited coagulation process optimization potential and a potential for improved process control, i.e. a better adaptation of coagulation condition to the prevailing raw water quality. The filtration rates applied during the sampling period is 2.3-4.0 m/h, which is regarded as a relatively moderate hydraulic filter loading.

A comparative study (utility benchmark) of the coagulation conditions and treatment performance among the utilities is found in Chapter 6.

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR sampling rounds are given in Table 5-1-1.

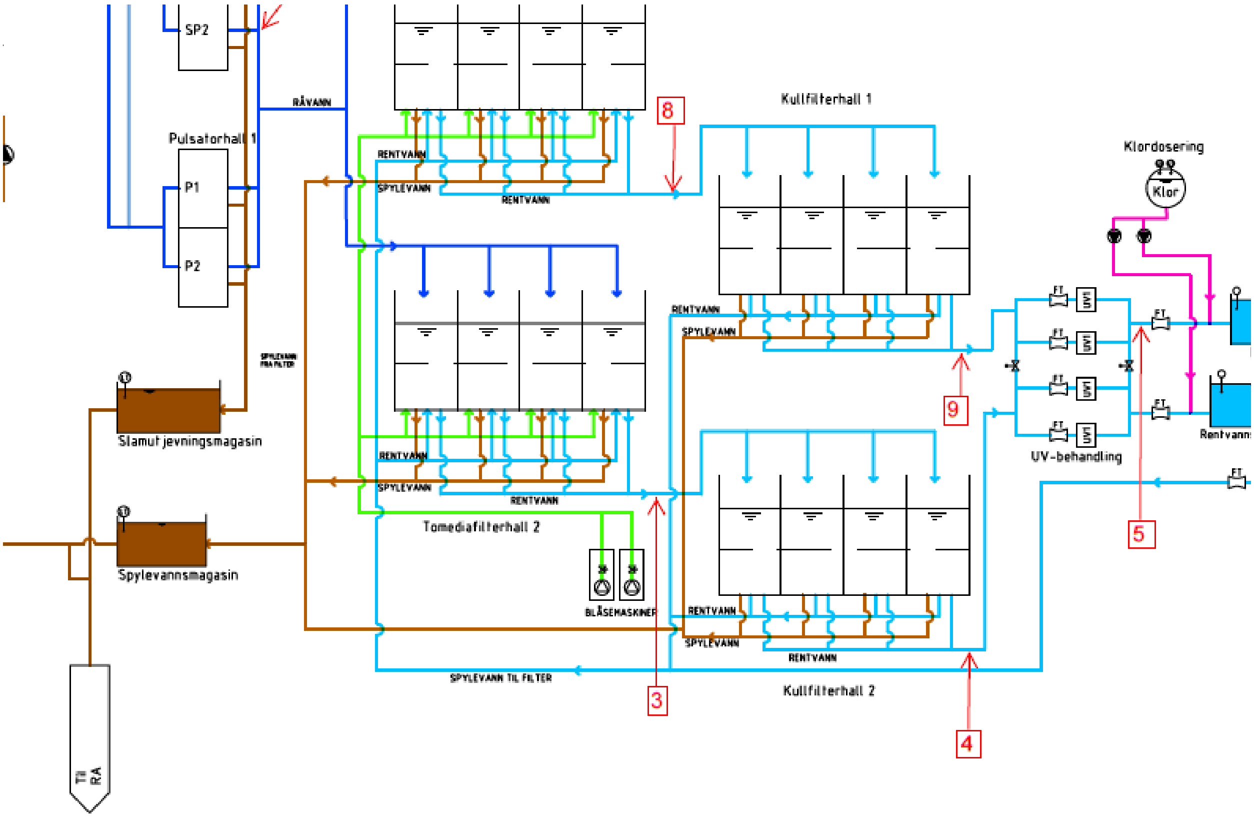


Figure 5-1-1 Treatment process flowchart and water sampling points at NRV WTW.

The raw water quality varies over the year, typical for a river source. Colour and UV-absorbance vary in the ranges of 24-51 mg Pt/L and 13-26 m^{-1}, respectively, turbidity within 0.6-14 NTU, and TOC within minimum and maximum levels of 3.4-6.3 mg/L. Practically all of the organic matter is dissolved, with DOC levels in the range of 3.4-5.5 mg/L during the four sampling rounds, i.e. 95 % of TOC on average. DOC is dominated by the hydrophobic NOM fractions (86 % of the total DOC; 72 % VHA and 14 % SHA). The hydrophilic fraction is 13 % (5 % CHA and 8 % NEU). The SUVA value is 4.1. These NOM characteristics are indicating good raw water treatability by coagulation. Raw water BDOC is on average 4.3 % of the total DOC, with minimum and maximum values of 2.5 and 5.5 %, respectively.

The clean water quality was good, with low levels of colour (1-4 mg Pt/L as min and max), UV-absorbance (2.3-4.1 m-1), turbidity (0.1 NTU), DOC (1.4-2.0 mg/L), and BDOC (0.04-0.20 mg/L). The CHA fraction and the BDOC concentrations increased somewhat during chlorination, likely due to oxidation breaking the larger molecules into more low-molecular weight compounds. These parameters then decreased in the distribution system, likely due to microbiological consumption and/or adsorption to metal deposits on the pipe walls. The ATP (microbial activity) was relatively high in the raw water (River Glomma) and then reduced significantly during treatment. There were minor amounts of ATP left even after UV and chlorination, and the ATP level appeared to increase a bit from the clean water tank to the distribution system, likely due to the increase in microbial substrate (BDOC) and the chlorine-free distribution system. With BDOC levels of 0.12 mg/L on average and maximum values of 0.20 mg/L, the clean water was considered being close to biologically stable for chlorine-free distribution.

Table 5-1-1 Water Quality data – NRV WTW. Average±StDev, minimum-maximum values (Sampling dates: May 4; Aug 17; Oct 26, 2015; Feb 8, 2016). Sampling spots: Out Sed: After coag, flocc, settling (super pulsator); Out Filter: After 2-M antracite-sand filtration; Out GAC; Out UV; Out CWT: After Clean Water Tank, incl. chlorination and pH control; DS: From the Distribution System.

NRV	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	31±13	16.7±6.0	7.3±7.0	4.0±1.4	72±4	14±2	5±1	8±3	4.1±0.4	0.17±0.06	324±199
	24-51	13.0-25.7	0.6-14.2	3.4-5.5	70-77	12-16	4-7	5-12	3.7-4.7	0.09-0.22	219-623
Out Sed	3±2	3.7±1.3	0.3±0.1	1.7±0.2	53±8	22±1	6±4	19±9	2.1±0.4	0.13±0.06	59±13
	2-6	2.9-5.6	0.2-0.4	1.5-2.1	42-61	21-22	0-8	11-29	1.8-2.7	0.09-0.23	44-75
Out Filter	3±1	3.6±1.1	0.1±0.0	1.6±0.3	49±10	23±8	9±2	18±9	2.2±0.3	0.12±0.06	22±14
	2-5	2.6-5.2	0.1-0.1	1.4-2.0	40-62	17-35	7-11	12-31	1.9-2.6	0.04-0.20	6-40
Out GAC	2±1	3.0±0.8	0.1±0.0	1.5±0.2	46±11	24±4	8±9	23±7	2.0±0.2	0.07±0.04	15±8
	1-4	2.4-4.2	0.1-0.1	1.3-1.8	34-60	20-30	2-21	15-32	1.9-2.5	0.03-0.12	6-25
Out UV	2±1	3.2±1.0	0.1±0.0	1.5±0.3	49±8	24±5	9±5	19±3	2.1±0.2	0.08±0.06	12±5
	1-4	2.5-4.6	0.1-0.1	1.3-1.9	42-61	18-30	3-16	14-21	1.9-2.5	0.03-0.12	5-16
Out CWT	2±1	2.8±0.9	0.1±0.0	1.5±0.2	47±8	22±2	12±6	19±5	1.9±0.3	0.12±0.06	1±1
	1-4	2.3-4.1	0.1-0.1	1.3-1.8	37-57	18-24	4-19	14-26	1.6-2.2	0.04-0.20	0-2
DS	2±1	2.7±0.8	0.1±0.0	1.5±0.2	49±9	25±4	7±3	19±3	1.8±0.3	0.06±0.05	3±3
	1-4	2.2-4.0	0.1-0.2	1.3-1.8	38-59	19-28	5-11	15-23	1.6-2.2	0.01-0.11	0-7

Analytical error. All the DOC analyses were performed as triplicate measurements, and standard deviations were calculated for all samples. Figure 5-1-2 shows a typical example from NRV WTW (the Aug 2015 Sampling Round) where DOC and the four NOM fraction concentrations are presented along with their standard error bars (±). For DOC and NEU the presented standard error is the standard deviation within the triplicate DOC measurements. For VHA, SHA and CHA, with fraction concentrations calculated as the difference between the inlet and outlet DOC from the respective fractionation columns, the standard error was calculated as the square root of the sum of the squared standard deviations for the inlet and outlet DOC values for the three fractionation columns/resins, i.e. DAX-8, XAD-4 and IRA-958, respectively.

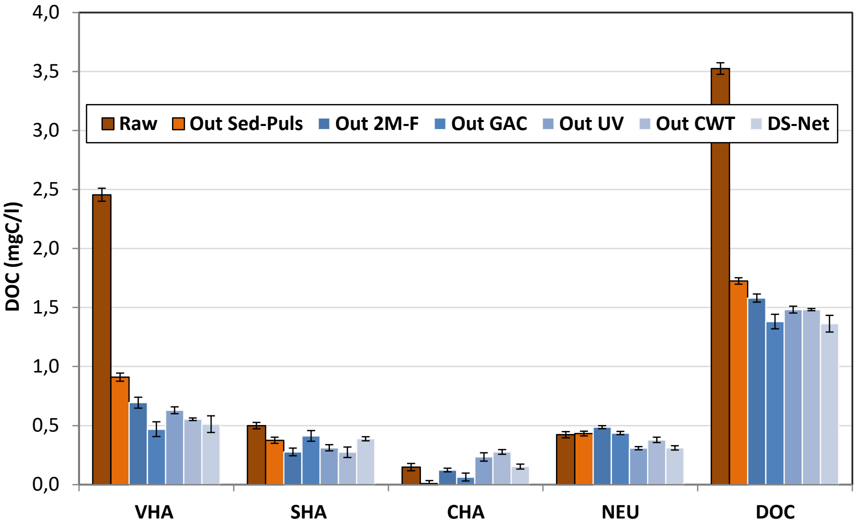


Figure 5-1-2 Water Quality data at NRV WTW (Aug 2015). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

Figure 5-1-2 shows that the standard error is within the range of 0.01-0.07 mg/L for all DOC and NOM fraction concentrations in this sampling round. This is identical to the error range found for BDOC. For cellular ATP, the standard errors were within the range of 0.000-0.006 nmol/L (Figures not shown).

Table 5-1-2 shows the calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites. In general, the analytical errors were low, with the highest absolute values found in raw water. The by far highest values for DOC and VHA (0.19 mg/L) was found in raw water in the May sampling round, and for cellular ATP in the Feb 2016 samplings (0.054 nmol/L). The second highest level found were 0.07 mg/L for DOC, NOM fractions and BDOC, and 0.008 nmol/L for cellular ATP. The May 2015 results, representing a "worst case" with respect to standard error for DOC and NOM fractions, are shown in Figure 5-1-3.

Table 5-1-2 Analytical Error Data – NRV WTW. Calculated standard analytical errors from the triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev (triplicate measurements)						
		mg/L						nmol/L
		DOC	VHA	SHA	CHA	NEU	BDOC	ATP
04.05.2015	**Raw**	0,19	0,19	0,03	0,02	0,00	0,03	0,008
	Out Sed-Puls	0,04	0,05	0,03	0,01	0,01	0,01	0,002
	Out 2-M F	0,02	0,03	0,03	0,04	0,03	0,03	0,002
	Out GAC	0,04	0,04	0,02	0,01	0,01	0,01	0,001
	Out UV	0,02	0,02	0,01	0,02	0,01	0,01	0,001
	Out CWT	0,04	0,04	0,03	0,03	0,02	0,03	0,000
	DS	0,04	0,04	0,02	0,05	0,00	0,00	0,000
17.08.2015	**Raw**	0,05	0,05	0,03	0,03	0,03	0,03	0,006
	Out Sed-Puls	0,03	0,03	0,03	0,03	0,02	0,05	0,004
	Out 2-M F	0,03	0,05	0,03	0,02	0,01	0,07	0,000
	Out GAC	0,06	0,06	0,04	0,03	0,01	0,02	0,003
	Out UV	0,03	0,03	0,03	0,03	0,01	0,01	0,001
	Out CWT	0,01	0,01	0,04	0,02	0,02	0,01	0,000
	DS	0,07	0,07	0,01	0,02	0,02	0,01	0,000
27.10.2015	**Raw**	0,02	0,05	0,06	0,05	0,03	0,01	0,003
	Out Sed-Puls	0,05	0,05	0,03	0,03	0,02	0,06	0,003
	Out 2-M F	0,03	0,05	0,04	0,04	0,03	0,02	0,001
	Out GAC	0,05	0,05	0,03	0,01	0,01	0,02	0,001
	Out UV	0,02	0,02	0,04	0,03	0,02	0,01	0,000
	Out CWT	0,04	0,04	0,01	0,05	0,02	0,00	0,000
	DS	0,01	0,01	0,02	0,03	0,01	0,01	0,000
08.02.2016	**Raw**	0,06	0,07	0,05	0,03	0,02	0,06	0,054
	Out Sed-Puls	0,03	0,05	0,05	0,02	0,02	0,01	0,001
	Out 2-M F	0,03	0,05	0,06	0,04	0,00	0,04	0,000
	Out GAC	0,02	0,02	0,03	0,02	0,03	0,01	0,001
	Out UV	0,06	0,06	0,01	0,02	0,00	0,02	0,000
	Out CWT	0,03	0,04	0,06	0,03	0,03	0,02	0,000
	DS	0,05	0,05	0,02	0,01	0,01	0,02	0,000
AVG		***0,04***	***0,05***	***0,03***	***0,03***	***0,02***	***0,02***	***0,003***
MIN		***0,01***	***0,01***	***0,01***	***0,01***	***0,00***	***0,00***	***0,000***
MAX		***0,19***	***0,19***	***0,06***	***0,05***	***0,03***	***0,07***	***0,054***
AVG-Raw		**0,08**	**0,09**	**0,04**	**0,03**	**0,02**	**0,03**	**0,018**
AVG-Sed/Puls		**0,04**	**0,05**	**0,04**	**0,02**	**0,02**	**0,03**	**0,003**
AVG-2M F		**0,03**	**0,05**	**0,04**	**0,04**	**0,02**	**0,04**	**0,001**
AVG-GAC		**0,04**	**0,04**	**0,03**	**0,02**	**0,02**	**0,02**	**0,002**
AVG UV		**0,03**	**0,03**	**0,02**	**0,03**	**0,01**	**0,01**	**0,001**
Avg CWT		**0,03**	**0,03**	**0,04**	**0,03**	**0,02**	**0,02**	**0,000**
AVG DS		**0,04**	**0,04**	**0,02**	**0,03**	**0,01**	**0,01**	**0,000**

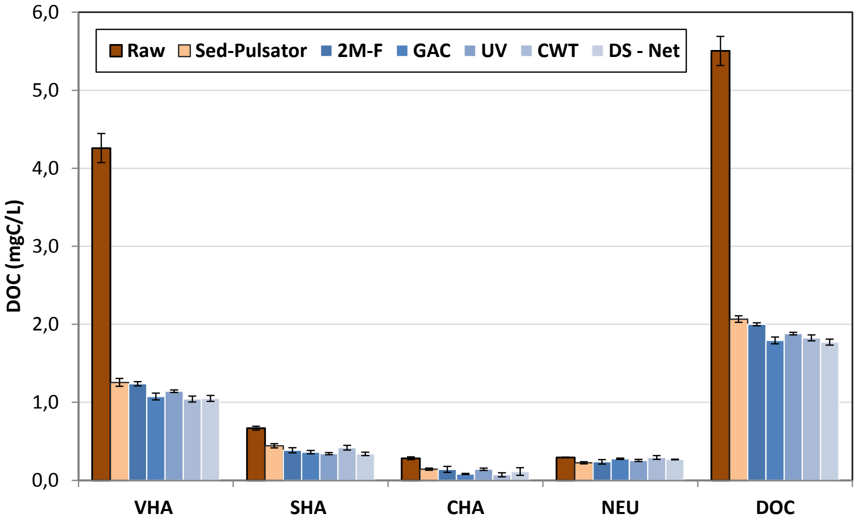


Figure 5-1-3 Water Quality data – NRV WTW (May 2015). DOC and NOM-fraction concentrations with standard error bars.

NOM fractions and NOM fraction removal. The removal of DOC during coagulation (out 2-M filter) was on average 59 %, with minimum and maximum values of 55 and 64 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 66 % with minimum and maximum values of 64 and 67 %, and 18 % (-7 to 35 %), respectively.

After GAC filtration the total DOC removal efficiencies increased to 62 % on average (58-67 %), thus illustrating the small (3 %) additional NOM removal obtained by the GAC filtration process step.

The applied UV-disinfection (40 mJ/cm^2) does not seem to change neither the NOM fraction concentrations nor the BDOC levels significantly.

Elements and residual metals. Regarding the elemental data (obtained by ICP-MS-analysis), a specific focus was put on metal coagulant residuals (Al, Fe) and specific elements that showed significant changes in concentration during treatment (Figure 5-1-4) and during distribution (Figure 5-1-5).

In the Feb-2016 sampling round, the concentration of Al was high in the raw water, with an additional increase after the coagulation, flocculation and sedimentation (super pulsator) steps (> 300 µg/L). After filtration however, the residual Al levels were low in all sampling rounds (29 µg/L at maximum).

It appears from Figure 5-1-4 that Fe, Cr and Mn are effectively removed during coagulation-filtration. For Mn, the GAC filter impose additional removal. The contribution from the PAX coagulant and the hypochlorite (NaOCl) dosing on the Cl-concentration increase is evident. The same is true for the increase in Ca from the dosage of micronized marble slurry ($CaCO_3$), for the increase in Sr from PAX and/or marble slurry, and for the increase in Na from the final pH-control (NaOH).

Figure 5-1-5 shows increasing concentrations of Cu and Zn in the distribution network and in the clean water tank, respectively (May samples only). The concentration of total P was high in raw water in the Feb-2016 sampling round (16 µg/L). In treated and distributed water samples however, the concentration levels were reduced to 2.7-4.5 g P/L. In the October 2015 sampling round, however, the P-concentration levels were much lower in all samples (2.1-3.7 µg P/L).

Elements that were analysed, without showing any significant changes in concentration during treatment and distribution include Si, S, K, Ba and B.

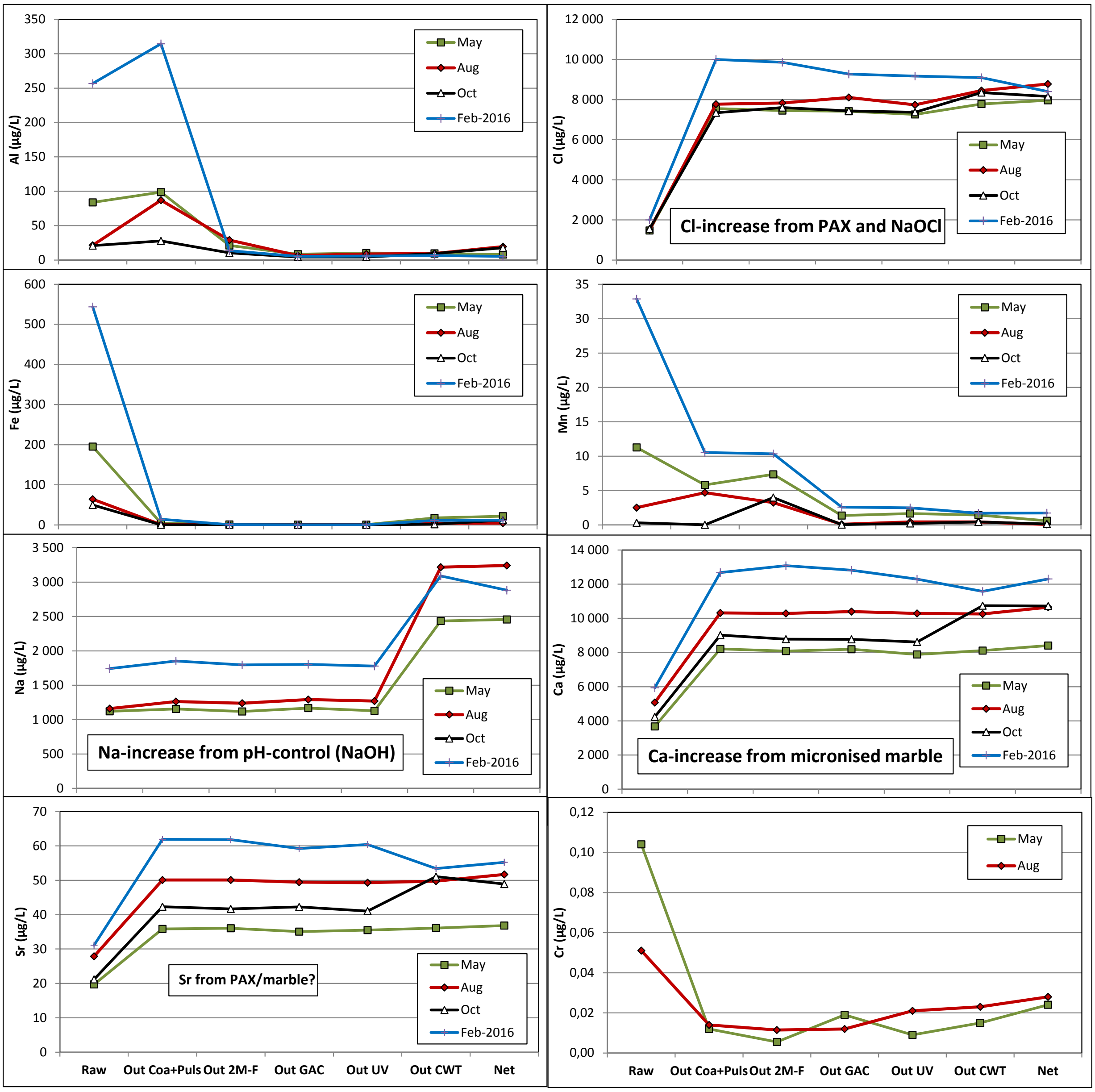


Figure 5-1-4 Water Quality data – NRV WTW. Al, Cl, Fe, Mn, Na, Ca, Sr and Cr concentration profiles during treatment and distribution.

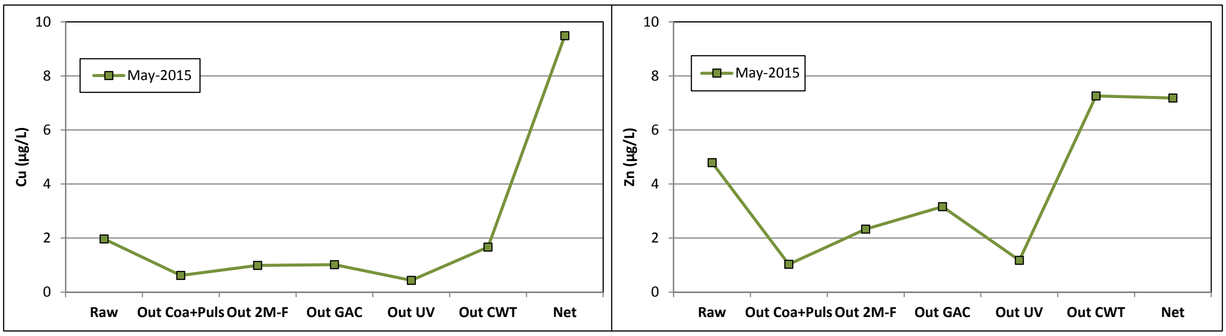


Figure 5-1-5 Water Quality data – NRV WTW. Cu and Zn concentration profiles during treatment and distribution.

For NRV, some major findings are summarized below.

- Large fluctuations in raw water NOM and turbidity levels during the sampling period: 3.4-5.5 mg DOC/L; Turbidity 0.6-14 NTU. This is typical for a river source
- Relatively high SUVA 3.7-4.7, and high hydrophobic NOM content (84-90 % VHA+SHA) indicate good treatability by Coagulation
- Varying Specific Coagulant Dose levels: 17-41 µmol Al/mg DOC
- High coagulation pH: 7.0-7.3
- High residual Al concentration after clarification in Feb 2016 (> 300 µg/L)
- Moderate filtration rates 2.3-4 m/hr
- Some BDOC increase from chlorination, and a minor ATP increase from the CWT to the DS/Network sample
- Increase in Cu and Zn from the DS/Net and CWT, respectively (May 2015 samples only)
- Coagulation optimization trials recommended

5.2. Burncrooks (BUR) WTW - Scotland

The water treatment process at Burncrooks WTW includes enhanced coagulation (alum) with lime for pH-control, polymer dosing prior to flocculation and upflow clarification, single medium sand filtration, chlorination, and finally lime dosing for pH and corrosion control. The water source is a series of reservoirs including Burncrooks, close to Glasgow. The plant supplies more than 50 000 people. The treatment flowsheet for the Burncrooks WTW along with the five sampling spots (Pt 1-5) is presented in Figure 5-2-1.

Manganese (Mn) was an issue prior to the installation of a reservoir mixing system for oxidation and simplified Mn-removal. In addition, lead (Pb) in tap water was an issue.

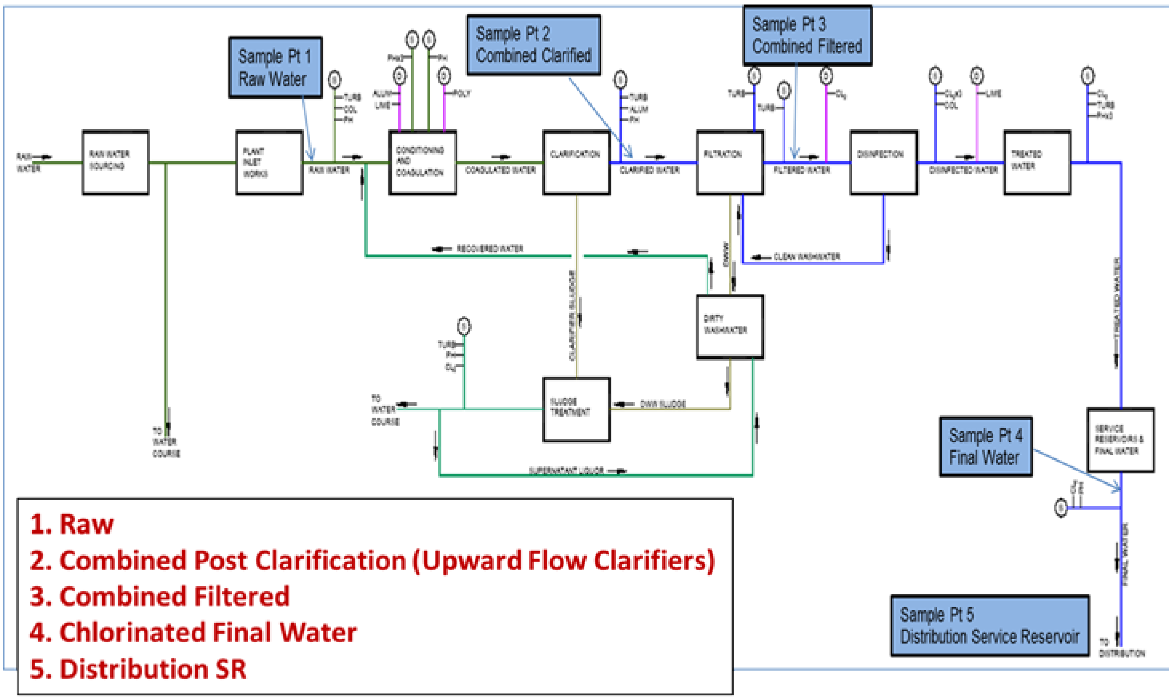


Figure 5-2-1 Treatment process flowchart and water sampling points at BURNCROOKS WTW.

Coagulation. During the four water sampling rounds at Burncrooks WTW, the alum coagulant dose was constant (4.9 mg Al/L), and so were the coagulation pH levels (5.9-6.0). The DOC-specific dose, however varied in the range of 0.42-0.69 mg Al/mg DOC, i.e. 15-26 µmol Al/mg DOC. The amount of DOC removed was in the range of 32-54 mg DOC per mmol of Al added. A close to stoichiometric (constant) relationship will normally exist between NOM content and coagulant dose requirement, i.e. a 1:1 relationship. At Burncrooks WTW the ratio between the maximum and minimum DOC-specific coagulant dosages was 1.7. Considering the relatively stable NOM fraction distribution in the raw water, this is taken as an indication of a coagulation process optimization potential and a potential for improved process control, i.e. a better adaptation of coagulation conditions to the prevailing raw water quality. The filtration rates applied during the sampling period is 2.8-3.3 m/h, which is regarded a low hydraulic filter loading.

A comparative study (benchmark) of the coagulation conditions and treatment performance among the utilities is presented in Chapter 6.

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR sampling rounds is shown in Table 5-2-1. The raw water DOC was dominated by the hydrophobic NOM-fractions (89 % VHA+SHA), and high SUVA levels (5.5), indicating good treatability by coagulation.

The raw water contained significant amounts of NOM. Colour and UV-absorbance vary in the ranges of 91-149 mg Pt/L and 41-65 m^{-1}, respectively, turbidity within 1-1.5 NTU, and TOC within minimum and maximum levels of 6.9 and 11.7 mg/L. Most of the organic matter was dissolved, with DOC levels of 98 % of TOC on average.

The clean water quality was good, with low levels of colour (min-max: 1-6 mg Pt/L), UV-absorbance (2.2-4.1 m^{-1}), turbidity (0.1-0.3 NTU), DOC (1.2-2.2 mg/L), and BDOC (0.07-0.26 mg/L).

Table 5-2-1 Water Quality data – Burncrooks WTW. Average±StDev, minimum-maximum values (Sampling dates: May 6, Sep 8, Nov 10, 2014; March 16, 2015). Sampling spots: Out Clar: After coagulation, up-flow clarification; Out RGF: After 1-M sand filtration; Out CWT: After Clean Water Tank (incl. chlorination); DS: From the Distribution System.

BUR	*Colour (mg Pt/L)*	*UV-A (m-1)*	*Turb (NTU)*	*DOC (mg/L)*	*VHA (%)*	*SHA (%)*	*CHA (%)*	*NEU (%)*	*SUVA (L/m mg)*	*BDOC (mg/L)*	*ATP (pmol/L)*
Raw Water	*112±26*	*50.6±10.7*	*1.3±0.2*	*9.3±2.2*	*80±0*	*9±2*	*5±3*	*6±2*	*5.5±0.3*	*0.14±0.07*	*471±482*
	91-149	*41.0-65.1*	*1.0-1.5*	*7.1-11.8*	*79-80*	*6-11*	*2-9*	*4-8*	*5.1-5.8*	*0.06-0.23*	*185-1027*
Out Clar	*5±3*	*4.4±1.4*	*0.3±0.1*	*1.8±0.6*	*50±5*	*19±3*	*9±5*	*22±5*	*2.4±0.2*	*0.11±0.04*	*26±18*
	3-10	*3.0-6.0*	*0.2-0.4*	*1.3-2.4*	*45-55*	*15-21*	*1-12*	*15-28*	*2.2-2.7*	*0.06-0.15*	*17137*
Out RGF	*5±3*	*4.1±1.2*	*0.1±0.0*	*1.7±0.5*	*51±4*	*20±5*	*7±3*	*23±6*	*2.5±0.1*	*0.06±0.03*	*17±6*
	3-9	*3.0-5.4*	*0.1-0.2*	*1.2-2.1*	*46-55*	*14-26*	*3-10*	*17-28*	*2.3-2.6*	*0.02-0.10*	*44470*
Out CWT	*3±2*	*3.0±0.9*	*0.2±0.1*	*1.6±0.5*	*50±8*	*18±1*	*11±1*	*21±7*	*1.9±0.0*	*0.17±0.09*	*0±0*
	1-6	*2.2-4.1*	*0.1-0.3*	*1.2-2.2*	*38-55*	*16-19*	*9-13*	*14-31*	*1.8-1.9*	*0.07-0.26*	*0-0*
DS	*3±3*	*2.9±0.9*	*0.2±0.1*	*1.6±0.5*	*46±11*	*23±8*	*5±4*	*26±7*	*1.8±0.1*	*0.19±0.09*	*1±2*
	1-7	*1.9-3.9*	*0.1-0.4*	*1.1-2.0*	*29-52*	*16-35*	*2-10*	*18-33*	*1.7-1.9*	*0.09-0.30*	*0-3*

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are shown in Table 5-2-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

Table 5-2-2 Analytical Error data – BURNCROOKS WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP. For abbreviations of sampling spots see Table 5-2-1.

Date	**Sampling site**	**StDev**						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
06.06.2014	**Raw**	0,01	0,03	0,04	0,04	0,03	0,08	
	Out RGF	0,03	0,04	0,05	0,04	0,04	0,01	No Sample
	Out CWT	0,03	0,03	0,03	0,01	0,02	0,00	
	DS	not measured					0,01	
08.09.2014	**Raw**	0,26	0,27	0,07	0,02	0,01	0,04	0,205
	Out RGF	0,04	0,06	0,11	0,10	0,03	0,01	0,002
	Out CWT	0,02	0,02	0,03	0,01	0,01	0,02	0,000
	DS	0,03	0,03	0,03	0,02	0,02	0,01	0,001
10.11.2014	**Raw**	0,17	0,17	0,05	0,04	0,02	0,15	0,004
	Out RGF	0,06	0,06	0,02	0,02	0,01	0,01	0,008
	Out CWT	0,04	0,04	0,04	0,04	0,02	0,02	0,000
	DS	0,02	0,02	0,03	0,02	0,03	0,01	0,001
16.03.2015	**Raw**	0,13	0,13	0,01	0,02	0,02	0,13	0,014
	Out RGF	0,06	0,06	0,02	0,02	0,02	0,03	0,001
	Out CWT	0,04	0,04	0,01	0,03	0,02	0,03	0,000
	DS	0,02	0,02	0,04	0,01	0,02	0,01	0,000
AVG		***0,06***	***0,07***	***0,04***	***0,03***	***0,02***	***0,04***	***0,020***
MIN		***0,01***	***0,02***	***0,01***	***0,01***	***0,01***	***0,00***	***0,000***
MAX		***0,26***	***0,27***	***0,11***	***0,10***	***0,04***	***0,15***	***0,205***
AVG-Raw		**0,14**	**0,15**	**0,04**	**0,03**	**0,02**	**0,10**	**0,074**
AVG-RGF		**0,05**	**0,06**	**0,05**	**0,05**	**0,03**	**0,02**	**0,004**
AVG CWT		**0,03**	**0,03**	**0,03**	**0,02**	**0,02**	**0,02**	**0,000**
AVG DS		**0,02**	**0,02**	**0,03**	**0,02**	**0,02**	**0,01**	**0,001**

In general, the analytical errors were low, with the highest absolute values found in raw water during the Sep 2014 sampling round. The results from this sampling are presented in Figure 5-2-2, and this represent a "worst case" with respect to standard error.

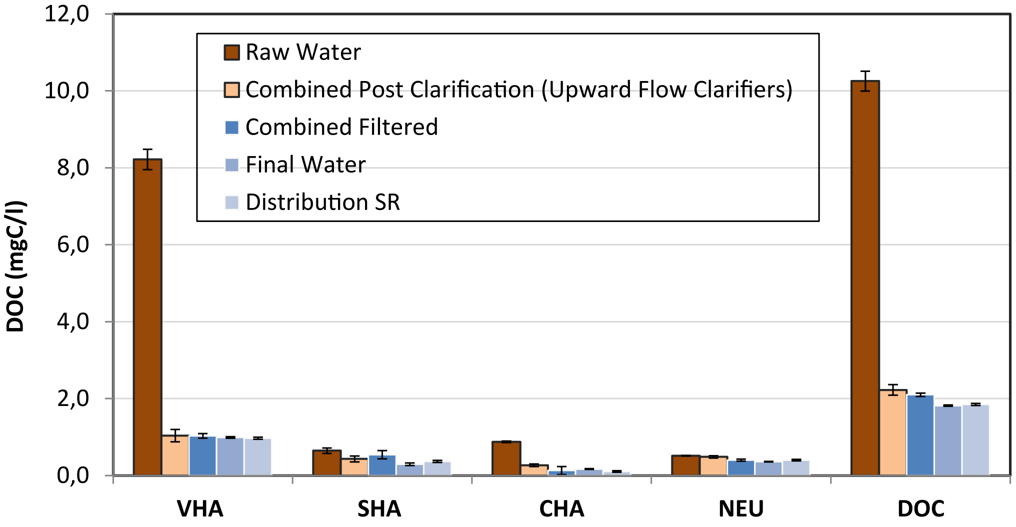


Figure 5-2-2 Water Quality data – BURNCROOKS WTW (Sep 2014). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

NOM fractions and NOM fraction removal. The raw water DOC was dominated by the hydrophobic NOM fractions (89 % of the total DOC; 80 % VHA and 19 % SHA). The hydrophilic fraction was 11 % (5 % CHA and 6 % NEU). The low content of hydrophilic moieties, i.e. the more low-molecular weight and biodegradable NOM fractions is reflected in a low BDOC, i.e. on average 1.4 % of the total DOC, with minimum and maximum values of 0.7 and 1.9 %, respectively.

The DOC removal efficiency during coagulation (out 1-M sand filter) was very high, on average 82 %, with minimum and maximum values of 80 and 85 %, respectively. This reflects the high content of hydrophobic NOM (89 %) in the raw water.

The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) fraction removal efficiencies were on average 86 %, with minimum and maximum values of 82 and 89 %, and 50 % (41 to 62 %), respectively. For the sum of the hydrophilic fractions the removal efficiency obtained by coagulation is only moderate, but it should be kept in mind that the average raw water concentration is only 1 mg/L (CHA+NEU).

The results in Table 5-2-1 show a significant microbial activity (ATP) in the raw water. The ATP levels were effectively removed during coagulation and filtration, and after chlorination the ATP levels were zero in all samples from the clean water tank outlet. In the distribution system, minor amounts of ATP were detected.

The BDOC levels were reduced significantly during coagulation and filtration. During chlorination however, the CHA and BDOC levels increased due to the effects of chlorine on the remaining NOM likely due to oxidation and splitting of the larger molecules into more low-molecular weight and more biodegradable compounds. In general, microbial substrate (BDOC) concentrations at levels above 0.2 mg/L may cause regrowth and increased microbial activity (ATP) in the distribution system. At this utility however, the microbiological activity (ATP) and the BDOC substrate consumption appeared to be controlled at low levels by the residual chlorine present, despite the increased level of microbial substrate (BDOC).

Elements and residual metals. Data from the elemental analyses, with a specific focus on metal coagulant residuals (Al) and specific elements that showed significant changes in concentration during treatment and distribution are presented in Figure 5-2-3.

When using alum, the increase in sulphur concentration from raw water to coagulated water samples reflects the coagulant dosage, and thus the concentration increase in S can be used to back-calculate/control the alum dosage. Figure 5-2-3 shows that the S-concentration, and thereby also the alum dose, was significantly lower in March-2015 compared to the other sampling rounds. Thus it is likely that the reported dose of 4.9 mg Al/L was not constant throughout the four sampling rounds. This is confirmed by the fact that the concentration of residual Al was high in the coagulated and clarified water (230 µg/L), a typical result when sub-optimal coagulant doses are being used. More discussion of coagulation and treatment performance is found in Chapter 5. After filtration however, the residual Al levels were low in all sampling rounds (14 µg/L at maximum).

It appears from Figure 5-2-3 that Fe, Pb and P were effectively removed during coagulation-filtration. For Mn, there was an increase from the filter effluent to the clean water tank in the September samples, and from the clean water tank to the distribution system samples in the May and Sep samples. The high Mn content in raw and treated water samples in Sep 2014 was likely due to poor performance of the source mixing arrangement and thus inefficient oxidation and poor treatability of Mn.

The contribution from the NaOCl dosing to the Cl-concentration increase is well illustrated in Figure 5-2-3. The same is true for the increase in Ca from the dosage of lime in the coagulation and final treatment steps. The high Cl-concentration in all samples from March 2015 is like due to strong wind (a sea-salt episode).

In addition to the increase in Pb concentration from the clean water tank to the distribution network samples, significant increases in Cu and Zn concentrations were detected in the September and May sampling rounds, respectively (data not shown).

For BUR WTW, the major findings are summarized below.

- Significant variation in raw water quality during the sampling period (7-12 mg DOC/L), with high levels of Fe (200-600 µg/L) and Mn (5-30 µg/L)
- High SUVA (5.1-5.8) and VHA+SHA (86-91 % of DOC) indicate very good treatability by coagulation.
- Constant Coagulant Doses applied (4.9 mg Al/L), but variable DOC-specific doses: 15-26 µmol Al/mg DOC
- Stable coagulation pH: 5.9-6.0
- High res-Al after clarification in Mar 2015 (> 200 µg/L)
- Low/Moderate filtration rates: 2.8-3.3 m/hr
- Elevated Mn levels in raw and treated water samples in Sep 2014
- BDOC increase from chlorination, and a minor ATP increase from CWT to DS Network samples
- Increase in Cu and Zn during DS and CWT respectively (May 2015 samples only)

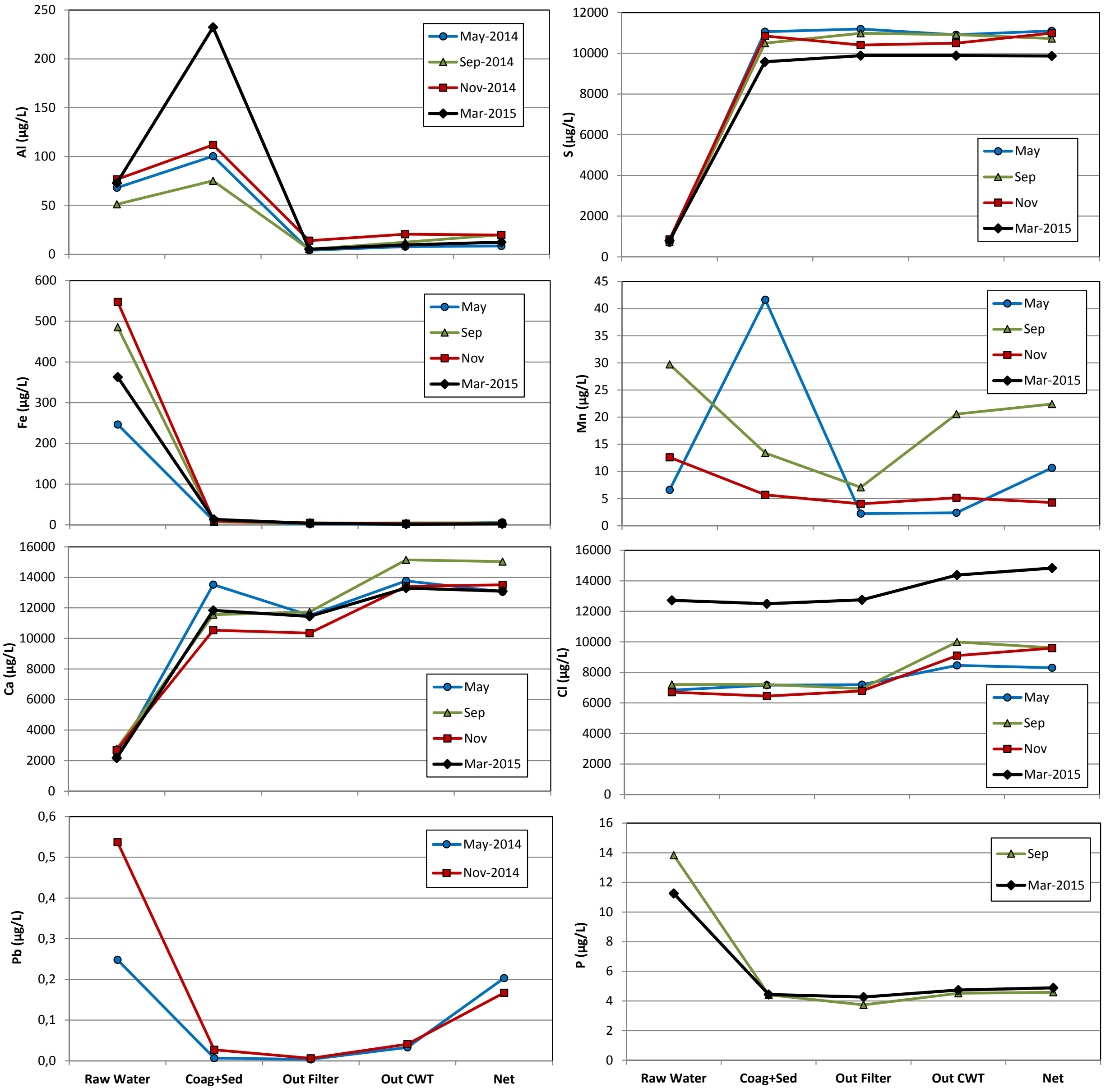


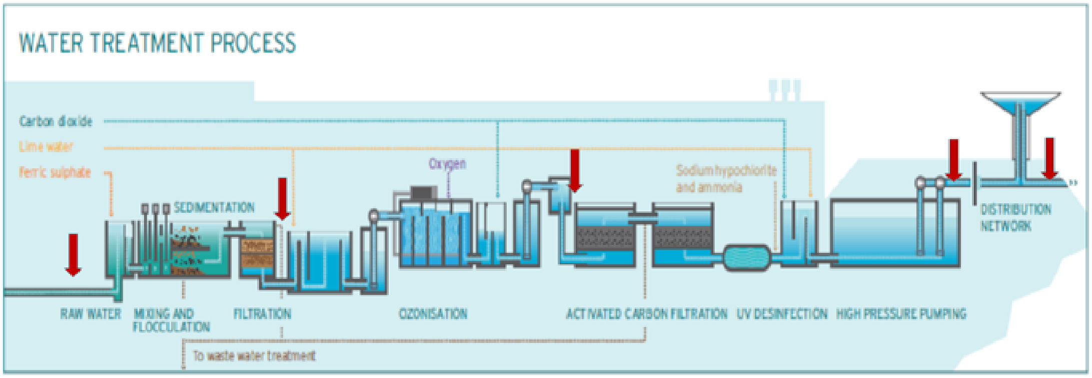
Figure 5-2-3 Water Quality data at BURNCROOKS WTW. Al, S, Fe, Mn, Ca, Cl, Pb and P concentration profiles during treatment and distribution.

5.3. Pitkäkoski (PIT) WTW, HSY – Finland

The water treatment process at Pitkäkoski WTW (PIT-HSY) is enhanced coagulation (Fe sulphate), flocculation and sedimentation, single medium sand filtration, ozonation and GAC filtration, UV disinfection and chloramination (NaOCl and ammonia). Carbon dioxide is added after ozonation, and to the chlorine contact tanks as part of the corrosion control process. The applied UV-dose is 25 mJ/cm^2, and the ozone doses were 0.6-1.0 mg/L. The water traveling time from the WTP to the distribution sampling point is approximately 25 hours. Figure 5-3-1 shows the treatment process flowsheet for the Pitkäkoski WTW (HSY) along with the five sampling spots (red arrows) applied within the NOMiNOR project.

Coagulation. During the four seasonal water sampling rounds at Pitkäkoski WTW (HSY), the Fe sulphate coagulant dose vary within the range of 6.0-6.5 mg Fe/L. The coagulation pH is stable at pH 4.9. The DOC-specific dose, however varies in the range of 0.84-0.98 mg Fe/mg DOC, i.e. 15-18 µmol Fe/mg DOC. The amount of DOC removed is in the range of 39-43 mg DOC per mmol of Fe added. In cases with only minor seasonal variability in NOM characteristics and treatability (constant NOM fraction distribution), a close to stoichiometric (constant) relationship is expected to exist between NOM content and coagulant dose requirement, i.e. a 1:1 relationship and a ratio of close to 1 between maximum and minimum dosage levels. At Pitkäkoski WTW the ratio between the maximum and minimum DOC-specific coagulant dosage levels is 1.1. Considering the relatively stable NOM fraction distribution in the raw water, this indicates a close to optimum coagulation performance and an adequate process control, i.e. coagulation conditions that are well adapted to the prevailing raw water quality. The filtration rates applied during the sampling period is 2.8-3.0 m/h, which is regarded as a low hydraulic filter loading.

A comparative study (benchmark) of the coagulation conditions and treatment performance among the utilities is presented in Chapter 6.



1. Raw Water ("Untreated raw water - "Raw")
2. Out Coag+Sed+Filt ("Coagulated, settled and filtered water - "Out filter 1")
3. Out OZ ("Ozonated - "Ozonated")
4. Out CWT ("After GAC and chlorine contact tank - "Chlorinated")
5. Distribution ("From distribution network - "Network")

Figure 5-3-1 Treatment process flowchart and water sampling points at PITKÄKOSKI WTW (HSY).

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR sampling rounds is given in Table 5-3-1.

The raw water quality appears relatively stable over the sampling period, with colour and UV-absorbance within the ranges of 28-30 mg Pt/L and 22-23 m^{-1}, respectively, turbidity within 0.2-0.7 NTU, and TOC within minimum and maximum levels of 6.7-7.3 mg/L. Most of the organic matter was dissolved, with DOC levels in the range of 6.6-7.1 mg/L during the four sampling rounds, i.e. 98 % of TOC on average. DOC was dominated by the hydrophobic NOM fractions (84 % of the total DOC; 66 % VHA and 18 % SHA). The hydrophilic fraction was 16 % (10 % CHA and 6 % NEU).

The SUVA value was 3.2, thus indicating moderate treatability by coagulation. Raw water BDOC was on average 1.2 % of the total DOC, with minimum and maximum values of 0.7 and 1.4 %, respectively.

The clean water quality was good, with low levels of colour (1 mg Pt/L as min and max), UV-absorbance (1.1-2.0 m^{-1}), turbidity (0.1-0.2 NTU), DOC (1.6-1.8 mg/L), and BDOC (0.02-0.11 mg/L).

Table 5-3-1 Water Quality data – Pitkäkoski WTW (HSY). Average±StDev, minimum-maximum values (Sampling dates: Mar 31; Sep 3; Nov 17, 2014; Mar 9, 2015). Sampling spots: Out Filter: After coagulation, sedimentation and 1-M sand filtration; Out Oz: Out Ozone contact tank; Out CWT: After Clean Water Tank, including GAC filtration, UV-disinfection and chloramination; DS: From the Distribution System.

PIT	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	29±1 28-30	22.2±0.4 21.7-22.5	0.3±0.2 0.2-0.7	6.9±0.2 6.6-7.1	66±0 65-66	18±0 17-18	10±1 9-12	6±1 5-6	3.2±0.1 3.0-3.4	0.08±0.02 0.05-0.10	46±15 29-61
Out Filter	2±0 2-3	3.9±0.2 3.7-4.2	0.2±0.0 0.1-0.2	2.4±0.2 2.2-2.6	54±2 52-57	22±2 20-24	8±2 6-10	16±2 13-18	1.6±0.1 1.5-1.7	0.06±0.02 0.04-0.09	2±1 0-3
Out Oz	2±1 1-3	2.3±0.2 2.0-2.4	0.2±0.1 0.1-0.2	2.3±0.1 2.2-2.5	44±3 40-46	25±2 23-28	13±5 8-19	18±4 13-22	1.0±0.1 0.8-1.1	0.24±0.05 0.17-0.30	0±0 0-0
Out CWT	1±0 1-1	1.7±0.4 1.1-2.0	0.2±0.1 0.1-0.2	1.7±0.1 1.6-1.8	40±2 38-42	28±1 26-29	13±2 11-16	19±1 17-20	1.0±0.2 0.7-1.1	0.07±0.04 0.02-0.11	1±1 0-1
DS	3±1 3-4	2.1±0.3 1.7-2.3	0.2±0.0 0.2-0.3	1.6±0.1 1.5-1.7	33±8 23-41	30±5 24-35	15±3 11-18	22±5 15-27	1.3±0.2 1.1-1.5	0.08±0.02 0.06-0.10	4±1 2-5

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are given in Table 5-3-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

In general, the analytical errors were low, with the highest absolute values found in raw water during the March 2014 sampling round. This "worst case" situation with respect to analytical error is illustrated in Figure 5-3-2.

Table 5-3-2 Analytical Error Data – PITKAKOSKI WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
31.03.2014	**Raw**	0,28	0,28	0,05	0,05	0,04	0,02	0,006
	Out RGF	0,05	0,06	0,05	0,04	0,02	0,00	0,000
	Out CWT	0,03	0,04	0,10	0,02	0,01	0,00	0,000
	DS	0,07	0,07	0,02	0,02	0,02	0,02	0,000
03.09.2014	**Raw**	0,16	0,16	0,04	0,03	0,01	0,06	0,002
	Out RGF	0,09	0,10	0,04	0,05	0,03	0,01	0,001
	Out CWT	0,04	0,04	0,03	0,03	0,04	0,01	0,000
	DS	0,02	0,02	0,02	0,03	0,02	0,01	0,000
17.11.2014	**Raw**	0,01	0,10	0,10	0,03	0,03	0,04	0,003
	Out RGF	0,09	0,09	0,04	0,03	0,02	0,01	0,000
	Out CWT	0,05	0,05	0,03	0,02	0,01	0,01	0,000
	DS	0,01	0,01	0,02	0,01	0,02	0,02	0,000
09.03.2015	**Raw**	0,09	0,12	0,09	0,03	0,02	0,07	0,002
	Out RGF	0,09	0,09	0,02	0,02	0,02	0,02	0,000
	Out CWT	0,08	0,09	0,03	0,03	0,03	0,01	0,000
	DS	0,04	0,04	0,03	0,02	0,01	0,03	0,000
AVG		***0,08***	***0,09***	***0,04***	***0,03***	***0,02***	***0,02***	***0,001***
MIN		***0,01***	***0,01***	***0,02***	***0,01***	***0,01***	***0,00***	***0,000***
MAX		***0,28***	***0,28***	***0,10***	***0,05***	***0,04***	***0,07***	***0,003***
AVG-Raw		***0,14***	***0,17***	***0,07***	***0,04***	***0,03***	***0,05***	***0,003***
AVG-RGF		***0,08***	***0,09***	***0,04***	***0,04***	***0,02***	***0,01***	***0,000***
AVG CWT		***0,05***	***0,06***	***0,05***	***0,03***	***0,02***	***0,01***	***0,000***
AVG DS		***0,04***	***0,04***	***0,02***	***0,02***	***0,02***	***0,02***	***0,000***

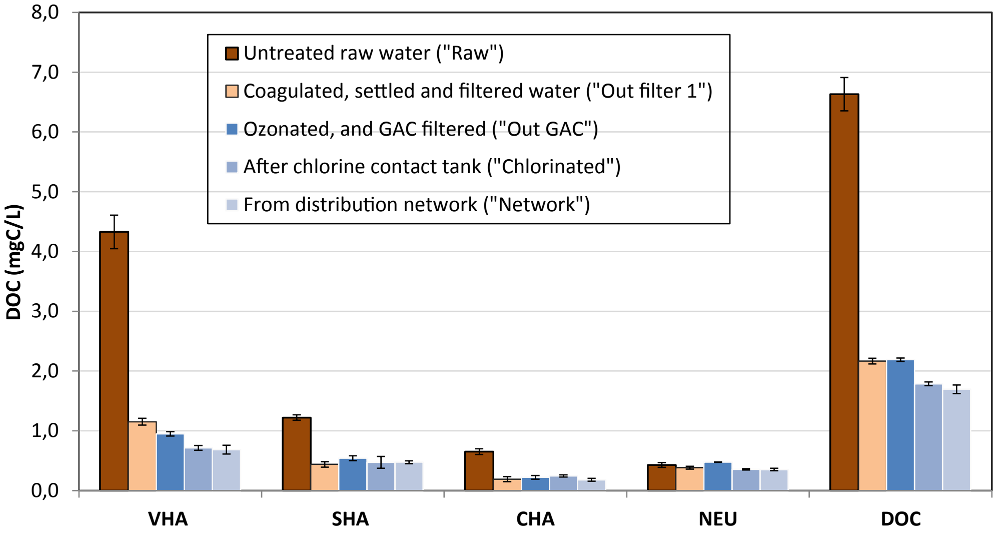


Figure 5-3-2 Water Quality data – PITKÄKOSKI WTW (March 2014). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

NOM fractions and NOM fraction removal. The removal of DOC during coagulation (out sand filter) was on average 66 %, with minimum and maximum values of 64 and 67 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 69 % with minimum and maximum values of 66 and 71 %, and 49 % (47-51 %), respectively.

After the clean water tank, the total DOC removal efficiencies increased to 75 % on average (73-77 %), thus illustrating the additional (9 %) NOM removal obtained from ozonation and GAC filtration.

The microbial activity data (ATP) presented in Table 5-3-1 showed that ATP was effectively removed during coagulation and filtration. After the ozone contact tank, the ATP levels were zero in all samples. The ATP values remained close to zero after the clean water tank while a small increase in ATP was detected in the distribution system samples despite the low BDOC values. This may be explained by the low doses of chlorine (0.5-0.6 mg/L) and the corresponding low chlorine residuals in the distribution system.

For the BDOC, the low levels found in the raw water were further reduced during coagulation and filtration. It appears from the data that the BDOC levels were significantly increased due to the oxidizing effects of ozone on the remaining NOM (mainly transfer of VHA to the more biodegradable CHA fraction). The additional microbial substrate (BDOC) formed during ozonation was however reduced again during the GAC filtration process, and BDOC was maintained at low levels (<0.1 mg/L) in the clean water tank and distribution system samples. It is likely that the chlorination process increased BDOC somewhat, and that the BDOC reduction during GAC filtration was even higher than shown by the results. The applied hypochlorite doses were however low (0.5-0.6 mg/L) and the corresponding chlorine-induced increase in BDOC is likely very low.

There are at least three possible explanations to the observed removal of NOM (DOC and BDOC) from ozonation and GAC filtration:

1) NOM is adsorbed to vacant adsorption sites in the GAC pores (the NOM adsorbing capacity is normally exhausted after a few weeks)
2) NOM is biologically degraded in the GAC filter (i.e. BAC: a GAC filter with active biomass)
3) NOM is adsorbed to metal deposits in the GAC filter bed (mostly Fe). Substantial amounts of Fe is retained in the GAC filter bed, and it is likely that ozonation splits NOM-Me complexes and thus promotes metal precipitation in the GAC filter bed.

Given the significant removal of Fe along with the reductions in DOC and BDOC that was observed during GAC filtration in all four sampling rounds (Figure 5-3-3), it is likely that mechanism No. 3 is dominant here. It is well known that Fe-hydroxide is an effective NOM adsorbent, and that coagulation of NOM can be modelled as an adsorption process with excellent fit (Edwards, 1997; Kastl et al., 2004). Figure 5-3-3 shows that the amounts of DOC and BDOC adsorbed/retained per unit mass of Fe within the GAC filter bed vary among the sampling rounds, with a distinct maximum in the Sep-2015 sampling round. The reason for this is unknown, but can probably be related to the pre-ozonation conditions, the backwash and regeneration regimes of the GAC filters, the Fe levels, etc. DOC seems more adsorbable to the Fe-deposits than BDOC, which is reasonable given the more hydrophilic nature of the BDOC and the higher surface charge of hydrophobic NOM.

Fe-deposits with adsorbed substances (NOM, particles, microorganisms, etc) may detach and deteriorate GAC filter effluent quality if the backwash frequency is too low. In the context of potential operation performance optimization, it is suggested that the major removal mechanism in the GAC filter is further studied and identified, and that the operation conditions are adapted to the findings from these studies.

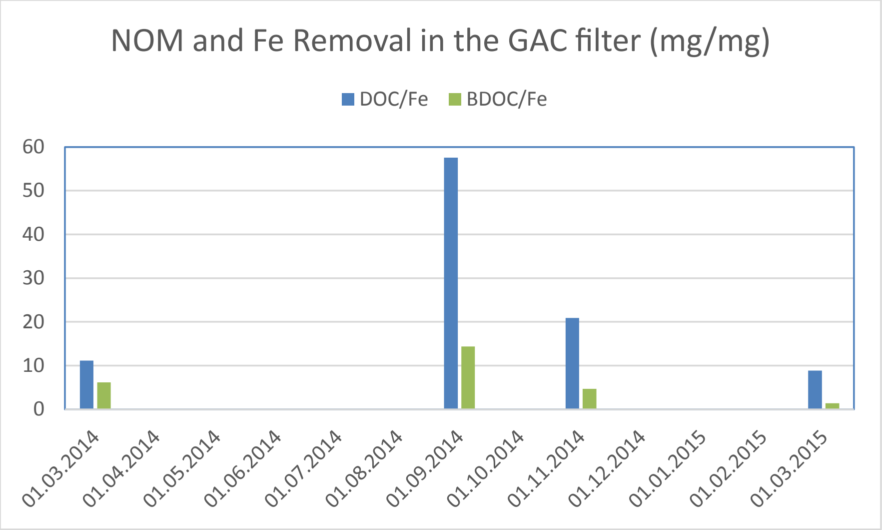


Figure 5-3-3 Removal/deposition of Fe, DOC and BDOC during GAC filtration – PITKÄKOSKI WTW (HSY).

Elements and residual metals. Data of metal coagulant residuals (Fe) and specific elements that showed significant changes in concentration during treatment and distribution are presented in Figure 5-3-4.

When using ferric sulphate, the increase in sulphur concentration from raw water to coagulated water samples reflects the applied coagulant dosage, and thus the concentration increase in S can be used to back-calculate/control the actual coagulant dosage. Figure 5-3-4 shows that the increase in S-concentration, and thereby also the coagulant dose, was higher in March-2014 compared to the other sampling rounds, in line with the reported coagulant dose levels. The concentration of residual Fe was relatively high in the coagulated and clarified water in three out of the four sampling rounds. This is a typical result when sub-optimal coagulant doses are used. However, significant reductions in residual Fe concentrations were obtained during the GAC filtration and chloramination/clean water tank. It is likely that this effect is mainly due to iron hydroxide deposition in the GAC pores as discussed above. This may lead to blockage of GAC pores over time and increased rates of head loss development.

After filtration however, the residual Al levels were low in all sampling rounds (14 µg/L at maximum). It appears from Figure 5-3-4 that Fe, Pb and P were effectively removed during coagulation-filtration. For Mn, there was an increase from the filter effluent to the clean water tank in the September samples, and from the clean water tank to the distribution system samples in the May and Sep samples.

Figure 5-3-4 shows only a minor contribution from the NaOCl-dosing to the Cl-concentration increase, due to the small doses of hypochlorite (0.5-0.6 mg/L) applied here. The increase in Ca from the dosage of lime in the coagulation and in the final treatment steps is however well demonstrated by the results in Figure 5-3-4. Significant increases in Fe and Zn concentrations from the clean water tank to the distribution system were detected in all sampling rounds, likely due to corrosion processes. It appears that the increased Ca levels detected during the March 2014 sampling may have resulted in reduced corrosion (Zn).

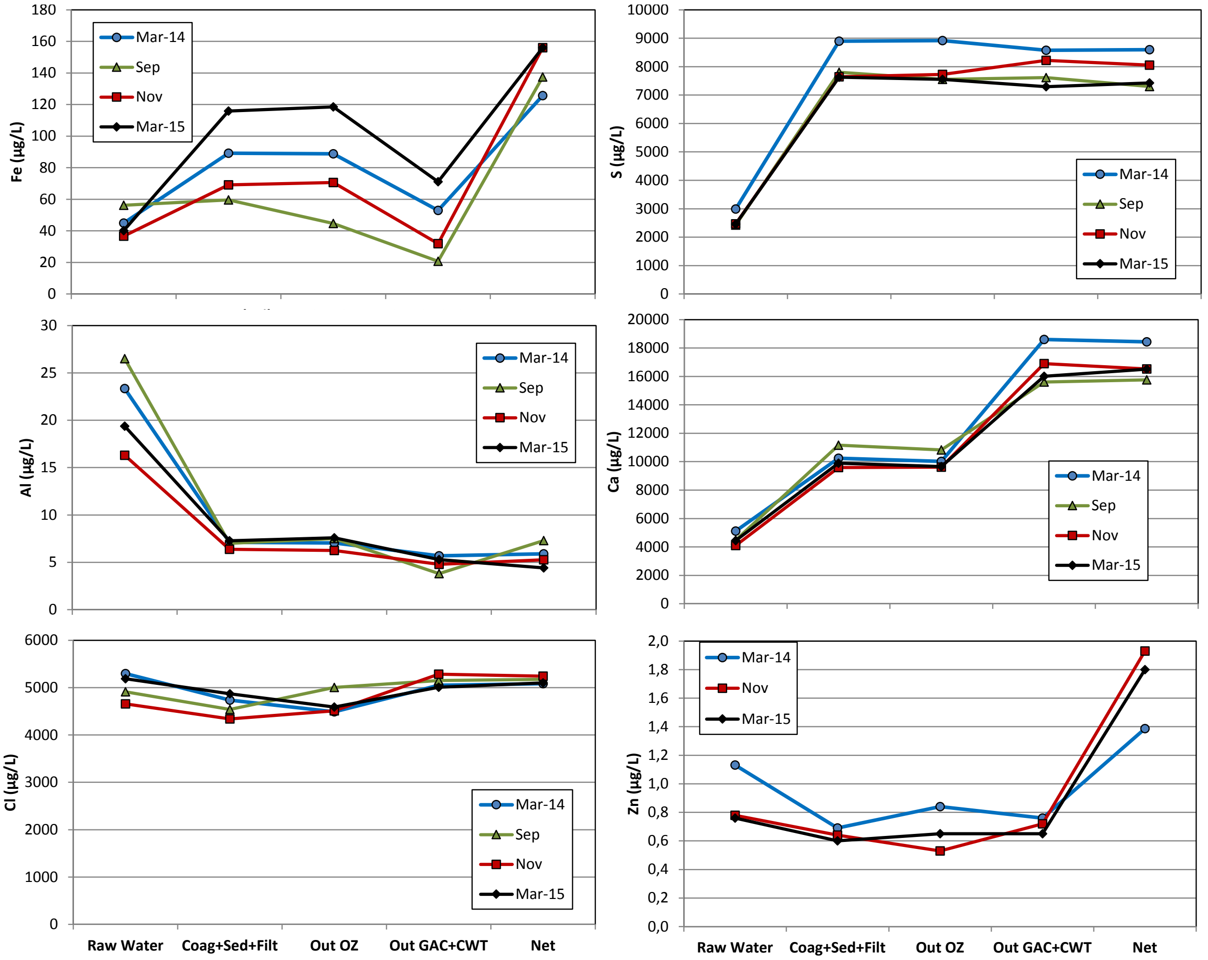


Figure 5-3-4 Water Quality data – PITKÄKOSKI WTW (HSY). Fe, S, Al, Ca, Cl and Zn concentration profiles during treatment and distribution.

For PIT WTW, the major findings are summarized below.

- Stable NOM content in raw water during the sampling period (6.6-7.1 mg DOC/L)
- Moderate SUVA (3.0-3.4) and hydrophobic NOM content VHA+SHA (83-84 % of DOC) indicate moderate treatability by coagulation
- Only minor variation in coagulant dose level: 6.0-6.5 mg Fe/L, and in DOC-specific doses: 15-18 µmol Fe/mg DOC
- Stable coagulation pH: 4.9
- Elevated residual-Fe after coagulation/filtration in March 2015 (120 µg/L)
- Low/Moderate filtration rates: 2.8-3.0 m/hr
- Additional NOM - and Fe - removal from Oz-GAC filtration, due to biological activity and/or adsorption to Fe-hydroxide deposits within the GAC filter bed
- Increase in hydrophilic NOM and BDOC from ozonation, and a minor ATP increase from CWT to DS Network samples
- Increase in Fe and Zn from the CWT to the DS sampling point (likely due to corrosion)

5.4. Bracadale (BRA) WTW – Scotland

The water treatment process at Bracadale WTW includes initial pre-filtration through strainers, pressure filters and cartridge filters, membrane filtration (NF), GAC filtration, chlorination and finally filtration through crushed limestone filters for pH and corrosion control. Figure 5-4-1 shows the flowsheet for the Bracadale Water Treatment Works in Scotland along with the five sampling spots (Pt 1-5) used within the NOMiNOR project. The water source is Voaker Burn (Isle of Skye), and the plant supplies some 250 people.

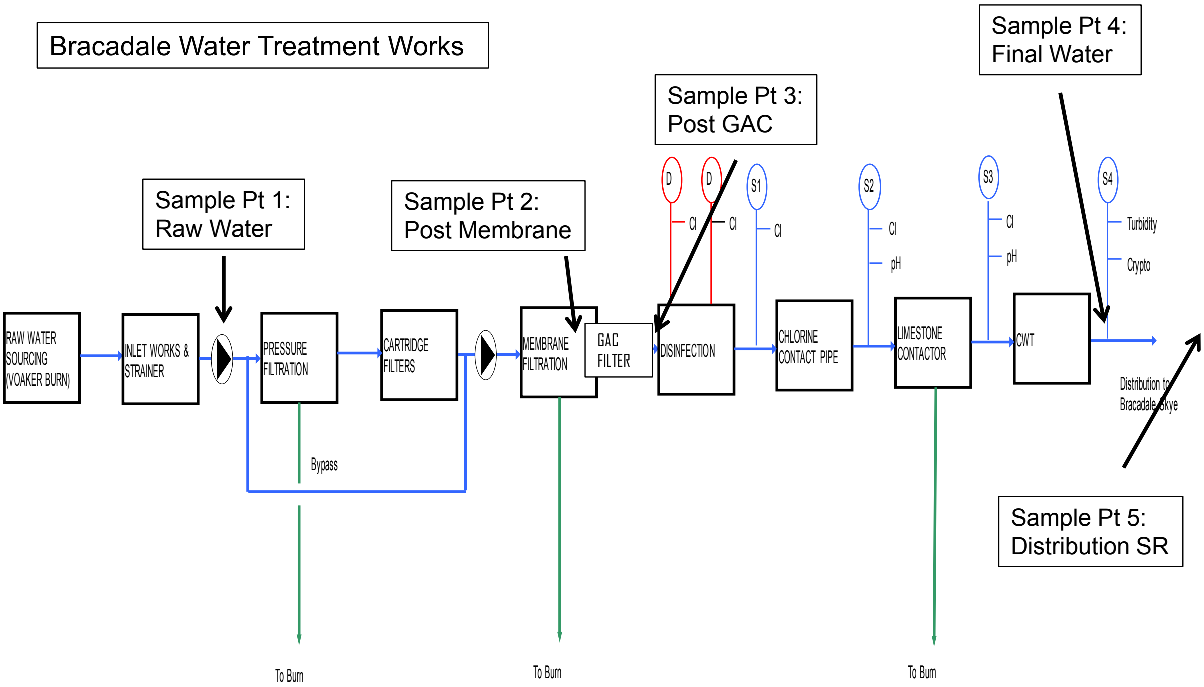


Figure 5-4-1 Treatment process flowchart and water sampling points at BRACADALE WTW.

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR sampling rounds is given in Table 5-4-1.

Table 5-4-1 Water Quality data – Bracadale WTW (HSY). Average±StDev, minimum-maximum values (Samplings: May 18; Aug 31; Nov 2, 2015; Feb 16, 2016). Sampling spots: Out Nano Filter (NF): After pressure and cartridge pre-filters; Out GAC; Out CWT: After Clean Water Tank, including GAC filtration, chlorination and limestone filtration; DS: From the Distribution System.

BRA	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	151±129 24-329	63.0±51.0 12.4-133.9	1.5±0.9 0.6-2.6	12.6±10.1 2.7-26.7	78±11 62-87	10±4 6-15	5±2 4-8	7±5 2-14	4.9±0.2 4.6-5.0	0.28±0.14 0.08-0.41	165±83 81-247
Out NF	5±3 2-8	3.4±1.9 1.4-5.4	0.1±0.0 0.1-0.1	1.3±0.6 0.7-1.9	52±10 39-60	16±1 15-17	6±5 0-11	25±12 12-36	2.5±0.4 2.0-2.9	0.07±0.02 0.05-0.09	8±5 3-13
Out GAC	4±1 2-5	2.6±1.7 0.8-4.1	0.1±0.0 0.1-0.1	1.0±0.4 0.5-1.3	46±7 39-53	20±3 17-23	7±6 0-10	27±15 14-44	2.5±0.8 1.7-3.1	0.02±0.01 0.01-0.03	38±12 26-49
Out CWT	1±0 0-1	1.5±1.1 0.3-2.9	0.1±0.1 0.1-0.2	0.9±0.4 0.5-1.2	39±11 28-49	15±6 8-20	14±3 12-18	32±12 18-44	1.5±0.6 0.6-2.0	0.14±0.07 0.06-0.21	0±1 0-1
DS	1±0 0-1	1.5±1.1 0.5-2.9	0.1±0.1 0.1-0.2	0.8±0.4 0.5-1.3	38±11 26-48	15±5 11-22	17±3 12-20	31±11 18-41	1.7±0.6 0.9-2.3	0.13±0.07 0.04-0.19	0±0 0-0

The raw water quality showed significant variation over the sampling period, with colour and UV-absorbance levels between 24-329 mg Pt/L and 12-134 m^{-1}, respectively. Turbidity varied from 0.6 to 2.6 NTU, and TOC from 2.6 to 27.2 mg/L.

Most of the organic matter was dissolved, with DOC levels in the range of 2.7-26.7 mg/L during the four sampling rounds, i.e. close to 99 % of TOC on average. DOC was dominated by the hydrophobic NOM fractions (88 % of the total DOC; 78 % VHA and 10 % SHA). The hydrophilic fraction was 12 % (5 % CHA and 7 % NEU). The SUVA value was 4.9, thus indicating good treatability by coagulation. The high iron levels at this utility may however affect the SUVA values significantly. Raw water BDOC was on average 2.7 % of the total DOC, with minimum and maximum values of 1.3 and 4.1 %, respectively. Moreover, the results in Table 5-4-1 show significant microbial activity (ATP) in the raw water.

The clean water quality was good, with low levels of colour (0 and 1 mg Pt/L as min and max), UV-absorbance (0.3-2.9 m^{-1}), turbidity (0.1-0.2 NTU), DOC (0.5-1.4 mg/L), and BDOC (0.06-0.21 mg/L). ATP was maintained at zero concentration.

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are presented in Table 5-4-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

Table 5-4-2 Analytical Error Data – BRACADALE WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev						
		mg/L						nmol/L
		DOC	VHA	SHA	CHA	NEU	BDOC	ATP
18.05.2015	**Raw**	0,02	0,02	0,01	0,02	0,01	0,20	0,007
	Out NF	0,06	0,06	0,10	0,09	0,01	0,00	0,000
	Out GAC	0,02	0,02	0,01	0,02	0,01	0,03	0,000
	Out CWT	0,01	0,01	0,01	0,02	0,01	0,02	0,000
	DS	0,02	0,02	0,01	0,02	0,02	0,01	0,000
31.08.2015	**Raw**	0,57	0,57	0,03	0,03	0,01	0,32	0,013
	Out NF	0,04	0,04	0,01	0,03	0,01	0,02	0,000
	Out GAC	0,03	0,03	0,02	0,02	0,01	0,03	0,001
	Out CWT	0,01	0,02	0,09	0,10	0,03	0,07	0,000
	DS	0,01	0,01	0,03	0,01	0,01	0,01	0,000
02.11.2015	**Raw**	0,22	0,22	0,03	0,02	0,02	0,09	0,003
	Out NF	0,10	0,10	0,04	0,04	0,02	0,01	0,001
	Out GAC	0,05	0,06	0,06	0,05	0,02	0,01	0,002
	Out CWT	0,04	0,04	0,02	0,02	0,02	0,02	0,000
	DS	0,03	0,03	0,02	0,05	0,02	0,01	0,000
16.02.2016	**Raw**	0,09	0,09	0,04	0,03	0,00	0,06	
	Out NF	0,04	0,04	0,03	0,04	0,03	0,01	
	Out GAC	No data						No data
	Out CWT	0,02	0,02	0,01	0,03	0,05	0,01	
	DS	0,01	0,01	0,03	0,02	0,01	0,00	
AVG		***0,07***	***0,07***	***0,03***	***0,03***	***0,02***	***0,05***	***0,002***
MIN		***0,01***	***0,01***	***0,01***	***0,01***	***0,00***	***0,00***	***0,000***
MAX		***0,57***	***0,57***	***0,10***	***0,10***	***0,05***	***0,32***	***0,013***
AVG-Raw		**0,23**	**0,23**	**0,03**	**0,03**	**0,01**	**0,17**	**0,008**
AVG-NF		**0,06**	**0,06**	**0,05**	**0,05**	**0,02**	**0,01**	**0,000**
AVG-GAC		**0,03**	**0,04**	**0,03**	**0,03**	**0,01**	**0,02**	**0,001**
Avg CWT		**0,02**	**0,02**	**0,03**	**0,04**	**0,03**	**0,03**	**0,000**
AVG DS		**0,02**	**0,02**	**0,02**	**0,03**	**0,02**	**0,01**	**0,000**

In general, the analytical errors are low, with the highest absolute values found in raw water during the August 2015 sampling round. This "worst case" situation with respect to analytical error is illustrated in Figure 5-4-2.

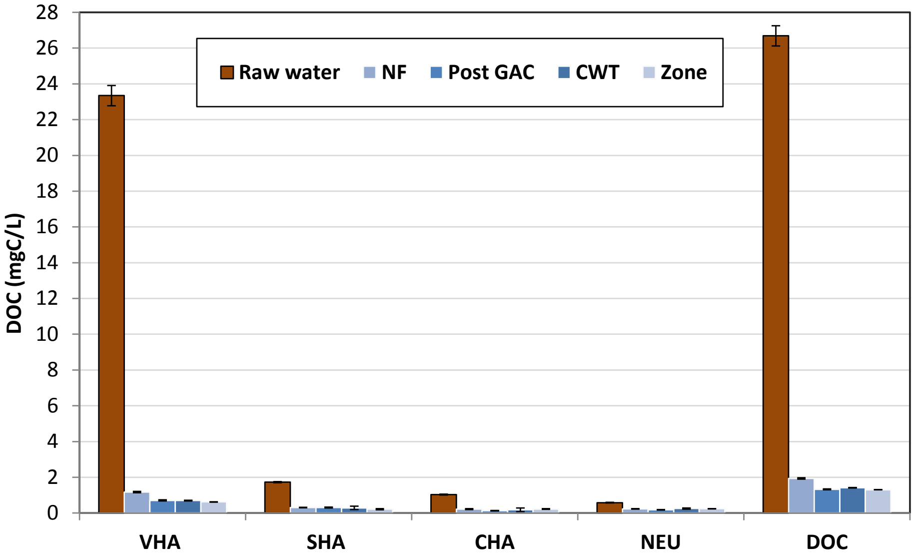


Figure 5-4-2 Water Quality data – BRACADALE WTW (Aug 2015). DOC and NOM-fraction concentrations with standard error bars.

NOM fractions and NOM fraction removal. The removal of DOC during nano filtration (Out NF) was on average 86 %, with minimum and maximum values of 74 and 93 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 89 % (with minimum and maximum values of 82 and 94 %), and 61 % (46-72 %), respectively. These are the best removal efficiencies obtained among the ten utilities sampled in NOMiNOR, thus demonstrating the capabilities of NF systems to remove not only DOC and hydrophobic NOM fractions, but also hydrophilic NOM fractions.

After the clean water tank, the total DOC removal efficiencies increased to 89 % on average (77-93 %), thus illustrating the additional (3 %) NOM removal obtained from the GAC filter and the limestone contactor.

The ATP present in raw water was removed effectively during NF. The ATP increased however somewhat during GAC filtration, likely due to detachment of microorganisms and/or metal deposits with adsorbed substances including microorganisms from the GAC filter bed. In the clean water samples, the ATP values were close to zero again due to the effects of chlorination. In the distribution system, the ATP levels were controlled at zero level due to the residual chlorine.

Also the BDOC concentrations were significantly reduced during NF and GAC filtration. In the clean water samples, the BDOC levels increased due to the oxidizing effects of chlorine on the remaining NOM (i.e. transfer of hydrophobic to hydrophilic and more biodegradable NOM fractions). A marginal decrease in BDOC was measured in the distribution system sample, indicating a minor microbial consumption and/or adsorption of BDOC to deposits in the distribution system. However, the residual chlorine present in the distribution system was capable of completely controlling the microbial activity (ATP) at zero concentration, at least at the sampling points studied here.

Elements and residual metals. Data from the elemental analyses are presented in Figure 5-4-3. NF is apparently capable of reducing residual Al, Fe, S and Mn significantly. The concentration levels of Na and Cl differ a lot among the sampling rounds, likely due to varying sea water influence.

The Ca concentration increased during the limestone contactor. The resulting Ca concentration levels were however low (< 5 mg/L) relative to the guidance levels used for corrosion control in e.g. Norway (15-25 mg Ca/L).

The results showed that the P concentration increased up to rather extreme levels (> 1000 µg/L) during GAC filtration in the November 2014 sampling round. This was probably due phosphorous leakage from a rather poor-quality activated carbon used at that time. In the February 2015 sampling round, the P-concentration was back to normal levels (< 10 µg/L).

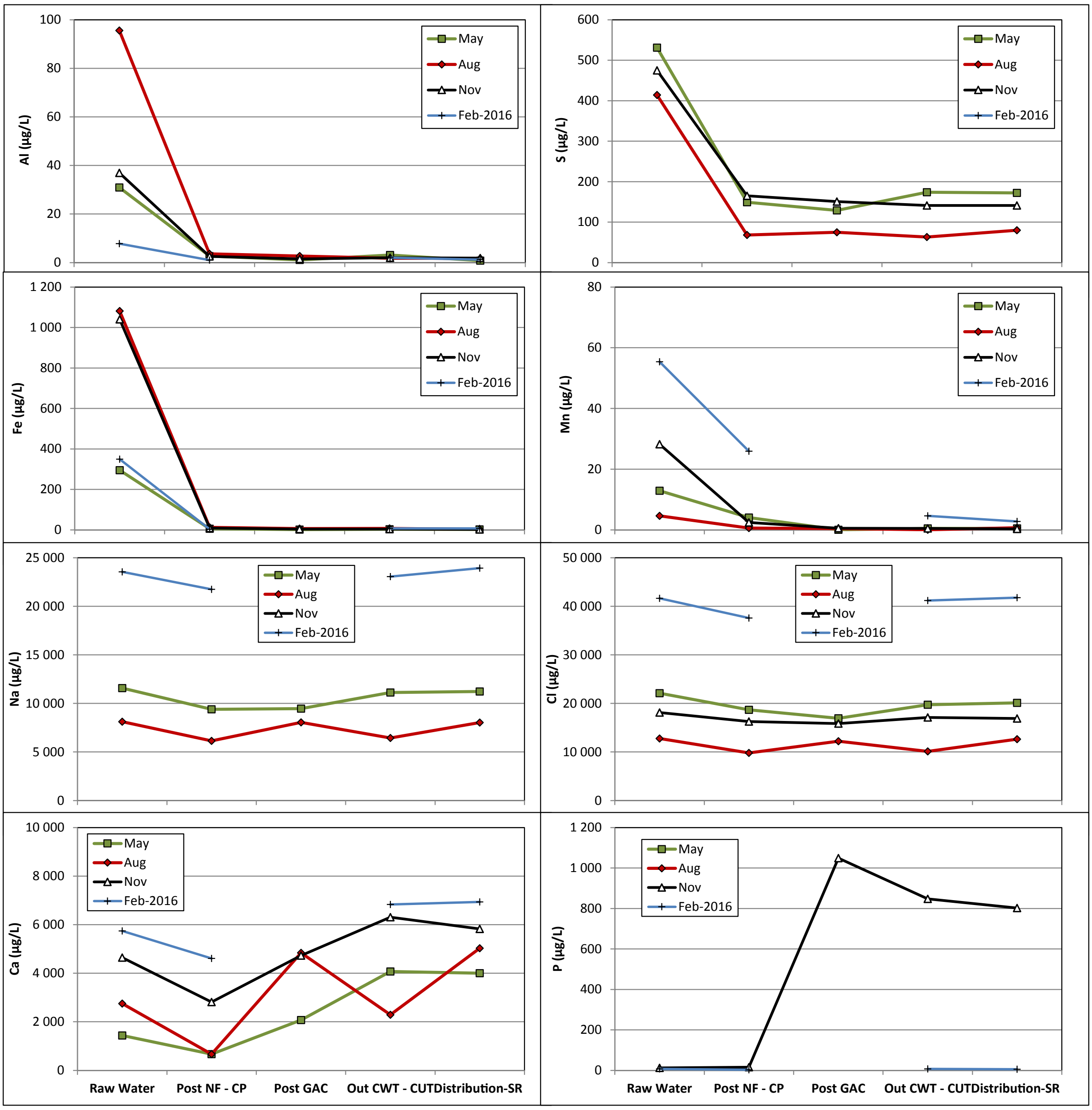


Figure 5-4-3 Water Quality data – BRACADALE WTW. Al, S, Fe, Mn, Na, Cl, Ca and P concentration profiles during treatment and distribution.

For BRA WTW, the major findings are summarized below.

- Large variation in raw water quality (2.7-26.7 mg DOC/L; 10-100 µg Al/L; 300-1100 µg Fe/L; 5-55 µg Mn/L)
- High SUVA (4.6-5.0), and VHA+SHA (77-94 % of DOC) values indicate good treatability by coagulation. However, NF and GAC is used here
- Large fluctuations in Na and Cl content – due to varying sea salt influence
- Metals effectively removed by NF (Al, Fe, Mn – except Feb 2016)
- Additional NOM removal during GAC filtration, as a result of biological activity and/or adsorption to Me-hydroxide deposits
- Very high P content after GAC in November 2015. Phosphorus may affect regrowth and corrosion processes, and the P increase is likely due to the use of poor quality GAC material
- Significant fluctuations in Ca content in clean water – despite the use of limestone contactors. This may be due to operational shortcomings (e.g. lack of limestone mass, short contact times, etc)
- Increase in hydrophilic NOM and BDOC from chlorination
- However, no ATP increase from CWT to DS network samples – regrowth likely controlled by the high residual chlorine concentration

5.5. Jordalsvatnet (JOR) WTW – Norway

The treatment process at Jordalsvatnet WTW includes enhanced coagulation (Fe chloride sulphate), contact filtration in 3-M filters (Filtralite-sand-crushed limestone, CaCO3), and UV disinfection as the final step. The flowsheet for the Jordalsvatnet treatment process along with the five sampling spots (red arrows) applied within the NOMiNOR project is shown in Figure 5-5-1.

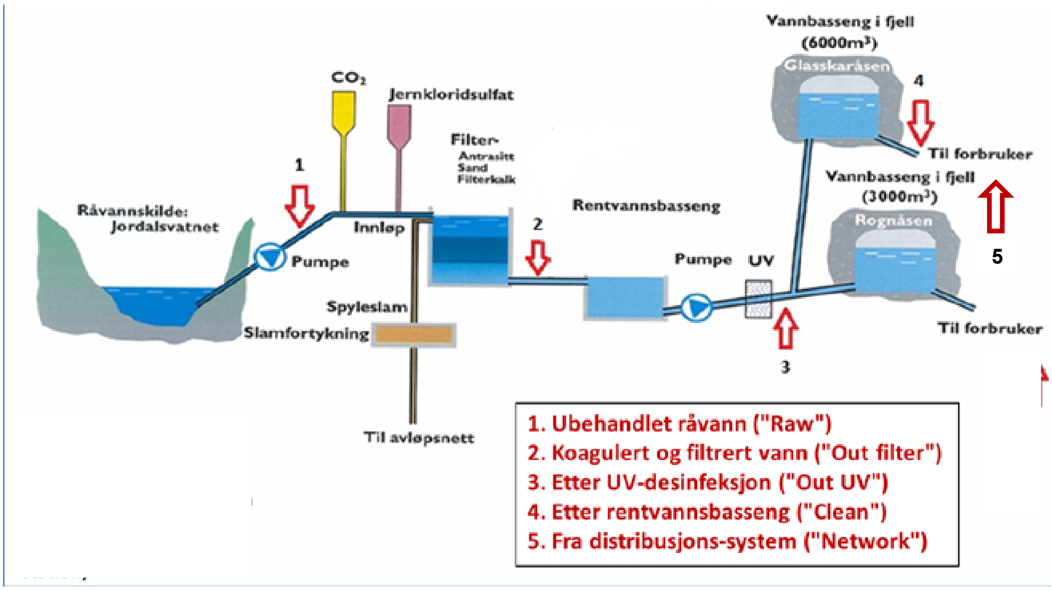


Figure 5-5-1 Treatment process flowchart and water sampling points at JORDALSVATNET WTW.

Coagulation. During the four water sampling rounds at Jordalsvatnet WTW, the iron chloride sulphate (PIX318) coagulant dose and the coagulation pH levels varied within the ranges of 3.4-3.5 mg Fe/L and pH 4.0-4.4, respectively. The DOC-specific dose varied in the range of 1.35-1.52 mg Fe/mg DOC, i.e. 24-27 µmol Fe/mg DOC. The amount of DOC removed was in the range of 27-32 mg DOC per mmol of Fe added. With constant NOM characteristics during the sampling period, a close to stoichiometric (constant) relationship is expected to exist between NOM content and coagulant dose requirement, i.e. a 1:1 relationship. At Jordalsvatnet WTW the ratio between the maximum and minimum DOC-specific coagulant dosages was 1.1. This indicates that the coagulation process is well optimized and that the process control is adequate, i.e. coagulation conditions that are well adapted to the prevailing raw water quality. The filtration rates applied during the sampling period was 2.2-4.6 m/h, which is regarded a moderate hydraulic filter loading that should not negatively affect the filter effluent quality.

A comparative study (benchmark) of the coagulation conditions and treatment performance among the utilities is presented in Chapter 6.

Water quality. A summary of the raw and clean water qualities from the four NOMiNOR sampling rounds is given in Table 5-5-1.

The raw water quality was stable over the sampling period, with colour and UV-absorbance levels within the ranges of 20-22 mg Pt/L and 11-12 m^{-1}, respectively. Turbidity was between 0.4 and 0.5 NTU, and TOC between 2.5 and 2.8 mg/L. Most of the organic matter was dissolved, with DOC levels in the range of 2.3-2.6 mg/L during the four sampling rounds, i.e. 93 % of TOC on average. DOC in raw water was dominated by the hydrophobic NOM fractions (78 % of the total DOC, i.e. 69 % VHA and 9 % SHA). In sum, the hydrophilic fractions constituted 21 % of total DOC, with CHA and NEU comprising 6 % and 15 %, respectively.

Raw water BDOC was on average 2 % of the total DOC, with minimum and maximum values of 0.8 and 4.4 %, respectively. The SUVA value was 4.6, indicating good treatability by coagulation.

The clean water quality was good, with low levels of colour (1 and 3 mg Pt/L as min and max), UV-absorbance (0.9-1.4 m^{-1}), turbidity (0.1 NTU), DOC (0.6-0.7 mg/L), and BDOC (0.03-0.06 mg/L).

Table 5-5-1 Water Quality data – Jordalsvatnet WTW. Average±StDev, Minimum-Maximum values (Sampling dates: Mar 24; Aug 26; Oct 27, 2014; Feb 23, 2015). Sampling spots: Out 3-M Filt: After coagulation and 3-M anthracite/Filtralite/sand/alkaline filtration; Out UV: After UV-disinfection (40 mJ/cm^2); Out CWT: After Clean Water Tank "Glasskaråsen basin"; DS: From the Distribution System (Klauvaneset pumping station).

JOR	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	21±1 20-22	11.2±0.5 10.8-11.9	0.4±0.1 0.4-0.5	2.4±0.1 2.3-2.6	69±4 64-73	9±5 4-14	6±5 1-11	15±4 9-19	4.6±0.4 4.3-5.2	0.05±0.04 0.02-0.11	58±32 31-101
Out 3-M Filt	2±1 1-3	1.4±0.2 1.0-1.6	0.1±0.0 0.1-0.1	0.6±0.1 0.5-0.6	31±19 6-48	19±16 1-39	9±7 3-18	40±5 34-46	2.5±0.4 2.0-2.9	0.03±0.03 0.00-0.07	2±1 1-3
Out UV	1±0 1-2	1.3±0.2 1.0-1.5	0.1±0.0 0.1-0.1	0.6±0.0 0.6-0.6	37±9 29-48	16±10 2-26	1±6 0-6	46±4 43-51	2.1±0.4 1.6-2.5	0.03±0.02 0.00-0.05	1±1 0-1
Out CWT	2±1 1-3	1.2±0.2 0.9-1.4	0.1±0.0 0.1-0.1	0.6±0.1 0.6-0.7	34±8 25-42	21±8 11-26	4±3 1-8	41±16 32-59	2.0±0.4 1.7-2.4	0.04±0.02 0.03-0.06	2±2 0-4
DS	2±0 1-2	1.3±0.2 1.0-1.5	0.1±0.0 0.1-0.1	0.6±0.0 0.5-0.6	34±5 31-41	16±12 1-29	8±7 0-16	42±14 30-60	2.3±0.3 1.8-2.5	0.04±0.04 0.01-0.09	3±1 1-3

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are given in Table 5-5-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

In general, the analytical errors are low, with the highest absolute values found in raw water during the August 2014 sampling round. This "worst case" situation with respect to analytical error is illustrated in Figure 5-5-2.

Table 5-5-2 Analytical Error Data – JORDALSVATNET WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
24.03.2014	**Raw**	0,02	0,03	0,03	0,05	0,05	0,01	0,003
	Out 3M-F	0,03	0,07	0,08	0,04	0,02	0,01	0,001
	Out UV	0,04	0,06	0,05	0,04	0,02	0,01	0,000
	Out CWT	No sample						
	DS	0,03	0,03	0,01	0,04	0,01	0,01	0,000
26.08.2014	**Raw**	0,09	0,10	0,06	0,06	0,03	0,03	0,005
	Out 3M-F	0,02	0,03	0,03	0,04	0,03	0,01	0,000
	Out UV	0,02	0,02	0,02	0,03	0,02	0,01	0,000
	Out CWT	0,06	0,08	0,01	0,04	0,02	0,01	0,001
	DS	0,01	0,01	0,01	0,03	0,02	0,01	0,000
27.10.2014	**Raw**	0,06	0,06	0,03	0,03	0,02	0,02	0,002
	Out 3M-F	0,02	0,02	0,02	0,03	0,02	0,01	0,001
	Out UV	0,01	0,05	0,07	0,07	0,02	0,01	0,001
	Out CWT	0,02	0,03	0,01	0,01	0,03	0,02	0,000
	DS	0,01	0,01	0,02	0,02	0,03	0,01	0,001
23.02.2015	**Raw**	0,08	0,08	0,04	0,04	0,01	0,03	0,010
	Out 3M-F	0,04	0,03	0,03	0,03	0,01	0,03	0,000
	Out UV	0,01	0,04	0,03	0,02	0,01	0,01	0,001
	Out CWT	0,02	0,03	0,01	0,01	0,01	0,01	0,000
	DS	0,02	0,02	0,03	0,02	0,01	0,00	0,001
AVG		***0,03***	***0,04***	***0,03***	***0,03***	***0,02***	***0,01***	***0,001***
MIN		***0,01***	***0,01***	***0,01***	***0,01***	***0,01***	***0,00***	***0,000***
MAX		***0,09***	***0,10***	***0,08***	***0,07***	***0,05***	***0,03***	***0,010***
AVG-Raw		***0,06***	***0,07***	***0,04***	***0,05***	***0,03***	***0,02***	***0,005***
AVG-3M-F		***0,03***	***0,04***	***0,04***	***0,04***	***0,02***	***0,02***	***0,001***
AVG-UV		***0,02***	***0,04***	***0,04***	***0,04***	***0,02***	***0,01***	***0,001***
AVG CWT		***0,03***	***0,05***	***0,01***	***0,02***	***0,02***	***0,01***	***0,000***
AVG DS		***0,02***	***0,02***	***0,02***	***0,03***	***0,02***	***0,01***	***0,001***

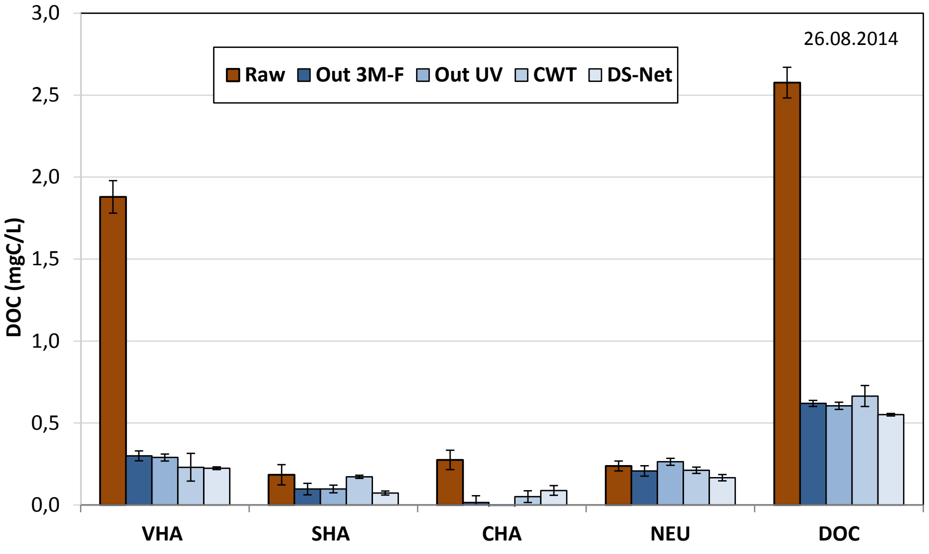


Figure 5-5-2 Water Quality data – JORDALSVATNET WTW (August 2014). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

NOM fractions and NOM fraction removal. The removal of DOC during coagulation (out 3-M filter) was on average 76 %, with minimum and maximum values of 74 and 79 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 85 % (with minimum and maximum values of 81 and 86 %), and 45 % (19-60 %), respectively.

After the clean water tank, the total DOC removal efficiencies were 75 % on average (74-77 %), thus illustrating the inability of the UV disinfection process (40 mJ/cm^2) to affect NOM and NOM fraction removals. No significant change in BDOC could be observed as a result of UV disinfection at the dose levels used here (40 mJ/cm2).

The results in Table 5-5-1 showed some microbial activity (ATP) in the raw water. ATP was effectively removed during coagulation and filtration, with ATP levels close to zero in all samples. The ATP values remained close to zero after the UV disinfection process. Minor increases of ATP were detected in samples from the clean water tank and the distribution system, but the levels were low (< 4 nmol ATP/L). The BDOC values were low in all water samples (<0.1 mg/L), thus indicating a biologically stable water. This may explain the low ATP levels found in distributed water, despite low doses of chlorine (0.5-0.6 mg/L) and zero chlorine residuals in the distribution system.

Elements and residual metals. Elemental data, focussing on metal coagulant residuals (Fe) and specific elements that showed significant changes in concentration during treatment and distribution are presented in Figure 5-5-3.

When using ferric chloride sulphate, the increases in Cl and S concentrations from raw water to coagulated water samples reflects the applied coagulant dosage, and thus the concentration increase in Cl and/or S can be used to back-calculate/control the actual coagulant dosage. The measured increases in Cl and S-concentrations from raw to treated water (Figure 5-5-3), and thereby also the coagulant doses, were relatively stable throughout the four sampling rounds, thus confirming the relatively constant coagulant dose levels reported from this plant. The concentration of residual Fe was low in the coagulated and clarified water in all four sampling rounds (< 40 µFe/L). The highest residual Fe-concentrations were found in the March 2014 sampling round, and this may be taken as an indication that the coagulant dose level was close to the minimum level at this time.

After the clean water tank, however, the residual Fe as well as the Al and Mn concentration levels were very low in all sampling rounds (with maximum levels of 11, 18 and 0.9 µg/L, respectively).

It appears from Figures 5-5-3 and 5-5-4 that the elements Mn, Al, and Zn were effectively removed during coagulation-filtration. For Cu, there was a significant increase from the clean water to the distribution system sample. Pb was also removed during coagulation and filtration. There was however an increase in Pb concentration from the filter and UV effluent samples to the clean water sample in the October 2014 sampling round. The reason for this is unclear, but it could be related to resuspension of sediments from the rock basins. The concentration of U also showed a decrease during coagulation and filtration, and then a slight increase in the clean water tank and distribution system samples. For Al, a significant removal was detected during coagulation and filtration, but the concentration increased again after the clean water tank. This probably due to the use of Al-containing mortar linings and/or re-suspension/detachment of Al-containing deposits from the pipelines.

The applied coagulant and/or filter materials used here is the source for the significant increase in Sr measured after coagulation and filtration.

In chlorine-free distribution systems, like the ones in Bergen, the concentration of the potentially limiting nutrient P is also relevant for biostability and regrowth issues. It appears from the data that coagulation-filtration effectively removed total phosphorus to levels of 2-4 µg/L or less. There were no indications of any P consumption during the distribution system. On the contrary, the P-levels in fact increased somewhat from the clean water sample to the distribution system sample. From Table 5-5-1, it appears that the BDOC and ATP levels remained constant as well, thus indicating a biologically stable clean water.

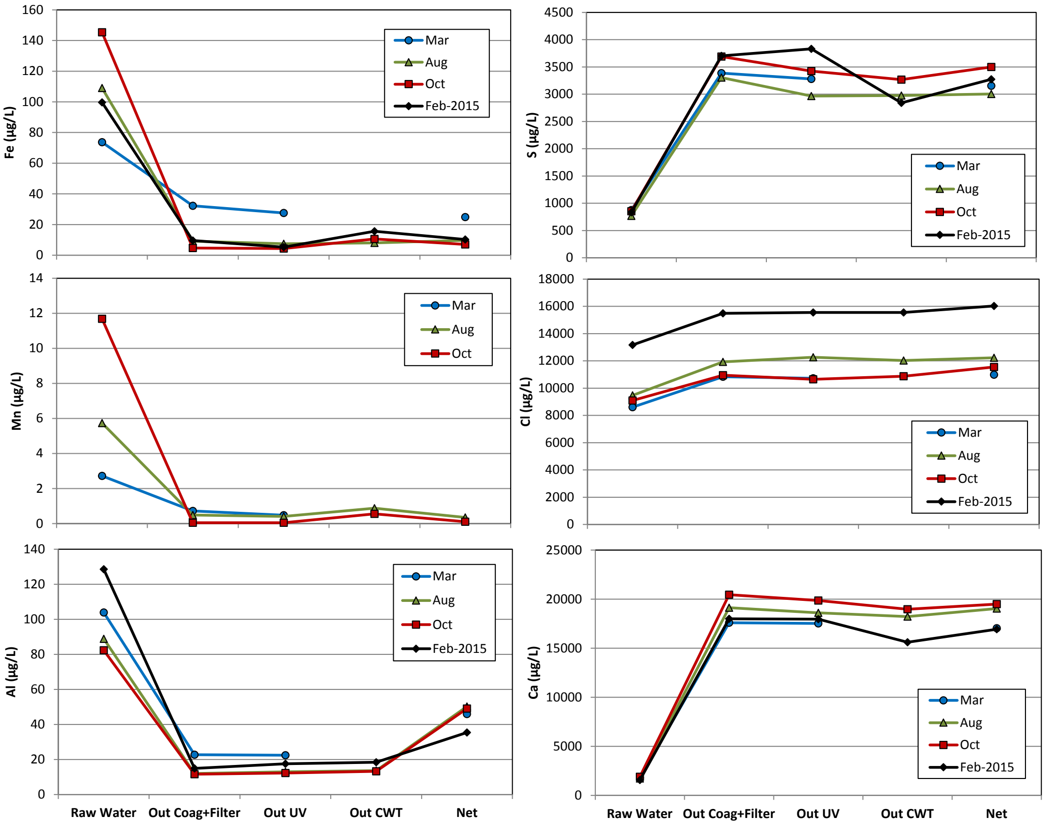


Figure 5-5-3 Water Quality data – JORDALSVATNET WTW. Fe, S, Mn, Cl, Al and Ca concentration profiles during treatment and distribution.

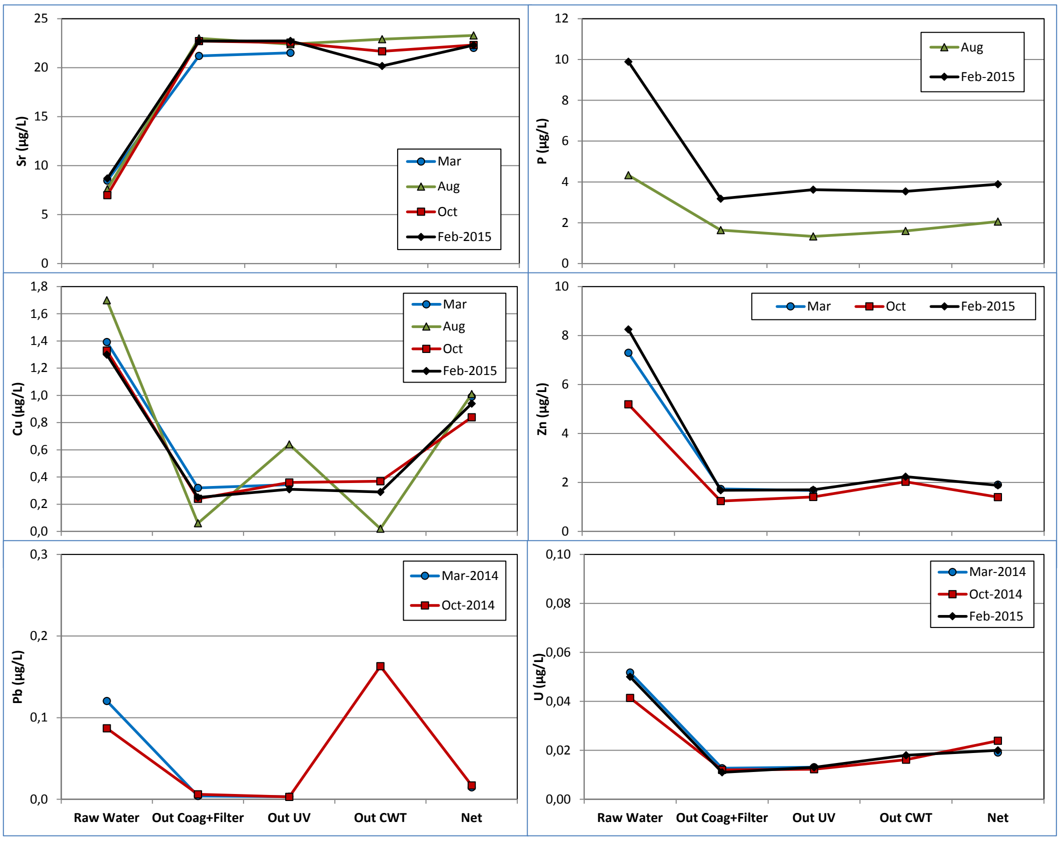


Figure 5-5-4 Water Quality data – Jordalsvatnet. Sr, P, Cu, Zn, Pb and U concentration profiles during treatment and distribution.

For JOR WTW, the major findings are summarized below.

- Stable and good raw water quality during the NOMiNOR sampling period (2.3-2.6 mg DOC/L; 0.4-0.5 NTU; 70-150 µg Fe/L; 3-12 µg Mn/L; 80-130 µg Al/L)
- High SUVA (4.3-5.2) and VHA+SHA (75-82 % of DOC) indicates good treatability by coagulation
- Only minor variation in Fe-chloride sulphate coagulant dose level (3.4-3.5 mg Fe/L) and in DOC-specific doses: 24-28 µmol Fe/mg DOC (Numbers supported by the increase in S-concentration from raw water to coagulated water)
- Coagulation pH: 4.0-4.4
- Somewhat higher residual-Fe after coagulation/filtration in March 2014 (still < 40 µg/L)
- Moderate contact filtration rates: 2.2-4.6 m/hr
- Low BDOC and ATP levels in CWT and DS samples
- Increase in Cu concentration from CWT to DS samples
- The numbers reflect the fact that JOR WTW has been subject to long-term full-scale optimization efforts

5.6. IVAR Pilot WTW - Norway

The water treatment process at the IVAR pilot plant includes ozonation, alkaline filtration through crushed limestone ($CaCO_3$), biofiltration, and UV-disinfection. Figure 5-6-1 shows the flow sheet for the pilot treatment process applied at the IVAR pilot plant, with the water sampling spots applied within the NOMiNOR project shown as numbers.

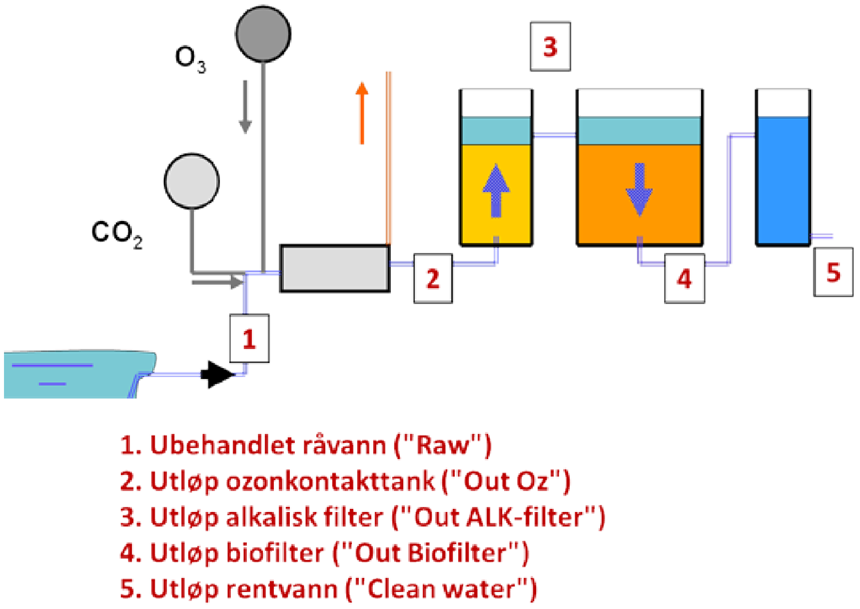


Figure 5-6-1 Treatment process flowchart and water sampling points at IVAR Pilot WTW.

Water quality. A summary of the water quality data from the seasonal sampling rounds at the IVAR pilot ozone-biofiltration pilot facility is given in Table 5-6-1.

The raw water quality was very good and stable over the sampling period, with colour and UV-absorbance within the ranges of 6-7 mg Pt/L and 4.3-4.6 m-1, respectively. The turbidity level was 0.5 NTU, and the TOC levels varied between 1.2 (min) and 1.5 mg/L (max). Most of the organic matter was dissolved, with DOC levels in the range of 1.1-1.3 mg/L during the sampling rounds, i.e. 91 % of TOC on average.

The clean water quality was good, with low levels of colour (3-4 mg Pt/L as min and max), UV-absorbance (1.6-2.1 m^{-1}*), turbidity (0.2-0.3 NTU), and DOC (1.0 mg/L). The BDOC and ATP levels in clean water were 0.14-0.16 mg/L and 5-23 pmol/L, respectively, thus somewhat higher than what was found in the clean water at utilities applying coagulation.*

Table 5-6-1 Water Quality data – IVAR Pilot WTW. Average±StDev, minimum-maximum values (Sampling dates: Mar 31; Oct 13, 2014; (March 23, 2015 not included in statistics due to operation problems)). Sampling spots: Out Oz: After ozone contact tank; Out ALK-F: After ozone contact and up-flow alkaline filtration; Out BF: Out Biofilter (BF); Out CWT: After Clean Water Tank.

IVAR	*Colour (mg Pt/L)*	*UV-A (m-1)*	*Turb (NTU)*	*DOC (mg/L)*	*VHA (%)*	*SHA (%)*	*CHA (%)*	*NEU (%)*	*SUVA (L/m mg)*	*BDOC (mg/L)*	*ATP (pmol/L)*
Raw Water	*7±1* *6-7*	*4.5±0.2* *4.3-4.6*	*0.5±0.0* *0.5-0.5*	*1.2±0.2* *1.1-1.3*	*53±1* *52-53*	*21±3* *19-24*	*9±5* *5-12*	*18±1* *17-19*	*3.6±0.3* *3.5-3.8*	*0.08±0.00* *0.08-0.09*	*66±22* *50-81*
Out Oz	*2±0* *2-2*	*2.2±0.3* *2.0-2.4*	*0.3±0.1* *0.3-0.3*	*1.3±0.2* *1.2-1.5*	*24±7* *19-30*	*23±3* *21-25*	*24±10* *17-31*	*29±6* *25-33*	*1.7±0.3* *1.5-1.9*	*0.32±0.02* *0.31-0.34*	*7±10* *0-14*
Out ALK-F	*3±1* *2-3*	*2.2±0.4* *2.0-2.5*	*3.1±4.0* *0.3-6.0*	*1.3±0.0* *1.3-1.3*	*31±4* *28-34*	*24±0* *24-24*	*19±3* *17-22*	*26±1* *25-27*	*1.7±0.3* *1.5-2.0*	*0.23±0.05* *0.19-0.27*	*103±117* *20-186*
Out	*3±0* *3-3*	*1.9±0.4* *43162*	*0.3±0.0* *1.7-2.2*	*1.0±0.0* *0.3-0.3*	*26±2* *24-27*	*30±4* *27-33*	*9±3* *7-11*	*35±1* *34-36*	*1.9±0.5* *34-36*	*0.16±0.01* *1.6-2.3*	*23±14* *13-33*
Out CWT	*3±1* *3-4*	*1.9±0.3* *1.6-2.1*	*0.3±0.1* *0.2-0.3*	*1.0±0.0* *1.0-1.0*	*30±1* *29-30*	*29±3* *27-31*	*15±2* *13-17*	*27±4* *24-30*	*1.8±0.3* *1.6-2.0*	*0.15±0.01* *0.14-0.16*	*14±13* *5-23*
DS	*No Sample*										

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are presented in Table 5-6-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

Table 5-6-2 Analytical Error Data – IVAR PILOT WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	**Sample**	**StDev**						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
	Raw	0,08	0,09	0,03	0,05	0,04	0,01	0,001
31.03.2014	**Out Oz**	0,02	0,05	0,05	0,03	0,02	0,00	0,002
	Out ALK-F	0,05	0,06	0,05	0,04	0,03	0,01	0,007
	Out BF	0,03	0,04	0,04	0,03	0,01	0,01	0,000
	CWT	0,03	0,03	0,05	0,02	0,03	0,00	0,000
	Raw	0,06	0,07	0,05	0,03	0,02	0,02	0,004
13.10.2014	**Out Oz**	0,04	0,06	0,05	0,02	0,01	0,01	0,001
	Out ALK-F	0,06	0,08	0,07	0,05	0,05	0,01	0,001
	Out BF	0,02	0,02	0,02	0,01	0,05	0,02	0,000
	CWT	0,02	0,02	0,01	0,02	0,03	0,02	0,006
	Raw	0,02	0,03	0,02	0,02	0,01	0,00	0,005
23.03.2015	**Out Oz**	0,01	0,03	0,03	0,05	0,05	0,02	0,006
	Out ALK-F	0,01	0,02	0,03	0,02	0,00	0,02	0,003
	Out BF	0,03	0,03	0,02	0,01	0,01	0,00	0,000
	CWT	0,04	0,04	0,02	0,01	0,04	0,02	0,001
AVG		***0,03***	***0,04***	***0,04***	***0,03***	***0,03***	***0,01***	***0,003***
MIN		***0,01***	***0,02***	***0,01***	***0,01***	***0,00***	***0,00***	***0,000***
MAX		***0,08***	***0,09***	***0,07***	***0,05***	***0,05***	***0,02***	***0,006***
AVG-Raw		***0,05***	***0,06***	***0,03***	***0,03***	***0,02***	***0,01***	***0,003***
AVG-Oz-Cont		***0,02***	***0,05***	***0,04***	***0,03***	***0,03***	***0,01***	***0,003***
AVG-ALK-F		***0,04***	***0,05***	***0,05***	***0,04***	***0,03***	***0,01***	***0,004***
AVG BF		***0,03***	***0,03***	***0,03***	***0,02***	***0,02***	***0,01***	***0,000***
AVG CWT		***0,03***	***0,03***	***0,03***	***0,02***	***0,03***	***0,01***	***0,002***

In general, the analytical errors are low, with the highest absolute values found in raw water during the March 2014 sampling round. This "worst case" situation with respect to analytical error is illustrated in Figure 5-6-2.

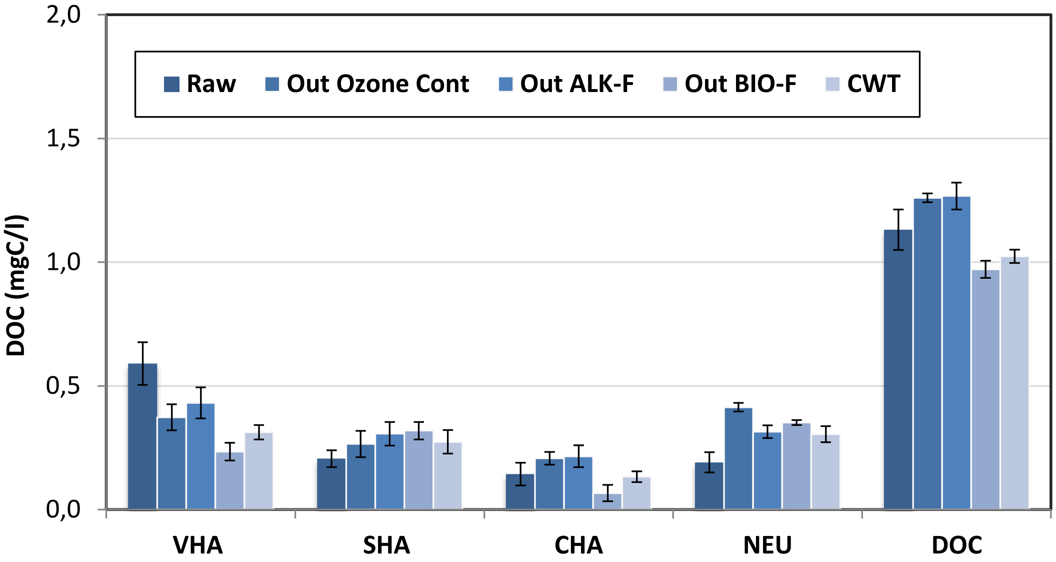


Figure 5-6-2 Water Quality data – IVAR PILOT WTW (March 2014). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

NOM fractions and NOM fraction removal. DOC in raw water at IVAR WTW is dominated by the hydrophobic NOM fractions (on average 74 % (71-77 %) of the total DOC, i.e. 53 % VHA and 21 % SHA). However, this is the lowest fraction of hydrophobic NOM-fractions found among the NOMiNOR utilities. Besides IVAR (74 %), only raw water from Jordalsvatnet WTW (78 %) had an average hydrophobic NOM-fraction concentration of less than 80 % of the total DOC.

The hydrophilic fractions constituted 27 % of total DOC, with 9 % CHA and 18 % NEU. This was the highest fraction of hydrophilic NOM and of the NEU fraction concentrations found among the ten NOMiNOR utilities. This was also reflected in a relatively low SUVA value (3.6 L/mg m), with lower SUVAs only detected at Görväln (2.8) and Pitkäkoski (3.2).

Raw water BDOC was on average 6.9 % of the total DOC, with minimum and maximum values of 6.4 and 7.3 %, respectively. This reflects the relatively high fraction of more biodegradable hydrophilic NOM (CHA and NEU) at this utility.

The removal of NOM (tot-DOC) during ozonation, alkaline prefiltration and biofiltration was on average 16 %, with minimum and maximum values of 9 and 22 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 33 % and -33 % (i.e. a concentration increase during treatment), respectively. As expected, the NOM and NOM-fraction removal efficiencies obtained by the ozonation-biofiltration (OBF) process were significantly lower than those obtained by coagulation or nanofiltration. On the other hand, the benefits of the OBF-process include process simplicity, less (non-existing) production of metal containing sludge, less sludge/less demanding sludge processing, less need for strict control of coagulant dose and coagulation-pH, less need for filter backwash and less consumption of backwash water, an additional ozone disinfection barrier, etc. It is however clear that the OBF-process should not be applied to source waters with too high NOM content. A high NOM content will demand a high ozone dose as well, thus inducing significant production of BDOC in the form of hydrophilic NOM fractions that will add to the organic load to the subsequent biofilter. If not removed in subsequent and adequately designed biofiltration or other relevant processes, the ozone-induced biodegradable NOM (BDOC) may lead to significant regrowth during distribution. According to Norwegian recommendations, single stage OBF-processes for NOM removal should be applied with care on raw waters high in NOM, e.g. with colour levels exceeding some 25-30 mg Pt/L (Eikebrokk and Gjerstad, 2013).

The effects of ozone on NOM fraction distribution and BDOC are well demonstrated by the data in Table 5-6-1, with significant ozone-induced transformation of VHA into more biodegradable CHA and NEU fraction concentrations, thereby also increasing BDOC concentrations significantly. The BDOC levels were reduced during the subsequent alkaline prefiltration and biofiltration processes.

The ATP data shows that the microbial activity present in raw water was significantly reduced during the ozonation process. The increased ATP level in the alkaline prefilter effluent reflects the existence of microbial biological activity within the prefilter bed, and/or the detachment of deposits containing adsorbed microorganisms. During the subsequent biofiltration process, the BDOC and ATP levels were reduced to levels of 0.14-0.16 mg/L and 5-23 pmol/L, respectively.

Elements and residual metals. Data of elements showing significant changes in concentration during treatment and distribution are presented in Figure 5-6-3.

There are at least three possible explanations to the observed removal of NOM (DOC and BDOC) and metals during ozonation and biofiltration:

1) NOM is adsorbed to vacant adsorption sites in the biofilter (GAC) pores (the NOM adsorbing capacity is normally exhausted after a few weeks)
2) NOM is biologically degraded in the biofilter
3) NOM is adsorbed to metal deposits in the alkaline and biofilter beds (mostly Fe).

The ozonation process may contribute to breaking up existing NOM-Me complexes, and thereby simplify precipitation and formation of adsorbing metal deposits in the filter bed.

Given the significant removal of Fe (Figure 5-6-3) along with the reductions in DOC and BDOC that were observed during biofiltration, it is likely that mechanism No. 3 plays an important role here. It is well known that Fe- and Al-hydroxides are effective NOM adsorbents, and that coagulation of NOM can be modelled as an adsorption process with excellent fit (Kastl 2004; Edwards 1997).

The results presented in Figure 5-6-3 illustrate the dynamics of metal deposition/detachment within the alkaline filter bed. Some metals are precipitated and deposited over time within the alkaline filter bed. Metal precipitates, especially iron hydroxides, may effectively adsorb NOM-fractions, BDOC and microorganisms (ATP). Normally alkaline prefilters and biofilters applied in OBF processes are backwashed with intervals of 1-2 weeks or more. If filter backwash and/or backwash frequency is not optimized however, the metal deposits including adsorbed substances (NOM, particles, microorganisms/ATP, etc) may detach from the filter bed and deteriorate filter effluent quality. It is likely that this occurred during the March 2014 sampling round where the data show distinct peaks in Fe, Mn, Zn, and Cu as well as ATP concentrations from the alkaline filter effluent sample. Also lead (Pb) showed a similar peak during this sampling round.

Figure 5-6-3 also illustrates a situation with no increase in Ca-concentration from the alkaline filter, i.e. in the November 2014 sampling round. This was due to a lack of alkaline filter material at that time. This fact along with the corresponding reduction in pH level is likely the cause for the increased Zn and Cu concentrations in the clean water tank sample in November 2014.

For IVAR Pilot WTW, the major findings are summarized below.

- Stable and good raw water quality (1.1-1.3 mg DOC/L; 14-25 µg Fe/L; 50-60 µg Al/L; 5-6 µg Mn/L)
- The high SUVA (4.3-4.6) indicates good treatability by coagulation. However, ozonation and biofiltration (OBF) with alkaline prefiltration used here
- IVAR's raw water has the lowest hydrophobic NOM (VHA+SHA) content (71-77 % of DOC) and the 2nd highest SHA fraction concentration (19-24 % of DOC) among the NOMiNOR raw waters. Contrary to SUVA, this indicate low/moderate treatability by coagulation
- Substantial reductions in colour and UV-abs are achieved during the OBF process, but only a moderate DOC removal (20 %)
- The ozonation process converts hydrophobic and coloured VHA to hydrophilic CHA and NEU fractions, thereby increasing also the BDOC levels
- The hydrophilic NOM fractions and BDOC fractions are then reduced in the subsequent alkaline filter and biofilter steps due to adsorption and biological degradation
- During the March 2014 sampling round however, the ATP levels are substantially increased during alkaline filtration, likely due to detachment of metal hydroxide deposits (Fe, Mn, Zn, Cu) with adsorbed NOM and microorganisms (ATP).

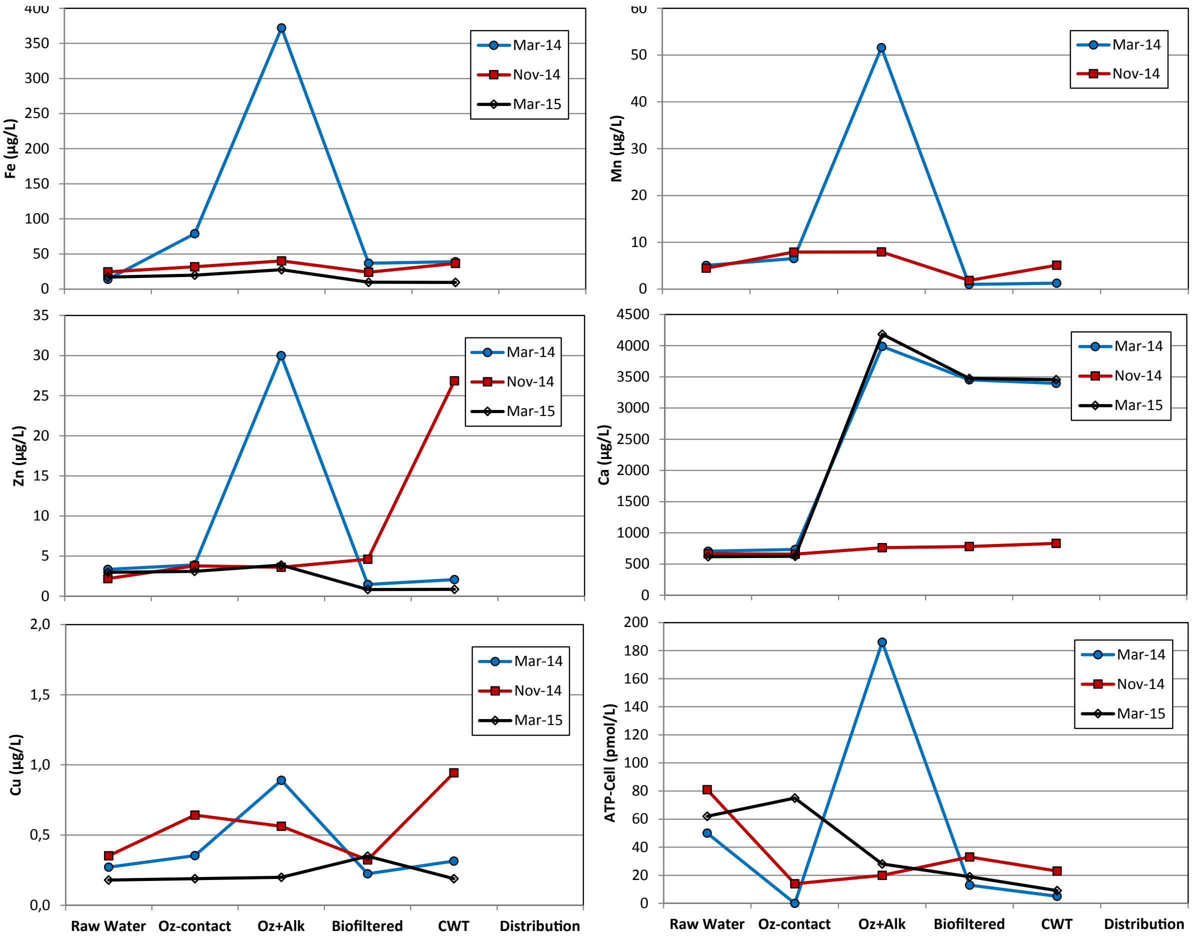


Figure 5-6-3 Water Quality data – IVAR OBF pilot plant. Fe, Mn, Ca, Cu and ATP concentration profiles during treatment and distribution.

5.7. Kärreberg (KÄR) WTW, VIVAB - Sweden

The water treatment process at Kärreberg WTP includes straining, coagulation (Ekofloc), continuous upflow sand filtration (Dynasand), pH-control (soda) prior to artificial ground water infiltration (> 14 days detention time), and final pH control (soda). Spent filter backwash water is treated in lamella settlers, with return of the settled clear water to the plant inlet. The water source is River Ätran. The flowsheet for the treatment process along with the water sampling spots applied at Kärreberg WTP is shown in Figure 5-7-1.

Coagulation. During the four water sampling rounds at Kärreberg WTW, the poly aluminium chloride (Ekofloc91) coagulant dose and the coagulation pH levels varied within the ranges of 3.3-4.6 mg Al/L, and pH 7.0-7.2, respectively. The DOC-specific dose varied in the range of 0.31-0.55 mg Al/mg DOC, i.e. 11-20 µmol Al/mg DOC. The amount of DOC removed was in the range of 30-51 mg DOC per mmol of Al added.

If NOM characteristics and treatability remain constant, a close to stoichiometric (constant) relationship will exist between NOM content and coagulant dose requirement, i.e. a 1:1 relationship. At Kärreberg WTW the ratio between the maximum and minimum DOC-specific coagulant dosages is close to 1.8. The NOM fraction distribution in the raw water was relatively stable, and the variable coagulant dosage (high ratio) thus indicates the existence of a coagulation process optimization potential. It is also indicative of a potential for improved process control, i.e. a better adaptation of coagulation conditions to the prevailing raw water quality. An additional indication of non-optimum coagulation conditions was the elevated residual Al concentrations in the filter effluent (> 1000 µg Al/L)

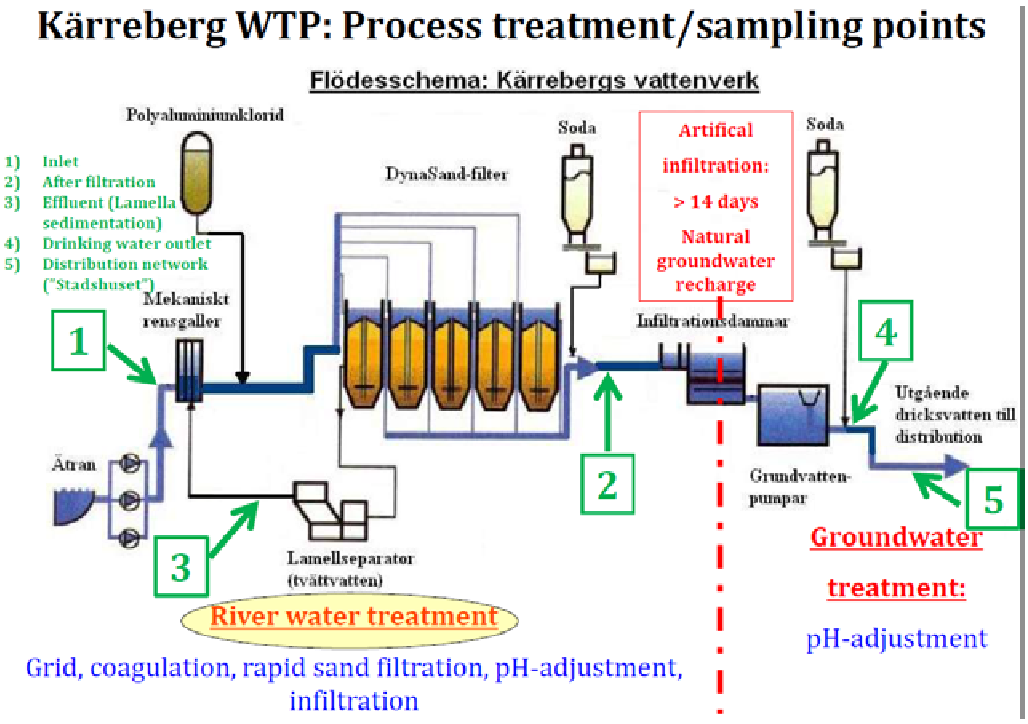


Figure 5-7-1 Treatment process flowchart and water sampling points at KÄRREBERG WTW.

measured in the June 2015 sampling round. The filtration rates applied during the sampling period was 5.8-6.9 m/h, which is regarded a normal hydraulic filter loading for continuous sand filters of this type.

Despite the rather poor coagulation performance, the clean water at Kärreberg WTW is excellent. This is due to the infiltration process that greatly improves water quality and removes additional NOM along with coagulant residuals. There is a risk however, that the pump will lose capacity over time due to increased head loss and reduced permeability from long-term metal deposition and blockage of the pores in the infiltration zone.

A comparative study (benchmark) of the coagulation conditions and coagulation performance among the utilities is presented in Chapter 6.

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR sampling rounds are given in Table 5-7-1. The raw water DOC was dominated by the hydrophobic NOM-fractions (87 % VHA+SHA), and high SUVA levels (4.4), indicating good treatability by coagulation.

The raw water quality showed significant variability, typical for river sources. It contained significant amounts of NOM, and during the four sampling rounds, colour and UV-absorbance varied within the ranges of 64-111 mg Pt/L and 36-53 m^{-1}, respectively, turbidity within 1.5-3.6 NTU, and TOC between levels of 8.5 to 12.4 mg/L. Most of the organic matter was dissolved, with DOC levels of 97 % of TOC on average.

The clean water quality was good, with low levels of colour (min-max: 0-1 mg Pt/L), UV-absorbance (1.0-1.3 m^{-1}), turbidity (0.1 NTU), DOC (0.8-0.9 mg/L), and BDOC (< 0.1 mg/L).

The results showed that significant improvements in water quality were obtained during the infiltration process at this utility. It should be pointed out, however, that a natural ground water flow (approximately one third of the infiltration water flow) dilutes the infiltrated water and thus contributes to the observed improvements in water quality during infiltration.

After coagulation and filtration, the minimum and maximum concentration levels were: Colour 4-18 mg Pt/L, UV-abs 5.5-14 m^{-1}, turbidity 0.2-1.5, DOC 2.5-5.1 mg/L, BDOC 0.04-0.21 mg/L, and residual Al 55-1006 µg/L. These values indicate a potential for optimization in the coagulation process step.

NOM fractions and NOM fraction removal. The raw water DOC at this utility is dominated by the hydrophobic NOM fractions (87 % of the total DOC; 74 % VHA and 13 % SHA). The hydrophilic fraction is 13 % (8 % CHA and 5 % NEU). The relatively low content of the hydrophilic, i.e. the more low-molecular weight and biodegradable NOM fractions, is reflected in a low BDOC, i.e. on average 1.2 % of the total DOC, with a maximum value of 1.8 % in the September sample.

During coagulation and filtration (out Dynasand filter) the DOC removal efficiency was on average 64 %, with minimum and maximum values of 58 and 70 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 67 and 42 %, with minimum and maximum values of 61 and 73 %, and 35 and 49 %), respectively. The poorest removal was obtained for the NEU fraction, with only 13 % removal on average.

As described above, significant improvements in removal efficiency and thereby in water quality were obtained during the ground infiltration process. On average, the total removal efficiencies for colour, UV-absorbance and DOC increased to levels of 99, 97 and 91 %, respectively. For BDOC, hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fractions, the levels were 77, 93 and 74 %, respectively. Even for the NEU fraction, the total removal efficiency increased to a level of 50 %.

Table 5-7-1 Water Quality data – Kärreberg WTW (VIVAB). Average±StDev, minimum-maximum values (Sampling dates: Jun 8; Sep 7; Nov 16, 2015; Feb 29, 2016). Sampling spots: Out Filter: After coagulation, flocculation, lamella sedimentation and single medium sand filtration; Out CWT: After Clean Water Tank (incl. ground infiltration and chlorination); DS: Distribution System sampling point ("Stadshuset").

KÄR	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	86±21 64-111	42.8±8.2 35.6-53.2	2.6±0.9 1.5-3.6	9.7±1.8 8.2-12.1	74±4 68-79	13±2 10-14	8±3 7-12	5±1 4-6	4.4±0.1 4.2-4.5	0.10±0.07 0.00-0.15	436±142 245-568
Out Filter	9±6 4-18	8.5±3.7 5.5-14.0	0.6±0.6 0.2-1.5	3.5±1.1 2.5-5.1	58±7 53-67	21±4 16-26	9±2 7-11	12±4 7-16	2.4±0.3 2.2-2.7	0.14±0.07 0.04-0.21	61±43 27-122
Out CWT	1±0 0-1	1.1±0.1 1.0-1.3	0.1±0.0 0.1-0.1	0.9±0.1 0.8-0.9	43±13 26-56	19±2 17-20	11±9 2-23	27±5 24-35	1.3±0.1 1.2-1.4	0.02±0.02 0.00-0.05	0±0 0-0
DS Stadsh	1±0 0-1	0.9±0.1 0.8-1.1	0.1±0.0 0.1-0.1	0.7±0.0 0.7-0.7	27±6 18-33	24±12 6-31	14±13 5-34	35±5 27-40	1.3±0.1 1.2-1.5	0.03±0.03 0.01-0.07	1±1 0-1

A significant microbial activity (ATP) was measured in the raw water (Table 5-7-1). ATP removal efficiency was 87 % after coagulation and filtration. After infiltration however, the ATP was completely removed (100 %).

For BDOC, the levels in raw water increased somewhat after coagulation and filtration (from 0.10 to 0.14 mg/L on average), mainly due to the BDOC present (0.19 mg/L on average) in the return water from the treatment (lamella settler) of spent filter backwash water. Contrary to the situation for BDOC, the ATP concentration in the return flow (108 pmol/L on average) is significantly lower that the ATP level in the raw water (436 pmol/L).

The biodegradable carbon (BDOC substrate) concentrations at the levels found here (< 0.1 mg/L) are not expected to cause significant regrowth and microbial activity (ATP) in the distribution system – not even in a chlorine-free distribution system like the one at this utility. This expectation is supported by the fact that the close-to-zero levels of ATP and BDOC substrate consumption found in samples from the clean water tank and distribution system.

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are presented in Table 5-7-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

In general, the analytical errors are low, with the highest absolute values found during the February 2016 sampling round. This "worst case" situation with respect to analytical error is illustrated in Figure 5-7-2.

Table 5-7-2 Analytical Error Data – KÄRREBERG WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
08.06.2015	**Raw**	0,16	0,18	0,10	0,06	0,01	0,06	0,067
	Out DynaF	0,08	0,11	0,08	0,04	0,01	0,04	0,003
	Out CWT	0,02	0,02	0,02	0,02	0,02	0,00	0,000
	DS-StadsH	0,00	0,00	0,02	0,02	0,01	0,00	0,000
07.09.2015	**Raw**	0,13	0,13	0,05	0,04	0,01	0,09	0,012
	Out DynaF	0,04	0,05	0,05	0,05	0,05	0,01	0,002
	Out CWT	0,02	0,02	0,00	0,02	0,01	0,01	0,000
	DS-StadsH	0,02	0,02	0,01	0,01	0,02	0,03	0,000
16.11.2105	**Raw**	0,10	0,11	0,04	0,03	0,02	0,17	0,038
	Out DynaF	0,14	0,14	0,04	0,04	0,01	0,04	0,012
	Out CWT	0,01	0,02	0,05	0,02	0,01	0,01	0,000
	DS-StadsH	0,03	0,04	0,08	0,02	0,03	0,01	0,000
29.02.2016	**Raw**	0,18	0,19	0,08	0,05	0,02	0,15	0,008
	Out DynaF	0,19	0,20	0,07	0,02	0,01	0,02	0,004
	Out CWT	0,03	0,03	0,05	0,03	0,01	0,02	0,000
	DS-StadsH	0,03	0,03	0,03	0,02	0,01	0,05	0,000
AVG		***0,07***	***0,08***	***0,05***	***0,03***	***0,02***	***0,04***	***0,009***
MIN		***0,00***	***0,00***	***0,00***	***0,01***	***0,01***	***0,00***	***0,000***
MAX		***0,19***	***0,20***	***0,10***	***0,06***	***0,05***	***0,17***	***0,067***
AVG-Raw		**0,14**	**0,15**	**0,07**	**0,05**	**0,02**	**0,12**	**0,031**
AVG-Dyna-SF		**0,11**	**0,13**	**0,06**	**0,04**	**0,02**	**0,03**	**0,005**
AVG CWT		**0,02**	**0,02**	**0,03**	**0,02**	**0,01**	**0,01**	**0,000**
AVG DS-StadsH		**0,02**	**0,02**	**0,04**	**0,02**	**0,02**	**0,02**	**0,000**

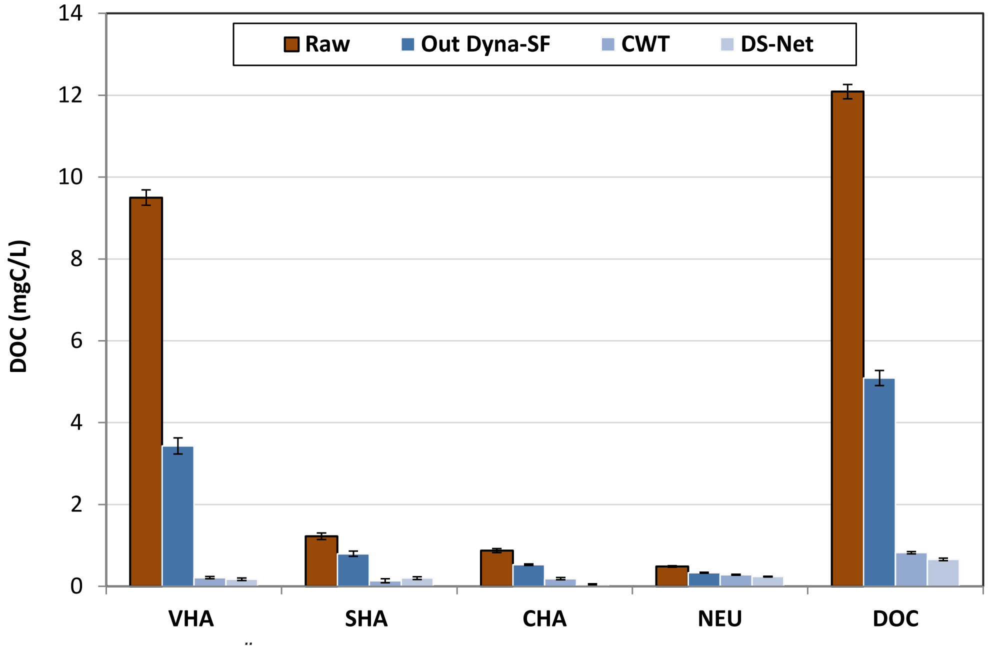


Figure 5-7-2 Water Quality data – KÄRREBERG WTW (Feb 2016). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

Elements and residual metals. Elemental data of selected elements, i.e. metal coagulant residuals (Al) and specific elements with significant changes in concentration during treatment and distribution are depicted in Figure 5-7-3.

When using poly aluminium chloride (Ekofloc), the increase in the chloride concentration from raw water to coagulated water samples reflects the coagulant dosage, and thus the concentration increase in Cl can be used to back-calculate/ control the coagulant dosage from information on the coagulant's Cl-content from the Ekofloc product data sheet.

Figure 5-7-3 shows significant variability in the Cl-concentration increase during coagulation and Dynasand filtration treatment, and thereby also in the Ekofloc dose. This is in line with the variability in coagulant dosage discussed above. The lowest specific coagulant dose was applied during the sampling round in June 2015, in line with the data showing the lowest increase in Cl concentration at that time. The increase in sodium and chloride (as well as sulphur) concentrations from the clean water tank to the distribution system sampling point (i.e. Stadshuset) is likely due to the fact that this sampling point was supplied also with water from another near-by WTW using alum coagulation (S-source) and sodium hypochlorite (Na and Cl-sources).

Very high residual Al concentrations (> 1000 µg/L) were found in coagulated and filtered water in the June 2015 sampling round (Figure 5-7-3). This is a good indication of sub-optimal coagulation conditions, likely due to a sub-optimum coagulant dose. After ground infiltration however, the residual Al levels were very low in all sampling rounds (2 µg/L or less). A similar pattern is valid also for Fe and Mn, with significant reductions during coagulation and filtration, and almost complete removal during ground infiltration.

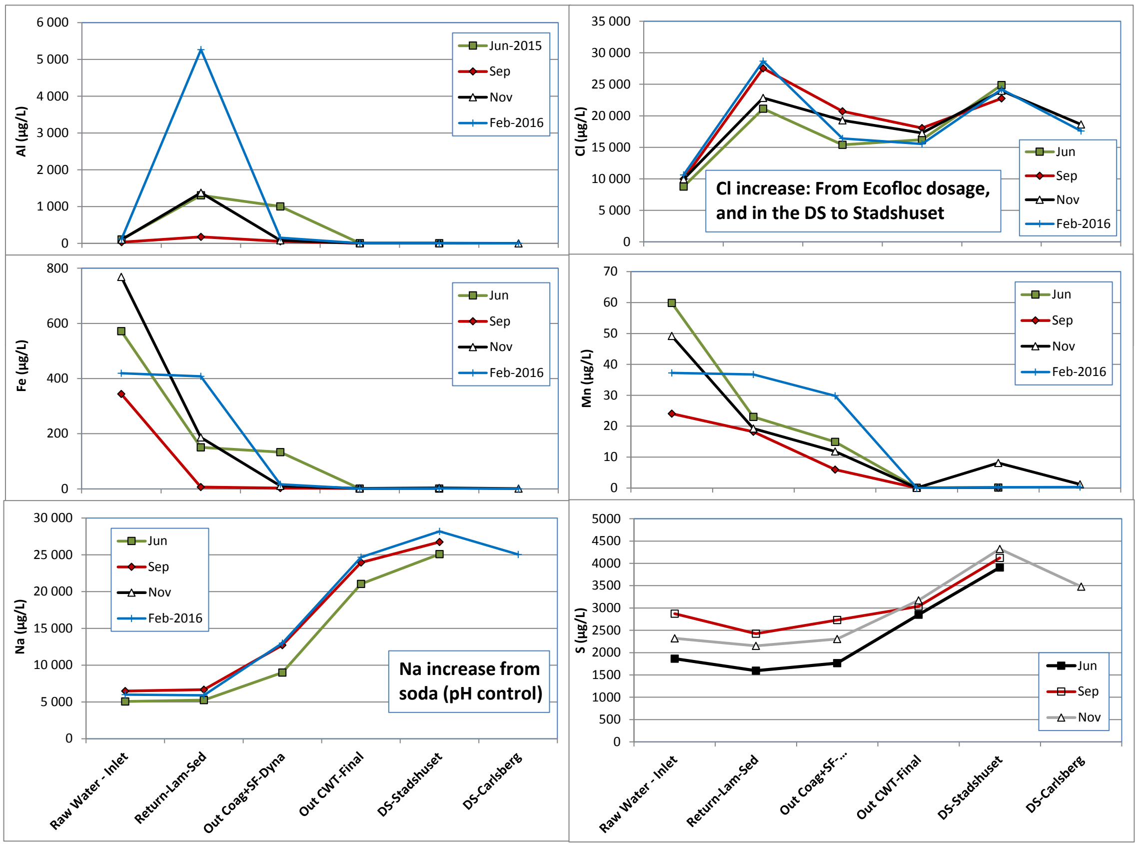
Ca-concentration levels in raw water varies considerably, within the range of 8-14 mg/L (Figure 5-7-4). The ground water infiltration process increases the concentrations of Si, Cu, Zn and Sr. The results also illustrate that P is effectively removed during coagulation-filtration. There is a significant increase in the Sr concentration levels in all four sampling rounds at the Stadshuset distribution system sampling point. As for Na, Cl and S, this is likely due to influence from another near-by WTW.

For KÄR WTW, the major findings are summarized below.

- Variable raw water quality (8.2-12.1 mg DOC/L; 340-770 µg Fe/L; 20-60 µg Mn/L; 30-120 µg Al/L)
- High SUVA (4.2-4.5) and VHA+SHA (82-89 % of DOC) indicates good treatability by coagulation
- Significant variation in Ekofloc Dose level: 3.3-4.6 mg Al/L, and in DOC-specific doses: 11-20 µmol Al/mg DOC
- Coagulation pH: 7.0-7.2 (high, but measured after Dynasand)
- Very high residual-Al after coagulation/filtration in June 2015 (> 1000 µg/L)
- Moderate/high contact filtration rates: 5.8-6.9 m/hr
- Variable coagulation performance, but substantial and consistent improvement in water quality during ground infiltration
- Low BDOC and ATP levels in CWT and DS samples
- Increase in Cu, Zn and Si concentrations during infiltration
- The decrease in Al, Fe and Mn during infiltration indicate deposition and a possible risk for clogging
- Increasing content of S, Cl, Ca and Sr was detected from the Clean Water Tank (CWT) to the distribution system (DS) sampling point Stadshuset (possibly due to influence from another treatment plant using ion exchange?)
- Coagulation optimization efforts are recommended

5.8. Ringsjöverket (RIN) WTW, Sydvatten - Sweden

The water treatment process at Ringsjöverket WTW includes coagulation (FeCl), flocculation, lamella sedimentation, rapid sand filtration (RSF), slow sand filtration (SSF), and chlorination (NaOCl) as the final process step. The water source is Lake Bolmen. The flowsheet for the treatment process along with the water sampling spots applied at Ringsjöverket WTP is shown in Figure 5-8-1.



Cl increase: From Ecofloc dosage, and in the DS to Stadshuset

Na increase from soda (pH control)

Figure 5-7-3 Water Quality data – KÄRREBERG WTW. Al, Cl, Fe, Mn, Na, and S concentration profiles during treatment and distribution.

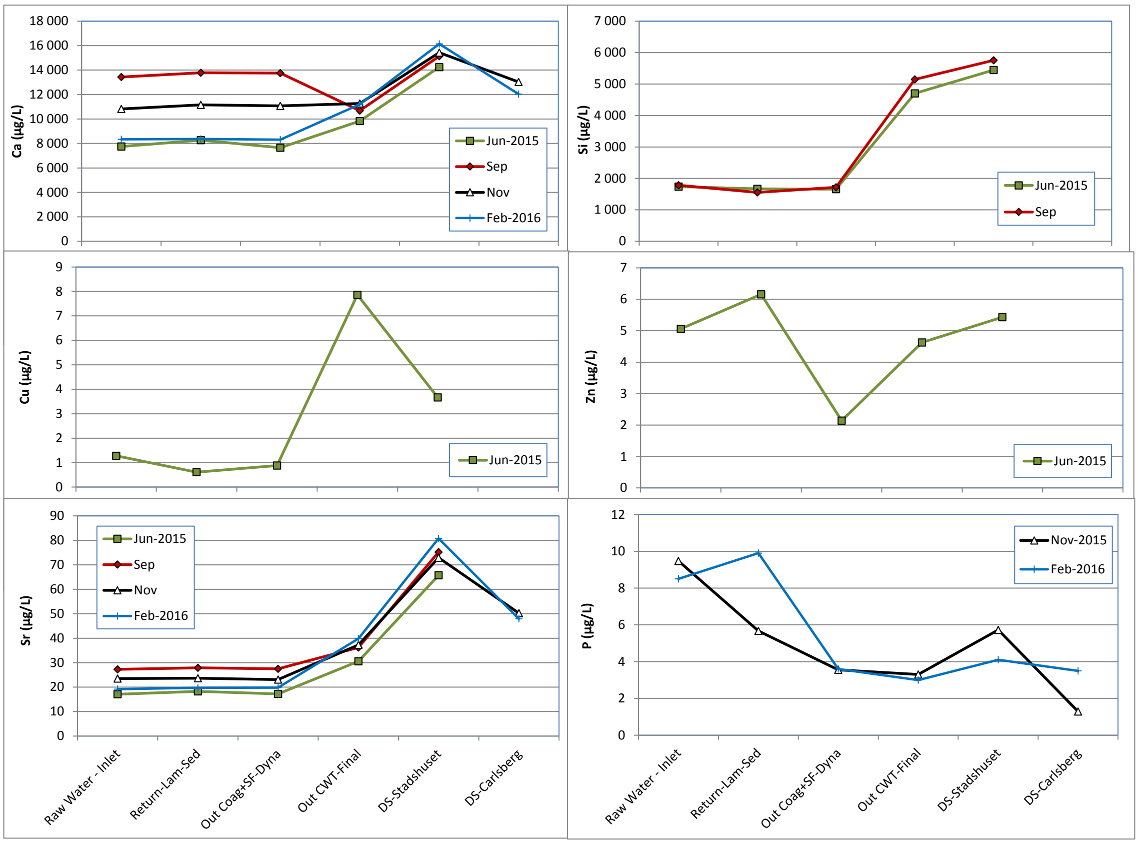
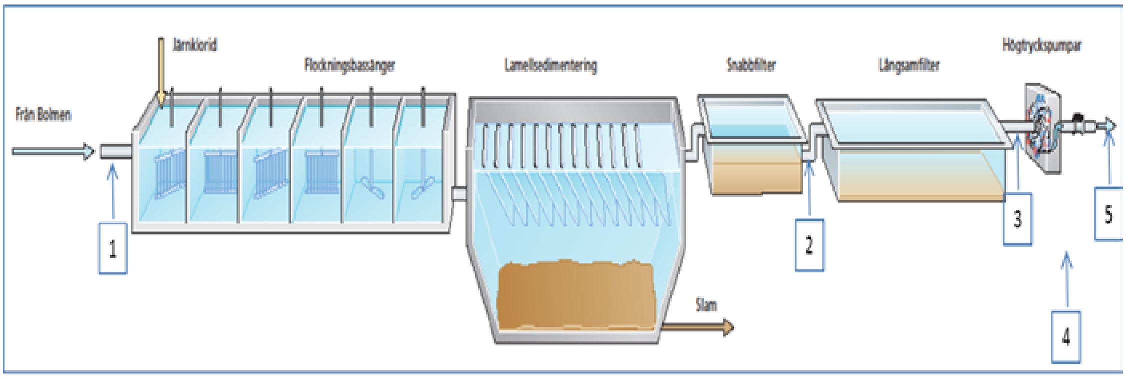


Figure 5-7-4 Water Quality data – KÄRREBERG WTW. Ca, Si, Cu, Zn, Sr, and P concentration profiles during treatment and distribution.

Coagulation. During the four water sampling rounds at Ringsjöverket WTW, the iron chloride coagulant dose levels varied within the range of 7.2-7.7 mg Fe/L. The coagulation pH was constant at pH 5.1. The DOC-specific dose varied within the range of 0.80-0.85 mg Fe/mg DOC, i.e. 14-15 µmol Fe/mg DOC. The amount of DOC removed was in the range of 47-53 mg DOC per mmol of Fe added. With constant NOM characteristics, a close to stoichiometric (constant) relationship will exist between NOM content and coagulant dose requirement, i.e. a 1:1 relationship. At Ringsjöverket WTW the ratio between the maximum and minimum DOC-specific coagulant dosages was less than 1.1. This indicate that the coagulation process is well optimized and that the process control is adequate, i.e. coagulation conditions that are well adapted to the prevailing raw water quality. The filtration rates applied during the sampling period was 3.9-5.3 m/h, which is regarded a moderate hydraulic filter loading.



1. Untreated raw water ("Raw")
2. Coagulated, settled and sand filtered water ("Out SF")
3. After slow sand filter ("Out slow sand")
4. After chlorine contact tank ("Chlorinated")
5. From distribution network (Network")

Figure 5-8-1 Treatment process flowchart and water sampling points at RINGSJÖVERKET WTW (SYDVATTEN).

A comparative study (benchmark) of the coagulation conditions and coagulation performance among the utilities is presented in Chapter 6.

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR sampling rounds is listed in Table 5-8-1. The raw water DOC was dominated by the hydrophobic NOM-fractions (88 % VHA+SHA) and high SUVA levels (4.0), indicating good treatability by coagulation.

The raw water quality showed some variability, and contained significant amounts of NOM. During the four sampling rounds, colour and UV-absorbance varied within the ranges of 58-70 mg Pt/L and 35-40 m^{-1}, respectively. Turbidity and TOC varied within 0.9-2.3 NTU, and 8.4-9.9 mg/L, respectively. Most of the organic matter was dissolved, with DOC levels of 99.7 % of TOC on average. The clean water quality was good, with low levels of colour (min-max: 2-4 mg Pt/L), UV-absorbance (3.7-4.3 m^{-1}), turbidity (0.1 NTU), DOC (2.0-2.5 mg/L), and BDOC (0.02-0.14 mg/L). A minor chlorine-driven increase in BDOC was detected in clean water samples. The BDOC concentration was reduced in the distribution system, indicating some microbial substrate (BDOC) consumption and/or adsorption of BDOC to metal precipitates on the pipe walls. The minor increase in measured ATP from the clean water samples to the distribution system samples, also indicates some microbial regrowth.

Table 5-8-1 Water Quality data – RINGSJÖVERKET WTW (Sydvatten). Average±StDev, minimum-maximum values (Sampling dates: Mar 31; Sep 09; Nov 10, 2014; Mar 2, 2015). Sampling spots: Out RSF: After coagulation, flocculation, lamella sedimentation and single medium sand filtration; Out SSF: After slow sand filtration; Out CWT: After Clean Water Tank and chlorine contact); DS: Distribution System sampling point (normally 17-18 hrs travelling time from the WTP).

RING	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	63±5 58-70	37.0±2.1 35.2-40.1	1.4±0.6 0.9-2.3	9.3±0.5 8.5-9.7	72±1 70-73	16±2 14-18	8±0 8-9	5±0 4-5	4.0±0.3 3.6-4.3	0.13±0.12 0.00-0.27	64±11 50-75
Out RSF	4±1 3-5	5.1±0.5 4.9-5.8	0.1±0.0 0.1-0.1	2.5±0.2 2.3-2.8	56±2 54-59	20±3 16-24	7±3 3-9	16±3 14-21	2.1±0.0 2.1-2.1	0.05±0.04 0.01-0.10	7±3 3-11
Out SSF	3±0 3-3	4.3±0.2 4.0-4.5	0.1±0.0 0.1-0.1	2.2±0.2 2.1-2.4	58±5 55-65	21±5 13-25	7±2 5-9	14±1 13-16	1.9±0.1 1.8-2.1	0.02±0.02 0.01-0.04	5±1 4-6
Out CWT	3±1 2-4	3.9±0.3 3.7-4.3	0.1±0.0 0.1-0.1	2.2±0.2 2.0-2.5	54±10 41-65	21±9 9-30	4±2 3-7	21±5 16-26	1.8±0.0 1.8-1.8	0.07±0.05 0.02-0.14	3±2 0-5
DS	3±1 3-4	4.0±0.3 3.6-4.3	0.1±0.0 0.1-0.1	2.2±0.2 2.0-2.4	56±5 51-62	19±8 7-26	8±2 5-10	17±6 12-26	1.8±0.1 1.8-2.0	0.03±0.03 0.01-0.08	8±4 3-12

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are given in Table 5-8-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

Table 5-8-2 Analytical Error Data – RINGSJÖVERKET WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
31.03.2014	**Raw**	0,13	0,14	0,05	0,07	0,06	0,02	0,003
	Out RGF	0,07	0,07	0,05	0,04	0,01	0,01	0,000
	Out SSF	0,03	0,04	0,04	0,04	0,02	0,01	0,000
	Out CWT	0,06	0,06	0,03	0,03	0,03	0,01	0,000
	DS	0,03	0,03	0,05	0,03	0,02	0,00	0,001
09.09.2014	**Raw**	0,17	0,18	0,07	0,06	0,02	0,06	0,015
	Out RGF	0,10	0,10	0,05	0,05	0,01	0,01	0,000
	Out SSF	0,03	0,04	0,03	0,04	0,04	0,01	0,001
	Out CWT	0,14	0,14	0,03	0,04	0,02	0,02	0,000
	DS	0,15	0,15	0,04	0,02	0,04	0,01	0,001
10.11.2014	**Raw**	0,20	0,20	0,03	0,03	0,01	0,04	0,001
	Out RGF	0,08	0,09	0,03	0,03	0,03	0,00	0,000
	Out SSF	0,04	0,05	0,03	0,02	0,01	0,01	0,000
	Out CWT	0,04	0,04	0,02	0,04	0,02	0,02	0,000
	DS	0,05	0,05	0,02	0,06	0,02	0,02	0,000
02.03.2015	**Raw**	0,17	0,17	0,03	0,05	0,05	0,10	0,001
	Out RGF	0,06	0,06	0,02	0,03	0,02	0,02	0,000
	Out SSF	0,06	0,08	0,06	0,03	0,02	0,01	0,000
	Out CWT	0,02	0,02	0,03	0,02	0,01	0,03	0,000
	DS	0,03	0,03	0,04	0,02	0,01	0,01	0,000
AVG		***0,08***	***0,09***	***0,04***	***0,04***	***0,02***	***0,02***	***0,001***
MIN		***0,02***	***0,02***	***0,02***	***0,02***	***0,01***	***0,00***	***0,000***
MAX		***0,20***	***0,20***	***0,07***	***0,07***	***0,06***	***0,10***	***0,015***
AVG-Raw		***0,17***	***0,17***	***0,05***	***0,05***	***0,04***	***0,06***	***0,006***
AVG-RGF		***0,08***	***0,08***	***0,04***	***0,04***	***0,02***	***0,01***	***0,000***
AVG-SSF		***0,04***	***0,05***	***0,04***	***0,03***	***0,02***	***0,01***	***0,000***
AVG CWT		***0,07***	***0,07***	***0,03***	***0,03***	***0,02***	***0,02***	***0,000***
AVG DS		***0,08***	***0,08***	***0,03***	***0,03***	***0,02***	***0,01***	***0,000***

In general, the analytical errors are low, with the highest absolute values found during the November 2014 sampling round. This “worst case” situation with respect to analytical error is illustrated in Figure 5-8-2.

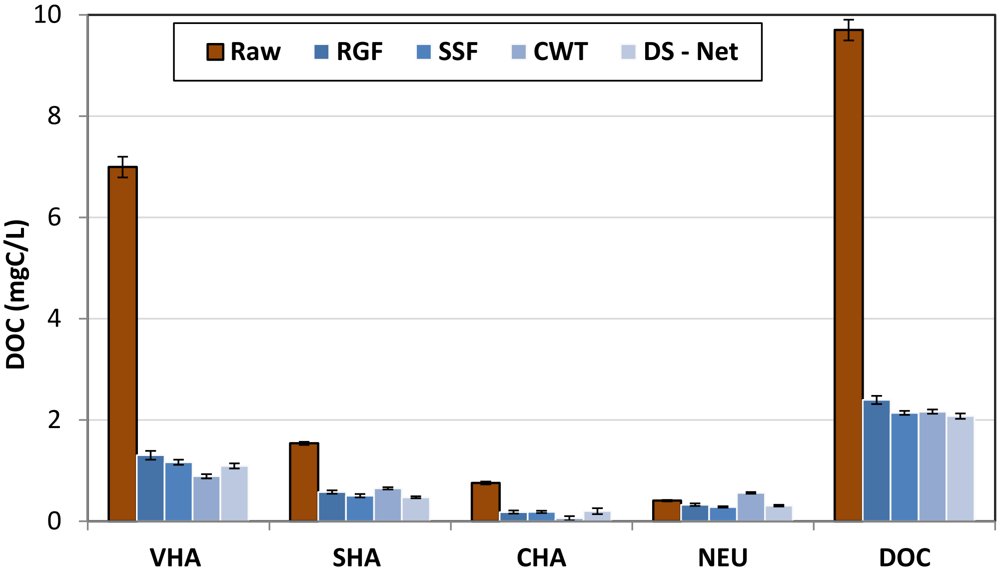


Figure 5-8-2 Water Quality data – RINGSJÖVERKET WTW (November 2014). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

NOM fractions and NOM fraction removal. The raw water DOC at this utility was dominated by the hydrophobic NOM fractions (88 % of the total DOC; 72 % VHA and 16 % SHA). The hydrophilic fraction was 13 % (8 % CHA and 5 % NEU). The low content of the hydrophilic NOM, i.e. the more low-molecular weight and more biodegradable fractions, was reflected in the low BDOC, i.e. on average 1.3 % of the total DOC, with a maximum value of 2.8 % (November sample).

During coagulation and filtration (out sand filter), the DOC removal efficiency was on average 73 %, with minimum and maximum values of 70 and 75 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 77 and 51 %, with minimum and maximum values of 74 and 78 %, and 46 and 56 %), respectively. As expected, the poorest removal during coagulation was found for the NEU fraction, with only 7 % removal efficiency on average.

The changes in water quality and removal efficiency during treatment and distribution are presented in Table 5-8-3. Here the total average removal efficiencies (i.e. % reduction relative to the content in raw water) are presented for selected water quality parameters.

Table 5-8-3 Water Treatment data – RINGSJÖVERKET WTW (Sydvatten). Average total Removal Efficiencies (%) obtained after different treatment steps (Samplings: Mar 31; Sep 09; Nov 10, 2014; Mar 2, 2015).

RINGSJÖVERKET (Total % Removal)	Out RSF	Out SSF	Out CWT	DS
UV-abs	86	88	89	89
DOC	73	76	76	77
VHA+SHA	77	78	80	80
CHA+NEU	51	59	53	54
NEU	7	24	-8	11
BDOC	50	65	44	55
ATP	88	92	95	86

It appears from Table 5-8-3 that significant removal was obtained during coagulation, with some small improvements during the additional process steps. Regarding UV-absorbance the removal efficiencies were 86 % after RSF, 88 % after SSF, 89 % after chlorination (Clean water tank), and 89 % in DS. For DOC the numbers were 73, 76, 76 and 77 %, and for the hydrophobic NOM fractions (VHA+SHA) 77, 78, 80 and 80 %.

Larger differences were obtained for the hydrophilic NOM fractions (CHA+NEU) with 51, 59, 53 and 54 % removal. The biological activity and the adsorption processes taking place in the slow sand filter was responsible for the increase from 51 to 59 % removal for these compounds. For the NEU fraction, the removal efficiency of 7 % achieved during coagulation and filtration, was increased to 24 % during slow sand filtration, thus indicating that SSF was capable of removing some hydrophilic NOM that was not amendable to removal by coagulation.

During chlorination however, some hydrophilic NOM was produced from hydrophobic NOM, thus increasing the overall removal of VHA+SHA from 78 to 80 %, and reducing the overall removal efficiency for CHA+NEU from 59 to 53 %. For the NEU fraction, the overall removal efficiency was reduced to -8 % after chlorination (CWT). During distribution, some NEU was consumed or removed by adsorption, thereby increasing the overall NEU removal efficiency to 11 %.

This pattern fits well also for BDOC. The BDOC removal increased from 50 % after coagulation/filtration to 65 % after slow sand filtration, due to increased removal of hydrophilic and biodegradable NOM fractions (CHA+NEU) in the SSF. After chlorination however, the BDOC concentration increased (Table 5-8-1), and the overall BDOC removal was reduced to 44 %, due to the formation of more hydrophilic NOM as described above. The increased concentration of bacterial substrate (BDOC) was used for regrowth in the DS, as illustrated by the increase in ATP. Thus the overall removal of ATP was 88 % after RGF, 92 % after SSF, 95 % after CWT (including chlorination), and only 86 % in the distribution system.

A significant microbial activity (ATP) was measured in the raw water (Table 5-8-1). ATP removal efficiency was 88 % after coagulation and filtration. After slow sand filtration, the ATP removal increased to 92 %, and after the chlorine contact/clean water tank to 95 %. As discussed above, ATP removal was reduced to 86 % in the DS. This is likely due to some regrowth, despite the fact that the BDOC concentrations were low in clean water (the maximum concentration was 0.14 mg BDOC/L in November 2014).

Elements and residual metals. Elemental data of metal coagulant residuals (Al) and specific elements with significant changes in concentration during treatment and distribution are presented in Figure 5-8-3.

When using iron chloride for coagulation, the increase in the chloride concentration from raw water to coagulated water samples reflects the coagulant dosage, and thus the concentration increase in Cl can be used to back-calculate/control the coagulant dosage from information on the coagulant's Cl-content from the product data sheet. Metal coagulant residuals, i.e. residual Fe-concentrations, remained low in all sampling rounds (< 35 µg/L), thus indicating optimal or close to optimal coagulation conditions.

Figure 5-8-3 shows only small variations in the Cl-concentration increase during coagulation, settling and filtration, and thereby also in the applied Fe-chloride coagulant dose. This is in line with the nearby constant coagulant dosage used at this utility, as discussed above. The increase in average Cl-concentration from the outlets of the SSF (25 713 µg/L) to the CWT (26 324 µg/L) along with the increase in Na-concentration (7387 to 8137 µg/L) reflects also the small chlorine (NaOCl) dosages used here (0.6-0.9 mg/L).

Al, Cu, Zn, Pb and P were effectively removed during coagulation (Figure 5-8-3). Substantial removal of Mn was achieved during coagulation (except in March 2014), however, also the SSF contributed significantly to the overall Mn removal at this utility. The Cr concentration increased significantly during the coagulation-filtration process steps, likely due to the presence of Cr in the coagulant. The reason for the increase in Cu concentration in all samples collected from the CWT is unknown, but it may be related to sampling lines/taps containing Cu.

The average Ca-concentrations in samples from raw water, RGF, SSF, CWT and DS (not included in Figure 5-8-3) are 5.9, 12.2, 12.6, 20.3 and 19.6 mg/L, respectively. This reflects the use of lime for the purposes of coagulation pH-control and final pH/corrosion control.

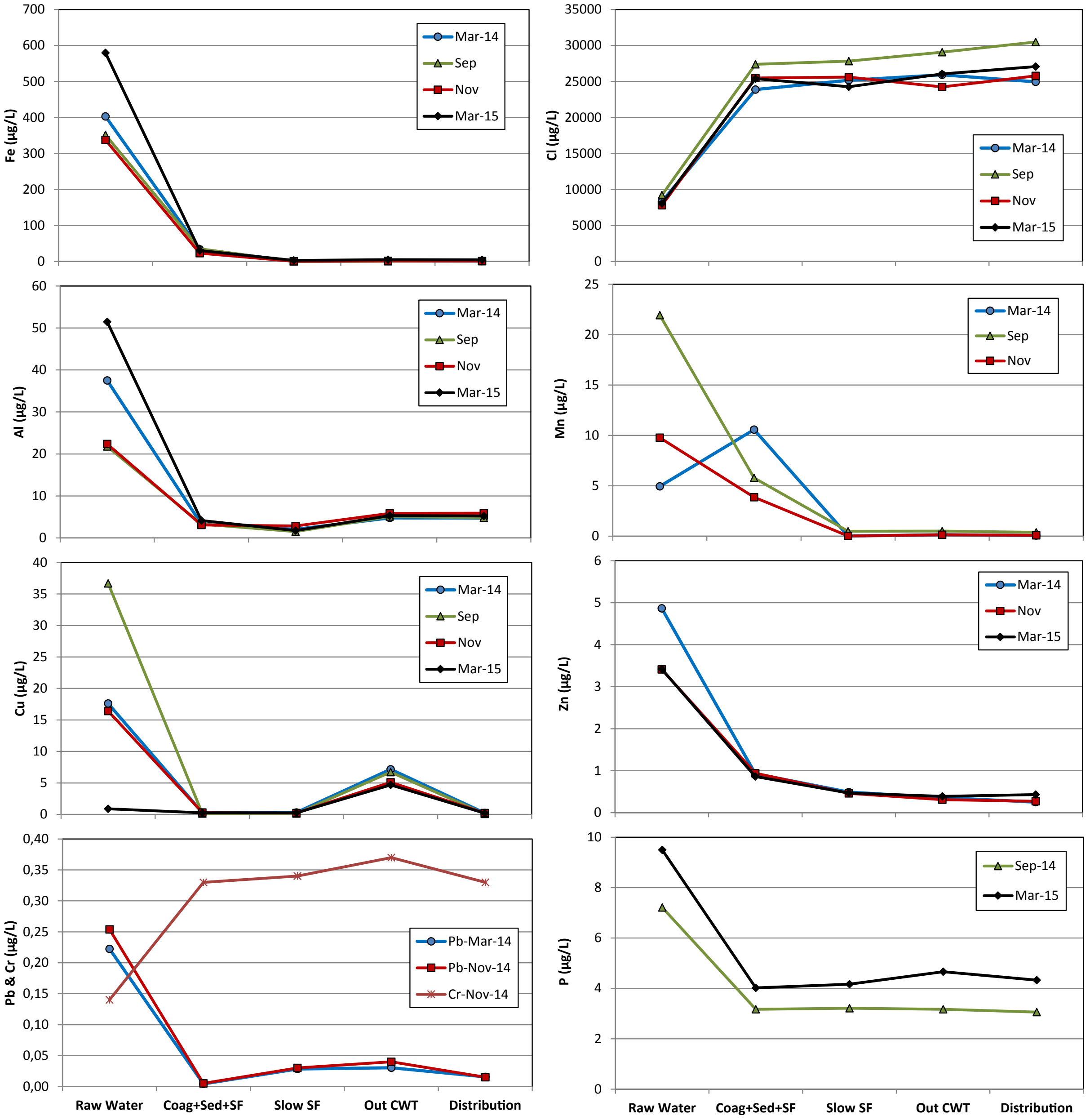


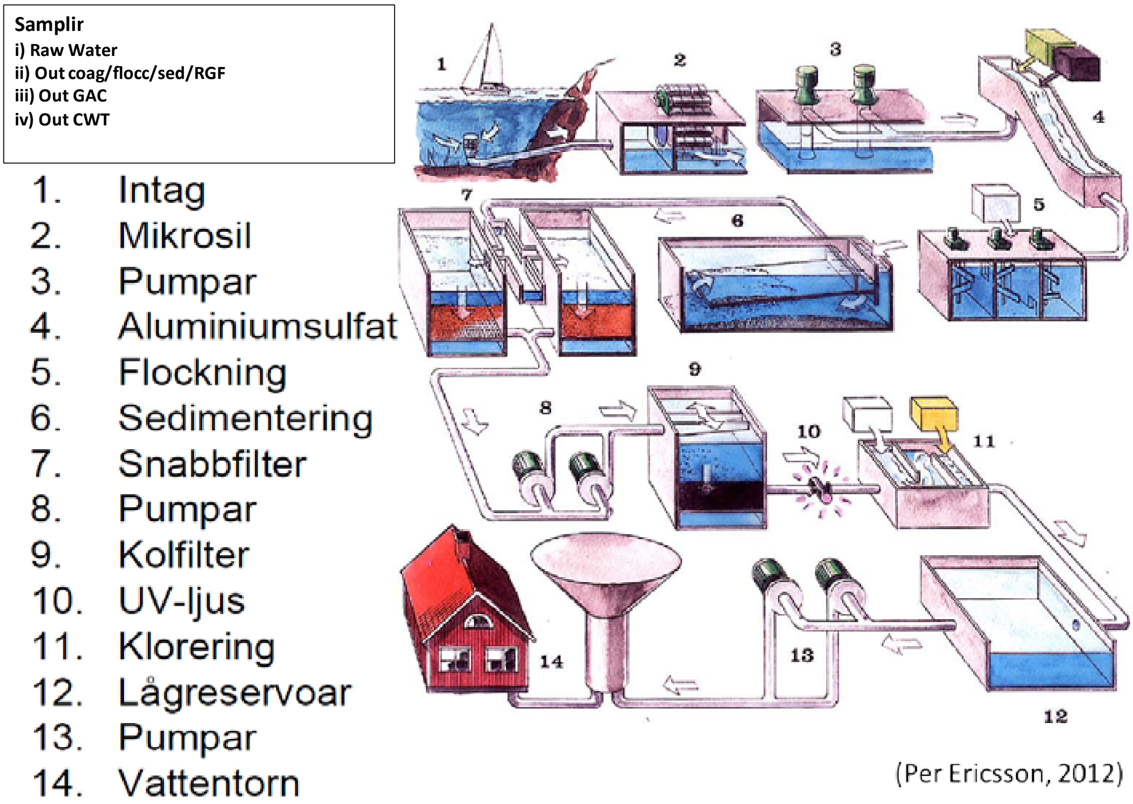
Figure 5-8-3 Water Quality data – RINGSJÖVERKET WTW. Fe, Cl, Al, Mn, Cu, Zn, Pb, Cr and P concentration profiles during treatment and distribution.

For RIN WTW, the major findings are summarized below.

- Relatively stable raw water quality (8.5-9.7 mg DOC/L; 330-580 µg Fe/L; 5-22 µg Mn/L; 20-50 µg Al/L; 2-37 µg Cu/L)
- High SUVA (3.6-4.3) and VHA+SHA (86-88 % of DOC) indicate good treatability by coagulation
- Only minor variation in coagulant dose level (7.2-7.7 mg Fe/L) and in DOC-specific dosage (14-15 µmol Fe/mg DOC) (dosage well reflected in the Cl-concentration increase)
- Constant coagulation pH of 5.1
- Moderate filtration rates of 3.9-5.3 m/hr (no negative effects on filtered water quality)
- Pb, Cu, Al, Mn, Zn and P are effectively removed by coagulation
- A small additional increase in NOM removal observed during SSF
- Low BDOC levels, but a minor increase in CWT (due to chlorine)
- A minor increase in ATP from CWT to DS samples
- Increase in Cu concentration from SSF to CWT samples, and for Cr after coagulation (Nov 2014 samples)

5.9. Görvälnverket (GÖR) WTP, Norrvatten - Sweden

The water treatment process at Görvälnverket WTW includes microscreening, coagulation (alum), flocculation, sedimentation, rapid sand filtration (RGF), activated carbon (GAC) filtration, UV-disinfection and chloramination as the final treatment step. The water source is Lake Mälaren. Figure 5-9-1 shows the flowsheet for the treatment process along with the applied water sampling spots.



(Per Ericsson, 2012)

Figure 5-9-1 Treatment process flowchart and water sampling points at GÖRVÄLNVERKET WTW.

Coagulation. During the four water sampling rounds at Görvälnverket WTW (Norrvatten), the alum coagulant dose and the coagulation pH levels varied within the ranges of 4.2-5.5 mg Al/L and pH 6.7-6.8, respectively. The DOC-specific dose varied in the range of 0.53-0.66 mg Al/mg DOC, i.e. 20-24 μmol Al/mg DOC. The amount of DOC removed was in the range of 19-24 mg DOC per mmol of Al added.

With constant NOM characteristics, a close to stoichiometric (constant) relationship is expected to exist between NOM content and coagulant dose requirement, i.e. a 1:1 relationship. At Görvälnverket WTW the ratio between the maximum and minimum DOC-specific coagulant dosages was 1.25. This indicate that the coagulation process was fairly well optimized and that the process control was adequate, i.e. coagulation conditions that were relatively well adapted to the prevailing raw water quality. The coagulation pH, however, seems high. The filtration rates applied during the sampling period is 4.7-5.4 m/h, which is regarded a moderate to normal hydraulic filter loading that should not negatively affect the filtered water quality.

A comparative study (benchmark) of the coagulation conditions and coagulation performance among the utilities is presented in Chapter 6.

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR sampling rounds is given in Table 5-9-1. The raw water DOC was dominated by the hydrophobic NOM-fractions (82 % VHA+SHA), although only two out of the 10 utilities had average hydrophobic NOM fractions lower than this. The SHA fraction concentration (22 % of tot-DOC) was the highest among all utilities. The average SUVA level (2.8) was by far the lowest among all raw water samples, indicating relatively poor treatability by coagulation.

The raw water quality was relatively constant, with colour and UV-absorbance levels that varied within the ranges of 20-24 mg Pt/L, and 21-25 m^{-1} during the four samplings rounds. Turbidity and TOC varied within the ranges of 1.2-4.6 NTU, and 7.7-8.3 mg/L, respectively. Most of the organic matter was dissolved, with DOC levels close to 100 % of TOC on average.

The clean water quality was relatively good, with residual colour (min-max): 5-6 mg Pt/L, UV-absorbance 7.3-8.2 m^{-1}, turbidity 0.1 NTU, DOC 4.1-4.5 mg/L, and BDOC 0.00-0.25 mg/L. The high residual DOC levels reflect the poor treatability by coagulation. In the November 2015 samplings, the BDOC was found to increase from < 0.1 mg/L to 0.25 mg/L during the CWT, possibly due to the chloramination. In the other samplings rounds however, no significant BDOC increase was detected, and the oxidizing effect of chloramination is likely to small to cause any substantial BDOC increase, despite the relatively high residual DOC (> 4 mg/L). The BDOC concentration was maintained at the CWT-level in the distribution system, indicating no major microbial substrate (BDOC) consumption on the way from the CWT to the DS sampling point. This finding is supported by the fact that the ATP levels were stable and close to zero in both the clean water samples and the distribution system samples, thus indicating no major microbial regrowth.

Table 5-9-1 Water Quality data – Görvälnverket WTW (Norrvatten). Average±StDev; minimum-maximum values (Sampling dates: Jun 15; Sep 14; Nov 23, 2015; Mar 7, 2016). Sampling spots: Out RGF: After coagulation, flocculation, sedimentation and sand filtration; Out GAC: After GAC filter; Out UV: After UV-disinfection; Out CWT: After Clean Water Tank (and chloramination); DS: From the Distribution System (Roseberg Pumping Station).

GÖR	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	23±2 20-24	22.7±1.5 20.9-24.6	3.3±1.6 1.2-4.6	8.1±0.2 7.8-8.4	60±3 56-63	22±2 20-25	12±1 12-13	6±0 6-6	2.8±0.1 2.7-2.9	0.18±0.18 0.00-0.39	67±46 11-119
Out RGF	5±0 5-6	8.3±0.4 7.9-8.7	0.1±0.0 0.1-0.1	4.3±0.1 4.2-4.5	56±1 54-57	24±1 23-25	9±1 8-9	12±1 11-13	1.9±0.1 1.8-2.0	0.09±0.04 0.05-0.14	11±11 44197
Out GAC	5±0 5-6	8.1±0.4 7.6-8.6	0.1±0.0 0.1-0.1	4.2±0.1 4.1-4.3	56±1 54-57	23±2 21-26	9±5 2-13	12±4 10-18	1.9±0.1 1.9-2.0	0.13±0.08 0.07-0.24	9±8 42736
Out UV	5±1 5-6	8.2±0.5 7.9-8.5	0.1±0.0 0.1-0.1	4.2±0.2 4.1-4.4	52±1 51-52	25±0 25-25	10±3 8-12	13±2 12-14	1.9±0.0 1.9-1.9	0.06±0.04 0.03-0.08	5±6 0-9
Out CWT	5±0 5-6	7.7±0.5 7.3-8.2	0.1±0.0 0.1-0.1	4.3±0.2 4.1-4.5	55±2 53-58	24±2 22-25	10±1 9-11	11±0 11-12	1.8±0.0 1.8-1.8	0.11±0.11 0.00-0.25	1±1 0-3
DS Roseb	5±1 5-6	7.8±0.3 7.5-8.2	0.1±0.0 0.1-0.1	4.2±0.1 4.1-4.3	53±5 47-57	21±5 15-25	13±3 9-16	13±3 11-18	1.8±0.1 1.8-2.0	0.11±0.10 0.02-0.21	1±1 0-3

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are given in Table 5-9-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

Table 5-9-2 Analytical Error Data – GÖRVÄLNVERKET WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
15.06.2015	**Raw**	0,30	0,30	0,05	0,04	0,02	0,20	0,002
	Out RGF	0,01	0,02	0,03	0,03	0,02	0,00	0,001
	Out GAC	0,08	0,09	0,03	0,02	0,01	0,02	0,003
	Out CWT	0,04	0,04	0,01	0,04	0,02	0,04	0,000
	Out UV							
	DS	0,09	0,09	0,02	0,02	0,01	0,12	0,000
14.09.2015	**Raw**	0,12	0,13	0,06	0,03	0,01	0,05	0,004
	Out RGF	0,06	0,07	0,04	0,02	0,02	0,07	0,001
	Out GAC	0,05	0,06	0,02	0,02	0,01	0,10	0,000
	Out CWT	0,08	0,08	0,04	0,03	0,02	0,02	0,001
	Out UV							
	DS	0,12	0,03	0,01	0,01	0,01	0,01	0,000
23.11.2015	**Raw**	0,08	0,08	0,01	0,02	0,02	0,25	0,011
	Out RGF	0,02	0,05	0,03	0,03	0,01	0,15	0,002
	Out GAC	0,08	0,11	0,09	0,06	0,04	0,05	0,001
	Out CWT	0,08	0,09	0,07	0,02	0,02	0,02	0,001
	Out UV	0,04	0,04	0,04	0,03	0,04	0,01	0,000
	DS	0,05	0,05	0,04	0,01	0,02	0,05	0,000
07.03.2016	**Raw**	0,12	0,12	0,04	0,02	0,01	0,03	0,006
	Out RGF	0,12	0,13	0,04	0,02	0,02	0,01	0,004
	Out GAC	0,09	0,10	0,06	0,07	0,05	0,04	0,001
	Out CWT	0,09	0,09	0,06	0,03	0,02	0,09	0,000
	Out UV	0,07	0,08	0,02	0,03	0,05	0,01	0,000
	DS	0,10	0,10	0,03	0,01	0,03	0,02	0,001
AVG		***0,09***	***0,09***	***0,04***	***0,03***	***0,02***	***0,06***	***0,002***
MIN		***0,01***	***0,02***	***0,01***	***0,01***	***0,01***	***0,00***	***0,000***
MAX		***0,30***	***0,30***	***0,09***	***0,07***	***0,05***	***0,25***	***0,011***
AVG-Raw		**0,16**	**0,16**	**0,04**	**0,03**	**0,02**	**0,13**	**0,006**
AVG-RGF		**0,05**	**0,07**	**0,04**	**0,03**	**0,02**	**0,06**	**0,002**
AVG-GAC		**0,08**	**0,09**	**0,05**	**0,04**	**0,03**	**0,05**	**0,001**
AVG CWT		**0,07**	**0,08**	**0,05**	**0,03**	**0,02**	**0,04**	**0,001**
Avg UV		**0,06**	**0,06**	**0,03**	**0,03**	**0,05**	**0,01**	**0,000**
AVG DS		**0,09**	**0,07**	**0,03**	**0,01**	**0,02**	**0,05**	**0,000**

In general, the analytical errors were low, with the highest absolute values found during the June 2015 sampling round. This "worst case" situation with respect to analytical error is illustrated in Figure 5-9-2.

NOM fractions and NOM fraction removal. The raw water DOC at this utility is dominated by the hydrophobic NOM fractions (82 % of the total DOC) with 60 % VHA and 22 % SHA. This is the largest average SHA-fraction found in all raw waters. The maximum SHA concentration was found in the November 2015 sampling round (2 mg/L; 25 % of DOC). The hydrophilic fraction was on average 18 % (12 % CHA and 6 % NEU). The 12 % CHA-fraction concentration is the largest among all utilities. Despite the relatively high fraction of hydrophilic NOM in raw water, the BDOC is not very high - on average 2.2 % of the total DOC, with a maximum value of 4.9 % (November 2015 sample).

During coagulation and filtration (out rapid gravity filter, RGF), the DOC removal efficiency was on average 47 %, with minimum and maximum values of 46 and 48 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic

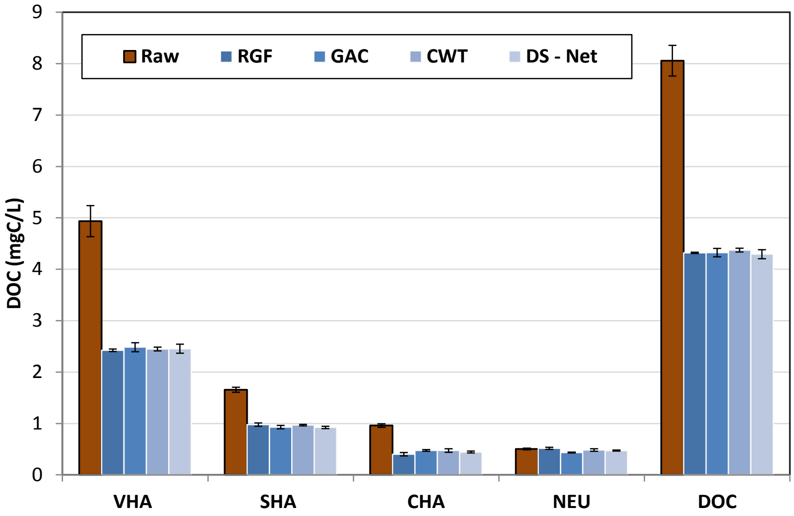


Figure 5-9-2 Water Quality data – GÖRVÄLNVERKET WTW (June 2015). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

(CHA+NEU) NOM fraction removal efficiencies were on average 48 and 39 %, within the min and max ranges of 48-49 %, and 37-42 %, respectively. The poorest removal during coagulation was found for the NEU fraction, and instead an increase (7 %) in average NEU concentration was detected during this treatment step. This is a rather common observation during coagulation treatment using neutralizing metal coagulants.

The changes in water quality and overall removal efficiency during treatment and distribution are presented in Table 5-9-3. Here the total average removal efficiencies (i.e. % reduction relative to the content in raw water) are presented for selected water quality parameters.

A minor bleaching effect was found (as a reduced UV-A) from the chloramination (Table 5-9-3). The DOC concentration remained constant throughout the entire treatment train, showing that coagulation was the one and only NOM removing process step. The GAC filter step did not appear to have any beneficial influence at all on the water quality parameters measured here. The average hydrophobic NOM fractions concentration decreased (higher % removal), and the hydrophilic NOM concentration increased (i.e. decreased % removal) from the CWT to the distribution system (DS) sampling point. According to Table 5-9-1, the average BDOC concentration remained constant (0.11 mg/L), thus reflecting the strong capability of the chloramine residuals to control BDOC substrate consumption and regrowth (ATP) at close to zero levels, at least on the way to the DS sampling point used here.

It should be pointed out that the average results from the "Out UV" sampling point includes two sampling rounds only, and thus that the results (e.g. NEU and BDOC) are not directly comparable to those from the other sampling points. The results from the November 2015 and March 2016 sampling rounds, in which UV sampling were included, show only minor changes in water quality (including NEU and BDOC) from the UV disinfection process.

Table 5-9-3 Water Treatment data – GÖRVÄLNVERKET WTW (Norrvatten). Average total Removal Efficiencies (%) obtained after different treatment steps (Samplings: Jun 15; Sep 14; Nov 23, 2015; Mar 7, 2016).

GÖRVÄLNVERKET (Total % Removal)	Out RSF	Out GAC	Out UV	Out CWT	DS
UV-abs	63	64	64	66	66
DOC	47	48	48	47	48
VHA+SHA	48	49	50	49	53
CHA+NEU	39	39	35	39	27
NEU	-7	-9	-15	1	-14
BDOC	59	8	84	30	35
ATP	85	88	95	97	99

The results in Table 5-9-1 show relatively moderate levels of microbial activity (ATP) in the raw water, and that substantial reductions in ATP were achieved during coagulation and filtration. Table 5-9-3 shows that the ATP removal efficiency was 85 % after coagulation and filtration. After GAC filtration, the ATP removal increased to 88 %, and after UV and the chlorine contact/clean water tank it increased further to 95 and 97 % respectively. Likely due to the disinfection action of remaining chloramine, the average ATP removal increased to 99 % in the samples taken from the DS. The BDOC concentration remained the same from the CWT to the DS sampling point, thus indicating no significant BDOC substrate consumption or regrowth.

Elements and residual metals. Data of metal coagulant residuals (Al) and specific elements with significant changes in concentration during treatment and distribution are shown in Figure 5-9-3.

Metal coagulant residuals, i.e. residual Al-concentrations after the RSF remained low in all sampling rounds. High coagulant residuals are normally a signal of sub-optimal coagulant doses. The maximum residual Al concentration (41 µg/L) was measured in March 2016. The DOC-specific Al-dose was at its highest during this sampling round, so it is unlikely that the residual Al is a result of sub-optimal coagulant dosage. On the other hand, an average VHA removal efficiency of only 50 % indicate sub-optimal coagulation. During the March-2016 sampling, the Ca-concentration levels were higher than normal (Figure 5-9-3) and the applied coagulation pH was at its highest level (pH 6.8). This pH is considered (too) high for optimum NOM removal by alum coagulation. The increase in S-concentration from raw water to the RGF effluent indicate that different coagulant dosages were applied, especially during the June and September sampling rounds – despite similar raw water qualities. This may indicate a potential for improvements in process control, i.e. better adaption of coagulation conditions to the prevailing raw water quality at all times.

When using alum for coagulation, the increase in the sulphur (S) concentration from raw water to coagulated water samples reflects the coagulant dosage, and thus the measured concentration increase in S can be used to back-calculate/control the coagulant dosage from information on the coagulant's product data sheet.

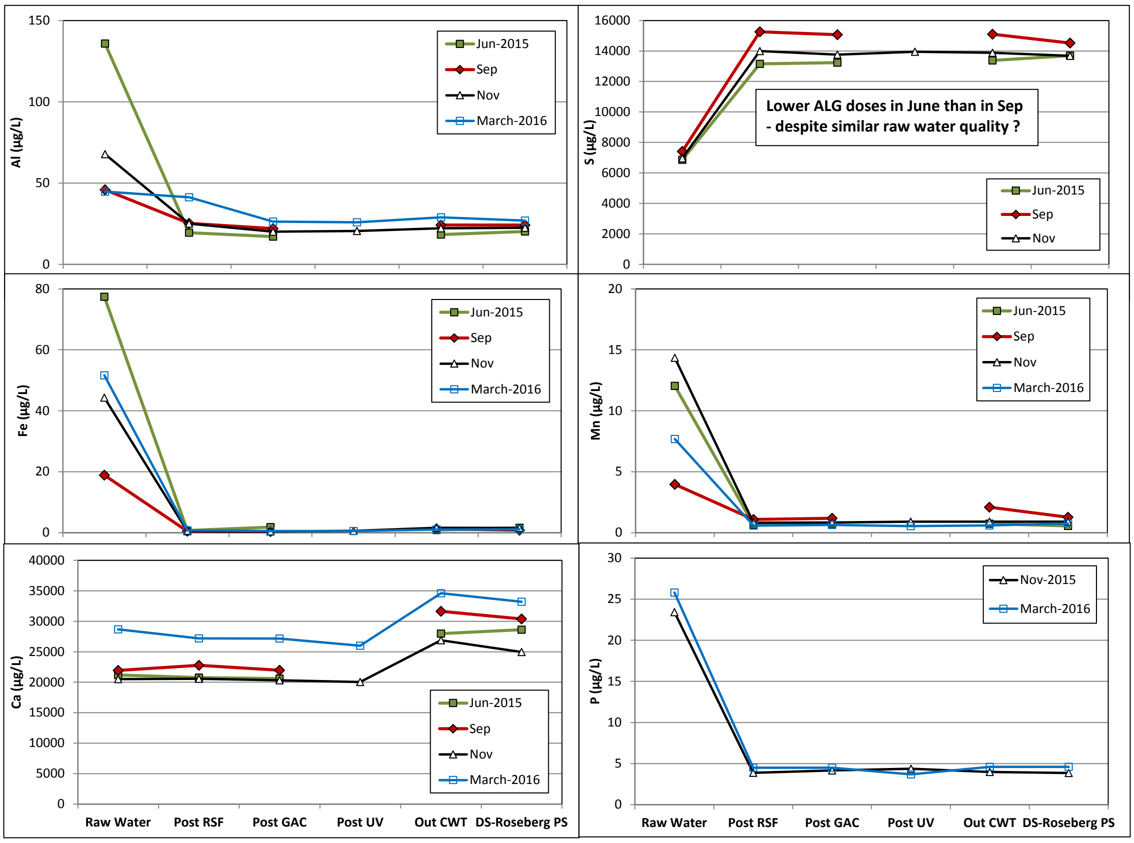


Figure 5-9-3 Water Quality data – GÖRVÄLNVERKET WTW. Al, S, Fe, Mn, Ca and P concentration profiles during treatment and distribution.

Fe, Mn and P were effectively removed during coagulation (Figure 5-9-3). It should also be noticed that the concentration levels of Ca in raw water samples increased from about 20-22 mg/L in June, September and November 2015, and up to about 28 mg/L in March 2016. The effects of lime dosing for pH- and corrosion control is demonstrated in Figure 5-9-3, with elevated levels of Ca in the CWT samples. The increase in average Cl-concentration from the GAC filter effluent to the CWT outlet was marginal (from 14.3 to 14.9 mg/L). Along with a negligible change in Na concentrations, this is indicative of very small dosage levels of chloramine.

The concentration levels of Cu increased considerably from the GAC filter effluent to the CWT outlet (from 1 to 13 µg/L). It was found that the Cu was coming from a copper pipe, and this pipe was changed to stainless steel in 2016 after complaints from the waste water treatment plant that got too high Cu content in the sludge. The concentration of Zn increased as well, from 0.5 to 1.1 mg/L during the CWT. The reason for this is unknown. It should be pointed out however, that Cu and Zn were analysed only once (June 2015).

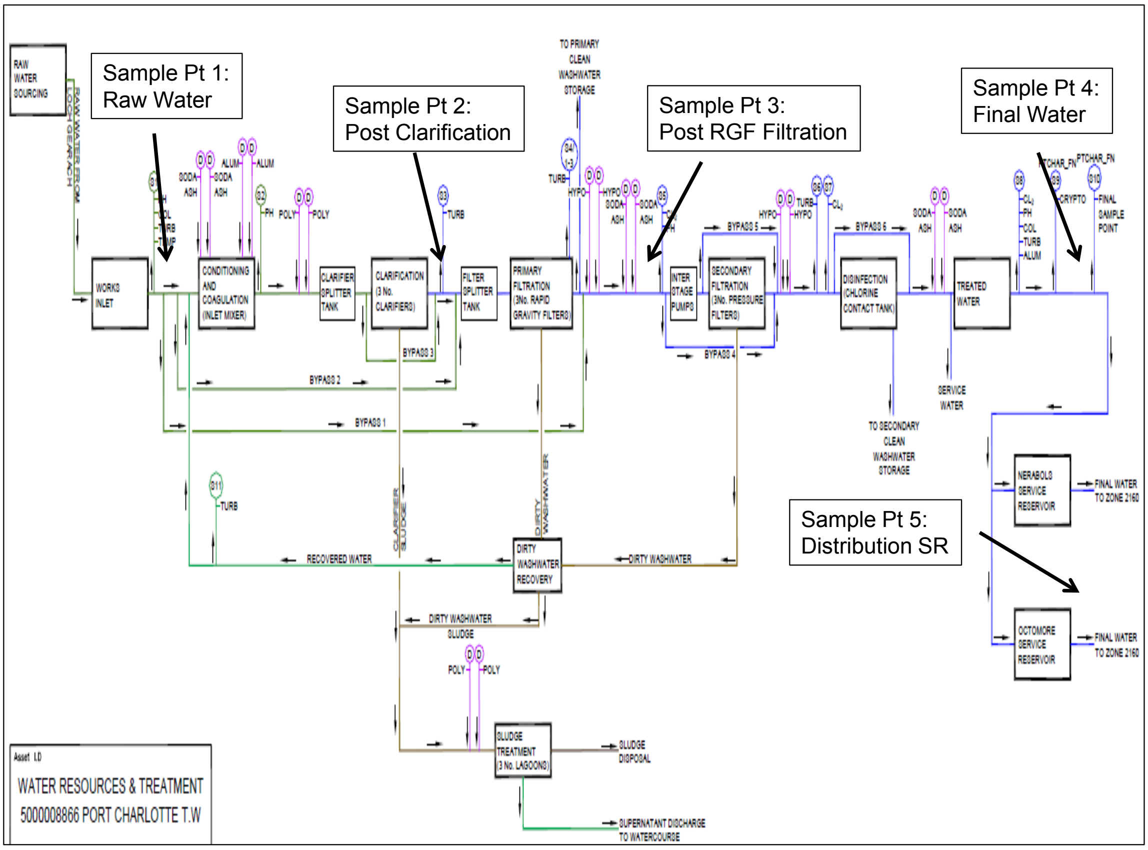
For GÖR WTW, the major findings are summarized below.

- Stable raw water quality (7.8-8.4 mg DOC/L; 20-80 µg Fe/L; 4-15 µg Mn/L; 40-140 µg Al/L; 20-28 mg Ca/L; 20-30 µg P/L)
- Low SUVA (2.7-2.9) indicate poor treatability by coagulation
- High hydrophobic NOM content (VHA+SHA) (81-82 % of DOC), but the lowest VHA (56-63 %) and the highest SHA fraction concentration (20-25 % of DOC) observed among the NOMiNOR utilities applying coagulation
- Coagulant dose levels varied within 4.2-5.5 mg Al/L, and within 20-24 µmol Al/mg DOC for DOC-specific doses (dosage level supported by the increase in S-concentration)
- Coagulation pH: 6.7-6.8 – too high for alum?
- Moderate contact filtration rates: 4.7-5.4 m/hr
- Relatively poor NOM removal achieved during coagulation, mainly due to poor treatability by coagulation (low SUVA, high SHA)
- Only marginal improvement in NOM removal from GAC filtration (saturated GAC)
- Low BDOC and ATP levels in CWT and DS samples, with a minor increase in BDOC due to chlorination
- Fe, Mn and P effectively removed during coagulation
- Increase in Cu concentration from GAC outlet to CWT (Cu-pipeline now replaced)
- Coagulation optimization efforts are recommended

5.10. Port Charlotte (PC) WTW - Scotland

The water treatment process at Port Charlotte WTW includes coagulation (alum) with soda for pH-control, polymer, sedimentation (up-flow clarification), rapid sand filtration, chlorination, soda for pH-control, pressure filters (2nd filter stage), and finally chlorination and final pH-control by soda. Water from backwash/sludge treatment is returned to the inlet of the plant. The water source is Loch Gearach, (Isle of Islay). Periodically, high levels of iron and manganese are found in the source water. The treatment flowsheet along with the water sampling spots applied at Port Charlotte WTW, Scottish Water is shown in Figure 5-10-1.

Coagulation. During the four water sampling rounds at Port Charlotte WTW, the alum coagulant dose and the coagulation pH levels varied in the range of 5.7-18.1 mg Al/L and pH 5.9-6.1, respectively. The DOC-specific dose varied in the range of 0.54-1.35 mg Al/mg DOC, i.e. 20-50 µmol Al/mg DOC. The amount of DOC removed was in the range of 17-42 mg DOC per mmol of Al added. With constant NOM characteristics, a close to stoichiometric (constant) relationship is expected to exist between NOM content and coagulant dose requirement, i.e. a 1:1 relationship. At Port Charlotte WTW the ratio between the maximum and minimum DOC-specific coagulant dosages is 2.5. Because of the relatively stable NOM fraction distribution in the raw water, this is taken as an indication of a coagulation process optimization potential and a potential for improved process control, i.e. a better adaptation of coagulation conditions to the prevailing raw water quality.



Figur 5-10-1 Port Charlotte WTW

The filtration rates applied during the sampling period were 2.6-3.2 m/h, which is regarded a low to moderate hydraulic filter loading.

A comparative study (benchmark) of the coagulation conditions and coagulation performance among the utilities is presented in Chapter 6.

Water quality: Routine parameters, NOM fractions, BDOC and ATP. A summary of the raw and treated water qualities from the four NOMiNOR seasonal sampling rounds is listed in Table 5-10-1. A high hydrophobic content (90 % on average) and a high average SUVA-value (4.7) indicate good treatability by coagulation.

The raw water quality was very variable, with min and max colour and UV-absorbance levels within the broad ranges of 74-321 mg Pt/L, and 29-140 m^{-1}, during the four samplings rounds. Turbidity and TOC varied within the ranges of 0.7-2.5 NTU, and 7.7-29.5 mg/L, respectively. Most of the organic matter was dissolved, with DOC levels at 95 % of TOC on average.

Despite the poor raw water quality, the clean water quality was good. The process control challenges related to the great variability in raw water quality were however reflected in some variability in the clean water quality. The min and max levels of colour varied within the range of 0-6 mg Pt/L, UV-absorbance within 1.8-8.9 m^{-1}, turbidity within 0.1-0.3 NTU, DOC within 1.3-4.4 mg/L, and BDOC within 0.23-1.27 mg/L (0.53 mg/L on average). This was in fact by far the highest BDOC levels measured in any water sample from the 10 utilities, and was due to a substantial chlorine-driven increase in BDOC in clean water samples. To illustrate the effects of chlorine, the average BDOC values measured after chlorination and in the RGF outlet prior to chlorination were 0.53 and 0.08 mg/L, respectively (Table 5-10-1).

The BDOC concentration levels were reduced substantially in the distribution system, indicating microbial substrate (BDOC) consumption on the way from the CWT to the DS sampling point. This observation was supported by the fact that the ATP levels were also increasing from the clean water samples to the distribution system samples, thus indicating microbial regrowth - despite the presence of chlorine residuals.

Table 5-10-1 Water Quality data – Port Charlotte WTW. Average±StDev, minimum-maximum values (Sampling dates: May 18; Aug 31; Nov 2, 2015; Feb 16, 2016). Sampling spots: Out Clarifier: After coagulation, up-flow clarification; Out RSF: After 1-M sand filtration; Out CWT: After Clean Water Tank (incl. secondary filtration and chlorination); DS: From the Distribution System.

PC	Colour (mg Pt/L)	UV-A (m-1)	Turb (NTU)	DOC (mg/L)	VHA (%)	SHA (%)	CHA (%)	NEU (%)	SUVA (L/m mg)	BDOC (mg/L)	ATP (pmol/L)
Raw Water	173±119 74-321	75.3±52.9 29-140	1.5±0.8 0.7-2.5	15.7±10.5 7.0-28.8	80±5 75-85	10±2 8-12	6±1 5-7	4±2 2-6	4.7±0.5 3.9-5.0	0.70±0.51 0.28-1.40	363±102 287-1512
Out Clarif	6±2 4-7	7.7±3.8 24.0-11.5	0.2±0.1 0.1-0.3	3.5±1.4 2.0-4.9	59±2 58-61	20±1 19-21	4±3 1-7	16±5 12-22	2.2±0.2 2.0-2.4	0.14±0.05 0.10-0.19	63±57 19-127
Out Filter	6±3 2-9	6.3±3.8 2.5-11.1	0.1±0.0 0.1-0.1	2.8±1.5 1.2-4.5	54±4 48-57	21±1 20-22	7±4 3-11	23±6 17-28	2.2±0.2 2.1-2.5	0.08±0.04 0.04-0.11	29±12 14-42
Out CWT	3±3 0-6	4.8±3.3 1.8-8.9	0.1±0.1 0.1-0.3	2.8±1.4 1.3-4.4	54±8 41-60	19±2 16-21	9±3 5-13	18±10 12-33	1.6±0.3 1.3-2.0	0.53±0.50 0.23-1.27	0±1 0-1
DS	3±3 0-5	4.8±3.2 1.7-8.7	0.1±0.1 0.1-0.2	2.8±1.4 1.3-4.5	47±10 39-57	22±3 19-25	9±4 5-15	21±12 9-31	1.6±0.3 1.3-2.0	0.37±0.11 0.26-0.51	18±37 0-73

Analytical errors. Calculated analytical errors for DOC, VHA, SHA, CHA, NEU, BDOC and cellular ATP for all four sampling rounds and all sampling sites are listed in Table 5-10-2. In addition, average as well as minimum and maximum values are presented for all samples, along with average values found for each of the sampling sites.

Table 5-10-2 Analytical Error Data – PORT CHARLOTTE WTW. Standard errors calculated from triplicate measurements of DOC, NOM fractions, BDOC and cellular ATP.

Date	Sample	StDev						
		mg/L						nmol/L
		DOC	**VHA**	**SHA**	**CHA**	**NEU**	**BDOC**	**ATP**
18.05.2015	**Raw**	0,07	0,08	0,02	0,02	0,02	0,20	0,012
	Out RGF	0,02	0,03	0,02	0,02	0,01	0,01	0,002
	Out CWT	0,02	0,02	0,02	0,01	0,01	0,02	0,000
	DS	0,02	0,02	0,01	0,01	0,02	0,01	0,000
31.08.2015	**Raw**	0,38	0,39	0,12	0,07	0,01	0,41	0,034
	Out RGF	0,13	0,14	0,05	0,03	0,01	0,02	0,001
	Out CWT	0,09	0,09	0,06	0,02	0,02	0,03	0,001
	DS	0,03	0,03	0,04	0,02	0,02	0,04	0,001
02.11.2015	**Raw**	0,17	0,21	0,13	0,03	0,01	0,77	0,020
	Out RGF	0,09	0,09	0,05	0,06	0,02	0,05	0,001
	Out CWT	0,04	0,04	0,05	0,03	0,02	0,02	0,000
	DS	0,07	0,07	0,01	0,02	0,01	0,07	0,004
16.02.2016	**Raw**	0,14	0,15	0,06	0,05	0,03	0,21	0,069
	Out RGF	0,07	0,07	0,03	0,03	0,02	0,00	0,000
	Out CWT	0,03	0,03	0,01	0,02	0,01	0,02	0,000
	DS	0,02	0,02	0,01	0,01	0,01	0,01	0,000
AVG		***0,09***	***0,09***	***0,04***	***0,03***	***0,02***	***0,12***	***0,009***
MIN		***0,02***	***0,02***	***0,01***	***0,01***	***0,01***	***0,00***	***0,000***
MAX		***0,38***	***0,39***	***0,13***	***0,07***	***0,03***	***0,77***	***0,069***
AVG-Raw		***0,19***	***0,21***	***0,08***	***0,04***	***0,02***	***0,40***	***0,034***
AVG-RGF		***0,08***	***0,08***	***0,04***	***0,04***	***0,02***	***0,02***	***0,001***
AVG CWT		***0,05***	***0,05***	***0,04***	***0,02***	***0,02***	***0,02***	***0,000***
AVG DS		***0,04***	***0,04***	***0,02***	***0,02***	***0,02***	***0,03***	***0,001***

In general, the analytical errors were low, with the highest absolute values found during the August 2015 sampling round. This “worst case” situation with respect to analytical error is illustrated in Figure 5-10-2.

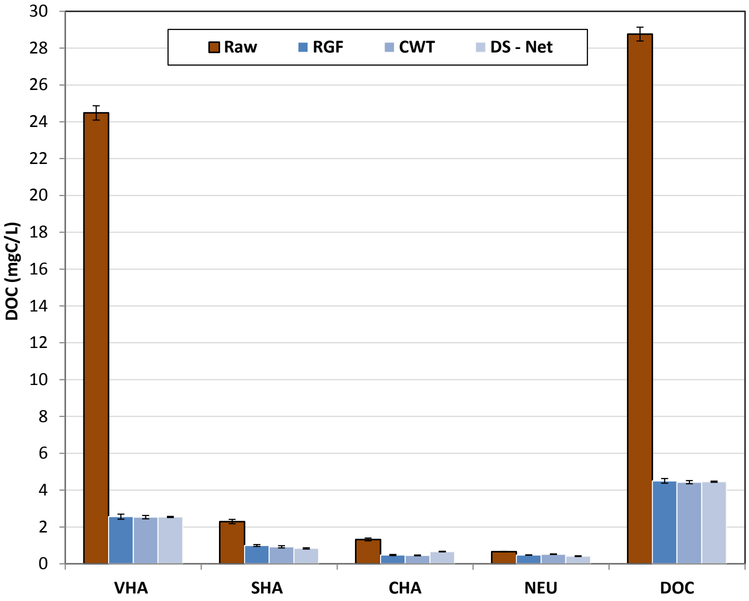


Figure 5-10-2 Water Quality data – PORT CHARLOTTE WTW (August 2015). DOC and NOM-fraction concentrations with standard error bars calculated from triplicate measurements.

NOM fractions and NOM fraction removal. As mentioned above, the raw water DOC at this utility is dominated by the hydrophobic NOM-fractions (90 % VHA+SHA on average), which is the highest value measured among all ten utilities. Accordingly, the hydrophilic fraction concentration (10 %), with 6 % CHA and 4 % NEU) is the lowest value found among all utilities. Despite the low fraction of hydrophilic NOM, the BDOC is very high in raw water - on average 0.7 mg/L, i.e. 4.4 % of the total DOC, within a min to max range of 3.8-5.3 %. Only IVAR’s raw water has a higher average BDOC fraction (6.9 % of tot-DOC).

During coagulation and filtration (out rapid gravity filter, RGF), the DOC removal efficiency was on average 81 %, with minimum and maximum values of 74 and 84 %, respectively. The hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) NOM fraction removal efficiencies were on average 84 and 52 %, within the min and max ranges of 76-85 %, and 49-56 %, respectively. The poorest removal during coagulation was as expected found for the NEU fraction, with an average removal of 20 % (7-32 %) during this treatment step.

The changes in water quality and overall removal efficiency during treatment and distribution are presented in Table 5-10-3. Here the total average removal efficiencies (i.e. % reduction relative to the content in raw water) are presented for selected water quality parameters.

Table 5-10-3 Water Treatment data – PORT CHARLOTTE WTW (Scottish Water). Average total Removal Efficiencies (%) obtained after different treatment steps (Sampling dates: May 18; Aug 31; Nov 2, 2015; Feb 16, 2016).

PORT CHARLOTTE WTW (Total % Removal)	Post Clarification	Out RGF	Out CWT1)	DS
UV-abs	90	91	93	93
DOC	79	81	81	81
VHA+SHA	82	84	84	85
CHA+NEU	54	52	46	39
NEU	5	20	16	3
BDOC	75	87	6	31
ATP	85	92	100	95
Incl. chlorination and secondary filtration				

A slight bleaching effect can be seen as a reduced UV-A in Table 5-10-3 (i.e. increased % removal) from the chlorine contact in the CWT. DOC removal increased from 79 % after coagulation and clarification, to 91 % after sand filtration (RGF), and eventually to 93 % after the CWT. These numbers illustrate well the major effects of coagulation. The results also demonstrate how chlorine was able to increase the concentration (and reduce % removal) of hydrophilic NOM, including the NEU fraction, thereby increasing the BDOC concentration substantially. Due to the high BDOC, the ATP levels increased during distribution, despite the residual chlorine present.

The secondary filter step installed primarily for Mn removal, did not appear to have any great influence on the water quality parameters presented here. The average concentration of Mn decreased from 41 µg/L in raw water to 19, 16, 11 and 12 µg/L after clarification, RGF, CWT and DS, respectively. For iron (Fe) the numbers were 1254, 9, 1, 1 and 3 µg/L, and for Al 98, 135, 12, 12 and 13 µg/L, respectively.

It should be pointed out that the average results from the "Post Clarification" sampling point included three sampling rounds only, and that the results therefore are not directly comparable to those from the other sampling points.

Elements and residual metals. The elemental data of metal coagulant residuals (Al) and specific elements with significant change in concentration during treatment and distribution are presented in Figure 5-10-3.

When using alum for coagulation, the increase in the sulphur (S) concentration from raw water to coagulated water samples reflects the coagulant dosage, and thus the measured concentration increase in S can be used to back-calculate/control the coagulant dosage from information on the coagulant's product data sheet. At Port Charlotte WTW, the increase in S-concentration levels varied a lot between the sampling rounds (11-34 mg/L), in line with the great variability in the applied alum coagulant doses discussed before (5.7-18.1 mg Al/L).

Metal coagulant residuals, i.e. residual Al-concentrations after coagulation and clarification were high in the May and August 2015 sampling rounds. After the RGF, however, residual Al was low (18 µg/L at maximum) in all sampling rounds, thus indicating close to optimal coagulation conditions. The DOC-specific Al-dose varied considerably, and the highest dose was applied during the February 2016 sampling round (1.35 mg Al/mg DOC), and the lowest in August 2015 (0.54). The NOM content in the raw water quality was significantly higher during the August and November 2015 samplings rounds, and this was clearly reflected in the clean water quality as well, despite the higher coagulant dosages used during these periods.

The large S-concentration increase from raw water to treated water reflects the high alum sulphate doses applied during the August and November 2015 samplings (Figure 5-10-3). The Na-concentration patterns show the influence of the soda ash dosage prior to the coagulation step, and of the dosage of soda ash and NaOCl after the RGF. The measured increase in Cl-concentration from the clarifier to the CWT was 2-4 mg/L, thus indicating the range and variability of the applied NaOCl doses.

Fe and Mn were effectively removed during coagulation and separation (Figure 5-10-3). However, Mn removal was very poor (non-existing) during the August 2015 sampling round. The reason for this is unknown, but as stated above the dosage level was at its lowest levels during this time, both in terms of absolute and DOC-specific dosage.

The levels of Ca in the raw water varied from one sampling time to the other, though the Ca concentrations remain unaffected by the treatment process (i.e. no dosing of Ca-containing substances for pH and/or corrosion control, only soda ash that is reflected in the Na concentration patterns).

It should also be mentioned that the Cu concentration increased considerably from the RGF outlet (1.4 µg/L) to the DS sampling point (11.2 µg/L). Likewise, the concentration of Ni increased from the RGF sample (1.4 µg/L) to the CWT sample (> 1 µg/L). The reason for this is unknown, but it can be due to Cu/Ni-containing materials and/or sampling taps. It should be kept in mind however, that Cu was analysed only once (May 2105 sampling round), and Ni twice (May and August 2015).

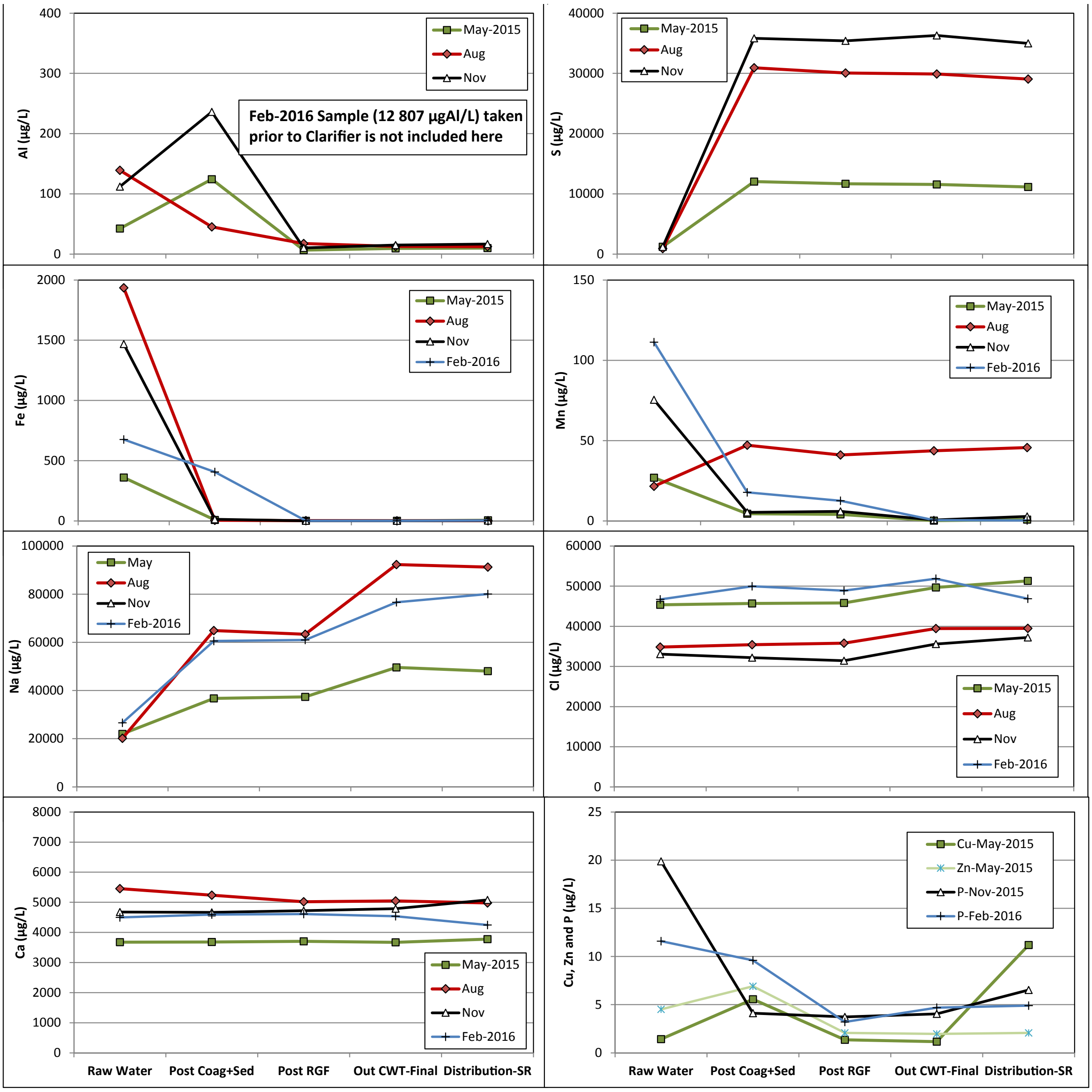


Figure 5-10-3 Water Quality data – PORT CHARLOTTE WTW. Al, S, Fe, Mn, Na, Cl, Ca, Cu, Zn and P concentration profiles during treatment and distribution.

For PC WTW, the major findings are summarized below.

- Large seasonable variation in raw water quality (7-29 mg DOC/L; 360-1935 µg Fe/L; 30-120 µg Mn/L; 40-140 µg Al/L)
- High SUVA (3.9-5.0) and high hydrophobic NOM content (VHA+SHA 87-93 % of DOC) indicates good treatability by coagulation
- Substantial variation in coagulant dose level: 5.7-18.1 mg Al/L, and in DOC-specific doses: 20-50 µmol Al/mg DOC (can be controlled by the S-concentration increase)
- Coagulation pH: 5.9-6.1
- A high residual-Al after coagulation/clarification observed in May (> 100) and November 2015 (> 200 µg Al/L) indicate sub-optimal coagulation conditions
- Fe, P and Mn (except Aug 2015) effectively removed during coagulation
- Low filtration (RGF) rates: 2.6-3.2 m/hr
- No significant effects on NOM from the secondary filter (some Mn removal achieved)
- Substantial increase in BDOC from chlorination
- The low ATP in CWT samples are significantly increased in DS samples. Regrowth not controlled by chlorine residuals
- Increase in Cu concentration from CWT to DS samples (May 2015)
- Optimisation of coagulation/process control recommended

5.11. Advanced water quality analyses

5.11.1. FT-ICR-MS analyses – SINTEF (K. Zahlsen)

FT-ICR-MS - Methodological considerations
Ultrahigh resolution mass spectrometry by FT-ICR-MS is a relatively new analytical technique that is especially useful for the characterization of complex chemistry. The FT-ICR-MS analyses in the NOMiNOR project had a descriptive main focus where the major aim was to understand better how the results from the project could contribute generically to the understanding of water chemistry related to water treatment processes.

Quality assurance
The solid phase sampling procedure was adopted from literature (Dittmar et al. 2008). The reason was that this procedure has been the prevailing methodology for most studies with FT-ICR-MS during the latest years. For the instrumental FT-ICR-MS methodology, electrospray ionization in the negative mode was chosen on the basis of the literature (Andrilli et al. 2013). We compared our specifications and found complete compliance with the mass spectrometric mass determinations and the assignment of elemental formulae.

We have studied the precision of the methodology by checking the reproducibility by repeated injections (5 replicates) of the same samples from our local water supply system in Trondheim (Lake Jonsvatnet (JV). Here we found good precision. Figure 5-11-1-1 shows the results for the O5 to O15 compounds (i.e. NOM compounds containing 5 to 15 oxygen atoms). We have used a reference sample from JV as a quality control sample when analyzing unknown samples throughout the NOMiNOR study.

Results
The results section shows generalized data with some main findings highlighted as examples. The results from all ten waterworks are presented (Round 4), with comments. The results are discussed in a separate section.

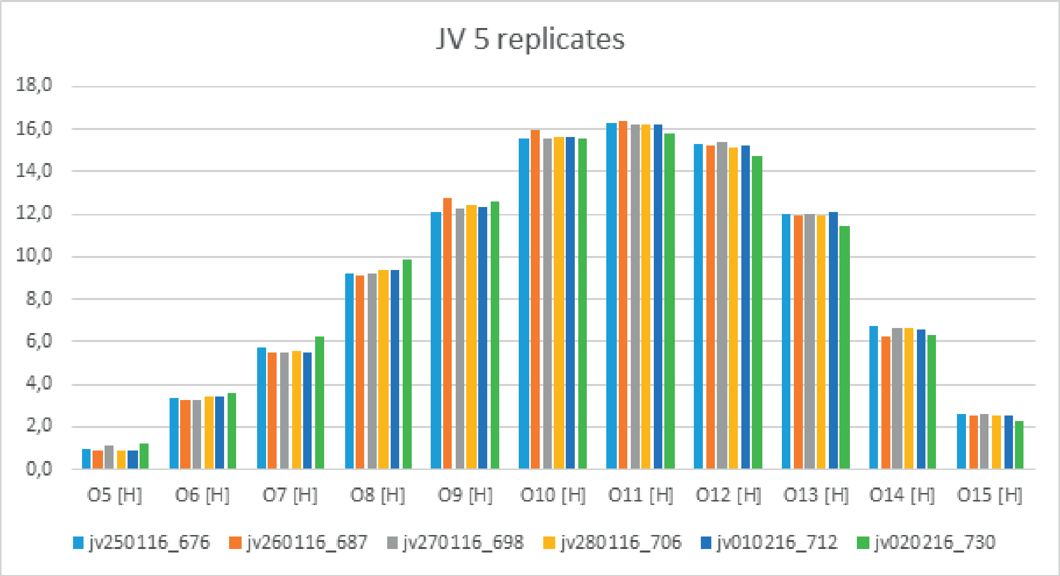


Figure 5-11-1-1. Method precision for the response for O5 to O15 compounds in n=5 repetitive analyses shown as bar plot in a quality control sample from Jonsvatnet (JV) in Trondheim.

The NOM analyses of WTW samples by FT-ICR-MS have revealed:

- Differences do exist between different WTW and different treatments (Figure 5-11-1-2)
- Seasonal differences do exist as well (Figure 5-11-1-2)

Figure 5-11-1-2 below shows differences between different WTW treatments (S1 to S5) and seasonal differences (Round 1 to 4). The example is taken from Ringsjöverket, Sydvatten. The mass spectra display molecular weight ranges from 200 to 1200 Dalton, and it can be seen that most of the NOM lies within the range of 200 to 600 Dalton. However, the samples from round 2 (September) seem to have a broader range in molecular weight compared to round 1, 3 and 4.

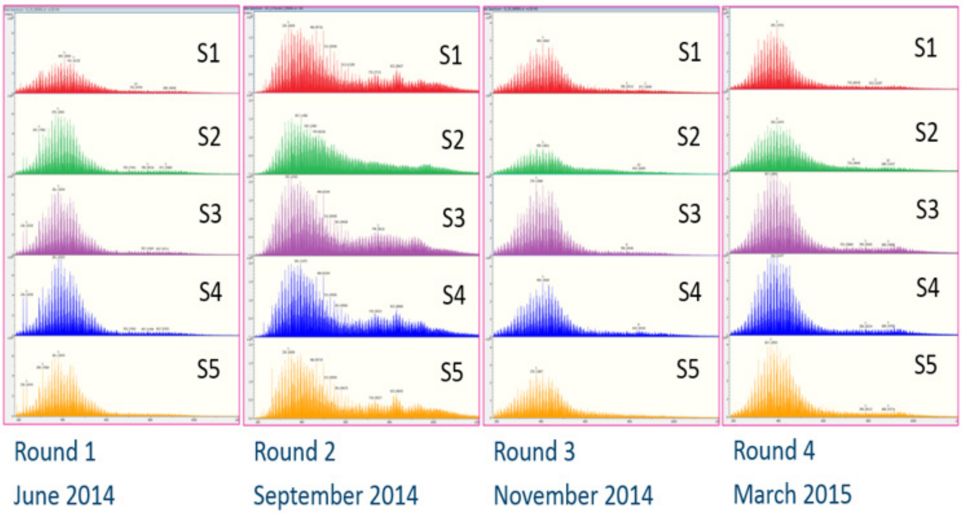


Figure 5-11-1-2 Differences between different WTW treatment (S1 to S5) and seasonal differences (Round 1 to 4). The example shown is Sydvatten. The x-axes show the molecular weights of the NOM compounds displayed as the mass-to-charce (m/z) ratio. For all figures, the same range is displayed (200 to 1200). The y-axes show the response (arbitrary units) using the same range so that the responses are comparable from one spectrum to another. Differences between WTW treatments (S1 to S5) and seasonal differences (Round 1 to 4) are shown. Example Sydvatten. S1: Raw water; S2: Coagulated, settled and sand filtered; S3: After slow sand filter; S4: Chlorinated water (CWT); S5: Distributed water (from network).

The data processing and interpretation of results show:

- Information about different elements in formula (C, H, O, Cl)
- It is possible to characterize NOM by:
  - o Carbon number
  - o Double bond equivalents (aromaticity)
  - o Molecular weights
  - o Relative abundance

Figure 5-11-1-3 below shows the overall change in the number of oxygen atoms of NOM by the relative content of O2 to O15 molecules. Examples are taken from Ringsjöverket, Sydvatten and Görväln, Norrvatten. Both examples indicate that the treatments influence on the types of NOM from raw water (S1) to distributed water (S5). The overall effect is that the relative amount of large molecules is lower in treated and distributed water than in the raw water.

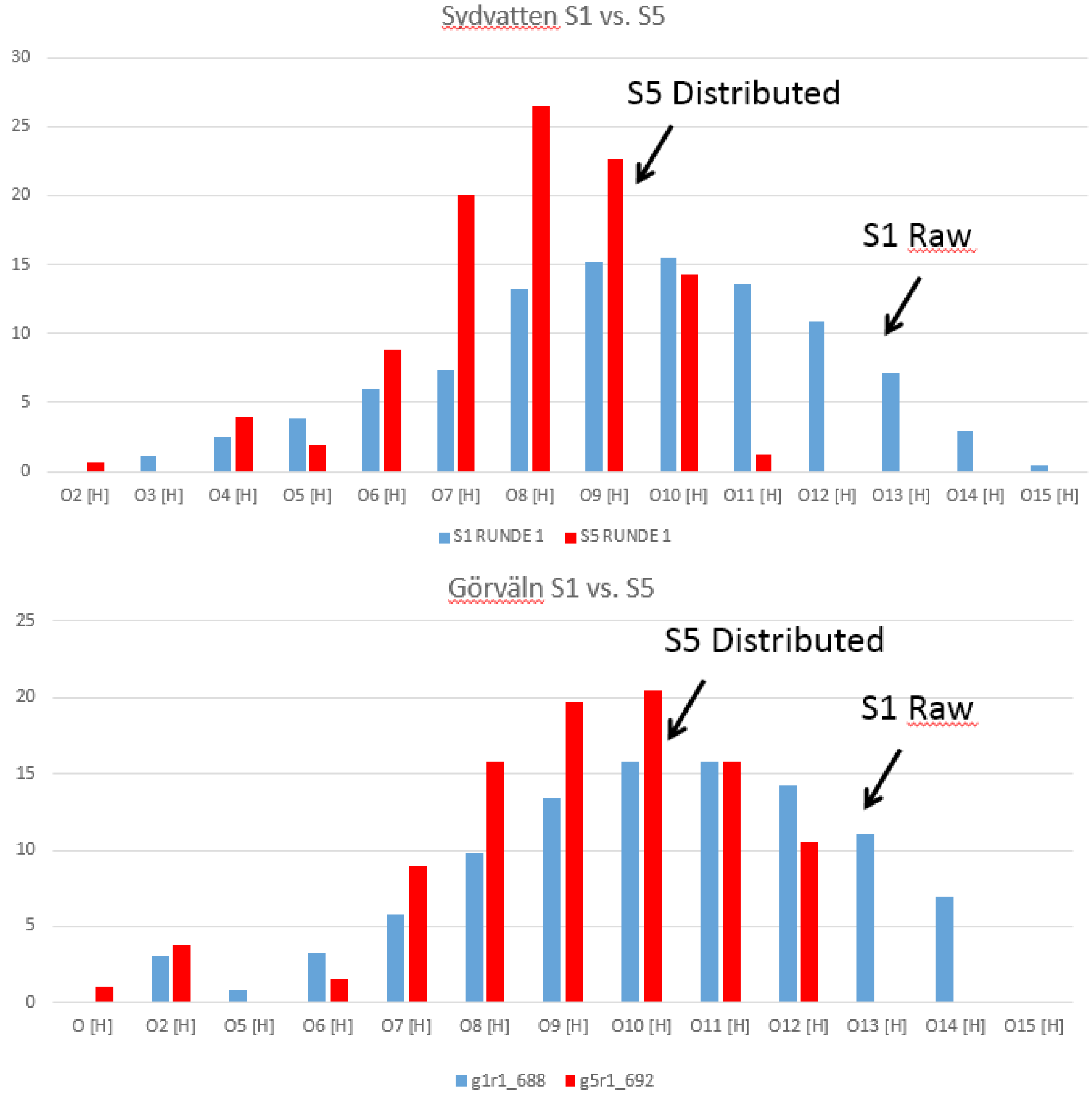


Figure 5-11-1-3 Differences between main groups of molecules, O2 to O15 (molecules with 2 to 15 oxygen atoms per molecule) Example Sydvatten (upper) and Görväln (lower).

Figure 5-11-1-4 show (tabulated), carbon number (# carbons), double bond equivalents (DBE) and molecular weight (MW) for groups of NOM molecules containing 3 to 15 oxygen atoms (compound class O3 to O15). The table gives an overview of chemical information that can be derived from the FT-ICR-MS analyses. The table also show the relative response for the different groups O3 to O15.

Sydvatten S1 Round 1				
Class	Rel. Response %	#Carbons	DBE	MW
O3	1.1	11-16	5-7	194-260
O4	2.53	11-17	4-8	205-293
O5	3.84	11-20	4-9	223-347
O6	5.96	11-23	5-10	241-401
O7	7.38	12-25	5-11	269-445
O8	13.29	12-28	5-12	285-503
O9	15.19	14-29	6-13	327-533
O10	15.53	15-30	6-14	353-561
O11	13.64	16-30	7-15	383-577
O12	10.87	17-30	8-16	409-593
O13	7.11	18-31	9-15	441-621
O14	2.91	20-31	10-13	481-633
O15	0.42	20-31	12	479-633

Figure 5-11-1-4 Table showing chemical information derived from FT-ICR-MS data. Carbon number (# carbons), double bond equivalents (DBE) and molecular weight (MW) for NOM compounds containing 3 to 15 oxygen atoms (O3 to O15) and relative response (Rel. response %).

Data processing and interpretation of results from the different WTWs have revealed:

- Alteration of NOM composition by different treatments
- Selective reduction of certain NOM classes (O11 to O15)
- Selective reduction of certain compound classes (aromatics)
- Nanofiltration and coagulation removes different NOM classes

Figure 5-11-1-5 shows Van Krevelen plots of NOMs in samples taken after coagulation and clarification, after rapid gravity filtration, and from the distribution system (Example from Port Charlotte (PC) WTW Scotland). The Van Krevelen plots show that the first coagulation-clarification step removes NOMs, but mostly the compound classes that show the highest degree of aromaticity. However, the subsequent filtration (RGF) step seems to remove a considerable portion of the remaining components before the water is distributed.

Figure 5-11-1-6 shows Van Krevelen plots of NOMs after treatment with nanofiltration-NF (Example taken from Bracadale (BRA) WTW Scotland). The plot demonstrates the removal of more classes of NOMs than for example the coagulation step at Port Charlotte (Figure 5-11-1-5). The observed removal of more classes of NOM compounds by NF at Bracadale is consistent with other results in this study (see for example Ch. 6, Figures 6-1 and 6-2).

Results from each of the WTWs

For comparison between the individual waterworks in this study, Van Krevelen plots are presented below for each waterworks (Figures 5-11-1-7 to 5-11-1-16). Due to the great amount of data generated in this study, results are presented for Round 4 (R4) only. The figures present each treatment process step in a consecutive order from upper left to lower right. The result from each treatment step is labelled in accordance with the sample number from sample number 1 (raw water) and upwards.

The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1 (same scale for all). The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2 (same scale for all).

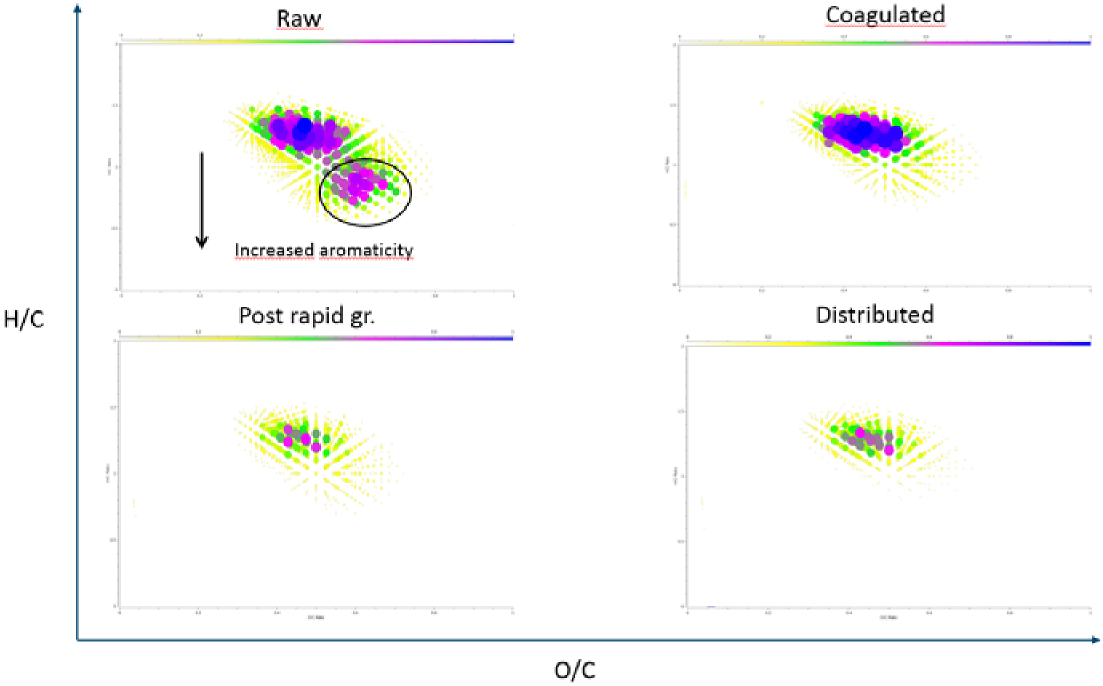


Figure 5-11-1-5 Removal/changes of different NOM compounds during coagulation-clarification and post gravity filtration (Example Port Charlotte (PC) WTW Scotland). Note that some of the more aromatic compounds seems to be removed selectively during coagulation.

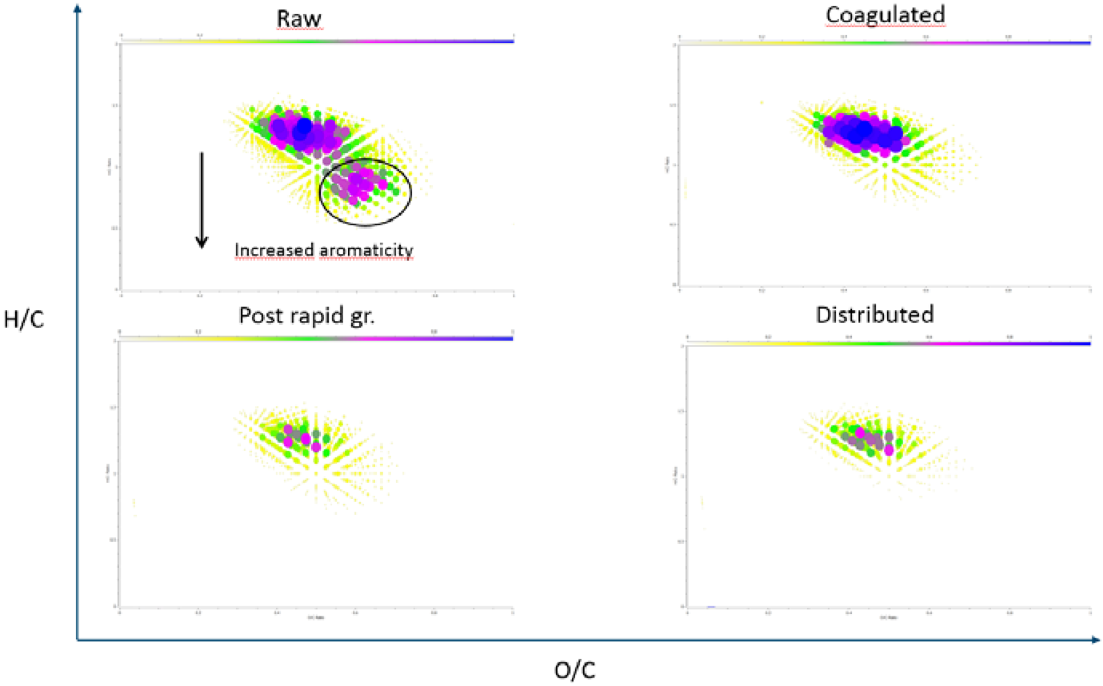


Figure 5-11-1-6 Removal/changes of different NOM compounds during nanofiltration (NF) and active carbon (GAC) filtration. (Example Bracadale (BRA) WTW Scotland) Note the larger number of NOM classes are removed by nanofiltration.

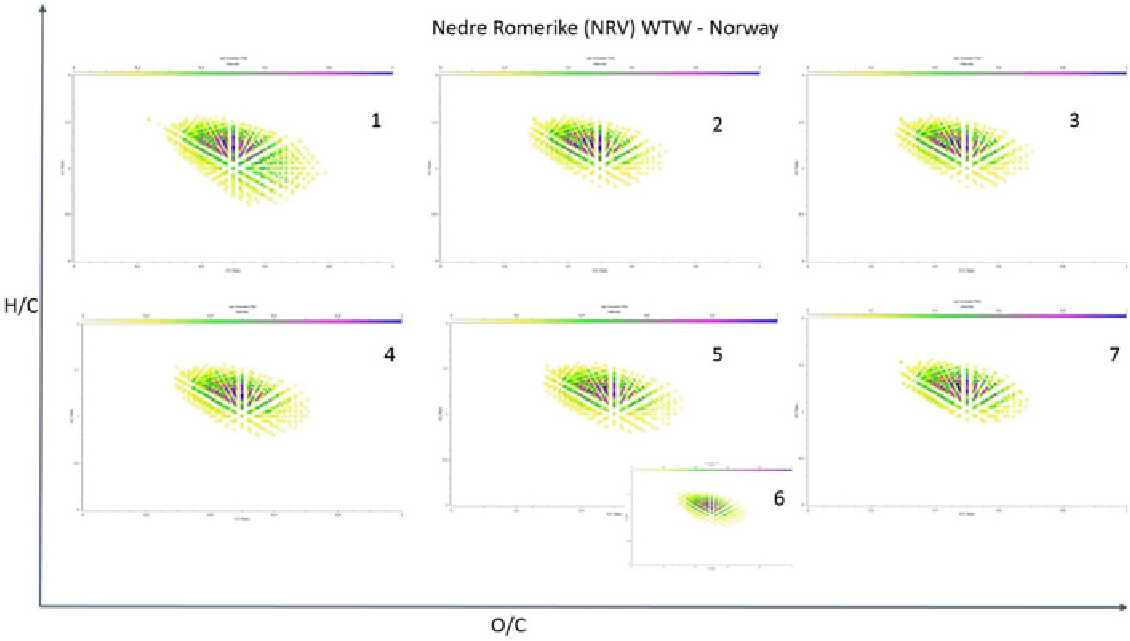


Figure 5-11-1-7 Van Krevelen plots generated from mass spectral data of samples from NRV. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. Legend 1: Untreated Raw water; 2: After coagulation (sed-super pulsator); 3: After 2-M filtration; 4: After GAC-filtration (line 2, 2 years old GAC); 5: After UV – before chlorination and pH adjustment; 6: Out after chlorination and pH adjustment K100; 7: Distribution network (K534)

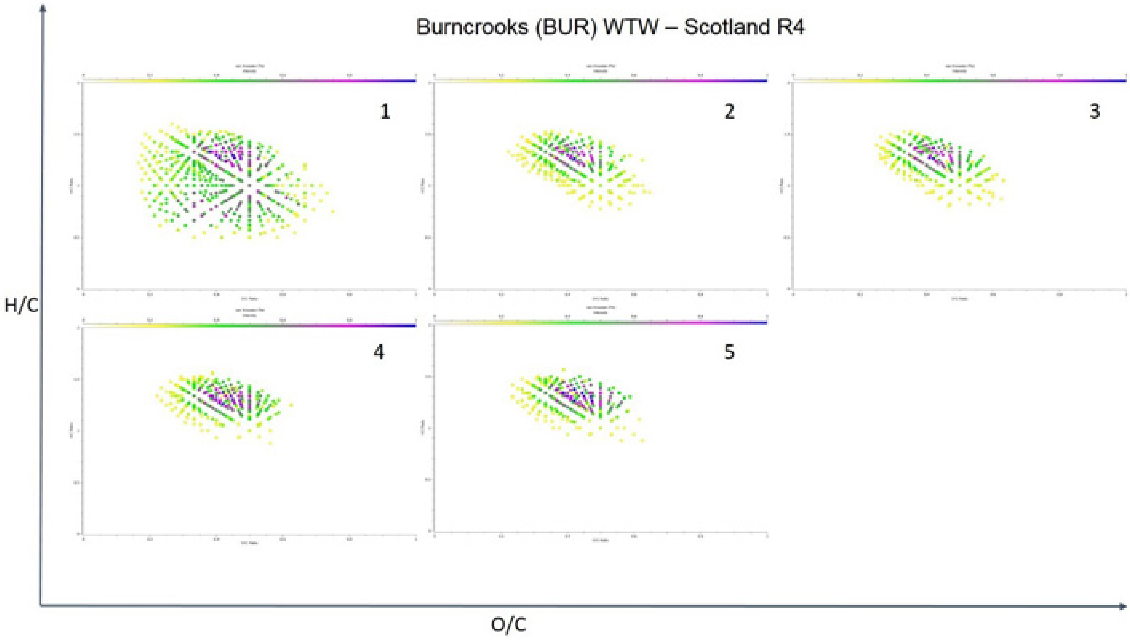


Figure 5-11-1-8 Van Krevelen plots generated from mass spectral data of samples from BUR. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Raw; 2: Combined post clarification (upward flow clarifiers); 3: Combined filtered; 4: Chlorinated final water; 5: Distribution SR

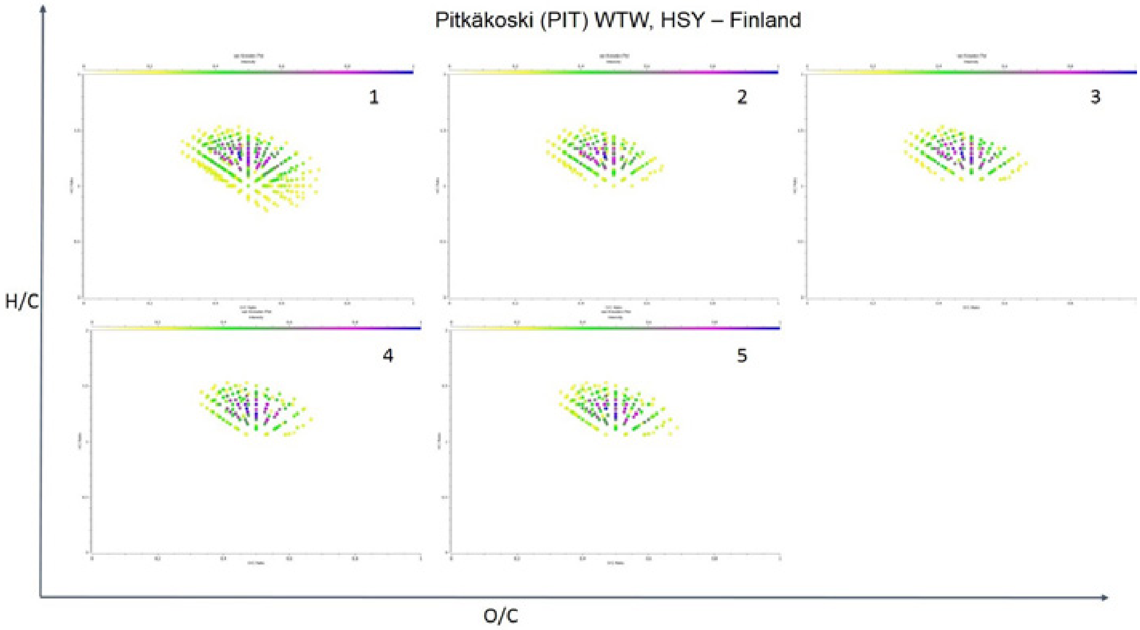


Figure 5-11-1-9 Van Krevelen plots generated from mass spectral data of samples from PIT. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Raw water (untreated raw water); 2: Out Coag+Sed+Filt (Coagulated settled and filtered water-Out filter 1); 3: Out Oz (Ozonated); 4: Out CWT (After GAC and chlorine contact tank -Chlorinated); 5: Distribution (from distribution network)

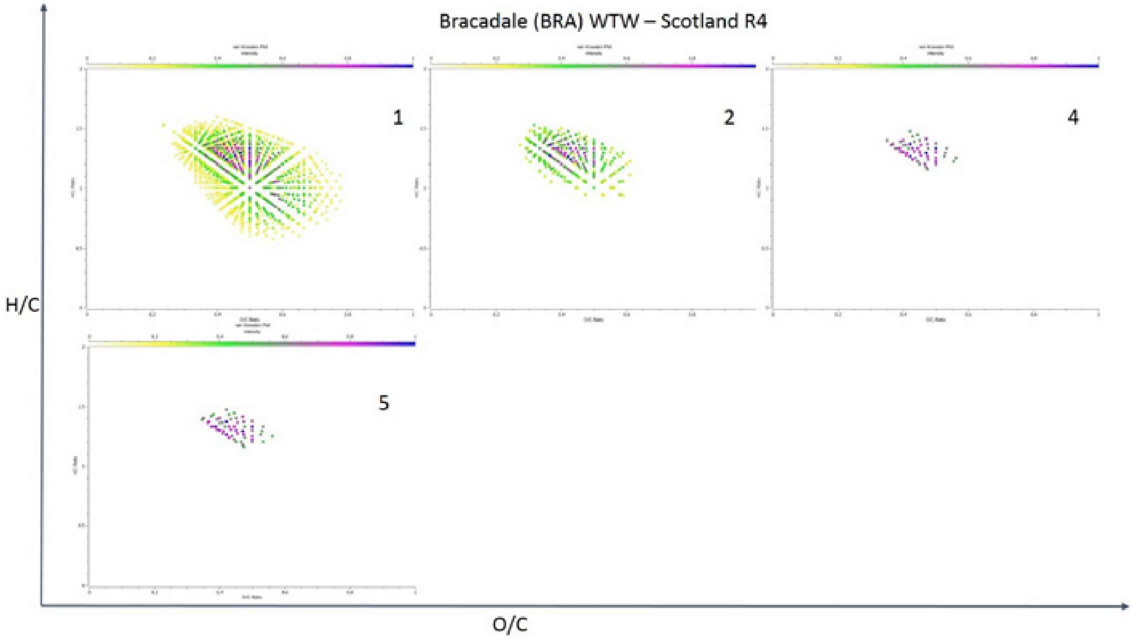


Figure 5-11-1-10 Van Krevelen plots generated from mass spectral data of samples from BRA. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Raw water; 2: Post membrane (nanofiltration); 3: Post GAC (sample missing); 4: Final water; 5: Distribution SR

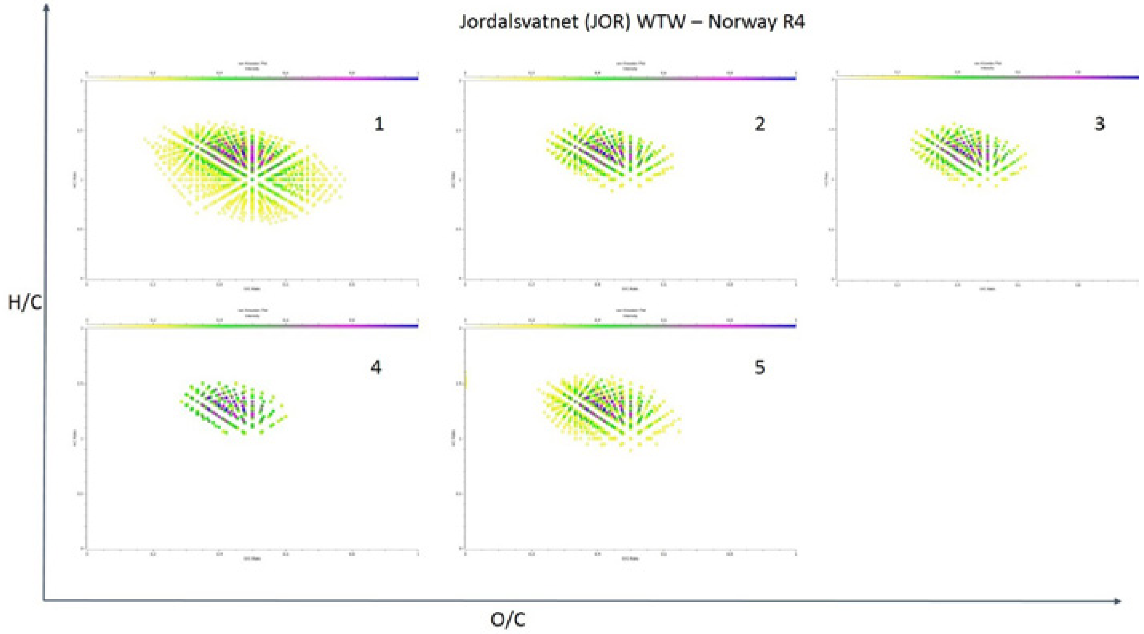


Figure 5-11-1-11 Van Krevelen plots generated from mass spectral data of samples from JOR. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Raw; 2: Coagulated and 3-M filtered (Out filter); 3: Out UV; 4: Out CWT; 5. Distribution system (Network)

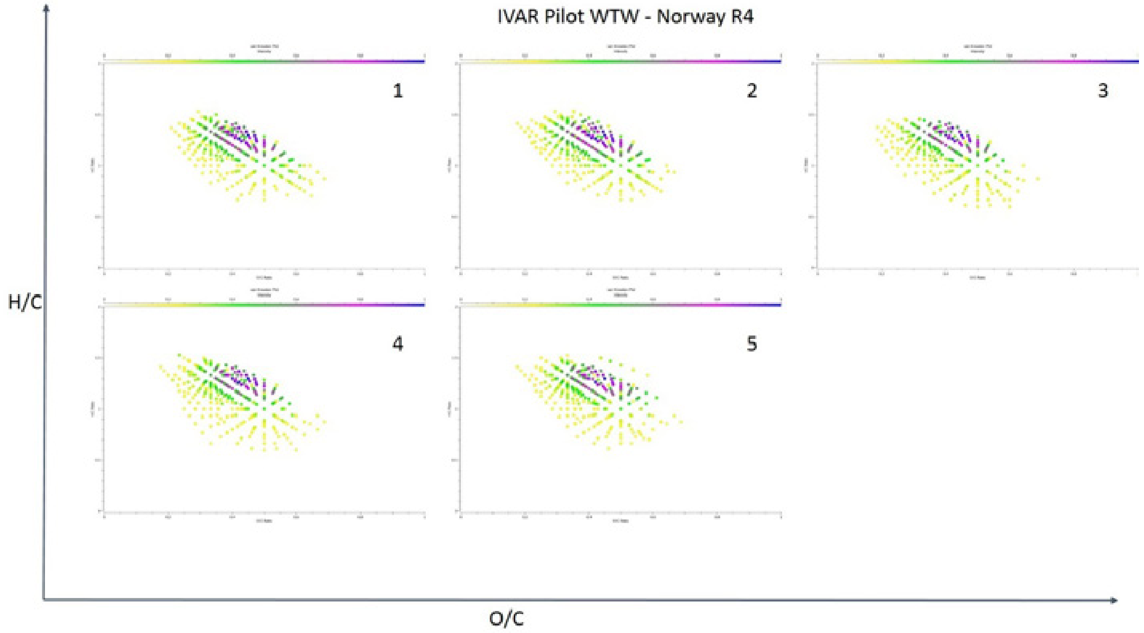


Figure 5-11-1-12 Van Krevelen plots generated from mass spectral data of samples from IVAR. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Raw; 2: Ozonated (Out Oz); 3: Alkaline Filter (Out ALK-filter); 4: Out Biofilter; 5: Clean water

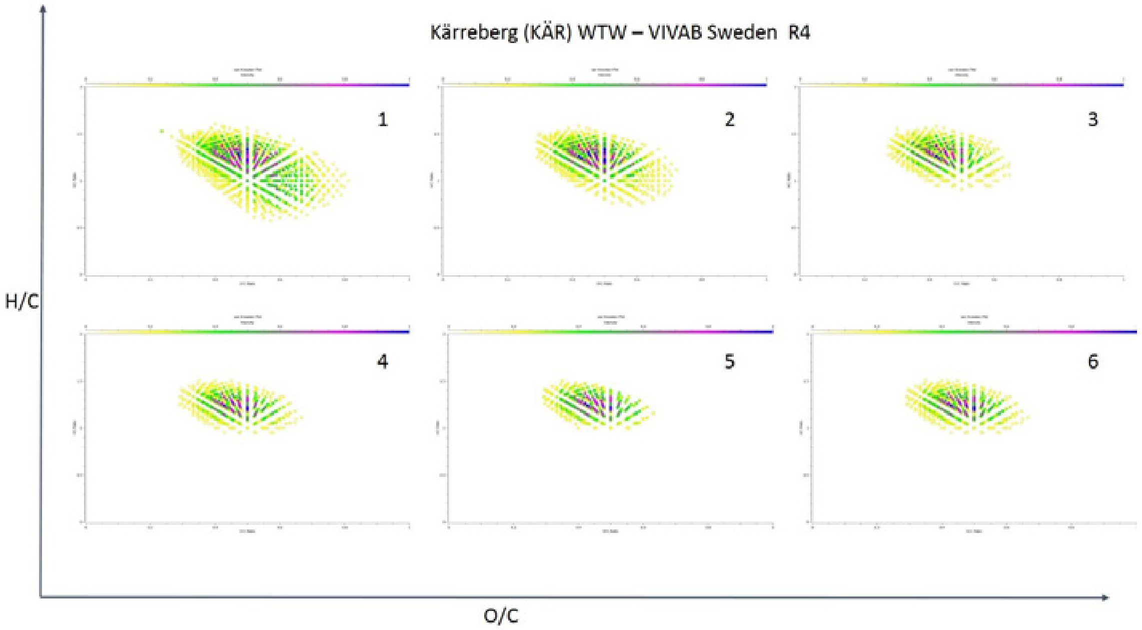


Figure 5-11-1-13 Van Krevelen plots generated from mass spectral data of samples from KÄR. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Inlet; 2: After filtration; 3: Effluent (Lamella sedimentation); 4: Drinking water outlet; 5: Distribution network (Stadshuset)

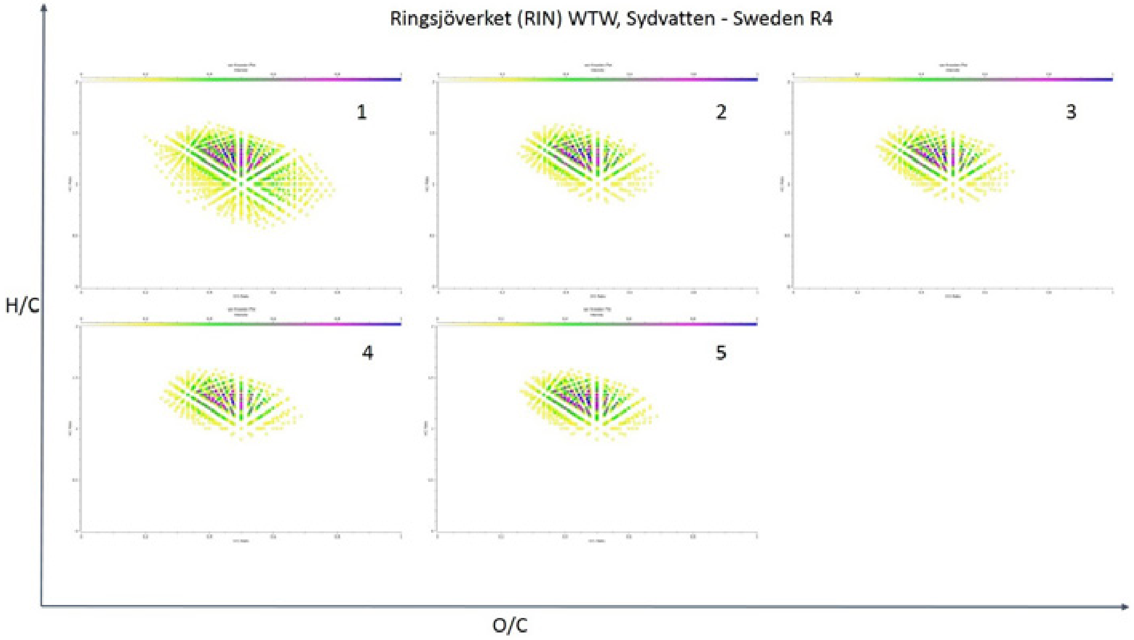


Figure 5-11-1-14 Van Krevelen plots generated from mass spectral data of samples from RIN. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Untreated raw water (Raw); 2: Coagulated, settled and sand filtered water (Out SF); 3: After slow sand filter (Out slow sand); 4: After chlorine contact tank (Chlorinated); 5: From distribution network (Network)

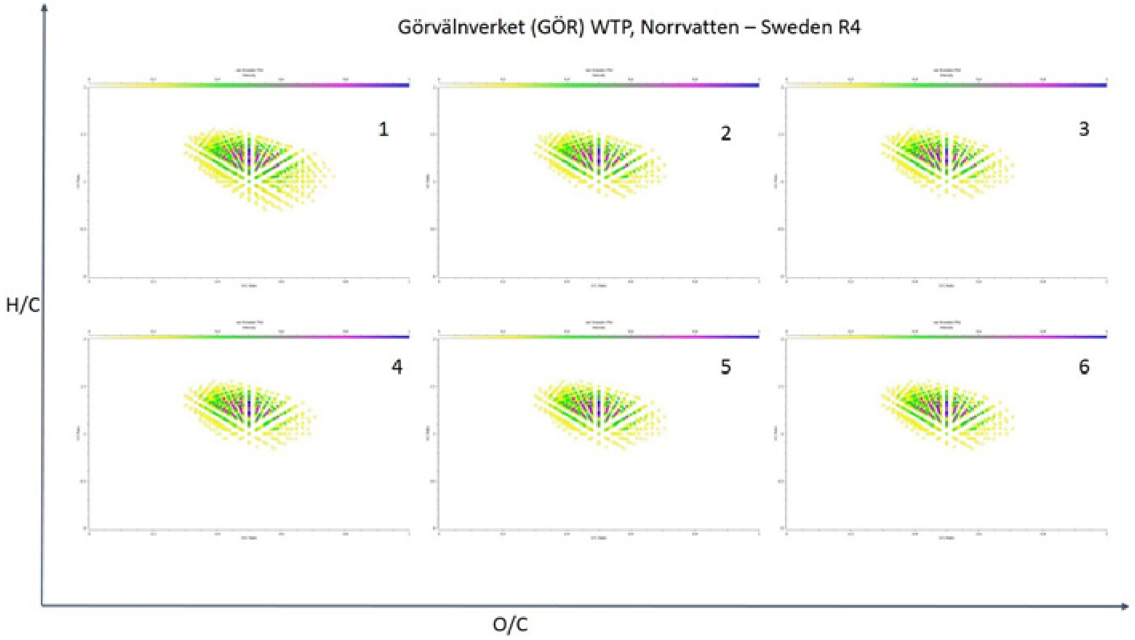


Figure 5-11-1-15 Van Krevelen plots generated from mass spectral data of samples from RIN. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Raw water; 2: Sand filtrate; 3: GAC filtrate; 4: Drinking water; 5: Distribution system Rosenberg; 6: After UV

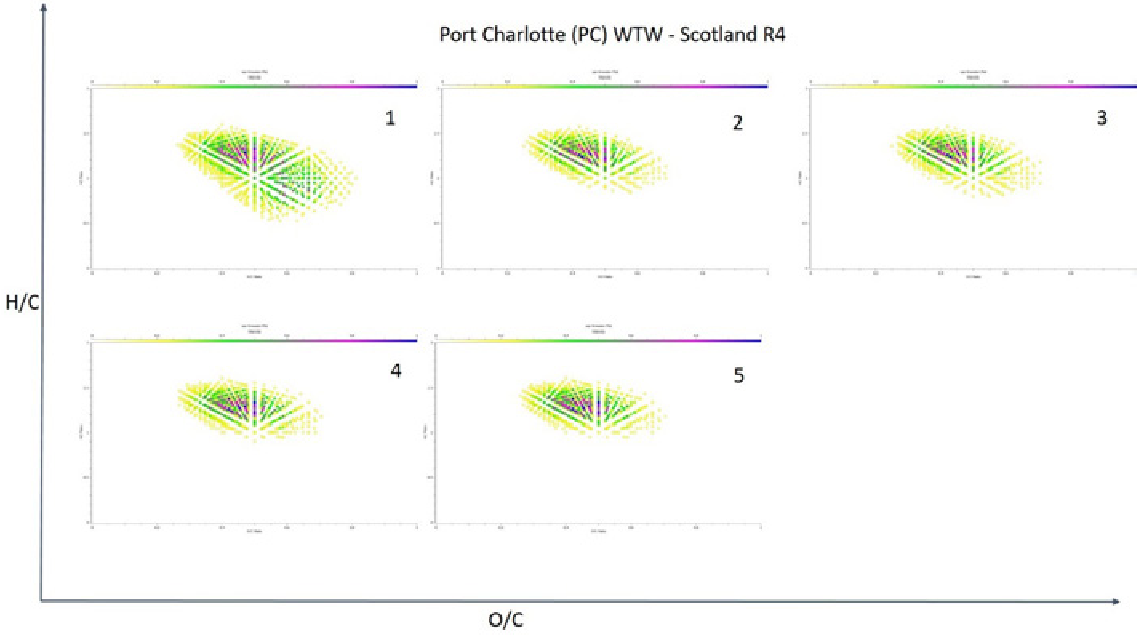


Figure 5-11-1-16 Van Krevelen plots generated from mass spectral data of samples from PC. The horizontal axis shows the oxygen to carbon ratio (O/C) ranging from 0 to 1. The vertical axis shows the hydrogen to carbon (H/C) ratio ranging from 0 to 2. 1: Raw water; 2: Post clarification; 3: Post RGF filtration; 4: Final Water; 5: Distributed water.

A main observation from nearly all WTWs is that the first treatment step (coagulation; NF for BRA) seems to be the most efficient, and that additional removal of NOM during the subsequent treatment steps is low. IVAR pilot plant is an exception as none or very little NOM is removed by ozonation, which is the first treatment step at this water treatment plant.

Discussion / conclusions

There are many aspects of the FT-ICR-MS methodology that can be discussed on the basis of the results from the NOMiNOR study. A main observation from the individual waterworks is that the initial treatment steps (coagulation or nanofiltration) have by far the largest effect on NOM removal, with only marginal supplementary effects from subsequent treatment steps. This observation is in accordance with results from other assays in the project, like the colour, DOC and SUVA results. In a study by Lavonen and coworkers (2015), a similar conclusion was drawn.

Regarding the observation that the molecular weights of the NOM decrease during treatment, as demonstrated by the results from Ringsjöverket (Sydvatten) and Görväln (Figure 5-11-1-3), we found that most of the reduction of the largest NOMs took place at the first coagulation step. In our study, NOMs with molecular weights larger than 400 to 450 Dalton were removed in the first treatment step.

The observed efficiency of nanofiltration (Bracadale) on the removal of NOMs is striking as shown in Figure 5-11-1-6. The Van Krevelen plots shows that nanofiltration removes NOMs with a higher O/C ratio and NOMs with a higher degree of aromaticity, here displayed by a lower H/C ratio. The removal of NOM by NF is strongly related to the MVCO of the membrane (a NF membrane with MWCO of 8000 D is applied at BRA).

Regarding seasonal variation, the samples from Sydvatten (Figure 5-11-1-2), Round 1 to 4, visually display differences throughout the period from June 2014 - September 2014 – November 2014 to March 2015. Figure 5-11-1-2 indicates that the NOM profile on samples from raw water (S1) from September (Round 2) contain a broader spectrum and a broader molecular weight range than the raw water samples from the other sampling times. One may speculate whether the broader spectrum of molecular weights reflects that larger NOM molecules from the growth season are broken down into smaller molecules during the autumn and the winter. From a treatment process point of view, the data from Sydvatten displayed in Figure 5-11-1-2 does not indicate that the NOM composition is altered from raw water (Sample S1) to distributed water (Sample S5) with respect to the molecular weight range and the presence of more of the higher molecular weight compounds in Round 2 (September).

It should be noted that the FT-ICR-MS methodology and the experimental conditions applied in this study have been chosen to be in accordance with other FT-ICR-MS studies on NOM. The reason for this was to keep the possibility to compare our results with results from other studies. A consequence of this, is that the present methodology may have different response for certain NOM classes that have not been investigated before. It is also possible that other classes of NOM compounds may have a different range in molecular weight than those observed in this study. It should also be noted that the FT-ICR-MS methodology still must be considered as a research tool to increase the understanding of NOM chemistry, and not yet as a routine method for NOM characterization.

However, from the FT-ICR-MS results presented in the NOMiNOR study it can be concluded that the ultra-high-resolution mass spectrometry have a potential to contribute as a characterization method for a better understanding of NOM chemistry. The understanding of NOM chemistry has relevance for future treatment process selection, operation and optimization of water treatment plants, and also for the development of new and improved methods for water treatment.

Within this study, a unique data set was created (210 water samples analyzed). These data constitute a valuable basis for further studies and research.

5.11.2. Supplementary analyses – Cranfield University (P. Jarvis)

Nedre Romerike WTW, Norway. The water source was of low to moderate DOC, with a relatively big change in NOM between sampling campaigns, increasing from 2.7 mg/L to 8.4 mg/L in November and March respectively. The treated water DOC was between 1.5 and 2.5 mg/L, with the highest DOC being observed when the raw water DOC was highest. On both sampling rounds, the DOC in the raw water was classified as 50-65% hydrophobic (HPO)

NOM (Figure 5.11.2.1.). In November, the DOC in the treated water was very low, with approximately half being defined as HPO in all of the samples, although to differentiate between fractions at this low concentration becomes quite difficult. In the higher DOC samples in the treated water in March 2016, there was more variability in the split of hydrophobicity in the treated water, although the overall DOC remained constant through the different treatment stages following coagulation. All fractions were reduced following coagulation, but the biggest reduction was seen in the HPO fraction such that when residual DOC was higher, most DOC was hydrophilic in nature. This would be expected for a coagulation process due to the affinity of coagulants for removal of HPO NOM. There was little change in the NOM following filtration. There was a shift in the distribution of organic compounds following the GAC treatment stage, which resulted in an increase in the proportion of hydrophilic NOM, from 50% to 70% of the sample, presumably through selective adsorption of humic type molecules in the GAC bed. Subsequent samples following the UV treatment stage resulted in some small fluctuations of the fraction distribution, within the error of the DOC instrument.

The trihalomethanes (THM) disinfection by-products (DBPs) measured through the treatment stages show a good correlation with the DOC of the sample, with total THMs being similar through the treatment train and the raw water having the highest THM concentration (Figure 5.11.2.2.). The treated water in March contained NOM in the treated water that had a higher reactivity than in November (March range was 45-60 μg THMs per mg DOC; November range 20-50 μg THMs per mg DOC). Of interest here, there appeared to be an increase in the reactivity of the water following treatment by UV light as the reactivity increased by 14 and 25 μg THMs per mg DOC in November and March respectively. These results show how different treatment processes can transform organic matter into more reactive material.

The zeta potential analysis shows how the charge profile of the organic compounds changes with treatment (Figure 5.11.2.3.). For each sampling campaign, the raw water source had the most negative zeta potential value (-10 and -20 mV in November and March, respectively). Following coagulation, there was a significant reduction in the negative zeta potential to a value closer to zero. This is consistent with the removal of highly charged organic compounds by coagulants. The subsequent further reduction of charge in March following filtration was unexpected, as was the big change to more negative zeta potential after UV and at the outlet of the WTWs. Given that these samples did not see any significant changes to other water quality parameters, it was thought that these samples were contaminated or that the instrument was malfunctioning.

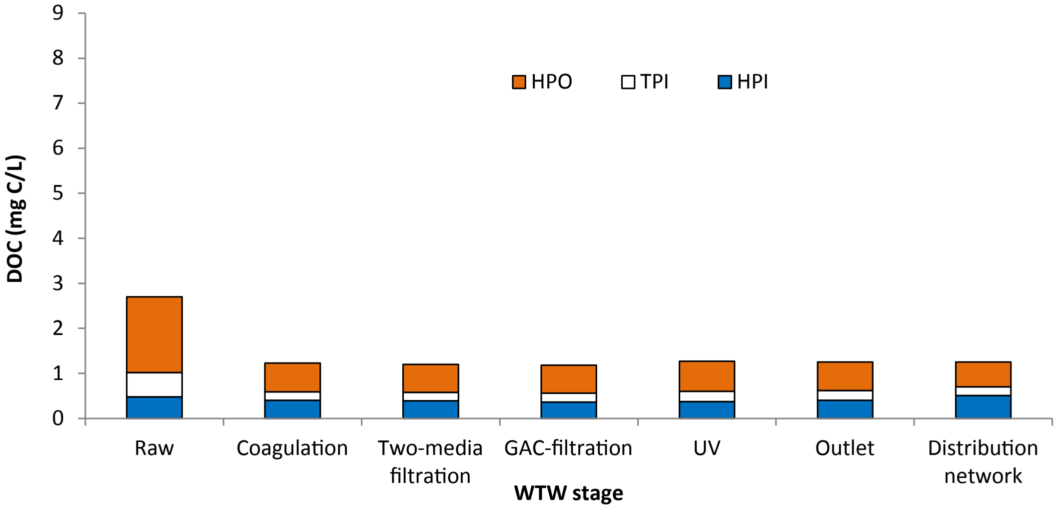
The fluorescence excitation/emission matrix spectra (FEEMS) showed another fingerprint of the organic compounds present in the sample (Figure 5.11.2.4; Figure 5.11.2.5). The plots show how the different treatment stages remove organic compounds for November and March sampling campaigns. The biggest change in the distribution of the fluorescence emission was between the raw water and coagulation stages. Two peaks in emission were seen for the fulvic and humic-like substances. Coagulation, as would be expected, removed the peak of the humic materials. There was little change in the emission spectra following subsequent treatment stages in both sampling rounds.

The HPSEC results showed that coagulation removed a large proportion of the higher molecular weight organic compounds (Figure 5.11.2.6). All of the treated samples contained a similar range of molecular weights of UV254 absorbing organic compounds. It should be noted that the source water had a low overall absorbance of UV254, so this analytical technique does not account for a large proportion of the organic compounds present in the water.

When bacteria removal was considered using FCM, the results showed continued removal of cells across the treatment train. The removal of cells was good across the coagulation stage, with up to half the cells removed resulting in a log removal of 0.29. The dual media filter reduced the bacterial numbers by a further 0.21 log and the GAC by another 0.22 log. UV had no effect on the total cell counts (TCC) and they stayed similar. Some decrease in intact cells after the UV stage was seen but only a reduction of 0.1 log. These results were expected as the FCM instrument is not effective at measuring cell damage achieved by UV light. Most of the intact cell (ICC) inactivation was achieved at the final sample stage after chlorine disinfection, which accounts for a further 1.81 log removal of ICC but little change in TCC. There was a reduction of %ICC/TCC of 70.9% after chlorination. Total cells were stable in the network and remained similar, but intact cells increased by over four-fold, with a significantly larger increase occurring in the network in the warm water sampling campaign, perhaps indicating that the residual chlorine was not sufficient to prevent bacterial regrowth.

Overall, the site seemed to be operating effectively. When the DOC in the treated water was high, most of this was hydrophilic NOM that is difficult to remove by coagulation processes. However, when the DOC of the source water was high, the reactivity of the NOM also increased suggesting that good control of residual DOC is needed at these times to ensure that DBP levels are kept low. Bacterial removal across the plant was good, although there was a high potential for bacterial re-growth in the network shown by the higher levels of intact cells measured in the distribution samples, particularly during the warm weather sampling campaign: this may have been from low residual chlorine in the water and or biofilm release from the pipe walls.

November 2015



March 2016

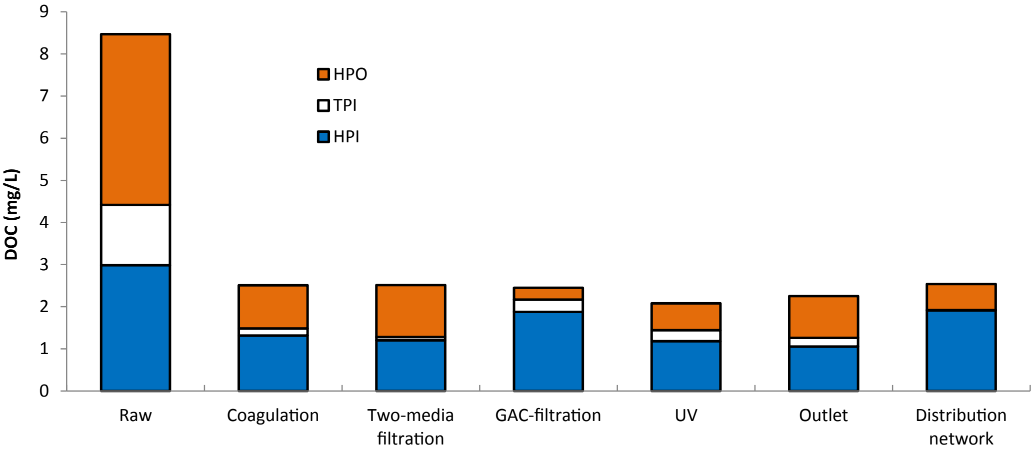
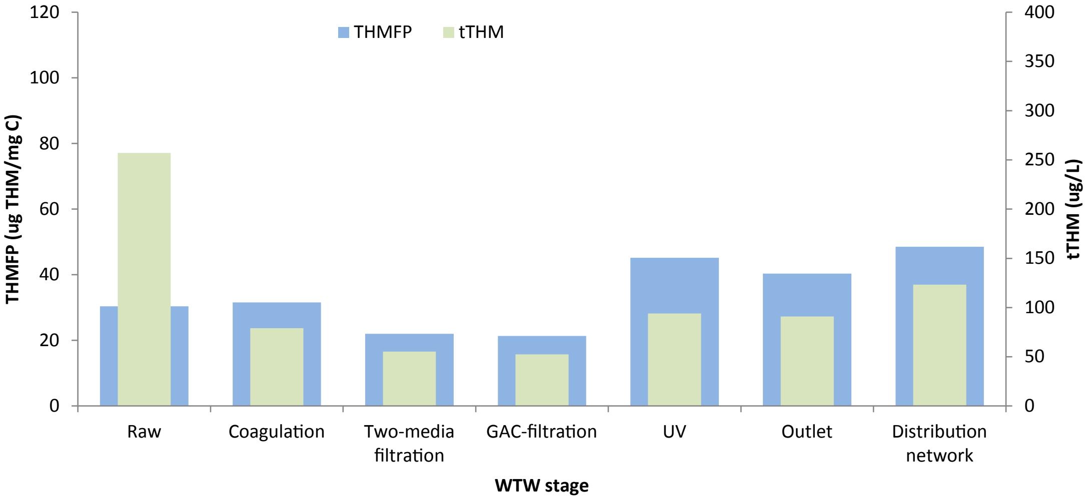


Figure 5.11.2.1. Fractionation for NRV sampling rounds.

November 2015



March 2016

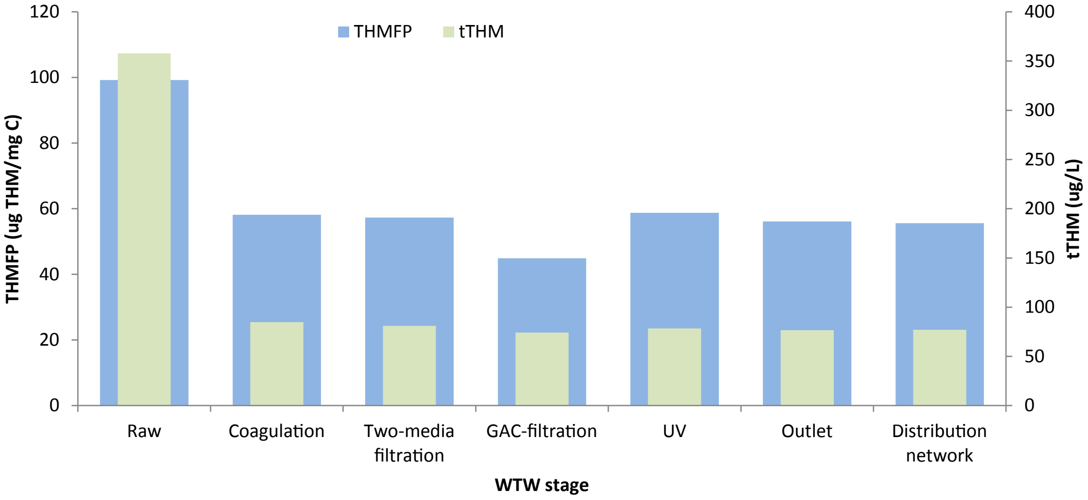
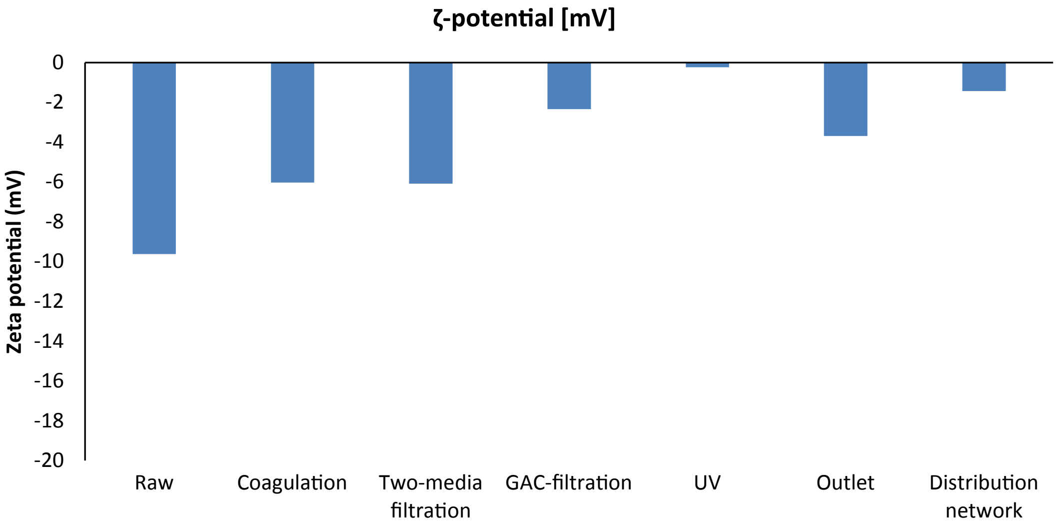


Figure 5.11.2.2. Disinfection by-products for NRV sampling rounds.

November 2015



March 2016

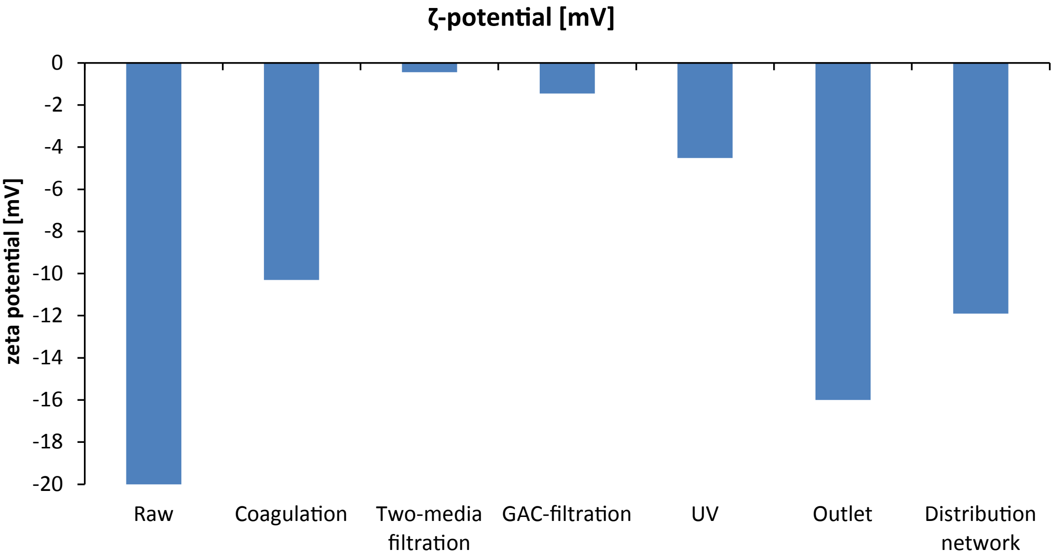
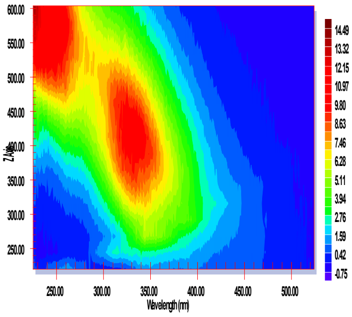


Figure 5.11.2.3. Interstage zeta potential for NRV sampling rounds.



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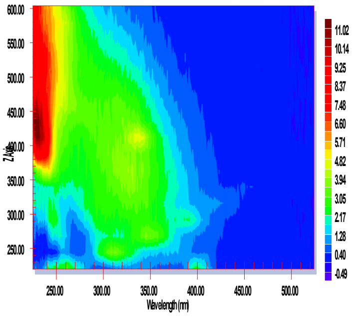
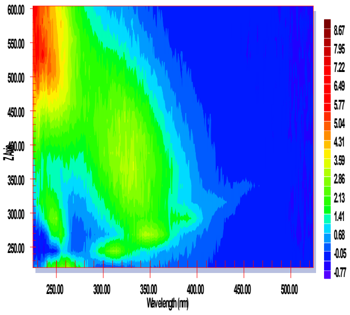
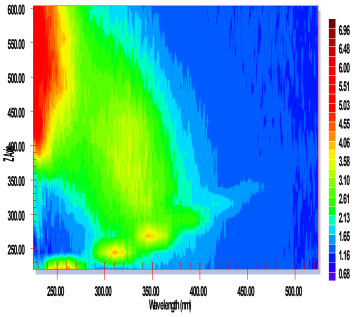


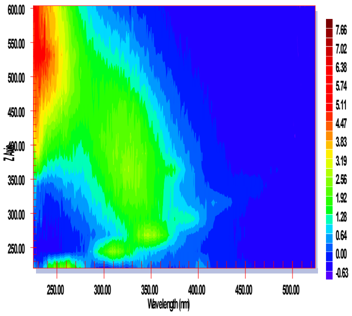
Coagulation



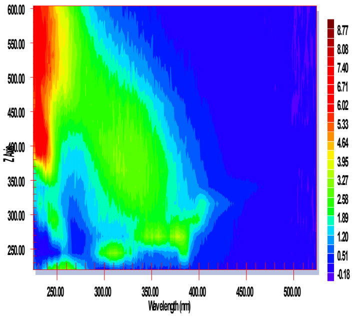
Two media filtration



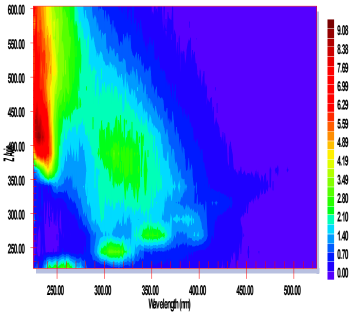
GAC filtration



UV



Outlet

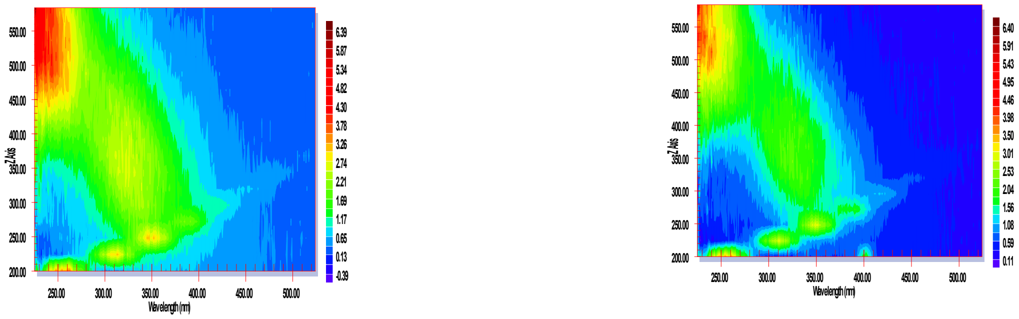


Distribution network

Figure 5.11.2.4. Fluorescence spectroscopy for NRV sampling round November 2015

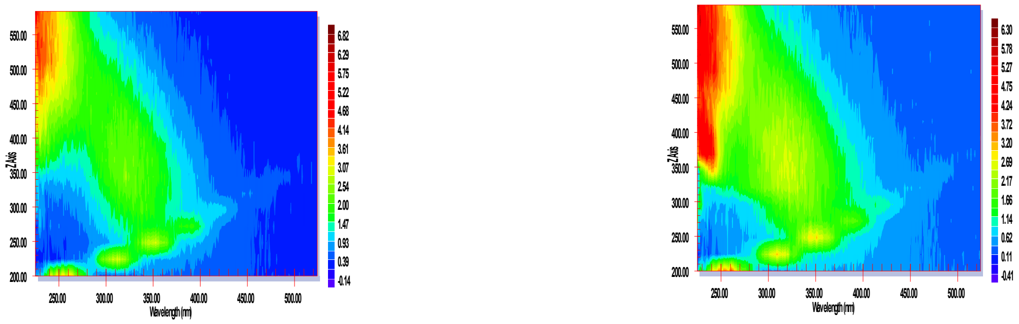
Raw

Coagulation



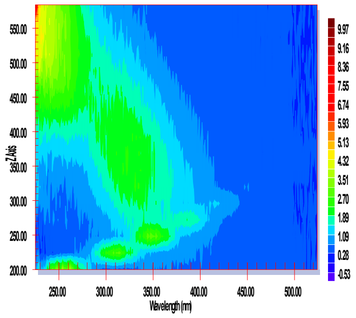
Two media filtration

GAC filtration



UV

Outlet



Distribution network

Figure 5.11.2.5. Fluorescence spectroscopy for NRV sampling round March 2016

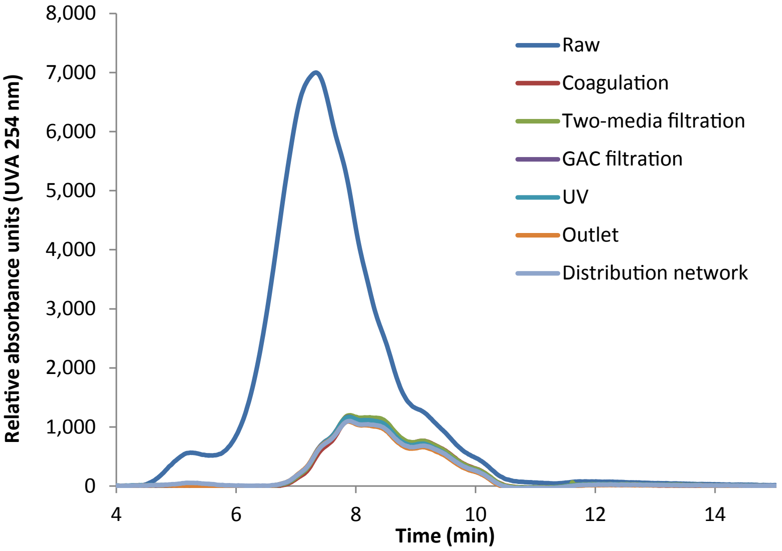


Figure 5.11.2.6. HPSEC NRV March 2016.

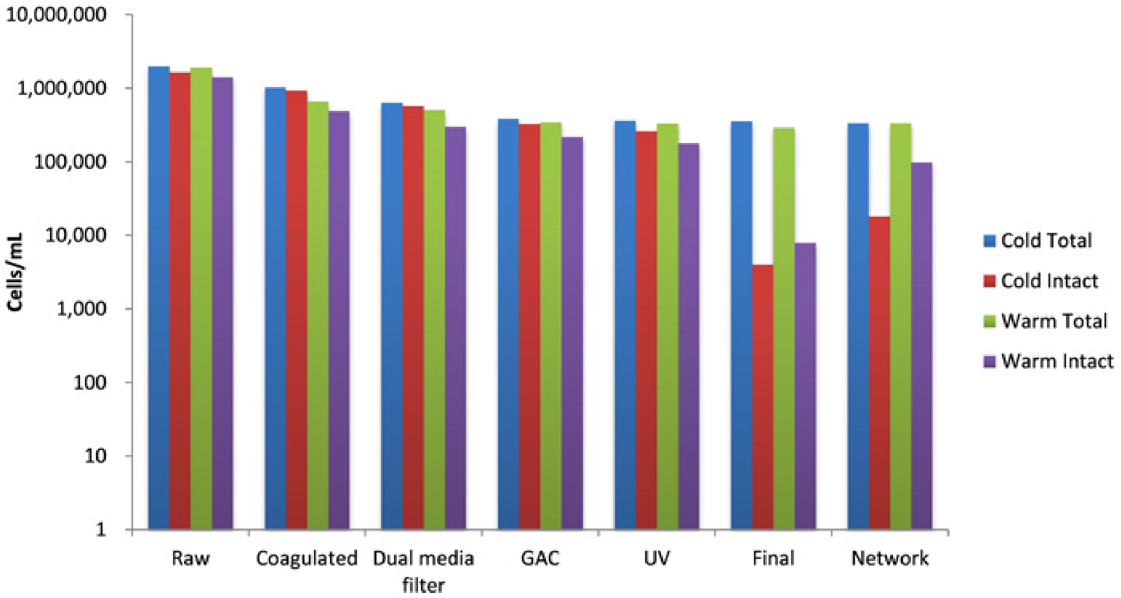


Figure 5.11.2.7. Cell removal across treatment processes measured by flow cytometry for Nedre Romerike over two sampling rounds.

Burncrooks WTW, Scotland. Over the two sampling rounds, the DOC in the untreated raw water was between 9 and 12 mg/L, with a higher DOC being measured in March 2015. The water was dominated by hydrophobic NOM, with between 66 and 76% characterised as HPO (Figure 5.11.2.8.). Residual DOC in the treated water was between 2.2 and 2.5 mg/L. Surprisingly, there was a high proportion of HPO in the treated water, with over 50% of the DOC being classified as hydrophobic NOM. These results were consistent with the THM data, where it was clear that the water had a high degree of reactivity with chlorine (Figure 5.11.2.9.). The formation potential of the water was high and the residual DOC after treatment also has a high DBP at nearly 100 µg per mg of DOC. This was one of the highest formation potentials that we measured in the study.

The coagulation process appeared to be operating effectively, as shown by the inter-stage zeta potential values through the WTWs (Figure 5.11.2.10.). The raw water zeta potential moved from -14 mV to -4 mV, well within the recommended zone for coagulation (-10 to +4 mV). This suggested that the hydrophobic material that appeared in the treated water was not easy to coagulate and carried minimal associated charge. However, the high DBP formation potential was indicative of reactive NOM that may need other treatment in order to remove it from the water.

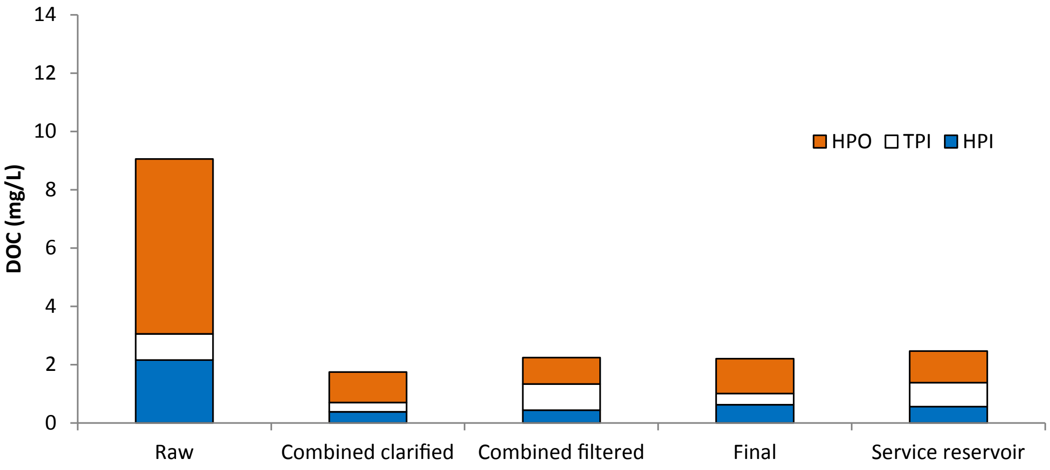
The FEEMs data was similar to the other water sources investigated with a high proportion of fulvic and humic acid like compounds being detected (Figure 5.11.2.11 and 12.). The humic footprint was removed effectively by the coagulation process, leaving behind the more fulvic-like organic substances. These organic compounds could have been the source of the high DBP forming organic substances in the treated water. However, because most of the water sources had this footprint of fulvic substances in treated water, it was apparent that the technique could not distinguish between high and low THM forming substances.

The HPSEC trace from Burncrooks showed the water to contain a high proportion of strongly UV absorbing organic substances, with a high content of UV absorbing organics eluting at 7.5 minutes (Figure 5.11.2.13.). Following coagulation, the bulk of these organic compounds were removed and a residual of lower molecular weight compounds were left, eluting around 8 minutes. These traces were as expected for a coagulation site.

Effective removal of microorganisms was seen across the water treatment stages (Figure 5.11.2.14.). In the cold weather sampling, clarification and filtration achieved a combined 0.81 log removal. Of interest here the filtration stage only increased the log removal by 0.18, with the bulk of the removal being achieved through coagulation and clarification. A similar observation was seen for the warm weather sampling, although the overall log reductions were lower. However, in summer the number of cells in the raw water was significantly higher, with approximately double the number of cells present than for the cold water sampling ($2.8x10^6$ compared to $1.4x10^6$ cells per mL). The biggest reduction in cells occurred through the chlorination stage with log reductions of total cells of 1.87 and 2.36 in cold and warm water conditions respectively. Bigger reductions were seen for intact cells, with log reductions of 3.8 and 3,5 in cold and warm water conditions respetively. This was not surprising given that chlorine is meant to target living cells. The ratio of IC to TCC fell to below 1% after chlorination, demonstrating how effective the process was at inactivating cells. Some regrowth occurred within the network. This was likely to be from pipe wall biofilms releasing cells into the water, but total cells decreased even further due to increased exposure with free chlorine breaking down cells.

Overall, the WTWs was operating effectively with good removal of DOC through coagulation and clarification. The high DBP formation potential of the NOM was of some concern suggesting that if there is any ineffective treatment of the water that causes significant concentrations of HPO to enter the treated water, then THM levels could become very high. The site may want to consider pre-treatment options, in addition to coagulation, for more removal of high DBP forming NOM.

January 2015



March 2015

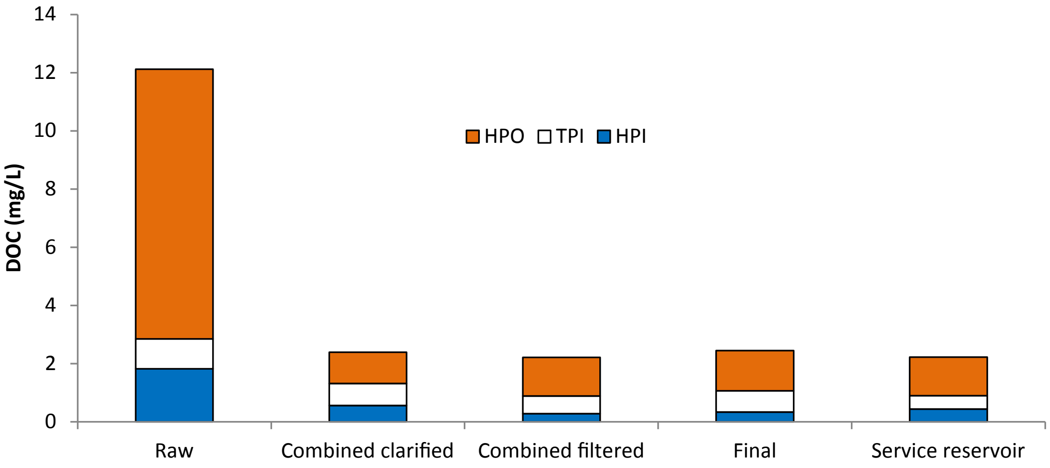
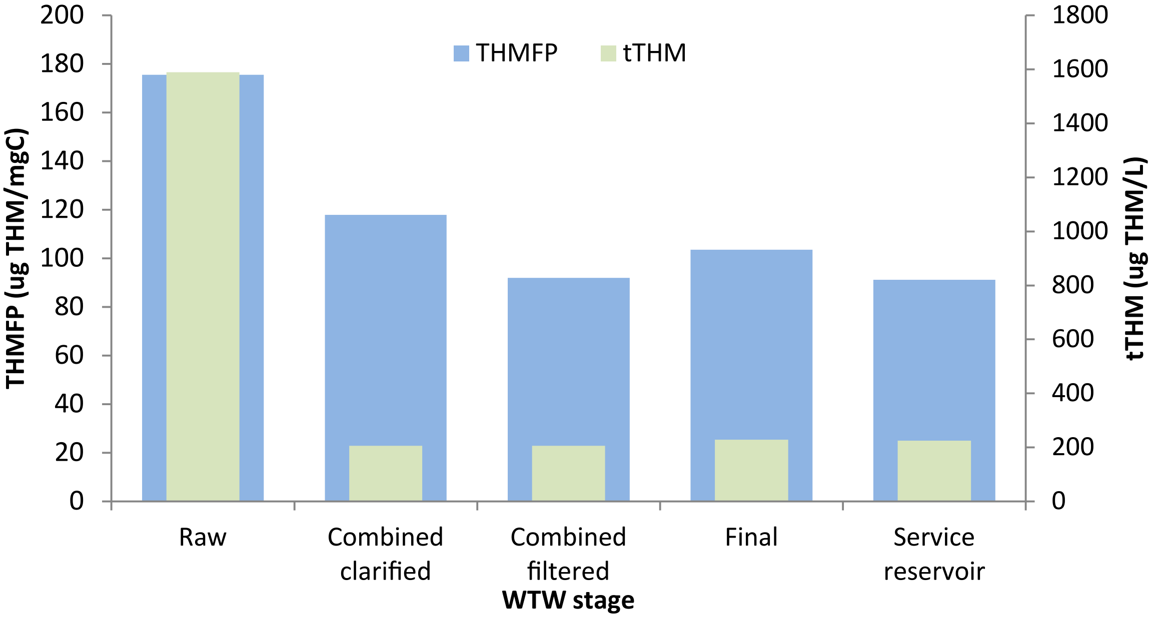


Figure 5.11.2.8. Fractionation for Burncrooks source water over two sampling rounds.



January 2015

Figure 5.11.2.9. Disinfection by-products for Burncrooks over one sampling round.

January 2015

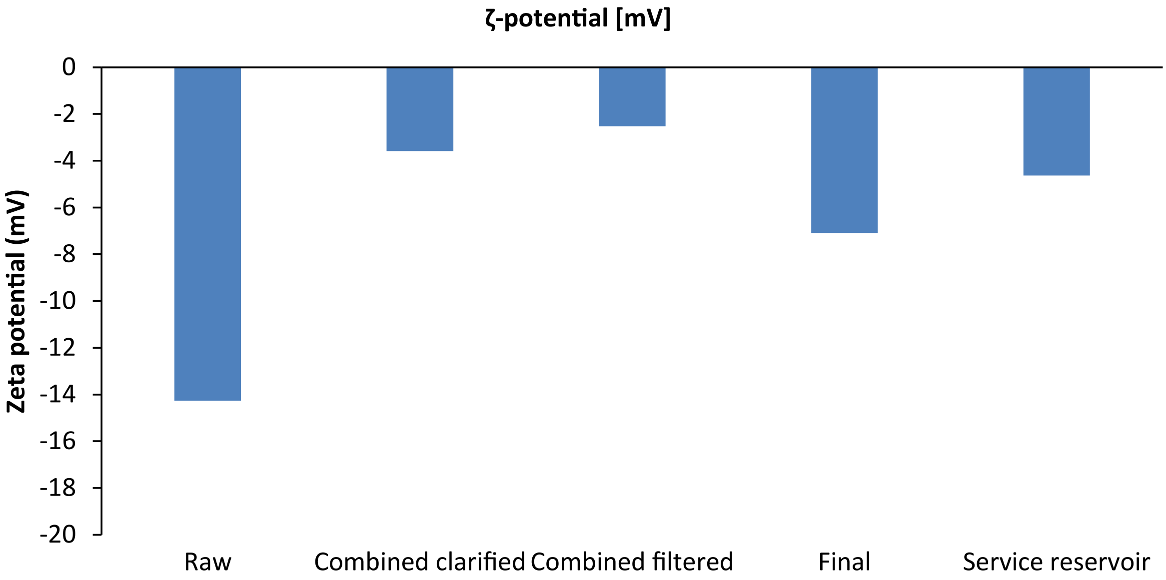
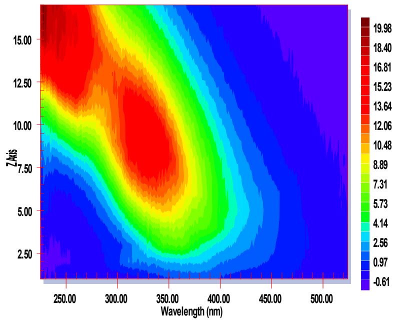


Figure 5.11.2.10. Interstage zeta potential for Burncrooks sampling rounds.



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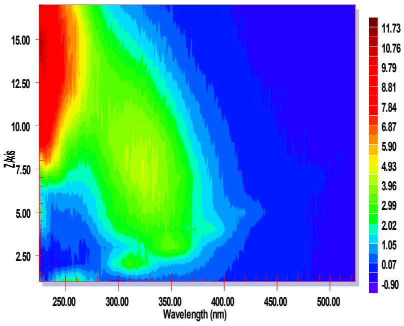

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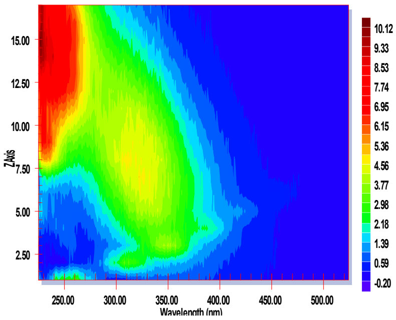

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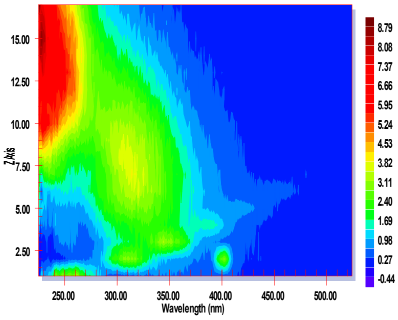

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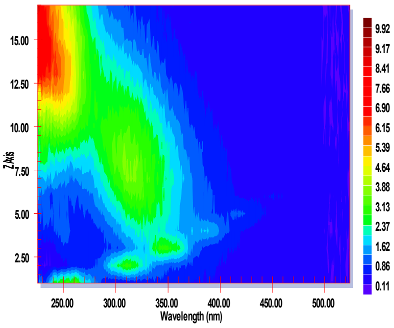
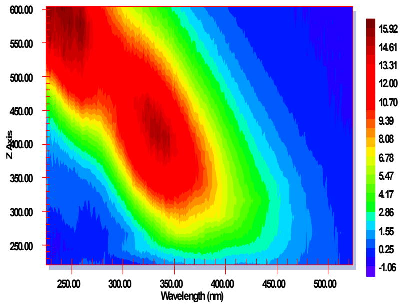
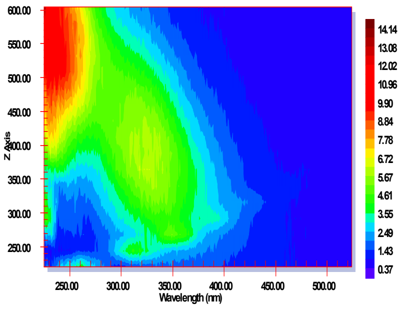


Service reservoir

Figure 5.11.2.11. Fluorescence spectroscopy for Burncrooks sampling round January 2015



Raw



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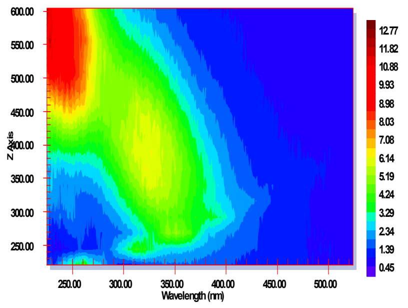

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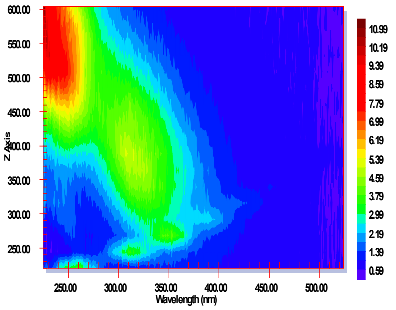

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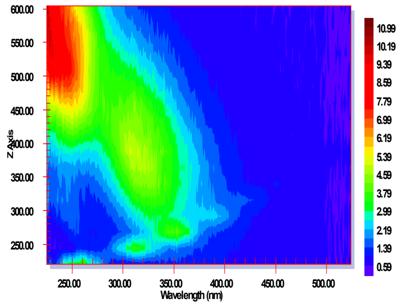
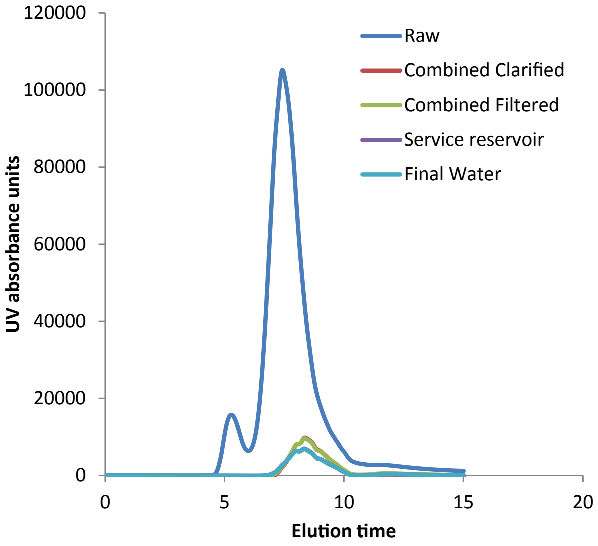


Service reservoir

Figure 5.11.2.12. Fluorescence spectroscopy for Burncrooks sampling round March 2015



January 2015

Figure 5.11.2.13. HPSEC for Burncrooks over one sampling round.

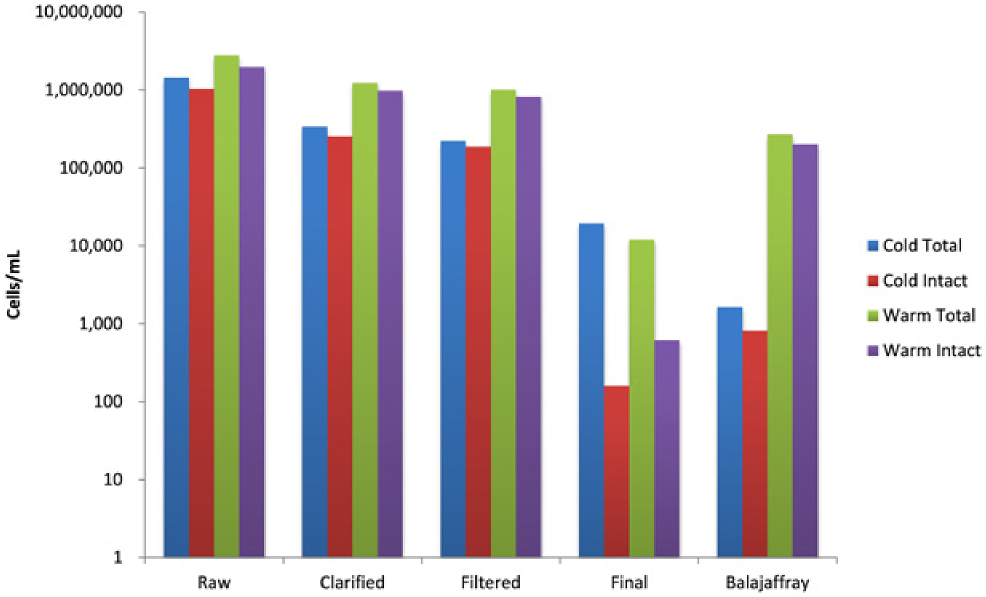


Figure 5.11.2.14. Cell removal across treatment processes measured by flow cytometry for Burncrooks over two sampling rounds.

Pitkäkoski WTW, HSY, Finland

The source water was of moderate DOC that was stable across the two sampling campaigns (Figure 5.11.2.15). The residual DOC was less than 2 mg/L after treatment, suggesting that coagulation was effective at the site. The hydrophobic split of the NOM in the source water and treated water samples was very consistent. More than half of the DOC in the raw water was HPO (55-56%), with the next largest fraction being HPI NOM (28-29%). The proportions of the different NOM fractions did not change much during treatment, although there was a jump in HPI between the final and network samples, suggesting some transformation of NOM in the distribution system.

Although the THM concentration of the raw water was quite high (823 µg/L), there was progressive reduction of the THMs through the treatment stage, resulting in a concentration of < 100 µg/L at the outlet of the WTWs (Figure 5.11.2.16). This reduction was in-line with a reduction in the DOC of the water and a reduction in the reactivity of the NOM through the treatment stages. Reactivity of chlorine with the DOC reduced from 114 to 42 µg THMs per mg of DOC. The treated water therefore had a low THM formation potential. Although the site uses chloramination as its disinfectant, so the results may not be directly applicable to the site in question, they serve as a useful demonstration to show how different processes, while not removing NOM per se, can change the characteristics of NOM to more or less reactive species.

The charge profile through the WTWs showed that following coagulation, the zeta potential was close to the minimum recommended for effective charge neutralization (Figure 5.11.2.17). Here it is recommended that the charge should be closer to zero than -10 mV and the site was therefore on the cusp of this from the January sampling round. An addition of a small amount of coagulant may increase the robustness and resilience of the WTWs through additional DOC removal. In both the January and March sampling rounds, there was an increase in the negativity of one or both of the disinfected and network samples. It was not clear as to why this occurred, but may have resulted from DOC transformations occurring following addition of the disinfectant or processes occurring in the network (such as water blending for example).

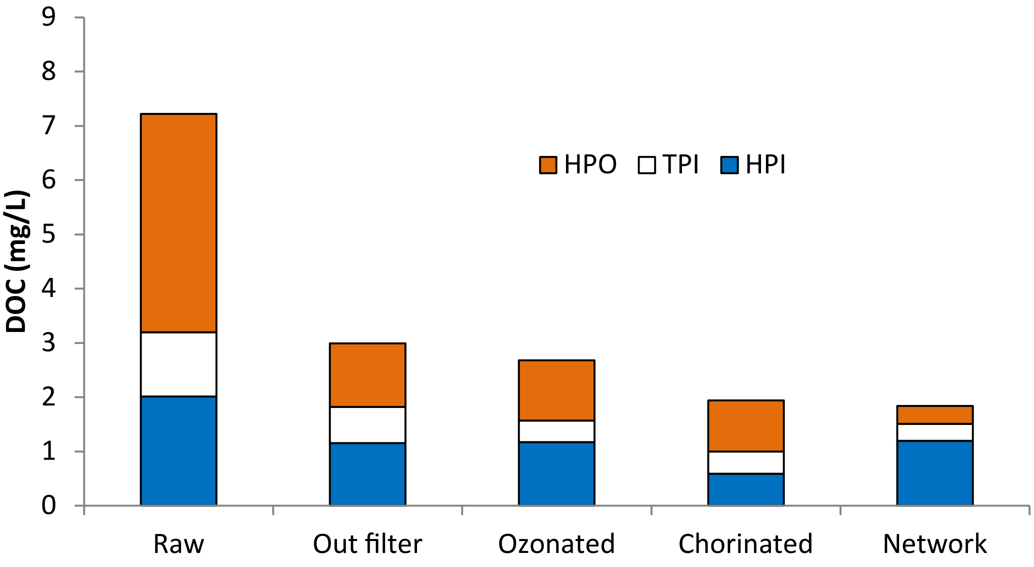
The FEEMS plots showed similar profiles of the raw water as seen for the other sites, with spikes of NOM linked to humic and fulvic substances (Figure 5.11.2.18 and 19). However, there was less humic material in the samples than for many of the upland sites studied as part of this programme of work. The January data set resulted in some unusual profiles following treatment as an un-recognisable peak appeared midway down the plot on the left-hand side. It was unclear as to whether this was a real signal, a contaminated set of samples or instrument error. The March data set was much more as expected, with a significant decrease in the humic matter following coagulation. One point of interest was the apparent reduction in the fulvic profile after ozonation, presumably through bleaching of the organic matter through oxidation.

This bleaching effect was evident in the HSPEC plots (Figure 5.11.2.20), where there was a reduction in the profile of the residual UV_{254} between the filtration and ozonation samples. A smaller, but significant reduction was seen between the ozone and disinfected samples, presumably as a result of DOC removal through adsorption onto the GAC stage that exists between these two stages of treatment.

Microbe removal was effective across the clarification stages, with nearly 1 log reduction observed across the filters. Very good removal was observed through the ozone stages with log reduction from the raw water of 1.9 and 2,7 in the cold and warm weather sampling campaigns respectively. Cell numbers were shown to increase following chloramination, with intact cells increasing by 3,000 and 16,000 cells per mL in cold and warm conditions respectively. This could be attributed to the GAC process that occurs between the ozone and disinfected samples, but a sample following the GAC was not available to test. However, previous results at other sites have shown significant cell increases in samples after GAC due to the biological activity occurring in these systems. As seen for some of the other sites, regrowth was evident in the network evidenced through an increase in total cells and the proportion of intact cells.

Overall, the site was performing well from this analysis. More DOC removal could be achieved by coagulation through improved charge neutralisation for removal of negatively charge NOM, although overall THM-FP for water was low. However, there may be risks for formation of other DBPs.

January 2015



March 2015

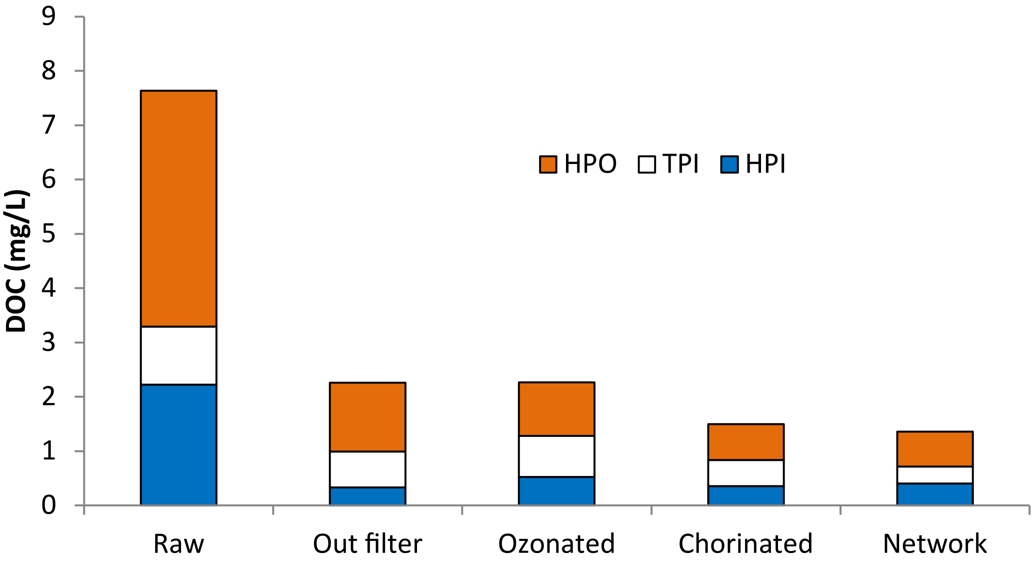


Figure 5.11.2.15. Fractionation HSY over two sampling rounds.

January 2015

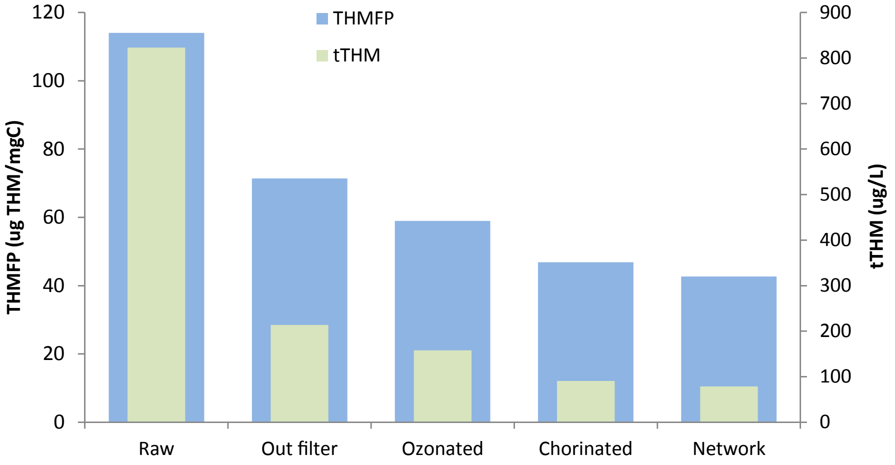
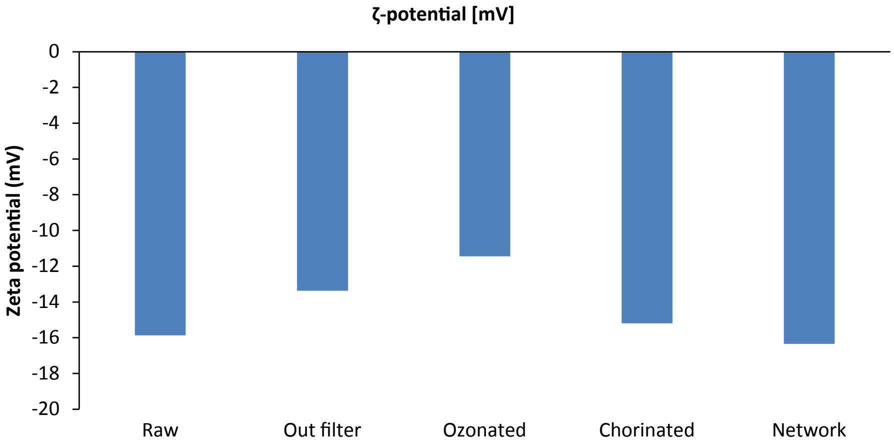


Figure 5.11.2.16. Disinfection by-products for HSY over one sampling round.

January 2015



March 2015

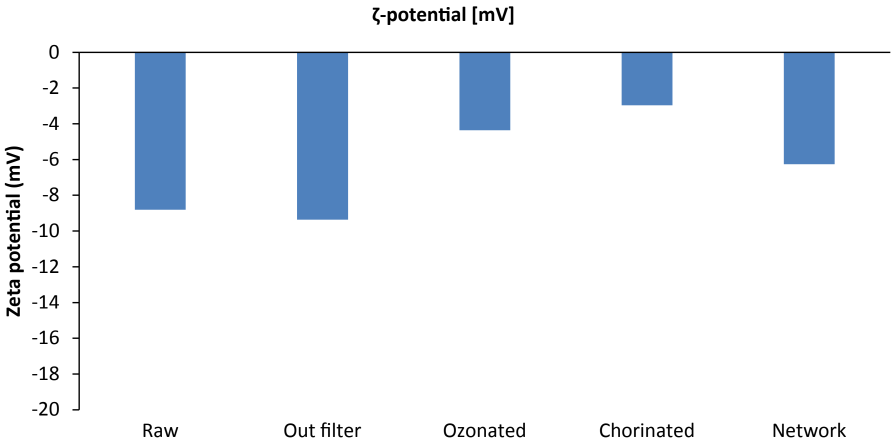
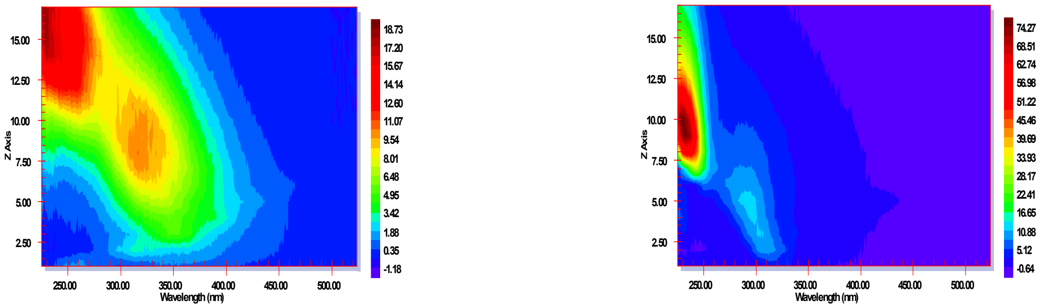
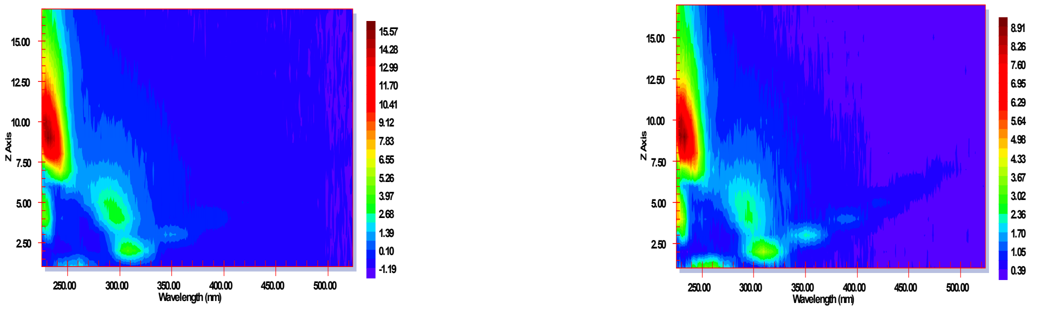


Figure 5.11.2.17. Interstage zeta potential for HSY sampling rounds.



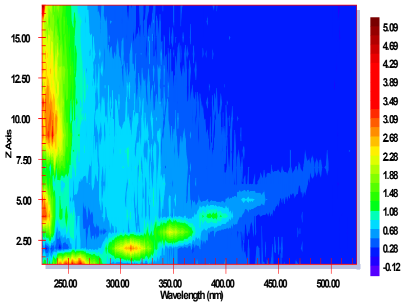
Raw

Filter outlet



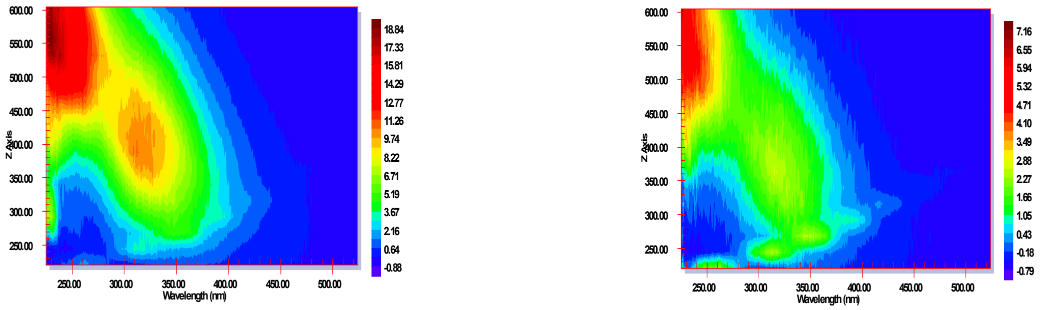
Ozonated

Chlorinated



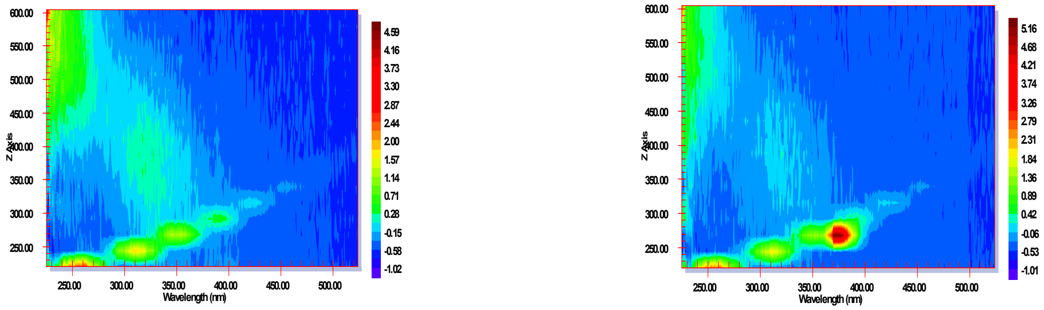
Network

Figure 5.11.2.18. Fluorescence spectroscopy for HSY sampling round January 2015



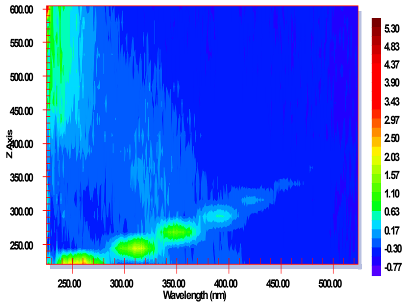
Raw

Filter outlet



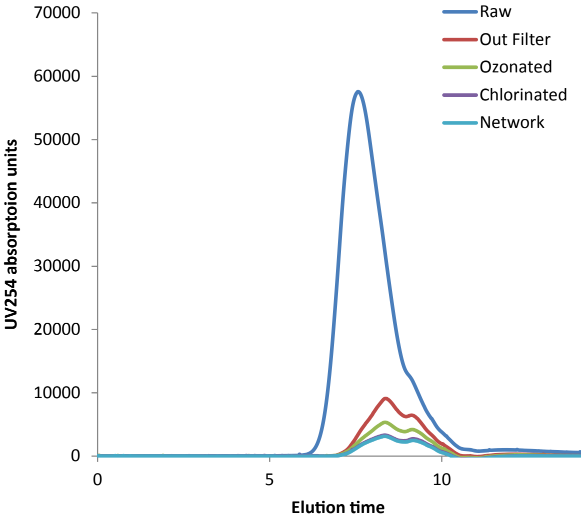
Ozonated

Chlorinated



Network

Figure 5.11.2.19. Fluorescence spectroscopy for HSY sampling round March 2015



January 2015

Figure 5.11.2.20. HPSEC for HSY over one sampling round.

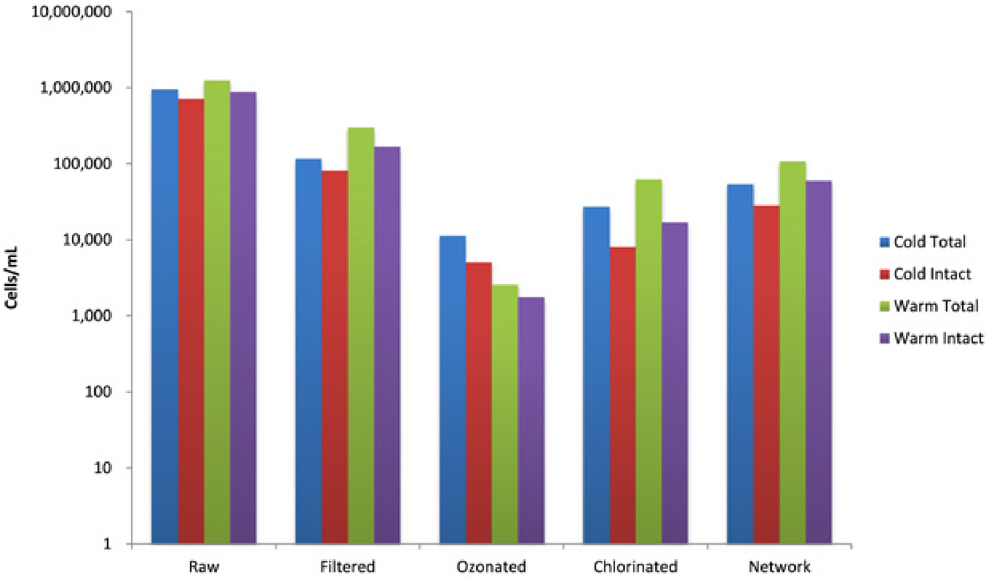


Figure 5.11.2.21. Cell removal across treatment processes measured by flow cytometry for HSY over two sampling rounds.

Bracadale WTW, Scotland. The source water at Bracadale showed some of the highest variability in DOC concentration of all of the sources investigated in this programme of works (Figure 5.11.2.21.). In the November 2015 sampling, the DOC was at 26 mg/l, while in March 2016, the DOC had reduced to 2 mg/L. The source water was dominated by hydrophobic NOM, with 55-70% of the DOC defined as HPO. The residual DOC following treatment was between <0.5 and 2.0 mg/L DOC, with the highest residual being observed when the source water DOC was highest. The primary treatment stage in place for removal of NOM was nanofiltration. This process would be expected to be selective for DOC of higher MW rather than for hydrophobicity of the organic compounds. As such, there appeared to be little change in the distribution of the NOM fractions following treatment, with some significant HPO still left in treated water (>50%), although the levels of DOC were close to the limit of detection for the instrument, particularly during the March sampling campaign.

The THM concentration levels were in-line with the DOC concentrations, with values of 1644 and 250 µg/L being seen in the raw water for the high and low DOC source waters (Figure 5.11.2.22.). THM concentrations in the treated water were between 33-41 µg/L when the DOC was very low in the source water and between 79-164 µg/L when the DOC was very high. However, the reactivity of the NOM with chlorine did not correlate with the increase in the overall DOC concentration. The raw water reactivity was highest when the DOC was lowest at 96 µg THMs per mg of DOC and reduced to 63 µg THMs per mg of DOC for the low DOC water. For the low DOC source water, the reactivity in the treated water reduced to a constant value around 60 µg THMs per mg of DOC, while for the high DOC water the reactivity fluctuated between 57 and 98 THMs per mg of DOC. This suggested that the interstage treatment processes were changing the nature of the NOM in some way. This was particularly evident after the GAC treatment in November, when the reactivity increased by 30µg THMs per mg of DOC.

With respect to charge removal, the results showed that the raw water zeta potential was between -16 and -23 mV (Figure 5.11.2.23.). Changes in the charge of the organics were observed after the nanofiltration membrane, but these results were thought to be unreliable because of the exclusion of colloids and particulates by the membrane treatment stage. Charge measurement relies on the presence of such particles in order to be able to determine the electrophoretic mobility of the system. It was therefore not considered prudent to consider the results of the zeta potential analysis from after the membrane.

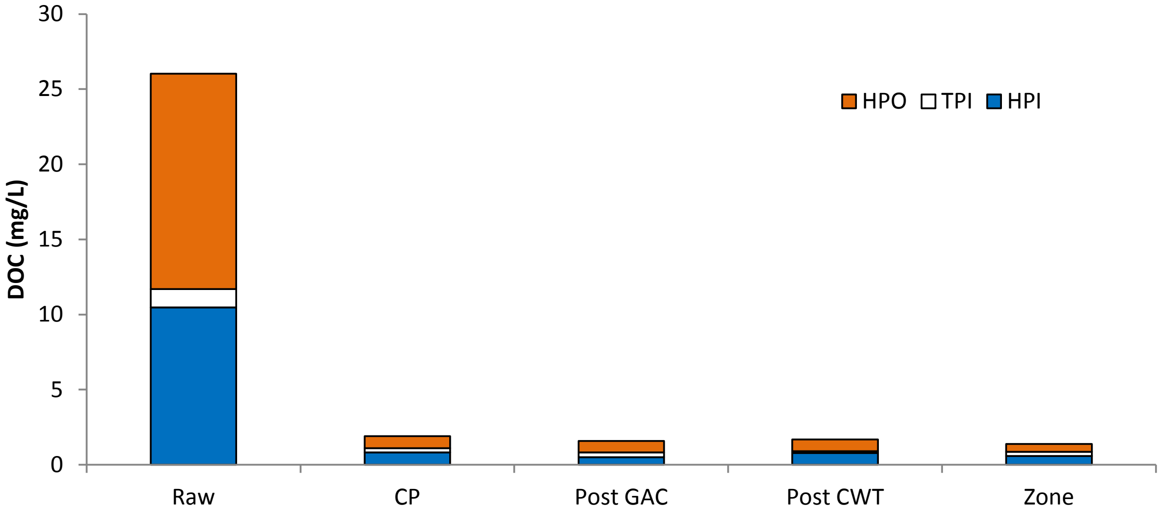
The FEEMs results showed a very strong signal for the humic-like substances for the raw water from November 2015 when the DOC was very high (Figure 5.11.2.24.). The signal was much weaker for the low DOC raw water collected in March 2016 (Figure 5.11.2.25.). It was interesting to note that the humic-like substances were still present in the treated samples after the membrane, although the strongest signal was from the fulvic materials. This agreed with the view that the membrane had less selectivity for hydrophobic NOM compared to coagulation processes, where this peak was effectively removed. It is known that humic materials generally have higher THM formation potential than other types of NOM. It was therefore not surprising that the November water had higher levels of THMs present, although the reactivity may have been expected to have been higher.

The HPSEC traces showed good agreement with the previous results (Figure 5.11.2.26.) showing the expected removal of high MW NOM across the membrane and continued removal of DOC into the final treated water, leaving behind a small amount of low MW UV254 absorbing NOM.

One of the clearest aspects from the microbiological analysis was the effective removal of cells across the membrane barrier, with between 1.9 and 2.5 log removal of TCCs. As might be expected from a nanofiltration membrane, cell removal was therefore very high resulting in cell concentrations of between 2,200 and 7,600 cells per mL in the membrane effluent. Following the GAC treatment stage, the cells concentration increased by between 1.2 and 1.8 log, which was in-line with that seen previously for other GAC systems, which contribute a cell content to the water. There was then an expected drop in the ICC following disinfection as a result of cell damage caused by chlorine. However, there was a more surprising drop in the TCC after the chlorination stage, which suggested that cells were in some way being removed from the system or being so oxidized by the disinfectant that they were not identifiable as cells. This requires some further investigation on site.

Overall, the site appeared to be working very effectively in removing significant quantities of DOC. The more non-specific removal of DOC by the membrane means that significant hydrophobic NOM could pass through the membrane and potentially result in water with a high DBP formation potential. Better removal of this NOM may be needed, particularly during periods of high DOC in the source water, when residual DOC in the treated water was higher. This could be achieved through coagulation or ion exchange prior to the membranes.

November 2015



March 2016

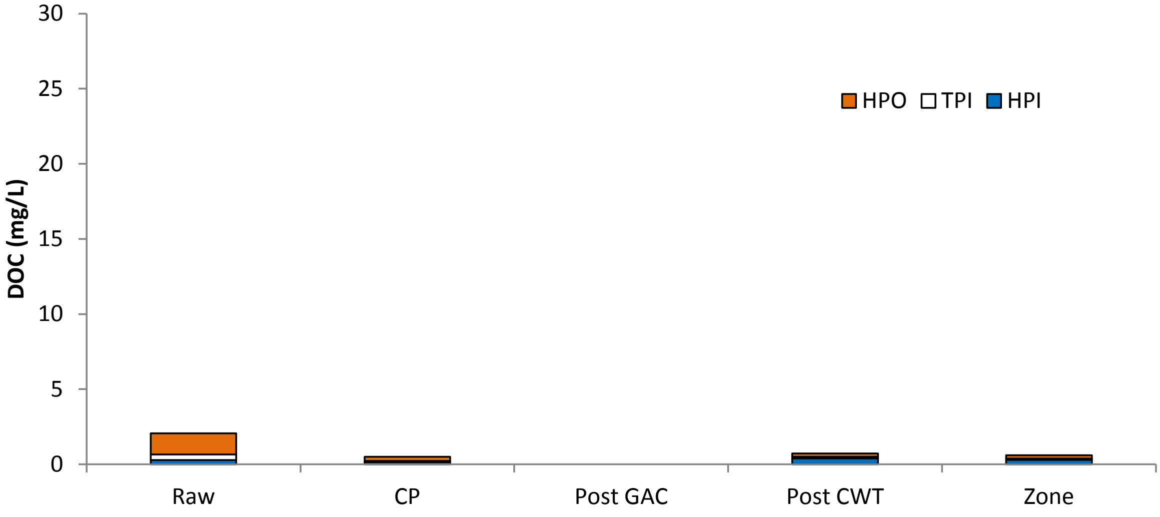
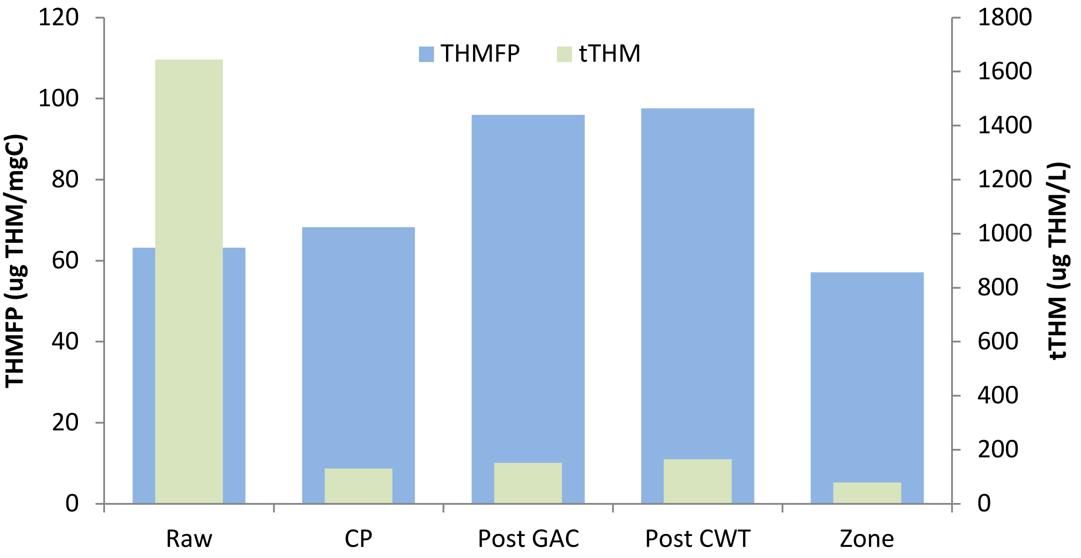


Figure 5.11.2.21. Fractionation of Bracadale water over two sampling rounds.

November 2015



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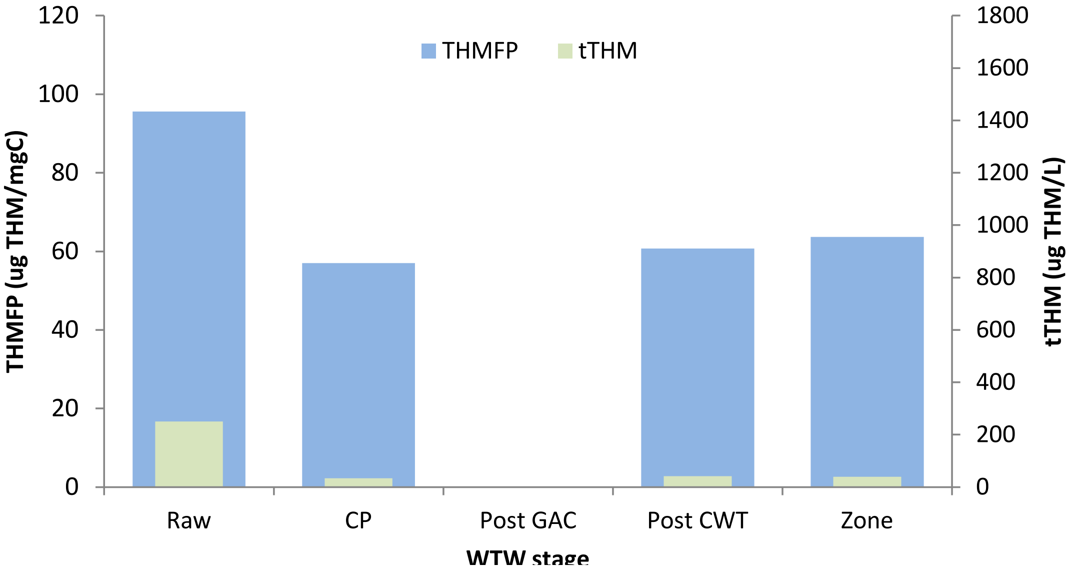
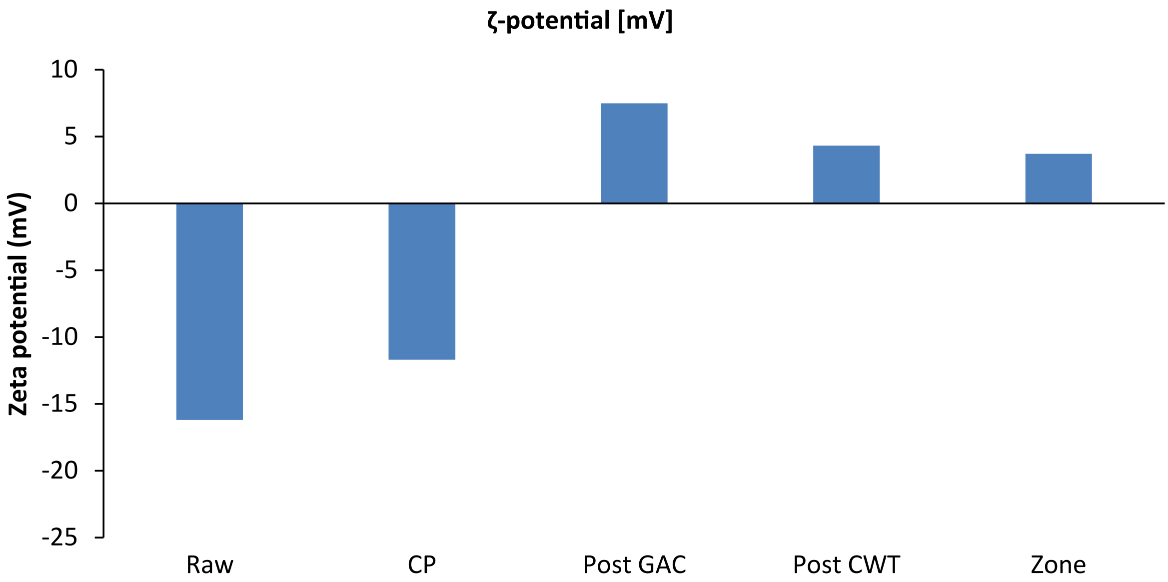


Figure 5.11.2.22. Disinfection by-products for Bracadale sampling rounds.

November 2015



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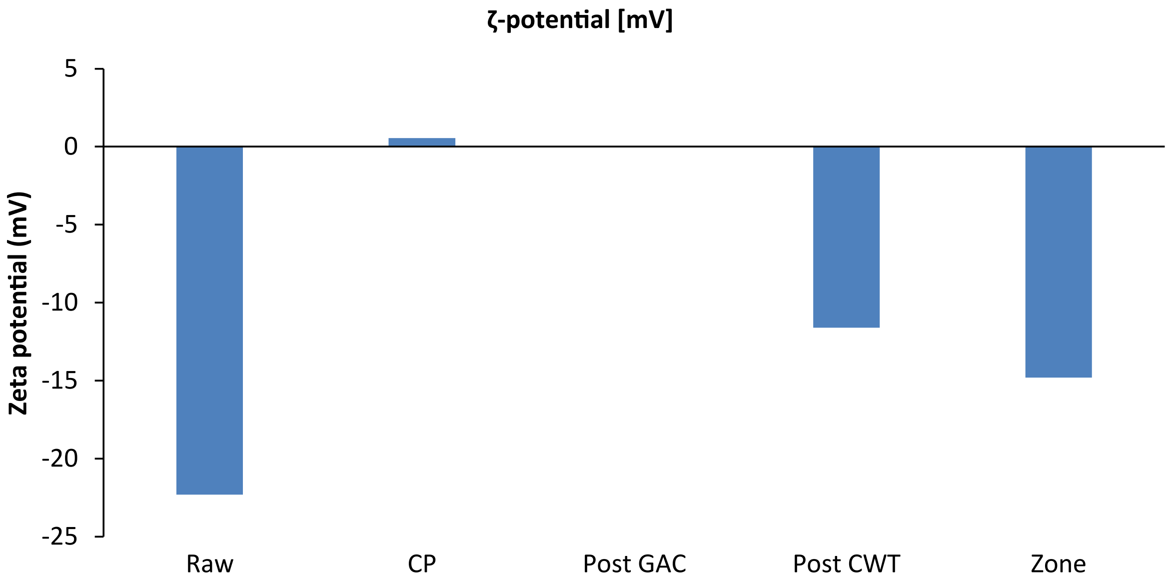
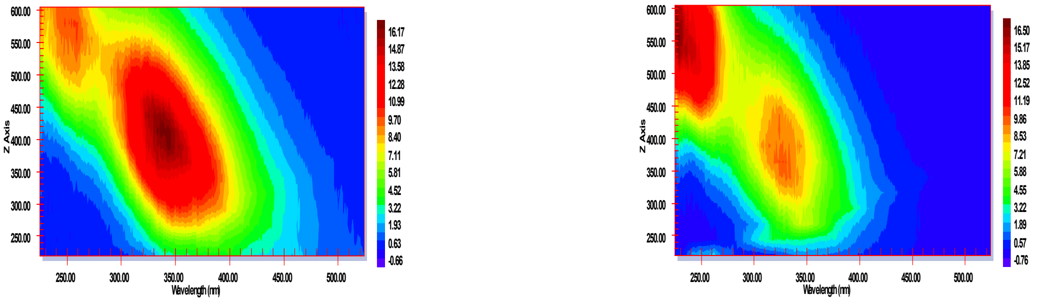
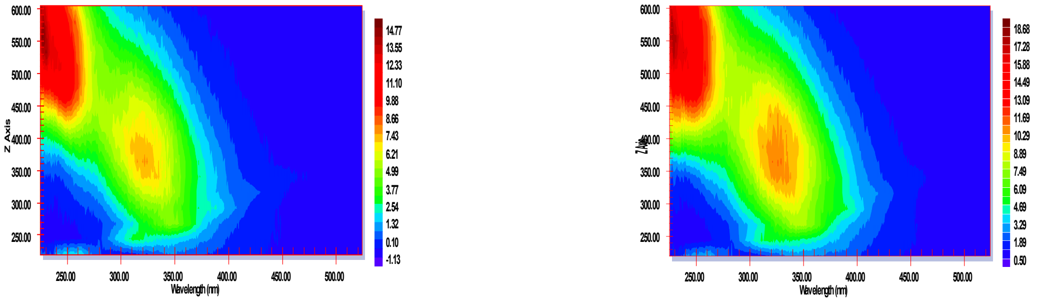


Figure 5.11.2.23. Interstage zeta potential for Bracadale sampling rounds.



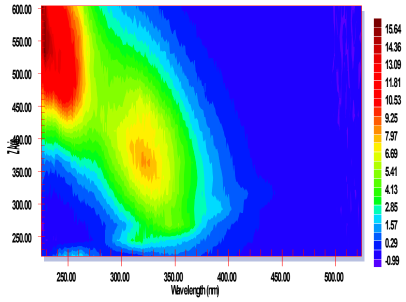
Raw

Combined permeate



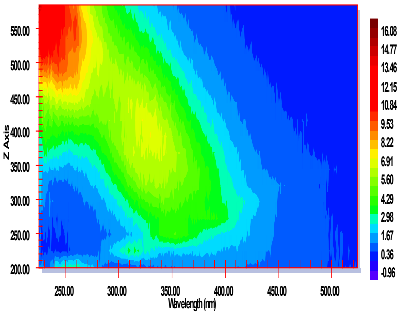
Post GAC

Final

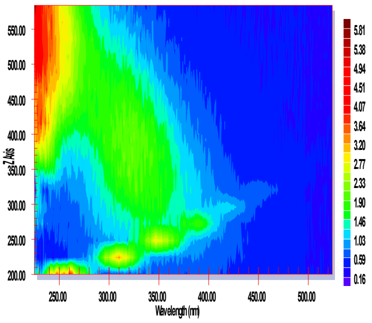


Zone

Figure 5.11.2.24. Fluorescence spectroscopy for Bracadale sampling round November 2015



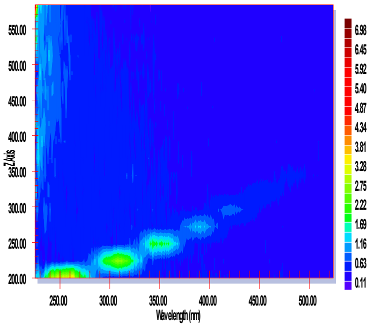
Raw



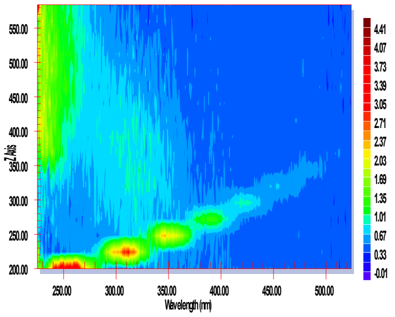
Combined permeate

NO RESULT OBTAINED

Post GAC

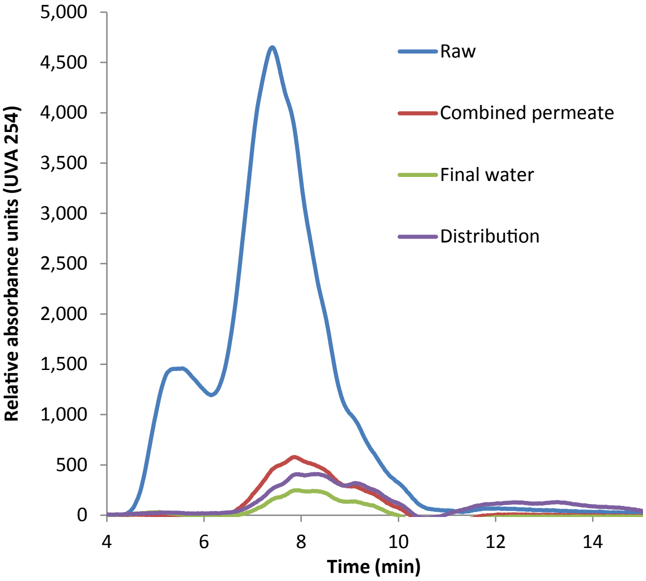


Final



Zone

Figure 5.11.2.25. Fluorescence spectroscopy for Bracadale sampling round March 2016



March 2016

Figure 5.11.2.26. HPSEC for Bracadale over one sampling round, March 2016.

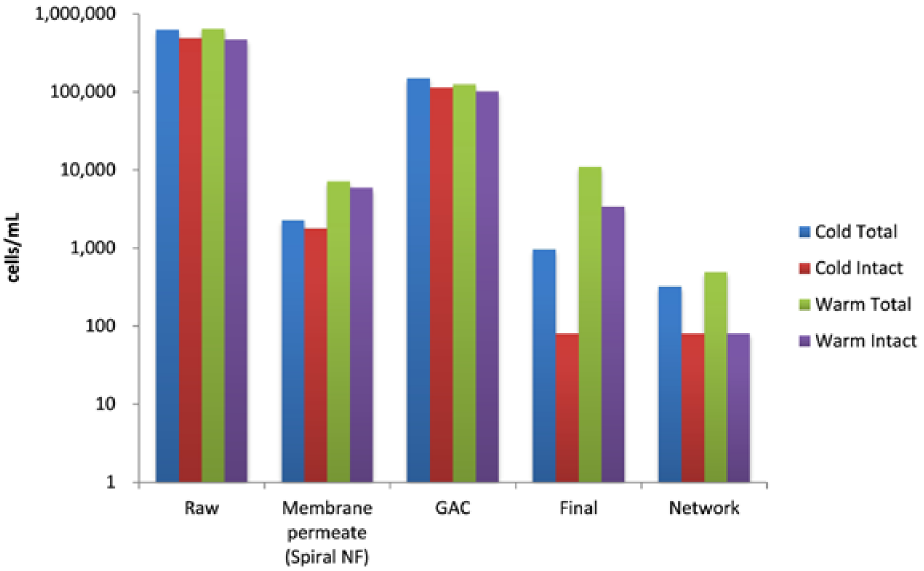


Figure 5.11.2.27. Cell removal across treatment processes measured by flow cytometry for Bracadale over two sampling rounds.

Jordalsvatnet WTW, Norway. The source water at Jordalsvatnet was of low DOC and comprised mainly of hydrophobic organic matter (66% HPO), with a smaller proportion of TPI (24%) and HPI (10%) (Figure 5.11.2.28.). Residual DOC after treatment was very low at <1 mg/L. The characterisation analysis suggested that the DOC of the treated water contained more than 50% HPO. However, characterisation of such low DOC content water can be quite inaccurate due to the range of the instrument used for the analysis. The distribution samples were of interest, because the site sends part of its treated water to one basin and part to another storage basin. The first of the storage reservoirs was measured to have a DOC of 1 mg/L (sample point 4), while the other had a value closer to 0.5 mg/L (sample point 5). It would therefore be of interest to determine whether the first storage reservoir had other inputs or different biological processing that would explain this increase in DOC.

The zeta potential moved from -6.5 mV to 4.5 mV following coagulation (Figure 5.11.2.29.). These results suggested that the site was operating effectively with respect to its coagulant dosing. There were small further reductions in the negativity of the organics in the water following treatment.

The FEEMs plots for the site suggested that there was more fulvic-like organic matter present in the treated water, similar to that seen for the other water sources although the signal was very weak as a result of the low DOC in the treated water samples (Figure 5.11.2.30.). The raw water FEEMS plot showed an unusual emission spectra that was not consistent with other source water samples and suggested that this was an analytical instrumentation problem.

The HPSEC traces were consistent with the other water sources, although because the raw water was of very low UV254 absorbance, the signal picked up by the detector was very low (Figure 5.11.2.31.). However, the results showed removal of the higher MW organic substances, leaving behind a small residual of lower MW NOM.

The cell reduction across the treatment stages was just less than a 1 log reduction across the coagulation and filtration processes in both the warm and cold weather sampling rounds (Figure 5.11.2.32.). A small amount of removal in TCC and ICC was observed following the UV treatment, but as stated previously, the FCM method was not effective for detecting changes in bacterial cells as a result of damage caused to DNA by the UV light. Of interest, the two distribution samples showed some significant differences. The sample labelled as basin (sample point 4), saw a big reduction in cells, both ICC and TCC, in the cold weather sampling round but saw an increase in the later warm weather campaign, while the sample labelled as 'network' (sample point 4), saw a consistent increase in cells for both sampling campaigns. Without more understanding of the system, it is hard to draw firm conclusions form these results. However, it was apparent that in most cases, presumably due to there being no residual chlorine in the water, distribution samples saw an increase in the concentration of viable, living cells. In the case when cells reduced significantly from the UV treatment to the basin, some other external factor must have caused cells to have been removed from the water.

Overall, the site was performing very effectively, with low residual DOC in the treated water. Further investigation of bacterial population changes throughout the WTWs and in the network would be of interest for this site to understand the importance of such fluctuating cell concentrations and the make-up of the bacterial populations.

November 2015

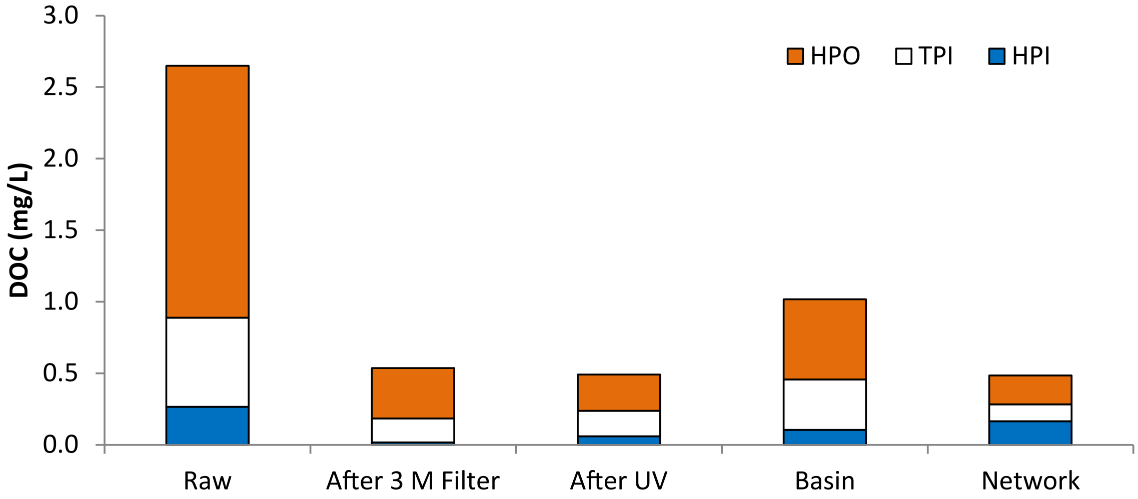


Figure 5.11.2.28. Fractionation at Jordalsvatnet WTWs over one sampling round.

November 2015

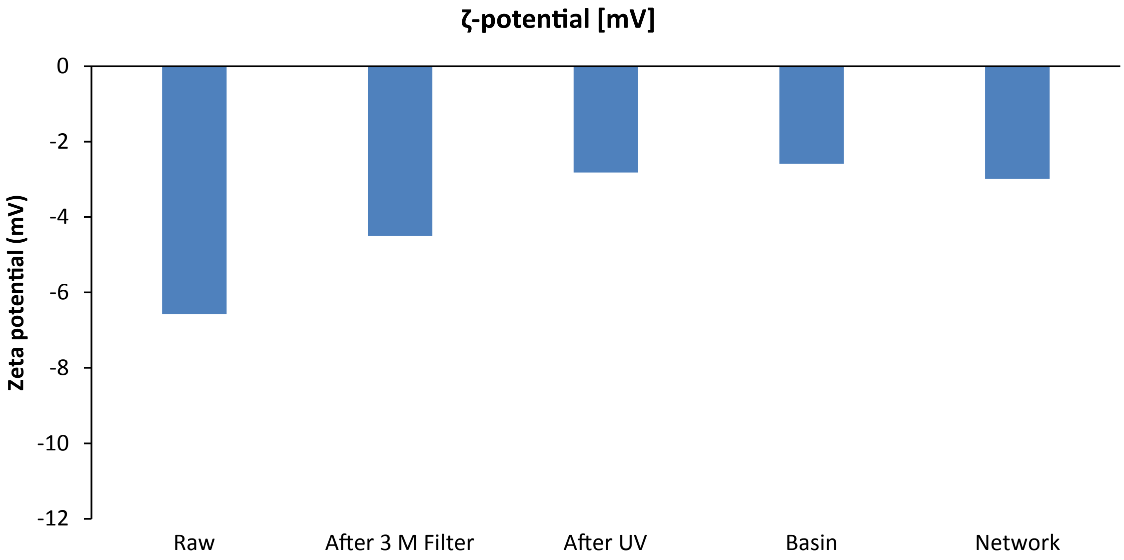
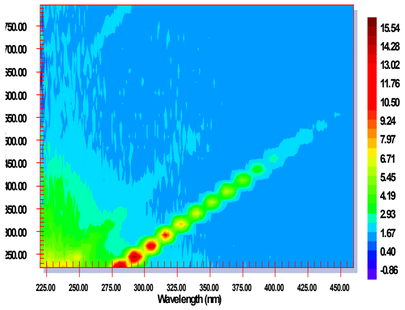


Figure 5.11.2.29. Interstage zeta potential for Jordalsvatnet sampling round.



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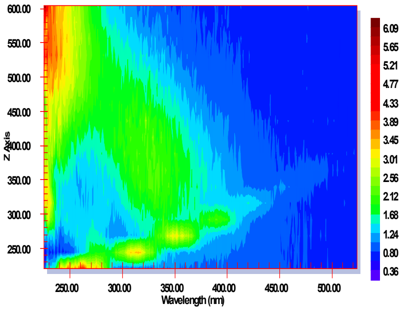
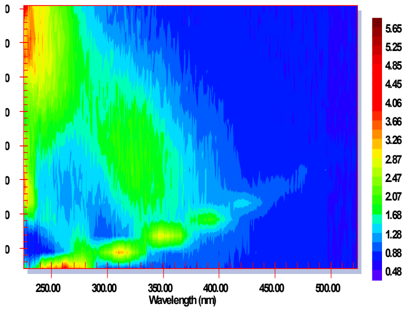
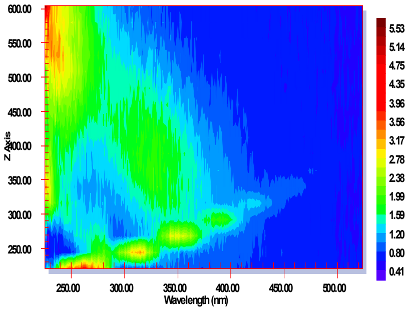


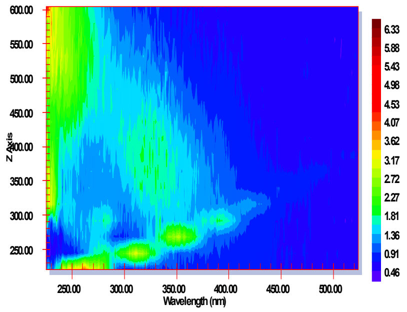
3M filter



UV

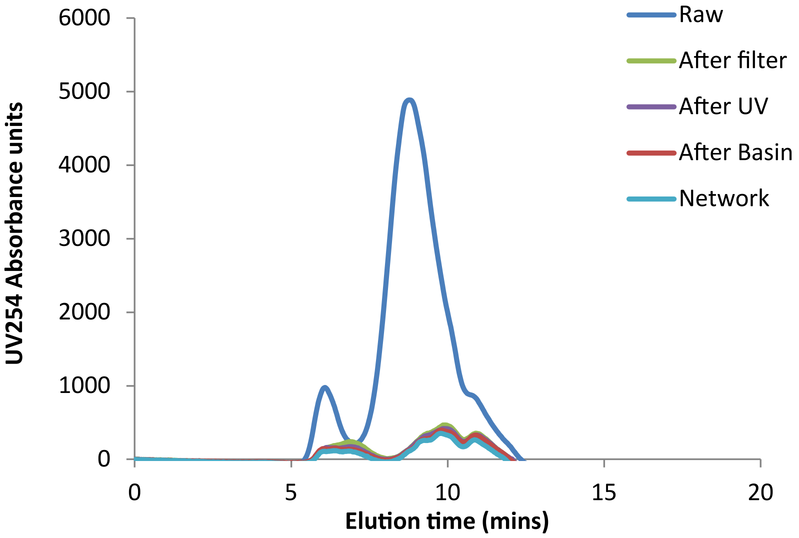


Basin



Network

Figure 5.11.2.30. Fluorescence spectroscopy for Jordalsvatnet sampling round November 2015.



March 2016

Figure 5.11.2.31. HPSEC for Jordalsvatnet sampling round November 2015.

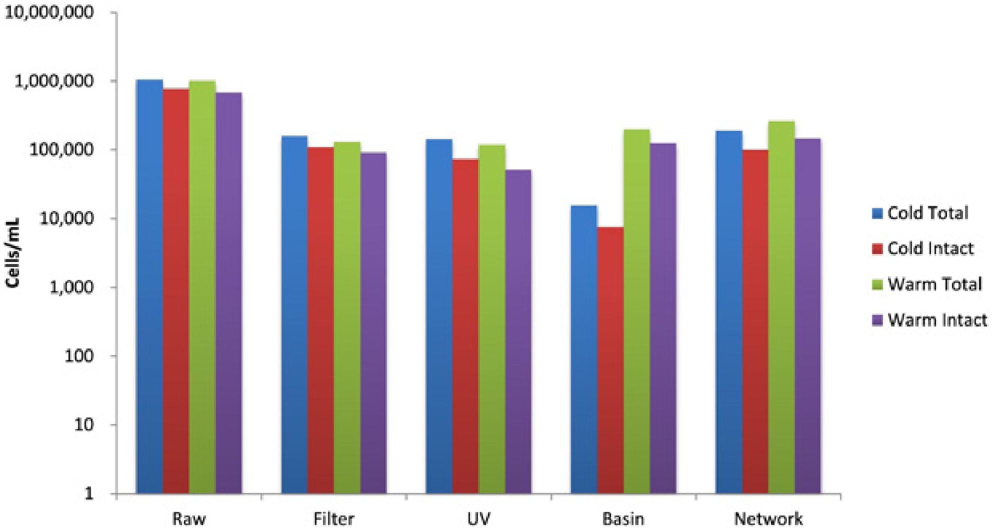


Figure 5.11.2.32. Cell removal across treatment processes measured by flow cytometry for HSY over two sampling rounds.

IVAR Pilot WTP, Norway. The source water was of low to moderate DOC at 4.2 mg/L (Figure 5.11.2.34.). The water had an equal split of organic matter as HPO (43%) and TPI (42%), with a smaller residual of HPI (15%). Following treatment, the residual DOC was reduced to 1 mg/L. The one significant change in the proportion of fractions occurred following the bio-filter, where a much larger proportion of TPI fraction was seen (58% of the total DOC), although the significance of this was not fully understood given the low levels of DOC measured.

Given that the water undergoes minimal treatment for removal of charged DOC (in other words, not a coagulation process), it was unsurprising that the zeta potential did not change significantly through the treatment processes at the WTWs (Figure 5.11.2.35).

The FEEMs plots also showed minimal signals in the raw water, suggesting that the DOC present had a very low absorbance and excitability for a range of UV wavelengths (Figure 5.11.2.36.). There was some evidence that the water underwent a degree of oxidation/bleaching through the ozonation treatment stage as shown by an overall reduction in the signals observed for the excitation emission spectra in samples taken after the ozone treatment stage.

Due to the low UV254 absorbance of the water, there was a low signal obtained from the HPSEC traces for the IVAR pilot plant (Figure 5.11.2.37.). However, it was seen that the intensity of the two spikes at 6 and 8 minutes retention time were reduced following ozone and then following bio-filtration, showing some continued removal of trace levels of NOM across these processes.

The cell removal across the ozone treatment stage was 0.4 and 0.7 log reduction for the total and intact cells respectively (Figure 5.11.2.38.). Cells then increased after the ozone treatment stage, presumably through re-introduction of cells from the bio-filtration stage and from re-growth in the network/distribution system.

Overall, the pilot appeared to be very effective and was producing a very high quality treated water.

November 2015

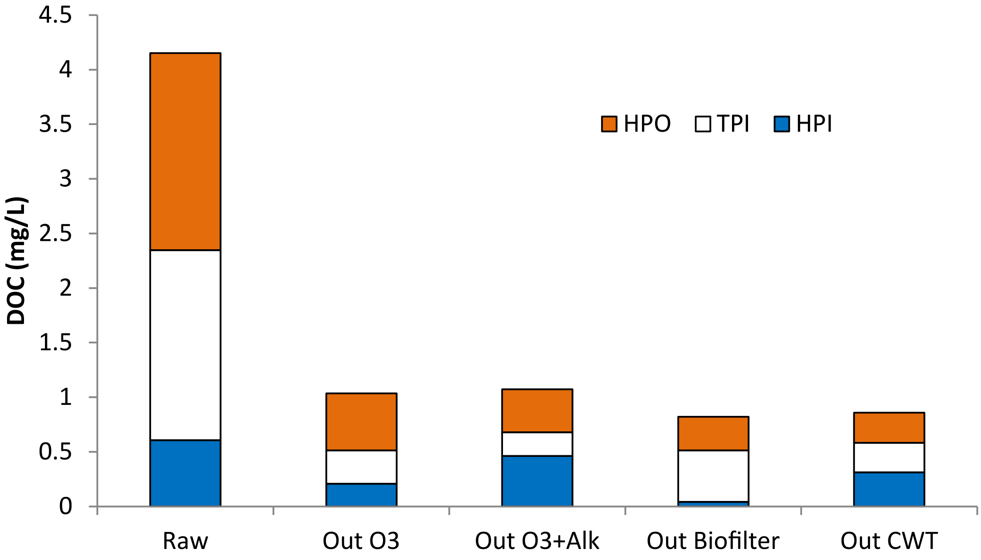


Figure 5.11.2.33. Fractionation at IVAR over one sampling round.

November 2015

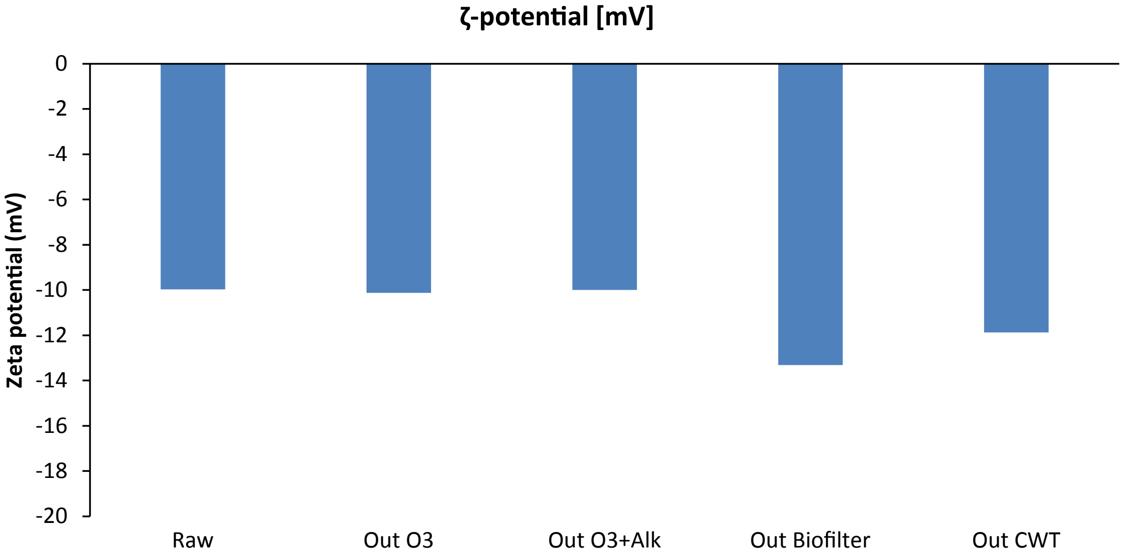
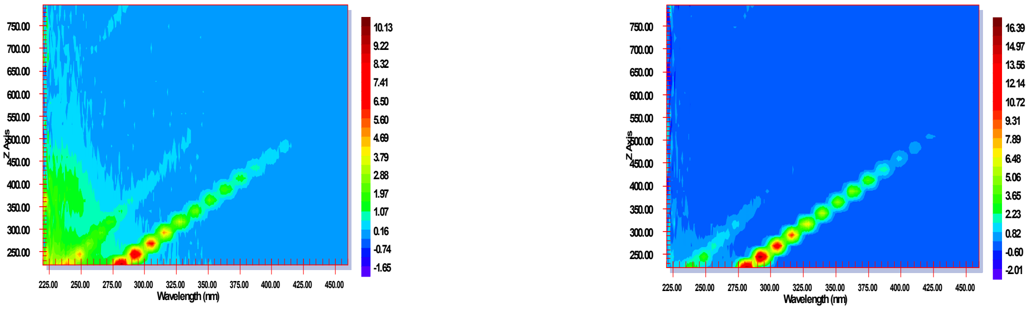
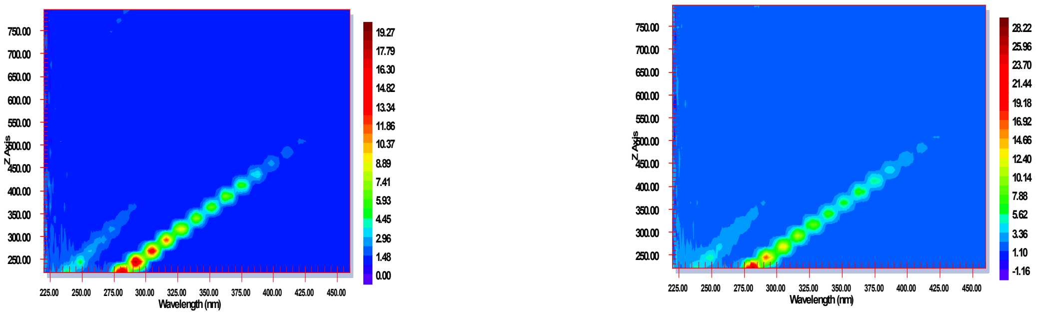


Figure 5.11.2.34. Interstage zeta potential for IVAR sampling round.



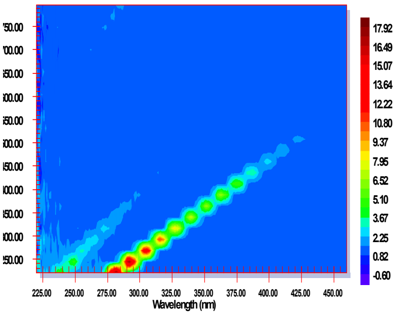
Raw

Ozone



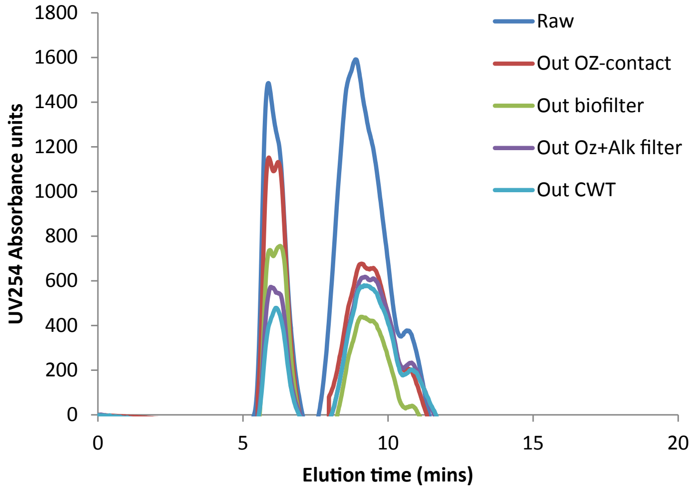
Ozone and alk filter

Biofilter



Clearwater tank

Figure 5.11.2.35. Fluorescence spectroscopy for IVAR sampling round November 2015.



March 2016

Figure 5.11.2.36. HPSEC for IVAR sampling round November 2015.

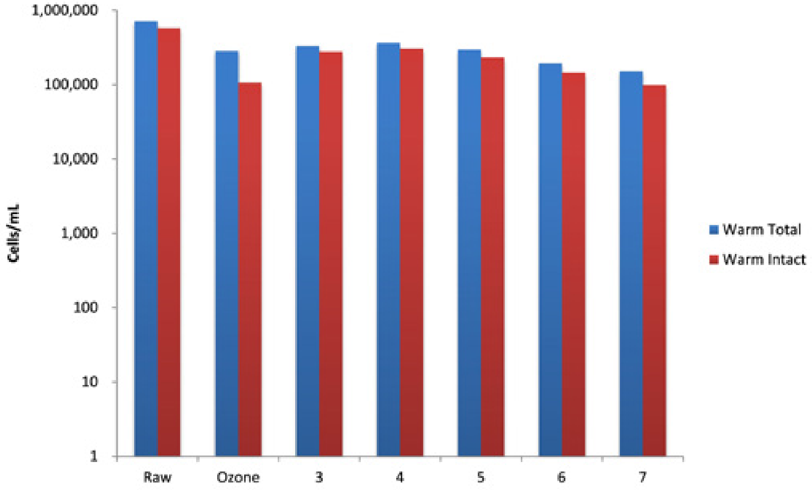


Figure 5.11.2.37. Cell removal across treatment processes measured by flow cytometry for IVAR over one sampling round.

Kärreberg WTW, VIVAB, Sweden. The source water at Kärreberg was a moderate to high DOC source water that varied between 6.2 and 8.4 mg/L over the two sampling rounds (Figure 5.11.2.38.). The raw water was dominated by HPO in the March 2016 sampling with over 62% DOC. There was a more even split of DOC in the November 2015 raw water sample with a significant concentration of HPI (45% of the sample) and HPO (39%). There was a moderate reduction in DOC after coagulation and filtration, with DOC being reduced by 60-70%. In the November sampling, when the DOC of the source water was higher, the residual DOC in the treated water was more than 3 mg/L, suggesting that the coagulation process could be operated more effectively. However, the outlet and distribution samples resulted in very low concentrations of NOM at <1 mg/L DOC, showing the effectiveness of the infiltration basin at removing NOM from the water. The lamella sedimentation line represented a return line from the filter backwash that went back to the head of the WTWs for treatment back through the treatment stages, so it was not surprising to see an elevated level of DOC in this sample. Of interest, in the November sampling, this sample was predominantly hydrophilic (72% HPI), which could then impact on the treatability of the water, depending on the mass loading of DOC back into the water.

The NOM in the source water had a high reactivity at 80-115 µg THM per mg of DOC (Figure 5.11.2.39). Although the overall concentration of THMs reduced after coagulation and filtration in-line with the reduction in DOC, the reactivity of the NOM increased to 120 µg THM per mg of DOC in the November sampling round. This may have been a combination of factors, including the contribution of NOM from the return backwash water and the poor removal of DBP precursors by PACI coagulants. Here, it was interesting to note that the water from the lamella treated water had a very similar reactivity as for the treated filtered water, suggesting that it could be an important contributor to the change in reactivity of the filtered water. At the outlet of the WTWs and in distribution both the overall THM concentration and reactivity had significantly decreased to 20-33 μg/LTHMs and 28-41 μg THM per mg of DOC, respectively. This clearly showed the benefit of the long infiltration period in removal of NOM and selective removal of reactive NOM towards chlorine.

The charge profile for the works was consistent with expectations with reduction in sample zeta potential through the treatment processes from -18.4 mV to -9.5 mv after coagulation and filtration (Figure 5.11.2.40.). This was just on the cusp of where we would normally expect to see effective charge neutralisation and coagulation, so the site may benefit from a slight increase in the coagulant dose applied. Further removal of charge was seen across the infiltration basin. Of note, there was a very positive charge observed in the sample from the lamella clarification line. This may have been cause through the use of a positively charged polymer in the clarification stage, but this warrants further investigation.

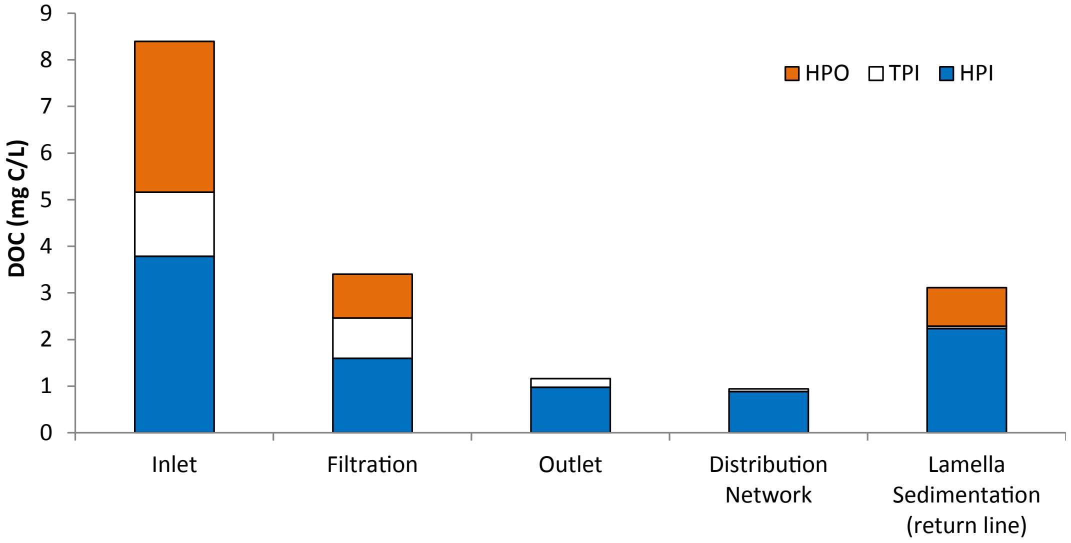
The FEEMs plots were consistent with that seen before for the other sites with both raw water samples showing a strong fingerprint for humic and fulvic-like NOM (Figure 5.11.2.41 and 42). Both the fulvic and humic fraction were not effectively removed by coagulation and filtration, suggesting that the coagulant was not effective in removing humic-like substances, as also indicated by the fractionation results. However, some further removal of this fraction was seen across the infiltration basin, which meant that the treated water had low DOC and THM formation potential. The lamella return line contained mainly fulvic-like NOM, although there was a significant signal from the humic-like NOM.

The HPSEC plots were consistent with the removal data from the fractionation and FEEMS, showing good removal of higher MW organic compounds and further removal following the infiltration system, leaving behind a very low residual of UV_{254} absorbing organic compounds (Figure 5.11.2.43.).

The removal of microbial cells across the WTWs showed very consistent removal for the two sampling rounds, with approximately 2-log removal achieved across the WTWs (Figure 5.11.2.44.). Most of the removal is achieved across the infiltration system, with only 0.36 and 0.49 log reduction of TCC and ICC respectively across the Dynasand filters.

Overall, the WTWs appears to be operating very effectively. While the coagulation stage is perhaps operating sub-optimally, significant benefit is offered by the infiltration system which removes bacteria and DBP precursors to very low levels.

November 2015



March 2016

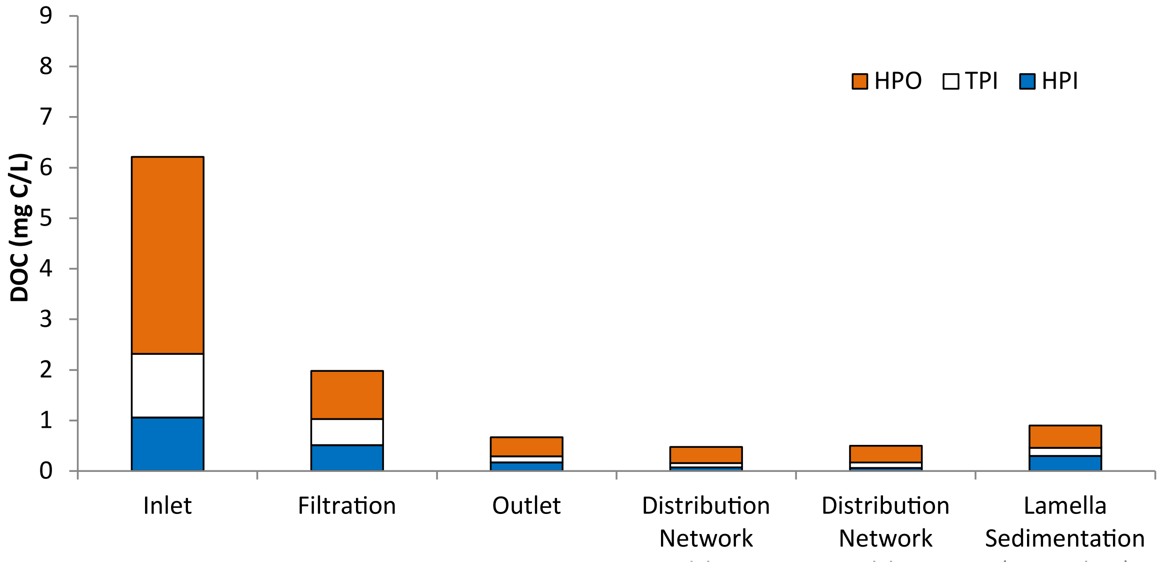
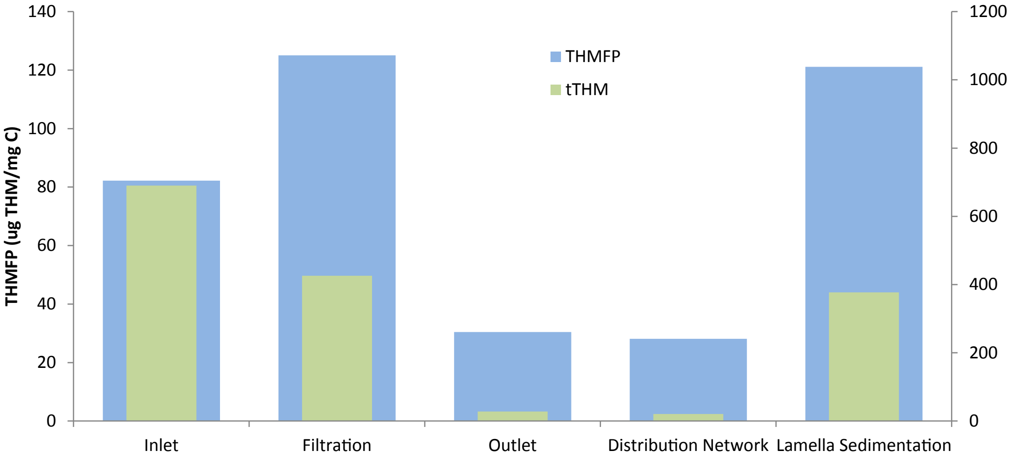


Figure 5.11.2.38. Fractionation for Karreberg over two sampling rounds.

November 2015



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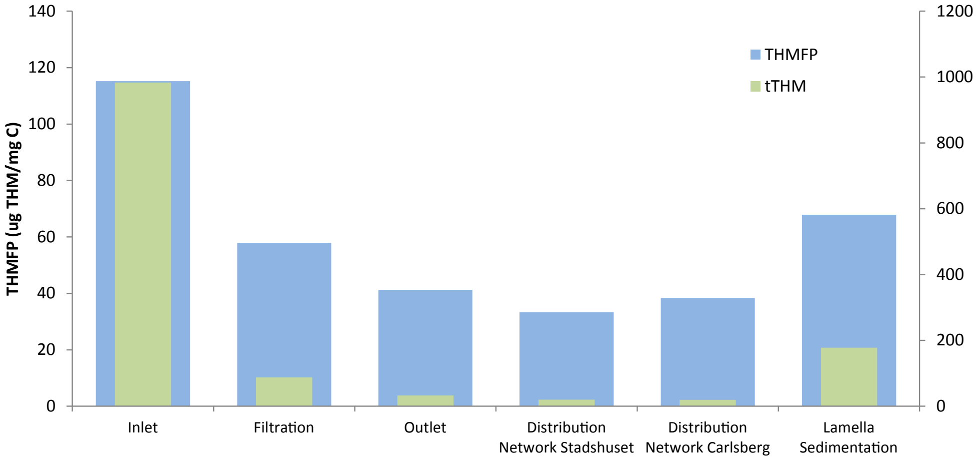


Figure 5.11.2.39. Disinfection by-products for Karreberg sampling rounds.

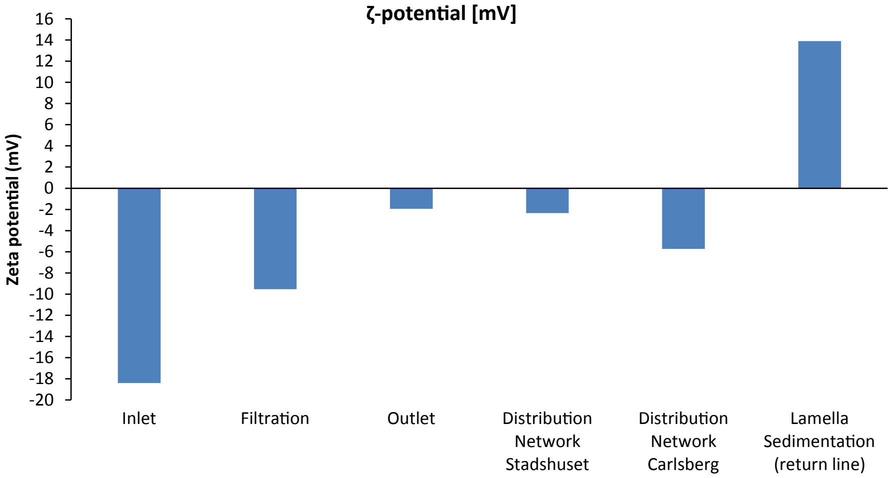
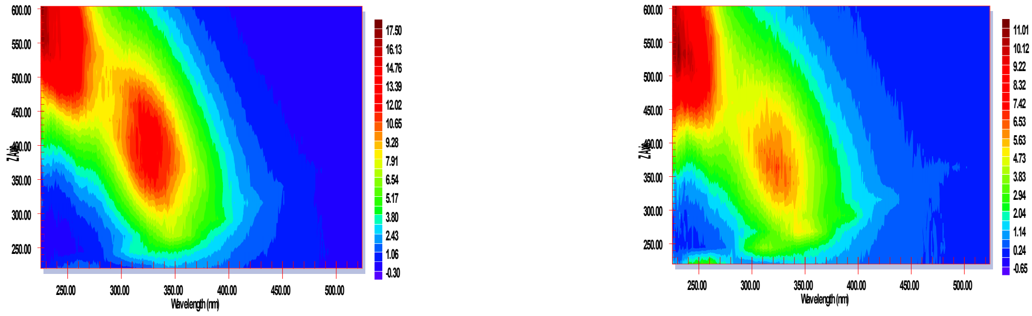
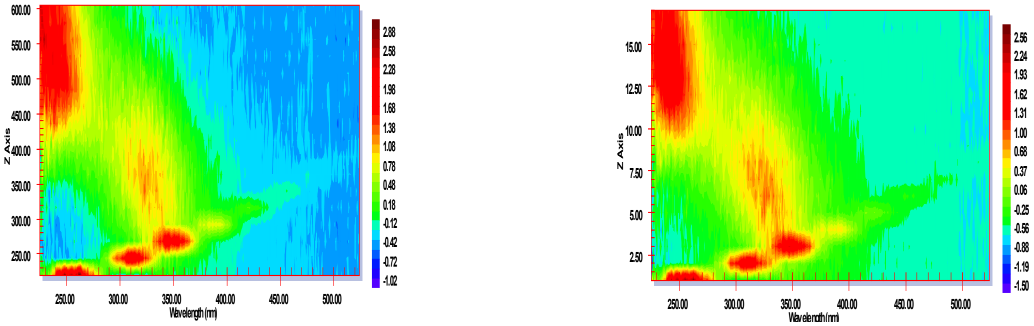


Figure 5.11.2.40. Interstage zeta potential for Karreberg sampling round.



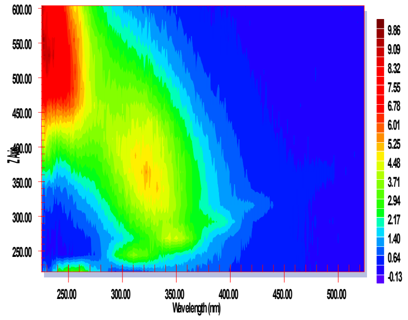
Raw

Filtration



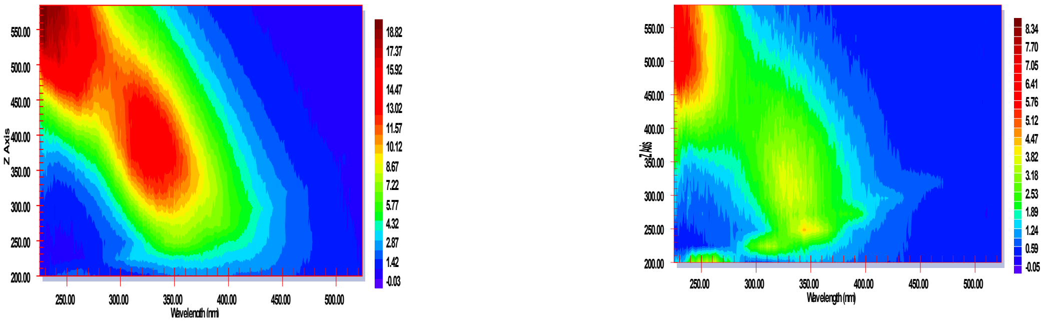
Outlet

Distribution



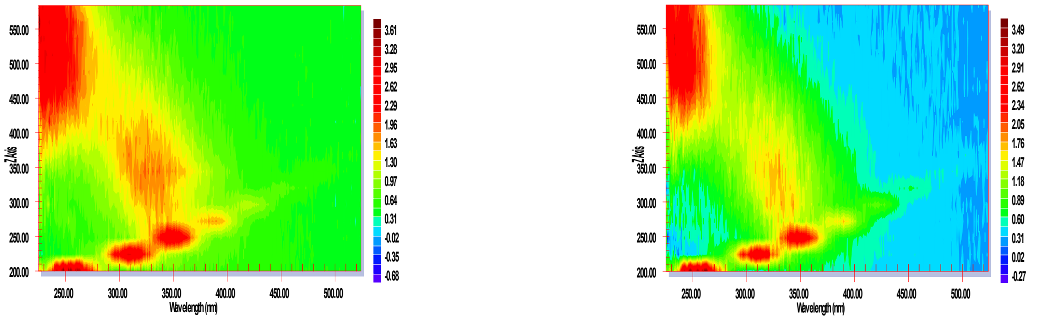
Lamella (return line)

Figure 5.11.2.41. Fluorescence spectroscopy for Karreberg sampling round November 2015



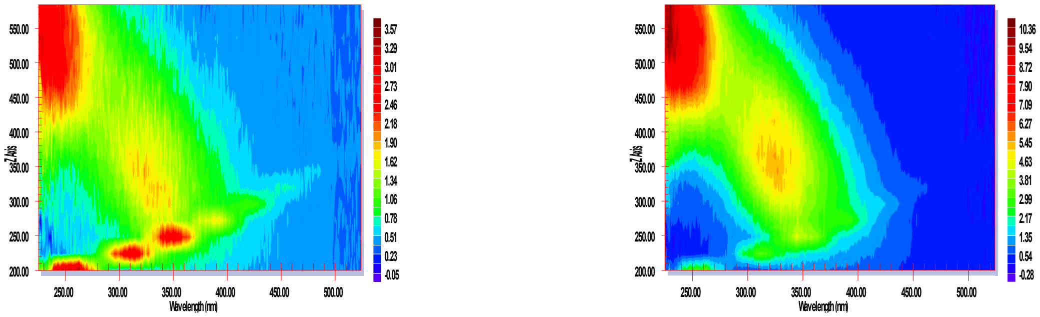
Raw

Filtration



Outlet

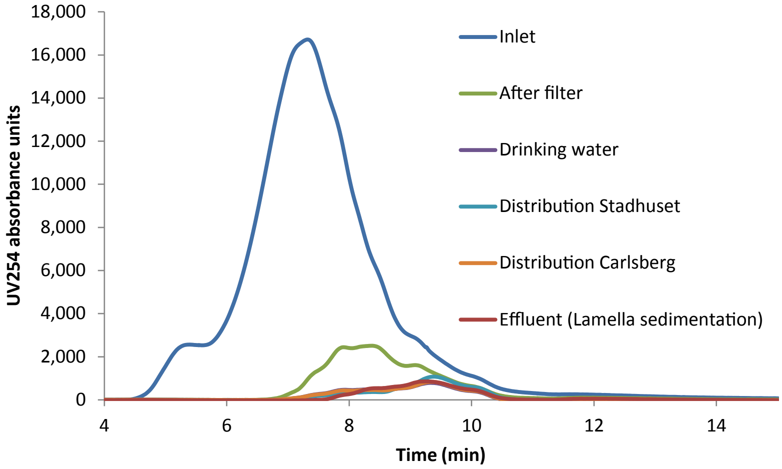
Distribution Network Stadshuset



Distribution Network Carlsberg

Lamella (return line)

Figure 5.11.2.42. Fluorescence spectroscopy for Karreberg sampling round March 2016



FFigure 5.11.2.43. HPSEC Karreberg March 2016.

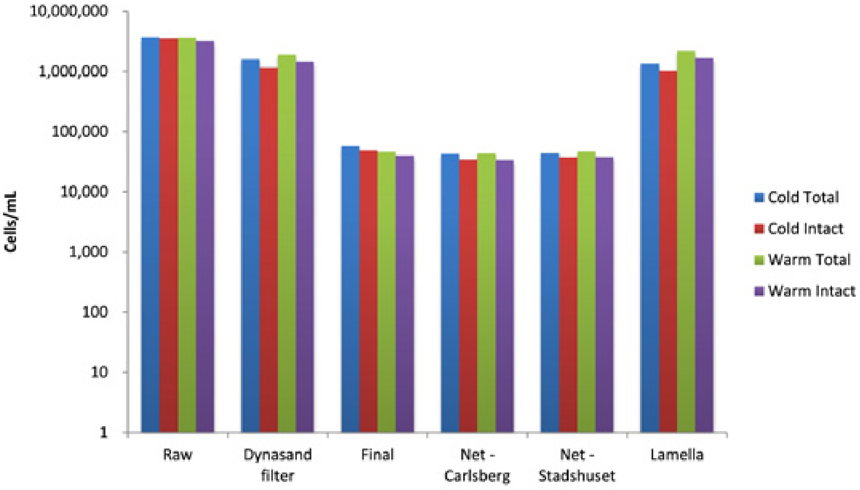


Figure 5.11.2.44. Cell removal across treatment processes measured by flow cytometry for Karreberg over two sampling rounds.

Ringsjöverket WTP, Sydvatten, Sweden. The site contained stable and moderate to high NOM levels, with a DOC content between 8.6 and 8.9 mg/L DOC (Figure 5.11.2.45). The DOC was predominantly hydrophobic in nature, with levels of HPO between 58-71%. After treatment, the DOC was reduced to levels between 2-3 mg/L resulting in quite a high residual of organic matter that had a similar fractional distribution to the raw water. There were therefore significant quantities of HPO in the treated water (>50% of the total DOC).

The DBP formation potential of the raw water source was very high at 158 µg THMs per mg of DOC, resulting in a very high concentration of overall THMs that could potentially form in the source water (1357 µg/L) (Figure 5.11.2.46). This was significantly reduced in the treated waters to a stable value of 70-90 µg THMs per mg of DOC. However, this was still a high value and puts the site at some risk of exceeding THM regulations given that more than 2 mg/L of DOC may be present in the treated water.

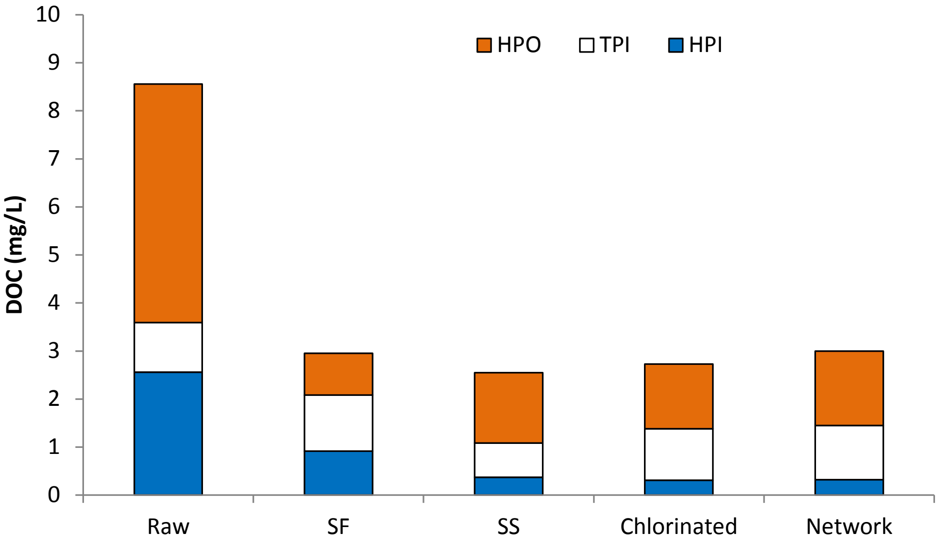
The charge profile of the water through the different treatment stages was indicative of effective coagulation, given that the zeta potential following filtration was in a zone considered optimum for charge neutralization (Figure 5.11.2.47.). This suggested that the NOM in the water was difficult to coagulate and left behind a residual of NOM with a high reactivity towards chlorine.

Both the FEEMS and HPSEC plots were consistent with the previous coagulation WTWs investigated in this programme of work, with good removal of humic substances and high MW organic compounds leaving behind a low residual of fulvic-like and low MW organics (Figures 5.11.2.48-50.).

Microbe removal across the WTWs was consistent with many of the other sites (Figures 5.11.2.51.). Removal of 0.8 log was seen across the coagulation-clarification-filtration processes for ICC and TCC. No removal of cells was seen across the slow sand filtration process. Disinfection had no effect on the TCCs, but reduced the ICCs by 2.1-2.6 log compared to the raw water source. Cell concentration increased in the network, presumably as a result of a loss of chlorine residual or from cell contribution from the network biofilm.

Overall, the site could consider changing its coagulation regime as a high residual DOC was observed following this process. However, the charge data suggested that the site was operating in an effective coagulation zone. This may, therefore, mean that the site was treating a very difficult water to coagulate such that alternative treatment options should be considered for removal of high DBP forming NOM.

November 2015



March 2016

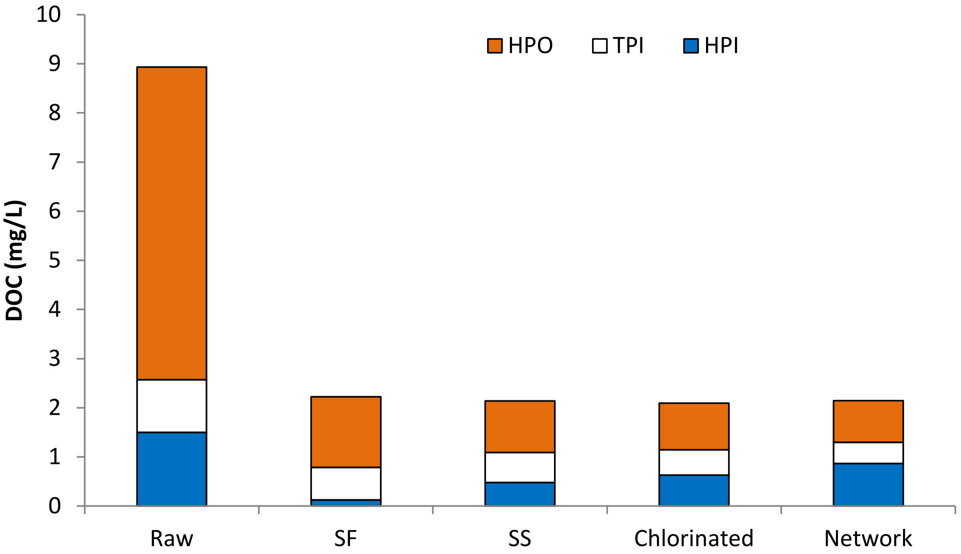


Figure 5.11.2.45. Fractionation for Sydvatten sampling rounds.

November 2015

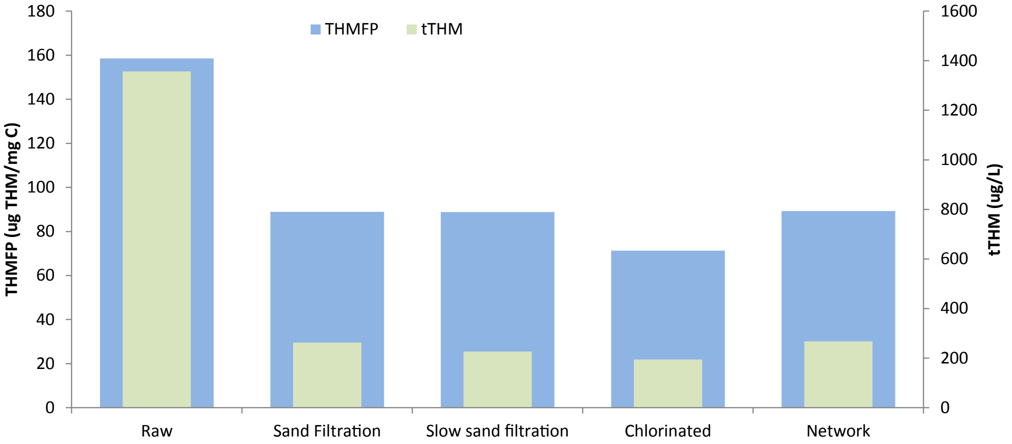
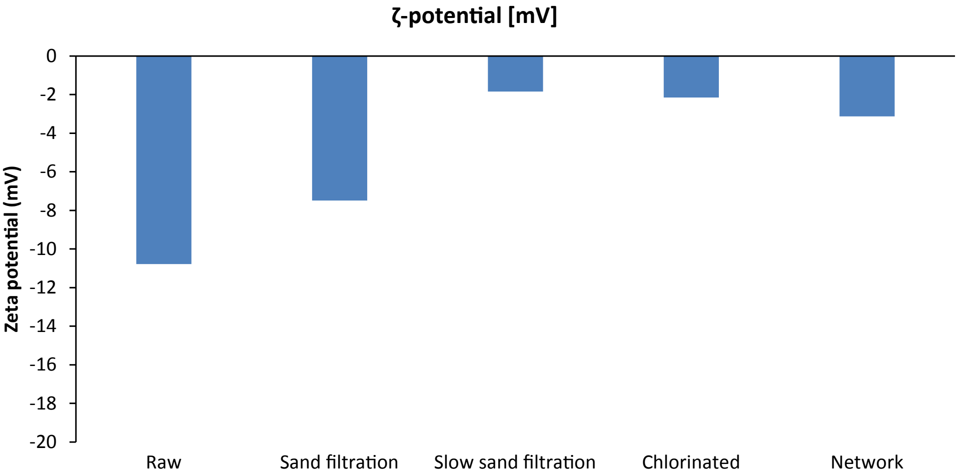


Figure 5.11.2.46. Disinfection by-products for Sydvatten sampling round.

November 2015



March 2016

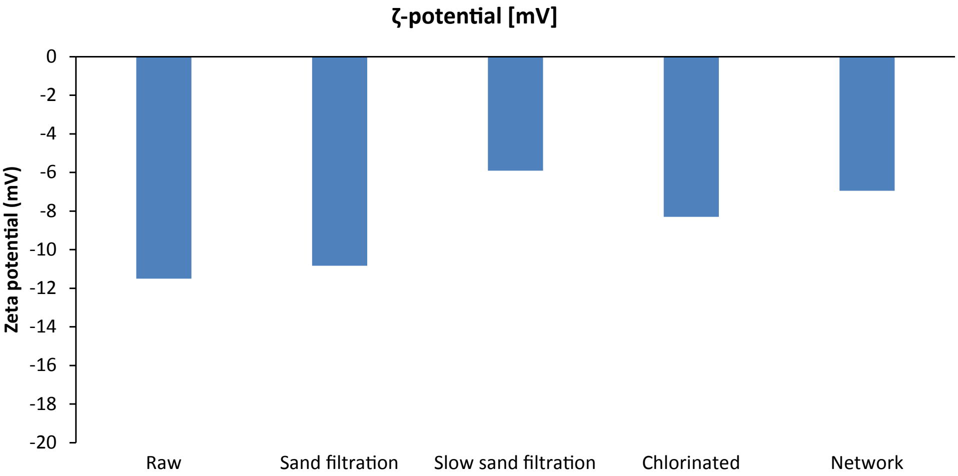
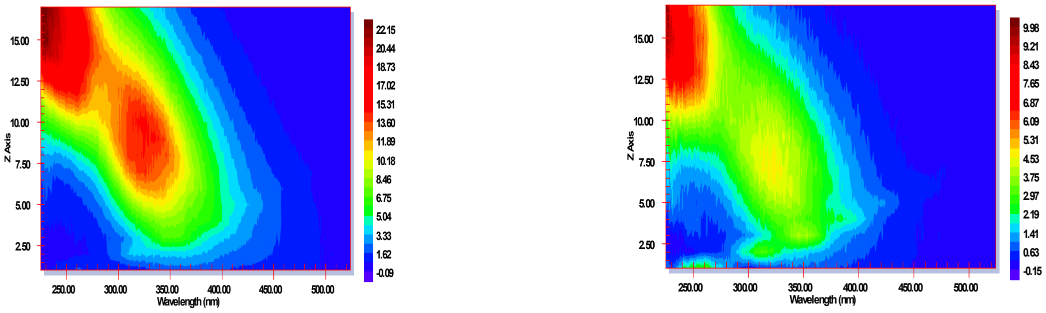
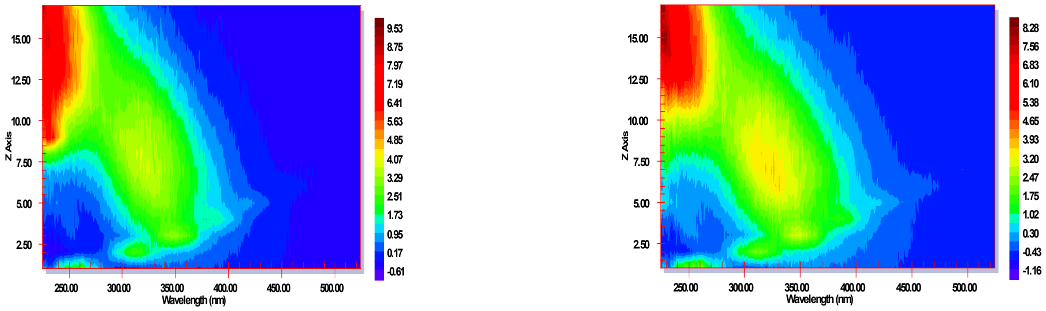


Figure 5.11.2.47. Interstage zeta potential for Sydvatten sampling rounds.



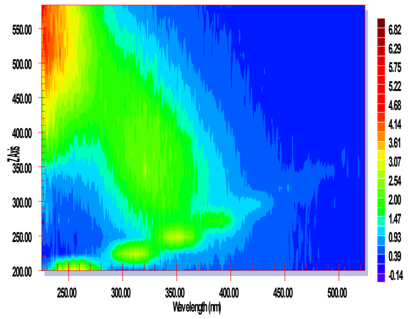
Raw

Sand filtration



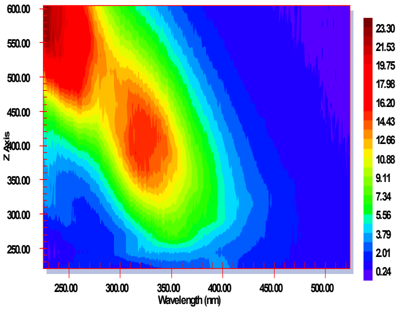
Slow sand filtration

Chlorinated

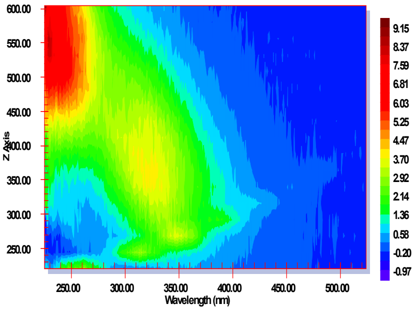


Network

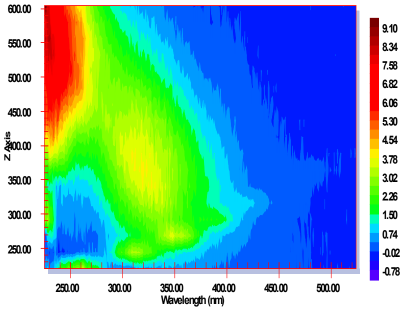
Figure 5.11.2.48. Fluorescence spectroscopy for Sydvatten sampling round November 2015



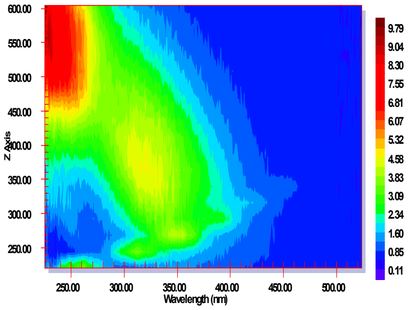
Raw



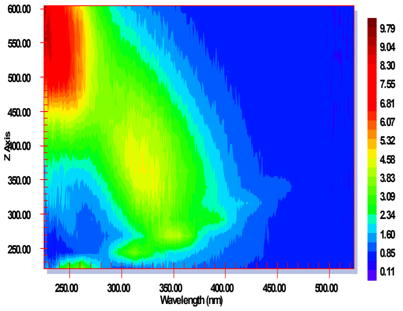
Sand filtration



Slow sand filtration

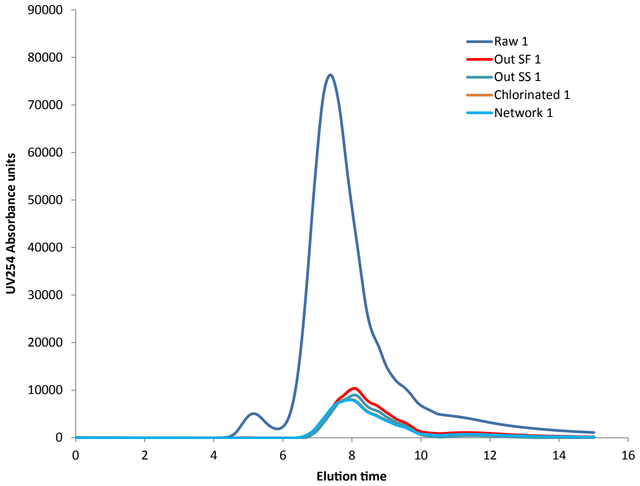


Chlorinated



Network

Figure 5.11.2.49. Fluorescence spectroscopy for Sydvatten sampling round March 2016



November 2015

Figure 5.11.2.50 HPSEC Sydvatten for the one sampling rounds.

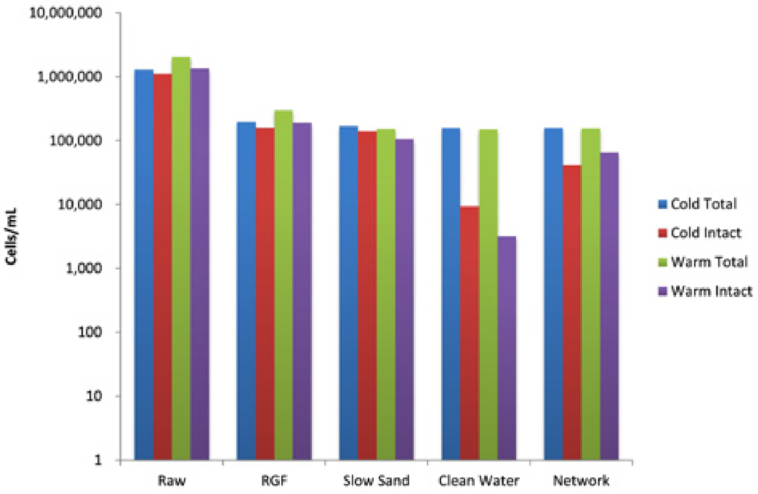


Figure 5.11.2.51. Cell removal across treatment processes measured by flow cytometry for Sydvatten over two sampling rounds.

Görvälnverket WTP, Norrvatten, Sweden. The Görvälnverket source water was of moderate to high DOC, between 6.5 and 8.2 mg/L (Figure 5.11.2.52.). Unlike most of the other source waters investigated, this site treated water that contained DOC which was predominantly HPI or TPI (between 58 and 65% of the total DOC). This suggested that the NOM would be hard to treat by coagulation based processes and was confirmed by the high residual DOC following treatment (between 3-4 mg/L). In the November 2015 sampling campaign, the majority of the treated water samples contained more than 50% HPI, while there was a more similar split in the organic compounds in treated water for the March 2016 sampling.

In the treated water samples, the THM formation potential was very similar in the raw water and treated water samples, suggesting that the treatment processes were not very selective for THM precursor removal (Figure 5.11.2.53.). The THM formation potential was higher in the March 2016 sampling round at 76 µg THMs per mg of DOC in the raw water and between 61 and 66 µg THMs per mg of DOC in the treated water. Equivalent values for the November samples were 48 µg THMs per mg of DOC in the raw water and between 38 and 49 µg THMs per mg of DOC in the treated water. The higher value in the March samples could have been due to the increased HPO content of these samples, which is known to usually have a higher THM formation potential. An anomalous result was seen for the network sample which had a very high formation potential of 81 µg THMs per mg of DOC in the treated water.

Although there was a degree of variability in the reactivity of the NOM in the treated water, because of the high levels of residual DOC the site would be routinely at risk of exceeding THM regulatory limits.

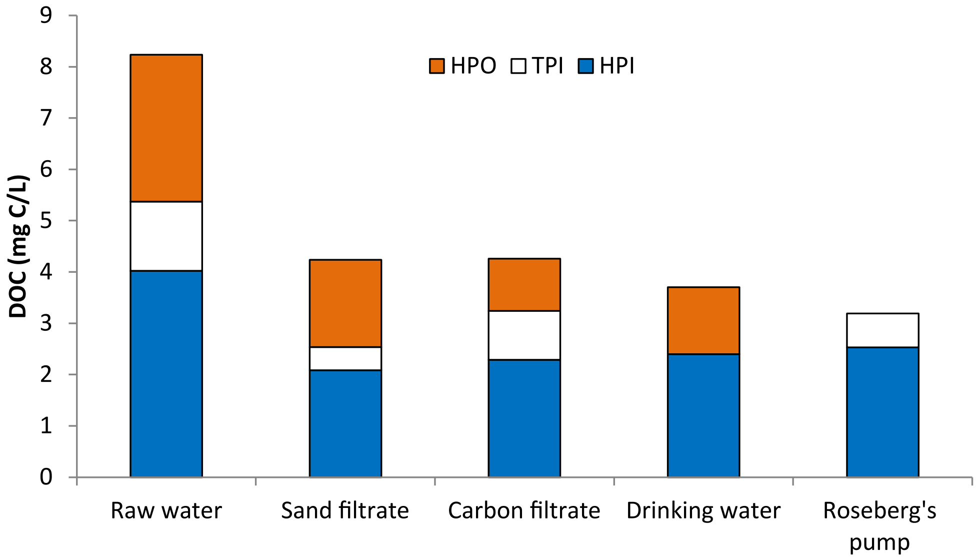
The charge profile through the WTWs was consistent with what would be expected for a coagulation based WTWs (Figure 5.11.2.54.), with a significant reduction in the negative zeta potential following coagulation between the raw water and the filtered sample. This indicated that the coagulation process was effectively optimised and that the high residual NOM was as a result of the presence of DOC that could not be easily coagulated.

Both the FEEMS and HPSEC plots were consistent with the previous coagulation WTWs investigated (Figures 5.11.2.55-57.). However, while there was some removal of the humic substance peak, there was still a significantly strong signal after coagulation, suggesting that this was a range of organics of apparent similarity to humic substances that were not removed by coagulation. It may have been these organic compounds that were causing treated water to have occasionally high DBP formation potential.

With respect to microbial removal, it was noted that the incoming cell concentration was very high during the cold weather sampling campaign, with over 4,000,000 cells being measured per mL of sample (Figure 5.11.2.58.). This reduced to more typical concentrations in the warm weather sampling campaign at 1,800,000 cells per mL. It was unclear as to whether the high sample count in the cold weather sample was a real reflection of the environmental concentration of bacteria or as a result of sample contamination or cell proliferation between the sample having been taken and being measured in the laboratory. Overall, the cell removal across the WTWs was low, with only a 0.4-0.6 log reduction across the WTWs for both ICC and TCC. The site employs UV disinfection. As has already been discussed, flow cytometry is not very effective for assessment of cell damage caused by UV, so this process efficacy could not be determined from this work. However, the site does then employ chlorine disinfection, but the usual ICC reduction following chlorination was not seen for this site. This may have been a reflection of some deterioration in the sample or as a result of a very low chlorine residual having been present.

Overall, the site faces treatment of a challenging water. The NOM in the water was difficult to coagulate which resulted in a high residual DOC in the treated water. Given that the DBP formation of the water was observed to be high on occasion, alternative processes may need to be considered to reduce overall NOM levels prior to chlorine disinfection. Investigation into the microbial composition of the water would also be of interest, given the high levels of cells seen in the raw water and in the treated samples.

November 2015



March 2016

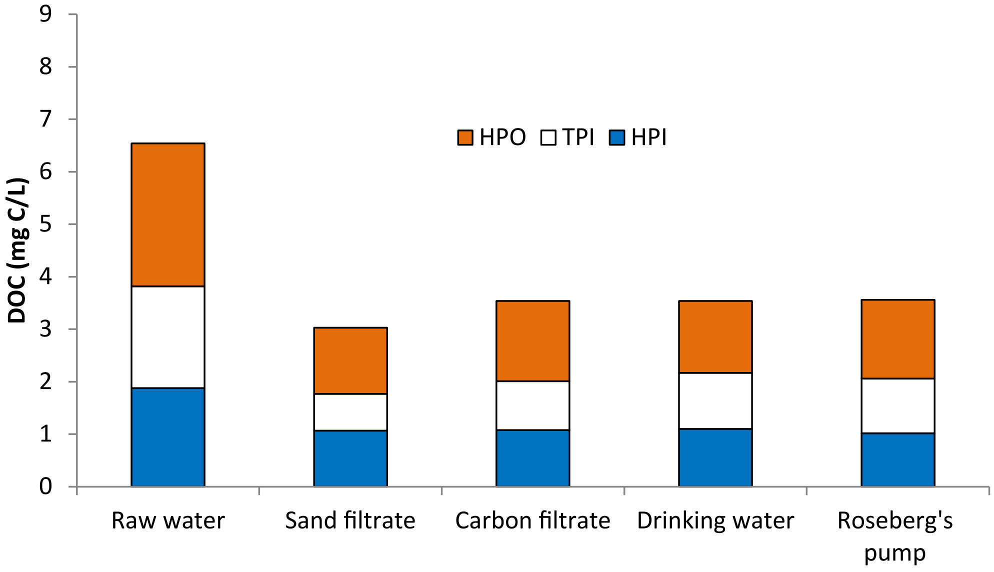
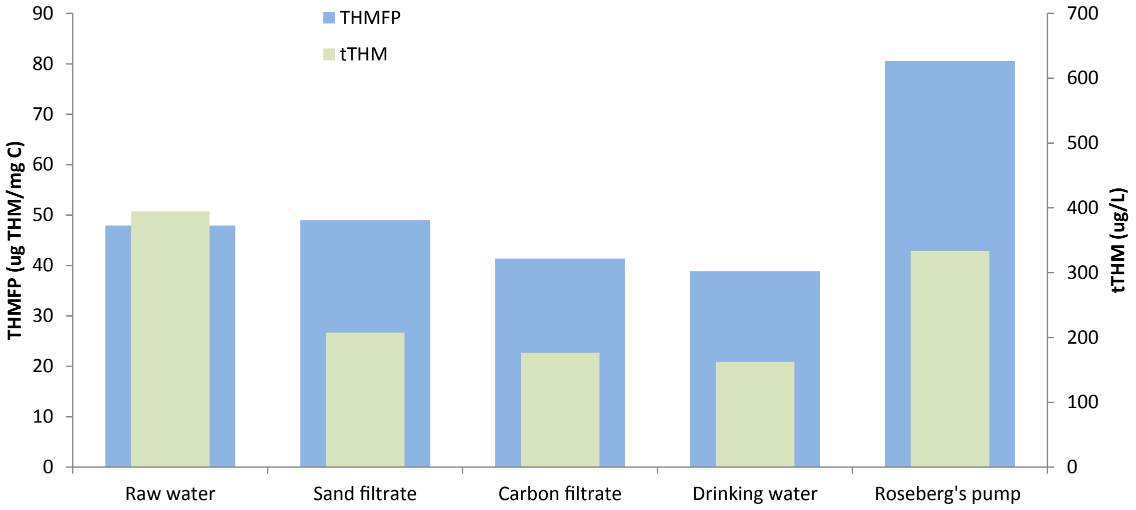


Figure 5.11.2.52. Fractionation for Görvälnverket sampling rounds.

November 2015



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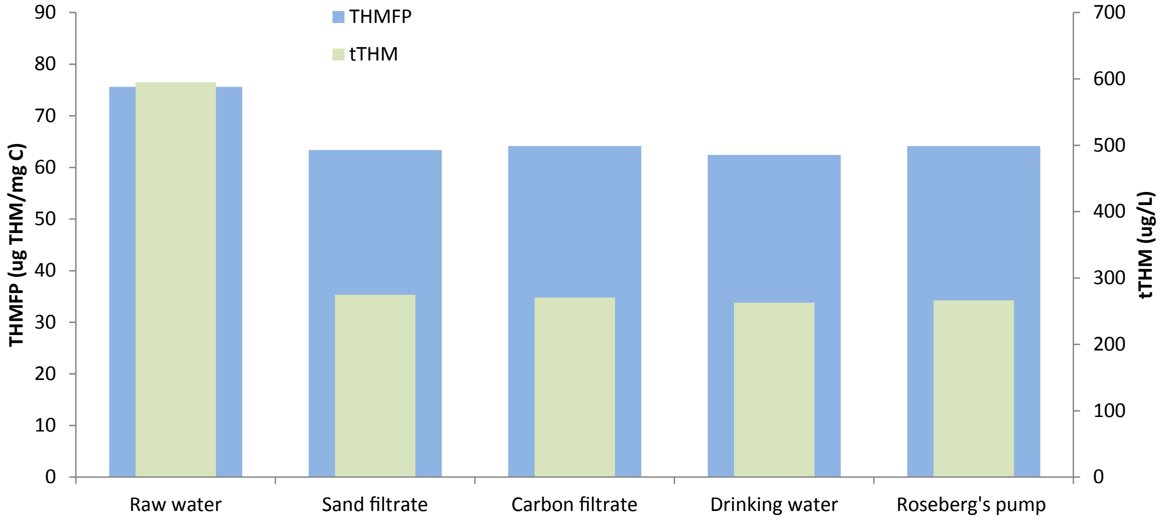
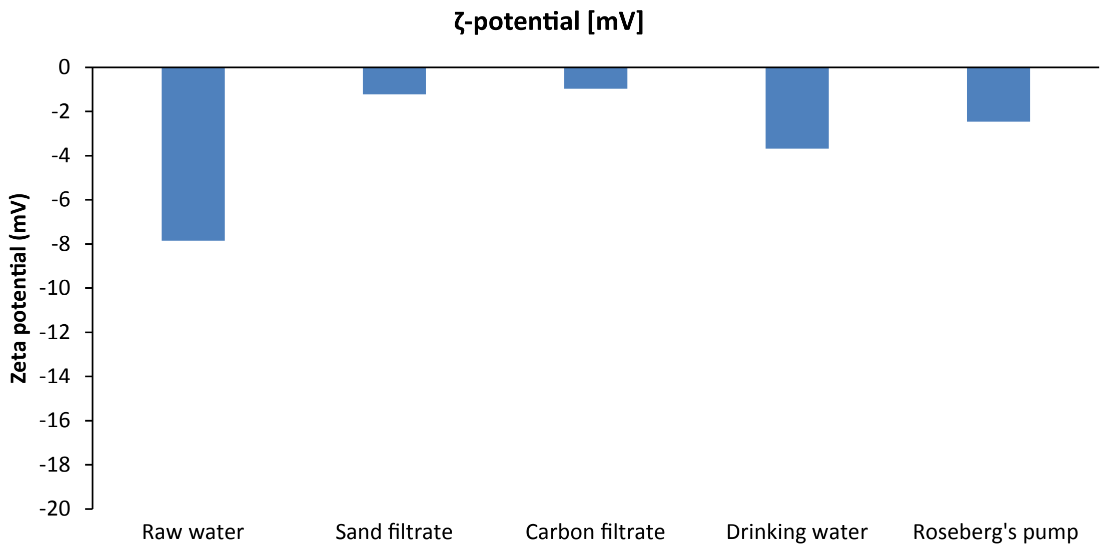


Figure 5.11.2.53. Disinfection by-products for Görvälnverket sampling rounds.

November 2015



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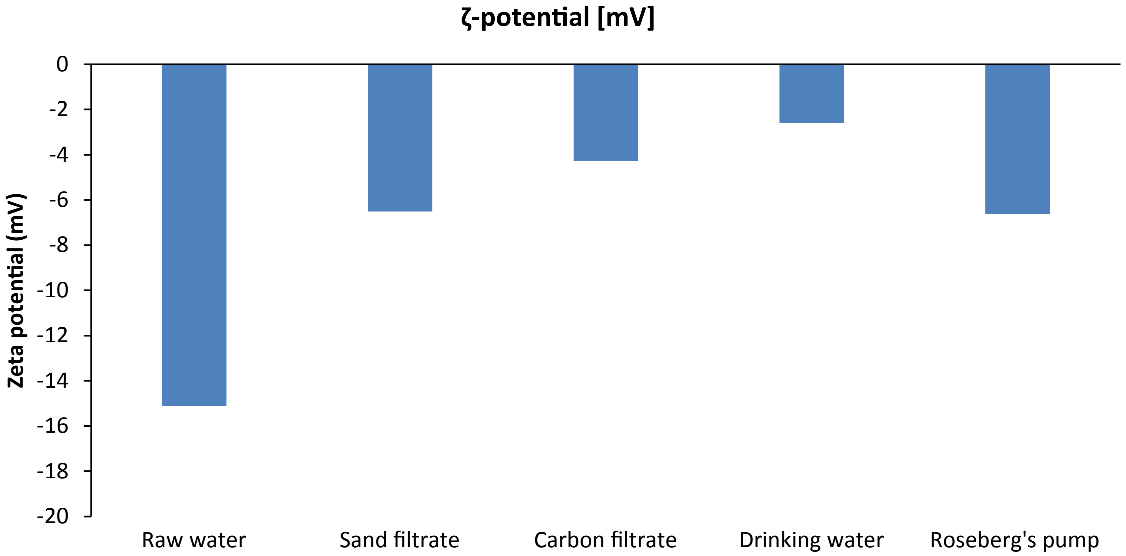
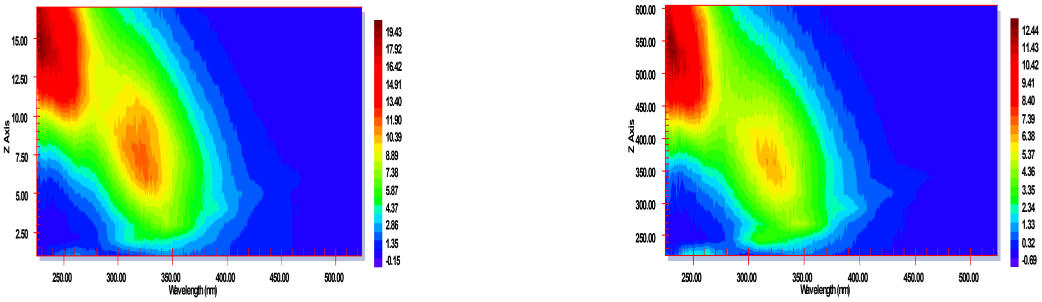
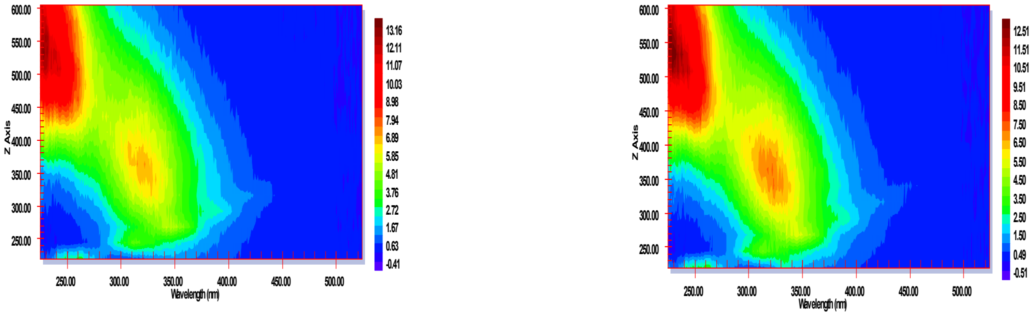


Figure 5.11.2.54. Interstage zeta potential for Görvälnverket sampling rounds.



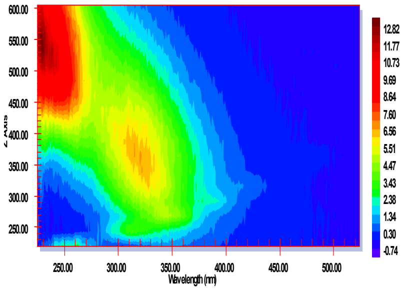
Raw

Sand filtration



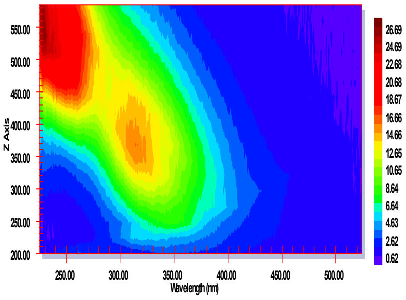
GAC filtration

Drinking water

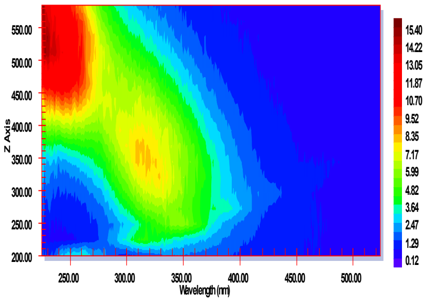


Roseberg's pump

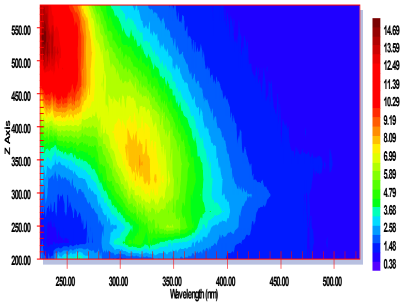
Figure 5.11.2.55. Fluorescence spectroscopy for Görvälnverket sampling round November 2015



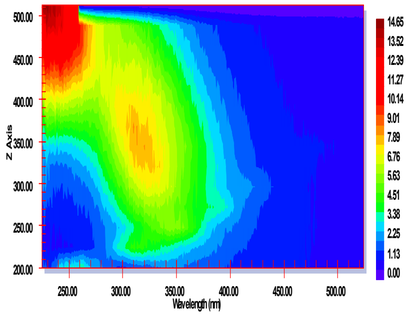
Raw



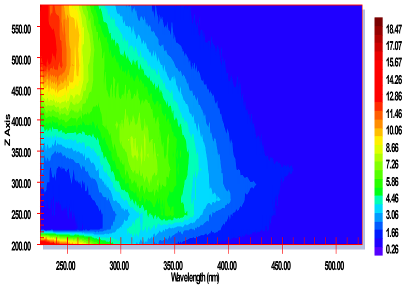
Sand filtration



GAC filtration

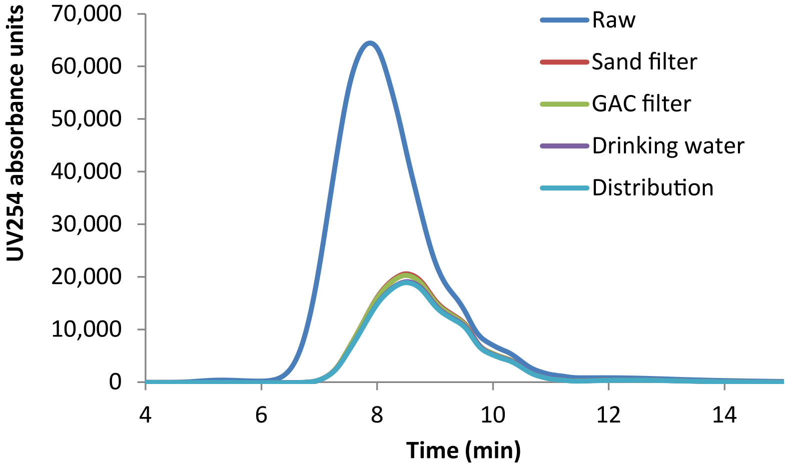


Drinking water



Roseberg's pump

Figure 5.11.2.56. Fluorescence spectroscopy for Görvälnverket sampling round March 2016



November 2015

Figure 5.11.2.57. HPSEC Görvälnverket for one sampling round.

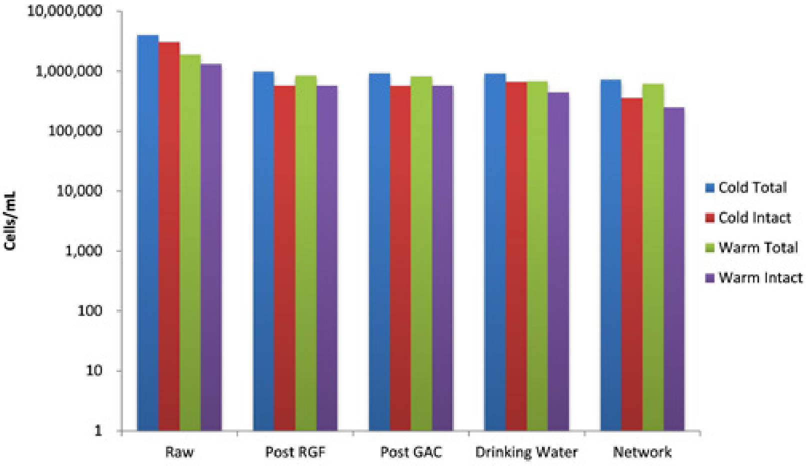


Figure 5.11.2.58. Cell removal across treatment processes measured by flow cytometry for Görvälnverket over two sampling rounds.

Port Charlotte WTW, Scotland. The Port Charlotte water source was a very variable NOM source water, going from moderate to very high DOC (6.8 to 24.1 mg/L). The sample taken in November 2015 contained the high NOM concentration and had an equal split between HPO and HPI (45% in each fraction (Figure 5.11.2.59.). The high level of HPI was an indication that the water source would be difficult to coagulate. In the March 2016 sampling round, the DOC was much more hydrophobic, with an HPO content of 73%. The DOC after coagulation treatment was reduced to between 1 and 4 mg/L, with the high residual being observed when the source water DOC was high. The treated water DOC was very similar in its hydrophobicity composition to the raw water sources, with over 50% HPO present in most of the treated water samples.

The DBP formation for the water was very high, with over 1500 µg/L being measured in the high DOC November sample and 807 µg/L being measured for the March sample (Figure 5.11.2.60.). Although the DOC was higher in November, the reactivity of the NOM to chlorine was higher in March with values of 63 and 122 µg THMs per mg of DOC observed respectively. Treated water samples contained NOM that still had high reactivity in most cases, with values of between 79 and 132 µg THMs per mg of DOC across both sampling campaigns. There was a reduction in the reactivity of the NOM in the network sample, particularly in March 2016, but the high levels of DOC observed in some of the treated samples would put this site at risk of breaching THM regulations.

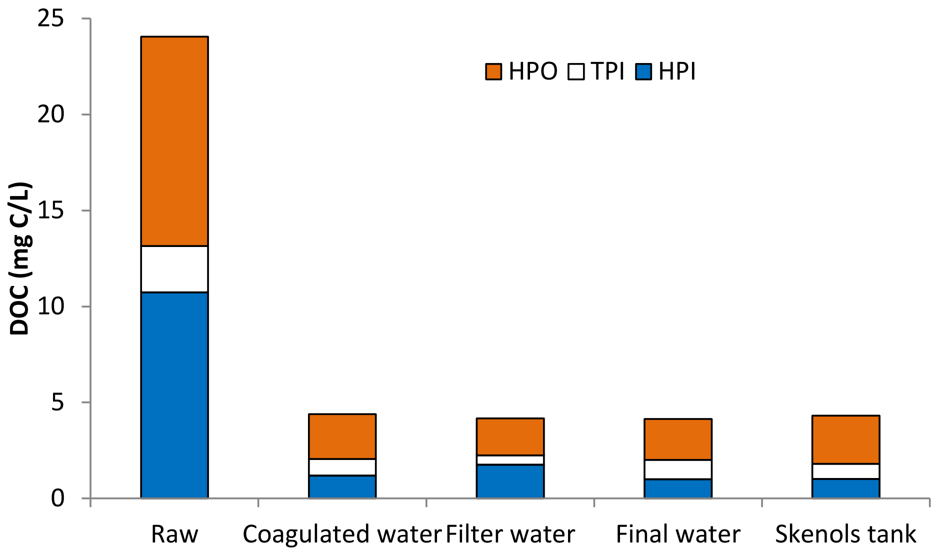
The zeta potential results through the WTWs showed a typical profile for a coagulation works with a big reduction in the charge between the raw water and the coagulated samples during both sampling campaigns. The zeta potential was within a zone that would be regarded as being very effective for coagulation.

The FEEMS and HPSEC plots were typical of the results seen for the other coagulation based WTWs involved in this study (Figure 5.11.2.61-63.). When the DOC was very high in November, there was a very strong signal in the humic peak, suggesting a very heavy load of humic NOM was present in the raw water. On the whole, the humic signal was effectively removed following coagulation and subsequent treatment stages, leaving behind a residual of fulvic-like NOM.

Bacterial cell removal was effective across the coagulation stage with a reduction of TCC and ICC of 0.9 and 1.0 log respectively (Figure 5.11.2.64.). There was an increase in all cell types following filtration. This observation was hard to explain, but could be related to filter wash water return water, but without further investigation, no firm conclusions could be drawn here. Most of the removal of bacterial cells took place between the filtration stage and the final water sample. This is where chlorination based disinfection took place and a 1.1 and 3.2 log reduction of TCC and ICC was observed.

Overall, the site may wish to consider additional treatment above coagulation in order to achieve more robust removal of NOM. The site receives source water that is very high in DOC and contains NOM that may not be amenable to coagulation. As was seen in this study, high DOC was measured in the treated water when the raw water was high, suggesting that the WTWs is unable to keep up with such a high DOC loading. Further investigation into the bacterial removal profile across the WTWs is proposed, particularly in light of the apparent increase in cells across the filtration stage.

November 2015



March 2016

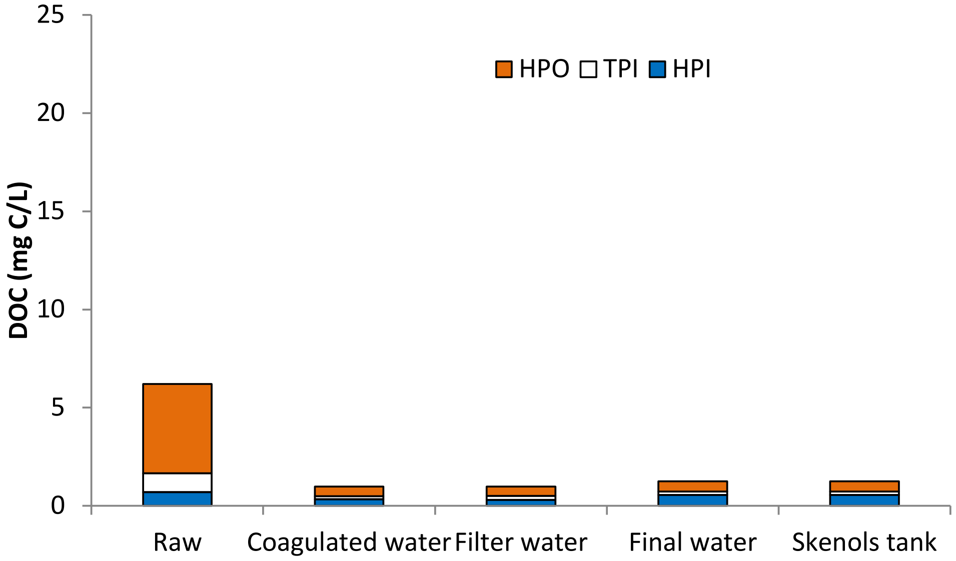
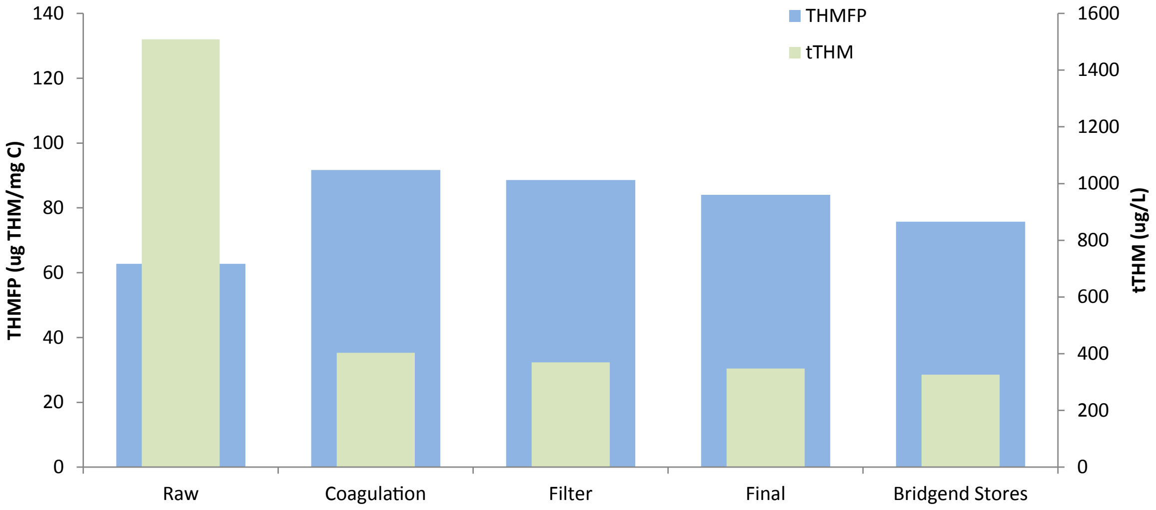


Figure 5.11.2.59. Fractionation for Port Charlotte sampling rounds.

November 2015



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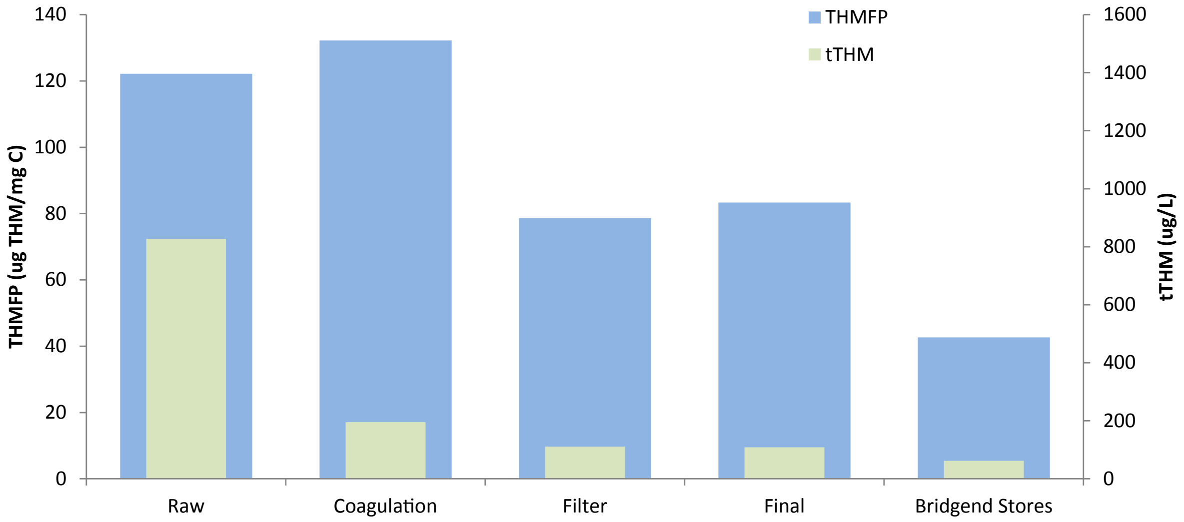
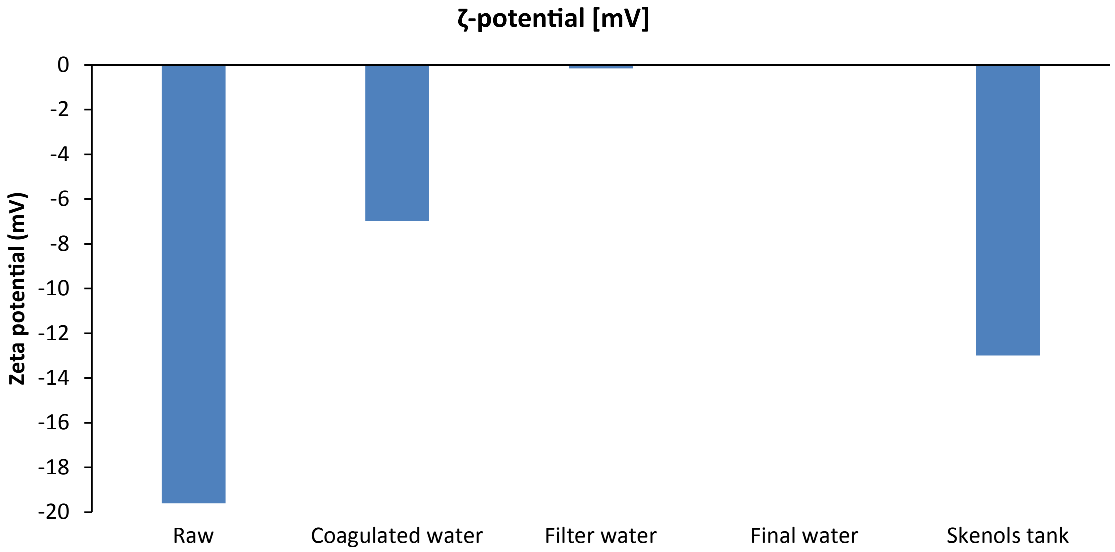


Figure 5.11.2.60. Disinfection by-products for Port Charlotte sampling rounds.

November 2015



March 2016

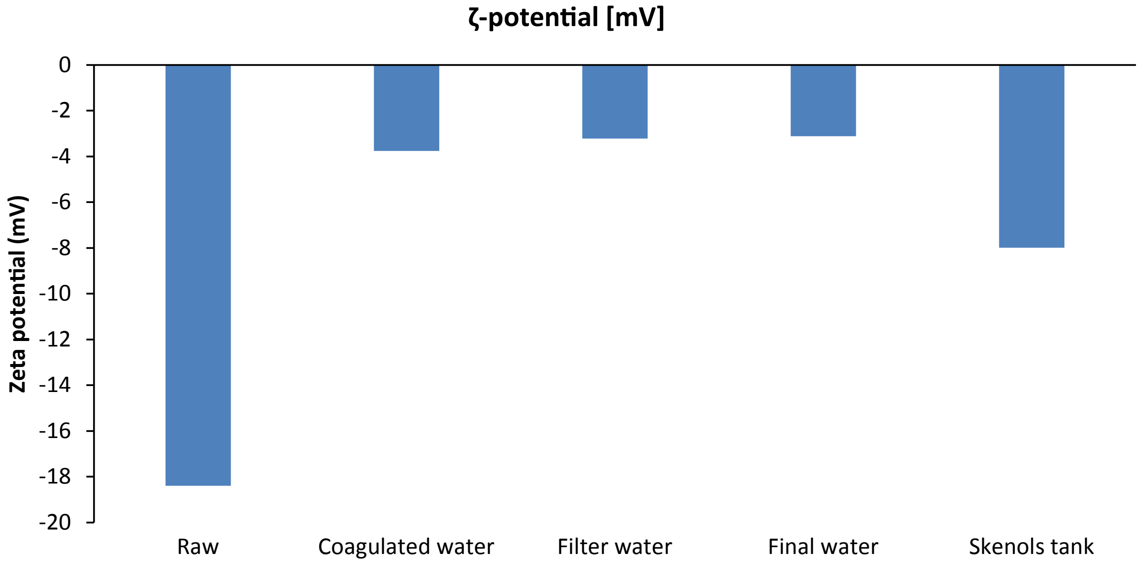
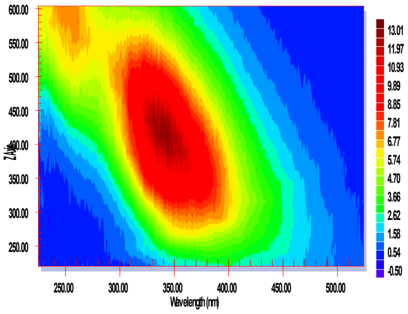
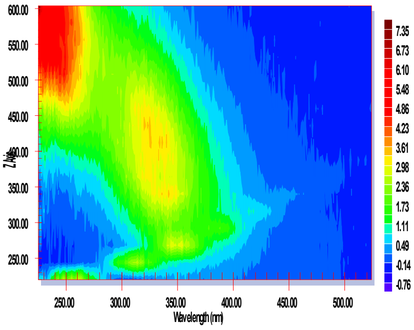


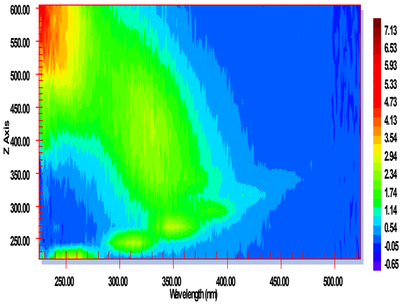
Figure 5.11.2.61. Interstage zeta potential for Port Charlotte sampling rounds.



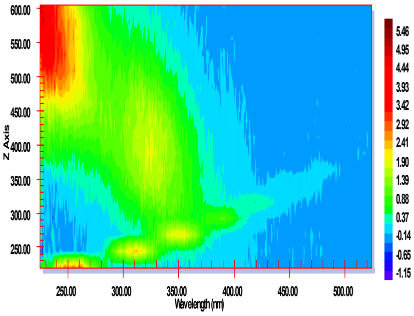
Raw



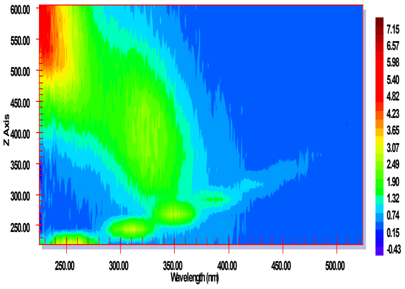
Coagulation



Filtration

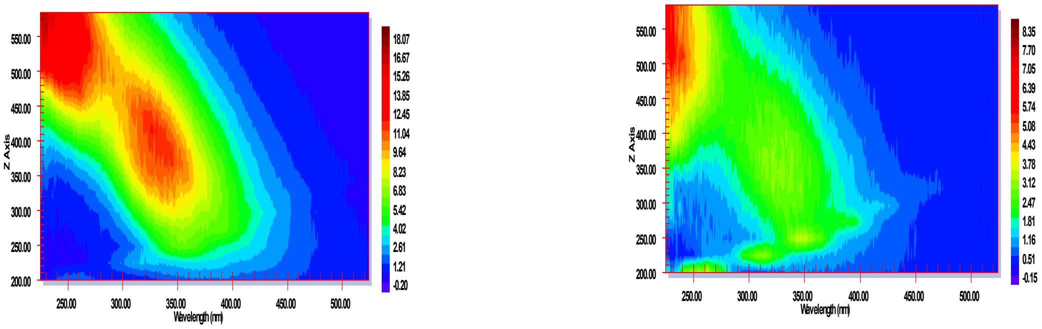


Drinking water



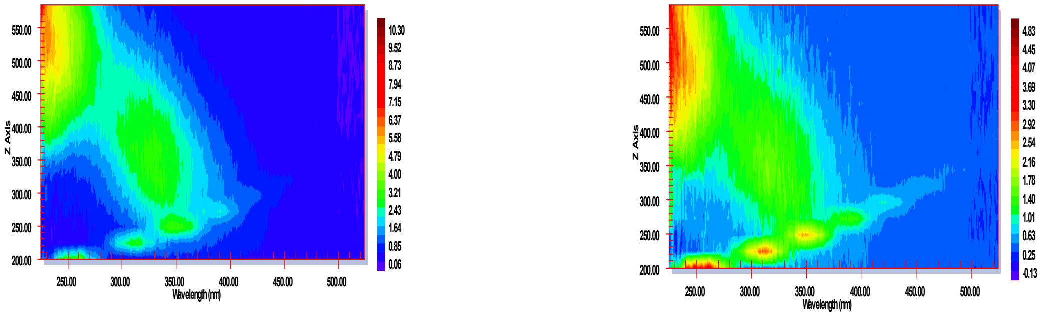
Skenols tank

Figure 5.11.2.62. Fluorescence spectroscopy for Port Charlotte sampling round November 2015



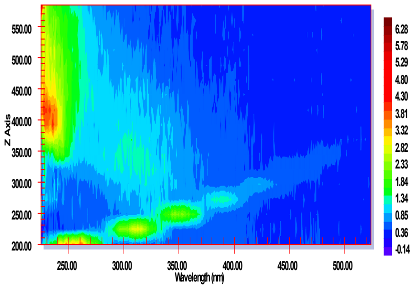
Raw

Coagulation



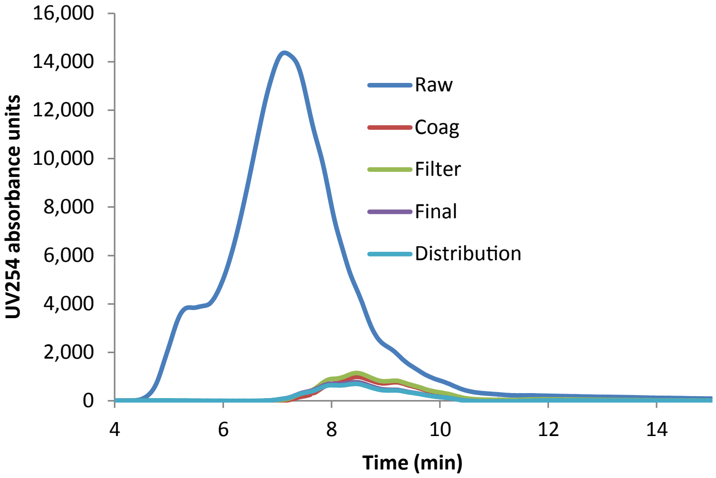
Filtration

Drinking water



Skenols tank

Figure 5.11.2.63. Fluorescence spectroscopy for Port Charlotte sampling round March 2016



March 2016

Figure 5.11.2.64. HPSEC Port Charlotte for one sampling round.

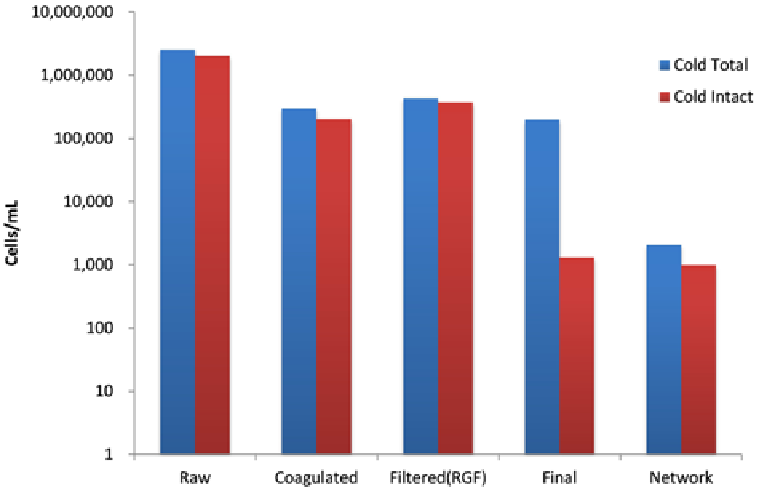


Figure 5.11.2.65. Cell removal across treatment processes measured by flow cytometry for Port Charlotte over two sampling rounds.

Microbial removal summary. A summary of the cell removal across the different WTWs is shown below (Figure 5.11.2.66.). This is not presented as an order of 'best performing' works, but rather to show the wide range of cells removal achieved across the different types of treatment works. The data shown is dependent on a number of factors, including the number of cells coming onto the WTWs and the treatment stages in place at the site. Some WTWs, such as IVAR, had low cell numbers in the incoming water source and minimal barriers of treatment for micro-organisms. However, sites such as Bracadale utilize a nanofiltration membrane that should be a near complete barrier for most microorganisms, so it was not surprising to see such high log reductions at this site. Sites that used UV as their primary means of disinfection were not well represented in this analysis because the flow cytometry technique is not yet well suited to detecting cell damage caused by UV light.

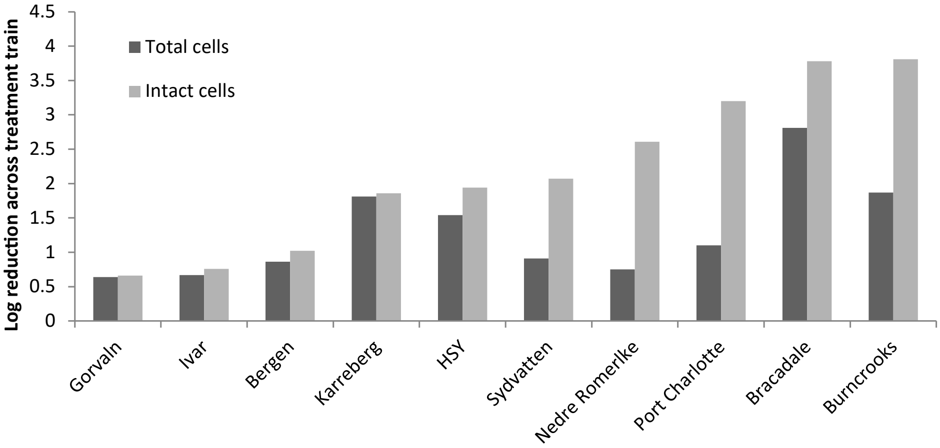


Figure 5.11.2.66. Summary of the cell removal across treatment processes measured by flow cytometry.

6. UTILITY BENCHMARK

In this Chapter, raw and treated water qualities, treatment operation conditions as well as treatment performances at the ten participating utilities are compared and discussed.

6.1. Raw water quality, NOM fractions and treatability

Table 6-1 shows a summary of raw water characteristics including DOC and NOM fraction distributions, BDOC and SUVA. For the purpose of benchmarking in this Chapter, the utilities are ranked from high to low DOC-content in the raw waters. Treatment performance data (% DOC removal) for the 10 NOMiNOR utilities are presented as well. For the eight utilities that apply coagulation treatment, the reported DOC removal efficiencies are those obtained during the coagulation/filtration step (filter outlet samples).

Data from the two utilities not applying coagulation (Bracadale and IVAR) are presented at the bottom of Table 6-1. The reported DOC removal efficiencies for BRA and IVAR are calculated after NF and after ozonation-biofiltration, respectively.

AVG data	Raw Water										Coag/filt
	Tot-DOC	**VHA**	**SHA**	**CHA**	**NEU**	**VHA+SHA**	**CHA+NEU**	**BDOC**	**BDOC**	**SUVA**	**DOC Rem**
	mg/L	**% of DOC**				**% of DOC**		**mg/L**	**% of DOC**	**L/mg m**	**%**
PC-SW	15,7	80	10	6	4	90	10	0,70	4,4	4,7	81
KÄR-VIVAB	9,7	74	13	8	5	87	13	0,10	1,2	4,4	64
BUR-SW	9,3	80	9	5	6	89	11	0,14	1,4	5,5	82
RIN-SYDV	9,3	72	16	8	5	87	13	0,13	1,3	4,0	73
GÖR-NORRV	8,1	60	22	12	6	82	18	0,18	2,2	2,8	47
PIT-HSY	6,9	66	18	10	6	84	16	0,08	1,2	3,2	66
NRV	4,0	72	14	5	8	86	14	0,17	4,3	4,1	59
JOR	2,4	69	9	6	15	78	21	0,05	2,0	4,6	76
BRA-SW (NF)	12,6	78	10	5	7	88	12	0,28	2,7	4,9	86
IVAR (OBF)	1,2	53	21	9	18	74	26	0,09	6,9	3,6	19

Table 6-1 Utility benchmark: Average DOC and NOM fraction concentrations, BDOC and SUVA levels in raw waters from the NOMiNOR utilities, along with data on DOC removal (%) during coagulation and separation/filtration. Utilities are sorted from high to low DOC levels in raw water.

The results show that the three Scottish raw waters have the highest content of hydrophobic NOM (88-90 %), and that two of the three Norwegian raw waters have the lowest content of hydrophobic NOM (74-78 %). The opposite picture is of course true for the hydrophilic NOM content (CHA+NEU), with IVAR (26 %), JOR (21 %) and GÖR (18 %) on top of the hydrophilic NOM content list.

In terms of DOC removal (%), the three Scottish utilities with the highest hydrophobic NOM content are on top of the list, thus indicating a relationship between hydrophobic fraction concentration and treatability by coagulation and/or NF. There is no consistent relationship however between hydrophobic NOM content and DOC removal efficiency in the data set. JOR WTW for instance, achieve a high 76 % DOC removal efficiency (Rank 3 among coagulation utilities after PC and BUR), despite the low hydrophobic NOM fraction concentration (78 %; Rank 8). GÖR WTW on the other hand, achieve a low 47 % DOC removal despite the higher hydrophobic NOM content (82 %). It should be mentioned however, that although the hydrophobic fraction concentration is high (82 %), the raw water at GÖR WTW has the lowest average VHA fraction concentration (60 %) and the highest SHA fraction concentration (22 %) among the eight utilities applying coagulation treatment. The removal efficiencies of both VHA and SHA are low at GÖR WTW.

From the above discussion, it is obvious that the DOC removal efficiency achieved is not only dependent on the NOM concentration and NOM fraction distribution, but also on the prevailing treatment operations, i.e. if the coagulation conditions are well optimized or not.

Regarding the effect of the applied treatment technology, Table 6-1 shows that Bracadale (NF) and IVAR (O-BF), i.e. the two utilities that do not apply coagulation treatment, achieve the highest (86 %) and lowest DOC removal efficiency (19 %), respectively, thus demonstrating the benefits of nano filtration (NF).

Is it well known from literature that the hydrophobic NOM fractions are more amendable to removal by coagulation than the more low-molecular weight hydrophilic fractions. Based on the data from Table 6-1, Figure 6-1 shows the average hydrophobic NOM fraction concentrations in raw water versus the achieved DOC removal (%) for all 10 utilities. The blue line represents a situation with a DOC removal equivalent to complete removal of all hydrophobic NOM (VHA+SHA). Thus, from the results in Table 6-1 and Figure 6-1, the hydrophobic NOM content (VHA+SHA) may be used as a possible predictor for treatability, i.e. the maximum DOC removal that can be achieved by coagulation. If all hydrophobic NOM was removed, the data points would have been distributed on the blue line. The vertical distance from the blue line and down to a data point from a utility may represent the coagulation optimization potential for that specific utility and that specific raw water/NOM fraction distribution, given that hydrophobic NOM can be completely removed by coagulation.

As mentioned above, JOR and GÖR WTWs represents a high and a low "extreme" among the coagulating utilities, i.e. the utility with the smallest and greatest deviation respectively, from the line representing 100 % hydrophobic NOM (DOC) removal efficiency. Thus, JOR has a raw water with 78 % hydrophobic DOC and achieve 76 % DOC removal, while GÖR WTW on the other hand has 82 % hydrophobic DOC and achieve only 47 % DOC removal by coagulation. From Figure 6-1, the potentials for coagulation optimization seem highest at GÖR, NRV, and KÄR WTW.

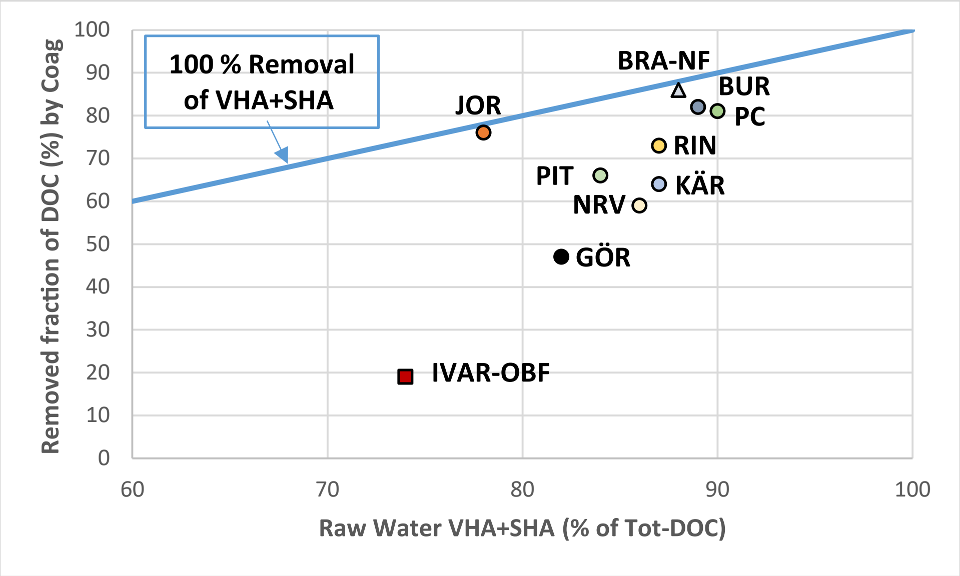


Figure 6-1 Utility benchmark: Hydrophobic NOM fraction concentrations,versus DOC removal by coagulation (% of tot-DOC).

However, experience has shown that also the hydrophilic CHA fraction is amendable to removal by coagulation. In line with this, Figure 6-2 shows the relationship between the achieved DOC removal (%), and the hydrophobic VHA+SHA plus the hydrophilic CHA content (% of DOC) of the raw waters from all 10 utilities. The blue line represents a situation equivalent to a complete removal of the hydrophobic VHA+SHA plus the hydrophilic CHA fraction (i.e. VHA+SHA+CHA). Again, JOR and GÖR WTWs are the two utilities representing the upper and lower extremes. In raw water from JOR WTW 85 % the DOC is within the VHA+SHA+CHA fractions, and the achieved DOC removal is 76 %. In raw water from GÖR WTW 94 % of the DOC is within the VHA+SHA+CHA fractions, and the achieved DOC removal is 47 %. This is taken as an indication of the differences in unexploited coagulation optimization potential at the two utilities.

In addition to GÖR, NRV, and KÄR WTW, also PIT and RIN WTWs appear to have some unexploited coagulation optimization potentials, while PC, JOR and BUR WTWs are located close to the "blue line". The results from BRA WTW illustrate the efficiency of NF for NOM removal (93 % of DOC is VHA+SHA+CHA, and 86 % of DOC is removed). The results from IVAR on the other hand show that ozone-biofiltration is not an effective treatment process for NOM removal (82 % of DOC is VHA+SHA+CHA, and only 19 % of DOC is removed).

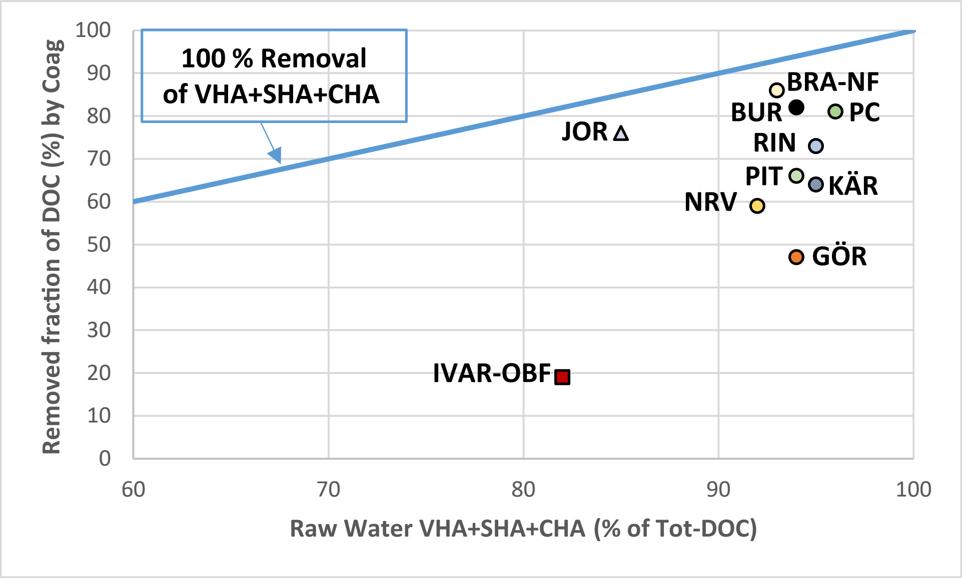


Figure 6-2 Utility benchmark: VHA+SHA+CHA fraction concentrations, versus DOC removal by coagulation (% of tot-DOC).

Treatability and treatment performance. With respect to treatability by different methods, Figure 6-1 shows that the NF process at Bracadale WTW, and the optimized coagulation process at JOR WTW is capable of removing NOM equivalent to almost complete removal of the hydrophobic NOM content. The ozone-biofiltration (OBF) treatment process used at IVAR however, achieve 19 % removal only of the hydrophobic NOM content in the raw water.

For the coagulation utilities, the achieved DOC removal efficiencies vary between 47 and 82 %. The achieved removal however, is not only dependent on the NOM treatability by coagulation, i.e. the NOM fraction distribution and the SUVA (aromaticity) in the raw water, but also on the actual coagulation process design and treatment operation performance.

Thus the reason why JOR WTW achieve a high DOC removal efficiency close to the "blue line" representing 100 % removal of all hydrophobic NOM, may be due to the fact that this utility has been subject to comprehensive and long-time coagulation optimization efforts. For other utilities, e.g. GÖR, NRV, KÄR, PIT and RIN WYWs, the results indicate the existence of unexploited coagulation optimization potentials, while PC and BUR WTWs operate close to the optimal "blue line".

The specific UV-adsorption SUVA (UV-abs/DOC) is often used as a predictor for NOM treatability by coagulation: The higher the SUVA, the higher the DOC removal efficiency. In line with this, Figure 6-3 shows the relationship between average SUVA values in raw waters and DOC removal (%) by coagulation (after clarification and/or filtration) for all the 10 NOMiNOR utilities. The results for Bracadale (nano filtration) and IVAR (ozone-biofiltration) is included for comparison only. It should be kept in mind, however, that the SUVA is affected by UV-absorbing constituents in the water, e.g. Fe.

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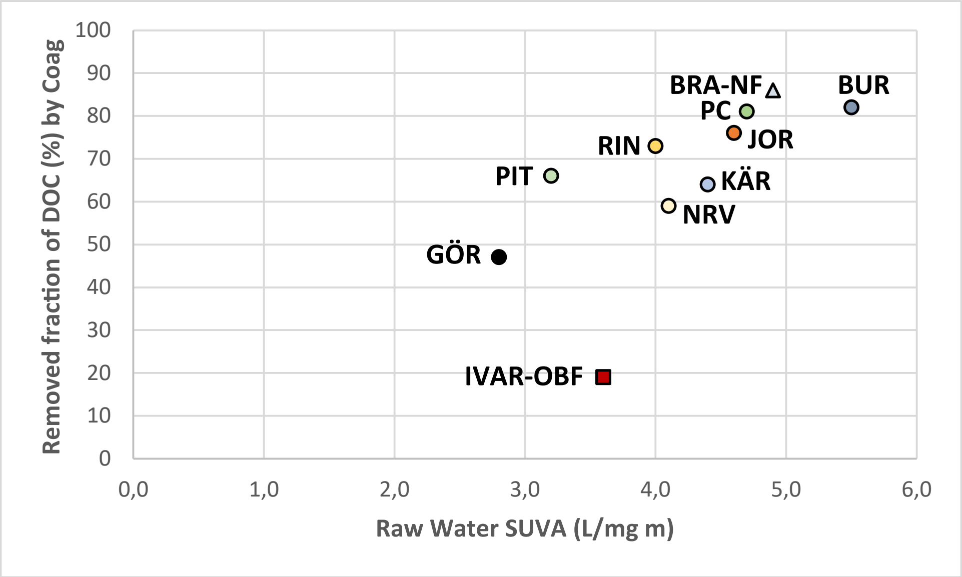

Figure 6-3 Utility benchmark: Raw water SUVA versus DOC removal by coagulation (% of tot-DOC).

Figure 6-3 illustrates well the relationship between SUVA and the observed DOC removal efficiency. Among the coagulation utilities, Görvälnverket WTW has the lowest SUVA (2.8) and the poorest DOC removal (47 %), while Burncrooks WTW on the other hand has the highest SUVA (5.5) and the highest DOC removal (82 %). Also Kärreberg WTW has a high SUVA (4.4), but achieve a moderate DOC removal by coagulation (64 %). NRV WTW has a relatively high SUVA of 4.1, with a DOC removal of 59 % only. Both NRV and KÄR WTWs have river sources.

The similarities between Figures 6-1, 6-2 and 6-3 indicate that the fractions of DOC (%) found within VHA+SHA or VHA+SHA+CHA, as well as SUVA, can be used to predict NOM (DOC) treatability by coagulation. In addition, these factors can be applied for assessing treatment performance and to identify coagulation optimization potentials.

Figure 6-4 illustrates the relationship between SUVA and hydrophobic NOM (VHA+SHA) content in raw waters (Raw Water), and in coagulated and clarified/filtered waters (Coag-RGF). There is a close to linear relationship between the hydrophobic NOM content and SUVA for eight out of the ten raw waters: The higher the hydrophobic NOM fraction, the higher the SUVA. The exceptions are the raw waters from IVAR and JOR WTWs, that maintain a relatively high SUVA despite a lower hydrophobic NOM content (74-78 %) compared to the other utilities (82-90 %).

All water samples collected after coagulation and clarification/filtration treatment have reduced hydrophobic content and reduced SUVA values, thus showing a preferential removal of hydrophobic and aromatic NOM. SUVA values in treated waters are within the range of 1.6-2.5 L/mg m, reduced from levels of 2.8-5.5 L/mg m in the raw waters. As was the case for raw water, the data show that treated water from JOR and IVAR WTWs contain substantially lower hydrophobic NOM fraction concentrations (51-56 %) compared to the other utilities (68-79 %). PIT and IVAR WTW both achieve SUVAs below 2, mainly thanks to the bleaching effects of the ozone applied at these utilities.

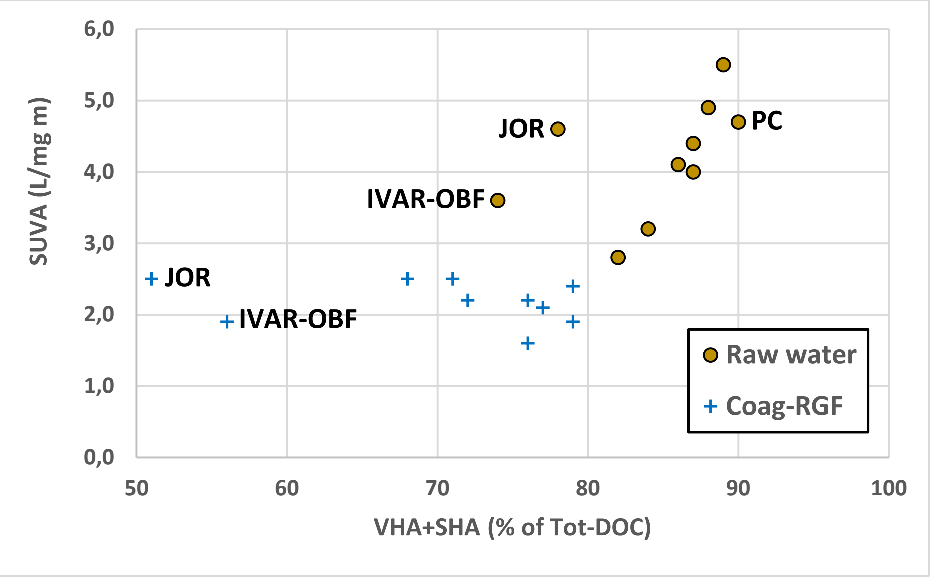

Figure 6-4 Utility benchmark: Hydrophobic NOM versus SUVA in raw water and in coagulated-filtered water (Coag-RGF).

6.2. Effects of coagulation and additional treatment steps

In this section, results on water quality and treatment performance are presented and discussed. The specific effects of single process steps like coagulation, supplementary treatment steps (e.g. ozonation, GAC filtration), and disinfection will be discussed as well.

Water quality: Figures 6-5 to 6-10 show water quality data from all ten utilities., i.e. color, UV-absorbance, turbidity, DOC, SUVA and BDOC respectively, for: (i) untreated raw water; (ii) after coagulation and separation/filtration; (iii) after CWT, i.e. all treatment steps including disinfection, and (iv) in the distribution system (Net). The type of coagulant (Al or Fe) used by the different utilities is indicated as well.

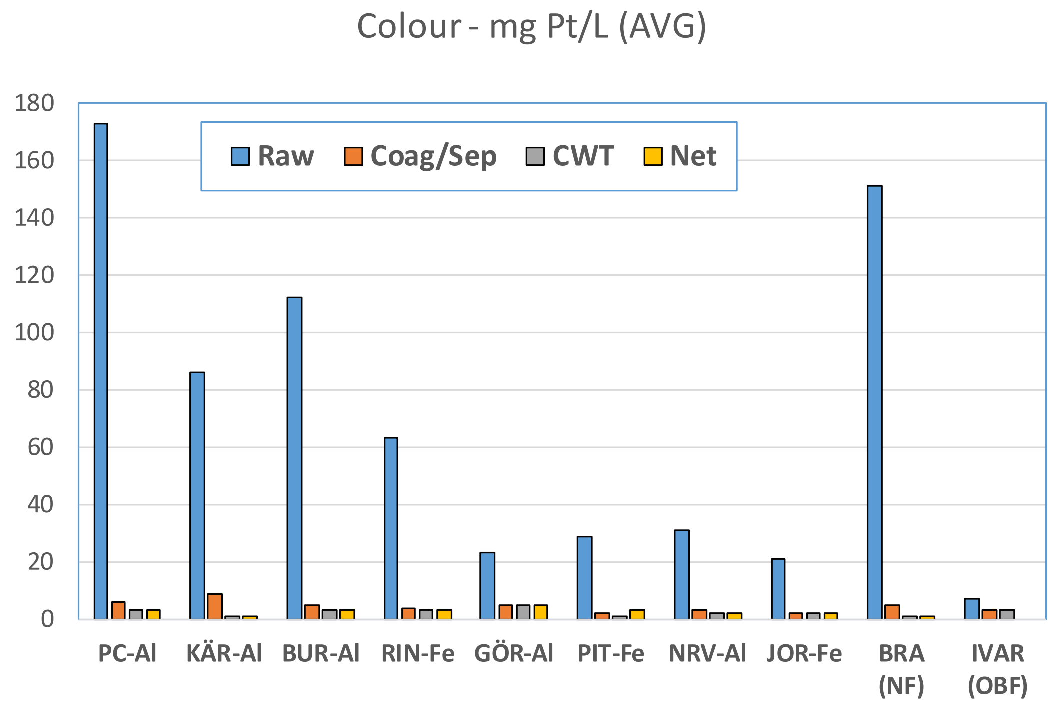

Figure 6-5 Utility benchmark: Average color concentrations (mg Pt/L) in raw water (Raw), after coagulation and separation (Coag/sep), after all treatment and disinfection steps (CWT), and in the distribution system (Net).

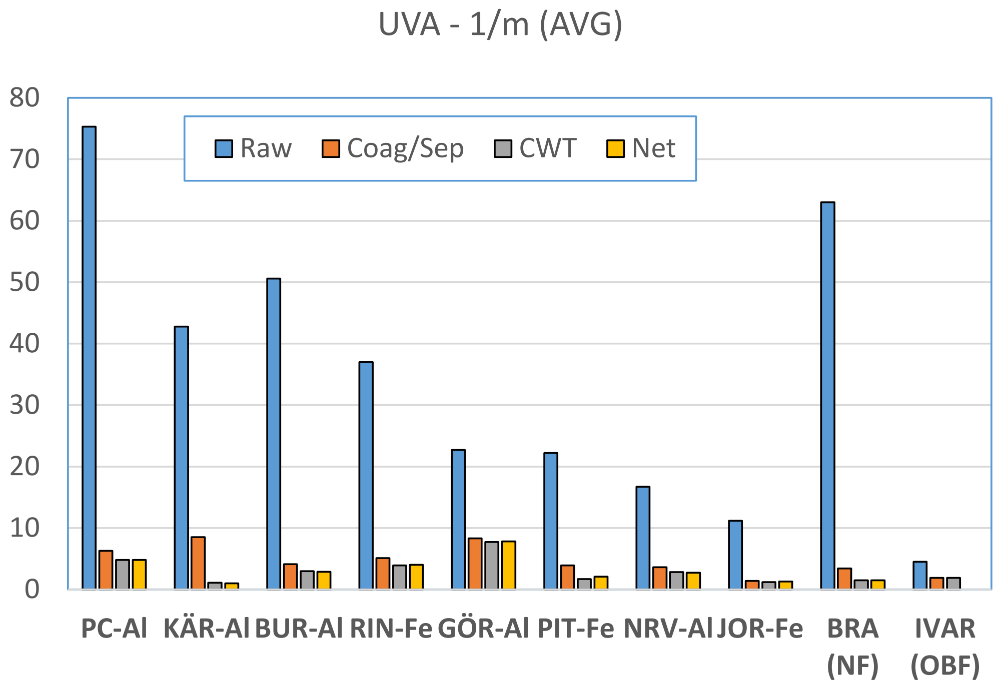

Figure 6-6 Utility benchmark: Average UV-absorbance (m^{-1}) in raw water (Raw), after coagulation and separation (Coag/sep), after all treatment steps (CWT), and in the distribution system (Net).

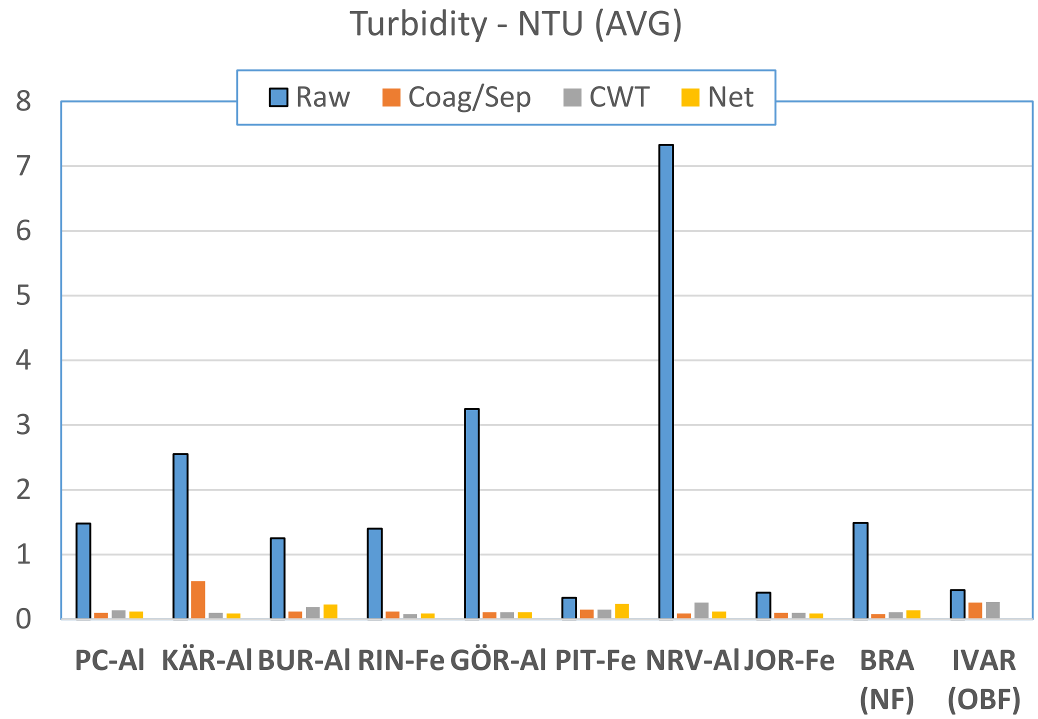

Figure 6-7 Utility benchmark: Average turbidity (NTU) in raw water (Raw), after coagulation and separation (Coag/sep), after all treatment steps (CWT), and in the distribution system (Net).

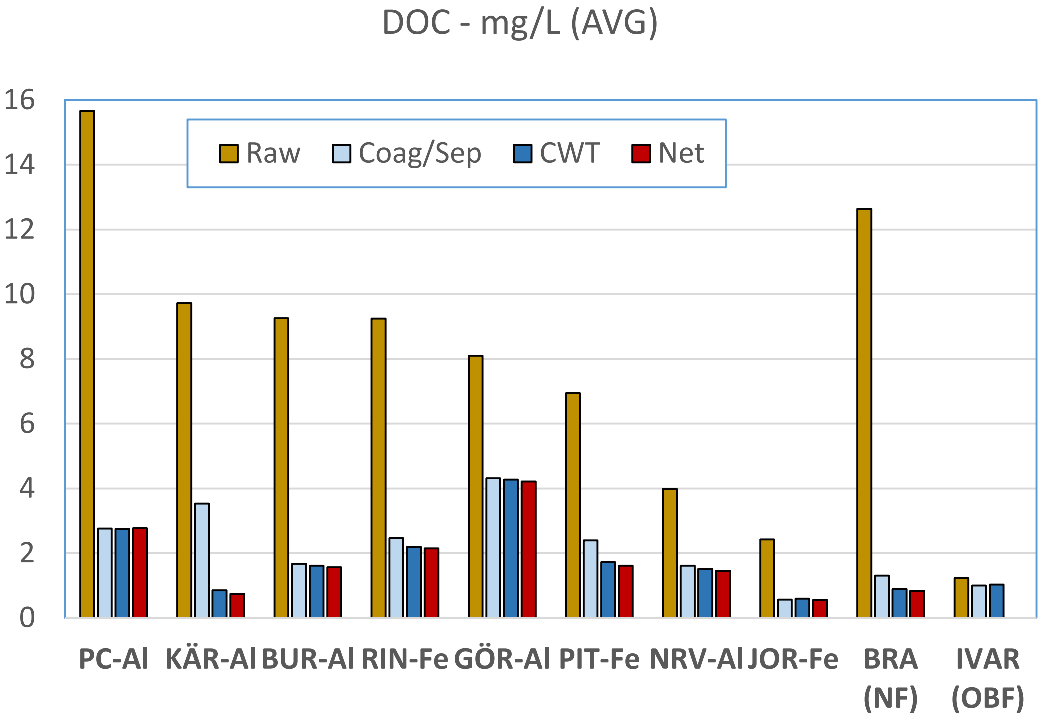

Figure 6-8 Utility benchmark: Average DOC concentrations (mg/L) in raw water (Raw), after coagulation and separation (Coag/sep), after all treatment steps (CWT), and in the distribution system (Net).

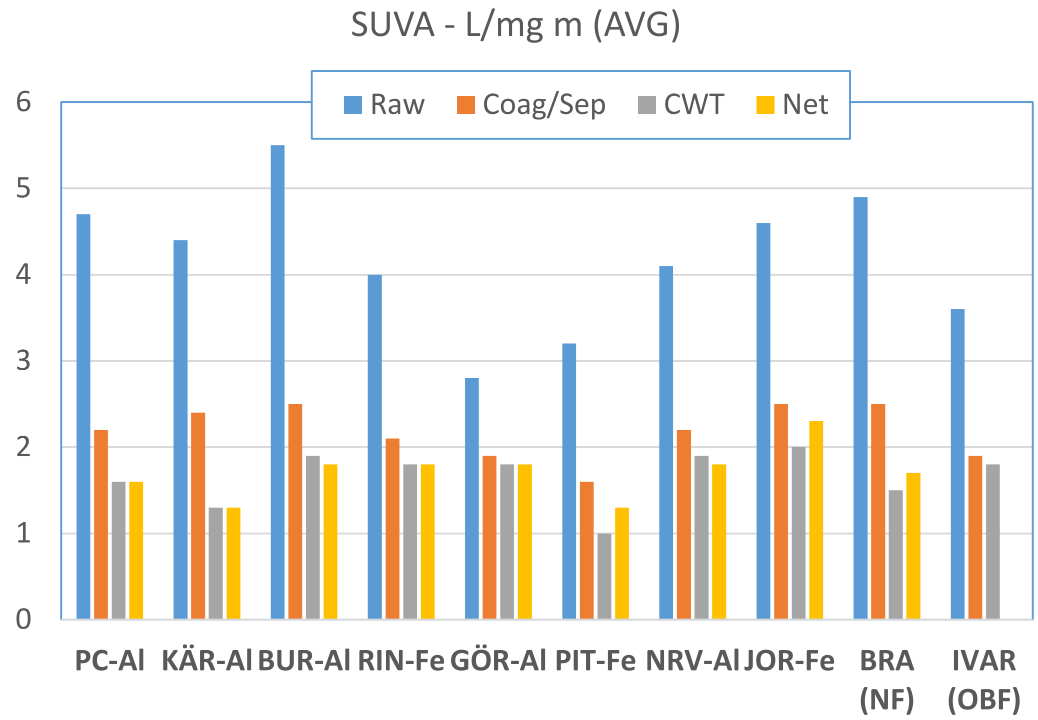

Figure 6-9 Utility benchmark: Average SUVA levels (L/mg m) in raw water (Raw), after coagulation and separation (Coag/sep), after all treatment steps (CWT), and in the distribution system (Net).

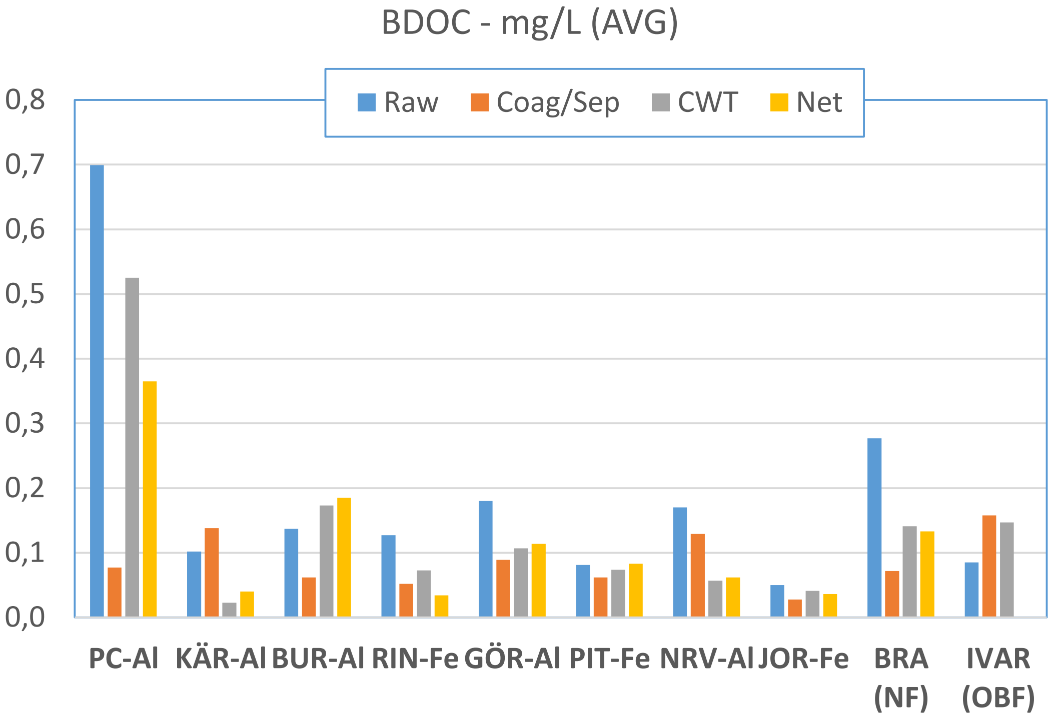

Figure 6-10 Utility benchmark: Average BDOC concentrations (mg/L) in raw water (Raw), after coagulation and separation (Coag/sep), after all treatment steps (CWT), and in the distribution system (Net).

From the results presented here, there is little doubt that coagulation is the treatment step of major importance with respect to water quality improvement for color, UV-absorbance, turbidity, DOC and SUVA. For some utilities, e.g. Kärreberg and Pitkäkoski WTWs, there are significant improvements in NOM/DOC removal also from the additional treatment steps, i.e. ground infiltration, and ozone-GAC filtration, respectively.

Reductions in SUVA by additional treatment steps are evident. This occurs mainly due to the bleaching effects from ozone (PIT and IVAT WTWs), and chlorine (e.g. PC, BUR and BRA WTWs). The ground infiltration process at KÄR WTW also effectively reduce UV-abs and SUVA levels.

The substantial effects of ozone and chlorine on the levels of biodegradable NOM (BDOC) concentrations are evident from Figure 6-10. Following a reduction in BDOC after coagulation, the levels increase significantly after chlorination. The increase in BDOC is dependent of the applied chlorine dose, and it is especially high at PC WTW. At this utility, BDOC levels are reduced again in the distribution system, thus indicating BDOC adsorption to metal (Fe) containing deposits in the pipelines, and/or microbial consumption (BDOC substrate utilization – despite the residual chlorine concentration present).

NOM and NOM fraction removal. As shown above, coagulation/separation is the major NOM removing process, with efficient removal of color, UV-absorbance, turbidity and DOC.

Figure 6-11 illustrates that the DOC removal efficiency varied considerably (47-82 %) between the eight utilities applying coagulation treatment, despite similarities in NOM fraction distribution in the respective raw waters. Thus, the differences in removal efficiency are more likely explained by differences in NOM concentration levels and from differences in treatment operation conditions, rather than from differences in raw water quality and NOM fraction distribution. A more detailed analysis of the coagulation process and operation conditions will follow in Chapter 6.3.

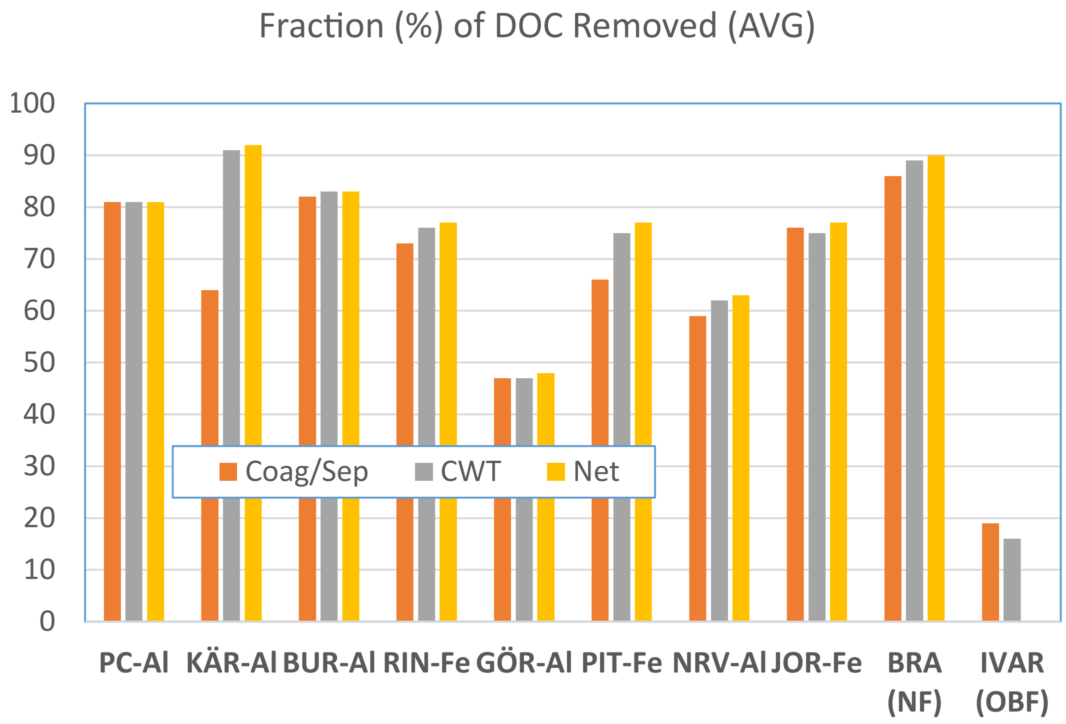

Figure 6-11 Utility benchmark: Average NOM (DOC) removal efficiency (% of tot-DOC) achieved after coagulation and separation (Coag/sep), after all treatment steps (CWT), and in samples from the distribution network.

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No additional treatment steps are applied at PC, BUR, and JOR WTWs, i.e. those utilities are using conventional filtration (with flocculation and pre-clarification), direct or contact filtration systems only, along with disinfection by chlorine, chloramine and/or UV.

For the utilities that apply more treatment steps in supplement to coagulation, clarification and filtration, it appears that in terms of NOM removal, the additional treatment steps are more or less polishing steps only. The major exception from this statement is KÄR WTW. Here the coagulation performance is rather poor, but the additional ground infiltration process increases the overall DOC removal efficiency significantly (from 64 to 91 %). Also at PIT WTW, the intermediate ozone-GAC filtration process improves DOC removal significantly (from 66 to 75 %). At RIN WTW, the slow sand filtration process improves DOC removal somewhat (from 73 to 76 %). At NRV WTW there are also some additional benefits from the GAC treatment steps, i.e. the DOC removal increases from 59 to 62 %. For GÖR WTW however, there are no measurable benefits from GAC filtration on DOC removal, likely due to a NOM-saturated carbon filter material.

For the non-coagulating utilities, the NF process at BRA WTW turns out as a very effective process with respect to DOC removal. A slight additional benefit is obtained by the GAC filtration/chlorination at this utility (average DOC removal increases from 86 to 89 %). At the IVAR ozone-biofiltration pilot plant, substantial reductions in color and UV-absorbance are achieved. However, DOC removal is poor, with removal efficiencies of 16-19 % during ozonation, alkaline filtration and biofiltration.

Figures 6-12 and 6-13 illustrate the achieved removal of hydrophobic and hydrophilic NOM fractions, respectively. It appears that the poorest hydrophobic NOM fraction removal efficiency is achieved at GÖR and IVAR WTWs. Relatively poor removal by coagulation is also shown for KÄR WTW, but this is “repaired” by the efficient additional removal obtained by the ground infiltration process. Unlike the situation at KÄR WTW, the existing additional treatment step at GÖR WTW (GAC) is however not capable of removing any more NOM, thus illustrating the need for new additional treatment steps (e.g. NF) at this utility.

The low hydrophobic NOM fraction removal efficiency achieved at IVAR WTW is typical for ozone-biofiltration processes where some hydrophobic NOM is transformed by the ozone into hydrophilic NOM fractions, thus increasing the CHA and NEU fraction concentrations as well as the BDOC (Figure 6-14). Figure 6-14 demonstrates well also the ability of ozonation and chlorination processes to transform NOM into more biodegradable fractions. The increase in NOM biodegradability and in BDOC fraction concentrations (as % of DOC) are very well illustrated by the results from PC, BUR, BRA (chlorine) and IVAR (ozone) WTWs.

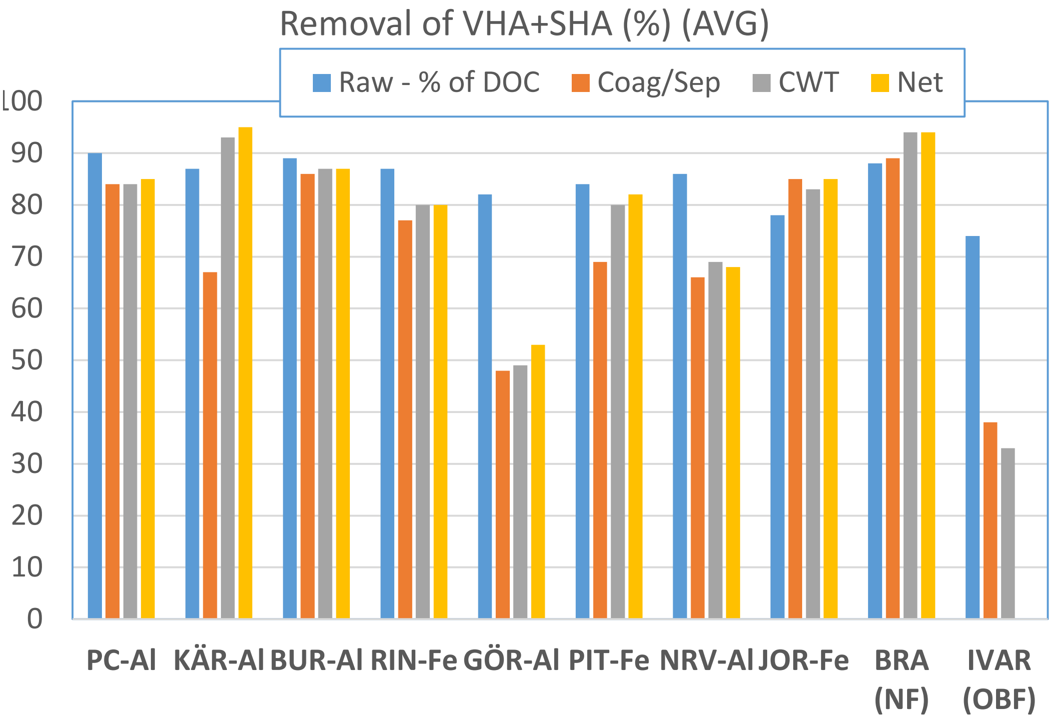

Figure 6-12 Utility benchmark: Average hydrophobic NOM fraction removal efficiency (% of tot-DOC) achieved after coagulation and separation (Coag/sep), after all treatment steps (CWT), and after distribution (Net). The fraction of hydrophobic NOM in the raw waters (% of DOC) is shown as well (in blue).

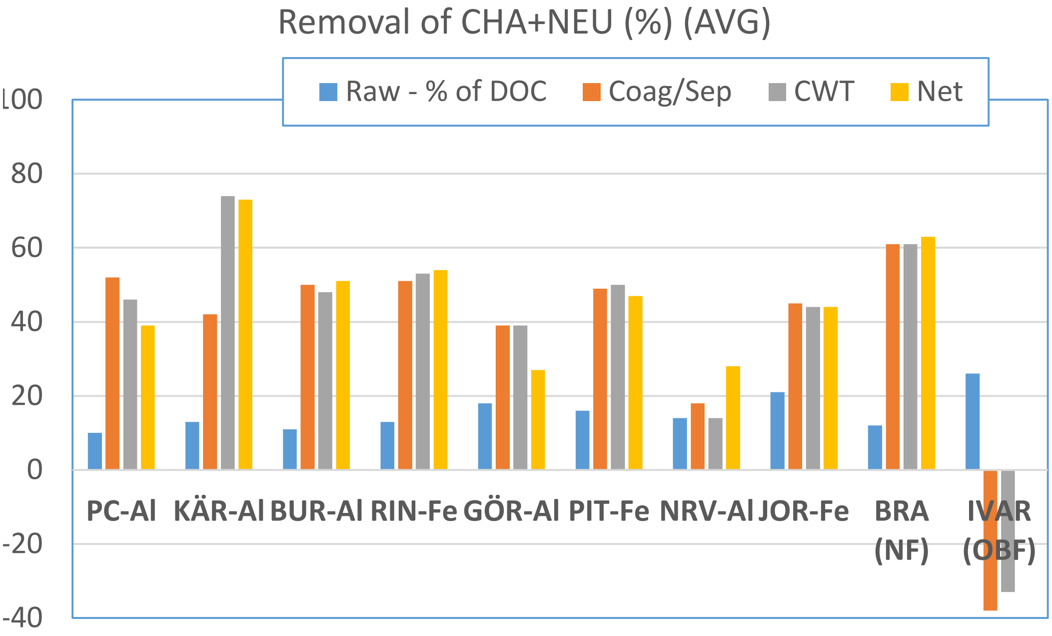

Figure 6-13 Utility benchmark: Average hydrophilic NOM removal efficiency (% of tot-DOC) achieved after coagulation and separation (Coag/sep), after all treatment steps (CWT), and after distribution (Net). The fraction of hydrophilic NOM in the raw waters (% of DOC) is shown as well (in blue).

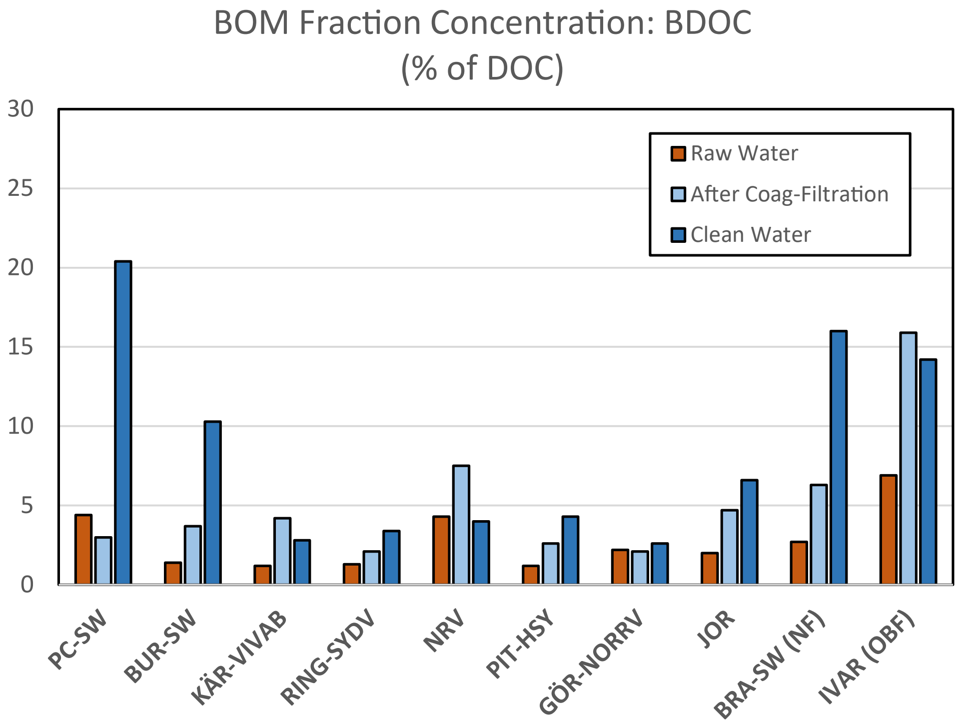

Figure 6-14 Utility benchmark: Average BDOC concentrations (% of DOC) in raw water (Raw), after coagulation and separation (Coag/sep), after all treatment steps (CWT), and after distribution (Net).

The average removal efficiencies of microorganisms (measured as ATP) are presented in Figure 6-15. Average ATP removal during coagulation is within the range of 85-97 %, and after additional treatment including disinfection within the range of 94-100 % (an average of 100 % is achieved at 5 utilities). The ozone-biofiltration pilot at IVAR WTW apply no chlorine or UV disinfection, and the average ATP removal is only 29 %.

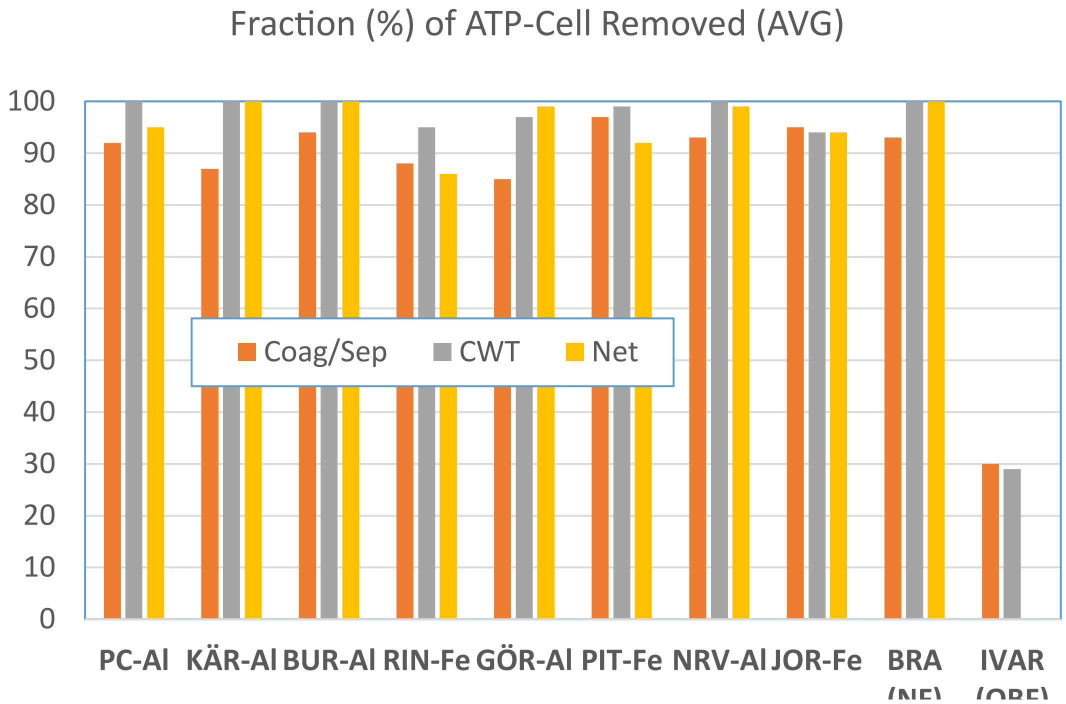

Figure 6-15 Utility benchmark: Average Cellular ATP removal efficiency (%) achieved after coagulation and separation (Coag/sep), after all treatment steps (CWT), and after distribution (Net).

6.3. Coagulation treatment performance

From the treatment performance data presented above, there is little doubt that coagulation constitutes a major NOM removing step. In addition, the hydrophobic NOM fractions are more amendable to removal by coagulation. In case of non-specific removal, the distribution between hydrophobic and hydrophilic NOM after coagulation treatment would have been equal to the distribution in untreated raw water. Figure 6-16 illustrate well that the hydrophobic NOM fraction concentrations (VHA+SHA as % of Tot-DOC) are being preferentially reduced during coagulation treatment at all utilities, and that the relative proportion of the remaining hydrophilic fractions increase similarly. This is also true for nanofiltration (BRA WTW) and for ozonation-biofiltration processes (IVAR Pilot). In clean waters, the hydrophobic NOM concentrations are even lower in most cases, illustrating that the additional treatment steps (ground infiltration, GAC, chlorination) are also attacking/reducing primarily the hydrophobic fractions of NOM.

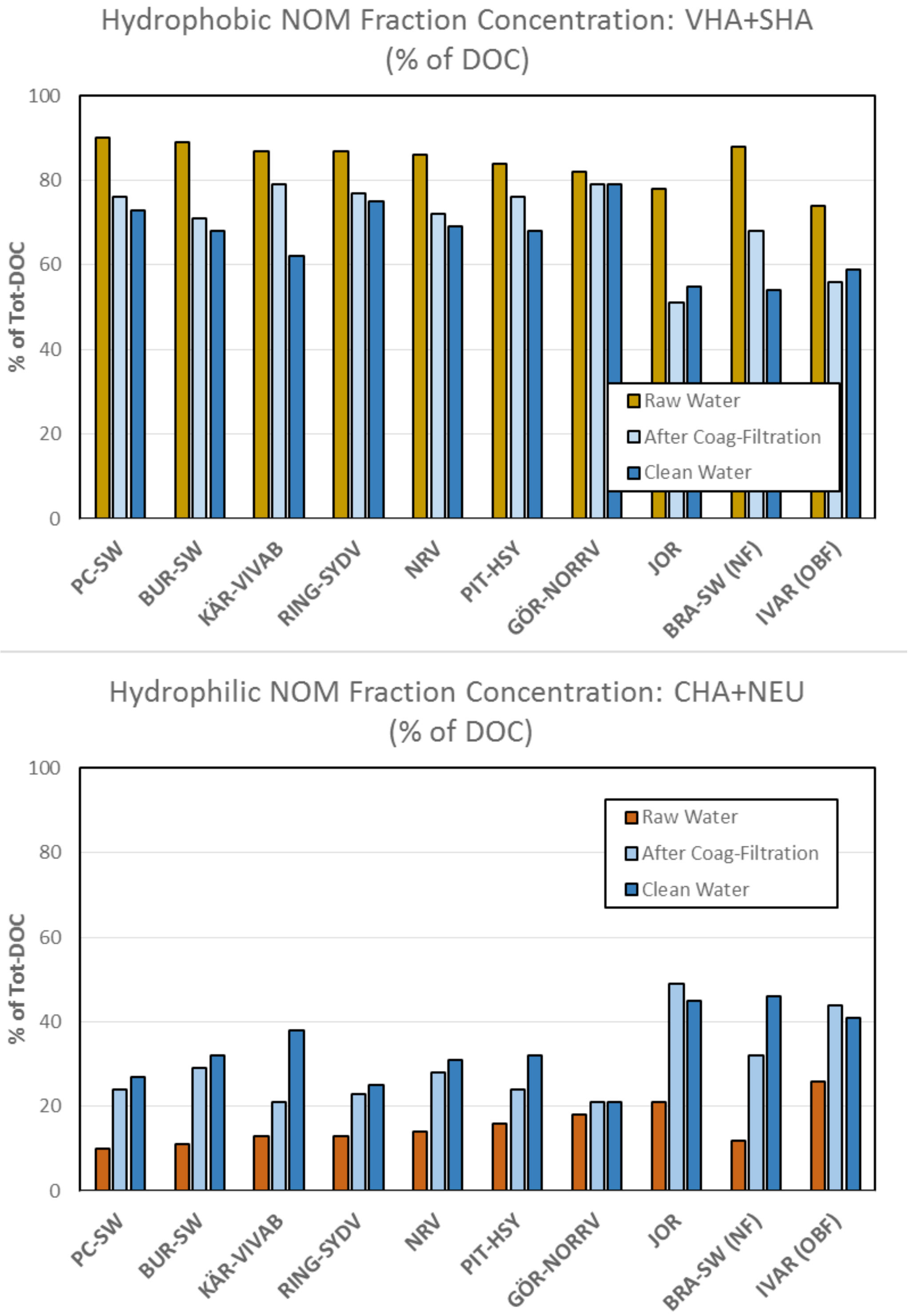

Figure 6-16 Utility benchmark: Average NOM fraction distribution in raw water, after coagulation-separation (Coag/sep), and after all treatment and disinfection process steps (CWT).

A good coagulation performance is dependent on the application of optimal coagulation conditions, i.e. levels of coagulant dose and coagulation-pH that are well adapted to the raw water quality/NOM at all times. Coagulant demand is linked to NOM properties, and preferential removal by coagulation is reported for the hydrophobic, aromatic, high molecular weight and charged fractions of NOM. On the other hand, neutral hydrophilic NOM fractions are not amendable to removal by coagulation. Thus coagulant demand is closely linked to the NOM fraction distribution. For a raw water with small or no seasonal variation in NOM-fraction distribution, it is likely that the DOC-normalized (DOC-specific) coagulant demand also remains relatively constant over the season. However, the coagulant dosage levels (mg/L) have to be adjusted in line with the variations in raw water NOM (DOC) concentrations.

The coagulant dose requirement is normally determined from experience and from measurements of color, UV-adsorption, SUVA, and/or DOC. For the daily operations, this information is implemented in the process control / SCADA system through algorithms relating coagulant dose needs to the prevailing raw water quality measures.

Coagulant doses can also be predicted from laboratory experiments (jar-tests, pilot treatment), from measurements of charge (zeta potential) in coagulated water, on-line measurements of clean water quality, NOM fraction distributions (i.e. those fractions amendable to removal by coagulation), etc.

As discussed above, the observed substantial differences in NOM removal efficiency cannot be explained by differences in raw water quality, i.e. from NOM concentrations and NOM fraction distribution alone. Thus, in order to explain the differences in observed treatment performance, there is a need for addressing differences in applied operation conditions and treatment performances among the utilities.

The criteria used for coagulation process assessments and utility benchmarking include:

- Type of coagulant and coagulation pH
- Absolute coagulant dose (mg Me/L)
- Specific coagulant dose (mg Me/mg Pt; mg Me/mg DOC
- Absolute and specific molar dose (mmol Me/L; µmol Me/mg DOC)

In addition, other relevant operation data like polymer type and doses, flocculation conditions, clarifier surface load (m/hr), rapid gravity filtration rates (m/hr), and slow sand filtration rates (m/hr), etc must be taken into consideration when evaluating treatment performance.

6.3.1. Coagulation process control and stability

It is well known from experience and from the literature that NOM will normally control coagulation dose and pH requirements. An "enhanced" coagulation process aimed for NOM control will normally require strict pH-control and substantially higher coagulant doses than conventional coagulation processes aimed for turbidity control.

Normally there will be a stoichiometric relationship between NOM content and coagulant dose requirement. Thus, increasing NOM concentrations will normally imply increasing coagulant dose requirements. A change in coagulant dose requirement may however result from a shift in the NOM fraction distribution, even if the NOM (Tot-DOC) concentration remains constant. If a utility observes no change in raw water quality, i.e. in the NOM (DOC) concentration and NOM fraction distribution, the coagulant requirement will also remain constant.

From the above, the absolute coagulant dose requirement will increase when the NOM (DOC) concentration level increases in the raw water. If the NOM fraction distribution remains constant however, the specific coagulant dose requirement, i.e. mg Me/mg DOC, or mmol Me/mg DOC, will remain constant. Varying specific coagulant doses in such a case may indicate an inadequate process control system, i.e. coagulation conditions that are not well adapted to the prevailing raw water (NOM) quality at the utility in question.

Figure 6-17 show the applied coagulant Al- or Fe-doses (mg/L and mmol/L), coagulation pH levels, and rates of filtration (in the single, dual or 3-M filters) for the eight utilities that apply coagulation treatment. It appears from Figure 6-17 that the applied Al- or Fe-coagulant doses vary within the range of 2.3-18.1 mg Al/L, and 3.4-7.7 mg Fe/L.

The difference in coagulation-pH between Al and Fe coagulants is substantial, i.e. pH 5.9-7.3, and pH 4.0-5.1 for Al- and Fe-coagulation, respectively. The large span in coagulation-pH at utilities using Al-based coagulation is mainly due to the fact that utilities using pre-polymerized Al-coagulants (NRV and KÄR WTWs) can apply higher coagulation-pH levels (pH 7.0-7.3) than the utilities using alum (pH 5.9-6.8). Applied filtration rates vary within 2-7 m/hr.

There is no clear tendency in the data that raw waters that are high in NOM concentration and thus need higher coagulant dosage require lower coagulation-pH levels. These utilities do however tend to use lower filtration rates in order to maintain reasonably long filter run lengths.

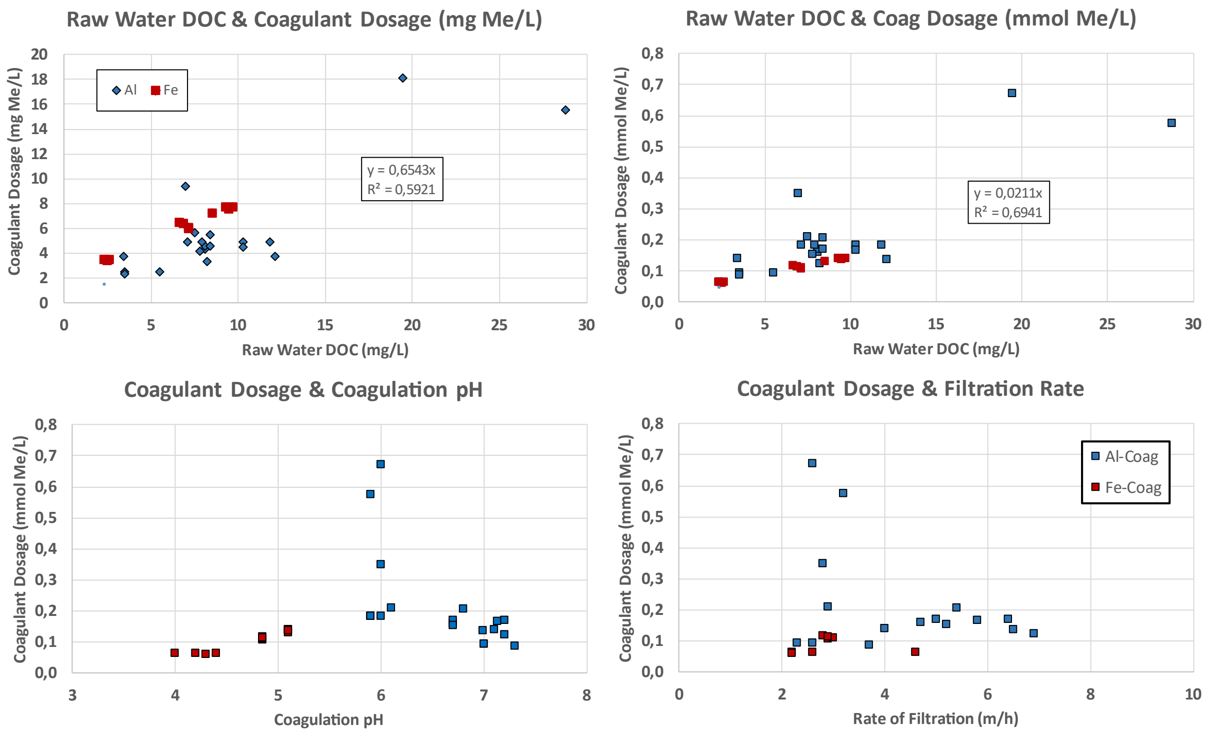

Figure 6-17 Raw water quality (DOC), applied coagulant doses, coagulation pH and rates of filtration (All samples/data from the 8 utilities using coagulation treatment).

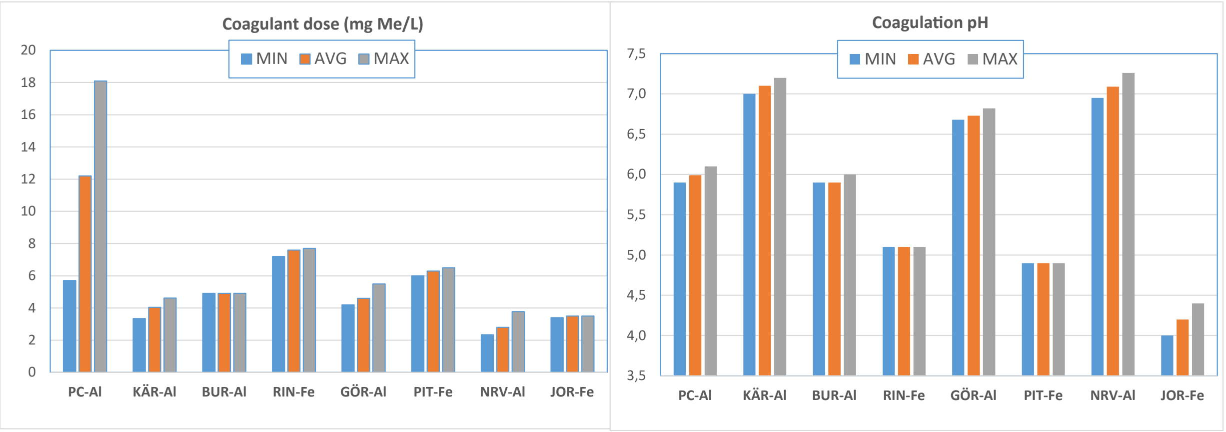

Figure 6-18 Applied coagulant doses and coagulation pH for the 8 NOMiNOR utilities using coagulation treatment (Minimum, average and maximum values during the NOMiNOR sampling period).

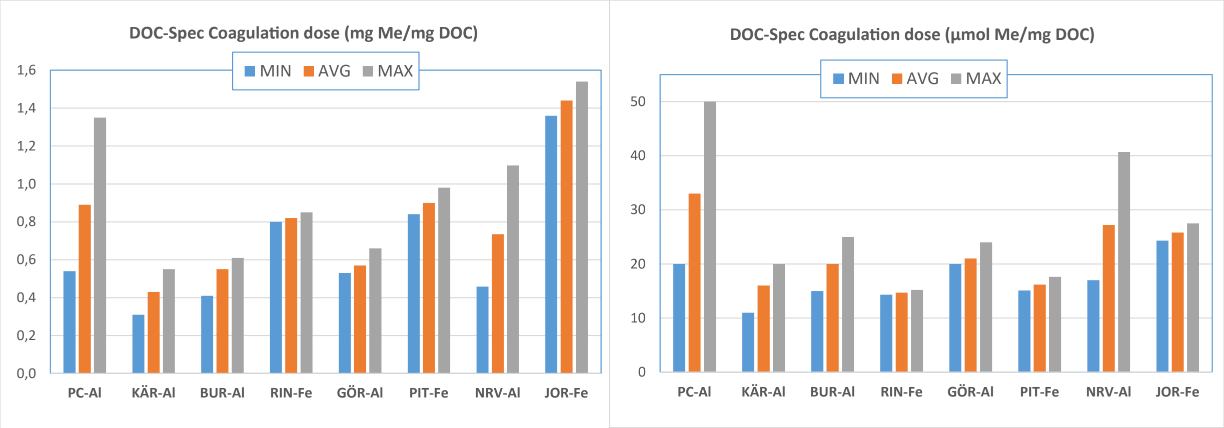

Figure 6-19 Applied DOC-specific coagulant doses for the 8 NOMiNOR utilities using coagulation treatment (Minimum, average and maximum values during the NOMiNOR sampling period).

Figure 6-19 shows that there is a great variation in the seasonal DOC-specific coagulant dosage at some utilities, e.g. from 0.5 to 1.4 mg Al/mg DOC at PC WTW, and 0.5 to 1.1 mg Al/L at NRV WTW. As discussed before, there is no reason to believe that the specific coagulant dose needed will increase when the DOC concentration increases as long as the NOM fraction distribution remain constant in the raw water, and the pH levels are maintained at close to optimum levels. Thus this great variability in DOC-specific dosage is likely due to poor process control, and lack of adaptation of process conditions to the prevailing raw water quality. In addition, this is also indicative of a significant optimization potential.

The data in Figure 6-17 and 6-19 indicate that the utilities that apply Fe-coagulants not only require less molar dosages, but also tend to apply more stable coagulant dose levels, i.e. more constant DOC-specific dosages.

Coagulation process stability is also illustrated in Figure 6-20, showing minimum, average and maximum removal efficiency (%) of hydrophobic (VHA+SHA) and hydrophilic (CHA+NEU) fractions. It may be deducted from this Figure that well operated coagulation facilities can achieve hydrophobic NOM removal efficiencies in line with that achieved by nano filtration (NF). For hydrophilic NOM however, NF tend to be more effective. This is mainly due to the poor NEU fraction removal efficiency achieved by coagulation.

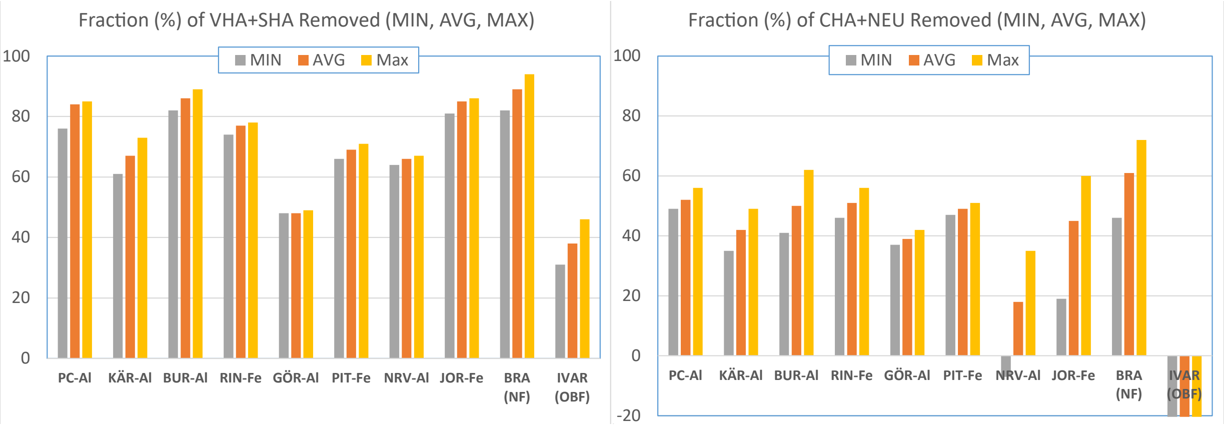

Figure 6-20 Achieved removal efficiencies for hydrophobic and hydrophilic NOM (Minimum, average and maximum values measured during the seasonal NOMiNOR sampling period).

6.3.2. Treatment optimization potentials

As discussed above, SUVA and the hydrophobic NOM fraction concentration can be applied to predict NOM treatability by coagulation. In line with this, Figure 6-21 shows the average VHA and VHA+SHA fraction concentrations as well as SUVA in the NOMiNOR raw waters along with the average DOC removal achieved in coagulation treatment. The results support the application of SUVA and/or the hydrophobic NOM fraction concentrations for at least two purposes:

- Assessments of raw water treatability by coagulation
- Assessments of best possible DOC removal, and thus identification of treatment optimization potentials at a specific site

The results in Figure 6-21 also show a close to 100 % removal of the hydrophobic NOM content during the nanofiltration process applied at BRA WTW. A close to complete removal of all hydrophobic NOM is also achieved by the well optimized enhanced coagulation process applied at JOR WTW. For the remaining utilities, the vertical distance between the actual DOC removal achieved and the VHA+SHA curve representing the removable NOM can be taken as a remaining coagulation treatment optimization potential. Thus, the largest coagulation treatment optimization potential seems to exist at KÄR, GÖR and NRV WTWs.

Even with the poor and very variable raw water quality at PC WTW (7-29 mg DOC/L), it is interesting to observe that good final water quality was achieved by coagulation treatment. To illustrate the importance of optimum coagulation conditions (i.e. applied coagulant dose), Figure 6-22 show the applied DOC-specific alum coagulant doses and the resulting "bleeding" of DOC from the different NOM fractions at Port Charlotte WTW. It appears from Figure 6-22 that the VHA fraction is still the largest contributor to the DOC bleeding to treated water from the coagulation step, specifically at sub-optimum coagulant dosage conditions like the ones prevailing during Sampling Round No. 2 (i.e. when applying 20 µmol Al/mg DOC as the DOC-specific coagulant dose).

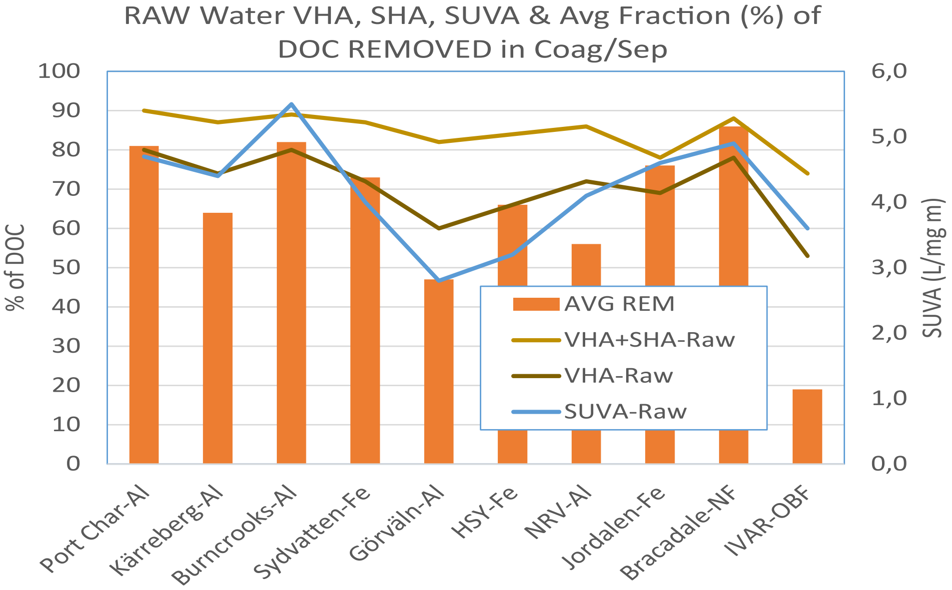

Figure 6-21 SUVA and hydrophobic NOM fraction concentrations in raw waters, along with the DOC removal efficiencies achieved by the NOMiNOR utilities.

In periods with relatively similar raw water qualities, it is also interesting to observe that the coagulation treatment applied at Burncrooks WTW is performing almost as good as the NF treatment at Bracadale WTW (Figure 6-23). The NF process is however able to handle high incoming DOC levels (i.e. close to 27 mg DOC/L during Sampling Round 2) without exceeding a DOC bleeding level of 2 mg/L.

Besides the NOM treatment optimization potentials, possible improvements are identified also for other target parameters and elements, as presented and discussed in Chapter 5.

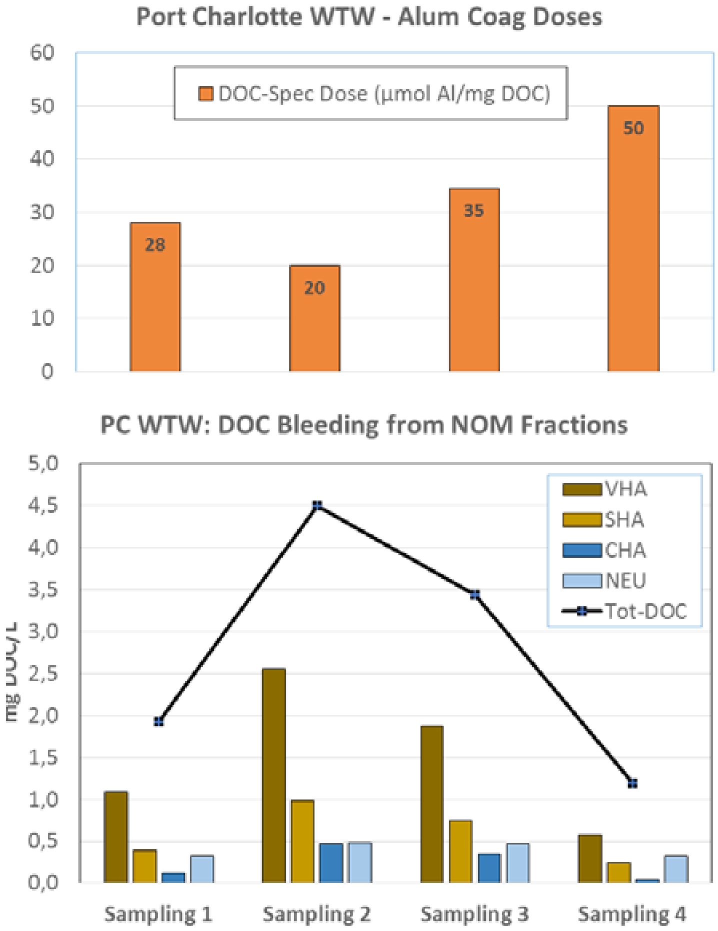

Figure 6-22 Applied DOC-specific alum doses and corresponding DOC bleeding from different NOM fractions during the four sampling rounds at Port Charlotte WTW.

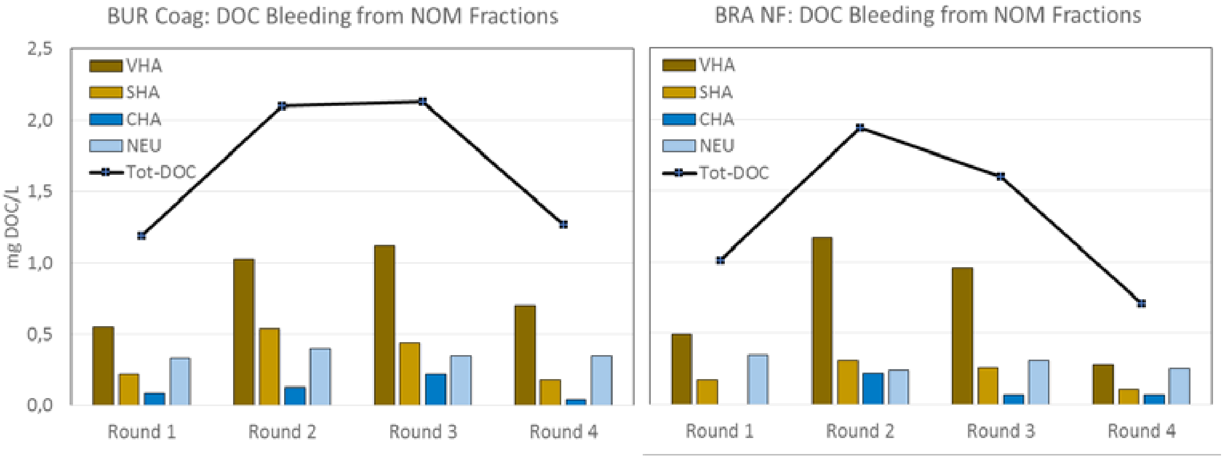

Figure 6-23 DOC bleeding from different NOM fractions during the four sampling rounds at Burncrooks WTW (coagulation; left) and at Bracadale WTW (NF; right).

6.3.3. NOM concentration and NOM fraction distribution

There are significant differences in the NOM concentration levels among the NOMiNOR utilities. There is also substantial site-specific seasonal variability in the NOM concentration levels.

In order to investigate if the NOM fraction distribution was affected by the actual NOM (i.e. Tot-DOC) concentration level, the NOM fraction distributions were characterized at the minimum and maximum DOC levels measured during the four seasonal samplings for each of the NOMiNOR utilities applying coagulation treatment.

The results presented in Figure 6-24 show that the hydrophobic and hydrophilic NOM fraction distributions remained surprisingly constant despite substantial differences in tot-DOC levels at the ten NOMiNOR utilities. At 7 out of the 8 utilities, the NOM fraction distributions were found to be almost identical at the minimum and maximum DOC levels observed during the four sampling rounds. The largest difference was found at NRV (5 %). At these three utilities, there was a tendency of increasing hydrophobic NOM fraction concentrations - and likely increased treatability by coagulation or NF - with increasing DOC levels. However, the differences were rather small, as shown in Figure 6-24. The utilities in Figure 6-24 are ranked in the order of declining raw water DOC levels. The results may also indicate that the highest hydrophilic NOM fraction concentrations are found at utilities with the lowest raw water DOC levels.

These findings indicate that the utility-specific process control and coagulant dosing algorithm can be based on a linear relationship between the dose requirement and the raw water NOM content that is amendable to removal by coagulation, i.e. raw water colour, UV-absorbance or hydrophobic NOM content (VHA+SHA). With a constant site-specific NOM fraction distribution, there is no need for any dose compensation for a changing distribution with less removable NOM.

However, these site-specific findings cannot be taken as indicators that the NOM fraction distribution and thus NOM treatability will not change if NOM levels increase further as a result of climate change, e.g. more allochthonous NOM, algae, etc.

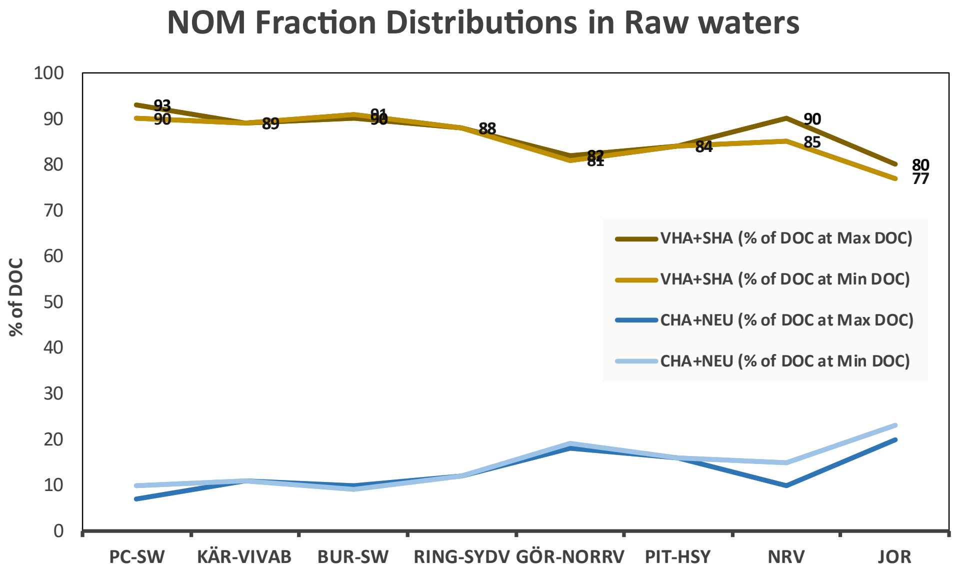

Figure 6-24 Hydrophobic and hydrophilic NOM fraction distributions at minimum and maximum raw water DOC levels during the four sampling rounds at the coagulating NOMiNOR utilities.

6.4. Biostability and ATP

In Norway, UV is the dominating disinfection technology, and so are chlorine-free distribution systems. If chlorine is used, the residual free chlorine shall be detectable, i.e. > 0.05 mg/L, after 30 minutes contact time, according to the national drinking water standards and regulations. With no chlorine to control microbial activity/regrowth in the distribution network, biological stability, including control and limitations of microbial substrate (BDOC) are important issues.

In Scotland, on the other hand, the national drinking water standards and regulations require that free chlorine residuals are present even at customer's taps. In spite of the fact that the microbial substrate (e.g. BDOC) concentrations increases due to the NOM oxidation by chlorine, the microbial activity and regrowth is controlled by the significant amounts of chlorine residuals present throughout the entire distribution networks. These effects are well demonstrated by the NOMiNOR results, i.e. from the BDOC and ATP measurements. A major disadvantage of this chlorination practice is the potential formation of chlorination by-products from the reactions between chlorine and organic matter, thus making effective NOM removal even more important.

The chlorination practice in Sweden and Finland is somewhere between that in Norway and Scotland. The chlorine doses applied are moderate compared to those used in Scotland, and chloramine is widely used due to the longer-lasting effects during distribution. Also in Sweden and Finland, the use of UV for disinfection is widespread and increasing.

Figure 6-25 shows the average and maximum BDOC and ATP concentrations found in the water samples taken from the raw water, from the clear water tank (CWT) and from the distribution network at the NOMiNOR utilities.

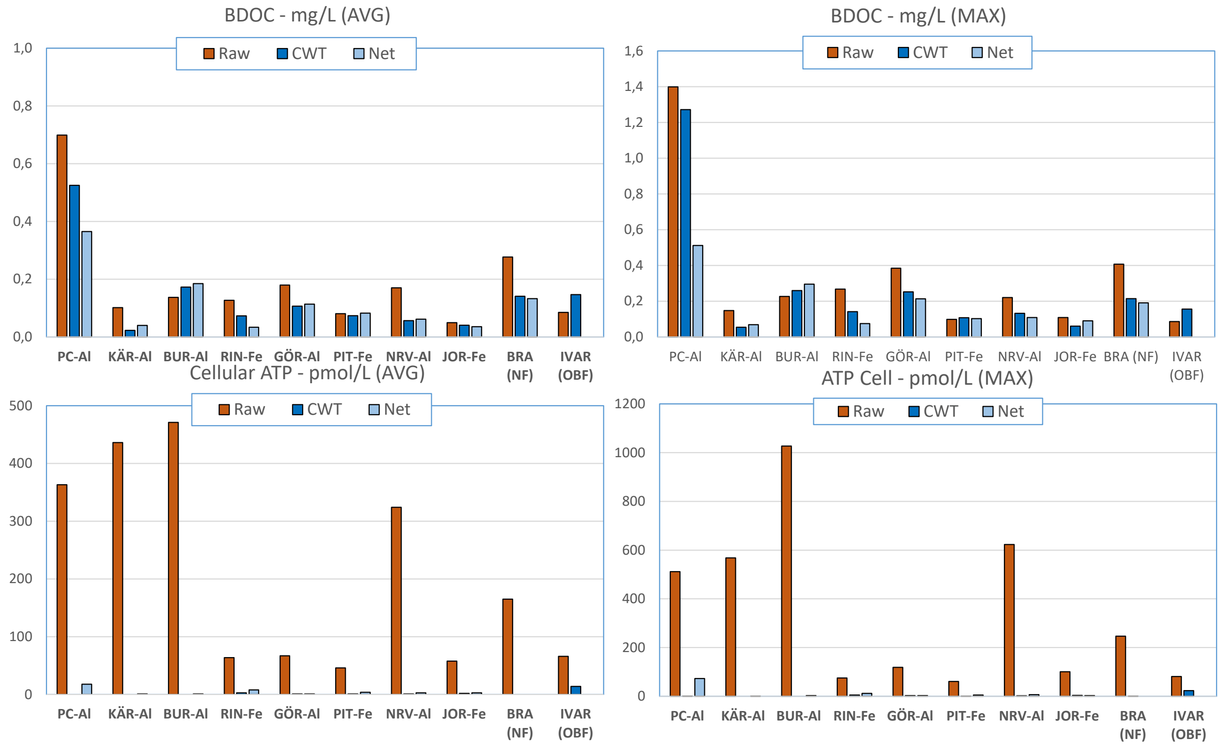

Figure 6-25 Average and maximum BDOC and ATP concentrations in raw water, clean water and distributed water samples from the NOMiNOR utilities. The type of coagulant used are shown as well (Fe or Al).

The highest levels of microbial activity (ATP) are found in raw waters from PC, KÄR, BUR, and NRV WTWs, but as can be seen from the figure, the levels are substantially reduced during treatment down to levels close to zero in clean water.

The by far highest BDOC concentrations in treated water were found at PC WTW. In spite of the fact that chlorination controls regrowth, some ATP is still present in distributed water samples at this utility. Thus the substantial reduction in BDOC from the CWT to the network sampling point is likely not due to microbial consumption, but rather from adsorption of BDOC to metal deposits (e.g. Fe) on the pipe walls (Chapter 6.5).

Also BUR, GÖR and BRA WTWs have maximum BDOC levels above 0.2 mg/L. This may be taken as an upper limit for a biologically stable water, i.e. not causing substantial regrowth - even without any chlorine residuals to control it.

6.5. Elements and Metals

Concentrations of chloride (Cl), calcium (Ca) and sulphur (S) in the raw waters is shown in Figure 6-26. The content of inorganic constituents reflects the influence from proximity to the sea, from minerals in the watershed, etc. PC, GÖR and BRA WTWs have the highest chloride content, and GÖR the highest content of calcium and sulphur.

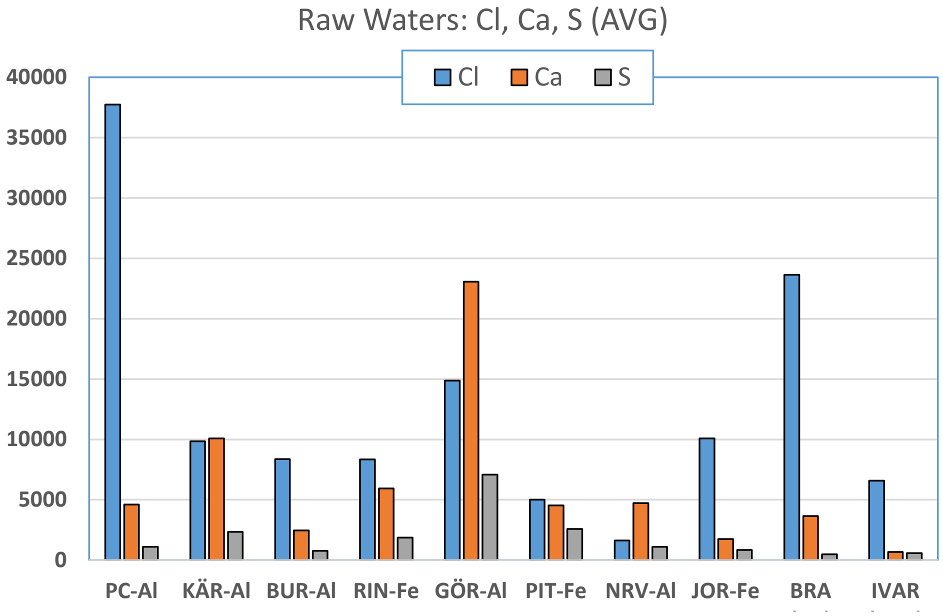

Figure 6-26 Average concentrations (µg/L) of Cl, Ca and S in raw water samples from the NOMiNOR utilities.

Figure 6-27 shows the average content of iron (Fe), manganese (Mn), aluminium (Al) and calcium (Ca) in samples from raw water, coagulated/clarified/filtered water (Coag/Sep), clean water (CWT) and network.

The high NOM levels found in the raw water at PC WTW were accompanied by high levels of Fe (Figure 6-27), likely present as NOM-Fe complexes. Also KÄR, BUR, RIN and BRA WTWs had average Fe concentration levels above 400 µg/L in their raw waters. PC and KÄR WTWs had average Mn-levels above 40 µg/L in their raw waters, and NRV WTW had Mn-levels above 20 µg/L.
PC, KÄR, NRV and JOR WTWs had average levels of Al around 100 µg/L. Regarding Ca, the levels varied significantly, with GÖR (23 mg/L) and IVAR (0.7 mg/L) representing the upper and lower average raw water concentrations.

Furthermore, Figure 6-27 shows that the Fe was effectively removed during coagulation treatment. The highest Fe-residuals were found at PIT WTW (84 µg/L on average, 116 µg/L at maximum), and at KÄR WTW (average 41 µg/L, maximum 133 µg/L). Regarding Al, the average concentrations after coagulation treatment were low (< 30 µg/L) at all utilities, except KÄR WTW where the average Al concentration was 324 µg/L. The maximum levels found were 1006 g/L at KÄR WTW, and 315 g/L at NRV WTW. These high levels were likely due to prevailing sub-optimal coagulation treatment conditions during the sampling rounds in June 2015 and February 2016, respectively.

Manganese (Mn) was also effectively removed during treatment. Coagulation (all utilities except PIT WTW with very low Mn concentration), ground infiltration (KÄR), slow sand filtration (RIN), and GAC filtration processes (NRV and BRA) appear as effective unit processes for Mn removal. At BUR WTW, the average Mn concentration increased from the rapid sand filter outlet to the clean water tank and further to the distribution system sampling point. The reason for this increase is not clear, but it may be due to the large variation in the raw water Mn concentration (7-30 µg/L).

Ca concentrations differ significantly between the WTWs (Figure 6-27). The differences are large also in clean and distributed waters, with levels ranging from 1-3 and up to more than 34 mg/L. The levels of Ca, along with pH and alkalinity are important to control corrosion of pipeline and plumbing materials. As an example, the Norwegian guidelines recommend 15-25 mg/L of Ca, pH 8-8.5, and alkalinity of 0.6-1 mmol/L.

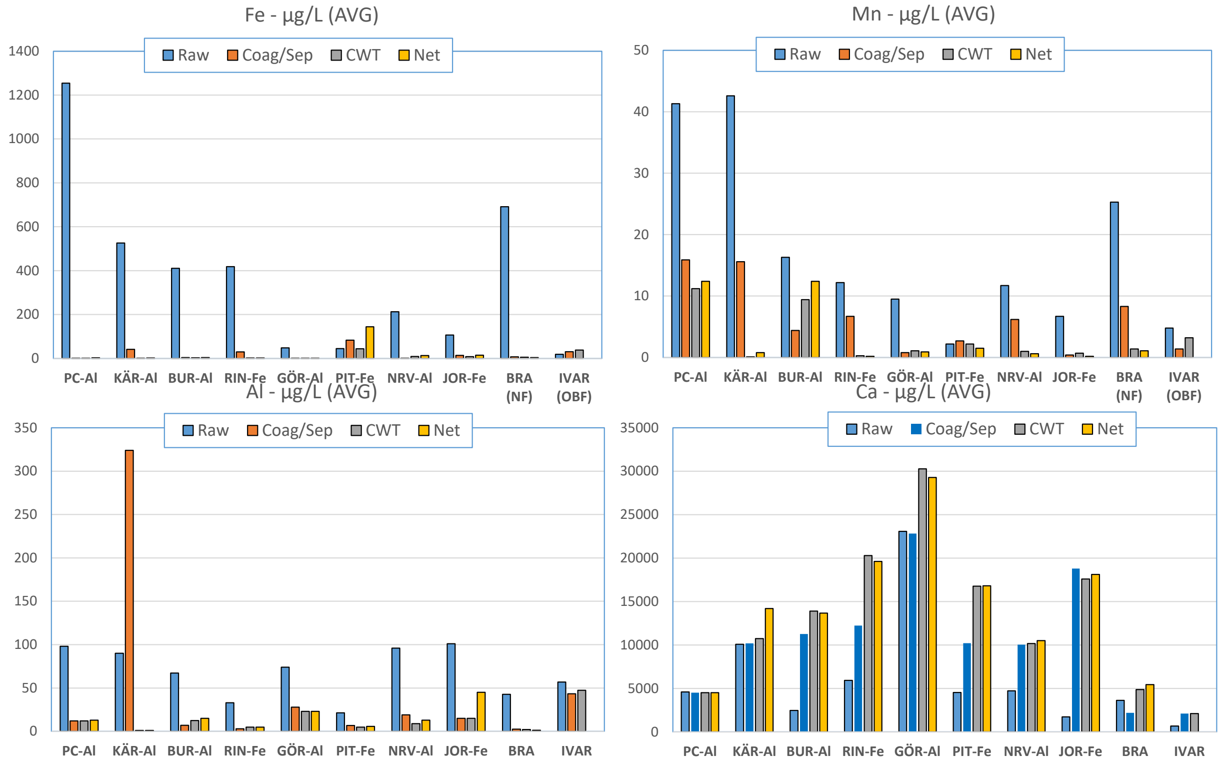

Figure 6-27 Average concentrations of Fe, Mn, Al and Ca in raw water, coagulated water, clean water (CWT) and network samples from the NOMiNOR utilities.

Biostability and regrowth potentials are not only dependent on the available carbon sources (e.g. BDOC). Also nutrients like phosphorus are important for the microorganisms to grow. Figure 6-28 shows the average total phosphorus concentrations in water samples from the NOMiNOR utilities.

Leaking of P from the GAC used at BRA WTW during the November 2015 sampling round (Figure 6-28) is discussed in previous chapters. PC and GÖR WTW have average P-levels of 20-25 µg/L in their raw waters. Coagulation effectively removes P down to average levels of 2.4-4.2 µg/L at all the coagulation utilities. However, neither the NF process applied at BRA nor the ozone-biofiltration process at IVAR WTW seem capable of providing significant P-removal.

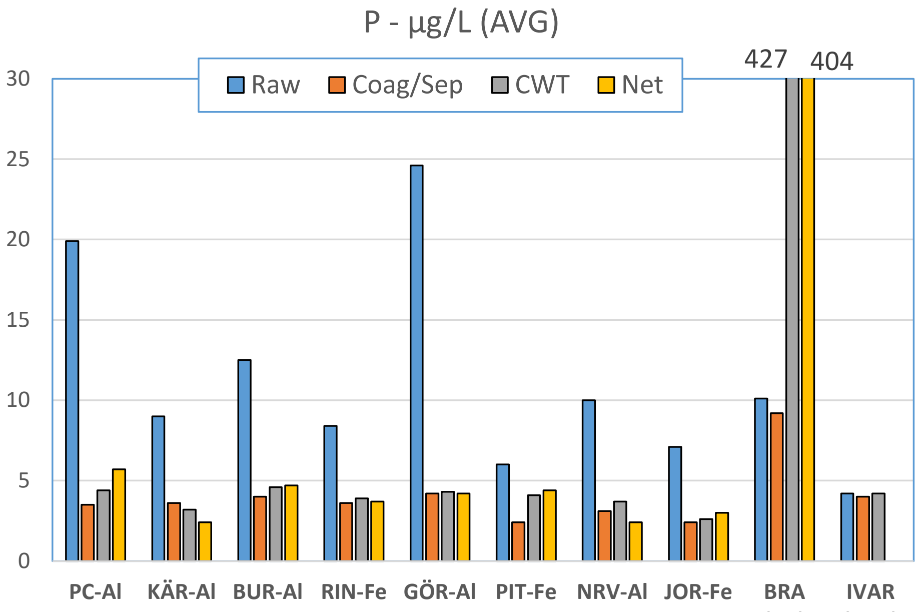

Figure 6-28 Average concentrations of total phosphorus (P) in raw water, coagulated water, clean water (CWT) and network samples from the NOMiNOR utilities. The high levels for BRA (> 400 µg/L) is due to a P-leaking GAC in the Nov 2015 sampling round.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Watershed and NOM predictions

- There will most probably be an increase in NOM and color at all the NOMiNOR sites. In most NOMiNOR water sources the NOM content is predicted to increase by 15-25 % towards the year 2100.
- The predicted increase in NOM is mainly related to a predicted increase in air temperature.
- The NOMiNOR sites also have a positive relationship between NOM and precipitation amounts, with an exception for Jordalsvatnet.
- Increased concentration of ions into the systems (i.e. chlorides from sea-salt or carbonates) can depress the solubility of NOM.
- The NOMiNOR utilities are recommended to consider use of in situ sensors on temperature and rainfall along with weather forecasts in order to get an early warning of potential high NOM concentration episodes.
- There are large uncertainties regarding the future NOM predictions; both within datasets, NOM-models and with the climate predictions.

7.2. NOM treatability and water treatment performance

- The concentration of NOM has increased significantly in many Nordic and northern European drinking water sources during the past decades. Because NOM is controlling treatment processes and impacting on the processes going on in the distribution network as well, it is imperative to be able to control NOM through adequate, well designed and well operated water treatment processes.
- The NOMiNOR project has demonstrated that simple and easily available NOM diagnoses can provide a new world of valuable information - relevant to treatment process assessments, operation performance and optimization efforts. In addition, more advanced NOM analyses can increase our understanding of NOM proxies, NOM characteristics, NOM behavior and NOM treatability.
- The NOMiNOR project has detected significant differences in NOM concentration levels and in NOM fraction distribution in raw waters from the 10 participating utilities. The variability is seasonal, i.e. between the seasonal samples taken within each source/utility, and site-specific, i.e. between the 10 utilities.
- Raw waters are dominated by hydrophobic NOM, and specifically the VHA fraction. On average, VHA constitute 71 %, SHA 14 %, CHA 7 % and NEU 8 % of DOC (VHA+SHA 85 % and CHA+NEU 15 % of Tot-DOC). The VHA content vary within the range of 52-87 %, and the hydrophobic content (VHA+SHA) within the range of 71-94 % of DOC. The average BDOC fraction is 2.8 % of DOC, and average ATP in the raw waters is 206 pmol/L.
- Despite the generally good treated (clean) water quality achieved by the NOMiNOR utilities, substantial differences in treatment performance are detected. The differences can be attributed to differences in two major factors: (1) Source water treatability (NOM fraction distribution), and/or (2) Treatment performance and operation conditions, including process control/adaptation to the prevailing raw water quality.
- For utilities applying a coagulation treatment, this is the major NOM-removing step: Average removal efficiencies achieved during coagulation/clarification/filtration steps at the 8 coagulation WTWs are 76 % for VHA, 50 % for SHA, 41 % for CHA and 14 % for NEU, 73 for VHA+SHA, 43 % for CHA+NEU, 36 % for BDOC, and 91 % for ATP.

- For comparison, the average overall removal efficiencies (including additional treatment and disinfection) achieved at the 8 coagulation WTWs are 81 % for VHA, 55 % for SHA, 57 % for CHA and 19 % for NEU (78 and 46 % for VHA+SHA and CHA+NEU), 23 % for BDOC and 98 % for ATP.

- The site-specific NOM fraction distributions appear to remain constant during the sampling seasons at the utilities applying coagulation treatment, regardless of large seasonal variation in raw water NOM (DOC) content. The maximum difference detected was 5 % (NRV). This indicates that the site- and DOC-specific coagulant demand is also relatively constant over the season. Thus, the observed and substantial seasonal differences in coagulation conditions cannot be explained by changes in NOM fraction distribution and treatability alone, but should also be attributed to process control systems not capable of adapting treatment conditions to the prevailing raw water quality at all times.

- The most effective NOM removal was achieved by NF treatment, and the fractions removed were 89 % for VHA+SHA, and 61 % for CHA+NEU, 60 % for BDOC and 93 % for ATP. For BDOC and ATP the fractions removed after additional treatment (GAC) and chlorine disinfection were 25 and 100 %, thus not only illustrating the disinfection power of residual chlorine (ATP), but also the BDOC formed by chlorination. It should be pointed out however, that the best operated coagulation utilities achieve NOM removal efficiencies close to that achieved by NF.

- The NOM fraction distribution show effects from the applied treatment and disinfection technologies, e.g. preferential removal of VHA by coagulation, and production of hydrophilic NOM and BDOC by ozonation and chlorination processes.

- The residual chlorine present in Scottish distribution systems seems capable of controlling regrowth (ATP), despite the BDOC produced (PC WTW a possible exception).

- The results from the NOMiNOR project have demonstrated that simple NOM diagnostics form a good basis for treatment performance assessments and identification of optimization potentials. Although coagulation and NF are by far the most efficient treatment steps, additional treatment like GAC filtration with or without preozonation, slow sand filtration (SSF), and ground infiltration may have good effects on water quality. From the performance data, ground infiltration, and ozonation-GAC filtration appear as the additional treatment processes with the most significant impact on water quality.

- Advanced NOM analyses can improve our understanding of NOM nature, NOM properties and NOM behavior during treatment, disinfection and distribution systems. This includes valuable information on DBP formation and formation potentials, hygienic safety/barrier efficiency and microbial log reductions, surface charges, etc. Furthermore, sophisticated information is provided on molecular size fractions, fluorescence spectra and specific organic substances removed during different treatments and different operational circumstances. Thus the data from the advanced analyses also constitute a valuable data base for future use and interpretation, despite the fact that all the practical implications of the data and findings may still be unclear.

- Based on the results from water sample analyses and utility benchmarking, site-specific recommendations are provided on treatment performance, treatment peculiarities, as well as needs for additional treatment, optimization of treatment, and/or process control systems.

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