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"Investigation of pre-ozonation on the performance of membrane filtration (Oxeram 1 – D 4.2)"

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Abstract

Low-pressure membrane filtration of secondary effluents allows disinfection and, combined with chemical coagulation, advanced phosphorus removal. However, the loss of filtration performance due to membrane fouling is still a fundamental problem and has a strong impact on the costs of the process. Biopolymers as well as colloids in the range of 50 to 350 nm were identified as main foulants during ultrafiltration (UF).

In this project the impact of a pre-treatment by ozonation (2-10 mg O_3/L) and subsequent coagulation ($FeCl_3$: 2-6 mg Fe^{3+}/L) on the performance of a polymer UF membrane was studied. No free dissolved ozone was in contact with the membrane. Lab tests were performed using Amicon test cells in dead-end mode fed with 500 mL secondary effluent of the WWTP Ruhleben (Berlin) and the flux decline during filtration was measured. The effect of the two pre-treatment steps on the character of DOC, especially the biopolymer fraction, was investigated using size exclusion chromatography.

The pre-treatment enables phosphorus removal of 75 up to 95 % with permeate concentrations of 30 to 50 µg P/L. In filtration tests pre-ozonation without flocculation leads to a less distinct flux decline (1-7 %). Coagulation without pre-ozonation increases the flux by 5 to 14 % compared to filtration of effluent without pre-tretament. The combination of both pre-treatment steps improves the filtration performance up to 30 % and reduces the filtration time for 500 mL by 50 %.

Different mechanisms are considered as reasons for the improved performance. It is known that coagulation partially removes the fouling-active biopolymers and humic substances. The pre-treatment with ozone, even at low dosages (2 mg/L), leads to a significant decrease of UV_{254} absorbance, pointing on a shift to more polar molecules. Higher ozone dosages (> 6 mg/L) additionally induce disintegration of biopolymers and a shift to smaller organic compounds.

The interaction between ozonation and coagulation leads to a partial complexation of iron in solution. As a consequence, less iron is provided for the coagulation process. As the percentage of complexation of iron decreases with increasing coagulant dosage, the synergetic effect of pre-ozonation and coagulation on the filtration performance increases with increasing iron dosage.

These results suggest that combining pre-ozonation and coagulation can be a promising pre-treatment process to reduce the fouling of organic membranes, without the necessity of applying free dissolved ozone on the membrane surface.

Zusammenfassung

Die Filtration von Klärwerksabläufen mit Niederdruckmembranen bietet in Kombination mit einer Flockungsstufe eine wirkungsvolle Möglichkeit für das Erreichen niedriger Phosphorkonzentrationen und einer zusätzlichen Entfernung von Pathogenen. Das Hauptproblem beim Betrieb von Niederdruckmembranen stellt nach wie vor der durch Fouling auftretende Verlust der Filtrationsleistung dar. Als Folge des Foulings müssen die Membranen regelmäßig physikalisch bzw. chemisch gereinigt werden, was zu einer Verringerung ihrer Standzeit und somit zu höheren Kosten führt. Biopolymere und Kolloide in der Größenordnung 50-350 nm wurden als Hauptverursacher des Foulings während der Ultrafiltration (UF) identifiziert.

Im Rahmen dieses Projektes wurde untersucht, ob durch eine Ozonierung (2-10 mg O_3/L) vor der Flockungsstufe ($FeCl_3$: 2-6 mg Fe^{3+}/L) das Fouling der nachgeschalteten Membran reduziert und somit die Leistungsfähigkeit der Membranfiltration verbessert werden kann. Es wurden Labortests mit Amicon-Zellen im Dead-End-Modus durchgeführt, wobei die Membran zu keiner Zeit mit freiem Ozon in Kontakt stand. 500 ml Klarlauf der Kläranlage Ruhleben (Berlin) wurden filtriert und die Fluxabnahme kontinuierlich gemessen. Die Auswirkungen der beiden Vorbehandlungen auf den Charakter des DOC, im speziellen auf die Biopolymerfraktion, wurden mit Hilfe der Größenausschlußchromatographie untersucht.

Die Behandlung des Klarlaufes mit einer Kombination aus Flockung und UF-Membran ermöglichte, unabhängig von der Ozonierung, Phosphorentfernungsraten von 75 bis 95 %, korrespondierend mit Phosphorkonzentrationen von 30 bis 50 µg P/L im Permeat der UF-Membran. Die Ozonierung führte zu einem geringen Anstieg des Fluxes zwischen 1 und 7 %. Ein weitaus größerer Effekt von 5 bis 14 % Fluxzunahme, verglichen mit der Filtration des Klarlaufes ohne weitere Vorbehandlungen, wurde durch die Flockung erzielt. Die Kombination aus Ozonierung und Flockung verbesserte die Filtrationsleistung der Membran um bis zu 30 % und reduzierte die Filtrationszeit für 500 ml Klarlauf um 50 %.

Für die verbesserte Filtrationsleistung kommen verschiedene Ursachen in Betracht. Es ist bekannt, dass Flockung die fouling-aktiven Biopolymere und Huminstoffe teilweise entfernt. Die Vorbehandlung mit Ozon führt schon bei niedrigen Ozondosen (2 mg/L) zu einer signifikanten Abnahme des SAK_{254}, was auf eine Verschiebung hin zu polareren Molekülen hindeutet. Höhere Ozondosen (> 6 mg/L) induzieren zusätzlich eine Zerkleinerung der Biopolymere und eine Veränderung hin zu kleineren organischen Bestandteilen.

Das Zusammenwirken von Ozonierung und Flockung führt zu einer partiellen Komplexierung des Eisens in Lösung, weshalb weniger Eisen für den Flockungsprozess zur Verführung steht. Da der prozentuale Anteil an komplexiertem Eisen mit steigender Flockungsmitteldosis abnimmt, vergrößert sich der synergetische Effekt von Ozonierung und Flockung auf die Filtrationsleistung mit steigender Eisendosis.

Die bisher im Rahmen des Projekts durchgeführten Versuche zeigen, dass die Kombination aus Ozonierung und Flockung eine viel versprechende Vorbehandlung vor der Ultrafiltration darstellt, um Fouling von organischen Membranen zu reduzieren ohne die Notwendigkeit, die Membranoberfläche mit freiem Ozon in Kontakt zu bringen.

Contents

List of Figures

List of Tables

List of Abbreviations

BP	Biopolymer
BW	Backwash
LC-OCD	Liquid Chromatography - Organic Carbon Detection
J	measured flux
J_0	pure water flux
MF	Microfiltration
MWCO	Molecular weight cut off
RPM	Rotations per minute
UF	Ultrafiltration
WWTP	Wastewater treatment plant

1 Introduction

The European Water Framework Directive (EU-Wasserrahmenrichtlinie 2000) establishes several principles for water management with the goal to reach a "good ecological status" of all surface waters until 2015. Consequently, the Berlin regional wastewater disposal scheme (Senatsverwaltung für Stadtentwicklung (Ed.) 2001) aims at water quality class II for the local rivers (River Spree and River Havel), corresponding with a low eutrophic status.

In order to prevent eutrophication and growth of algae, the discharge of phosphorus from the Berlin waste water treatment plants into the surface waters of the region (Berlin/Brandenburg) has to be minimized. According to a previous study and following a verified mathematical correlation of total phosphorus and algae growth (expressed by chlorophyll-A concentration), the average tolerable phosphorus level to ensure surface water quality class II is 16-82 µg P/L. (Senatsverwaltung für Stadtentwicklung (Ed.) 2001)

As a consequence, the Berlin public utilities (Berliner Wasserbetriebe) consider to expand the treatment train of the wastewater treatment plant (WWTP) Ruhleben by a process consisting of (pre-)coagulation and subsequent membrane filtration process, a so-called "advanced treatment stage" (Gnirß 2008). This additional treatment shall reduce the medium annual phosphorus effluent concentration from 0.3 – 0.4 mg P/L down to a target concentration of 0.05 – 0.1 mg P/L, which is believed to guarantee the above mentioned water quality class II.

In general, low-pressure membrane filtration of secondary effluents allows disinfection and, combined with chemical coagulation, advanced phosphorus removal. However, the loss of filtration performance due to membrane fouling is still a fundamental problem and has a strong impact on the costs of the process.

Organic fouling of membranes by formation of a cake layer on the membrane surface, pore blocking or in-pore adsorption results in a reduction of the trans-membrane flux (operating with a constant trans-membrane pressure) or an increase of the trans-membrane pressure loss (operating with a constant trans-membrane flux) with increasing filtration time. As a consequence, membranes have to be periodically cleaned applying physical or chemical cleaning procedures, leading to a reduction of operation time.

Organic fouling is caused by particles and by larger dissolved organic substances. Zheng et al. (2009) and Te Poele (2006) found that biopolymers (BP) in the form of proteins and polysaccharides as well as colloids in the size of 10–450 nm are mainly responsible for the fouling of low-pressure membranes. With regard to dissolved organic substances (DOC), only 10 % of the DOC contained in Ruhleben effluent contributes to the fouling process (Laabs 2004). Using size exclusion chromatography (LC-OCD), these substances typically elute within the so-called "biopolymer peak", consisting mainly of polysaccharides, organic colloids and proteins.

A promising approach to reduce organic fouling and to improve the membrane filtration performance is the application of ozone. The combination of coagulation and ozonation using relative low O_3 dosages (1 - 2 mg/L) can lead to the formation of larger, more stable flocs as a

result of the so-called “microflocculation effect” (Jekel 1998), hence having a positive effect on the membrane filtration performance. Beyond this microflocculation effect higher ozone dosages (10 - 12 mg O_3/L) lead to partial oxidation of organic substances and micropollutants (Bahr et al. 2007).

The present study investigates more precisely the question if a pre-treatment by ozonation would be suitable to improve the subsequent coagulation/membrane filtration process at the WWTP Ruhleben. Lab-scale tests were performed using Amicon test cells applying simultaneous monitoring of filtration performance by measuring trans-membrane flux and fouling potential by BP analysis. Furthermore, it is investigated which combination of the two processes ozonation/coagulation leads to optimal results, with the aim to find the optimal ratio of ozone dosage and coagulant concentration.

2 Material and Methods

In this project the impact of a pre-treatment by ozonation and subsequent coagulation on the performance of a polymeric ultrafiltration (UF) membrane was studied. Secondary effluent of the WWTP Ruhleben was treated with different combinations of coagulant concentration and ozone dosages. Ferric Chloride ($FeCl_3$) was used as coagulant. As shown in Table 1, two different trial series were conducted. Series 1 comprised experiments with a constant ozone dosage of 2 and 10 mg O_3/L, respectively, and a varying coagulant concentration (0-6 mg Fe^{3+}/L), whereas series 2 consisted of experiments with varying ozone dosage (0-10 mg O_3/L) and constant coagulant concentration of 2 and 6 mg Fe^{3+}/L, respectively. All trials were conducted in 2009.

Table 1: Fixed and variable parameters

Name of experiment	Ozone dosage [mg/L]	Coagulant concentration [mg/L]	Date
UF I-A	10	2, 6	02.06. *
UF I-B			08.06.
UF I-C			07.07.
UF II-A	2	2, 6	15.06.
UF II-B			30.06.
UF II-C			14.07.
UF III-A	0, 2, 4, 6, 8 und 10	2	21.07.
UF III-B			28.07.
UF IV-A	0, 2, 6 und 10	6	11.08.
UF IV-B			08.09.
UF V-A	0, 2, 6 und 10	4	15.09.
UF V-B			22.09.
UF V-C			17.11.

* not all parameters measured

Additionally to these UF filtration tests, backwash (BW) experiments have been conducted (described in chapter 2.1.4) and filtration tests with an MF membrane (described in chapter 2.1.5).

2.1.1 Jar tests

To optimise the coagulation jar tests were performed according to „technical rule DVGW W 218 (1998)“ with secondary treated effluent from WWTP Ruhleben. $FeCl_3$ was used as coagulant with a concentration of 1-6 mg Fe^{3+}/L. Two types of jar tests were conducted:

- Coagulation
- Pre-ozonation with Coagulation

During the experiments there was no variation of pH due to the high buffer capacity of the secondary treated effluent and all experiments were conducted at room temperature. The ozonated water was prepared using an ozone generator from WEDECO. The preparation was performed in a separate container by continuously bubbling ozone gas into a small volume of

distilled-deionized water. Aliquots of this ozone stock solution were drawn and injected into the jar. The volume of each aliquot to deliver a predetermined ozone dosage of 1-2 mg O_3/L to the test water in the jar had been calculated before. The addition of ozonated water was followed by a stirring period of 1.5 minutes at 100 rpm and the subsequent mixing with the coagulant $FeCl_3$. Table 2 depicts the test conditions of the coagulation with 1 - 6 mg Fe^{3+}/L in jar tests with and without pre-ozonation.

Table 2: Conditions of the coagulation in jar tests with and without pre-ozonation

Performance		Pre-ozonation and Coagulation conditions
Coagulation	Pre-ozonation and coagulation	Ozone addition: 1-2 mg O_3/L Stirring: 1.5 minutes at 100 rpm Coagulant addition: 1-6 mg Fe^{3+}/L Stirring: 30 seconds at 400 rpm 5 minutes at 60 rpm

2.1.2 Ozonation unit

Pre-ozonation and coagulation trials should also be conducted with higher ozone dosages of 10 mg O_3/L. Obtaining these ozone dosages with the help of a stock solution as described in chapter 2.1.1 would have let to an intense dilution of the sample due to the relatively huge amount of stock solution needed. Therefore preparation of samples with high ozone dosages was conducted with an ozonation unit existing since March 2009 at the TU Berlin.

As this ozonation unit is either able to produce low ozone dosages of 2 mg O_3/L or high ozone dosages of 10 mg O_3/L in Ruhleben secondary effluent and in order to achieve a good comparability of the experiments, from the end of April all ozonation steps were performed at the ozonation unit. Therefore ozonation for Amicon test cell experiments was only conducted using the ozonation unit, which is shown in Figure 1.

Figure 1: Ozonation unit

The ozonation unit produces gaseous ozone from pure oxygen using an ozone generator from WEDECO (type Modular 8HC, ITT WEDECO GmbH, Germany). The gaseous ozone provided by the ozone generator was directly introduced into the sample in a 4-L-semi-batch stirred tank reactor. An ozone mass balance according to Equation 1 was set up automatically by a computer as in-gas and off-gas ozone concentration, dissolved ozone and gas flow rate were measured continuously.

$$O_{3,consumed} = \int \left(O_{3,in-gas} - O_{3,off-gas} \right) dt - O_{3,dissolved} \qquad \textbf{Equation 1}$$

Additionally, analysis of the pH was carried out in a by-pass. Figure 2 shows an example from ozonation for filtration tests with a target ozone dosage of 10 mg O_3/L. For completion of the mass balance, the off-gas ozone was completely stripped with pure oxygen. Target ozone dosage was 2 mg O_3/L and 10 mg O_3/L, respectively, corresponding to 0.2 and 0.9 mg O_3/mg DOC. These specific ozone dosages are in the range of those used from Bahr et al. (2007), who showed a decrease in BP concentration with increasing specific ozone consumptions from 0.2 - 1.4 mg O_3/mg DOC. As a variance of factors influence the consumption of ozone in secondary effluent, aspired ozone dosages were slightly variable as an exact adjustment was not possible.

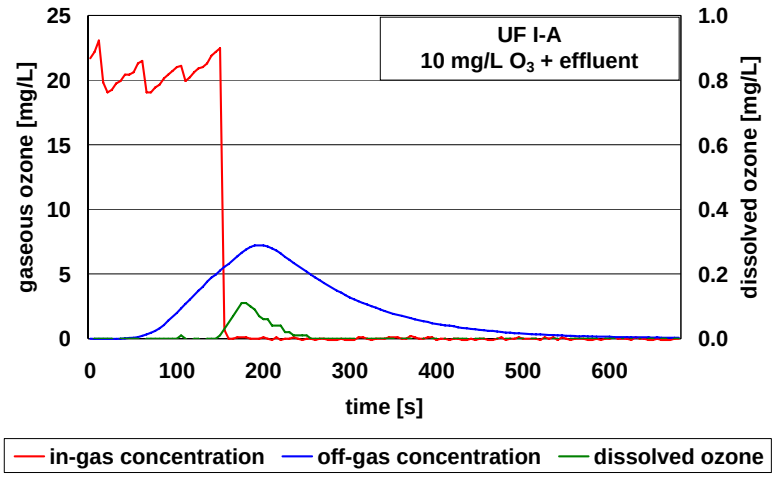

Figure 2: Ozonation of Ruhleben secondary effluent for filtration tests (2009-06-02)

Depending on water quality and the target ozone dosage, ozone input lasted about 5 - 15 minutes and was carried out at 360 rotations per minute (rpm). Free dissolved ozone was only detectable in small amounts up to 0.2 mg O_3/L during trials with pre-ozonation dosages of 10 mg O_3/L and high in-gas ozone concentrations of approximately 20 mg O_3/L. By application of lower in-gas ozone concentrations of approximately 12 mg O_3/L no free dissolved ozone was detectable. Coagulation with $FeCl_3$ was conducted according to „technical rule DVGW W 218“ with secondary treated effluent from WWTP Ruhleben except the volume of the beaker, which was 4 L instead of 2 L. Direct addition of $FeCl_3$ into the 4-L-semi-batch stirred tank reactor was followed by a stirring period of 30 seconds at 360 rpm with subsequent stirring at 60 rpm for 5 minutes.

2.1.3 Filtration tests

Amicon dead-end test cells (stirred ultrafiltration cell, model 8200, Millipore Corporation, USA) with a volume of 200 ml and an effective membrane filtration area of 28.7 cm² were used to determine the fouling potential as flux decline over time. The attached feed reservoir permits filtration of samples up to 4 L. The sample is filled into the water reservoir and pressurized using nitrogen gas. Slowly stirring prevents the flocs from settling. Membrane flux is measured by collecting permeate in a beaker on an electric balance which is connected with a computer. Thus change in weight is measured over time. Flux decline results from the stirred cell experiments are shown as normalized flux J/J_0 over permeate volume. J_0 is the pure water flux and J the permeate flux. This presentation allows for a better comparison of different flux decline curves, i.e. all curves start at $J/J_0=1$. A schematic set-up of the Amicon test cell trials is illustrated in Figure 3.

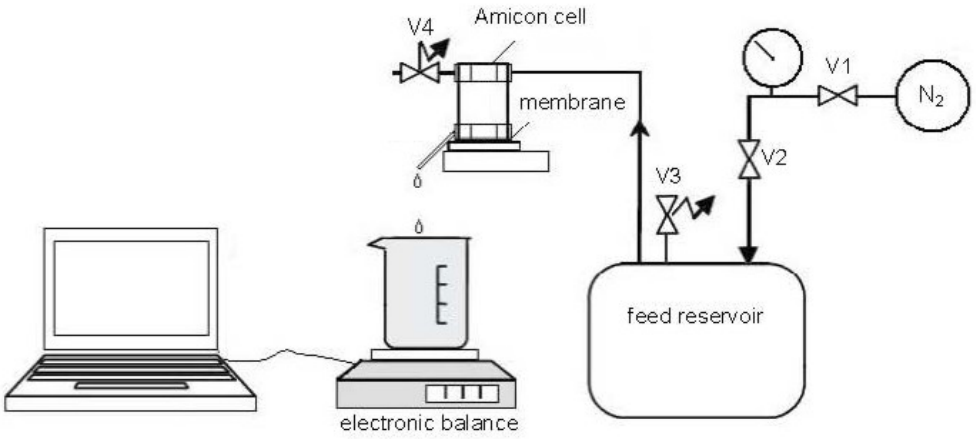

Figure 3: Schematic set-up for trials with the Amicon test cell (adapted from Zheng (2010))

Amicon test cells were fed in dead-end mode with 500 ml sample. The membrane is fixed at the bottom of the Amicon test cell. For all trials a NADIR® UP150 ultrafiltration membrane (MICRODYN-NADIR GmbH, Germany) was used. This UF-membrane is made of permanent hydrophilized polyethersulphone (PES) and has a molecular weight cut off (MWCO) of 150 kDa corresponding to a pore size of 26 nm. Each filtration test was performed using a new membrane. Prior to the experiments, each membrane was washed by a leaching procedure. Membranes were soaked in pure water for at least 24 h and subsequently filtrated with 2 L pure water in order to remove wetting agents and production residues and to reach a stable permeate flux under 1 bar. 100 ml of pure water are filtered through the membrane immediately before the experiment for determining the pure water flux J_0 of the membrane. As during the experiments, flux is recorded with the help of a balance that is connected with a computer. For each filtration trial only membranes within a 20 % variation of pure water flux were applied. Pre-treated Ruhleben secondary effluent was filled into the feed reservoir and a constant pressure of 1 bar was applied. All experiments are run at room temperature (approximately 22°C) and constant pressure (1 bar). Figure 4 shows the Amicon test cell set-up in the laboratory at the TU Berlin.

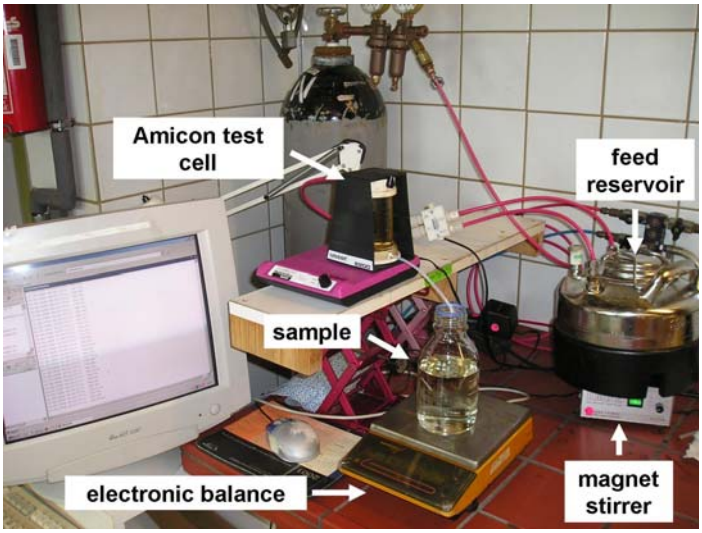

Figure 4: Set-up for trials with the Amicon test cell

2.1.4 Backwash trials

UF backwash (BW) experiments were performed to study fouling of differently treated Ruhleben effluent. Coagulated samples were again compared to samples treated with a combination of pre-ozonation and subsequent coagulation. Three different trial series of BW experiments were conducted and are displayed in Table 3. The concentrations used were 0 and 4 mg Fe^{3+}/L and pre-ozonation was either conducted with 0, 2 or 6 mg O_3/L. The preparation of the membrane was performed as described by Jermann et al. (2008) and Zheng et al. (2009). Deviant from these procedures pressure was always 1 bar and the number of filtration cycles amounted to five instead of the descried three cycles. Before each trial pre-treatment of the membrane and determination of pure water flux were performed as described in chapter 2.1.3. Each cycle 500 ml permeate were generated. Afterward the membrane was backwashed using 50 ml of the previously generated permeate. Additionally, prior to every cycle membrane flux was assessed with 100 ml of pure water. Parameters measured were the same as for the filtration tests shown in Table 5, except for turbidity < 1 µm. Samples were taken from the effluent, treated effluent, permeate after 1st, 3rd and 5th cycle. Additionally samples from the BW water were withdrawn after every 1st, 3rd and 5th cycle for LC-OCD analysis.

Table 3: Trial series of the backwash experiments

Name of experiment	Ozone dosage [mg/L]	Coagulant concentration [mg/L]	Date
BW I-A	0	0	29.09.2009
BW I-B	6	4	
BW I-C	0	0	06.10.2009
BW I-D	6	4	
BW II-A	0	4	14.10.2009
BW II-B	6		
BW II-C	0	4	21.10.2009
BW II-D	6		
BW III-A	0	4	27.10.2009
BW III-B	2		
BW III-C	6		
BW III-D	0	4	28.10.2009
BW III-E	2		
BW III-F	6		
BW III-G	10		

2.1.5 Microfiltration (MF) tests

Filtration tests with a MF-membrane were conducted using the same experimental set-up as described for UF tests in chapter 2.1.3. For these trials a NADIR® MV020 MF-membrane (MICRODYN-NADIR GmbH, Germany) made of polyvinylidene fluoride (PVDF) with a nominal pore size of 0.2 µm was used. In order to work with comparable permeate flowrates as in the UF tests, the theoretically needed pressure for these MF experiments was calculated (annex, chapter 6.1). Hence, the initial pressure for the MF-trials was 0.2 bar. Filtration of Ruhleben effluent and Ruhleben effluent treated with 4 mg Fe^{3+}/L took about 4 hours for the generation of 500 ml permeate. This was approximately four times longer than with the UF-membrane and an applied pressure of 1 bar and made a realisation of the experiments during one day unfeasible. Thus trial with higher pressures of 0.5 and 0.7 bar, respectively were conducted. All trial series conducted with the MF-membrane are listed in Table 4.

Table 4: Trial series of the MF tests

Name of experiment	Pressure [bar]	Ozone dosage [mg/L]	Coagulant concentration [mg/L]	Date
MF I-A	0,2	0	0,4	20.10.2009
MF I-B	0,5	0	0	
		0	4	
		6	4	
MF I-C	0,7	0	0,4	

2.2 Analytics

The sum parameters Ultraviolet Absorbance at 254 nm (UVA 254), Absorbance at 436 nm (Colour 436), Dissolved Organic Carbon (DOC), Dissolved Chemical Oxygen Demand (COD_f), Turbidity and Turbidity < 1 µm were determined. The effect of the two pre-treatment steps on the character of DOC, especially the BP fraction, was investigated by use of size

exclusion chromatography (Liquid Chromatography – Organic Carbon Detection (LC-OCD)). Additionally to these parameters phosphate, total soluble phosphorus and residual iron concentration were measured. The standard parameters temperature, pH and electric conductivity were also determined. Table 5 shows all measured parameters with their corresponding pre-filtration through a cellulose nitrate filter.

Table 5: Examined parameters

Parameter	Filtered through
Temperature	-
pH	-
Electric Conductivity	-
Ultraviolet Absorbance at 254 nm (UVA 254)	0.45 µm
Absorbance at 436 nm (Colour 436)	0.45 µm
Dissolved Chemical Oxygen Demand (COD_f)	0.45 µm
Dissolved Organic Carbon (DOC)	0.45 µm
Liquid Chromatography – Organic Carbon Detection (LC-OCD)	0.45 µm
Turbidity < 1µm	1.00 µm
Phosphate (PO_4-P)	0.45 µm
Total Soluble Phosphorus ($P_{T,f}$)	0.45 µm
Residual Iron Concentration	0.45 µm

UVA 254 and Colour 436 were measured with a photometer (Lambda 12, Perkin-Elmer, Germany). COD_f analysis was performed with the help of COD Cuvette Tests (LCK 414 COD, HACH LANGE GmbH, Germany). DOC was determined according to DIN EN 1484 (Water analysis – Guidelines for the determination of total organic carbon (TOC) and dissolved organic carbon (DOC); German version EN 1484: 1997) using a HighTOC analyser (Elementar, Germany). LC-OCD analysis was performed utilizing a system of the DOC-Laboratory Dr. Huber (Germany) that quantitatively distinguishes between different fractions of DOC. Turbidity < 1 µm was analysed according to DIN EN ISO 7027. The turbidimeter (Turbidimeter 2100N, HACH LANGE GmbH, Germany) is calibrated with the help of formazine standards and turbidity is directly readable in NTU (Nephelometric Turbidity Unit). Flow injection analysis (FIAstar 5000, FOSS, Germany) was used to analyse phosphate and total soluble phosphorus. Determination of residual iron was realized by atomic absorption spectroscopy (Atomic Absorption, Spectrometer SpectrAA400, Graphite Tube Atomizer GTA 96, Varian Deutschland GmbH, Germany).

2.2.1 Turbidity < 1 µm

As colloids between 10 - 450 nm are known to be exceptionally responsible for membrane fouling, a closer look on these small colloids is obtained by a 1 µm filtration. Figure 5 depicts the steel filter, which is used for the preparation of 1 µm samples for the turbidity measurement. This special filter is used, because it allows filtration without formation of a cake layer, which would prevent particles even smaller than 1 µm from merging into the permeate. The steel filter is wrapped with an aquarium tube (left picture in Figure 5). Compressed air, coming out of this aquarium tube, creates bubbles, which enclose the filter and prevent the formation of a cake layer.

Figure 5: Steel filter used for the 1 µm filtration

3 Results

3.1 Filtration Tests

Diagrams in this chapter are chosen exemplarily and represent typical results of the corresponding trial series. Data of all parameters and trial series are listed in the annex (chapter 6.3). Additionally, all diagrams of flux decline curves, BW trials and BP peaks of the LC-OCD analysis are shown in chapter 6.2.2 and chapter 6.2.4. For a better overview, the annex contains also diagrams of the parameters turbidity < 1 µm (chapter 6.2.7) and residual iron (chapter 6.2.6), as they were not consistent during all trial series. Diagrams of the ozonation unit showing the in-gas, off-gas and dissolved ozone concentration are depicted in chapter 6.2.1. Diagrams for BW trials are exemplarily shown in the corresponding sections of chapter 6.2.

In most of the diagrams bars of a distinct colour present samples after application of 0-6 mg Fe^{3+}/L and corresponding samples with additional pre-ozonation are shown as striped bars of the same colour. Different shades of a distinct colour of plain-coloured and striped bars, respectively, indicate the time of sample drawing. Samples drawn before UF are shown in a more intense shade of colour than samples drawn after UF.

Results of data after UF for COD_f, DOC, UVA 254 and Colour 436 were only a few percentage points below those after 0.45 µm filtration. This deviation is in the range of measuring inaccuracy Therefore only samples after 0.45 µm filtration were taken into consideration for calculation of elimination rates.

3.1.1 Flux decline and filtration time

Flux decline results from Amicon filtration tests are shown as normalized flux J/J_0 over permeate volume. J_0 represents the pure water flux, whereas J is the measured flux. This presentation allows for a better comparison of different flux decline curves, as all curves start at $J/J_0=1$. In each experiment 500 ml treated or untreated Ruhleben effluent has been filtered. Flux decline curves of samples treated without pre-ozonation are depicted in red (0 mg Fe^{3+}/L), orange (2 mg Fe^{3+}/L) and yellow (6 mg Fe^{3+}/L), whereas corresponding samples pre-treated with ozone are displayed in different shades of green. Average flux decline for untreated Ruhleben effluent after filtration of 500 ml was 90 %.

In Figure 6 flux decline curves of trial series with a constant pre-ozonation dosage of 2 mg O_3/L (Figure 6b) and 10 mg O_3/L (Figure 6a), respectively, and two coagulant concentrations (2 and 6 mg Fe^{3+}/L) are presented. Pre-ozonation without subsequent coagulation results in a slight flux increase of 2 % applying 2 mg O_3/L and leads to a maximum flux increase of 3 % with an application of 10 mg O_3/L (Figure 6a). The effect of coagulation exceeds the effect of pre-ozonation clearly. Both trials reveal a remarkable flux increase of approximately 10 % with coagulant concentrations of 2 mg Fe^{3+}/L, whereas application of higher coagulant concentrations of 6 mg Fe^{3+}/L lead only to an additional slight flux increase of 3 %. Application of ozone raises the flux additionally. This effect is hardly detectable with low ozone dosages of 2 mg O_3/L (Figure 6b) but clearly visible with high

ozone dosages of 10 mg O_3/L (Figure 6a) resulting in an additional flux increase of 6 % with the application of 6 mg Fe^{3+}/L. Application of 10 mg O_3/L and subsequent coagulation with 6 mg Fe^{3+}/L results in the maximum flux increase of 20 % compared to the untreated Ruhleben effluent.

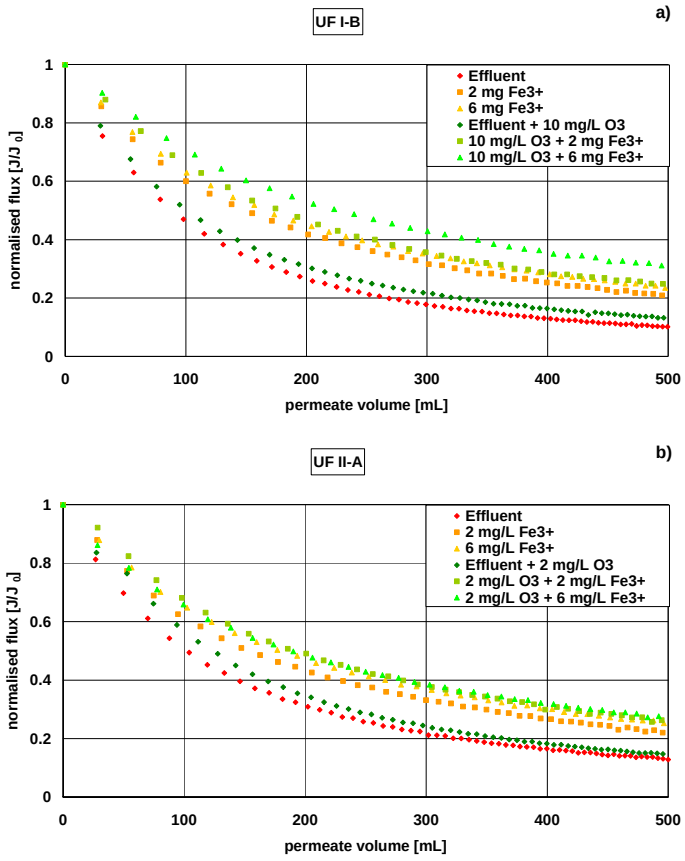

Figure 6: Flux decline curves for different coagulant dosages of 0-6 mg Fe^{3+}/L with and without pre-ozonation (Figure 6a: 10 mg O_3/L, Figure 6b: 2 mg O_3/L)

As visible in Figure 7 flux decline decreases significantly with application of $FeCl_3$, and, as it had been in previous trial series described in Figure 6, higher coagulant concentrations of 6 mg Fe^{3+}/L (Figure 7b) again result in a comparable higher flux of 12 %. Combining pre-ozonation and coagulation improves the filtration performance and becomes apparent due to the additional higher flux. This synergetic effect deriving from both treatment steps, pre-ozonation and coagulation, increases with the concentration of the applied coagulant. Application of 2 mg Fe^{3+}/L results in a successive flux increase of 2 %, whereas coagulation with 6 mg Fe^{3+}/L leads to a stepwise increase of 3 % in flux. Thus, maximum flux after filtration of 500 ml effluent is achieved with 10 mg O_3/L pre-ozonation and subsequent coagulation with 6 mg Fe^{3+}/L (Figure 7b). This corresponds to an improvement in flux at the end of the experiment of 20 % compared with the effluent without pre-treatment and 9 % compared to the coagulated sample. This maximum flux increase is equal to the maximum flux improvement of trial UF I- B (Figure 6a), conducted under the same conditions (10 mg O_3/L and 6 mg Fe^{3+}/L). Oxidation effects on the surface of the membrane can be excluded as in none of the samples free dissolved ozone was present after the pre-ozonation step, as the off-gas ozone was completely stripped with pure oxygen.

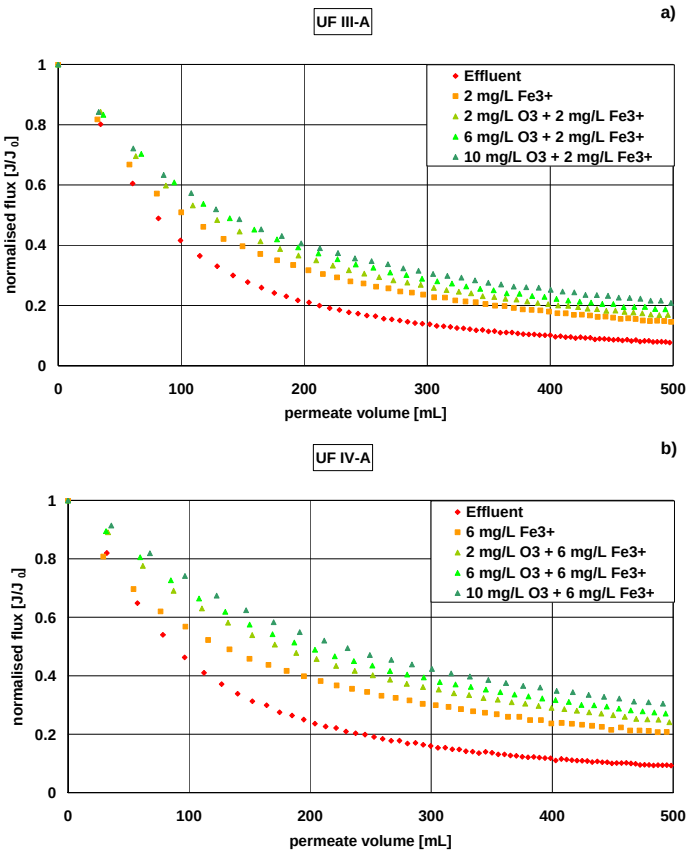

Figure 7: Flux decline curves for different ozone dosages of 0-10 mg O_3/L and a constant $FeCl_3$ addition of 2 mg Fe^{3+}/L (Figure 7a) and 6 mg Fe^{3+}/L (Figure 7b)

Increase of filtration performance and especially the positive effect of pre-ozonation become even more considerable in Figure 8 showing the filtration times needed for each sample corresponding to both trials of Figure 7. A combination of 10 mg O_3/L and subsequent coagulation with 2 mg Fe^{3+}/L diminishes the filtration time needed for 500 ml Ruhleben effluent by 51 % compared with the effluent without pre-treatment (Figure 8a), whereas filtration time is reduced by 61 % applying the same pre-ozonation dosage followed by a coagulation with 6 mg Fe^{3+}/L (Figure 8b). Comparing coagulated samples and samples treated with a combination of pre-ozonation and subsequent coagulation, filtration time is reduced by a maximum of 28 % (2 mg Fe^{3+}/L) and 33 % (6 mg Fe^{3+}/L), respectively, compared to the flux of the coagulated sample (ozone effect alone).

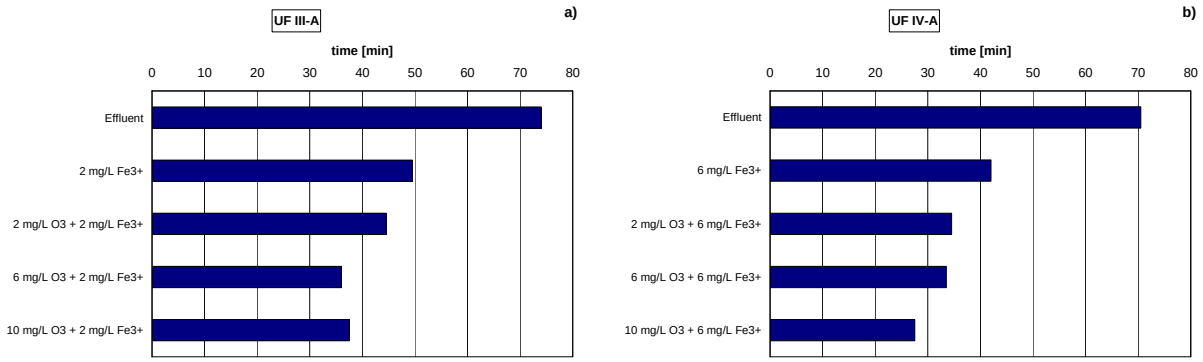

Figure 8: Filtration times for different ozone dosages of 0-10 mg O_3/L and a constant coagulant addition of 2 mg Fe^{3+}/L (Figure 8a) and 6 mg Fe^{3+}/L (Figure 8b)

Conclusion:

- ⇨ Pre-ozonation without subsequent coagulation results in a slight flux increase of approximately 2 %, independent on ozone dosage.
- ⇨ Coagulation with 2 mg Fe^{3+}/L (6 mg Fe^{3+}/L) increases the flux by 10 % (13 %) and minimizes filtration time by 33 % (40 %).
- ⇨ Pre-ozonation raises the flux additionally. This effect is hardly detectable with low ozone dosages of 2 mg O_3/L but application of 10 mg O_3/L results in an additional significant flux increase of approximately 6 %.
- ⇨ Combination of pre-ozonation with 10 mg O_3/L and subsequent coagulation with 2 mg Fe^{3+}/L (6 mg Fe^{3+}/L) leads to a decrease in filtration time of 51 % (61 %) compared to the effluent without pre-treatment, whereas a comparison with the coagulated effluent results in decreasing filtration times of 28 % (2 mg Fe^{3+}/L) and 33 % (6 mg Fe^{3+}/L), respectively, compared to the flux of the coagulated sample.
- ⇨ Maximal flux increase of 20 % (9 %) after filtration of 500 ml is achieved with an ozone dosage of 10 mg O_3/L and subsequent coagulation with 6 mg Fe^{3+}/L in comparison with the effluent without pre-treatment (coagulated effluent).
- ⇨ The synergetic effect deriving from a combination of pre-ozonation and coagulation increases with the concentration of the applied coagulant.

3.1.2 Total Soluble Phosphorus ($P_{T,f}$)

Effluent concentrations of Total Phosphorus (P_T) varied during the whole project between 188 µg P/L and 763 µg P/L. Average concentration of P_T was 338 ± 175 µg/L. Diagrams in Figure 9 and Figure 10 only show Total Soluble Phosphorus ($P_{T,f}$) data as UF totally retains the fraction of particulate phosphorus. Therefore only $P_{T,f}$ is discussed. Error bars in these Figures are plotted but are invisible because of their small size. Average $P_{T,f}$ concentrations of the effluent without pre-treatment amounted to 126 ± 50 µg P/L. For all trials the average concentration of phosphate (PO_4-P) was 76 ± 41 µg P/L. An overview of all PO_4-P data measured is given in the annex (chapter 6.3.2).

$P_{T,f}$ data of trials with varying coagulant concentration and fixed ozone dosages are shown in Figure 9. There is no significant impact of ozonation on the concentration of $P_{T,f}$ visible, but coagulation leads to a decline in the amount of $P_{T,f}$. Application of 2 mg Fe^{3+}/L leads to an average $P_{T,f}$ concentration of 46 ± 9 µg P/L, whereas 6 mg Fe^{3+}/L result in an additional reduction of $P_{T,f}$ concentration and average values of 36 ± 6 µg P/L were obtained.

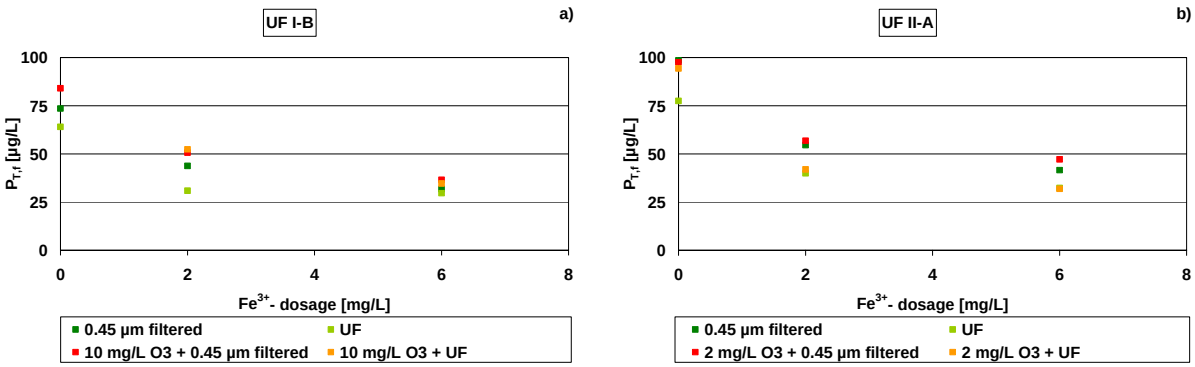

Figure 9: Phosphorus concentrations of Ruhleben effluent after 0.45 µm filtration and after UF for different Fe^{3+}-concentrations of 0 - 6 mg Fe^{3+}/L with 2 mg O_3/L (Figure 9b) and 10 mg O_3/L (Figure 9a) pre-ozonation

In Figure 10 results for $P_{T,f}$ concentrations of trials with a varying ozone dosage of 0-10 mg O_3/L and a fixed coagulant concentration of 2 mg Fe^{3+}/L (Figure 10a) and 6 mg Fe^{3+}/L (Figure 10b) are displayed. As in Figure 9 no significant effect of pre-ozonation is visible. Samples of the permeate seem to be a little lower in general during trial series UF II-A, but in Figure 10b showing trial series UF IV A this effect seems negligible. Pre-treatment with different ozone dosages and a coagulant concentration of 2 mg Fe^{3+}/L lead to an average $P_{T,f}$ concentration after UF of 52 ± 4 µg P/L (Figure 10a). An increase of coagulant concentration to 6 mg Fe^{3+}/L results in a lower average $P_{T,f}$ concentration after UF of approximately 41 ± 6 µg P/L. Compared to corresponding $P_{T,f}$ concentrations illustrated in Figure 9 during these trials a slightly minor reduction in $P_{T,f}$ is observed.

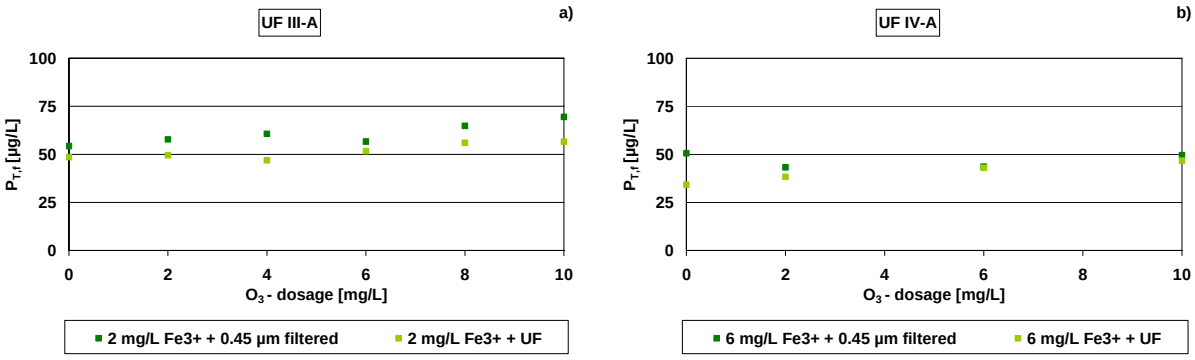

Figure 10: Phosphorus concentrations of Ruhleben effluent after 0.45 µm filtration and after UF for Fe^{3+}-concentrations of 2 mg Fe^{3+}/L (Figure 10 a) and 6 mg Fe^{3+}/L (Figure 10b) and ozone dosages of 0-10 mg O_3/L

A diagram of $P_{T,f}$ concentrations in the permeate against $P_{T,f}$ concentrations in the effluent for different coagulant concentrations of 2, 4 and 6 mg Fe^{3+}/L is depicted in Figure 11. It is clearly visible that in approximately 80 % of the data points coagulant concentrations of 2 mg Fe^{3+}/L result in phosphorus concentrations < 60 µg P/L. An increase in coagulant concentration to 4 mg Fe^{3+}/L leads to a reduction in $P_{T,f}$ of concentrations < 50 µg P/L. Application of higher coagulant concentrations (4 mg Fe^{3+}/L) does not lead to a further reduction in concentrations of $P_{T,f}$.

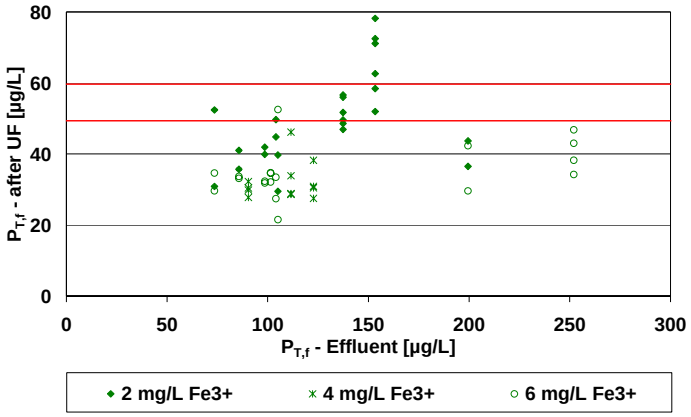

Figure 11: $P_{T,f}$ concentration in the permeate against $P_{T,f}$ concentrations in the effluent for different coagulant concentrations

Conclusion:

- ⇨ 2 mg Fe^{3+}/L leads to a concentration < 60 µg P/L.
- ⇨ Application of 4 mg Fe^{3+}/L reduces $P_{T,f}$ to a concentration < 50 µg P/L.
- ⇨ Coagulant concentrations > 4 mg Fe^{3+}/L do not result in an additional significant reduction of $P_{T,f}$ concentrations.
- ⇨ These findings are independent of pre-ozonation.

3.1.3 Liquid Chromatography – Organic Carbon Detection (LC-OCD)

A typical LC-OCD diagram is illustrated in Figure 12. It derives from an experiment with varying pre-ozonation dosage from 0-10 mg O_3/L and a fixed coagulant concentration of 2 mg Fe^{3+}/L. This diagram shows a decrease in BP concentration and an increase of the humic substances peak. Ruhleben effluent is always depicted as a black line and coagulated samples as red lines. In Figure 12 to Figure 16 blue and green lines represent samples treated with ozone.

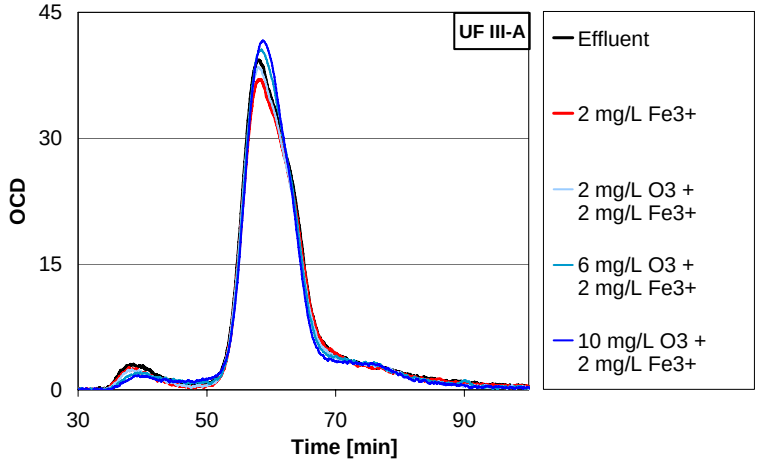

Figure 12: LC-OCD diagram of Ruhleben secondary treated effluent with ozone dosages of 0-10 mg O_3/L and a fixed coagulant concentration of 2 mg Fe^{3+}/L

As BP are known as main foulants during UF, Figure 13 to Figure 16 reveal a closer look at the BP fraction, eluting approximately between 33 and 48 minutes. BP peaks before UF are depicted in Figure 13a to Figure 16a, whereas Figure 13b to Figure 16b show BP peaks after UF.

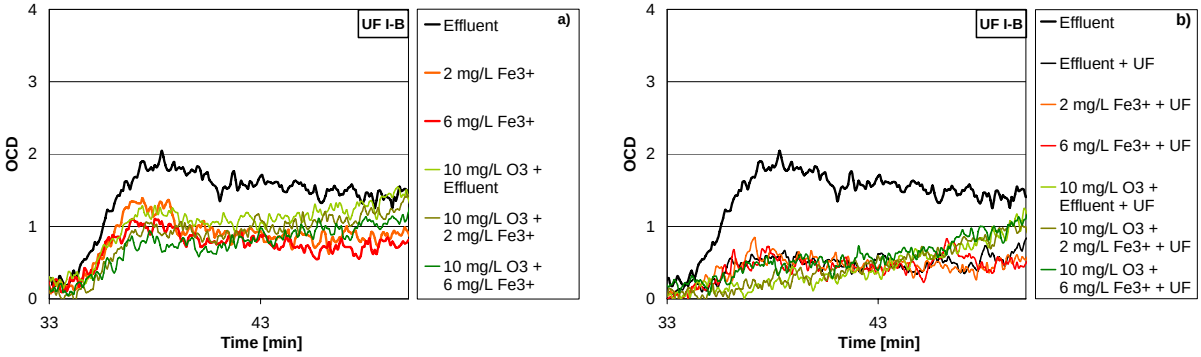

Figure 13: Biopolymer peak of Ruhleben secondary treated effluent analysed by LC-OCD with coagulant concentrations from 0 - 6 mg Fe^{3+}/L and an ozone dosage of 10 mg O_3/L before (Figure 13a) and after UF (Figure 13b)

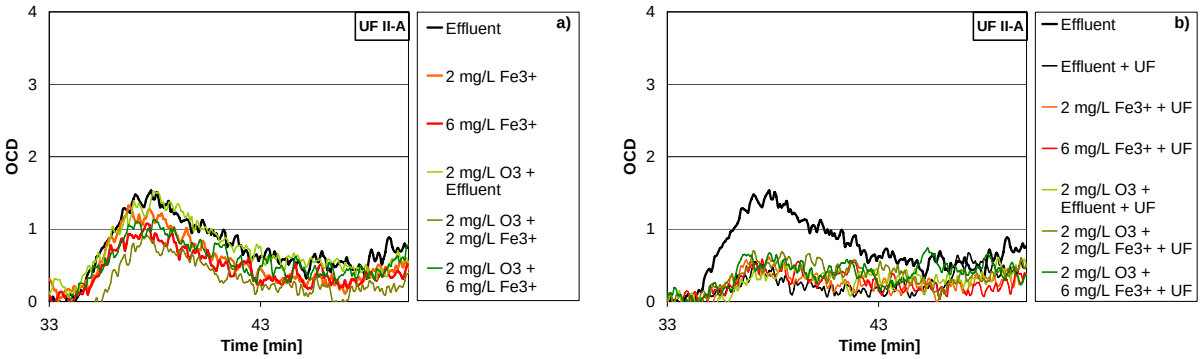

Figure 14: Biopolymer peak of Ruhleben secondary treated effluent analysed by LC-OCD with coagulant concentrations from 0 - 6 mg Fe^{3+}/L and an ozone dosage of 2 mg O_3/L before (Figure 14a) and after UF (Figure 14b)

Figure 13 and Figure 14 show BP peaks from trials with a constant ozone dosage of 2 and 10 mg O_3/L, respectively, and two different coagulant concentrations (2 and 6 mg Fe^{3+}/L). In both trials the BP peak representing the amount of BP in this sample, decreases with increasing dosage of $FeCl_3$. As visible in Figure 13a increasing the ozone dosage results in a further decline in the amount of BP eluting with the main BP peak around 38 minutes. Green lines, representing the ozonated samples, are always located below the corresponding sample without pre-ozonation (black and red lines). Simultaneously, ozonation with high ozone dosages of up to 10 mg O_3/L leads to a significant increase of BP with a smaller size, eluting around the 48 minutes (Figure 13a, green lines). The same increase is observed for the permeate. Green lines representing ozonated samples in the permeate with an elution time of approximately 48 minutes are clearly located above none ozonated permeate samples (black and red lines). As a shift to smaller BP is observed, ozone seems to transform BP to smaller BP fragments with longer retention times. In contrast to a change in the amount of BP another possibility is a change in the amount of BP that is detected by LC-OCD due to high ozone dosages. No conclusion can be drawn for the BP fraction of the samples treated with 2 mg O_3/L (Figure 14b), as there is no significant change in the BP peaks after pre-ozonation.

In general it is worth mentioning, that amounts of BP where relatively low during these trial series.

In Figure 15 and Figure 16 results for the BP fraction of Ruhleben secondary treated effluent with coagulant concentrations of 2 mg Fe^{3+}/L (Figure 15) and 6 mg Fe^{3+}/L (Figure 16) and different ozone dosages (0-10 mg O_3/L) before and after UF are presented. Black lines again represent the effluent without pre-treatment, red lines the coagulated effluent and the set of blue lines stands for pre-ozonated samples.

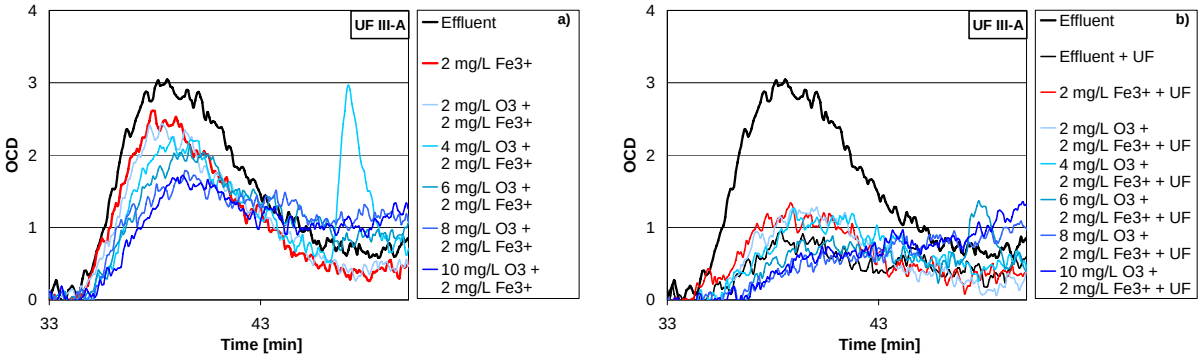

Figure 15: Biopolymer peak of Ruhleben secondary treated effluent analysed by LC-OCD with a coagulant concentration of 2 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) before (Figure 15a)and after UF (Figure 15b)

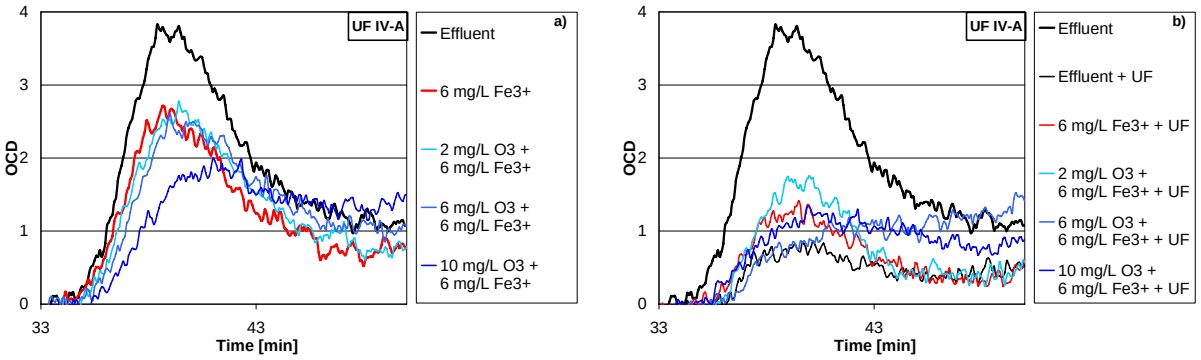

Figure 16: Biopolymer peak of Ruhleben secondary treated effluent analysed by LC-OCD with a coagulant concentration of 6 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) before (Figure 16a) and after UF (Figure 16b)

The BP fractions illustrated in Figure 15 and Figure 16 show a significant decrease for the samples only treated with coagulant. This removal in the amount of BP increases with increasing coagulant concentration from 2 mg Fe^{3+}/L (Figure 15a, red line) to 6 mg Fe^{3+}/L (Figure 16a, red line). A further decrease in the amount of BP and a shift to smaller molecules is observed with increasing dosage of ozone. This effect is more distinct with low coagulant concentrations (Figure 15a, 2 mg Fe^{3+}/L). There is an overall change in the quantity of BP as the amount of BP eluting with the main BP peak around 38 minutes decreases clearly, whereas the amount of BP eluting around 48 minutes only increases slightly. These findings, equally to the results of Figure 13a, indicate a change in the structure as the amount of smaller BP increases. This increase is also observed for the samples after UF. Hence these smaller BP are not retained by the UF. In contrast, the amount of BP eluting around 38 minutes (higher molecular size) decreases significantly after UF. Thus this BP fraction is to a great extent retained by the UF leading to a decline in flux.

Conclusion:

- ⇨ The amount of BP decreases significantly after application of coagulant. This effect increases with increasing coagulant concentration.
- ⇨ Pre-ozonation has two effects on BP:
  - o Decrease in the amount of BP eluting with the main peak around 38 minutes. This effect is more distinctive with low coagulant concentrations and increases with increasing ozone dosages.
  - o High ozone dosages result in a shift to smaller molecules, which do not contribute to membrane fouling.
  - → These effects either result from fragmentation of BP molecules or the detectable amount of BP changes due to pre-ozonation.

3.1.4 Dissolved Organic Carbon (DOC)

DOC varied slightly during the project and was 10.9 ± 0.8 mg/L. A slight decrease of DOC due to coagulation can be observed in Figure 17 as well as in Figure 18. Coagulation with 6 mg Fe^{3+}/L leads to a maximum reduction of 10 % (Figure 17b), corresponding to a minimum DOC concentration of 9.1 mg/L. Increases of DOC in experiments with pre-ozonation can be explained with dissolving of particulate organic carbon due to ozonation.

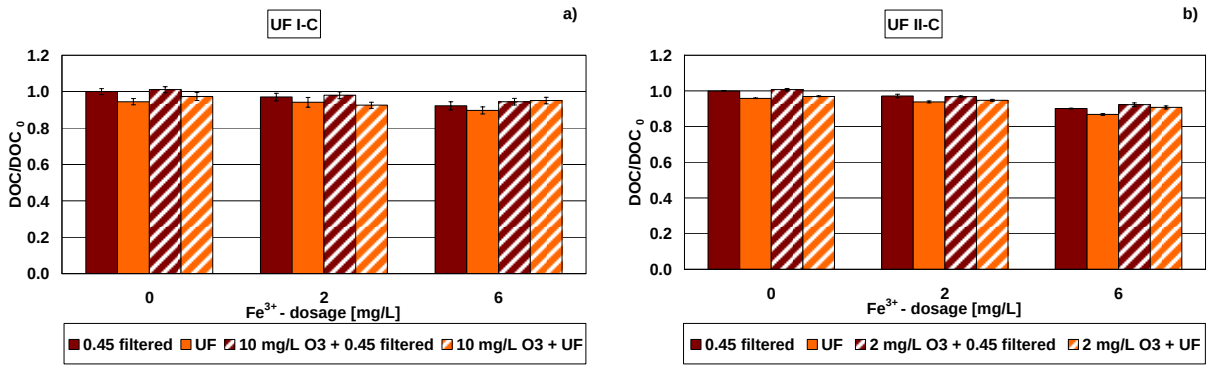

Figure 17: Relative DOC concentration for different coagulant dosages of 0-6 mg Fe^{3+}/L with and without pre-ozonation (Figure 17a: 2 mg O_3/L, DOC_0: 9.8 mg/L; Figure 17b: 10 mg O_3/L, DOC_0: 10.1 mg/L)

Figure 18 shows the results for a varying ozone dosage (0-10 mg O_3/L) and a constant $FeCl_3$ concentration of 2 and 6 mg Fe^{3+}/L, respectively. It is clearly visible, that pre-ozonation has no effect on the removal of DOC. Coagulation with 2 mg Fe^{3+}/L results in an average reduction of 2 % DOC (Figure 13a) whereas 6 mg Fe^{3+}/L decrease DOC by 6 % (Figure 13b).

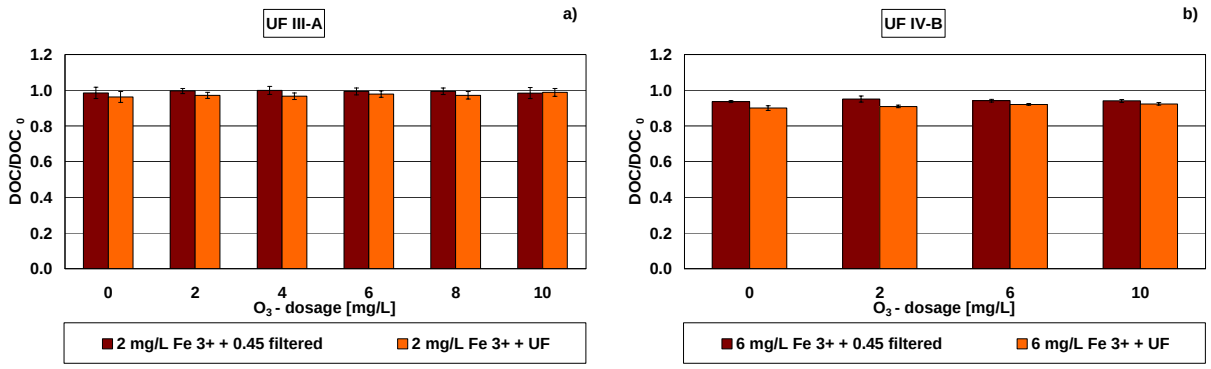

Figure 18: Relative DOC concentration for different ozone dosages of 0-10 mg O_3/L and a constant $FeCl_3$ addition of 2 mg Fe^{3+}/L (Figure 18a, DOC_0: 9.7 mg/L) and 6 mg Fe^{3+}/L (Figure 18b, DOC_0: 10.9 mg/L)

3.1.5 Residual Iron

Results of residual iron concentrations after 0.45 µm filtration and after UF are presented in Figure 19 and Figure 20. Ozone dosage is fixed in trials presented in Figure 19 and coagulant concentrations vary, whereas during the experiments shown in Figure 20 ozone dosages vary and coagulant concentrations are fixed. Initial residual iron concentrations of the untreated Ruhleben effluent after 0.45 µm filtration were 24.9 ± 3.6 µg/L during trial series UF I and UF II, whereas a higher initial residual iron concentration after 0.45µm filtration of 41.2 ± 1.2 µg/L was measured during trial series UF III and UF IV.

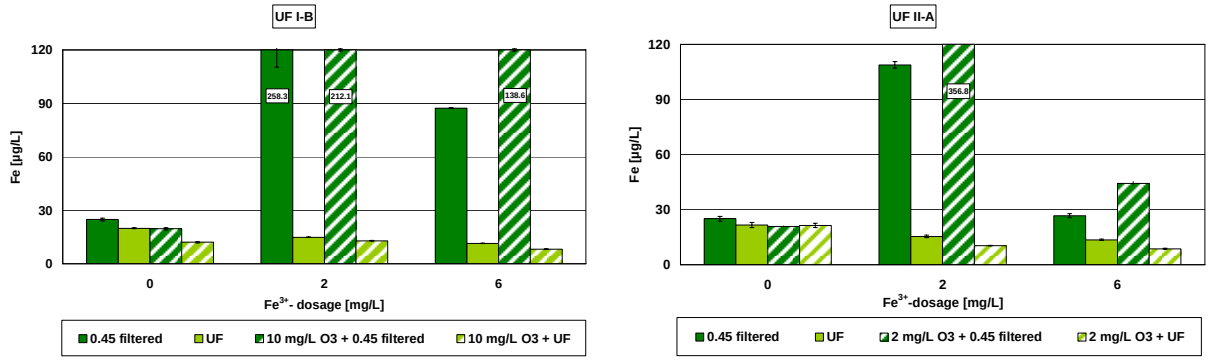

Figure 19: Residual iron concentrations of Ruhleben effluent after 0.45 µm filtration and after UF for different Fe^{3+}-concentrations of 0 - 6 mg Fe^{3+}/L with pre-ozonation dosages of 2 mg O_3/L (UF II-A) and 10 mg O_3/L (UF I-B)

Concentrations for residual iron after 0.45 µm filtration increase with the application of $FeCl_3$ (Figure 19). This increase is higher with 2 mg Fe^{3+}/L than with 6 mg Fe^{3+}/L resulting in a maximum residual iron concentration of 258 µg/L (Figure 19a). Independent on the applied ozone dosage and despite of the huge variability in residual iron concentrations after 0.45 µm filtration an additional increase in residual iron concentrations is observed predominantly after pre-ozonation. This increase in colloidal iron comes to a maximum concentration of 357 µg/L after pre-ozonation with 2 mg O_3/L and subsequent coagulation with 2 mg Fe^{3+}/L (Figure 19b). Thus it comes to a filtering function of the UF-membrane due to the increased colloidal iron making the cake layer more dense and an increase in flux decline. Most probably in samples with pre-ozonation organo-metal-complexes are formed which can not contribute to the process of coagulation any more. In trial series UF I-B depicted in Figure 19a the quantity of iron that is not available for the process of coagulation due to pre-ozonation amounts to

11 % for coagulation with 2 mg Fe^{3+}/L and 2 % for coagulation with 6 mg Fe^{3+}/L. Hence, with the application of low $FeCl_3$ concentrations of 2 mg Fe^{3+}/L the percentage of coagulant that is lost for the process of coagulation is significant. As the percentage of formed organo-metal-complexes decreases with increasing iron dosage, the synergetic effect of pre-ozonation and coagulation on the filtration performance also increases with increasing coagulant concentration. After UF residual iron concentration is always low, even lower than in the effluent without pre-treatment. The average concentration of residual iron in trial UF I-B and UF II-A after UF was 14.2 ± 4.6 µg/L.

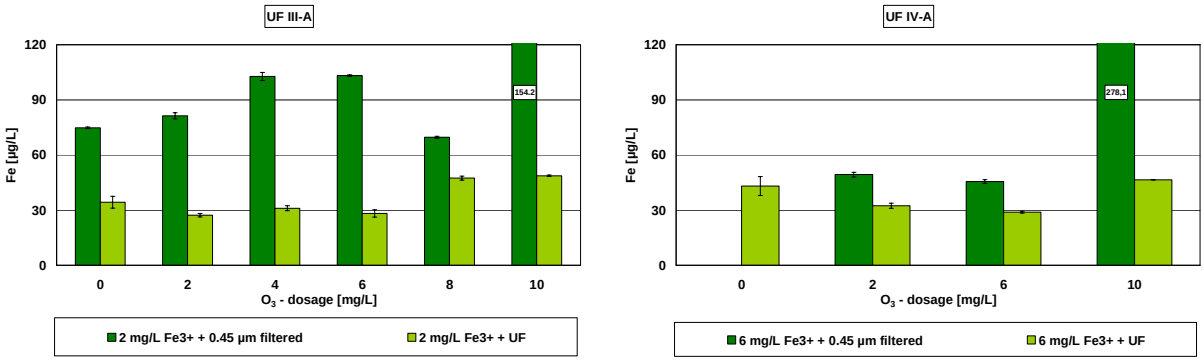

Figure 20: Residual iron concentrations of Ruhleben effluent after 0.45 µm filtration and after UF for Fe^{3+}-concentrations of 2 mg Fe^{3+}/L (UF III-A) and 6 mg Fe^{3+}/L (UF IV-A) and ozone dosages of 0-10 mg O_3/L

In Figure 20 there is no distinct effect of pre-ozonation with different ozone dosages visible. Results of these trials show again that lower dosages of $FeCl_3$ lead to higher concentrations of residual iron. Diagrams of all trial series conducted are displayed in the annex (chapter 6.2.6). Considering results of all trials, in most of the cases residual iron concentration increases with increasing ozone dosage.

Conclusion:

- ⇨ Concentrations of residual iron (0.45 µm filtrate) increase with the application of $FeCl_3$. This increase is higher with low coagulant concentrations of 2 mg Fe^{3+}/L than with 6 mg Fe^{3+}/L.
- ⇨ Pre-ozonation in combination with coagulation causes increased residual iron concentrations most probably due to complexation.
- ⇨ Residual iron concentration after 0.45 µm filtration showed a tendency to increases with ozone dosage.
- ⇨ 10 mg O_3/L (2 mg O_3/L) combined with 2 mg Fe^{3+}/L lead up to 212 µg/L (357 µg/L) residual iron.
- ⇨ No significant increase in residual iron concentration after UF-membrane is observed, thus the iron colloids are larger in diameter than the UF pores.

3.1.6 Turbidity < 1 µm

Average turbidity during trial series UF I and UF II was 2.9 ± 0.6 NTU. Figure 21 and Figure 22 display results of turbidity < 1 µm measurements. Exemplarily only four results of

turbidity < 1 µm measurements are displayed. Chapter 6.2.1 contains all diagrams showing turbidity < 1 µm data. Figure 21 depicts samples treated with 10 mg O_3/L and different subsequent coagulant concentrations of 0-6 mg Fe^{3+}/L whereas in Figure 22 pre-ozonation was conducted with 2 mg O_3/L. Even though the shown results in each of these figures derive from the same trial series no evaluation of these data was performed as the results are inconsistent and therefore a comparison of different trial series was not useful. Moreover no conclusion concerning a context between turbidity < 1 µm and flux decline could be drawn. However it is noteworthy, that in several trials, for example UF I-C (Figure 21), turbidity < 1 µm was always significantly lower for pre-ozonated samples, which correlates with the increasing flux after pre-ozonation. Contrary to the thesis that turbidity < 1 µm correlates with flux decline, higher fluxes are observed with increasing coagulant concentration (Figure 6), whereas in most cases turbidity < 1 µm was higher with 6 mg Fe^{3+}/L than with 2 mg Fe^{3+}/L. As colloids in the range of 10-450 nm were identified as main foulants during UF, the 1 µm filter used in these trials seems not adequate, as the fraction 450-1000 nm also passes this 1 µm filter and contributes to an unknown extent to turbidity measurements. Therefore more research is necessary, especially with a more appropriate filter, to check if after all there exists any correlation and if there is a chance to predict flux decline by turbidity measurement.

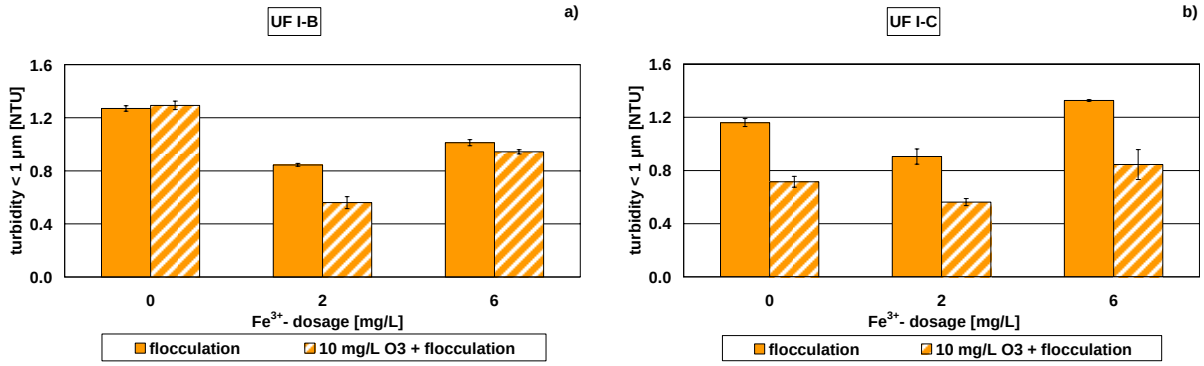

Figure 21: Turbidity < 1 µm for samples treated with 10 mg O_3/L and different subsequent coagulant dosages of 0-6 mg Fe^{3+}/L

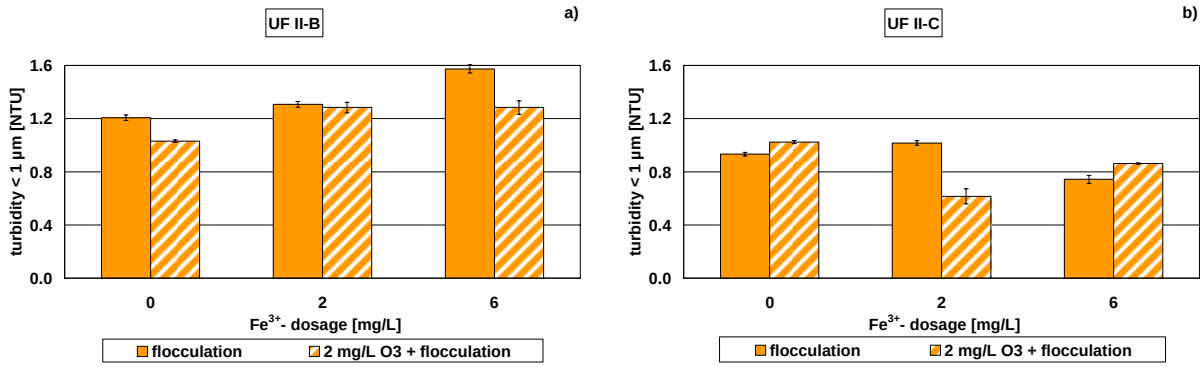

Figure 22: Turbidity < 1 µm for samples treated with 2 mg O_3/L and different subsequent coagulant dosages of 0-6 mg Fe^{3+}/L

3.1.7 Temperature, pH and electric conductivity

Temperature was nearly constant at 22.9 ± 1.5 °C, as all experiments were conducted at room temperature. pH was always measured before and after each treatment process. Due to a high

buffer capacity of the secondary treated effluent of Ruhleben it showed only a slight increase from 7.3 ± 0.1 before to 7.9 ± 0.0 after pre-ozonation with 2 mg O_3/L and 8.0 ± 0.1 after pre-treatment with 10 mg O_3/L. Increases in pH during ozonation occur most likely due to stripping of inorganic carbon. Conductivity is the third parameter which has been measured by default. It also showed a small variance and was approximately 1126 ± 138 µS/cm, depending on the predominant weather conditions.

3.1.8 Ultraviolet Absorbance at 254 nm (UVA 254)

Figure 23 and Figure 24 show the relative absorbance of UVA 254 characterizing the amount of aromatic compounds. Initial values of UVA 245 were approximately 28.05 ± 1.38/m. The addition of $FeCl_3$ leads to a constant decrease in relative absorbance with a maximum of 18 % of the initial relative absorbance (Figure 23a). Independent of coagulant concentration pre-ozonation leads to a decline of UVA 254 of 12 % (Figure 23b) and 42 % (Figure 23a) respectively, depending on the ozone dosage, indicating on the oxidation of aromatic structures. Comparing pre-ozonated samples among themselves an analogue decline of 10 % is observed for these samples. It is noticeable that there is no synergetic effect concerning pre-ozonation and subsequent coagulation, because the initial effect of 12 % and 42 % decrease is nearly constant, independent on the different combinations of pre-ozonation and coagulation. Altogether the maximum reduction (achieved with 10 mg O_3/L pre-ozonation and subsequent coagulation with 6 mg Fe^{3+}/L) of UVA 254 is 56 % (Figure 23a).

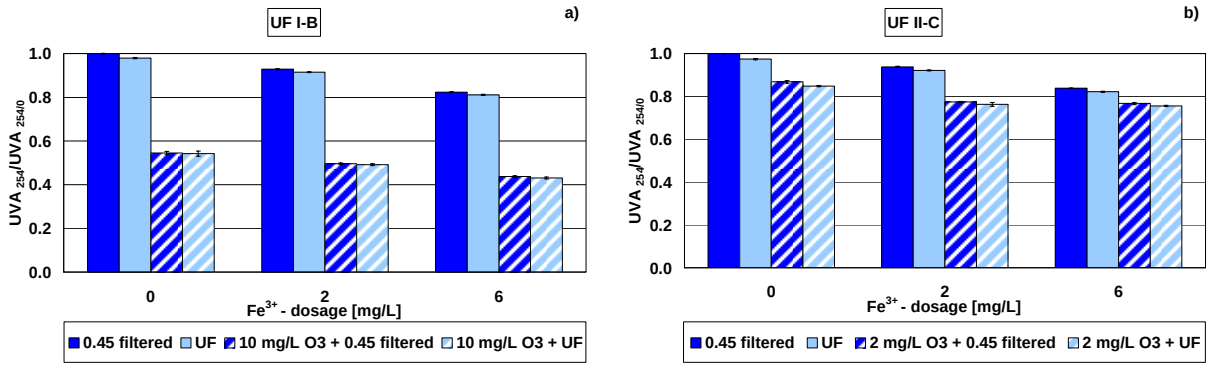

Figure 23: Relative UVA 254 for different coagulant dosages of 0-6 mg Fe^{3+}/L with and without pre-ozonation (Figure 23a: 2 mg O_3/L, UVA 254_0: 26.70/m; Figure 23b: 10 mg O_3/L, UVA 254_0: 27.08/m)

As displayed in Figure 24, increasing ozone dosages result in a constant decrease of relative UVA 254. Comparing Figure 24a and Figure 24b it becomes clear, that the effect of pre-ozonation exceeds the effect obtained due to coagulation, especially with ozone dosages > 2 mg O_3/L. The maximum decline applying 10 mg O_3/L amounts to 52 %, independent on coagulant concentration.

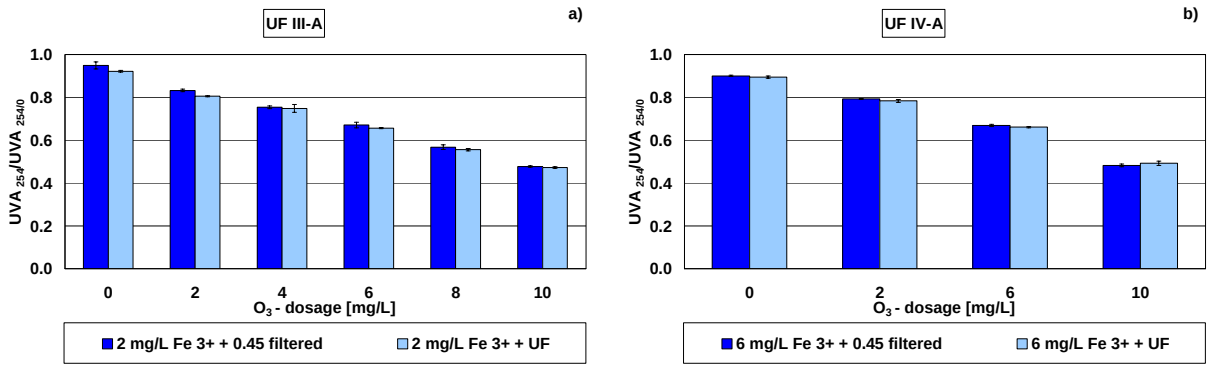

Figure 24: Relative UVA 254 for different ozone dosages of 0-10 mg O_3/L and a constant $FeCl_3$ addition of 2 mg Fe^{3+}/L (Figure 24a, UVA 254_0: 27.00/m) and 6 mg Fe^{3+}/L (Figure 24b, UVA 254_0: 27.04/m), respectively

In both trial series there is no significant difference between samples before and samples after UF.

3.1.9 Absorbance at 436 nm (Colour 436)

Results of Colour 436 primarily characterizing the amount of humic substances are depicted in Figure 25 and Figure 26 as relative absorbance. Initial values for Colour 436 in Figure 25 were 1.43/m and 1.68/m, respectively, whereas in Figure 26 Colour 436_0 was 1.72/m and 1.65/m, respectively. Average Colour 436 was 1.65 ± 0.11/m. As observed with UVA 254, increasing dosages of $FeCl_3$ decrease Colour 436 down to 82 % of the initial absorbance (Figure 25). An analogue decline of 11 % is observed for samples which were treated with ozone before coagulation. The initial effect of pre-ozonation is 39 % (2 mg O_3/L) and 74 % (10 mg O_3/L), respectively. As these initial effects are constant for each trial series, again no synergetic effect is obtained by the combination of pre-ozonation and coagulation. The maximum reduction in Colour 436 is 88 % (10 mg O_3/L and 6 mg Fe^{3+}/L).

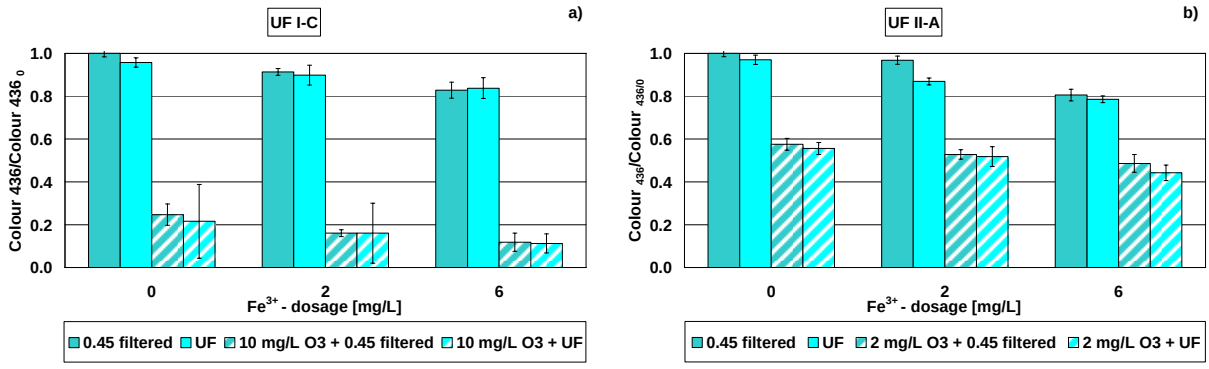

Figure 25: Relative Colour 436 for different coagulant dosages of 0-6 mg Fe^{3+}/L with and without pre-ozonation (Figure 25a: 2 mg O_3/L, Colour 436_0: 1.43/m; Figure 25b: 10 mg O_3/L, Colour 436_0: 1.68/m)

A constant decline of relative Colour 436 is revealed by the data presented in Figure 26. As with UVA 254, a comparison of different coagulant concentrations of 2 and 6 mg Fe^{3+}/L, respectively, combined with an increasing ozone dosage of 0-10 mg O_3/L, reveals approximately the same maximum reduction of Colour 436 (85 %). The effect of ozonation again exceeds the effect of coagulation especially with ozone dosages > 6 mg O_3/L.

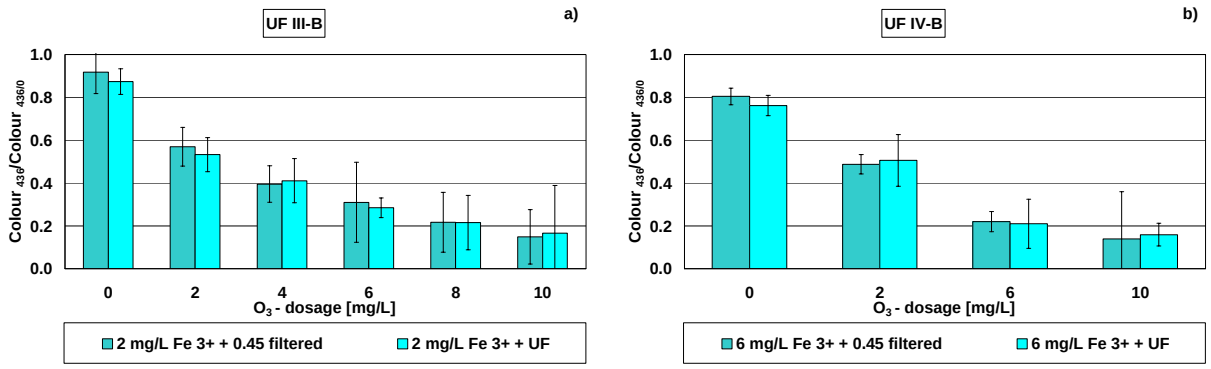

Figure 26: Relative Colour 436 for different ozone dosages of 0-10 mg O_3/L and a constant $FeCl_3$ addition of 2 mg Fe^{3+}/L (Figure 26a, Colour 436_0: 1.72/m) and 6 mg Fe^{3+}/L (Figure 26b, Colour 436_0: 1.65/m), respectively

3.1.10 Dissolved Chemical Oxygen Demand (COD_f)

COD_f of Ruhleben effluent was approximately 30.1 ± 2.1 mg/L during this project. Determination of COD_f was always a single value as this measurement is relatively time extensive. $COD_{f,0}$ in trial series UF I-C (Figure 27a) was 30.2 mg/L and in trial series UF II-A (Figure 27b) 30.1 mg/L. Coagulation lead to a constant decrease in COD_f (Figure 27). The maximum reduction of COD_f was achieved with a treatment combination of 6 mg Fe^{3+}/L and 10 mg O_3/L (Figure 27a) yielding in a relative COD_f of 85 %, corresponding to a concentration of 25.7 mg/L, whereas the samples treated without pre-ozonation but also coagulated with 6 mg Fe^{3+}/L had a COD_f of 28.0 mg/L. This corresponds to a slightly higher relative COD_f of 93 %.

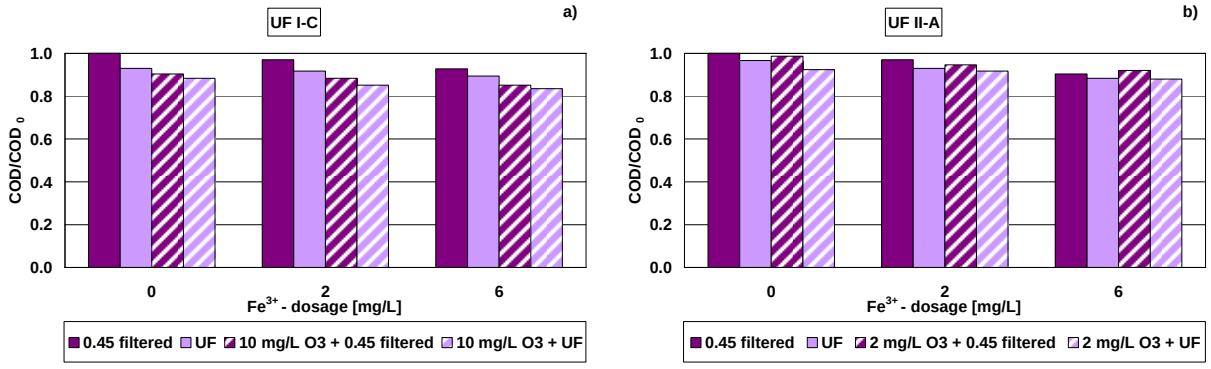

Figure 27: Relative COD_f for different coagulant dosages of 0-6 mg Fe^{3+}/L with and without pre-ozonation (Figure 27a: 2 mg O_3/L, $COD_{f,0}$: 30.2 mg/L ;Figure 27b: 10 mg O_3/L, $COD_{f,0}$: 30.1 mg/L)

The effect of pre-ozonation, especially with high dosages of 10 mg O_3/L, can be observed in Figure 28. Compared to the initial relative COD_f of the coagulated sample (Figure 28a and b), application of 10 mg O_3/L lead to an additional reduction of 7 % (10 mg O_3/L) and 5 % (2 mg O_3/L), respectively, corresponding to final COD_f concentrations of 25.3 mg/L and 25.0 mg/L, respectively. Total reduction of COD_f amounts to 9 % (10 mg O_3/L and 2 mg Fe^{3+}/L) and 14 % (10 mg O_3/L and 6 mg Fe^{3+}/L), respectively.

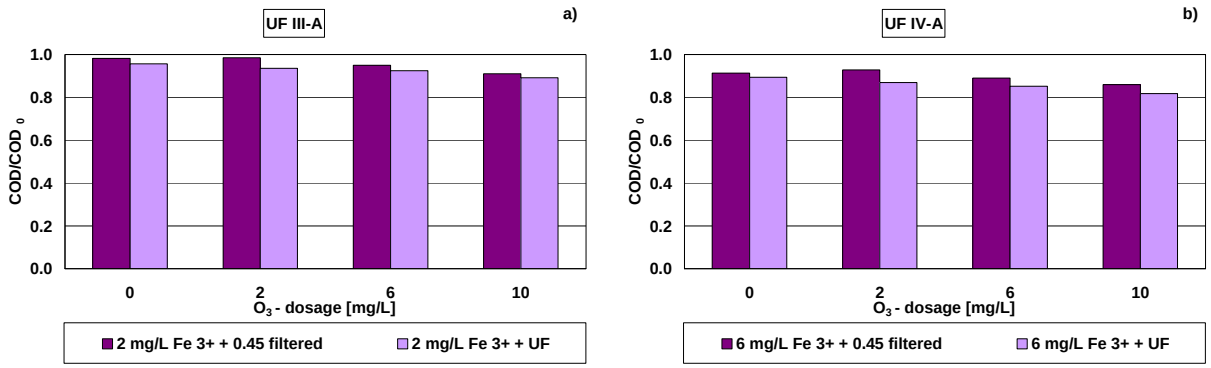

Figure 28: Relative COD_f for different ozone dosages of 0-10 mg O_3/L and a constant $FeCl_3$ addition of 2 mg Fe^{3+}/L (Figure 28a, $COD_{f,0}$: 27.8 mg/L) and 6 mg Fe^{3+}/L (Figure 28b, $COD_{f,0}$: 29.1 mg/L), respectively

3.2 Microfiltration (MF) tests

Figure 29 to Figure 31 show results of the microfiltration (MF) tests (0.2 µm pore size). Coagulation was always conducted with 4 mg Fe^{3+}/L. The only pre-ozonated sample shown in Figure 30 was prepared using 6 mg O_3/L. The first experimental trials were conducted with a pressure of 0.2 bar and resulted in an immediate flux decline of 91 % and 93 %, respectively after 100 ml of generated permeate dependent on pre-treatment (Figure 29). Due to these high flux decreases pressure was fixed at 0.5 bar during the second trial. Flux decline curves of this trial are displayed in Figure 30.

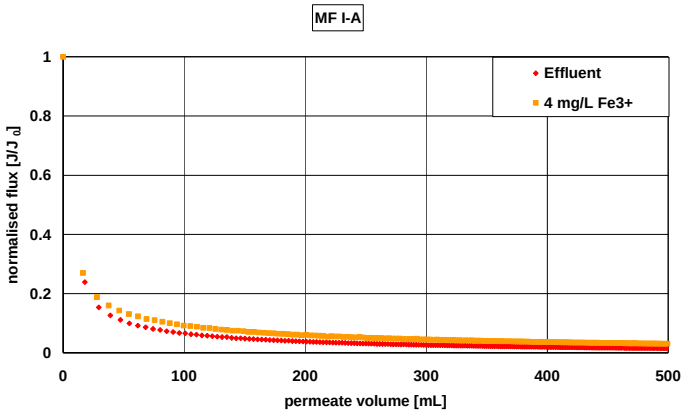

Figure 29: Flux decline curves for different coagulant concentrations of 0 and 4 mg Fe^{3+}/L with an applied pressure of 0.2 bar

The increased pressure seemed to improve the flux of the MF-membrane as after 100 ml of generated permeate flux decline of the untreated Ruhleben effluent and the coagulated sample was diminished to approximately 89 %. These findings were independent of pre-treatment as the increase in flux due to coagulation was negligible. Flux of the pre-ozonated sample increased slightly slower as after 100 ml of generated permeate flux decreased by 87 %.

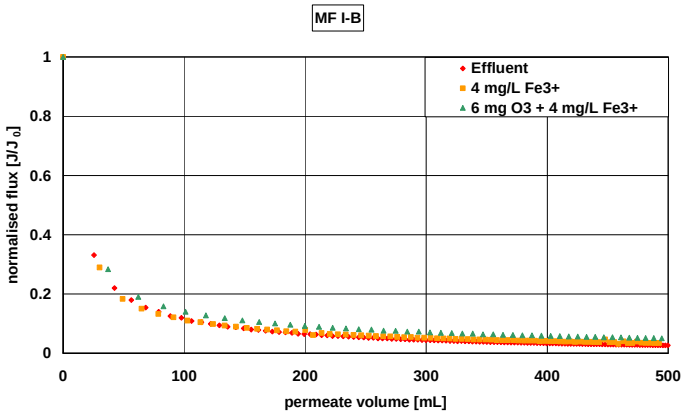

Figure 30: Flux decline curves for different ozone dosages of 0 and 6 mg O_3/L and coagulant concentrations of 0 and 4 mg Fe^{3+}/L with an applied pressure of 0.5 bar

During the third trial with an MF-membrane pressure was once again increased and amounted to 0.7 bar. Results of this trial are shown in Figure 31. No further increase in flux was

observed, as flux decreased and was approximately 7 % of the initial flux after filtration of 100 ml, comparable to the flux obtained with an applied pressure of 0.2 bar in Figure 29.

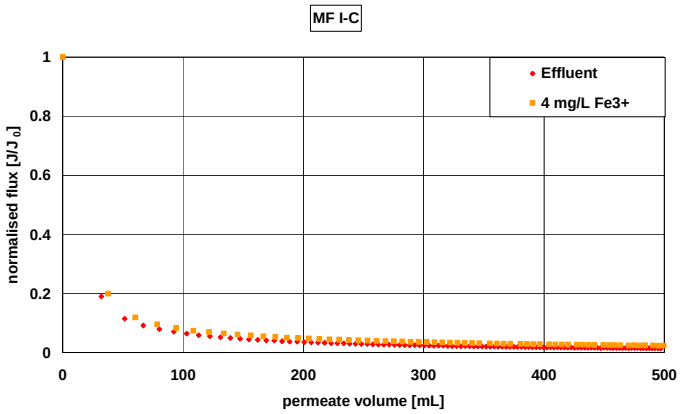

Figure 31: Flux decline curves for different coagulant concentrations of 0 and 4 mg Fe^{3+}/L with an applied pressure of 0.7 bar

Independent on the applied pressure and pre-treatment, during generation of the first 100 ml permeate flux gradients show a major decrease of 87-93 %. Flux during MF trials was reduced to approximately 3 % of the initial normalised flux after producing 500 ml permeate independent on pre-treatment, whereas trials using an UF-membrane (chapter 3.1.1) resulted in 10 % (effluent without pre-treatment) to 30 % (10 mg O_3/L and 6 mg Fe^{3+}/L) of the initial flux, depending on the different pre-treatment steps. This strong decrease in flux is likely caused by pore blocking of ferric colloids in the range of 0.2 µm due to the larger pore size of the MF-membrane of 0.2 µm compared to the pore size of 26 nm of the UF-membrane.

3.3 Backwash trials

In Figure 32 to Figure 34 flux decline curves and corresponding filtration times of the conducted BW trials are depicted. Each BW experiment was performed twice. As the results of corresponding BW experiments were analogue, only results of one experiment are shown. An overview of all obtained flux decline curves is given in the annex (chapter 6.2.2).

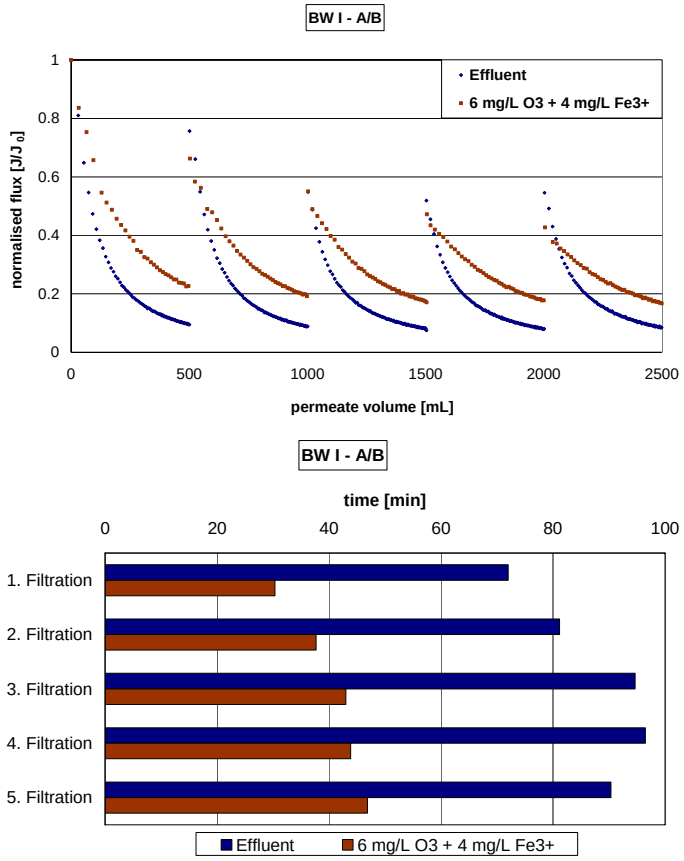

Figure 32: Flux decline curves of BW experiments and corresponding filtration times comparing untreated Ruhleben effluent and Ruhleben effluent pre-treated with 6 mg O_3/L and 4 mg Fe^{3+}/L

Figure 32 displays flux decline curves and associated filtration times for the effluent without pre-treatment and the effluent treated with 6 mg O_3/L and 4 mg Fe^{3+}/L. There are no significant differences in irreversible fouling visible. Flux decline curves of pre-treated samples are located above flux decline curves of the effluent without pre-treatment and flux at the end of each filtration cycle is always higher for pre-treated samples. This is also reflected in reduced filtration times of the treated effluent. Filtration of the effluent without pre-treatment took approximately twice as long as filtration of the treated effluent. Thus the formed filter cake layer on the membrane seems to be more porous as for the same amount of generated permeate less time is needed and higher fluxes are observed. For the effluent without pre-treatment flux is reduced to approximately 8 % of the initial flux, independent on the number of filtration cycles. In contrast flux of the treated effluent shows a decline in flux after each filtration cycle from 23 % to a minimum flux of 17 % after five filtration cycles. The first two filtration cycles cause similar main parts of irreversible fouling, as they reduce the initial flux by an average of 29 % (first filtration cycle) and 45 % (second filtration cycle), respectively, whereas irreversible fouling after four filtration cycles amounts to 45 % for the effluent and 57 % for the treated effluent. Reversible fouling is primarily caused by the first filtration cycle. After filtration of 500 ml effluent 76 % of the initial flux was restored by BW, whereas 66 % of the initial flux was recovered for the treated effluent. The percentage of reversible fouling caused by the first filtration cycle comes to 67 % for the effluent and 43 % for the treated effluent. Further filtration cycles lead to a nearly constant rate of reversible fouling of approximately 46 % for the effluent and 31 % for the ozonated and coagulated effluent. Filtration times reflect also the main fouling during the first two filtration cycles, as

filtration time of the effluent without pre-treatment increases from 72 minutes (first cycle) to 81 minutes (second cycle). Average time needed for the third, fourth and fifth filtration cycle is 94 minutes. An increase in filtration time from 30 minutes to 38 minutes to an average time of 45 minutes is observed for the treated effluent. Average reduction in filtration time during the first and second cycle amounts to 42 minutes, whereas time needed for filtration of 500 ml sample declined by an average of 49 minutes during filtration cycle 3 to filtration cycle 5.

Flux decline curves for the coagulated effluent (4 mg Fe^{3+}/L) and the corresponding pre-ozonated sample are shown in Figure 33. The fraction of irreversible fouling decreases significantly with the application of 4 mg Fe^{3+}/L compared to the effluent without pre-treatment in Figure 32 and comes to a maximum of only 22 % after the fifth filtration cycle. Application of 6 mg O_3/L and 4 mg Fe^{3+}/L results in flux decline curves comparable to those depicted in Figure 32, which originate from a different trial day. Therefore irreversible fouling amounts to a similar maximum of 51 % after the fourth filtration cycle. Comparing directly samples with a coagulant concentration of 4 mg Fe^{3+}/L with and without pre-ozonation shows that application of 6 mg O_3/L results in a clear increase of irreversible fouling. Analogue to these findings the percentage of reversible fouling decreases after pre-ozonation. Average flux of the coagulated sample at the end of each filtration cycle is constant and amounts to 16 %, whereas flux of the pre-ozonated and coagulated sample decreases from 21 % after the first cycle ad 19 % after the second cycle to 17 % after cycle 3 to cycle 5. It is obvious that pre-ozonation changes characteristics of foulants as after the application of ozone irreversible fouling increases significantly. In contrast this intense increase in irreversible fouling due to pre-ozonation resulting in a lower initial flux after BW, filtration times are reduced. During the first and second filtration cycle time needed for filtration of 500 ml sample is reduced by 14 and 7 minutes, respectively. Filtration times for cycle 3 to cycle 5 are nearly constant. Pre-ozonated samples needed only approximately 2 minutes less time.

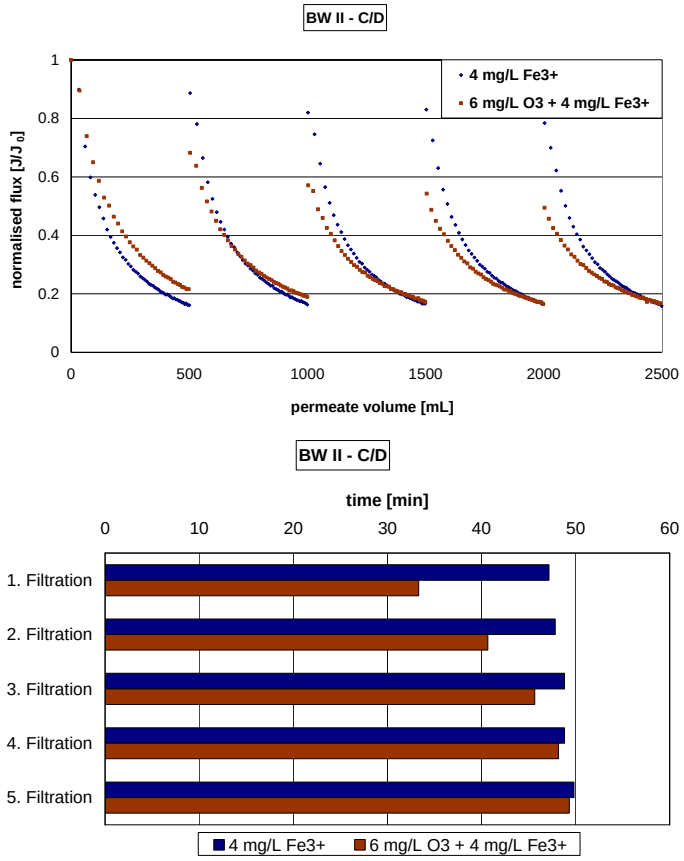

Figure 33: Flux decline curves of BW experiments and corresponding filtration times comparing coagulated Ruhleben effluent (4 mg Fe^{3+}/L) and Ruhleben effluent pre-treated with 6 mg O_3/L and 4 mg Fe^{3+}/L

In order to specify the influence of pre-ozonation on flux decline and fouling experiments with a constant coagulant concentration of 4 mg Fe^{3+}/L and an increasing ozone dosage of 0-10 mg O_3/L were conducted. Results of these experiments are shown in Figure 34. Consistent with previous results pre-ozonation increased irreversible fouling. This effect amplifies with increasing ozone dosage. Application of 2 mg O_3/L leads only to a slightly lower initial flux after BW of approximately 2 % compared to the coagulated sample without pre-ozonation. High ozone dosages of 6 and 10 mg O_3/L result in significantly lower initial fluxes. Comparing the initial flux of the coagulated sample with the initial flux of the samples pre-ozonated with 6 mg O_3/L and 10 mg O_3/L, the difference in initial flux at the beginning of each new filtration cycle is constant and amounts to 21 % and 36 %, respectively. Thus, the increase in irreversible fouling for pre-ozonated samples derives only from the first filtration cycle. At the beginning of the fifth filtration cycle minimum initial fluxes of 51 % (6 mg O_3/L) and 39 % (10 mg O_3/L) are reached. Flux decline curves flatten with increasing pre-ozonation dosage as irreversible fouling increases. Thus, flux at the end of each filtration cycle decreases for high ozone dosages from 27 % after filtration of 500 ml to 21 % after filtration of 2500 ml with the application of 6 mg O_3/L and from 25 % to 20 % applying 10 mg O_3/L. In contrast samples pre-treated with low ozone dosages and samples without pre-treatment showed an average flux at the end of each filtration cycle of 18 % (0 mg O_3/L) and 22 % (2 mg O_3/L). For these trials a diagram of filtration times does not deliver more information, as initial pure water fluxes of the used membranes varied too much. Flux decline curves are related to different initial pure water fluxes. Filtration times do not include the

different fluxes of pure water that have a strong influence on the time needed for filtration of 500 ml sample.

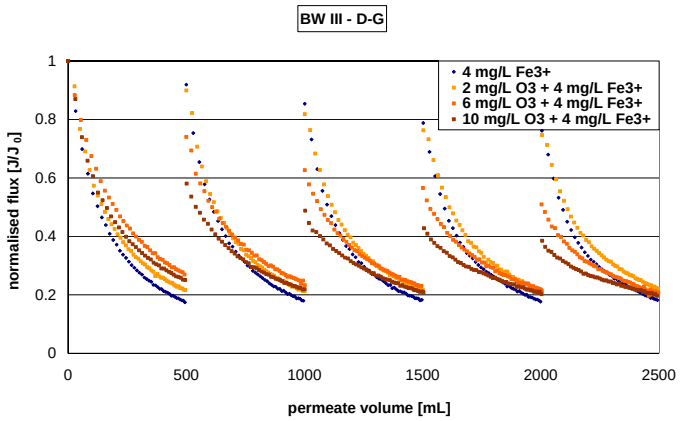

Figure 34: Flux decline curves of BW experiments comparing coagulated Ruhleben effluent and Ruhleben effluent pre-treated with 2, 6 or 10 mg O_3/L and 4 mg Fe^{3+}/L

LC-OCD analysis from the effluent, treated effluent, permeate after 1st, 3rd and 5th cycle and from the BW water, withdrawn after every 1st, 3rd and 5th cycle seemed promising for obtaining more information of the reasons of fouling. As these data are inconsistent, they are only shown in the annex (chapter 6.2.4). Severe problems during sample extraction could derive from the flocs, that detach during BW from the membrane and are therefore contained in the BW water. As samples for LC-OCD analysis have to be pre-filtered by a 0.45 µm filter, these flocs accumulate on the filter and form a filter cake layer that retains more BP. The amount of flocs depends on sample drawing and thus fluctuates to a great extent. An alternative option could be a fractionation of the BW water by centrifugation. After separation of the iron flocs the adsorbed fraction of organics and the dissolved fraction of the supernatant could be analysed separately by LC-OCD.

Conclusion:

- ⇨ Irreversible fouling decreases significantly with application of coagulant (4 mg Fe^{3+}/L) compared to the effluent without pre-treatment from 45 % to 22 % after 4 filtration cycles.
- ⇨ The first two filtration cycles cause main parts of irreversible fouling.
- ⇨ Pre-ozonation changes characteristics of foulants as especially high ozone dosages of 6 and 10 mg O_3/L result in a clear increase of irreversible fouling (21 % and 36 %, respectively), which is caused during the first filtration cycle.
- ⇨ Despite of the increase in irreversible fouling comparing samples coagulated with 4 mg Fe^{3+}/L and samples treated with a combination of 6 mg O_3/L and 4 mg Fe^{3+}/L filtration times of pre-ozonated samples are reduced by 30 % and 15 % during the first and second filtration cycle compared to the coagulated samples without pre-ozonation.
- ⇨ At the end of the first filtration cycle fluxes of samples pre-treated with ozone and coagulant are always higher as for the coagulated sample (up to 10 %), whereas flux after five filtration cycles is nearly the same for samples with and without pre-ozonation.

4 Conclusion and Perspective

The tested pre-treatment on Ruhleben effluent of pre-ozonation and subsequent coagulation enables good phosphorus removal with permeate concentrations of 25 to 50 µg P/L that are independent of pre-ozonation. Coagulation with 2 mg Fe^{3+}/L leads to $P_{T,f}$ concentrations < 60 µg P/L, whereas application of 6 mg Fe^{3+}/L reduces $P_{T,f}$ to concentrations < 50 µg P/L. In filtration tests with new membrane material pre-ozonation without coagulation leads to a less distinct flux decline of approximately 3 %. Coagulation without pre-ozonation increases the flux by 10 - 13 % (end of filtration) and reduces the filtration time by 33 - 40 % depending on the coagulant concentration. The combination of both pre-treatment steps applying 10 mg O_3/L and 6 mg Fe^{3+}/L improves the filtration performance compared to the effluent without pre-treatment up to 20 % and reduces the filtration time for 500 mL by 61 %. Combining high ozone dosages (10 mg O_3/L) and low coagulant concentrations of 2 mg Fe^{3+}/L increases the flux still by 15 % and leads to a reduction in filtration time of 51 % compared to effluent without pre-treatment. Thus, the synergetic effect deriving from a combination of pre-ozonation and coagulation increases with the concentration of the applied coagulant. Synergetic effects of low ozone dosages of 2 mg O_3/L are hardly visible.

The amount of BP correlates with flux decline. Different mechanisms are considered as reasons for the improved performance after pre-ozonation and subsequent coagulation. It is known that coagulation partially removes the fouling-active BP and humic substances. This effect increases with increasing coagulant concentration. The pre-treatment with ozone, even at low dosages (2 mg O_3/L), leads to a significant decrease of UVA 254, pointing on a shift to more polar molecules and reduces Colour 436 significantly. An increase in ozone dosage decreases the amount of BP eluting with the main peak around 38 minutes. This effect is more pronounced with low coagulant concentrations. Higher ozone dosages (> 6 mg/L) additionally seem to induce disintegration of BP and a shift to smaller organic compounds. The observed changes in the amount of BP and in elution times could also derive from a change in the detectable amount of BP due to pre-ozonation.

The interaction between ozonation and coagulation leads to a colloidal stabilisation of iron in solution. As a consequence, less iron is provided for the coagulation process. Thus, the synergetic effect of pre-ozonation and coagulation on the filtration performance increases with increasing iron dosage, as the percentage of stabilised colloidal iron in solution decreases with increasing iron dosage.

A clear impact of the microflocculation effect is not visible as results of turbidity < 1 µm measurements do not show a distinct effect on flux decline. In order to exclude the particle fraction of 450-1000 nm that also contributes to an unknown extent to turbidity measurements, further research with a filter of a pore size of approximately 450 nm seems reasonable. Thus only colloids in the range of 10-450 nm, which were identified as main foulants during UF, would be measured and a possible correlation could be shown. Hence, prediction of flux decline by turbidity measurement might be possible.

Concentrations of dissolved COD can be reduced by a combination of pre-ozonation and coagulation of up to 15 %, depending on the ozone dosage.

The conducted BW trials revealed that main parts of irreversible fouling were caused during the first two filtration cycles. Furthermore a clear increase of irreversible fouling due to pre-ozonation is observed after the first filtration cycle especially with high ozone dosages of 6 and 10 mg O_3/L. Thus, pre-ozonation seems to change characteristics of the foulants. In spite of the increase in irreversible fouling, filtration times of pre-ozonated samples are reduced by 30 % and 15 % for the first and second filtration cycle compared to corresponding samples, pre-treated only with coagulation. After the first filtration cycle the flux of samples without pre-ozonation is always lower than flux of samples pre-treated with ozone. At the end of five filtration cycles this effect is no more visible, as flux is nearly the same for all samples, independent on pre-ozonation, although initial flux was lower. One possible option for the increased irreversible fouling after pre-ozonation might be an increase of in-pore adsorption of disintegrated BP fragments.

These results suggest that combining pre-ozonation and coagulation is a promising pre-treatment process to reduce the fouling of organic membranes, without the necessity of applying free dissolved ozone onto the membrane surface. Concerning the problems of increased irreversible fouling after pre-ozonation it has to be considered, that BW conducted in these test trials differs from BW procedures at pilot plants. Beyond these differences in BW, Zheng (2010) found that high filtration pressures of approximately 1 bar result in more compact BP fouling which is more difficult to be hydraulically backwashed. Zheng (2010) showed an increase in irreversible fouling from 22 % to 30 % with an increase in filtration pressure from 0.8 to 1.0 bar, whereas filtration pressure of 0.6 and 0.4 bar only result in 19 % and 18 % irreversible fouling. This influence of filtration pressure on irreversible fouling was also confirmed by pilot-scale UF experiments. Furthermore only one type of PES UF-membrane with a MWCO of 150 kDa was tested. Possibly different UF-membranes differ in intensity of irreversible fouling and therefore more research is needed.

Conclusion:

- ⇨ Coagulation increases flux (10 % - 13 %) and minimizes filtration time (33 % - 40 %).
- ⇨ Pre-ozonation (10 mg O_3/L) leads to an additional maximum flux increase of 6 %.
- ⇨ Filtration time of the effluent without pre-treatment (coagulated effluent) is reduced by 50 % - 60 % (28 % - 33 %) with the combination of pre-ozonation and coagulation.
- ⇨ Benefits (maximal flux increase of 20 %) combining pre-ozonation (6 - 10 mg O_3/L) and coagulation increases with coagulant concentration.
- ⇨ Independent on pre-ozonation Total Soluble Phosphorus ($P_{T,f}$) is reduced to concentrations < 50 µg P/L by coagulation (4 and 6 mg Fe^{3+}/L).
- ⇨ Coagulation and pre-ozonation have a positive effect on biopolymer removal and therefore lead to reduced membrane fouling.
- ⇨ High ozone dosages result in disintegration of biopolymers.
- ⇨ Mainly high ozone dosages lead to a complexation of iron and therefore increased residual iron.
- ⇨ Irreversible fouling is primarily caused by the first two filtration cycles.
- ⇨ Pre-ozonation increases irreversible fouling and the benefit in reduced filtration times is only visible for the first two filtration cycles.

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6 Annex

6.1 Calculation of the pressure needed for MF filtration tests

Measured permeate flowrate at the beginning was approximately 35 ml/min. The effective membrane filtration area was 28.7 cm² = 0.00287 m². Hence, flux during UF trials can be calculated as shown in Equation 2.

$$Flux_{UF} = \frac{0.035 \cdot 60 L/h}{0.00287 m^2} = 731.7\ L/h \cdot m^2 \qquad \text{Equation 2}$$

Flux for the MF-membrane was declared with > 1500 ml/m²·h at 0.7 bar. Equation 3 displays the calculation of the permeability of the MF-membrane.

$$permeability_{MF} = \frac{1500\ L/m^2 \cdot h}{0.7\ bar} = 2142.9\ L/m^2 \cdot h \cdot bar \qquad \text{Equation 3}$$

The measured permeate flowrate of the UF-membrane divided by the permeability of the MF-membrane (Equation 4) delivers the theoretical flux needed to obtain an comparable permeate flow rate for the MF trials.

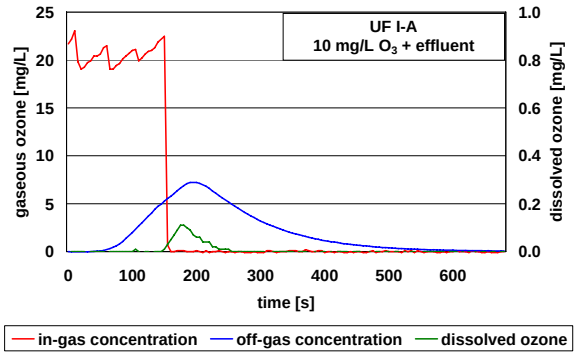
$$\frac{731.7\ L/h \cdot m^2}{2142.9\ L/m^2 \cdot h \cdot bar} = 0.34\ bar \qquad \text{Equation 4}$$

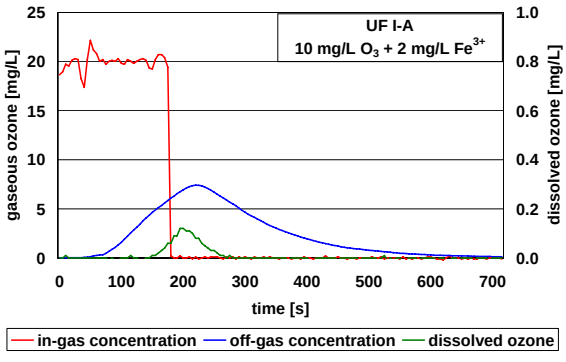
The determined pressure for the MF experiments was 0.34 bar. As the declaration in the data sheet for the MF-membrane for the flux was > 1500 L/m²·h the calculated pressure would decrease with increasing flux of the MF-membrane. Therefore it was decided to start with a pressure of 0.2 bar.

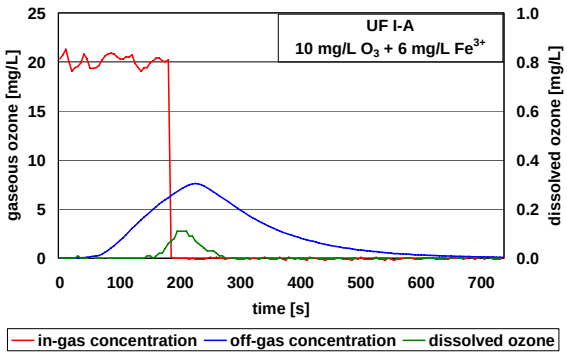
6.2 Diagrams

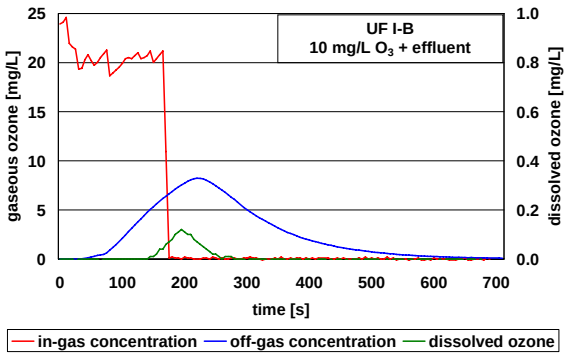
6.2.1 Ozonation

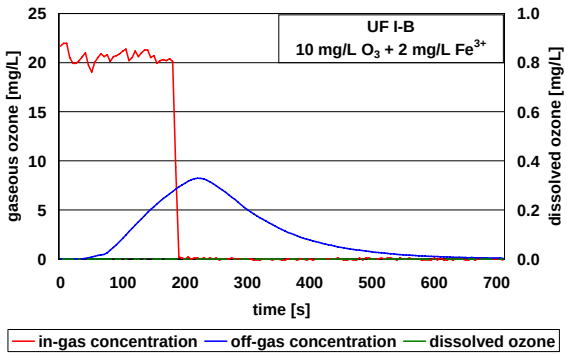
Table 6: Overview of results of UF trials – Ozonation of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – overview of results of UF trials

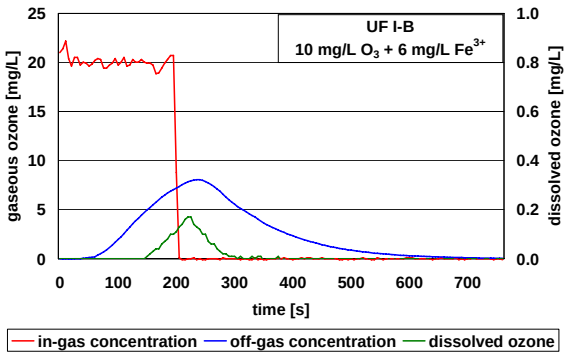


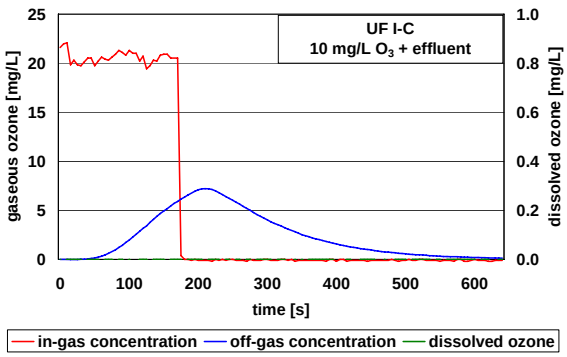


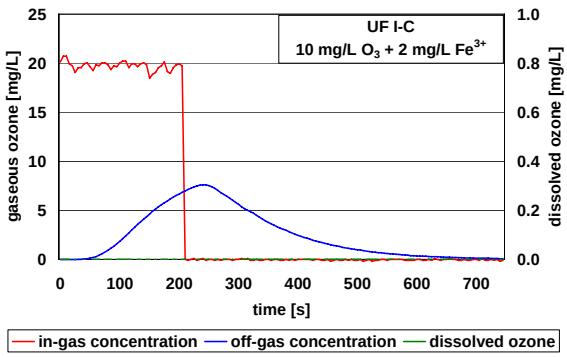

UF I-A
10 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF I-B
10 mg/L O3 + effluent
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF I-B
10 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF I-B
10 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF I-C
10 mg/L O3 + effluent
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF I-C
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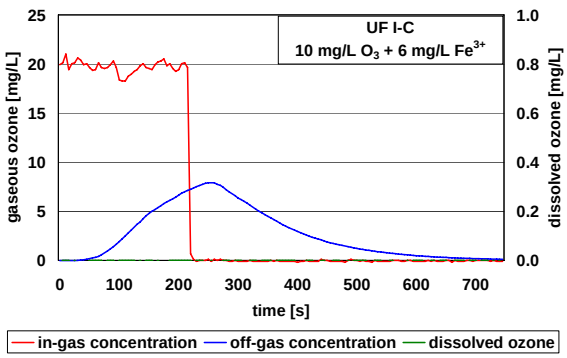
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF I-C
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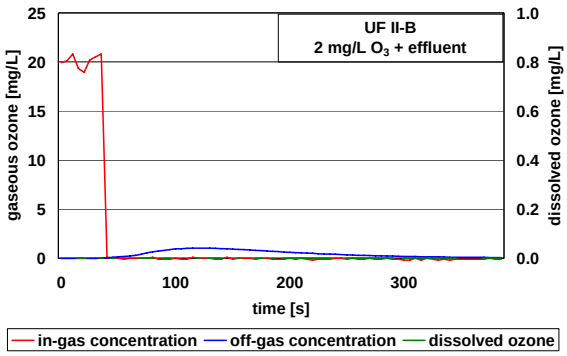
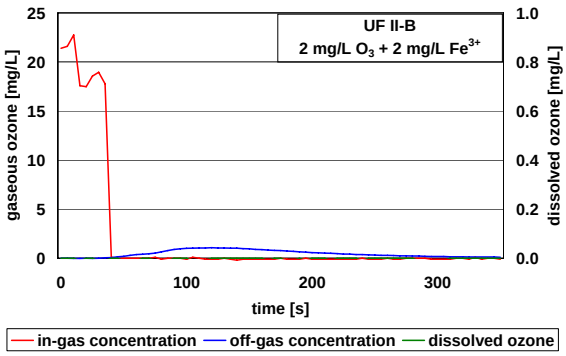
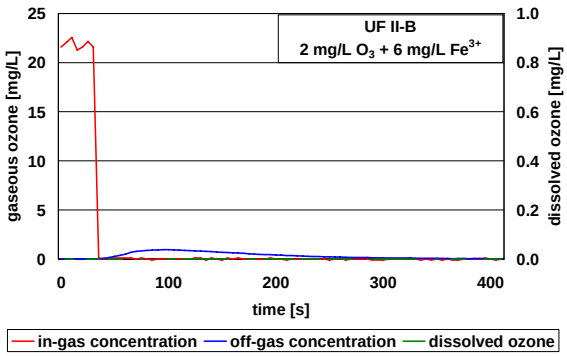
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF II-B
2 mg/L O3 + effluent
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF II-B
2 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF II-B
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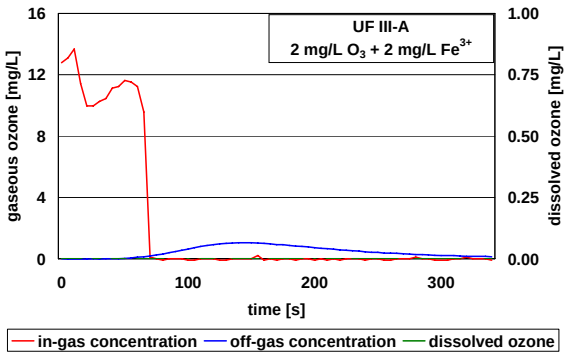
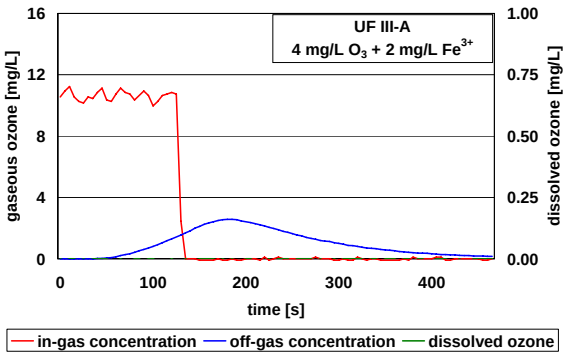
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF III-A
2 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone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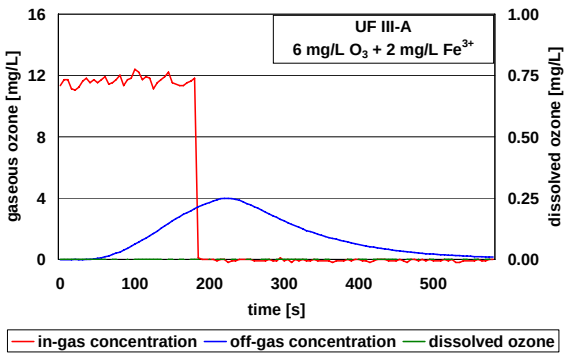
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF III-A
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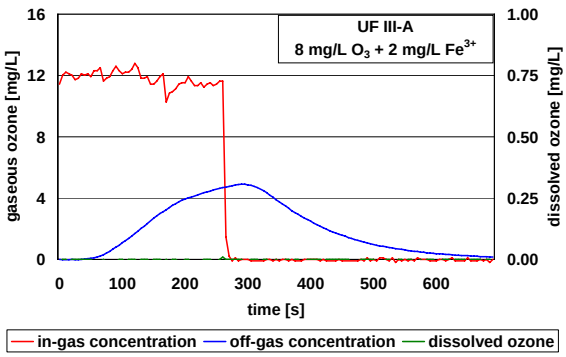
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone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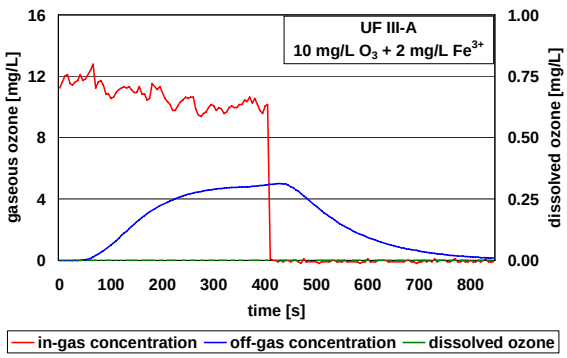
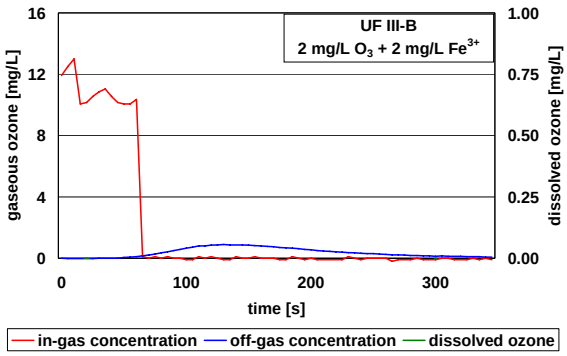
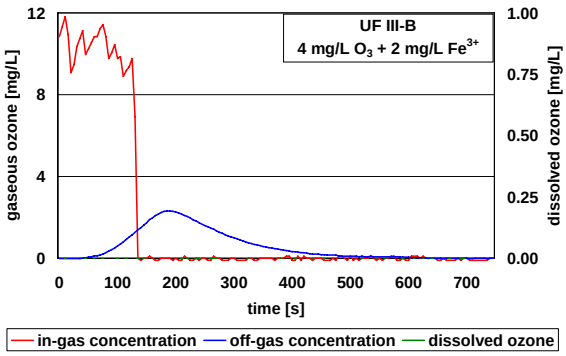
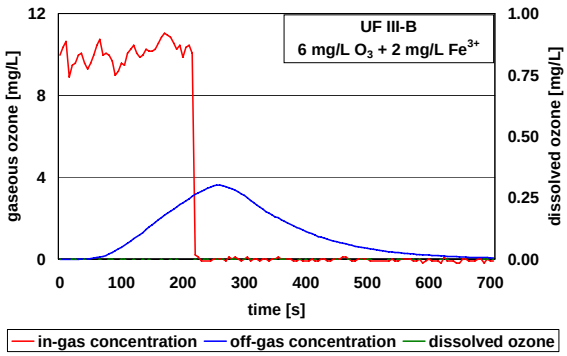
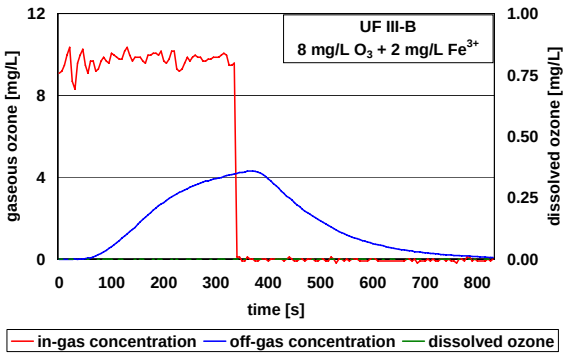
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

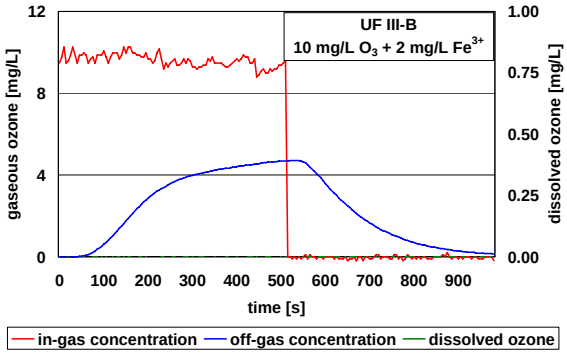

UF III-A
10 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

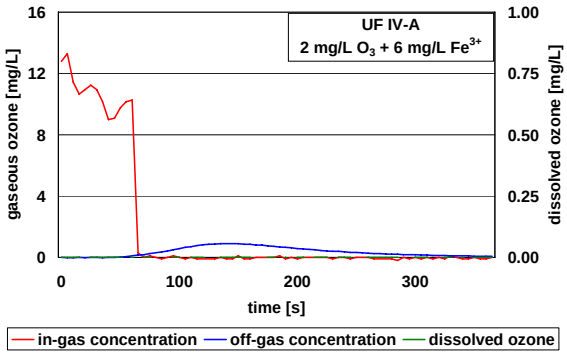

UF III-B
2 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

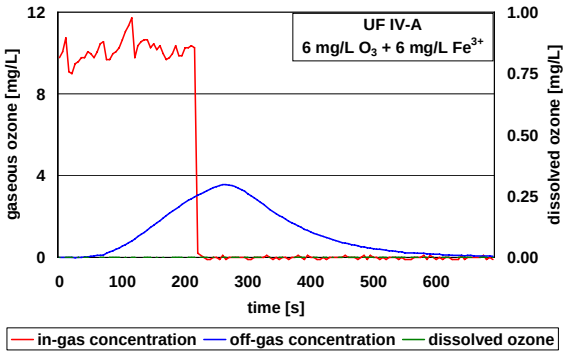

UF III-B
4 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

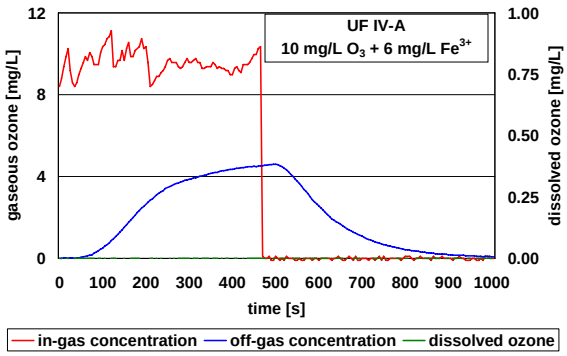

UF III-B
6 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

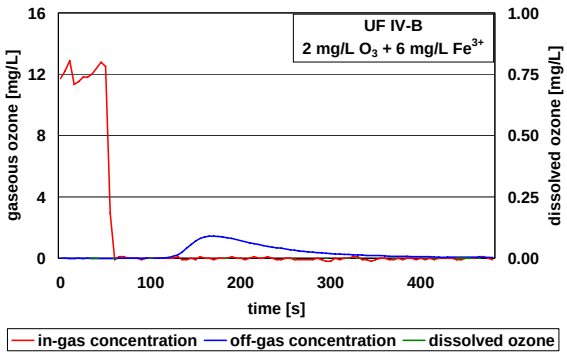

UF III-B
8 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

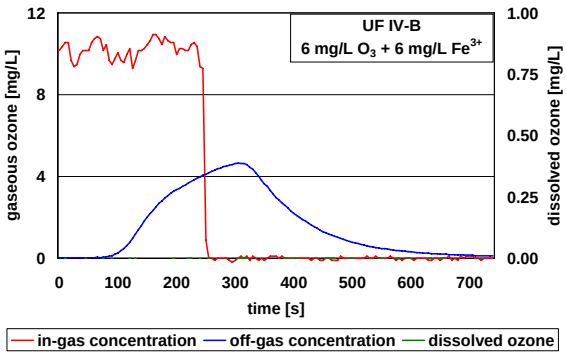

UF III-B
10 mg/L O3 + 2 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

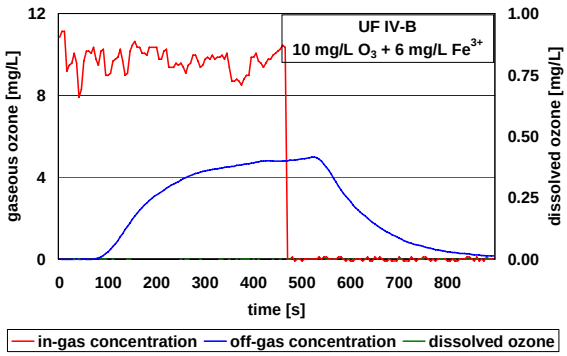

UF IV-A
2 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

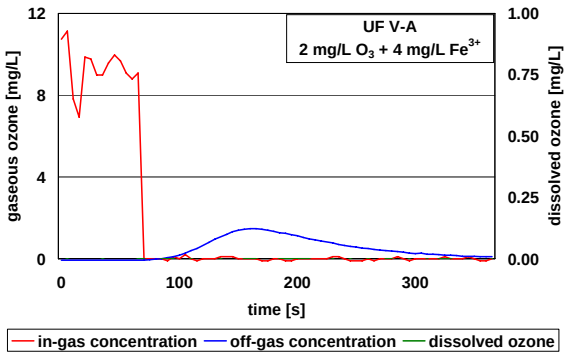

UF IV-A
6 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

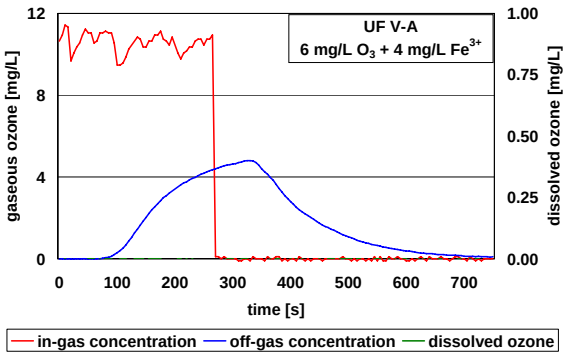

UF IV-A
10 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

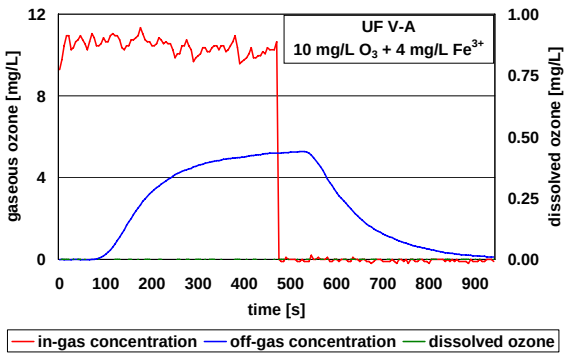

UF IV-B
2 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF IV-B
6 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF IV-B
10 mg/L O3 + 6 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF V-A
2 mg/L O3 + 4 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

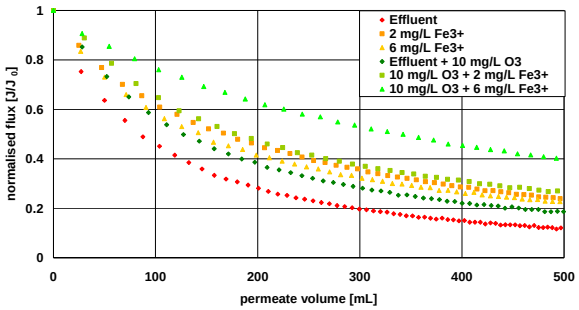

UF V-A
6 mg/L O3 + 4 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone


UF V-A
10 mg/L O3 + 4 mg/L Fe3+
gaseous ozone [mg/L]
dissolved ozone [mg/L]
time [s]
in-gas concentration
off-gas concentration
dissolved ozone

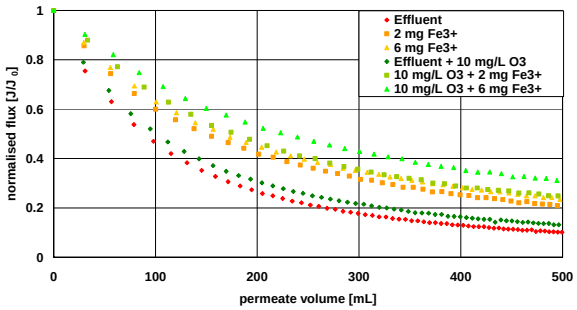
6.2.2 Flux decline

Table 7: Overview of results of UF trials – Flux decline curves of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L)

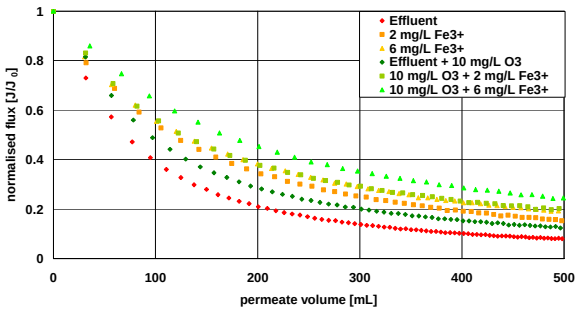
UF I-A



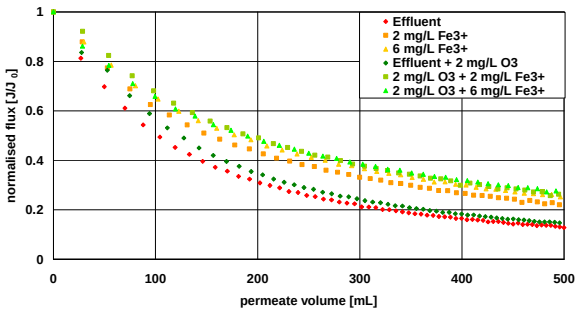
UF I-B



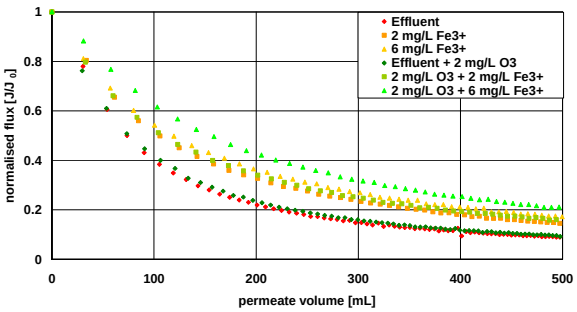
UF I-C



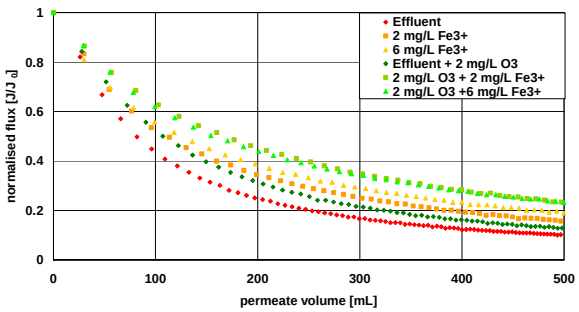
UF II-A



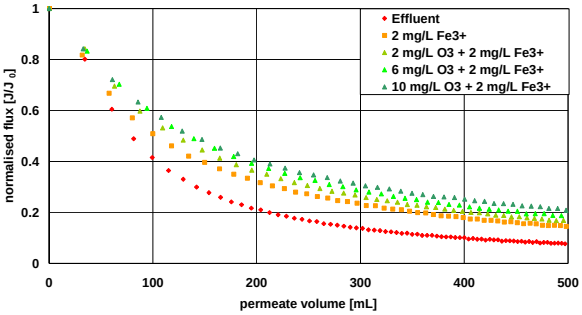
UF II-B



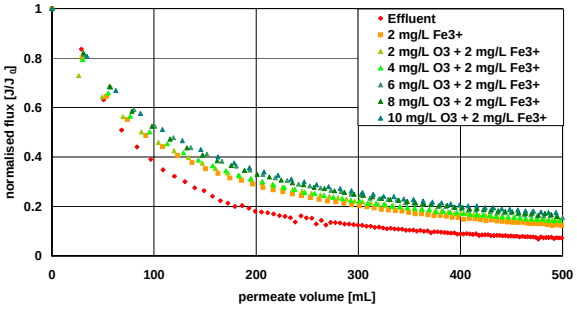
UF II-C



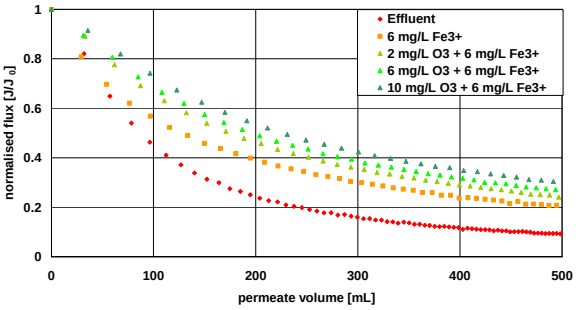
UF III-A



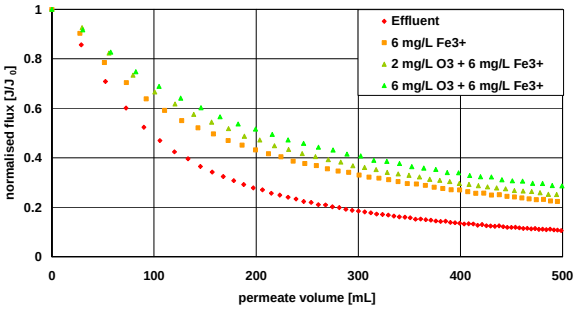
UF III-B



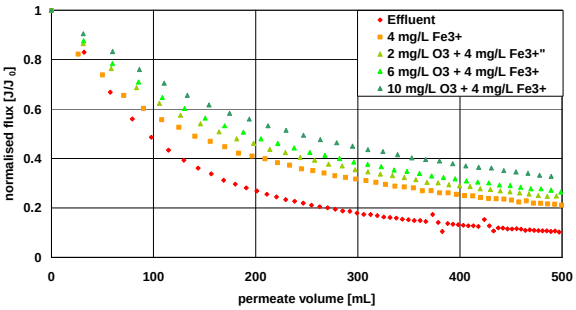
UF IV-A



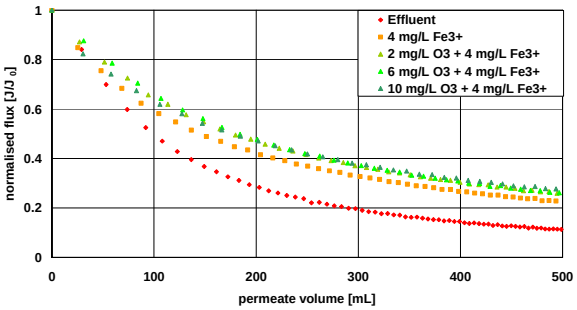
UF IV-B



UF V-A



UF V-B



UF V-C

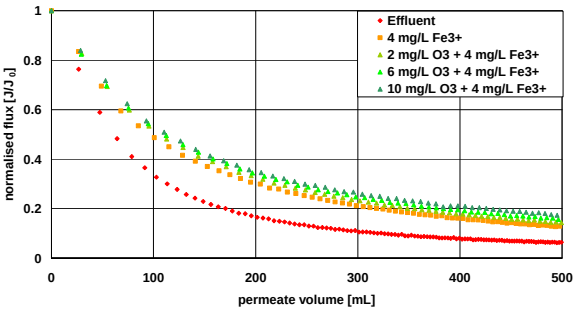
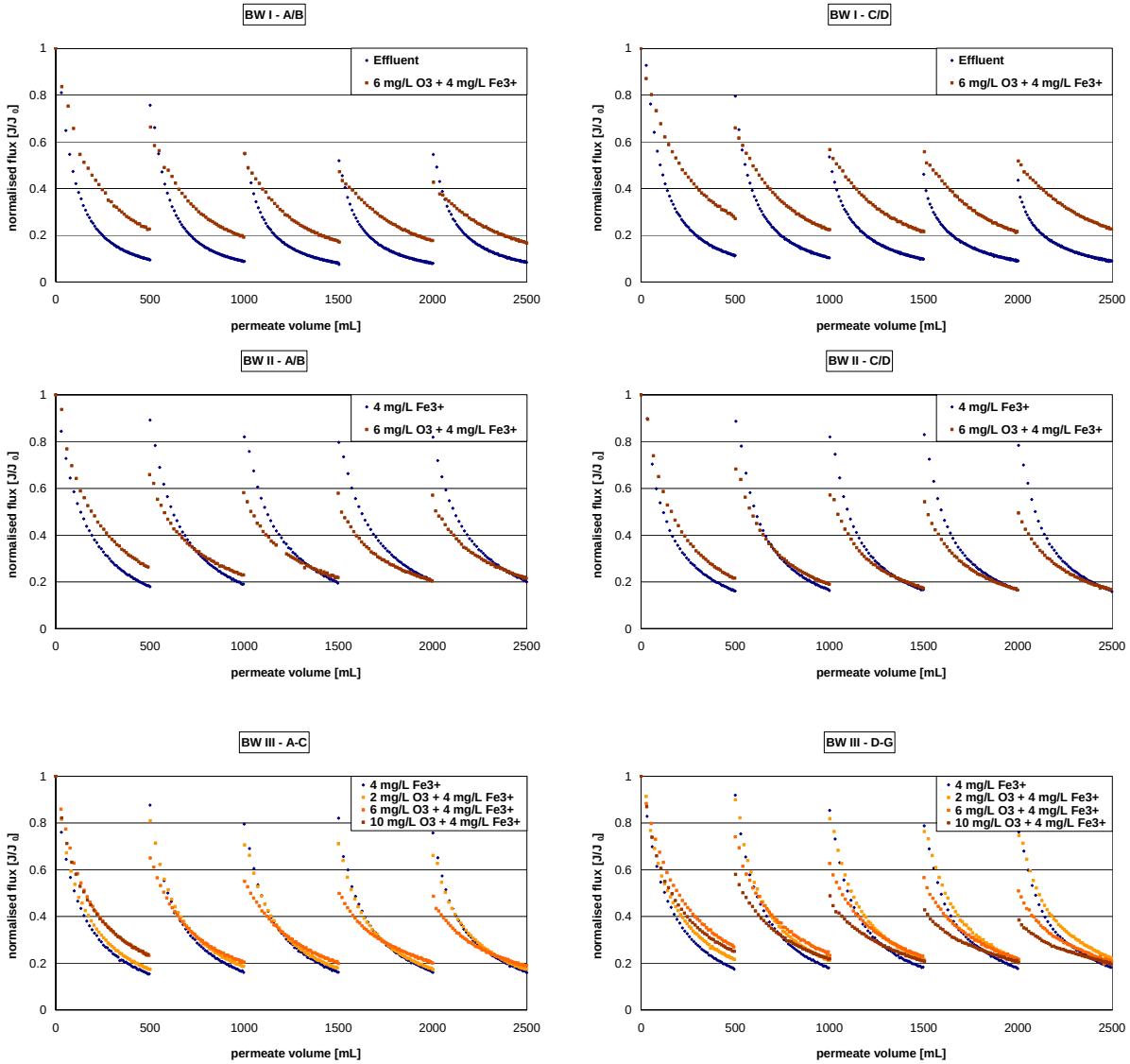
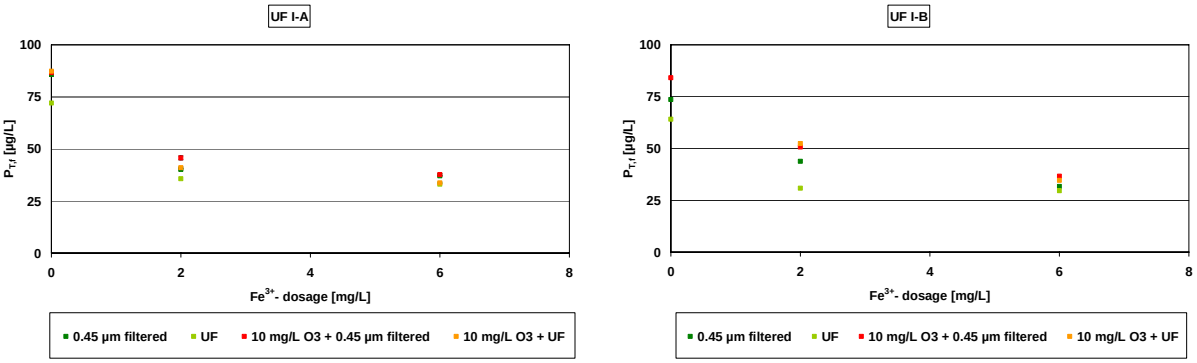


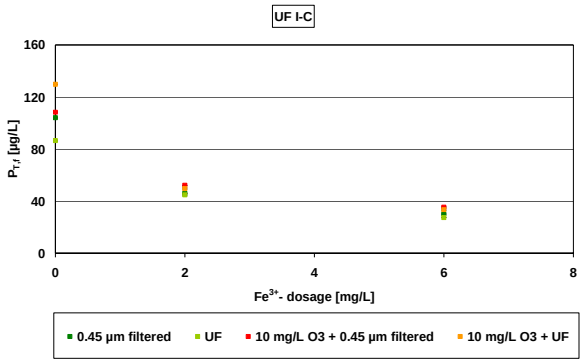
Table 8: Overview of results of BW trials – Flux decline curves of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)

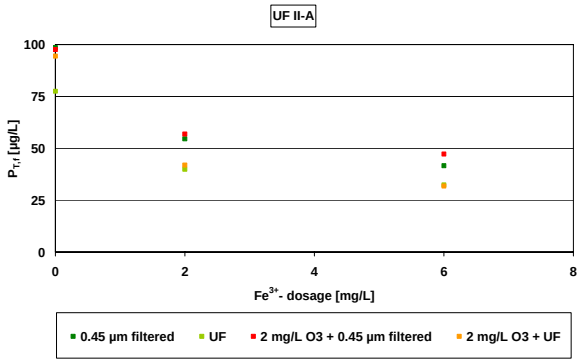


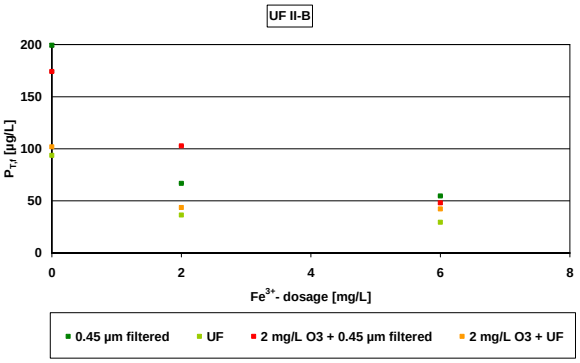
6.2.3 Total Soluble Phosphorus ($P_{T,f}$)

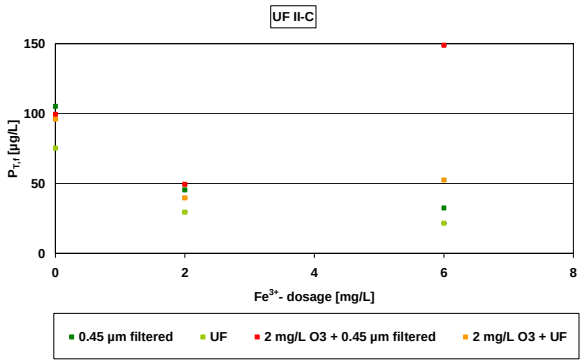
Table 9: Overview of results of UF trials – $P_{T,f}$ of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L)

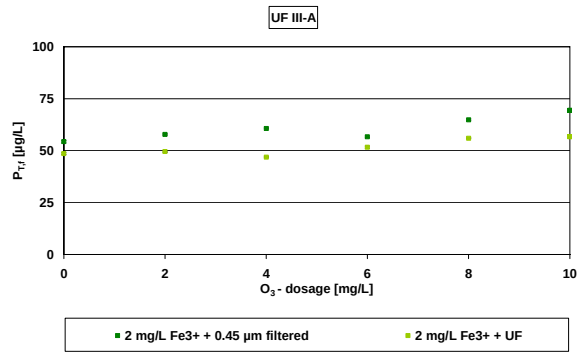


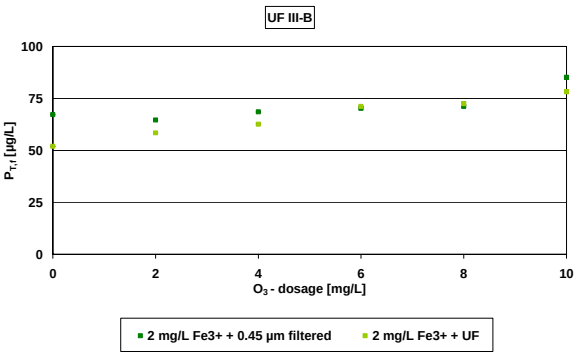

UF I-C
160
120
80
40
0
0
2
4
6
8
$P_{T,f}$ [µg/L]
Fe^{3+}- dosage [mg/L]
0.45 µm filtered
UF
10 mg/L O3 + 0.45 µm filtered
10 mg/L O3 + UF

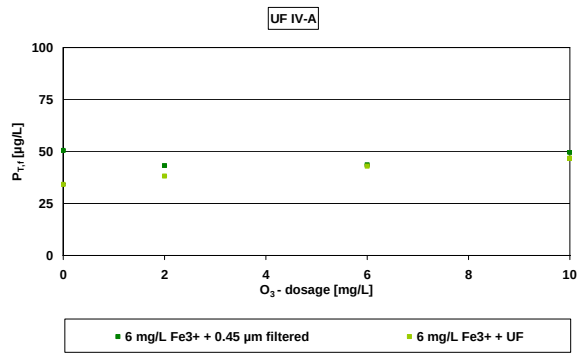

UF II-A
100
75
50
25
0
0
2
4
6
8
$P_{T,f}$ [µg/L]
Fe^{3+}- dosage [mg/L]
0.45 µm filtered
UF
2 mg/L O3 + 0.45 µm filtered
2 mg/L O3 + UF

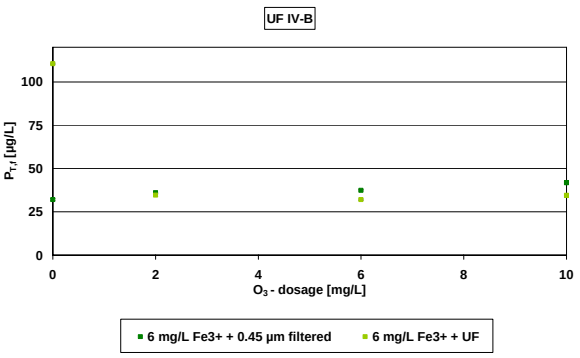

UF II-B
200
150
100
50
0
0
2
4
6
8
$P_{T,f}$ [µg/L]
Fe^{3+}- dosage [mg/L]
0.45 µm filtered
UF
2 mg/L O3 + 0.45 µm filtered
2 mg/L O3 + UF


UF II-C
150
100
50
0
0
2
4
6
8
$P_{T,f}$ [µg/L]
Fe^{3+}- dosage [mg/L]
0.45 µm filtered
UF
2 mg/L O3 + 0.45 µm filtered
2 mg/L O3 + UF


UF III-A
100
75
50
25
0
0
2
4
6
8
10
$P_{T,f}$ [µg/L]
O_3 - dosage [mg/L]
2 mg/L Fe3+ + 0.45 µm filtered
2 mg/L Fe3+ + UF


UF III-B
100
75
50
25
0
0
2
4
6
8
10
$P_{T,f}$ [µg/L]
O_3 - dosage [mg/L]
2 mg/L Fe3+ + 0.45 µm filtered
2 mg/L Fe3+ + UF


UF IV-A
100
75
50
25
0
0
2
4
6
8
10
$P_{T,f}$ [µg/L]
O_3 - dosage [mg/L]
6 mg/L Fe3+ + 0.45 µm filtered
6 mg/L Fe3+ + UF


UF IV-B
100
75
50
25
0
0
2
4
6
8
10
$P_{T,f}$ [µg/L]
O_3 - dosage [mg/L]
6 mg/L Fe3+ + 0.45 µm filtered
6 mg/L Fe3+ + UF

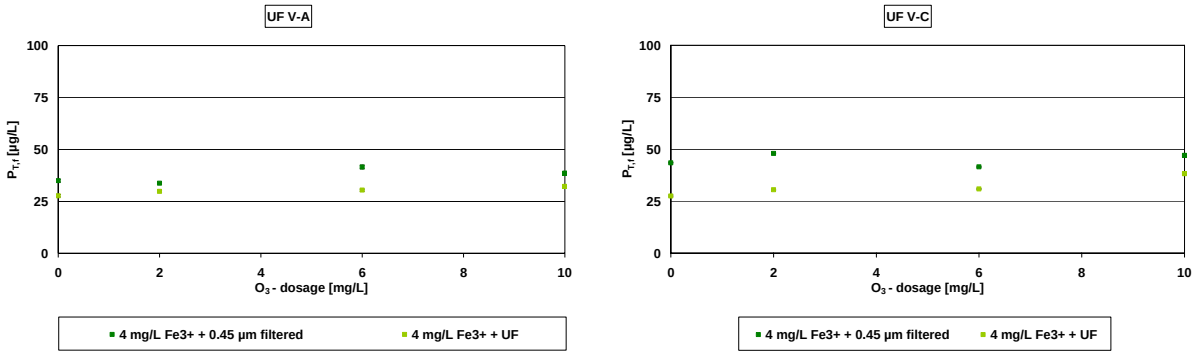


Table 10: Overview of results of BW trials – $P_{T,f}$ of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)

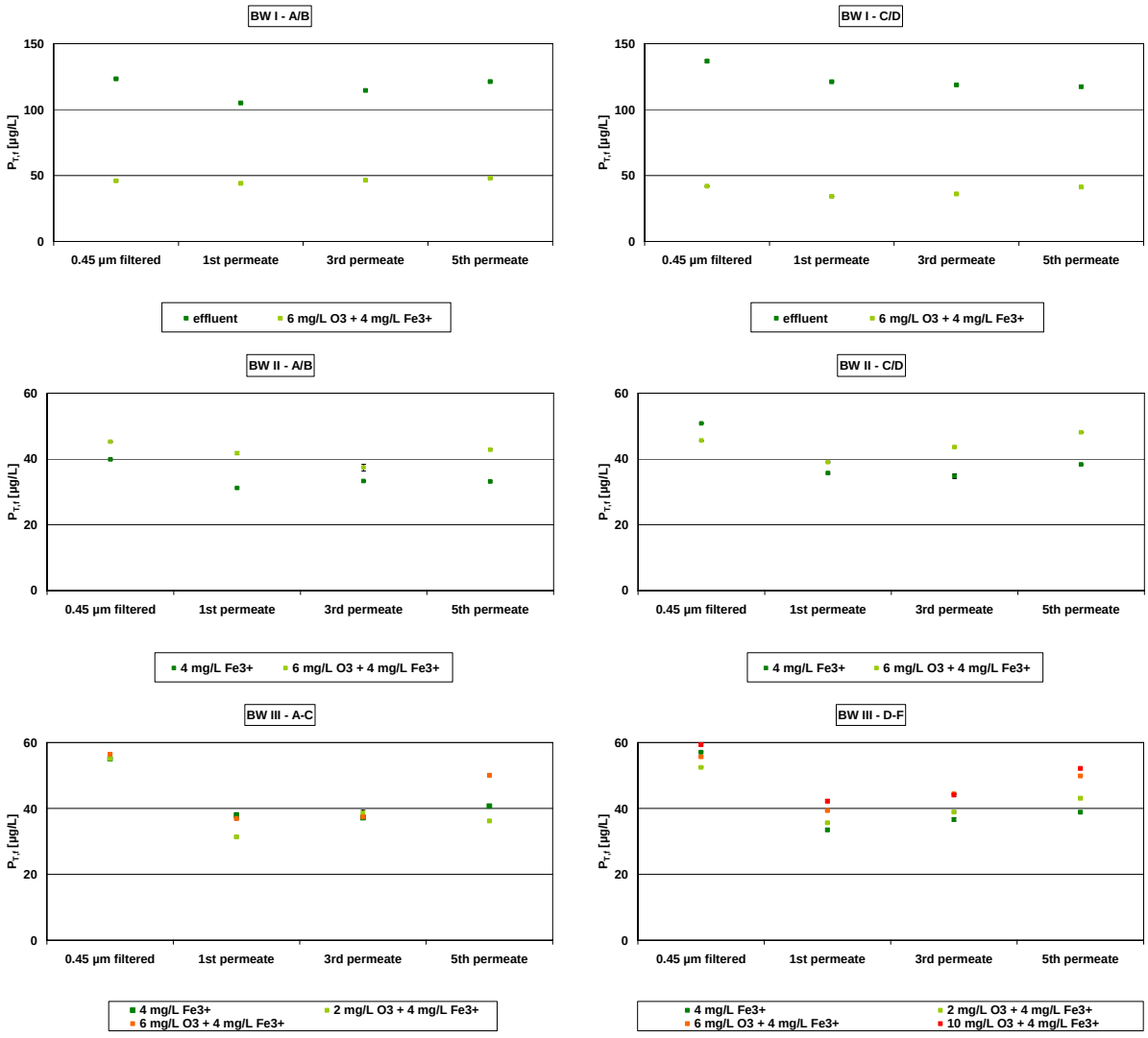
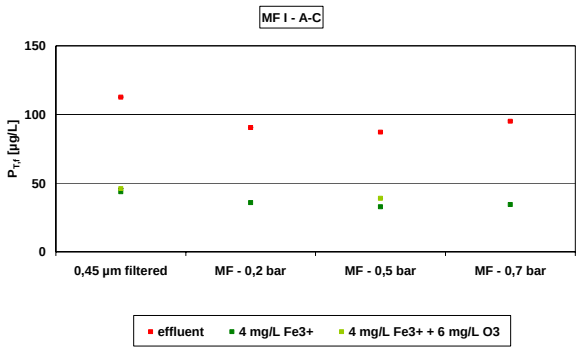
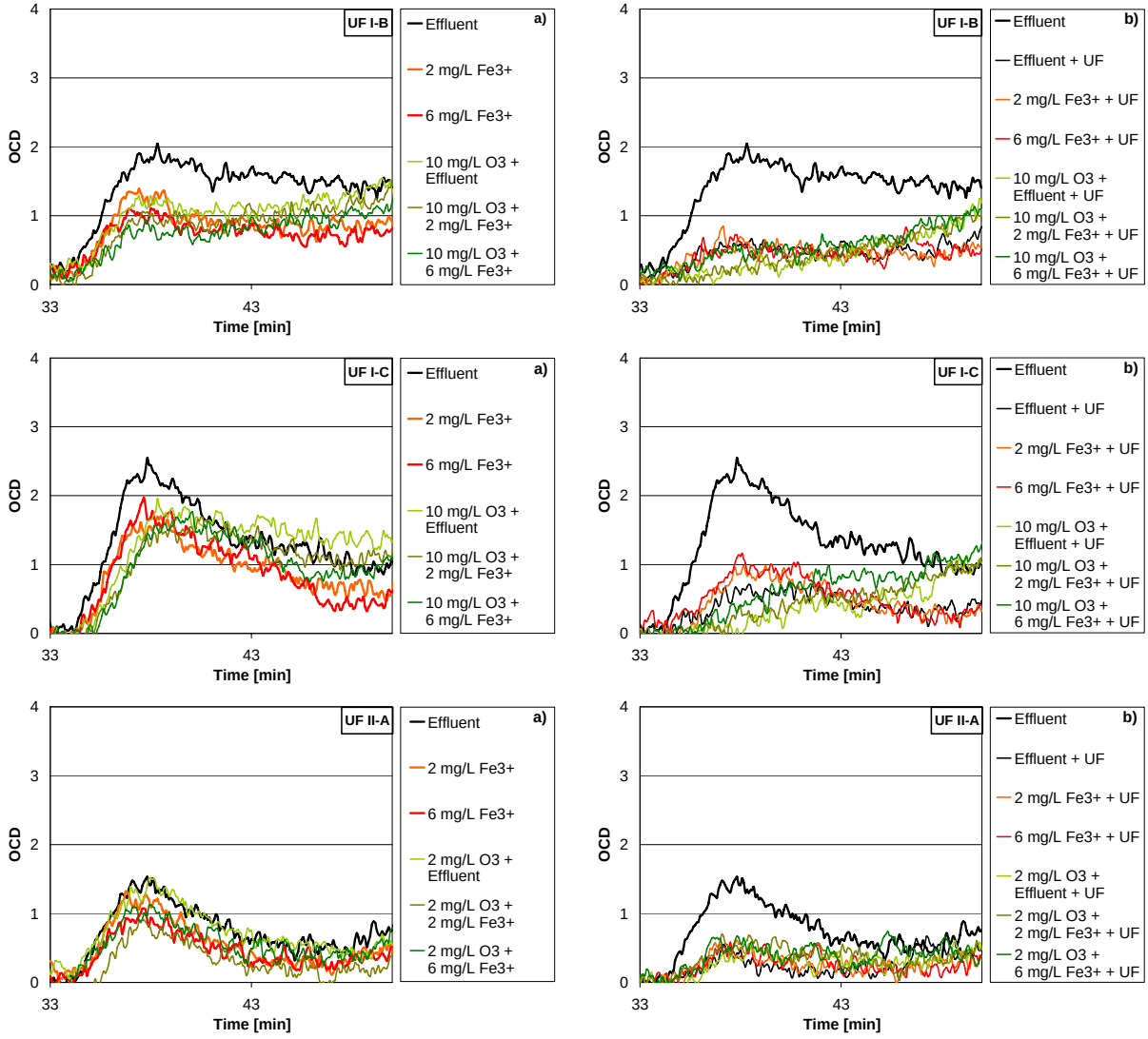


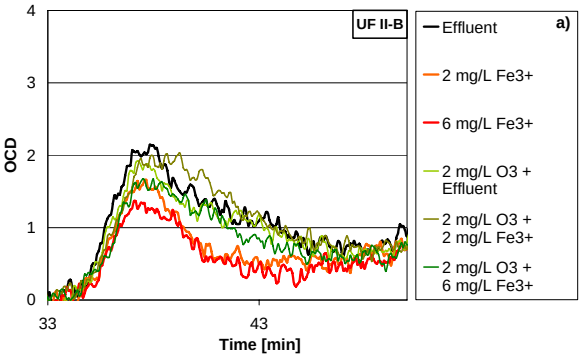
Table 11: $P_{T,f}$ results of MF trials

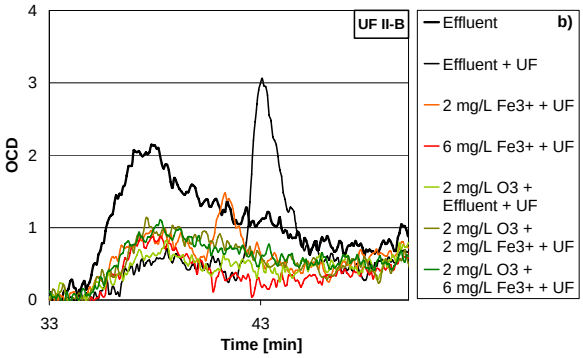


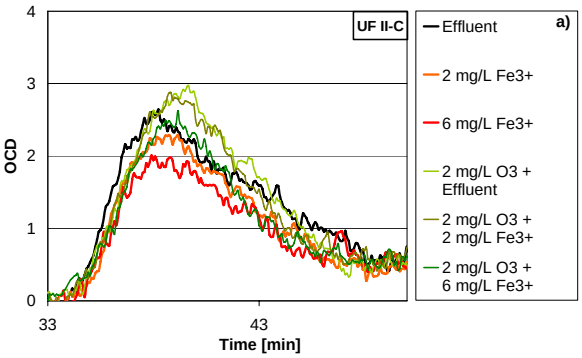
6.2.4 LC-OCD

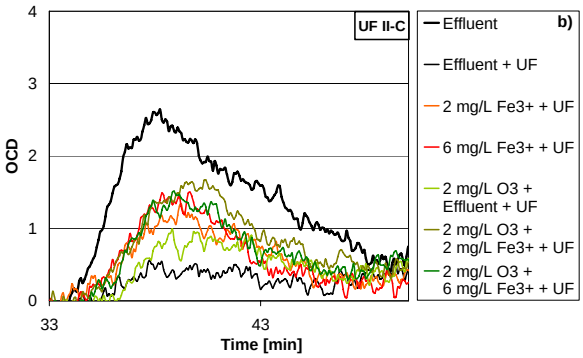
Table 12: Overview of results of UF trials – BP peaks of LC-OCD diagrams of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L)

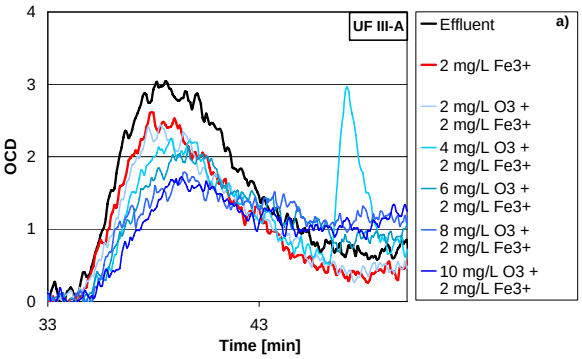


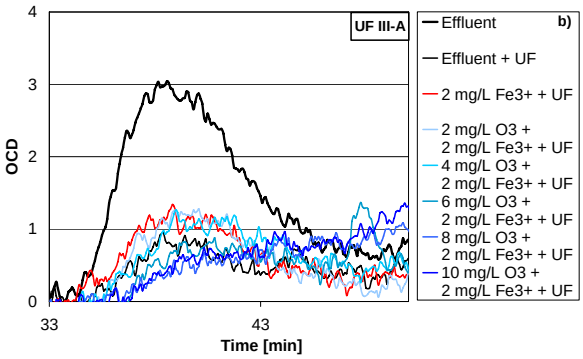

UF II-B
a)
Effluent
2 mg/L Fe3+
6 mg/L Fe3+
2 mg/L O3 + Effluent
2 mg/L O3 + 2 mg/L Fe3+
2 mg/L O3 + 6 mg/L Fe3+
OCD
Time [min]

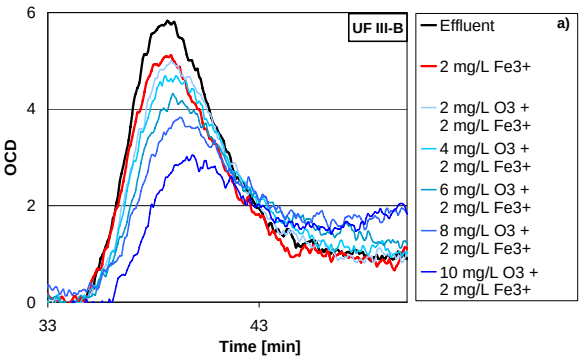

UF II-B
b)
Effluent
Effluent + UF
2 mg/L Fe3+ + UF
6 mg/L Fe3+ + UF
2 mg/L O3 + Effluent + UF
2 mg/L O3 + 2 mg/L Fe3+ + UF
2 mg/L O3 + 6 mg/L Fe3+ + UF
OCD
Time [min]

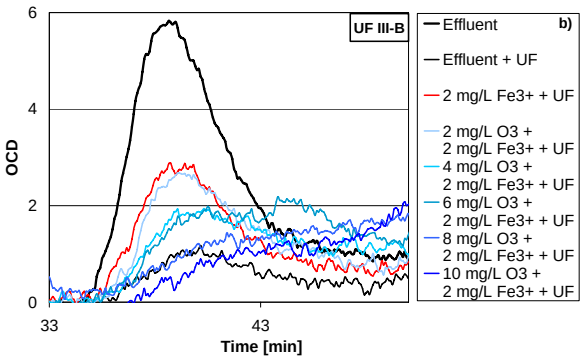

UF II-C
a)
Effluent
2 mg/L Fe3+
6 mg/L Fe3+
2 mg/L O3 + Effluent
2 mg/L O3 + 2 mg/L Fe3+
2 mg/L O3 + 6 mg/L Fe3+
OCD
Time [min]

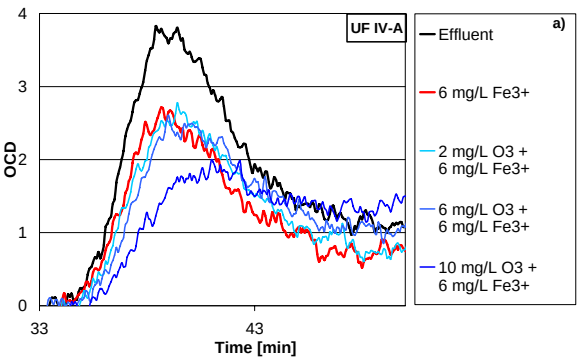

UF II-C
b)
Effluent
Effluent + UF
2 mg/L Fe3+ + UF
6 mg/L Fe3+ + UF
2 mg/L O3 + Effluent + UF
2 mg/L O3 + 2 mg/L Fe3+ + UF
2 mg/L O3 + 6 mg/L Fe3+ + UF
OCD
Time [min]

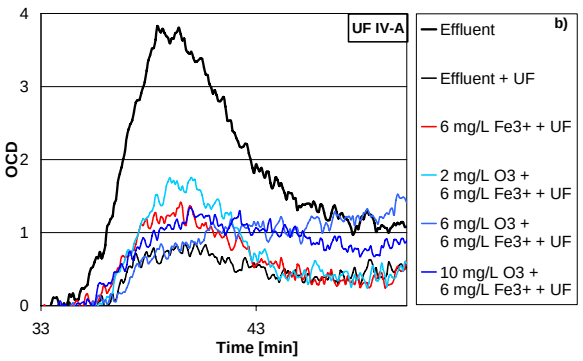

UF III-A
a)
Effluent
2 mg/L Fe3+
2 mg/L O3 + 2 mg/L Fe3+
4 mg/L O3 + 2 mg/L Fe3+
6 mg/L O3 + 2 mg/L Fe3+
8 mg/L O3 + 2 mg/L Fe3+
10 mg/L O3 + 2 mg/L Fe3+
OCD
Time [min]

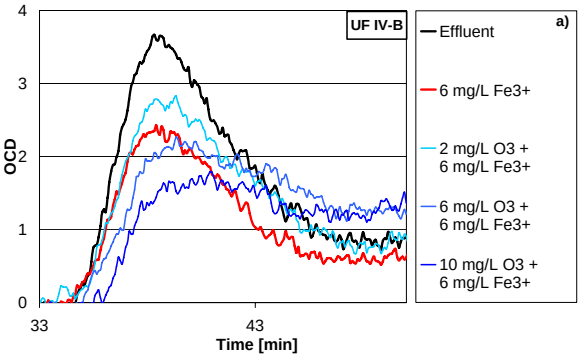

UF III-A
b)
Effluent
Effluent + UF
2 mg/L Fe3+ + UF
2 mg/L O3 + 2 mg/L Fe3+ + UF
4 mg/L O3 + 2 mg/L Fe3+ + UF
6 mg/L O3 + 2 mg/L Fe3+ + UF
8 mg/L O3 + 2 mg/L Fe3+ + UF
10 mg/L O3 + 2 mg/L Fe3+ + UF
OCD
Time [min]

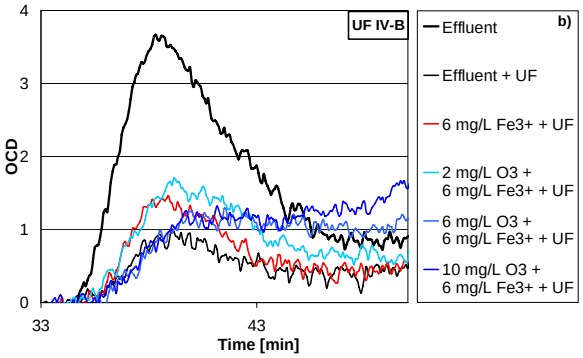

UF III-B
a)
Effluent
2 mg/L Fe3+
2 mg/L O3 + 2 mg/L Fe3+
4 mg/L O3 + 2 mg/L Fe3+
6 mg/L O3 + 2 mg/L Fe3+
8 mg/L O3 + 2 mg/L Fe3+
10 mg/L O3 + 2 mg/L Fe3+
OCD
Time [min]

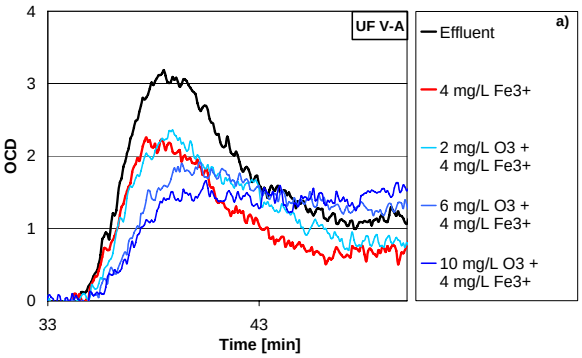

UF III-B
b)
Effluent
Effluent + UF
2 mg/L Fe3+ + UF
2 mg/L O3 + 2 mg/L Fe3+ + UF
4 mg/L O3 + 2 mg/L Fe3+ + UF
6 mg/L O3 + 2 mg/L Fe3+ + UF
8 mg/L O3 + 2 mg/L Fe3+ + UF
10 mg/L O3 + 2 mg/L Fe3+ + UF
OCD
Time [min]

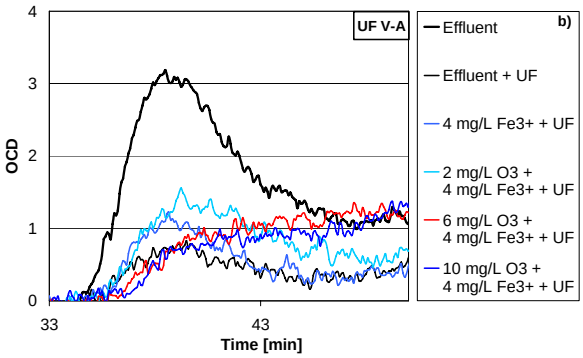

UF IV-A
a)
Effluent
6 mg/L Fe3+
2 mg/L O3 + 6 mg/L Fe3+
6 mg/L O3 + 6 mg/L Fe3+
10 mg/L O3 + 6 mg/L Fe3+
OCD
Time [min]

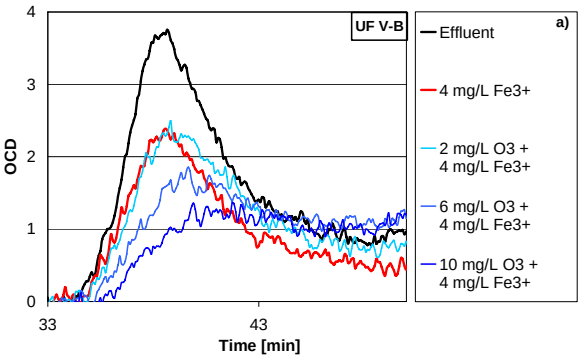

UF IV-A
b)
Effluent
Effluent + UF
6 mg/L Fe3+ + UF
2 mg/L O3 + 6 mg/L Fe3+ + UF
6 mg/L O3 + 6 mg/L Fe3+ + UF
10 mg/L O3 + 6 mg/L Fe3+ + UF
OCD
Time [min]

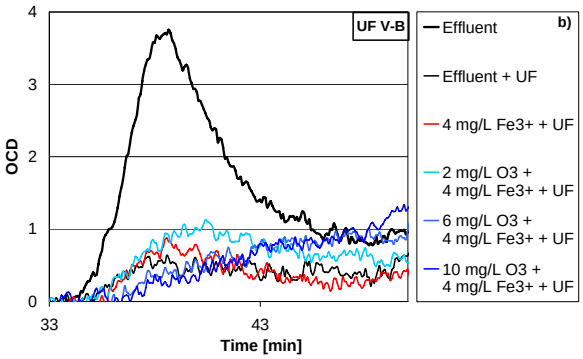

UF IV-B
a)
Effluent
6 mg/L Fe3+
2 mg/L O3 + 6 mg/L Fe3+
6 mg/L O3 + 6 mg/L Fe3+
10 mg/L O3 + 6 mg/L Fe3+
OCD
Time [min]

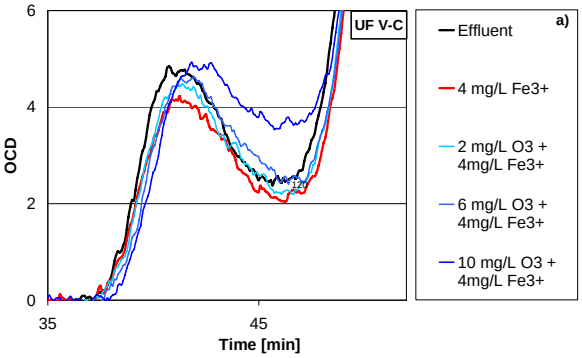

UF IV-B
b)
Effluent
Effluent + UF
6 mg/L Fe3+ + UF
2 mg/L O3 + 6 mg/L Fe3+ + UF
6 mg/L O3 + 6 mg/L Fe3+ + UF
10 mg/L O3 + 6 mg/L Fe3+ + UF
OCD
Time [min]


UF V-A
a)
Effluent
4 mg/L Fe3+
2 mg/L O3 + 4 mg/L Fe3+
6 mg/L O3 + 4 mg/L Fe3+
10 mg/L O3 + 4 mg/L Fe3+
OCD
Time [min]


UF V-A
b)
Effluent
Effluent + UF
4 mg/L Fe3+ + UF
2 mg/L O3 + 4 mg/L Fe3+ + UF
6 mg/L O3 + 4 mg/L Fe3+ + UF
10 mg/L O3 + 4 mg/L Fe3+ + UF
OCD
Time [min]


UF V-B
a)
Effluent
4 mg/L Fe3+
2 mg/L O3 + 4 mg/L Fe3+
6 mg/L O3 + 4 mg/L Fe3+
10 mg/L O3 + 4 mg/L Fe3+
OCD
Time [min]


UF V-B
b)
Effluent
Effluent + UF
4 mg/L Fe3+ + UF
2 mg/L O3 + 4 mg/L Fe3+ + UF
6 mg/L O3 + 4 mg/L Fe3+ + UF
10 mg/L O3 + 4 mg/L Fe3+ + UF
OCD
Time [min]


UF V-C
a)
Effluent
4 mg/L Fe3+
2 mg/L O3 + 4mg/L Fe3+
6 mg/L O3 + 4mg/L Fe3+
10 mg/L O3 + 4mg/L Fe3+
OCD
Time [min]

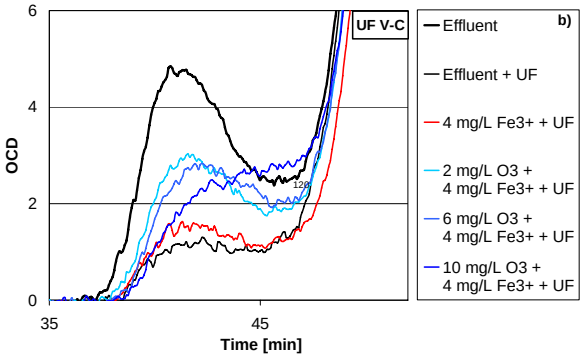
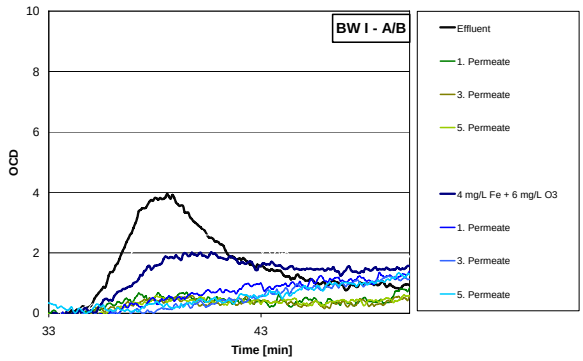
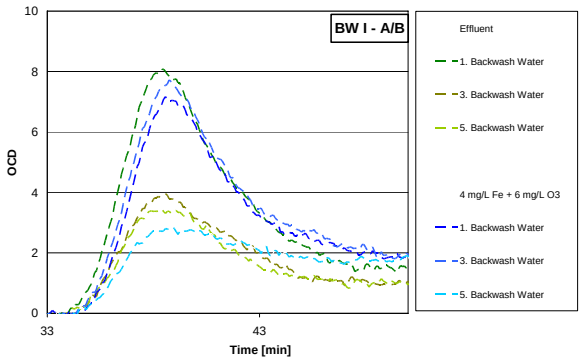
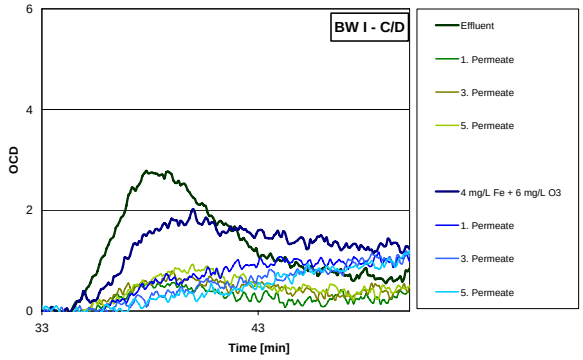
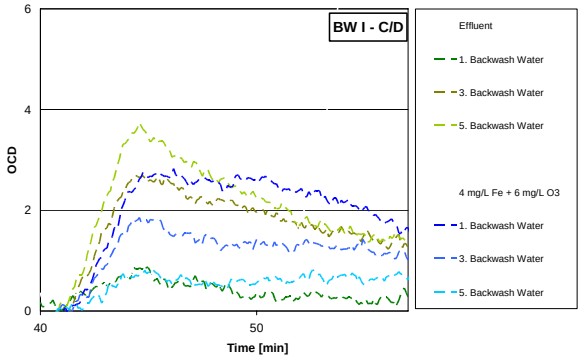

UF V-C
b)
Effluent
Effluent + UF
4 mg/L Fe3+ + UF
2 mg/L O3 + 4 mg/L Fe3+ + UF
6 mg/L O3 + 4 mg/L Fe3+ + UF
10 mg/L O3 + 4 mg/L Fe3+ + UF
OCD
Time [min]

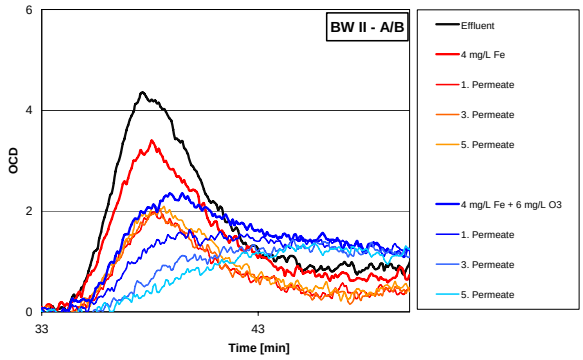
Table 13: Overview of results of BW trials – BP peaks of LC-OCD diagrams of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)

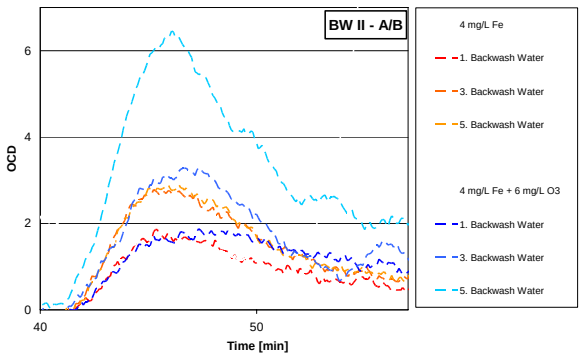


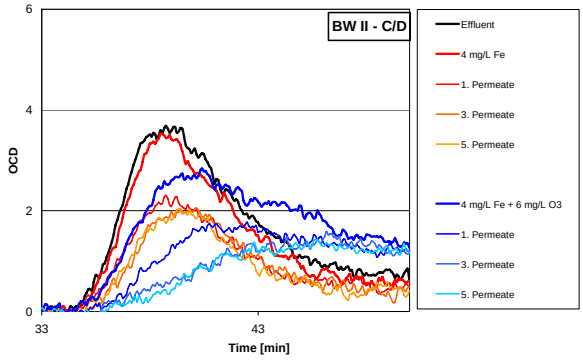


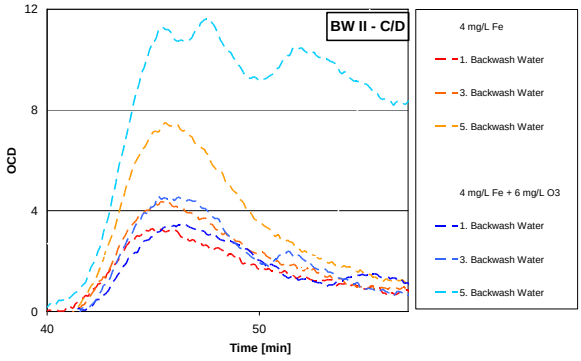












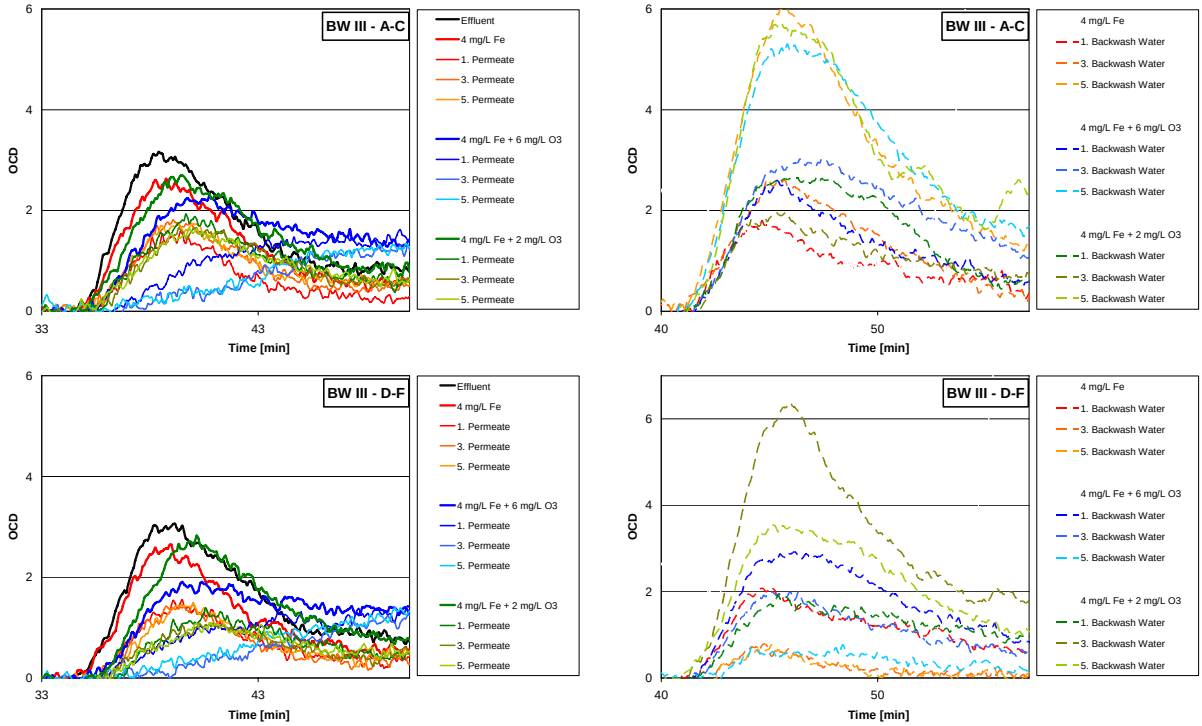
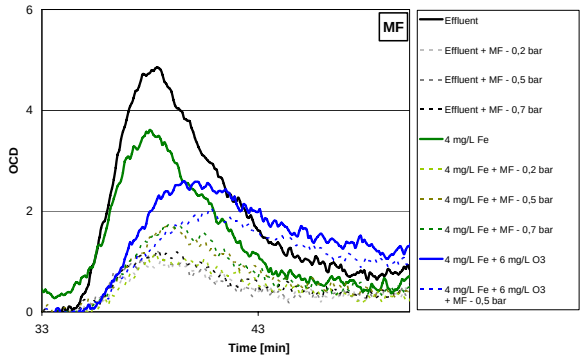
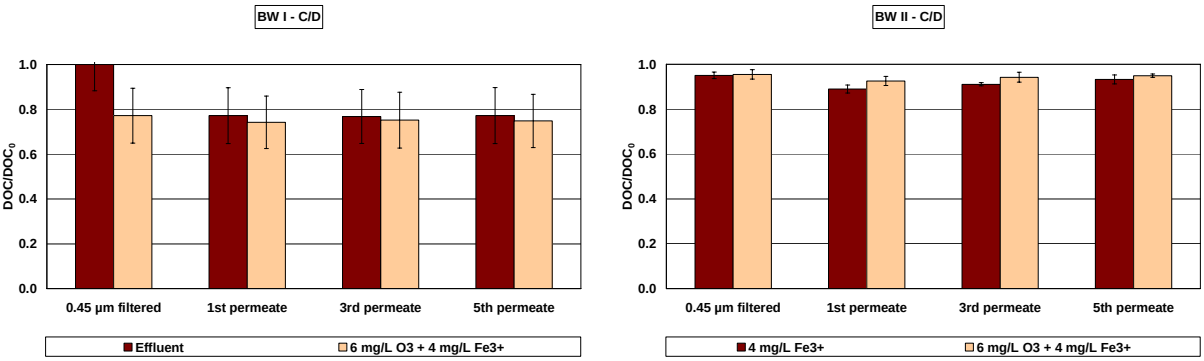


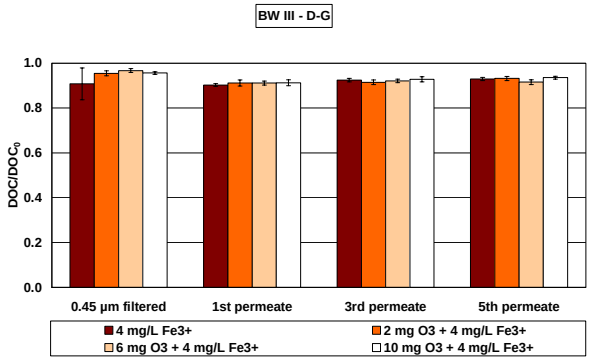
Table 14: BP peaks of LC-OCD diagrams - results of MF trials



6.2.5 DOC

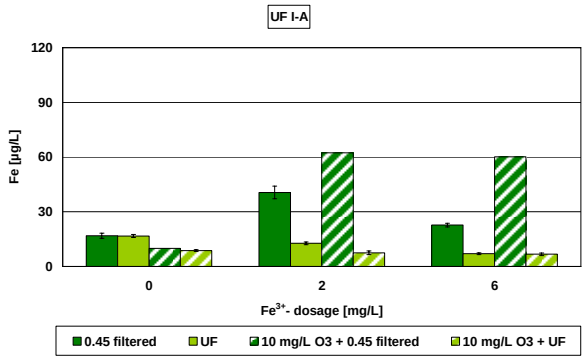
Table 15: Overview of results of BW trials – DOC of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)

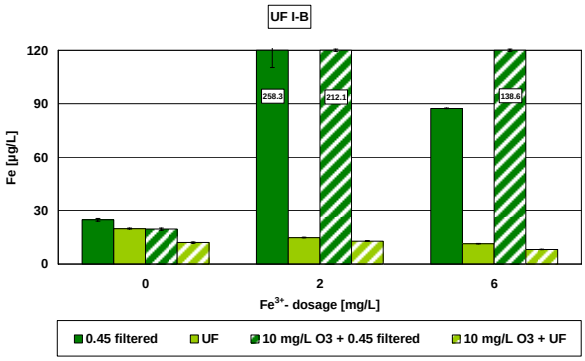


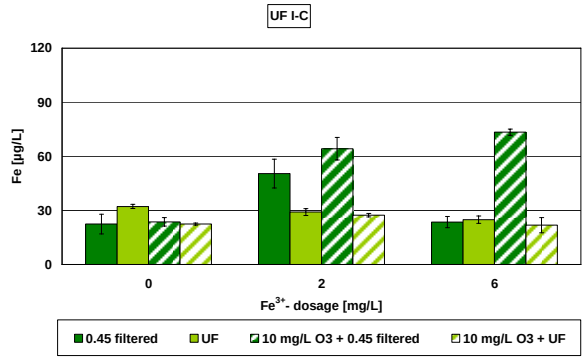


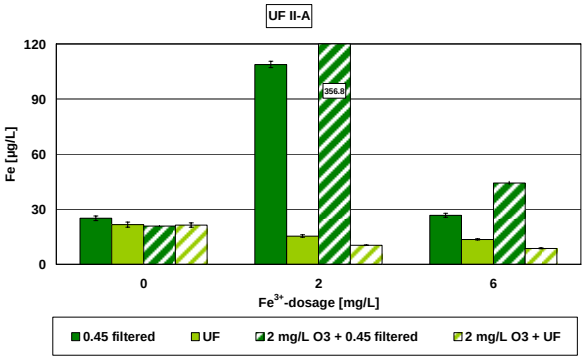
6.2.6 Residual Iron

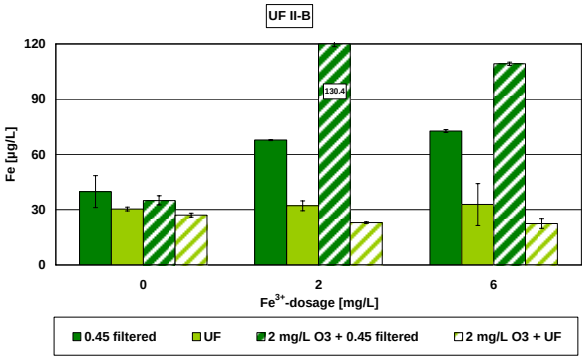
Table 16: Overview of results of UF trials – Residual iron of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L)

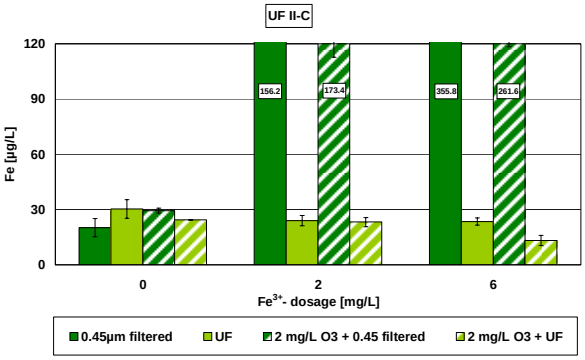


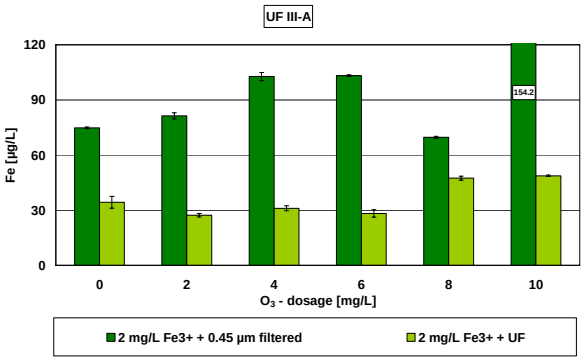


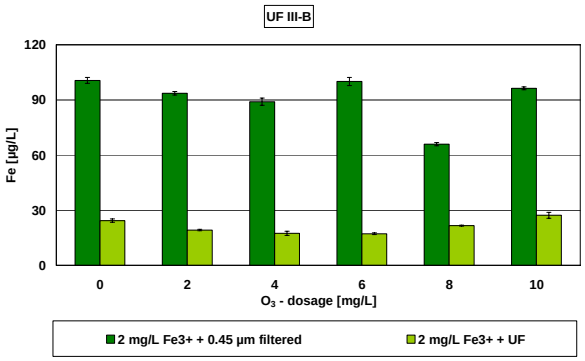


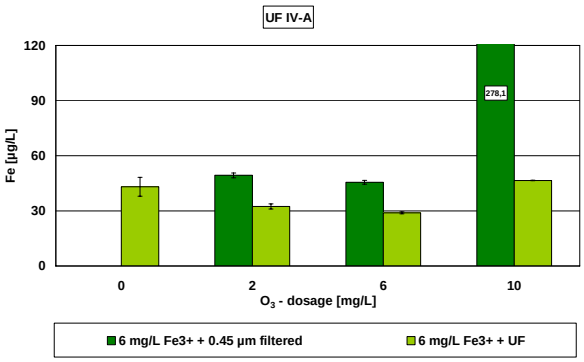


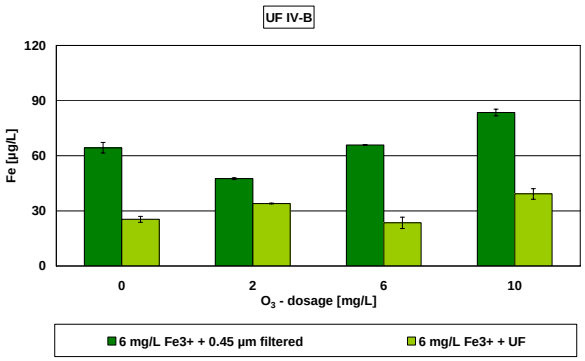


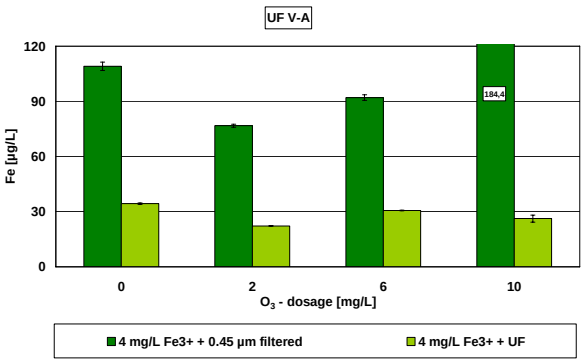

UF II-C
Fe [µg/L]
120
90
60
30
0
156.2
173.4
355.8
261.6
0
2
6
Fe3+- dosage [mg/L]
0.45µm filtered
UF
2 mg/L O3 + 0.45 filtered
2 mg/L O3 + UF

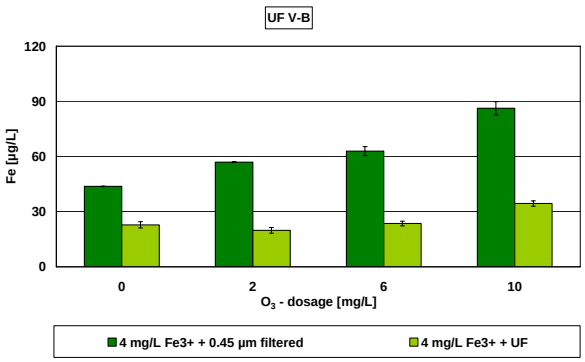

UF III-A
Fe [µg/L]
120
90
60
30
0
154.2
0
2
4
6
8
10
O3 - dosage [mg/L]
2 mg/L Fe3+ + 0.45 µm filtered
2 mg/L Fe3+ + UF


UF III-B
Fe [µg/L]
120
90
60
30
0
0
2
4
6
8
10
O3 - dosage [mg/L]
2 mg/L Fe3+ + 0.45 µm filtered
2 mg/L Fe3+ + UF


UF IV-A
Fe [µg/L]
120
90
60
30
0
278,1
0
2
6
10
O3 - dosage [mg/L]
6 mg/L Fe3+ + 0.45 µm filtered
6 mg/L Fe3+ + UF


UF IV-B
Fe [µg/L]
120
90
60
30
0
0
2
6
10
O3 - dosage [mg/L]
6 mg/L Fe3+ + 0.45 µm filtered
6 mg/L Fe3+ + UF


UF V-A
Fe [µg/L]
120
90
60
30
0
184,4
0
2
6
10
O3 - dosage [mg/L]
4 mg/L Fe3+ + 0.45 µm filtered
4 mg/L Fe3+ + UF


UF V-B
Fe [µg/L]
120
90
60
30
0
0
2
6
10
O3 - dosage [mg/L]
4 mg/L Fe3+ + 0.45 µm filtered
4 mg/L Fe3+ + UF

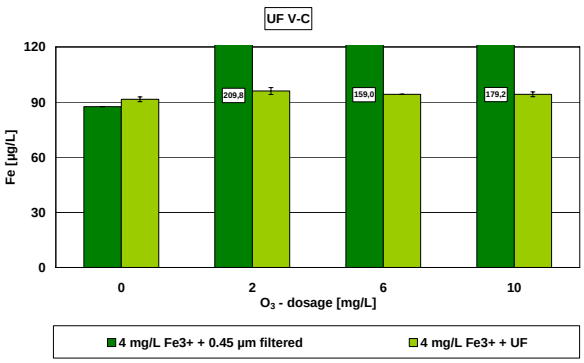
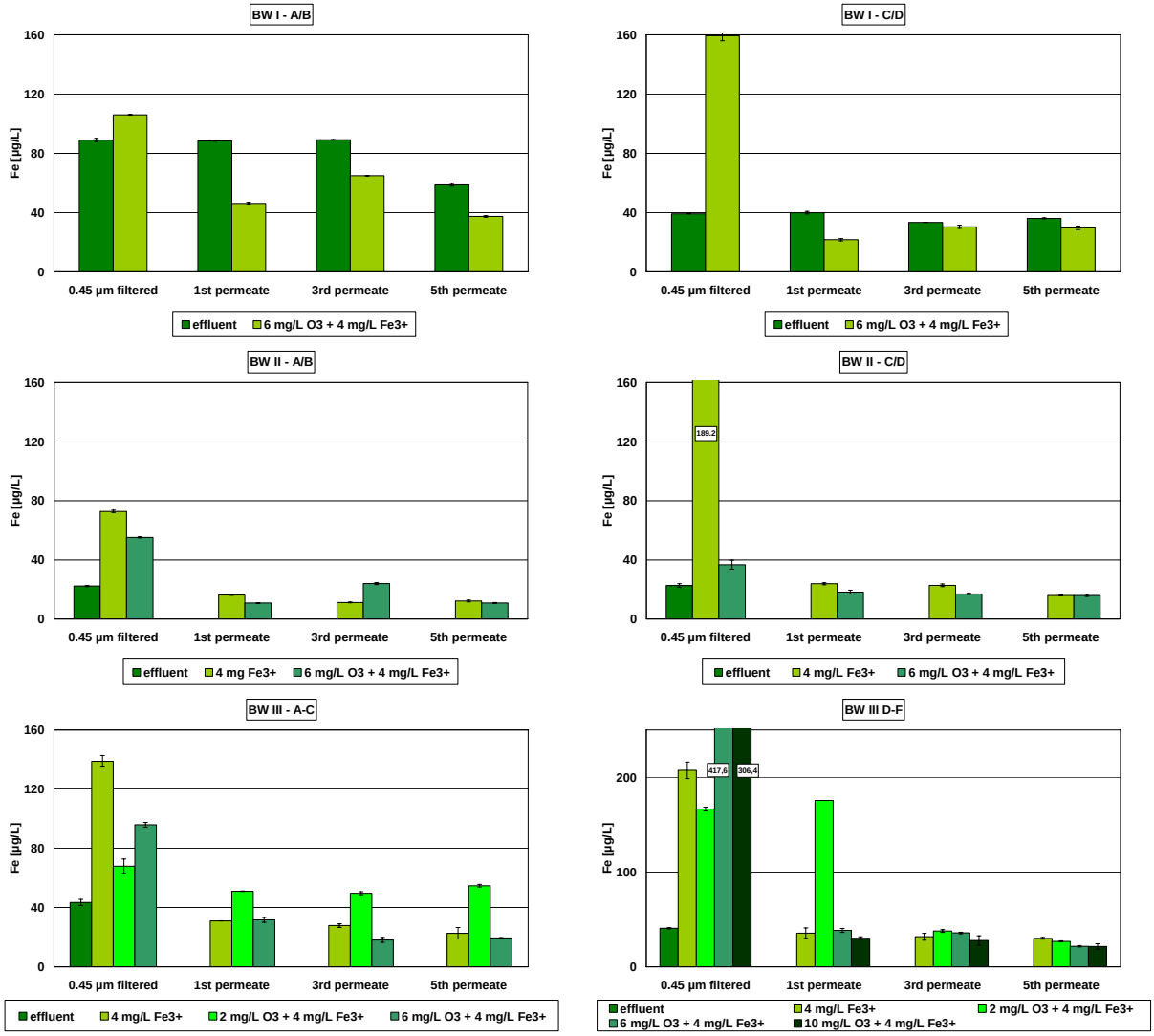
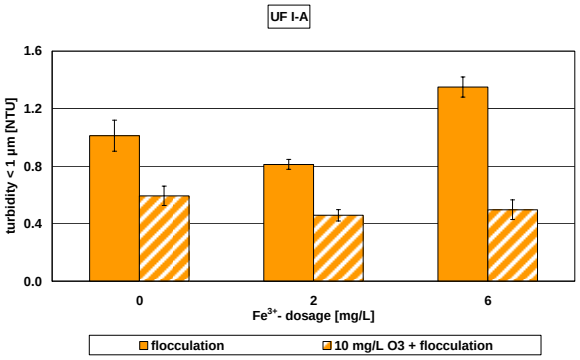

UF V-C
Fe [µg/L]
120
90
60
30
0
209,8
159,0
179,2
0
2
6
10
O3 - dosage [mg/L]
4 mg/L Fe3+ + 0.45 µm filtered
4 mg/L Fe3+ + UF

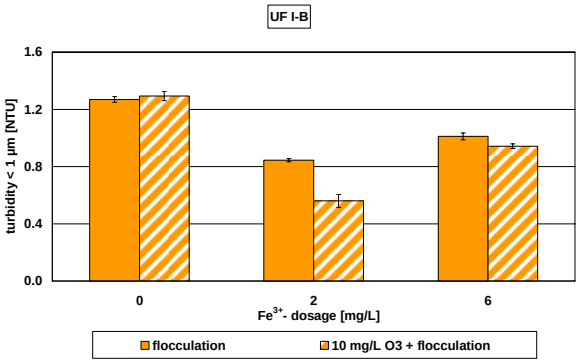
Table 17: Overview of results of BW trials – Residual iron of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)

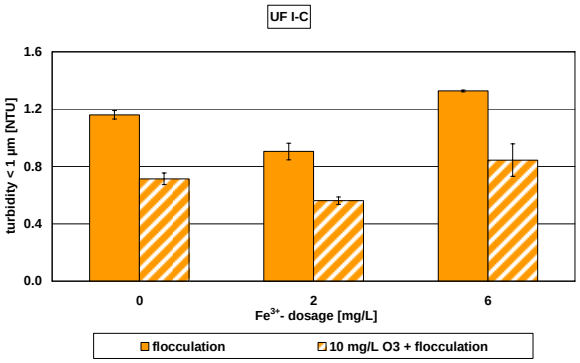


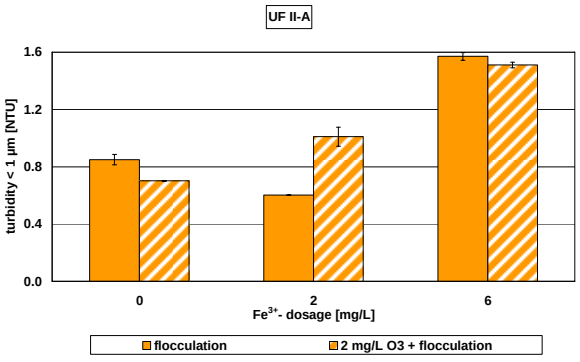
6.2.7 Turbidity < 1 µm

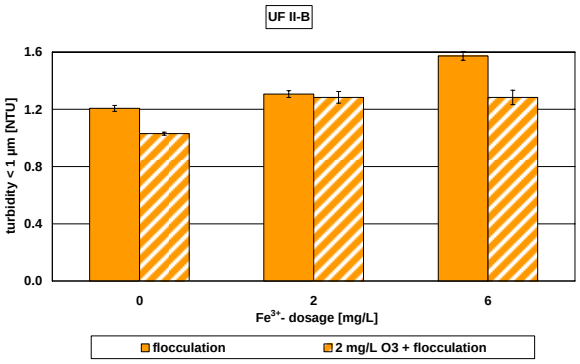
Table 18: Overview of results of UF trials – Turbidity < 1 µm of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L)



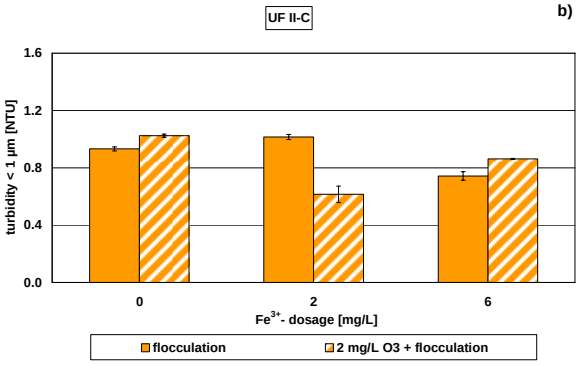


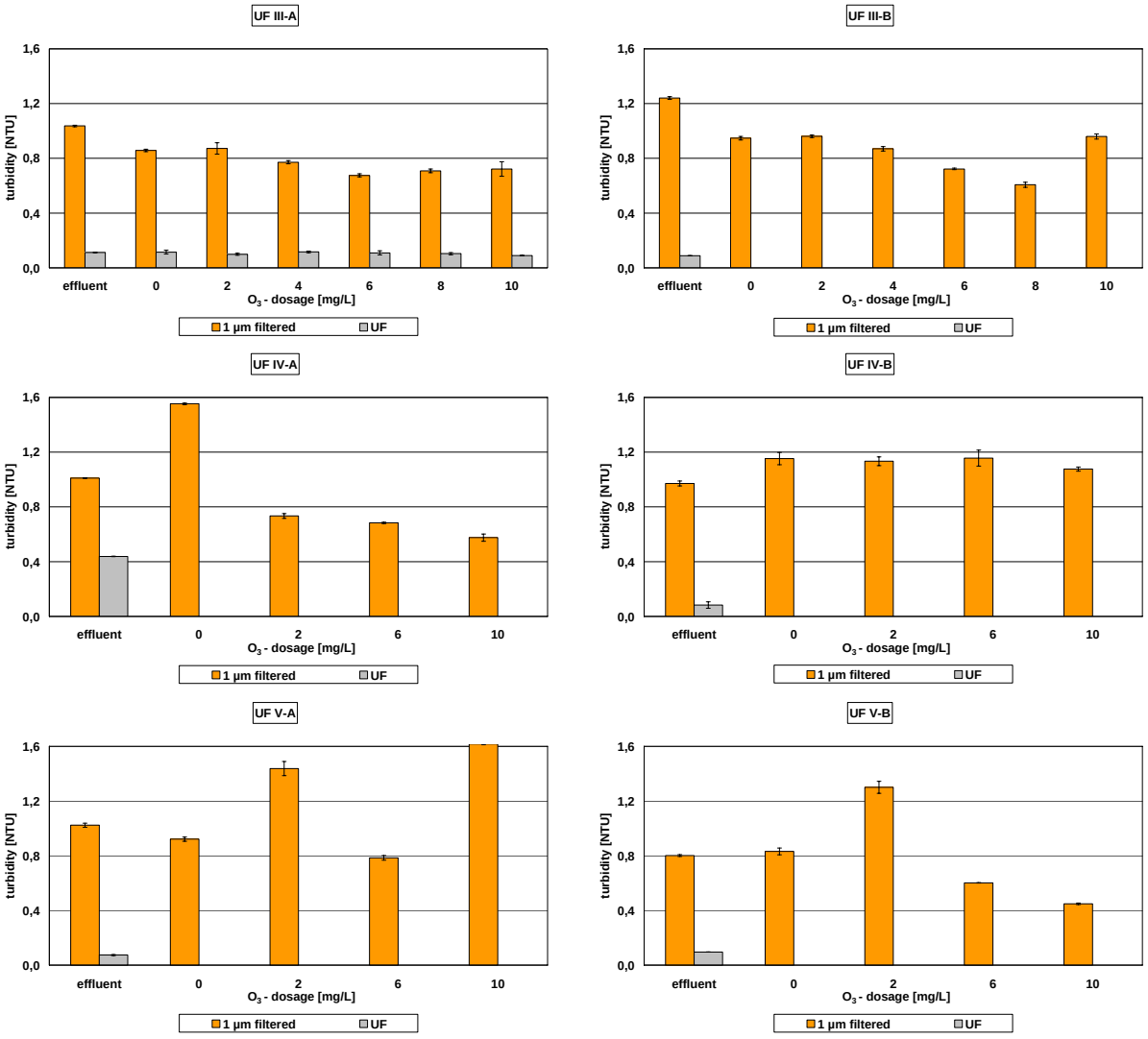






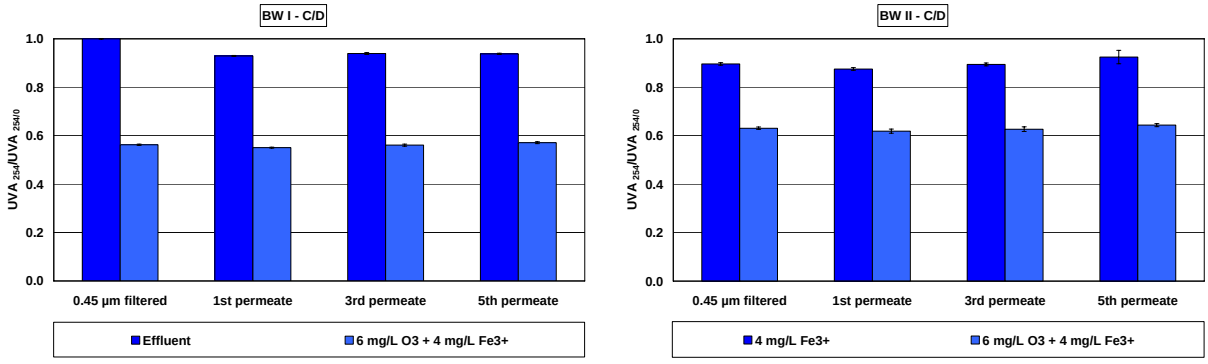
b)

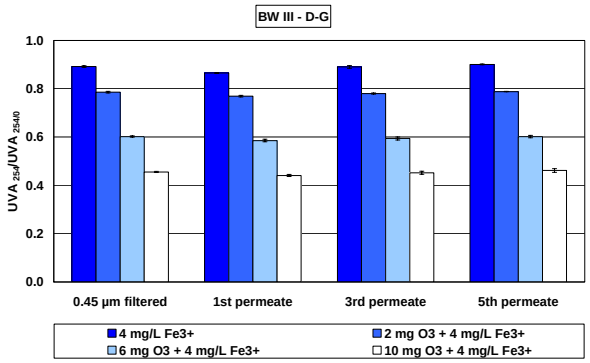




6.2.8 UVA 254

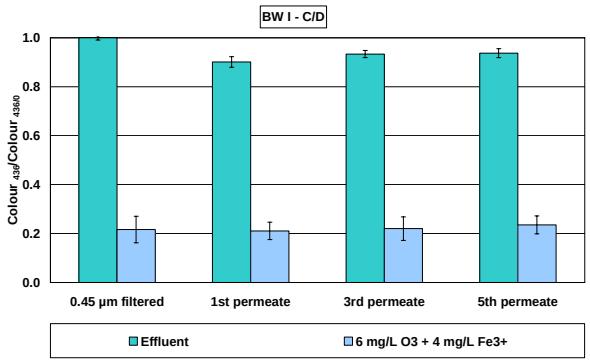
Table 19: Overview of results of BW trials – UVA 254 of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)

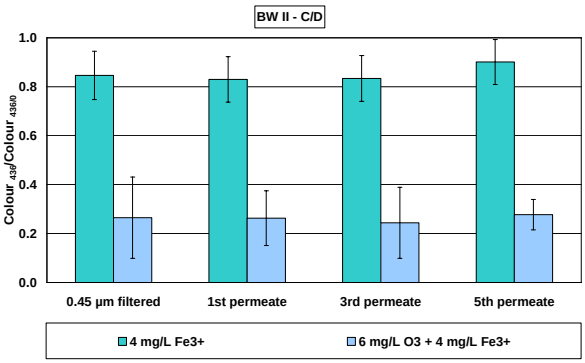


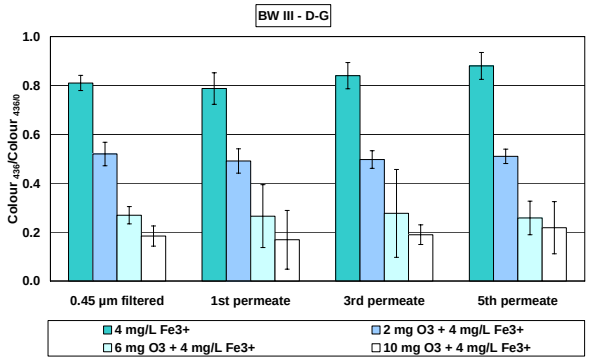


6.2.9 Colour 436

Table 20: Overview of results of BW trials – Colour 436 of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)

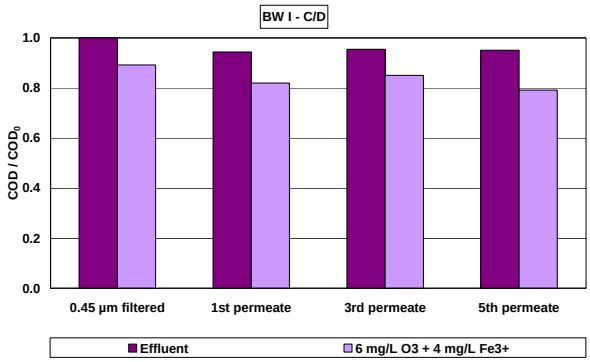


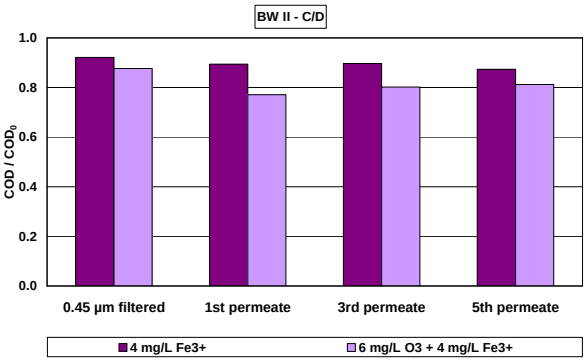


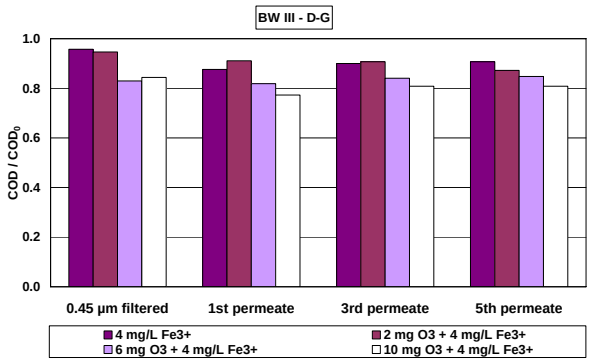


6.2.10 COD_f

Table 21: Overview of results of BW trials – COD_f of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L)







6.3 Data

6.3.1 $P_{T,f}$

Table 22: $P_{T,f}$ of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

		Trial A	Trial B	Trial C
Name of experiment	Sample	Measured value [µg/L]	Measured value [µg/L]	Measured value [µg/L]
UF I A-C	Effluent unfiltered	141	228 ± 1.06	188 ± 0.31
	Effluent 0.45 µm filtered	86	74 ± 0.46	104 ± 0.33
	2 mg/L Fe^{3+} 0.45 µm filtered	40	44 ± 0.20	46 ± 0.21
	6 mg/L Fe^{3+} 0.45 µm filtered	37	32 ± 0.11	30 ± 0.50
	Effluent + 10 mg/L O_3 0.45 µm filtered	87	84 ± 0.66	108 ± 0.33
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	46	51 ± 0.21	52 ± 0.15
	6 mg/L Fe^{3+} 10 mg/L O_3 0.45 µm filtered	38	37 ± 0.05	35 ± 0.38
	Effluent + UF	72	64 ± 0.43	87 ± 0.44
	2 mg/L Fe^{3+} +UF	36	31 ± 0.25	45 ± 0.77
	6 mg/L Fe^{3+} +UF	33	30 ± 0.29	27 ± 0.14

	Effluent + 10 mg/L O_3 + UF	87	116 ± 0.69	130 ± 0.08
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	41	52 ± 0.47	50 ± 0.36
	6 mg/L Fe^{3+} 10 mg/L O_3 + UF	34	35 ± 0.17	33 ± 0.52
UF II A-C	Effluent unfiltered		400 ± 1.00	
	Effluent 0.45 µm filtered	99 ± 1.21	199 ± 1.55	105 ± 0.25
	2 mg/L Fe^{3+} 0.45 µm filtered	55 ± 0.14	67 ± 0.21	45 ± 0.30
	6 mg/L Fe^{3+} 0.45 µm filtered	42 ± 0.42	55 ± 0.55	32 ± 0.74
	Effluent + 2mg/L O_3 0.45 µm filtered	98 ± 0.28	174 ± 0.58	99 ± 0.11
	2 mg/L Fe^{3+} + 2mg/L O_3 0.45 µm filtered	57 ± 0.06	103 ± 0.30	49 ± 0.41
	6 mg/L Fe^{3+} 2mg/L O_3 0.45 µm filtered	47 ± 0.24	48 ± 1.09	149 ± 0.10
	Effluent + UF	78 ± 0.46	94 ± 1.25	75 ± 0.33
	2 mg/L Fe^{3+} +UF	40 ± 0.07	37 ± 0.54	30 ± 0.48
	6 mg/L Fe^{3+} +UF	32 ± 0.20	30 ± 0.45	22 ± 0.28
	Effluent + 2mg/L O_3 + UF	94 ± 0.07	102 ± 0.09	96 ± 0.41
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	42 ± 0.18	44 ± 0.32	40 ± 0.77
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	32 ± 0.16	42 ± 0.36	52 ± 0.83
UF III A-B	Effluent unfiltered		356 ± 0.24	
	Effluent 0.45 µm filtered	137 ± 0.17	153 ± 0.30	
	2 mg/L Fe^{3+} 0.45 µm filtered	54 ± 0.61	67 ± 0.15	
	2 mg/L Fe^{3+} + 2mg/L O_3 0.45 µm filtered	58 ± 0.27	65 ± 0.04	
	2 mg/L Fe^{3+} + 4 mg/L O_3 0.45 µm filtered	61 ± 0.24	69 ± 0.21	
	2 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	57 ± 0.40	70 ± 0.30	
	2 mg/L Fe^{3+} + 8 mg/L O_3 0.45 µm filtered	65 ± 0.46	71 ± 0.32	
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	69 ± 0.23	85 ± 0.20	
	Effluent + UF	127 ± 0.15	157 ± 0.53	
	2 mg/L Fe^{3+} +UF	49 ± 0.43	52 ± 0.14	
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	50 ± 0.27	58 ± 0.13	
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	47 ± 0.23	63 ± 0.36	
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	52 ± 0.50	71 ± 0.19	
	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	56 ± 0.17	72 ± 0.40	
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	57 ± 0.30	78 ± 0.24	
UF IV A-B	Effluent unfiltered	763	246 ± 0.84	
	Effluent 0.45 µm filtered	252 ± 0.95	101 ± 0.38	

	6 mg/L Fe^{3+} 0.45 µm filtered	51 ± 0.33	32 ± 0.67	
	6 mg/L Fe^{3+} + 2 mg/L O_3 0.45 µm filtered	43 ± 0.25	36 ± 0.16	
	6 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	44 ± 0.06	37 ± 0.45	
	6 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	50 ± 0.19	42 ± 0.38	
	Effluent + UF	219 ± 0.78	83 ± 0.63	
	6 mg/L Fe^{3+} + UF	34 ± 0.37	111 ± 0.33	
	6 mg/L Fe^{3+} + 2 mg/L O_3 + UF	38 ± 0.15	35 ± 0.70	
	6 mg/L Fe^{3+} + 6 mg/L O_3 + UF	43	32 ± 0.39	
	6 mg/L Fe^{3+} + 10 mg/L O_3 + UF	47	35 ± 0.16	
UF V A-C	Effluent unfiltered	314 ± 0.73	207 ± 0.53	337 ± 0.27
	Effluent 0.45 µm filtered	90 ± 0.39	112 ± 0.35	123 ± 0.41
	4 mg/L Fe^{3+} 0.45 µm filtered	35 ± 0.71	35 ± 0.39	43 ± 0.09
	4 mg/L Fe^{3+} + 2 mg/L O_3 0.45 µm filtered	34 ± 0.37	36 ± 0.26	48 ± 0.20
	4 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	42 ± 0.87	38 ± 0.70	41 ± 0.22
	4 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	39 ± 0.73	46 ± 0.30	47 ± 0.20
	Effluent + UF	72 ± 0.42	85 ± 0.61	86 ± 0.23
	4 mg/L Fe^{3+} 1 µm filtered	28 ± 0.63	29 ± 0.34	28 ± 0.45
	4 mg/L Fe^{3+} + 2 mg/L O_3 + UF	30 ± 0.54	29 ± 0.19	30 ± 0.25
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF	30 ± 0.51	34 ± 0.28	31 ± 0.17
	4 mg/L Fe^{3+} + 10 mg/L O_3 + UF	32 ± 0.15	46 ± 0.20	38 ± 0.16

Table 23: $P_{T,f}$ of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

		Trial 1	Trial 2	Trial 3
Name of experiment	Sample	Measured value [µg/L]	Measured value [µg/L]	Measured value [µg/L]
BW I	Effluent unfiltered	290 ± 0.79		
BW I A/C	Effluent 0.45 µm filtered	123 ± 0.45	137 ± 0.84	
	Effluent + UF 1st permeate	105 ± 0.17	121 ± 0.40	
	Effluent + UF 3rd permeate	115 ± 0.23	119 ± 0.08	
	Effluent + UF 5th permeate	121 ± 0.25	117 ± 0.64	

BW I B/D	4 mg/L Fe^{3+} + 6 mg/L O_3	46 ± 0.57	42 ± 0.16		
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	44 ± 0.57	34 ± 0.25		
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	46 ± 0.09	36 ± 0.13		
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	48 ± 0.38	41 ± 0.35		
BW II	Effluent unfiltered		419 ± 0.47	383 ± 0.95	
	Effluent 0.45 µm filtered		96 ± 0.18	113 ± 0.27	
BW II A/C	4 mg/L Fe^{3+}		40 ± 0.30	51 ± 0.10	
	4 mg/L Fe^{3+} + UF 1st permeate		31 ± 0.26	36 ± 0.25	
	4 mg/L Fe^{3+} + UF 3rd permeate		33 ± 0.17	35 ± 0.73	
	4 mg/L Fe^{3+} + UF 5th permeate		33 ± 0.26	38 ± 0.19	
BW II B/D	4 mg/L Fe^{3+}+ 6 mg/L O_3		45 ± 0.10	46 ± 0.12	
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate		42 ± 0.36	39 ± 0.16	
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate		37 ± 1.02	44 ± 0.15	
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate		43 ± 0.27	48 ± 0.08	
BW III	Effluent unfiltered	334 ± 0.43	420 ± 0.87		
	Effluent 0.45 µm filtered	130 ± 0.53	164 ± 0.34		
BW III A/D	4 mg/L Fe^{3+}	55 ± 0.14	57 ± 0.19		
	4 mg/L Fe^{3+} + UF 1st permeate	38 ± 0.81	33 ± 0.39		
	4 mg/L Fe^{3+} + UF 3rd permeate	37 ± 0.49	37 ± 0.52		
	4 mg/L Fe^{3+} + UF 5th permeate	41 ± 0.26	39 ± 0.31		
BW III B/E	4 mg/L Fe^{3+}+ 2 mg/L O_3	55 ± 0.18	52 ± 0.14		
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	31 ± 0.29	36 ± 0.19		

	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	39 ± 0.87	39 ± 0.29
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	36 ± 0.27	43 ± 0.24
BW III C/F	4 mg/L Fe^{3+}+ 6 mg/L O_3	56 ± 0.15	56 ± 0.28
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	37 ± 0.24	39 ± 0.20
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	37 ± 0.65	44 ± 0.22
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	50 ± 0.41	50 ± 0.10
BW III G	4 mg/L Fe^{3+}+ 10 mg/L O_3		59 ± 0.32
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate		42 ± 0.45
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate		44 ± 0.39
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate		52 ± 0.21

Table 24: $P_{T,f}$ results of MF trials

Name of experiment	Sample	Measured value [µg/L]
MF I A-C	Effluent 0.45 µm filtered	113 ± 0.17
	Effluent + MF 0.2 bar	90 ± 0.21
	Effluent + MF 0.5 bar	87 ± 0.18
	Effluent + MF 0.7 bar	95 ± 0.60
	4 mg/L Fe^{3+} 0.45 µm filtered	44 ± 0.07
	4 mg/L Fe^{3+} +UF 0.2 bar	36 ± 0.02
	4 mg/L Fe^{3+} +UF 0.5 bar	33 ± 0.09
	4 mg/L Fe^{3+} +UF 0.7 bar	34 ± 0.08
	4 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	46 ± 0.08
	4 mg/L Fe^{3+} + 6 mg/L O_3 0.5 bar	39 ± 0.06

6.3.2 PO_4-P

Table 25: PO_4-P of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

	Trial A	Trial B	Trial C

Name of experiment	Sample	Measured value [µg/L]	Measured value [µg/L]	Measured value [µg/L]
UF I A-C	Effluent 0.45 µm filtered	46 ± 0.72	34 ± 0.30	57 ± 0.32
	2 mg/L Fe^{3+} 0.45 µm filtered	11 ± 0.25	13 ± 0.19	17 ± 0.36
	6 mg/L Fe^{3+} 0.45 µm filtered	7 ± 0.20	8 ± 0.20	13 ± 0.43
	Effluent + 10 mg/L O_3 0.45 µm filtered	45 ± 0.93	39 ± 0.22	69 ± 1.03
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	15 ± 0.96	15 ± 0.22	26 ± 0.18
	6 mg/L Fe^{3+} 10 mg/L O_3 0.45 µm filtered	8 ± 0.51	10 ± 0.20	15 ± 0.51
	Effluent + UF	39 ± 0.37	30 ± 0.28	51 ± 0.35
	2 mg/L Fe^{3+} +UF	7 ± 0.23	8 ± 0.13	11 ± 0.21
	6 mg/L Fe^{3+} +UF	6 ± 0.40	7 ± 0.13	10 ± 0.32
	Effluent + 10 mg/L O_3 + UF	49 ± 0.43	47 ± 0.63	73 ± 0.32
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	11 ± 0.35	17 ± 0.16	20 ± 0.12
	6 mg/L Fe^{3+} 10 mg/L O_3 + UF	8 ± 0.39	9 ± 0.39	11 ± 0.22
UF II A-C	Effluent 0.45 µm filtered	53 ± 0.28	73 ± 0.21	55 ± 1.16
	2 mg/L Fe^{3+} 0.45 µm filtered	14 ± 0.07	23 ± 0.15	21 ± 0.48
	6 mg/L Fe^{3+} 0.45 µm filtered	11 ± 0.79	75 ± 0.45	17 ± 0.26
	Effluent + 2mg/L O_3 0.45 µm filtered	59 ± 0.75	79 ± 0.24	63 ± 0.36
	2 mg/L Fe^{3+} + 2mg/L O_3 0.45 µm filtered	18 ± 0.40	26 ± 0.15	25 ± 0.23
	6 mg/L Fe^{3+} 2mg/L O_3 0.45 µm filtered	11 ± 0.16	17 ± 0.49	18 ± 0.75
	Effluent + UF	48 ± 1.35	77 ± 0.71	57 ± 1.16
	2 mg/L Fe^{3+} +UF	9 ± 0.67	21 ± 0.15	15 ± 0.29
	6 mg/L Fe^{3+} +UF	10 ± 0.57	22 ± 0.96	13 ± 0.18
	Effluent + 2mg/L O_3 + UF	54 ± 0.44	82 ± 0.88	67 ± 1.09
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	10 ± 0.20	56 ± 0.70	20 ± 0.65
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	10 ± 0.15	33 ± 0.72	14 ± 1.10
UF III A-B	Effluent 0.45 µm filtered	82 ± 0.85	107 ± 1.06	
	2 mg/L Fe^{3+} 0.45 µm filtered	21 ± 1.10	24 ± 0.25	
	2 mg/L Fe^{3+} + 2mg/L O_3 0.45 µm filtered	24 ± 1.02	23 ± 0.61	
	2 mg/L Fe^{3+} + 4 mg/L O_3 0.45 µm filtered	30 ± 1.04	31 ± 0.63	
	2 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	28 ± 1.13	36 ± 0.67	
	2 mg/L Fe^{3+} + 8 mg/L O_3 0.45 µm filtered	32 ± 1.20	37 ± 0.36	
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	31 ± 1.08	46 ± 0.54	
	Effluent + UF	79 ± 1.03	105 ± 1.01	

	2 mg/L Fe^{3+} +UF	17 ± 0.40	19 ± 0.43	
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	18 ± 0.41	23 ± 0.64	
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	19 ± 0.32	31 ± 0.06	
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	22 ± 0.27	34 ± 0.79	
	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	24 ± 0.28	36 ± 0.08	
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	25 ± 0.38	40 ± 0.13	
UF IV A-B	Effluent 0.45 µm filtered	199 ± 0.53	78 ± 1.14	
	6 mg/L Fe^{3+} 0.45 µm filtered	13 ± 0.19	17 ± 0.39	
	6 mg/L Fe^{3+} + 2 mg/L O_3 0.45 µm filtered	15 ± 0.09	18 ± 0.29	
	6 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	17 ± 0.23	18 ± 0.40	
	6 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	18 ± 0.18	17 ± 0.38	
	Effluent + UF	187 ± 0.52	69 ± 0.79	
	6 mg/L Fe^{3+} + UF	12 ± 0.59	13 ± 0.25	
	6 mg/L Fe^{3+} + 2 mg/L O_3 + UF	12 ± 0.05	14 ± 0.46	
	6 mg/L Fe^{3+} + 6 mg/L O_3 + UF	13 ± 0.25	14 ± 0.63	
	6 mg/L Fe^{3+} + 10 mg/L O_3 + UF	14 ± 0.12	14 ± 0.58	
UF V A-C	Effluent 0.45 µm filtered	67 ± 0.51	67 ± 0.89	73 ± 0.07
	4 mg/L Fe^{3+} 0.45 µm filtered	17 ± 0.68	10 ± 0.38	16 ± 0.22
	4 mg/L Fe^{3+} + 2 mg/L O_3 0.45 µm filtered	16 ± 0.93	11 ± 0.49	17 ± 0.20
	4 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	17 ± 0.20	11 ± 0.38	16 ± 0.41
	4 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	19 ± 0.66	14 ± 0.36	19 ± 0.32
	Effluent + UF	60 ± 0.39	61 ± 0.70	58 ± 0.47
	4 mg/L Fe^{3+} 1 µm filtered	14 ± 0.32	8 ± 0.44	12 ± 0.54
	4 mg/L Fe^{3+} + 2 mg/L O_3 + UF	14 ± 0.34	8 ± 0.29	12 ± 0.40
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF	14 ± 0.36	11 ± 0.42	12 ± 0.23
	4 mg/L Fe^{3+} + 10 mg/L O_3 + UF	14 ± 0.74	10 ± 0.18	12 ± 0.50

Table 26: PO_4-P of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

		Trial 1	Trial 2	Trial 3
Name of experiment	Sample	Measured value [µg/L]	Measured value [µg/L]	Measured value [µg/L]
BW I A/C	Effluent	94 ± 0.17	107 ± 0.51	

	Effluent + UF 1st permeate	78 ± 0.05	104 ± 0.36	
	Effluent + UF 3rd permeate	88 ± 0.08	106 ± 0.26	
	Effluent + UF 5th permeate	15 ± 0.12	106 ± 0.02	
BW I B/D	4 mg/L Fe^{3+} + 6 mg/L O_3	19 ± 0.02	26 ± 0.17	
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	15 ± 0.20	17 ± 0.09	
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	15 ± 0.16	19 ± 0.26	
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	93 ± 0.51	24 ± 0.17	
BW II	Effluent		64 ± 0.58	66 ± 0.12
BW II A/C	4 mg/L Fe^{3+}		17 ± 0.57	11 ± 0.15
	4 mg/L Fe^{3+} + UF 1st permeate		15 ± 0.42	9 ± 0.20
	4 mg/L Fe^{3+} + UF 3rd permeate		15 ± 0.19	9 ± 0.21
	4 mg/L Fe^{3+} + UF 5th permeate		16 ± 0.15	9 ± 0.09
BW II B/D	4 mg/L Fe^{3+}+ 6 mg/L O_3		17 ± 0.06	12 ± 0.16
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate		15 ± 0.47	9 ± 0.13
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate		17 ± 0.25	12 ± 0.11
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate		18 ± 0.25	15 ± 0.12
BW III	Effluent	66 ± 0.90	102 ± 0.10	
BW III A/D	4 mg/L Fe^{3+}	13 ± 0.62	15 ± 0.31	
	4 mg/L Fe^{3+} + UF 1st permeate	12 ± 0.63	12 ± 0.39	
	4 mg/L Fe^{3+} + UF 3rd permeate	11 ± 0.18	12 ± 0.19	
	4 mg/L Fe^{3+} + UF 5th permeate	11 ± 0.07	12 ± 0.19	
BW III B/E	4 mg/L Fe^{3+}+ 2 mg/L O_3	14 ± 0.46	23 ± 0.24	

	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	12 ± 0.53	12 ± 0.91
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	11 ± 0.24	12 ± 0.30
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	12 ± 0.04	12 ± 0.17
BW III C/F	4 mg/L Fe^{3+}+ 6 mg/L O_3	17 ± 0.79	46 ± 0.50
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	13 ± 0.30	12 ± 0.14
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	13 ± 0.09	12 ± 0.23
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	12 ± 0.31	12 ± 0.31
BW III G	4 mg/L Fe^{3+}+ 10 mg/L O_3		20 ± 0.33
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate		12 ± 0.30
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate		12 ± 0.40
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate		12 ± 0.26

6.3.3 DOC

Table 27: DOC of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

		Trial A	Trial B	Trial C		
Name of experiment	Sample	Measured value [mg/L]	Measured value [mg/L]	Measured value [mg/L]	Mean value [mg/L]	c/c_0
UF I A-C	Effluent	9.6 9.9	10.9 11.1		10.4 ± 0.73	1.00 ± 0.01
	Effluent + UF	9.6 9.6	10.4 10.4		10.0 ± 0.44	0.96 ± 0.11
	Effluent + 10 mg/L O_3	10.1 10.2	11.1 11.1		10.6 ± 0.56	1.02 ± 0.12
	Effluent + 10 mg/L O_3 + UF	10.0 9.9	10.7 10.8		10.3 ± 0.45	0.99 ± 0.11
	2 mg/L Fe^{3+}	9.4 9.4	10.6 10.7		10.0 ± 0.74	0.97 ± 0.14
	2 mg/L Fe^{3+} +UF	9.3 9.1	10.4 10.3		9.8 ± 0.66	0.94 ± 0.14
	2 mg/L Fe^{3+} + 10 mg/L O_3	9.9 9.9	10.8 10.8		10.3 ± 0.52	1.00 ± 0.12
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	9.6 9.6	10.2 10.2		9.9 ± 0.32	0.95 ± 0.10
	6 mg/L Fe^{3+}	8.7 8.8	10.2 10.1		9.4 ± 0.81	0.91 ± 0.16
	6 mg/L Fe^{3+} +UF	8.6 8.6	9.8 9.9		9.2 ± 0.74	0.89 ± 0.15
	6 mg/L Fe^{3+} 10 mg/L O_3	9.2 9.3	10.4 10.4		9.8 ± 0.67	0.95 ± 0.14

	6 mg/L Fe^{3+} 10 mg/L O_3 + UF	9.1 9.2	10.4 10.5		9.8 ± 0.76	0.95 ± 0.15
UF II A-C	Effluent	10.7 10.9	12.1 12.3	10.1 10.1	11.0 ± 0.95	1.00 ± 0.01
	Effluent + UF	10.7 10.6	11.7 11.8	9.7 9.7	10.7 ± 0.91	0.97 ± 0.17
	Effluent + 2mg/L O_3	11.2 11.0	12.3 12.3	10.2 10.1	11.2 ± 0.96	1.01 ± 0.17
	Effluent + 2mg/L O_3 + UF	11.0 10.8	11.9 11.9	9.8 9.8	10.9 ± 0.93	0.98 ± 0.17
	2 mg/L Fe^{3+}	10.7 10.9	11.8 11.8	9.8 9.9	10.8 ± 0.89	0.98 ± 0.17
	2 mg/L Fe^{3+} +UF	10.3 10.2	11.4 11.4	9.5 9.5	10.4 ± 0.88	0.94 ± 0.17
	2 mg/L Fe^{3+} + 2mg/L O_3	10.7 10.5	12.1 12.0	9.8 9.8	10.8 ± 1.03	0.98 ± 0.18
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	10.6 10.4	11.9 11.9	9.6 9.5	10.6 ± 1.05	0.96 ± 0.18
	6 mg/L Fe^{3+}	9.9 10.0	11.3 11.3	9.1 9.1	10.1 ± 0.97	0.92 ± 0.18
	6 mg/L Fe^{3+} +UF	9.9 9.8	11.2 11.1	8.8 8.8	9.9 ± 1.06	0.90 ± 0.19
	6 mg/L Fe^{3+} 2mg/L O_3	10.2 10.3	11.1 11.1	9.3 9.4	10.2 ± 0.80	0.93 ± 0.16
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	10.0 9.8	11.5 10.5	9.2 9.1	10.0 ± 0.87	0.91 ± 0.17
UF III A-B	Effluent	9.6 9.8	11.9 12.1		10.9 ± 1.38	1.00 ± 0.01
	Effluent + UF	9.3 9.4	10.9 11.0		10.1 ± 0.90	0.93 ± 0.22
	2 mg/L Fe^{3+}	9.6 9.4	11.2 11.3		10.4 ± 1.01	0.96 ± 0.22
	2 mg/L Fe^{3+} +UF	9.4 9.2	11.6 11.5		10.4 ± 1.30	0.96 ± 0.25
	2 mg/L Fe^{3+} + 2mg/L O_3	9.6 9.6	12.5 12.4		11.0 ± 1.64	1.02 ± 0.28
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	9.4 9.4	10.8 10.9		10.1 ± 0.84	0.93 ± 0.21
	2 mg/L Fe^{3+} + 4 mg/L O_3	9.6 9.7	13.8 13.8		11.7 ± 2.39	1.08 ± 0.33
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	9.4 9.3	11.3 11.2		10.3 ± 1.11	0.95 ± 0.23
	2 mg/L Fe^{3+} + 6 mg/L O_3	9.6 9.6	14.2 14.4		12.0 ± 2.73	1.10 ± 0.35
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	9.5 9.4	12.2 12.1		10.8 ± 1.55	0.99 ± 0.27
	2 mg/L Fe^{3+} + 8 mg/L O_3	9.6 9.6	12.2 12.0		10.8 ± 1.43	1.00 ± 0.26
	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	9.4 9.3	10.8 10.7		10.1 ± 0.79	0.93 ± 0.21
	2 mg/L Fe^{3+} + 10 mg/L O_3	9.6 9.4	12.6 12.7		11.1 ± 1.80	1.02 ± 0.29
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	9.5 9.6	10.9 10.8		10.2 ± 0.75	0.94 ± 0.20
UF IV A-B	Effluent	10.7 11.1	10.8 10.9		10.9 ± 0.15	1.00 ± 0.00
	Effluent + UF	10.6 10.6	10.5 10.6		10.5 ± 0.06	0.97 ± 0.02
	6 mg/L Fe^{3+}	10.2 10.3	10.2 10.2		10.2 ± 0.06	0.94 ± 0.02
	6 mg/L Fe^{3+} +UF	9.9 10.0	9.8 9.7		9.9 ± 0.12	0.91 ± 0.03
	6 mg/L Fe^{3+} + 2 mg/L O_3	10.2 10.3	10.4 10.2		10.3 ± 0.09	0.95 ± 0.02
	6 mg/L Fe^{3+} + 2 mg/L O_3 + UF	9.9 10.3	9.9 9.9		10.0 ± 0.18	0.92 ± 0.03

	6 mg/L Fe^{3+} + 6 mg/L O_3	10.4 10.5	10.3 10.2		10.3 ± 0.12	0.95 ± 0.03
	6 mg/L Fe^{3+} 6 mg/L O_3 + UF	10.0 10.0	10.0 10.0		10.0 ± 0.02	0.92 ± 0.02
	6 mg/L Fe^{3+} + 10 mg/L O_3	10.4 10.3	10.2 10.2		10.3 ± 0.07	0.94 ± 0.02
	6 mg/L Fe^{3+} + 10 mg/L O_3 + UF	10.1 10.1	10.1 10.0		10.1 ± 0.03	0.92 ± 0.02
UF V A-C	Effluent	10.8 11.0	11.4 11.5	11.2 11.1	11.2 ± 0.27	1.00 ± 0.00
	Effluent + UF	10.7 10.7	11.1 11.0	10.7 10.7	10.8 ± 0.19	0.97 ± 0.04
	4 mg/L Fe^{3+}	10.5 10.5	10.8 10.8	10.3 10.4	10.5 ± 0.22	0.94 ± 0.04
	4 mg/L Fe^{3+} +UF	10.2 10.2	10.7 10.5	10.1 10.1	10.3 ± 0.23	0.92 ± 0.05
	4 mg/L Fe^{3+} + 2 mg/L O_3	10.6 10.5	11.0 11.1	10.6 10.6	10.7 ± 0.24	0.96 ± 0.05
	4 mg/L Fe^{3+} + 2 mg/L O_3 + UF	10.2 10.4	10.6 10.8	10.2 10.2	10.4 ± 0.26	0.93 ± 0.05
	4 mg/L Fe^{3+} + 6 mg/L O_3	10.6 10.5	11.1 11.2	10.8 10.8	10.8 ± 0.26	0.97 ± 0.05
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF	10.3 10.4	10.9 10.6	10.4 10.4	10.5 ± 0.21	0.94 ± 0.04
	4 mg/L Fe^{3+} + 10 mg/L O_3	10.6 10.5	10.6 10.7	10.9 10.8	10.7 ± 0.14	0.96 ± 0.04
	4 mg/L Fe^{3+} + 10 mg/L O_3 + UF	10.3 10.4	10.3 10.4	10.4 10.5	10.4 ± 0.08	0.93 ± 0.03

Table 28: DOC of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

		Trial 1	Trial 2	Trial 3		
Name of experiment	Sample	Measured value [mg/L]	Measured value [mg/L]	Measured value [mg/L]	Mean value [mg/L]	c/c_0
BW I A/C	Effluent	11.8 12.1	14.5 12.3		12.7 ± 1.24	1.00 ± 0.01
	Effluent + UF 1st permeate	11.7 11.5	10.3 10.4		11.0 ± 0.73	0.86 ± 0.16
	Effluent + UF 3rd permeate	11.8 11.7	10.3 10.3		11.0 ± 0.83	0.87 ± 0.17
	Effluent + UF 5th permeate	11.7 11.7	10.4 10.3		11.0 ± 0.80	0.87 ± 0.17
BW I B/D	4 mg/L Fe^{3+} + 6 mg/L O_3	11.3 11.3	10.4 10.3		10.8 ± 0.56	0.85 ± 0.15
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	11.3 11.4	10.0 10.0		10.6 ± 0.81	0.84 ± 0.17
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	11.4 11.2	10.1 10.0		10.7 ± 0.70	0.84 ± 0.16
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	11.6 11.5	10.1 10.0		10.8 ± 0.88	0.85 ± 0.18
BW II	Effluent		8.8 9.0	10.8 10.7	9.8 ± 1.06	1.00 ± 0.01

BW II A/C	4 mg/L Fe^{3+}		8.1 8.2	10.3 10.1	9.2 ± 1.20	0.93 ± 0.24
	4 mg/L Fe^{3+} + UF 1st permeate		7.9 8.0	9.5 9.6	8.7 ± 0.92	0.89 ± 0.21
	4 mg/L Fe^{3+} + UF 3rd permeate		8.1 8.0	9.8 9.8	8.9 ± 0.99	0.91 ± 0.22
	4 mg/L Fe^{3+} + UF 5th permeate		8.5 8.5	9.9 10.1	9.3 ± 0.86	0.94 ± 0.20
BW II B/D	4 mg/L Fe^{3+}+ 6 mg/L O_3		8.7 8.5	10.3 10.1	9.4 ± 0.95	0.96 ± 0.21
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate		8.2 8.4	10.0 9.8	9.1 ± 0.94	0.93 ± 0.21
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate		8.3 8.3	10.2 10.0	9.2 ± 1.04	0.94 ± 0.22
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate		8.8 8.7	10.2 10.2	9.5 ± 0.82	0.97 ± 0.19
BW III	Effluent	11.1 10.6	10.8 10.9		10.9 ± 0.21	1.00 ± 0.00
BW III A/D	4 mg/L Fe^{3+}	10.6 10.5	10.3 9.4		10.2 ± 0.54	0.94 ± 0.07
	4 mg/L Fe^{3+} + UF 1st permeate	10.2 10.2	9.8 9.8		10.0 ± 0.22	0.92 ± 0.04
	4 mg/L Fe^{3+} + UF 3rd permeate	10.5 10.4	10.0 10.1		10.3 ± 0.25	0.95 ± 0.04
	4 mg/L Fe^{3+} + UF 5th permeate	10.5 10.5	10.1 10.1		10.3 ± 0.22	0.95 ± 0.04
BW III B/E	4 mg/L Fe^{3+}+ 2 mg/L O_3	10.7 10.9	10.4 10.3		10.6 ± 0.24	0.98 ± 0.04
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	10.5 10.4	10.0 9.9		10.2 ± 0.30	0.94 ± 0.05
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	10.5 10.6	9.9 10.0		10.2 ± 0.32	0.94 ± 0.05
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	10.5 10.5	10.2 10.1		10.3 ± 0.20	0.95 ± 0.04
BW III C/F	4 mg/L Fe^{3+}+ 6 mg/L O_3	10.9 10.8	10.6 10.5		10.7 ± 0.19	0.98 ± 0.04
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	10.6 10.5	9.9 9.9		10.2 ± 0.37	0.94 ± 0.06
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	10.6 10.4	10.0 10.0		10.3 ± 0.29	0.95 ± 0.05
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	10.5 10.5	10.0 9.9		10.2 ± 0.29	0.94 ± 0.05
BW III G	4 mg/L Fe^{3+}+ 10 mg/L O_3		10.4 10.4		10.4 ± 0.01	0.96 ± 0.02

	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate	9.9 10.0	9.9 ± 0.08	0.91 ± 0.03
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate	10.1 10.1	10.1 ± 0.06	0.93 ± 0.03
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate	10.2 10.2	10.2 ± 0.01	0.94 ± 0.02

6.3.4 Residual Iron

Table 29: Residual iron of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

		Trial A	Trial B	Trial C
Name of experiment	Sample	Measured value [µg/L]	Measured value [µg/L]	Measured value [µg/L]
UF I A-C	Effluent 0.45 µm filtered	16.9 ± 1.4	24.9 ± 0.8	22.4 ± 5.5
	2 mg/L Fe^{3+} 0.45 µm filtered	40.6 ± 3.5	258.3 ± 20.9	50.4 ± 8.0
	6 mg/L Fe^{3+} 0.45 µm filtered	22.7 ± 1.0	87.4 ± 0.2	23.5 ± 3.1
	Effluent + 10 mg/L O_3 0.45 µm filtered	9.9 ± 0.5	19.6 ± 0.6	23.6 ± 2.4
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	62.3 ± 0.9	212.1 ± 26.7	64.2 ± 6.3
	6 mg/L Fe^{3+} 10 mg/L O_3 0.45 µm filtered	60.1 ± 1.0	138.6 ± 1.1	73.4 ± 1.8
	Effluent 0.2 µm filtered	14.4 ± 0.6	21.4 ± 1.2	338.0 ± 106.5
	2 mg/L Fe^{3+} 0.2 µm filtered	33.5 ± 1.4	47.5 ± 0.2	83.1 ± 2.1
	6 mg/L Fe^{3+} 0.2 µm filtered	20.6 ± 0.6	53.3 ± 0.9	184.6 ± 1.5
	Effluent + 10 mg/L O_3 0.2 µm filtered	11.9 ± 1.0	18.7 ± 0.7	32.1 ± 5.6
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.2 µm filtered	30.9 ± 0.6	40.7 ± 0.7	53.4 ± 6.4
	6 mg/L Fe^{3+} 10 mg/L O_3 0.2 µm filtered	22.0 ± 0.4	20.0 ± 0.3	54.3 ± 1.3
	Effluent + UF	16.7 ± 0.8	19.9 ± 0.3	32.2 ± 1.1
	Effluent + 10 mg/L O_3 + UF	12.7 ± 0.7	14.9 ± 0.2	29.1 ± 1.9
	2 mg/L Fe^{3+} +UF	7.0 ± 0.5	11.5 ± 0.1	24.8 ± 2.1

	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	8.7 ± 0.5	12.1 ± 0.4	22.4 ± 0.6
	6 mg/L Fe^{3+} +UF	7.5 ± 1.0	12.9 ± 0.2	27.3 ± 1.0
	6 mg/L Fe^{3+} 10 mg/L O_3 + UF	6.7 ± 0.7	8.2 ± 0.2	21.8 ± 4.2
UF II A-C	Effluent 0.45 µm filtered	25.1 ± 1.3	39.8 ± 8.7	20.2 ± 4.9
	2 mg/L Fe^{3+} 0.45 µm filtered	108.8 ± 1.7	67.8 ± 0.3	156.2 ± 6.9
	6 mg/L Fe^{3+} 0.45 µm filtered	26.7 ± 1.1	72.7 ± 0.8	355.8 ± 6.4
	Effluent + 2mg/L O_3 0.45 µm filtered	20.9 ± 0.2	35.0 ± 2.5	29.4 ± 1.3
	2 mg/L Fe^{3+} + 2mg/L O_3 0.45 µm filtered	356.8 ± 40.2	130.4 ± 1.4	173.4 ± 7.3
	6 mg/L Fe^{3+} 2mg/L O_3 0.45 µm filtered	44.3 ± 0.9	109.2 ± 0.9	261.6 ± 1.6
	Effluent 0.2 µm filtered	25.4 ± 0.7	41.7 ± 0.8	
	2 mg/L Fe^{3+} 0.2 µm filtered	46.0 ± 1.4	57.6 ± 1.2	
	6 mg/L Fe^{3+} 0.2 µm filtered	56.3 ± 1.2	77.2 ± 0.6	
	Effluent + 2mg/L O_3 0.2 µm filtered	23.3 ± 1.4	37.0 ± 1.5	
	2 mg/L Fe^{3+} + 2mg/L O_3 0.2 µm filtered	72.7 ± 0.5	91.9 ± 1.3	
	6 mg/L Fe^{3+} 2mg/L O_3 0.2 µm filtered	21.9 ± 0.5	74.6 ± 0.1	
	Effluent + UF	21.6 ± 1.4	30.3 ± 1.1	30.3 ± 5.1
	2 mg/L Fe^{3+} +UF	15.4 ± 0.7	32.1 ± 2.7	24.0 ± 2.7
	6 mg/L Fe^{3+} +UF	13.6 ± 0.4	32.8 ± 11.3	23.5 ± 2.0
	Effluent + 2mg/L O_3 + UF	21.4 ± 1.2	27.0 ± 1.1	24.4 ± 0.2
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	10.4 ± 0.2	23.0 ± 0.4	23.2 ± 2.5
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	8.7 ± 0.3	22.5 ± 2.7	13.2 ± 2.7
UF III A-B	Effluent 0.45 µm filtered	39.3 ± 2.6	41.1 ± 1.0	

	2 mg/L Fe^{3+} 0.45 µm filtered	74.8 ± 0.4	100.6 ± 1.6
	2 mg/L Fe^{3+} + 2mg/L O_3 0.45 µm filtered	81.3 ± 1.6	93.6 ± 0.9
	2 mg/L Fe^{3+} + 4 mg/L O_3 0.45 µm filtered	102.7 ± 2.3	89.0 ± 2.0
	2 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	103.2 ± 0.4	100.0 ± 2.2
	2 mg/L Fe^{3+} + 8 mg/L O_3 0.45 µm filtered	69.6 ± 0.6	65.9 ± 0.9
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	154.2 ± 8.6	96.3 ± 0.8
	Effluent 0.2 µm filtered	32.0 ± 1.1	39.1 ± 2.3
	2 mg/L Fe^{3+} 0.2 µm filtered	34.7 ± 1.8	60.1 ± 0.3
	2 mg/L Fe^{3+} + 2mg/L O_3 0.2 µm filtered	66.8 ± 1.0	59.3 ± 3.1
	2 mg/L Fe^{3+} + 4 mg/L O_3 0.2 µm filtered	54.4 ± 0.9	64.9 ± 0.3
	2 mg/L Fe^{3+} + 6 mg/L O_3 0.2 µm filtered	40.6 ± 0.8	53.0 ± 0.5
	2 mg/L Fe^{3+} + 8 mg/L O_3 0.2 µm filtered	40.9 ± 0.8	56.0 ± 1.5
	2 mg/L Fe^{3+} + 10 mg/L O_3 0.2 µm filtered	90.5 ± 0.5	76.5 ± 0.9
	Effluent + UF	34.5 ± 1.6	24.5 ± 1.1
	2 mg/L Fe^{3+} +UF	34.3 ± 3.2	24.3 ± 0.9
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	27.3 ± 1.0	19.2 ± 0.4
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	31.0 ± 1.4	17.4 ± 1.1
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	28.2 ± 2.1	17.2 ± 0.5
	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	47.4 ± 1.1	21.6 ± 0.3
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	48.7 ± 0.4	27.2 ± 1.6
UF IV A-B	Effluent 0.45 µm filtered	47.4 ± 0.8	37.1 ± 0.4
	6 mg/L Fe^{3+} 0.45 µm filtered		64.3 ± 2.9

	6 mg/L Fe^{3+} + 2 mg/L O_3 0.45 µm filtered	49.3 ± 1.3	47.5 ± 0.4	
	6 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	45.5 ± 1.0	65.8 ± 0.1	
	6 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	278.1 ± 7.5	83.5 ± 1.8	
	Effluent 0.2 µm filtered	49.8 ± 0.4	32.7 ± 2.0	
	6 mg/L Fe^{3+} 0.2 µm filtered	141.0 ± 3.4	68.2 ± 0.5	
	6 mg/L Fe^{3+} + 2 mg/L O_3 0.2 µm filtered	97.0 ± 1.6	51.8 ± 0.4	
	6 mg/L Fe^{3+} + 6 mg/L O_3 0.2 µm filtered	107.2 ± 6.2	188.0 ± 4.5	
	6 mg/L Fe^{3+} + 10 mg/L O_3 0.2 µm filtered	142.8 ± 2.3	180.2 ± 3.2	
	Effluent + UF	65.4 ± 2.1	30.9 ± 1.1	
	6 mg/L Fe^{3+} + UF	43.1 ± 5.1	25.4 ± 1.6	
	6 mg/L Fe^{3+} + 2 mg/L O_3 + UF	32.4 ± 1.4	34.0 ± 0.2	
	6 mg/L Fe^{3+} + 6 mg/L O_3 + UF	28.9 ± 0.5	23.5 ± 3.1	
	6 mg/L Fe^{3+} + 10 mg/L O_3 + UF	46.5 ± 0.1	39.2 ± 2.9	
UF V A-C	Effluent 0.45 µm filtered	41.3 ± 0.2	35.4 ± 1.7	34.2 ± 0.4
	4 mg/L Fe^{3+} 0.45 µm filtered	109.0 ± 2.3	43.7 ± 0.1	87.5 ± 0.1
	4 mg/L Fe^{3+} + 2 mg/L O_3 0.45 µm filtered	76.7 ± 0.8	56.9 ± 0.1	209.8 ± 8.0
	4 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	92.0 ± 1.6	62.9 ± 2.5	159.0 ± 7.3
	4 mg/L Fe^{3+} + 10 mg/L O_3 0.45 µm filtered	184.4 ± 0.0	86.2 ± 3.6	179.2 ± 24.7
	Effluent 0.2 µm filtered	47.9 ± 0.0	32.8 ± 1.0	
	4 mg/L Fe^{3+} 0.2 µm filtered	70.0 ± 1.1	61.2 ± 0.7	
	4 mg/L Fe^{3+} + 2 mg/L O_3 0.2 µm filtered	219.8 ± 3.1	87.7 ± 0.6	
	4 mg/L Fe^{3+} + 6 mg/L O_3 0.2 µm filtered	77.8 ± 1.7	65.7 ± 0.1	

	4 mg/L Fe^{3+} + 10 mg/L O_3 0.2 µm filtered	178.4 ± 1.4	65.5 ± 2.0	
	Effluent + UF	31.8 ± 1.3	34.8 ± 1.7	95.9 ± 1.3
	4 mg/L Fe^{3+} 1 µm filtered	34.3 ± 0.4	22.8 ± 1.7	91.5 ± 1.3
	4 mg/L Fe^{3+} + 2 mg/L O_3 + UF	22.2 ± 0.1	19.8 ± 1.6	96.0 ± 1.8
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF	30.6 ± 0.2	23.5 ± 1.2	94.2 ± 0.0
	4 mg/L Fe^{3+} + 10 mg/L O_3 + UF	26.2 ± 1.9	34.4 ± 1.4	94.2 ± 1.3

Table 30: Residual iron of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

		Trial 1	Trial 2	Trial 3
Name of experiment	Sample	Measured value [µg/L]	Measured value [µg/L]	Measured value [µg/L]
BW I A/C	Effluent 0.45 µm filtered	89.0 ± 1.1	39.2 ± 0.0	
	Effluent 0.2 µm filtered	46.0 ± 0.8	34.1 ± 0.3	
	Effluent + UF 1st permeate	88.3 ± 0.2	39.9 ± 0.9	
	Effluent + UF 3rd permeate	89.1 ± 0.2	33.4 ± 0.1	
	Effluent + UF 5th permeate	58.7 ± 0.9	36.1 ± 0.4	
BW I B/D	4 mg/L Fe^{3+} + 6 mg/L O_3 0.45 µm filtered	106.0 ± 0.1	159.4 ± 3.5	
	4 mg/L Fe^{3+} + 6 mg/L O_3 0.2 µm filtered	60.7 ± 0.6	138.0 ± 4.1	
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	46.2 ± 0.6	21.7 ± 0.8	
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	64.8 ± 0.1	30.4 ± 1.1	
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	37.4 ± 0.5	29.7 ± 1.2	
BW II	Effluent 0.45 µm filtered		22.3 ± 0.4	22.7 ± 1.2
	Effluent 0.2 µm filtered		21.3 ± 0.7	33.4 ± 0.4
BW II A/C	4 mg/L Fe^{3+} 0.45 µm filtered		72.8 ± 0.8	189.2 ± 1.1

	4 mg/L Fe^{3+} 0.2 µm filtered		51.0 ± 2.1	54.1 ± 3.4
	4 mg/L Fe^{3+} + UF 1st permeate		16.2 ± 0.1	23.9 ± 0.7
	4 mg/L Fe^{3+} + UF 3rd permeate		11.2 ± 0.3	22.8 ± 0.8
	4 mg/L Fe^{3+} + UF 5th permeate		12.2 ± 0.6	15.9 ± 0.0
BW II B/D	4 mg/L Fe^{3+}+ 6 mg/L O_3 0.45 µm filtered		55.2 ± 0.4	36.8 ± 3.1
	4 mg/L Fe^{3+}+ 6 mg/L O_3 0.2 µm filtered		44.8 ± 0.3	42.2 ± 2.9
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate		10.8 ± 0.2	18.2 ± 1.3
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate		24.0 ± 0.6	17.0 ± 0.4
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate		10.9 ± 0.3	16.0 ± 0.7
BW III	Effluent 0.45 µm filtered	43.5 ± 2.0	40.6 ± 0.7	
	Effluent 0.2 µm filtered	55.9 ± 1.8	35.3 ± 0.5	
BW III A/D	4 mg/L Fe^{3+} 0.45 µm filtered	138.8 ± 3.9	207.4 ± 8.7	
	4 mg/L Fe^{3+} 0.2 µm filtered	44.6 ± 1.0	86.7 ± 3.2	
	4 mg/L Fe^{3+} + UF 1st permeate	31.0 ± 0.1	35.4 ± 5.5	
	4 mg/L Fe^{3+} + UF 3rd permeate	27.8 ± 1.1	31.7 ± 3.6	
	4 mg/L Fe^{3+} + UF 5th permeate	22.6 ± 3.8	30.0 ± 0.9	
BW III B/E	4 mg/L Fe^{3+}+ 2 mg/L O_3 0.45 µm filtered	67.9 ± 4.8	166.4 ± 2.0	
	4 mg/L Fe^{3+}+ 2 mg/L O_3 0.2 µm filtered	93.5 ± 1.0	144.0 ± 12.7	
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	51.0 ± 0.2	175.6 ± 0.0	
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	49.7 ± 1.0	37.7 ± 1.5	
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	54.7 ± 0.9	26.8 ± 0.6	
BW III C/F	4 mg/L Fe^{3+}+ 6 mg/L O_3 0.45 µm filtered	95.9 ± 1.6	417.6 ± 13.4	

	4 mg/L Fe^{3+}+ 6 mg/L O_3 0.2 µm filtered	49.4 ± 0.9	169.4 ± 3.7
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	31.7 ± 1.6	38.3 ± 2.1
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	18.1 ± 1.6	35.7 ± 0.8
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	19.5 ± 0.2	21.6 ± 0.7
BW III G	4 mg/L Fe^{3+}+ 10 mg/L O_3 0.45 µm filtered		306.4 ± 9.8
	4 mg/L Fe^{3+}+ 10 mg/L O_3 0.2 µm filtered		169.0 ± 5.7
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate		30.2 ± 1.3
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate		27.8 ± 4.9
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate		21.4 ± 2.9

6.3.5 Turbidity < 1 µm

Table 31: Turbidity < 1 µm of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

		Trial A		Trial B		Trial C	
Name of experiment	Sample	Measured value [NTU]	Mean value [NTU]	Measured value [NTU]	Mean value [NTU]	Measured value [NTU]	Mean value [NTU]
UF I A-C	Effluent unfiltered	2.60 2.55 2.33	2.49 ± 0.14	3.56 3.60 3.60	3.59 ± 0.02		
	2 mg/L Fe^{3+} unfiltered	3.25 3.02 3.48	3.25 ± 0.23	5.43 5.44 5.40	5.42 ± 0.02		
	6 mg/L Fe^{3+} unfiltered	5.44 5.20 5.09	5.24 ± 0.18	6.66 6.81 6.52	6.66 ± 0.15		
	Effluent + 10 mg/L O_3 unfiltered	1.84 1.72 1.66	1.74 ± 0.09	3.50 3.45 3.55	3.50 ± 0.05		
	2 mg/L Fe^{3+} + 10 mg/L O_3 unfiltered	3.05 3.16 3.20	3.14 ± 0.08	4.25 4.17 4.09	4.17 ± 0.08		
	6 mg/L Fe^{3+} 10 mg/L O_3 unfiltered	5.08 4.96 5.23	5.09 ± 0.14	6.38 6.40 6.23	6.34 ± 0.09		
	Effluent 1 µm filtered	0.90 1.12 1.01	1.01 ± 0.00	1.29 1.25 1.27	1.27 ± 0.02	1.19 1.16 1.13	1.16 ± 0.03
	2 mg/L Fe^{3+} 1 µm filtered	0.80 0.78 0.85	0.81 ± 0.00	0.85 0.83 0.85	0.85 ± 0.01	0.94 0.84 0.94	0.90 ± 0.06
	6 mg/L Fe^{3+} 1 µm filtered	1.30 1.43 1.32	1.35 ± 0.00	0.99 1.03 1.02	1.01 ± 0.02	1.33 1.32 1.33	1.33 ± 0.01

	Effluent + 10 mg/L O_3 1 µm filtered	0.53 0.58 0.67	0.59 ± 0.00	1.33 1.28 1.27	1.29 ± 0.03	0.75 0.67 0.73	0.71 ± 0.04
	2 mg/L Fe^{3+} + 10 mg/L O_3 1 µm filtered	0.41 0.48 0.49	0.46 ± 0.00	0.60 0.56 0.51	0.56 ± 0.05	0.53 0.57 0.58	0.56 ± 0.03
	6 mg/L Fe^{3+} 10 mg/L O_3 1 µm filtered	0.47 0.45 0.58	0.50 ± 0.00	0.93 0.94 0.96	0.94 ± 0.02	0.91 0.71 0.92	0.84 ± 0.11
	Effluent + UF	0.14 0.11	0.13 ± 0.02	0.09 0.09 0.09	0.09 ± 0.00	0.10 0.10 0.10	0.10 ± 0.00
	Effluent + 10 mg/L O_3 + UF	0.14 0.14	0.14 ± 0.00	0.09 0.09 0.09	0.09 ± 0.00	0.07 0.08 0.07	0.07 ± 0.00
	2 mg/L Fe^{3+} +UF	0.09 0.18 0.10	0.12 ± 0.05	0.10 0.10 0.11	0.10 ± 0.00	0.11 0.12 0.13	0.12 ± 0.01
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.09 0.11 0.09	0.10 ± 0.01	0.10 0.09 0.09	0.10 ± 0.01	0.10 0.08 0.07	0.08 ± 0.02
	6 mg/L Fe^{3+} +UF	0.09 0.10 0.19	0.13 ± 0.05	0.10 0.11 0.11	0.11 ± 0.01	0.09 0.09 0.08	0.09 ± 0.01
	6 mg/L Fe^{3+} 10 mg/L O_3 + UF	0.11 0.10 0.12	0.11 ± 0.01	0.10 0.11 0.09	0.10 ± 0.01	0.10 0.09 0.10	0.10 ± 0.01
UF II A-C	Effluent unfiltered	2.51 2.53 2.48	2.51 ± 0.03				
	2 mg/L Fe^{3+} unfiltered	4.62 4.70 4.73	4.68 ± 0.06				
	6 mg/L Fe^{3+} unfiltered	6.58 6.53 6.48	6.53 ± 0.05				
	Effluent + 2mg/L O_3 unfiltered	2.63 2.67 0.69	2.00 ± 1.13				
	2 mg/L Fe^{3+} + 2mg/L O_3 unfiltered	4.18 4.09 4.11	4.13 ± 0.05				
	6 mg/L Fe^{3+} 2mg/L O_3 unfiltered	6.43 6.36 6.33	6.37 ± 0.05				
	Effluent 1 µm filtered	0.87 0.87 0.81	0.85 ± 0.04	1.20 1.19 1.23	1.21 ± 0.02	0.93 0.95 0.92	0.93 ± 0.01
	2 mg/L Fe^{3+} 1 µm filtered	0.60 0.60 0.60	0.60 ± 0.00	1.28 1.32 1.32	1.31 ± 0.02	1.00 1.03 1.02	1.02 ± 0.02
	6 mg/L Fe^{3+} 1 µm filtered	1.54 1.59 1.58	1.57 ± 0.03	1.54 1.58 1.60	1.57 ± 0.03	0.75 0.77 0.71	0.74 ± 0.03
	Effluent + 2mg/L O_3 1 µm filtered	0.70 0.70 0.70	0.70 ± 0.00	1.04 1.03 1.02	1.03 ± 0.01	1.01 1.03 1.03	1.02 ± 0.01
	2 mg/L Fe^{3+} + 2mg/L O_3 1 µm filtered	1.07 1.02 0.94	1.01 ± 0.07	1.33 1.26 1.26	1.28 ± 0.04	0.62 0.67 0.56	0.61 ± 0.06
	6 mg/L Fe^{3+} 2mg/L O_3 1 µm filtered	1.49 1.51 1.53	1.51 ± 0.02	1.23 1.33 1.29	1.28 ± 0.05	0.87 0.86 0.86	0.86 ± 0.00
	Effluent + UF	0.14 0.13 0.14	0.14 ± 0.01	0.38 0.28 0.36	0.34 ± 0.07	0.10 0.10 0.12	0.11 ± 0.00

	2 mg/L Fe^{3+} +UF	0.09 0.10 0.10	0.10 ± 0.00	0.10 0.11 0.09	0.10 ± 0.01	0.11 0.14 0.14	0.13 ± 0.00
	6 mg/L Fe^{3+} +UF	0.13 0.12 0.13	0.13 ± 0.00	0.08 0.08 0.09	0.08 ± 0.01	0.08 0.09 0.09	0.09 ± 0.00
	Effluent + 2mg/L O_3 + UF	0.10 0.10 0.10	0.10 ± 0.00	0.11 0.09 0.09	0.10 ± 0.01	0.14 0.13 0.13	0.13 ± 0.00
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	0.14 0.13 0.15	0.14 ± 0.01	0.12 0.12 0.08	0.11 ± 0.02	0.09 0.10 0.11	0.10 ± 0.01
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	0.13 0.14 0.12	0.13 ± 0.01	0.10 0.09 0.11	0.10 ± 0.01	0.11 0.15 0.13	0.13 ± 0.02
	Effluent 1 µm filtered	1.03 1.04 1.04	1.04 ± 0.01	1.24 1.23 1.25	1.24 ± 0.01		
	2 mg/L Fe^{3+} 1 µm filtered	0.87 0.85 0.86	0.86 ± 0.01	0.94 0.94 0.96	0.95 ± 0.01		
	2 mg/L Fe^{3+} + 2mg/L O_3 1 µm filtered	0.92 0.84 0.86	0.87 ± 0.04	0.97 0.96 0.95	0.96 ± 0.01		
	2 mg/L Fe^{3+} + 4 mg/L O_3 1 µm filtered	0.78 0.78 0.76	0.77 ± 0.01	0.88 0.88 0.85	0.87 ± 0.02		
	2 mg/L Fe^{3+} + 6 mg/L O_3 1 µm filtered	0.69 0.67 0.67	0.68 ± 0.01	0.73 0.72 0.72	0.72 ± 0.01		
	2 mg/L Fe^{3+} + 8 mg/L O_3 1 µm filtered	0.72 0.71 0.70	0.71 ± 0.01	0.62 0.61 0.59	0.61 ± 0.02		
	2 mg/L Fe^{3+} + 10 mg/L O_3 1 µm filtered	0.73 0.77 0.67	0.72 ± 0.05	0.98 0.94 0.96	0.96 ± 0.02		
UF III A-B	Effluent + UF	0.11 0.11 0.12	0.11 ± 0.00	0.09 0.09 0.08	0.09 ± 0.00		
	2 mg/L Fe^{3+} +UF	0.12 0.10 0.12	0.11 ± 0.01				
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	0.09 0.10 0.10	0.10 ± 0.01				
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	0.11 0.12 0.12	0.12 ± 0.01				
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	0.11 0.12 0.09	0.11 ± 0.01				
	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	0.11 0.11 0.10	0.10 ± 0.01				
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.09 0.09 0.09	0.09 ± 0.00				
UF IV A-B	Effluent 1 µm filtered	1.01 1.01 1.01	1.01 ± 0.00	0.95 0.98 0.98	0.97 ± 0.02		
	6 mg/L Fe^{3+} 1 µm filtered	1.55 1.55 1.56	1.55 ± 0.01	1.11 1.15 1.20	1.15 ± 0.05		
	6 mg/L Fe^{3+} + 2 mg/L O_3 1 µm filtered	0.71 0.75 0.74	0.73 ± 0.02	1.17 1.11 1.12	1.13 ± 0.03		

	6 mg/L Fe^{3+} + 6 mg/L O_3 1 µm filtered	0.69 0.68 0.68	0.68 ± 0.01	1.09 1.18 1.20	1.16 ± 0.06		
	6 mg/L Fe^{3+} + 10 mg/L O_3 1 µm filtered	0.56 0.61 0.57	0.58 ± 0.03	1.06 1.09 1.08	1.08 ± 0.02		
	Effluent + UF	0.09 0.12 1.10	0.44 ± 0.02	0.11 0.07 0.07	0.08 ± 0.02		
UF V A-C	Effluent 1 µm filtered	1.01 1.04 1.02	1.02 ± 0.02	0.81 0.80 0.79	0.80 ± 0.00	5.29 5.31 5.68	5.43 ± 0.22
	4 mg/L Fe^{3+} 1 µm filtered	0.90 0.94 0.92	0.92 ± 0.02	0.80 0.85 0.84	0.83 ± 0.00		
	4 mg/L Fe^{3+} + 2 mg/L O_3 1 µm filtered	1.48 1.45 1.38	1.44 ± 0.05	1.25 1.32 1.33	1.30 ± 0.00		
	4 mg/L Fe^{3+} + 6 mg/L O_3 1 µm filtered	0.78 0.77 0.80	0.78 ± 0.02	0.60 0.60 0.60	0.60 ± 0.00		
	4 mg/L Fe^{3+} + 10 mg/L O_3 1 µm filtered	1.62 1.62 1.61	1.62 ± 0.01	0.45 0.44 0.45	0.45 ± 0.00		
	Effluent + UF	0.08 0.07 0.07	0.07 ± 0.00	0.09 0.09 0.10	0.10 ± 0.00		

6.3.6 Temperature, pH and electric conductivity

Table 32: Temperature, pH and electric conductivity of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

Name of experiment	Sample	pH before UF	pH after UF	Temperature [°C]	Conductivity before UF [µS/cm]	Conductivity after UF [µS/cm]
UF I-A	Effluent	7.2	7.6	22.2	875	871
	2 mg/L Fe^{3+}	7.5	7.6	24.2	878	867
	6 mg/L Fe^{3+}	7.1	7.3	24.2	879	876
	Effluent + 10 mg/L O_3	8.1	8.2	24.2	873	861
	2 mg/L Fe^{3+} + 10 mg/L O_3	7.8	7.8	24.7	873	866
	6 mg/L Fe^{3+} 10 mg/L O_3	7.4	7.6	24.9	883	873
UF I-B	Effluent	7.2	7.6	22.2	906	902
	2 mg/L Fe^{3+}	7.3	7.5	22.9	906	898
	6 mg/L Fe^{3+}	7.1	7.5	23.1	914	904
	Effluent + 10 mg/L O_3	8.0	8.2	22.4	901	898
	2 mg/L Fe^{3+} + 10 mg/L O_3	7.8	8.1	22.5	906	887
	6 mg/L Fe^{3+} 10 mg/L O_3	7.4	7.6	23.5	912	906
UF I-C	Effluent	7.4	7.6	24.6	1206	1193
	2 mg/L Fe^{3+}	7.3	7.6	25.1	1207	1191
	6 mg/L Fe^{3+}	7.2	7.5	25.2	1208	1195
	Effluent + 10 mg/L O_3	8.0	8.2	25.5	1193	1181
	2 mg/L Fe^{3+} + 10 mg/L O_3	7.9	8.1	25.6	1200	1186
	6 mg/L Fe^{3+} 10 mg/L O_3	7.6	7.8	25.9	1206	1192
UF II-A	Effluent	7.3	7.8	23.0	1171	1159
	2 mg/L Fe^{3+}	8.6	7.7	23.0	1151	1153
	6 mg/L Fe^{3+}	7.2	7.6	24.0	1172	1163
	Effluent + 2 mg/L O_3	8.0	8.1	23.8	1165	1153
	2 mg/L Fe^{3+} + 2 mg/L O_3	7.8	7.9	24.1	1171	1152
	6 mg/L Fe^{3+} 2 mg/L O_3	7.4	7.7	24.2	1176	1159
UF II-B	Effluent	7.6	7.8	24.9	1252	1256
	2 mg/L Fe^{3+}	7.4	7.7	24.9	1251	1233
	6 mg/L Fe^{3+}	7.2	7.6	24.9	1255	1249

	Effluent + 2 mg/L O_3	7.9	8.1	25.0	1246	1221
	2 mg/L Fe^{3+} + 2 mg/L O_3	7.8	7.9	25.0	1250	1241
	6 mg/L Fe^{3+} 2 mg/L O_3	7.6	7.9	24.9	1256	1249
UF II-C	Effluent	7.3	7.6	23.8	1010	998
	2 mg/L Fe^{3+}	7.3	7.5	24.9	1009	999
	6 mg/L Fe^{3+}	7.1	7.3	24.3	1012	1000
	Effluent + 2 mg/L O_3	7.9	8.0	25.2	1001	990
	2 mg/L Fe^{3+} + 2 mg/L O_3	7.8	7.9	25.0	1010	988
	6 mg/L Fe^{3+} 2 mg/L O_3	7.3	7.4	25.0	1011	1000
UF III-A	Effluent	7.3	7.7	23.9	1007	991
	2 mg/L Fe^{3+}	7.3	7.6	23.8	1008	994
	2 mg/L Fe^{3+} + 2 mg/L O_3	7.6	7.8	24.1	1006	994
	2 mg/L Fe^{3+} + 4 mg/L O_3	7.7	7.9	24.3	1004	992
	2 mg/L Fe^{3+} + 6 mg/L O_3	7.8	7.9	24.5	1004	995
	2 mg/L Fe^{3+} + 8 mg/L O_3	7.8	8.0	24.6	1001	993
	2 mg/L Fe^{3+} + 10 mg/L O_3	7.9	7.9	24.7	1004	994
UF III-B	Effluent	7.4	7.7	23.9	1172	1164
	2 mg/L Fe^{3+}	7.4	7.8	24.9	1174	1148
	2 mg/L Fe^{3+} + 2 mg/L O_3	7.7	7.9	24.4	1170	1162
	2 mg/L Fe^{3+} + 4 mg/L O_3	7.9	8.0	24.5	1168	1152
	2 mg/L Fe^{3+} + 6 mg/L O_3	7.9	8.0	24.8	1166	1151
	2 mg/L Fe^{3+} + 8 mg/L O_3	7.9	8.0	24.9	1169	1156
	2 mg/L Fe^{3+} + 10 mg/L O_3	7.9	8.0	24.8	1166	1151
UF IV-A	Effluent	7.2	7.7	24.3	1285	1271
	6 mg/L Fe^{3+}	7.2	7.4	24.5	1287	1275
	6 mg/L Fe^{3+} + 2 mg/L O_3	7.4	7.6	24.8	1280	1270
	6 mg/L Fe^{3+} + 6 mg/L O_3	7.5	7.7	24.9	1277	1262
	6 mg/L Fe^{3+} + 10 mg/L O_3	7.6	7.7	25.3	1274	1267
UF IV-B	Effluent	7.3	7.6	21.6	1180	1163
	6 mg/L Fe^{3+}	7.0	7.4	22.1	1182	1163
	6 mg/L Fe^{3+} + 2 mg/L O_3	7.4	7.6	22.9	1183	1166
	6 mg/L Fe^{3+} + 6 mg/L O_3	7.5	7.7	22.9	1181	1164
	6 mg/L Fe^{3+} + 10 mg/L O_3	7.5	7.6	23.0	1181	1167
UF V-A	Effluent	7.3	7.6	21.8	1108	1099
	4 mg/L Fe^{3+}	7.2	7.5	22.0	1112	1097
	4 mg/L Fe^{3+} + 2 mg/L O_3	7.5	7.8	22.4	1106	1094
	4 mg/L Fe^{3+} + 6 mg/L O_3	7.6	7.8	22.8	1106	1095
	4 mg/L Fe^{3+} + 10 mg/L O_3	7.6	7.8	22.9	1105	1097
UF V-B	Effluent	7.5	7.7	21.8	1307	1283
	4 mg/L Fe^{3+}	7.3	7.7	22.7	1305	1291
	4 mg/L Fe^{3+} + 2 mg/L O_3	7.6	7.8	22.9	1306	1289
	4 mg/L Fe^{3+} + 6 mg/L O_3	7.7	7.9	23.3	1304	1291
	4 mg/L Fe^{3+} + 10 mg/L O_3	7.7	7.9	23.3	1302	1280
UF V-C	Effluent	7.2	7.6	19.8	1165	1156
	4 mg/L Fe^{3+}	7.1	7.3	21.2	1168	1156
	4 mg/L Fe^{3+} + 2 mg/L O_3	7.4	7.6	21.1	1165	1150
	4 mg/L Fe^{3+} + 6 mg/L O_3	7.5	7.7	21.5	1161	1152
	4 mg/L Fe^{3+} + 10 mg/L O_3	7.6	7.8	21.9	1162	1149

Table 33: Temperature, pH and electric conductivity of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

Name of experiment	Sample	pH	Temperature [°C]	Conductivity [µS/cm]
BW I A/B	Effluent	7.6	21.9	1272
	Effluent + UF 1st permeate	7.7	22.5	1260
	Effluent + UF 3rd permeate	7.8	22.8	1267

	Effluent + UF 5th permeate	7.8	23	1267
	4 mg/L Fe^{3+} + 6 mg/L O_3	7.7	22.5	1271
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	8.0	22.6	1256
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	8.1	22.9	1260
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	8.2	22.9	1260
BW I C/D	Effluent	7.2	20.9	1197
	Effluent + UF 1st permeate	7.6	20.5	1184
	Effluent + UF 3rd permeate	7.7	21.2	1196
	Effluent + UF 5th permeate	8.2	22.3	1191
	4 mg/L Fe^{3+} + 6 mg/L O_3	7.7	20.8	1198
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	7.9	20.6	1178
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	7.9	21.2	1192
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	8.2	22.3	1191
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	7.6	21.9	1272
BW II A/C	Effluent	7.1	19.2	953
	4 mg/L Fe^{3+}	7.3	19.3	957
	4 mg/L Fe^{3+} + UF 1st permeate	7.7	18.8	940
	4 mg/L Fe^{3+} + UF 3rd permeate	8.0	19.4	945
	4 mg/L Fe^{3+} + UF 5th permeate	7.9	19.7	952
	4 mg/L Fe^{3+}+ 6 mg/L O_3	7.7	19.3	953
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	7.5	18.8	940
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	7.8	19.2	947
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	7.9	20	945
BW II B/D	Effluent	7.2	20.2	1358
	4 mg/L Fe^{3+}	7.2	20.4	1362
	4 mg/L Fe^{3+} + UF 1st permeate	7.5	20.6	1348
	4 mg/L Fe^{3+} + UF 3rd permeate	7.6	20.9	1355
	4 mg/L Fe^{3+} + UF 5th permeate	7.9	21.6	1356
	4 mg/L Fe^{3+}+ 6 mg/L O_3	7.6	20.5	1356
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	7.7	20.5	1337
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	7.8	20.6	1349
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	8.2	21.5	1345
BW III A-C	Effluent	7.3	21.2	1258

	4 mg/L Fe^{3+}	7.2	21.4	1261
	4 mg/L Fe^{3+} + UF 1st permeate	7.5	21.5	1251
	4 mg/L Fe^{3+} + UF 3rd permeate	7.9	21.7	1253
	4 mg/L Fe^{3+} + UF 5th permeate	7.8	21.8	1255
	4 mg/L Fe^{3+}+ 2 mg/L O_3	7.5	21.4	1257
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	7.7	21.6	1246
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	7.9	21.8	1247
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	8.0	22.3	1247
	4 mg/L Fe^{3+}+ 6 mg/L O_3	7.6	21.3	1259
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	7.7	21.8	1248
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	8.1	18.4	1245
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	8.1	21.9	1255
	4 mg/L Fe^{3+}+ 10 mg/L O_3	7.2	20.4	1195
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate	7.2	20.7	1198
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate	7.4	21	1182
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate	7.6	21.4	1189
BW III D-G	Effluent	8.0	21.9	1189
	4 mg/L Fe^{3+}	7.5	20.8	1197
	4 mg/L Fe^{3+} + UF 1st permeate	7.6	21.1	1183
	4 mg/L Fe^{3+} + UF 3rd permeate	7.8	21.5	1187
	4 mg/L Fe^{3+} + UF 5th permeate	8.1	22.6	1187
	4 mg/L Fe^{3+}+ 2 mg/L O_3	7.6	22.1	1197
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	7.8	22	1184
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	7.9	22.2	1189
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	8.1	22.3	1189
	4 mg/L Fe^{3+}+ 6 mg/L O_3	7.3	21.2	1258
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	7.2	21.4	1261
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	7.5	21.5	1251
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	7.9	21.7	1253
	4 mg/L Fe^{3+}+ 10 mg/L O_3	7.8	21.8	1255
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate	7.5	21.4	1257
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate	7.7	21.6	1246
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate	7.9	21.8	1247

	4 mg/L Fe^{3+}+ 10 mg/L O_3	7.8	21.8	1255
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate	7.5	21.4	1257
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate	7.7	21.6	1246
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate	7.9	21.8	1247

Table 34: Temperature, pH and electric conductivity results of MF trials

Name of experiment	Sample	pH	Temperature [°C]	Conductivity [µS/cm]
MF I A-C	Effluent	7.2	20.1	1275

6.3.7 UVA 254

Table 35: UVA 254 of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

		Trial A	Trial B	Trial C		
Name of experiment	Sample	Measured value [1/cm]	Measured value [1/cm]	Measured value [1/cm]	Mean value [1/m]	c/c_0
UF I A-C	Effluent		0.2675 0.2666 0.2668	0.2889 0.2888 0.2916	27.84 ± 1.25	1.00 ± 0.05
	Effluent + UF		0.2614 0.2612 0.2618	0.2807 0.2806 0.2815	27.12 ± 1.07	0.97 ± 0.08
	Effluent + 10 mg/L O_3		0.1448 0.1464 0.1451	0.1653 0.1646 0.1663	15.54 ± 1.10	0.56 ± 0.12
	Effluent + 10 mg/L O_3 + UF		0.1443 0.1464 0.1437	0.1599 0.1600 0.1626	15.28 ± 0.89	0.55 ± 0.10
	2 mg/L Fe^{3+}		0.2475 0.2480 0.2481	0.2731 0.2733 0.2728	26.05 ± 1.38	0.94 ± 0.10
	2 mg/L Fe^{3+} +UF		0.2444 0.2443 0.2442	0.2668 0.2670 0.2667	25.56 ± 1.23	0.92 ± 0.09
	2 mg/L Fe^{3+} + 10 mg/L O_3		0.1326 0.1323 0.1320	0.1531 0.1504 0.1485	14.15 ± 1.02	0.51 ± 0.12
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF		0.1309 0.1312 0.1316	0.1469 0.1468 0.1480	13.92 ± 0.88	0.50 ± 0.11
	6 mg/L Fe^{3+}		0.2197 0.2197 0.2200	0.2521 0.2507 0.2523	23.58 ± 1.75	0.85 ± 0.12
	6 mg/L Fe^{3+} +UF		0.2167 0.2165 0.2165	0.2540 0.2542 0.2583	23.60 ± 2.14	0.85 ± 0.14
	6 mg/L Fe^{3+} 10 mg/L O_3		0.1169 0.1165 0.1169	0.1365 0.1367 0.1360	12.66 ± 1.08	0.45 ± 0.13
	6 mg/L Fe^{3+} 10 mg/L O_3 + UF		0.1147 0.1153 0.1150	0.1346 0.1347 0.1345	12.48 ± 1.07	0.45 ± 0.13
UF II A-C	Effluent	0.3162 0.3146 0.3210	0.2710 0.2706 0.2708	0.2836 0.2831 0.2838	29.05 ± 2.09	1.00 ± 0.08

	Effluent + UF	0.3105 0.3120 0.3103	0.2631 0.2641 0.2644	0.2768 0.2765 0.2769	28.83 ± 2.11	0.98 ± 0.15
	Effluent + 2mg/L O_3	0.2855 0.2856 0.2857	0.2363 0.2339 0.2349	0.2472 0.2475 0.2478	25.60 ± 2.28	0.88 ± 0.16
	Effluent + 2mg/L O_3 + UF	0.2780 0.2788 0.2773	0.2293 0.2298 0.2301	0.2411 0.2408 0.2411	24.96 ± 2.19	0.86 ± 0.16
	2 mg/L Fe^{3+}	0.3056 0.3058 0.3058	0.2541 0.2545 0.2538	0.2739 0.2737 0.2740	27.79 ± 2.25	0.96 ± 0.15
	2 mg/L Fe^{3+} +UF	0.2995 0.2997 0.2993	0.2491 0.2497 0.2499	0.2606 0.2611 0.2612	27.00 ± 2.27	0.93 ± 0.16
	2 mg/L Fe^{3+} + 2mg/L O_3	0.2731 0.2729 0.2740	0.2099 0.2099 0.2096	0.2356 0.2357 0.2358	23.96 ± 2.77	0.82 ± 0.19
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	0.2714 0.2727 0.2704	0.2048 0.2068 0.2081	0.2302 0.2297 0.2310	23.61 ± 2.85	0.81 ± 0.19
	6 mg/L Fe^{3+}	0.2828 0.2813 0.2806	0.2270 0.2269 0.2270	0.2441 0.2439 0.2440	25.08 ± 2.42	0.86 ± 0.17
	6 mg/L Fe^{3+} +UF	0.2785 0.2827 0.2577	0.2225 0.2223 0.2232	0.2393 0.2400 0.2395	24.51 ± 2.32	0.84 ± 0.17
	6 mg/L Fe^{3+} 2mg/L O_3	0.2555 0.2556 0.2554	0.2087 0.2070 0.2076	0.2186 0.2187 0.2183	22.73 ± 2.17	0.78 ± 0.17
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	0.2521 0.2524 0.2543	0.2043 0.2050 0.2047	0.2117 0.2119 0.2123	22.31 ± 2.24	0.77 ± 0.17
UF III A-B	Effluent	0.2720 0.2701 0.26970	0.2810 0.2799 0.2794		27.51 ± 0.56	1.00 ± 0.02
	Effluent + UF	0.2633 0.2639 0.2640	0.2757 0.2760 0.2766		26.99 ± 0.68	0.98 ± 0.05
	2 mg/L Fe^{3+}	0.2603 0.2525 0.2562	0.2692 0.2677 0.2676		26.23 ± 0.70	0.95 ± 0.05
	2 mg/L Fe^{3+} +UF	0.2487 0.2498 0.2484	0.2612 0.2617 0.2617		25.53 ± 0.69	0.93 ± 0.05
	2 mg/L Fe^{3+} + 2mg/L O_3	0.2235 0.2257 0.2250	0.2339 0.2334 0.2342		22.93 ± 0.50	0.83 ± 0.04
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	0.2178 0.2172 0.2177	0.2313 0.2311 0.2309		22.43 ± 0.74	0.82 ± 0.05
	2 mg/L Fe^{3+} + 4 mg/L O_3	0.2047 0.2031 0.2027	0.2132 0.2136 0.2133		20.84 ± 0.54	0.76 ± 0.05
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	0.2008 0.2059 0.1993	0.2109 0.2113 0.2105		20.65 ± 0.53	0.75 ± 0.05
	2 mg/L Fe^{3+} + 6 mg/L O_3	0.1853 0.1792 0.1807	0.1910 0.1901 0.1889		18.56 ± 0.51	0.67 ± 0.05
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	0.1771 0.1771 0.1776	0.1883 0.1876 0.1877		18.26 ± 0.58	0.66 ± 0.05
	2 mg/L Fe^{3+} + 8 mg/L O_3	0.1531 0.1518 0.1549	0.1605 0.1607 0.1603		15.69 ± 0.41	0.57 ± 0.05

	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	0.1502 0.1494 0.1507	0.1604 0.1627 0.1623		15.60 ± 0.65	0.57 ± 0.06
	2 mg/L Fe^{3+} + 10 mg/L O_3	0.1291 0.1288 0.1286	0.1338 0.1342 0.1347		13.15 ± 0.30	0.48 ± 0.04
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.1275 0.1271 0.1278	0.1371 0.1360 0.1359		13.19 ± 0.49	0.48 ± 0.06
UF IV A-B	Effluent	0.2706 0.2704 0.2701	0.2851 0.2844 0.2847		27.76 ± 0.79	-
	Effluent + UF	0.2695 0.2686 0.2690	0.2748 0.2754 0.2753		27.21 ± 0.34	0.98 ± 0.04
	6 mg/L Fe^{3+}	0.2436 0.2428 0.2438	0.2484 0.2477 0.2476		24.57 ± 0.25	0.89 ± 0.04
	6 mg/L Fe^{3+} +UF	0.2407 0.2428 0.2423	0.2421 0.2410 0.2414		24.17 ± 0.08	0.87 ± 0.03
	6 mg/L Fe^{3+} + 2 mg/L O_3	0.2141 0.2144 0.2146	0.2211 0.2213 0.2210		21.78 ± 0.37	0.78 ± 0.05
	6 mg/L Fe^{3+} + 2 mg/L O_3 + UF	0.2129 0.2105 0.2121	0.2150 0.2166 0.2154		21.38 ± 0.23	0.77 ± 0.04
	6 mg/L Fe^{3+} + 6 mg/L O_3	0.1808 0.1817 0.1801	0.1655 0.1643 0.1644		17.28 ± 0.89	0.62 ± 0.08
	6 mg/L Fe^{3+} 6 mg/L O_3 + UF	0.1785 0.1791 0.1784	0.1617 0.1619 0.1608		17.01 ± 0.94	0.61 ± 0.08
	6 mg/L Fe^{3+} + 10 mg/L O_3	0.1297 0.1304 0.1311	0.1265 0.1266 0.1282		12.88 ± 0.20	0.46 ± 0.04
	6 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.1330 0.1342 0.1318	0.1319 0.1318 0.1321		13.25 ± 0.10	0.48 ± 0.04
UF V A-C	Effluent	0.2863 0.2873 0.2879	0.2881 0.2880 0.2882	0.2678 0.2668 0.2670	28.08 ± 1.02	
	Effluent + UF	0.2800 0.2790 0.2879	0.2797 0.2793 0.2794	0.2598 0.2601 0.2593	27.30 ± 1.00	0.97 ± 0.07
	4 mg/L Fe^{3+}	0.2599 0.2593 0.2597	0.2634 0.2633 0.2634	0.2361 0.2362 0.2358	25.30 ± 1.28	0.90 ± 0.09
	4 mg/L Fe^{3+} +UF	0.2552 0.2544 0.2551	0.2599 0.2588 0.2588	0.2318 0.2314 0.2311	24.85 ± 1.29	0.88 ± 0.09
	4 mg/L Fe^{3+} + 2 mg/L O_3	0.2287 0.2291 0.2299	0.2304 0.2306 0.2302	0.2134 0.2139 0.2130	22.44 ± 0.82	0.80 ± 0.07
	4 mg/L Fe^{3+} + 2 mg/L O_3 + UF	0.2265 0.2263 0.2259	0.2257 0.2258 0.2258	0.2095 0.2095 0.2086	22.04 ± 0.84	0.78 ± 0.07
	4 mg/L Fe^{3+} + 6 mg/L O_3	0.1674 0.1676 0.1670	0.1697 0.1692 0.1702	0.1757 0.1759 0.1753	17.09 ± 0.37	0.61 ± 0.06
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF	0.1640 0.1632 0.1631	0.1668 0.1668 0.1672	0.1725 0.1723 0.1726	16.76 ± 0.40	0.60 ± 0.06
	4 mg/L Fe^{3+} + 10 mg/L O_3	0.1301 0.1320 0.1297	0.1323 0.1317 0.1321	0.1337 0.1337 0.1325	13.18 ± 0.15	0.47 ± 0.05

	4 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.1283 0.1285 0.1276	0.1291 0.1282 0.1285	0.1317 0.1313 0.1311	12.94 ± 0.16	0.46 ± 0.05

Table 36: UVA 254 of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

		Trial 1	Trial 2	Trial 3		
Name of experiment	Sample	Measured value [1/cm]	Measured value [1/cm]	Measured value [1/cm]	Mean value [1/m]	c/c_0
BW I A/C	Effluent	0.3081 0.3089 0.3066	0.2839 0.2840 0.2845		29.60 ± 1.30	1.00 ± 0.0440
	Effluent + UF 1st permeate	0.2988 0.2993 0.2991	0.2643 0.2640 0.2639		28.16 ± 1.92	0.95 ± 0.1121
	Effluent + UF 3rd permeate	0.3026 0.3001 0.3011	0.2662 0.2668 0.2676		28.41 ± 1.89	0.96 ± 0.1104
	Effluent + UF 5th permeate	0.3020 0.3018 0.3020	0.2659 0.2666 0.2668		28.42 ± 1.94	0.96 ± 0.1124
BW I B/D	4 mg/L Fe^{3+} + 6 mg/L O_3	0.1787 0.1776 0.1772	0.1596 0.1601 0.1597		16.88 ± 0.99	0.57 ± 0.1026
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	0.1756 0.1749 0.1752	0.1563 0.1566 0.1563		16.58 ± 1.03	0.56 ± 0.1062
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	0.1762 0.1750 0.1754	0.1598 0.1595 0.1588		16.75 ± 0.89	0.57 ± 0.0970
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	0.1807 0.1795 0.1793	0.1619 0.1627 0.1620		17.10 ± 0.97	0.58 ± 0.1006
BW II	Effluent		0.2162 0.2156 0.2155	0.2636 0.2624 0.2643	23.96 ± 2.61	1.00 ± 0.11
BW II A/C	4 mg/L Fe^{3+}		0.1855	0.2357 0.2366 0.2360	22.35 ± 2.53	0.93 ± 0.22
	4 mg/L Fe^{3+} + UF 1st permeate		0.1809 0.1818 0.1805	0.2312 0.2304 0.2302	20.58 ± 2.71	0.86 ± 0.24
	4 mg/L Fe^{3+} + UF 3rd permeate		0.1881 0.1868 0.1866	0.2361 0.2356 0.2351	21.14 ± 2.65	0.88 ± 0.23
	4 mg/L Fe^{3+} + UF 5th permeate		0.1903 0.1907 0.1895	0.2409 0.2504 0.2395	21.69 ± 2.95	0.91 ± 0.25
BW II B/D	4 mg/L Fe^{3+}+ 6 mg/L O_3		0.1252 0.1253 0.1253	0.1660 0.1662 0.1664	14.57 ± 2.24	0.61 ± 0.26
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate		0.1218 0.1216 0.1217	0.1630 0.1622 0.1638	14.24 ± 2.26	0.59 ± 0.27
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate		0.1257 0.1282 0.1274	0.1640 0.1656 0.1658	14.61 ± 2.09	0.61 ± 0.25
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate		0.1285 0.1278 0.1273	0.1691 0.1695 0.1700	14.87 ± 2.28	0.62 ± 0.26
BW III	Effluent	0.2784 0.2779 0.2783	0.2717 0.2716 0.2718		27.50 ± 0.36	1.00 ± 0.0130

BW III A/D	4 mg/L Fe^{3+}	0.2460 0.2461 0.2457	0.2417 0.2421 0.2431		24.41 ± 0.20	0.89 ± 0.0213
	4 mg/L Fe^{3+} + UF 1st permeate	0.2430 0.2428 0.2425	0.2349 0.2352 0.2350		23.89 ± 0.42	0.87 ± 0.0307
	4 mg/L Fe^{3+} + UF 3rd permeate	0.2474 0.2474 0.2477	0.2432 0.2407 0.2416		24.47 ± 0.32	0.89 ± 0.0261
	4 mg/L Fe^{3+} + UF 5th permeate	0.2495 0.2513 0.2510	0.2444 0.2450 0.2447		24.77 ± 0.33	0.90 ± 0.0263
BW III B/E	4 mg/L Fe^{3+}+ 2 mg/L O_3	0.2188 0.2182 0.2185	0.2142 0.2133 0.2131		21.60 ± 0.28	0.79 ± 0.0257
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	0.2108 0.2107 0.2129	0.2084 0.2097 0.2090		21.03 ± 0.16	0.76 ± 0.0206
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	0.2152 0.2144 0.2138	0.2123 0.2120 0.2114		21.32 ± 0.15	0.78 ± 0.0200
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	0.2156 0.2154 0.2154	0.2142 0.2141 0.2141		21.48 ± 0.07	0.78 ± 0.0164
BW III C/F	4 mg/L Fe^{3+}+ 6 mg/L O_3	0.1631 0.1644 0.1634	0.1638 0.1637 0.1631		16.36 ± 0.05	0.59 ± 0.0160
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	0.1603 0.1618 0.1605	0.1583 0.1599 0.1590		16.00 ± 0.12	0.58 ± 0.0206
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	0.1626 0.1627 0.1626	0.1622 0.1603 0.1617		16.20 ± 0.09	0.59 ± 0.0186
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	0.1643 0.1638 0.1642	0.1643 0.1628 0.1634		16.38 ± 0.06	0.60 ± 0.0166
BW III G	4 mg/L Fe^{3+}+ 10 mg/L O_3		0.1236 0.1237 0.1240		12.38 ± 0.02	0.45 ± 0.0146
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate		0.1194 0.1203 0.1197		11.98 ± 0.05	0.44 ± 0.0168
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate		0.1223 0.1226 0.1236		12.28 ± 0.07	0.45 ± 0.0185
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate		0.1259 0.1260 0.1244		12.54 ± 0.09	0.46 ± 0.0201

6.3.8 Colour 436

Table 37: Colour 436 of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

		Trial A	Trial B	Trial C		
Name of experiment	Sample	Measured value [1/cm]	Measured value [1/cm]	Measured value [1/cm]	Mean value [1/m]	c/c_0
UF I A-C	Effluent		0.0144 0.0142 0.0142	0.0179 0.0179 0.0184	1.62 ± 0.21	1.00 ± 0.13
	Effluent + UF		0.0143 0.0142 0.0147	0.0173 0.0172 0.0174	1.59 ± 0.16	0.98 ± 0.23

	Effluent + 10 mg/L O_3		0.0022 0.0029 0.0023	0.0046 0.0043 0.0045	0.35 ± 0.11	0.21 ± 0.45
	Effluent + 10 mg/L O_3 + UF		0.0023 0.0029 0.0022	0.0035 0.0036 0.0046	0.32 ± 0.09	0.20 ± 0.41
	2 mg/L Fe^{3+}		0.0127 0.0128 0.0130	0.0165 0.0165 0.0165	1.47 ± 0.20	0.91 ± 0.27
	2 mg/L Fe^{3+} +UF		0.0132 0.0132 0.0128	0.0160 0.0168 0.0159	1.47 ± 0.18	0.91 ± 0.25
	2 mg/L Fe^{3+} + 10 mg/L O_3		0.0020 0.0017 0.0017	0.0029 0.0029 0.0029	0.24 ± 0.06	0.15 ± 0.39
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF		0.0019 0.0018 0.0025	0.0026 0.0028 0.0033	0.25 ± 0.06	0.15 ± 0.36
	6 mg/L Fe^{3+}		0.0108 0.0109 0.0109	0.0151 0.0146 0.0152	1.29 ± 0.23	0.80 ± 0.30
	6 mg/L Fe^{3+} +UF		0.0108 0.0106 0.0105	0.0148 0.0149 0.0157	1.29 ± 0.25	0.80 ± 0.32
	6 mg/L Fe^{3+} 10 mg/L O_3		0.0014 0.0008 0.0010	0.0021 0.0022 0.0021	0.16 ± 0.06	0.10 ± 0.51
	6 mg/L Fe^{3+} 10 mg/L O_3 + UF		0.0010 0.0010 0.0010	0.0020 0.0021 0.0020	0.15 ± 0.06	0.09 ± 0.50
UF II A-C	Effluent	0.0170 0.0165 0.0169	0.0166 0.0143 0.0188	0.0170 0.0164 0.0164	1.67 ± 0.12	1.00 ± 0.07
	Effluent + UF	0.0162 0.0163 0.0164	0.0188 0.0196 0.0204	0.0154 0.0155 0.0156	1.71 ± 0.19	1.03 ± 0.18
	Effluent + 2mg/L O_3	0.0096 0.0098 0.0096	0.0118 0.0118 0.0123	0.0114 0.0093 0.0099	1.06 ± 0.12	0.64 ± 0.18
	Effluent + 2mg/L O_3 + UF	0.0094 0.0092 0.0094	0.0136 0.0148 0.0118	0.0094 0.0093 0.0095	1.07 ± 0.22	0.64 ± 0.27
	2 mg/L Fe^{3+}	0.0163 0.0162 0.0163	0.0172 0.0180 0.0178	0.0146 0.0146 0.0146	1.62 ± 0.13	0.97 ± 0.15
	2 mg/L Fe^{3+} +UF	0.0146 0.0146 0.0146	0.0171 0.0174 0.0167	0.0135 0.0139 0.0141	1.52 ± 0.15	0.91 ± 0.17
	2 mg/L Fe^{3+} + 2mg/L O_3	0.0089 0.0089 0.0088	0.0113 0.0109 0.0113	0.0066 0.0067 0.0067	0.89 ± 0.20	0.53 ± 0.29
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	0.0088 0.0084 0.0089	0.0118 0.0127 0.0111	0.0062 0.0067 0.0076	0.91 ± 0.23	0.55 ± 0.32
	6 mg/L Fe^{3+}	0.0137 0.0134 0.0135	0.0183 0.0177 0.0161	0.0126 0.0125 0.0123	1.45 ± 0.23	0.87 ± 0.23
	6 mg/L Fe^{3+} +UF	0.0132 0.0132 0.0132	0.0149 0.0151 0.0121	0.0117 0.0114 0.0118	1.30 ± 0.14	0.78 ± 0.17
	6 mg/L Fe^{3+} 2mg/L O_3	0.0081 0.0084 0.0080	0.0100 0.0100 0.0102	0.0092 0.0078 0.0079	0.88 ± 0.10	0.53 ± 0.18
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	0.0073 0.0074 0.0076	0.0092 0.0093 0.0100	0.0074 0.0077 0.0075	0.82 ± 0.10	0.49 ± 0.20

UF III A-B	Effluent	0.0174 0.0162 0.0165	0.0181 0.0169 0.0166	1.70 ± 0.07	1.00 ± 0.04
	Effluent + UF	0.0177 0.0177 0.0174	0.0163 0.0161 0.0163	1.69 ± 0.08	1.00 ± 0.09
	2 mg/L Fe^{3+}	0.0179 0.0147 0.0172	0.0168 0.0153 0.0153	1.62 ± 0.13	0.96 ± 0.12
	2 mg/L Fe^{3+} +UF	0.0147 0.0148 0.0147	0.0148 0.0151 0.0152	1.49 ± 0.02	0.88 ± 0.06
	2 mg/L Fe^{3+} + 2mg/L O_3	0.0100 0.0102 0.0103	0.0100 0.0093 0.0101	1.00 ± 0.04	0.59 ± 0.08
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	0.0099 0.0086 0.0093	0.0091 0.0089 0.0095	0.92 ± 0.05	0.54 ± 0.09
	2 mg/L Fe^{3+} + 4 mg/L O_3	0.0073 0.0066 0.0064	0.0070 0.0069 0.0065	0.68 ± 0.03	0.40 ± 0.09
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	0.0089 0.0127 0.0061	0.0070 0.0075 0.0067	0.82 ± 0.24	0.48 ± 0.34
	2 mg/L Fe^{3+} + 6 mg/L O_3	0.0070 0.0041 0.0048	0.0061 0.0053 0.0046	0.53 ± 0.11	0.31 ± 0.24
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	0.0045 0.0048 0.0060	0.0049 0.0049 0.0049	0.50 ± 0.05	0.29 ± 0.14
	2 mg/L Fe^{3+} + 8 mg/L O_3	0.0040 0.0031 0.0061	0.0037 0.0041 0.0034	0.41 ± 0.11	0.24 ± 0.30
	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	0.0036 0.0030 0.0041	0.0034 0.0040 0.0037	0.36 ± 0.04	0.21 ± 0.15
	2 mg/L Fe^{3+} + 10 mg/L O_3	0.0029 0.0019 0.0024	0.0024 0.0025 0.0028	0.25 ± 0.04	0.15 ± 0.18
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.0017 0.0020 0.0030	0.0034 0.0028 0.0024	0.26 ± 0.06	0.15 ± 0.29
UF IV A-B	Effluent	0.0166 0.0166 0.0165	0.0171 0.0161 0.0164	1.66 ± 0.03	1.00 ± 0.02
	Effluent + UF	0.0194 0.0177 0.0183	0.0157 0.0158 0.0155	1.71 ± 0.16	1.03 ± 0.12
	6 mg/L Fe^{3+}	0.0144 0.0143 0.0149	0.0132 0.0133 0.0134	1.39 ± 0.07	0.84 ± 0.07
	6 mg/L Fe^{3+} +UF	0.0143 0.0151 0.0149	0.0128 0.0124 0.0126	1.37 ± 0.12	0.83 ± 0.11
	6 mg/L Fe^{3+} + 2 mg/L O_3	0.0095 0.0095 0.0100	0.0080 0.0082 0.0080	0.89 ± 0.09	0.54 ± 0.12
	6 mg/L Fe^{3+} + 2 mg/L O_3 + UF	0.0088 0.0086 0.0083	0.0076 0.0091 0.0084	0.85 ± 0.05	0.51 ± 0.08
	6 mg/L Fe^{3+} + 6 mg/L O_3	0.0049 0.0053 0.0048	0.0036 0.0036 0.0037	0.43 ± 0.08	0.26 ± 0.20
	6 mg/L Fe^{3+} 6 mg/L O_3 + UF	0.0044 0.0055 0.0048	0.0033 0.0038 0.0033	0.42 ± 0.09	0.25 ± 0.23

	6 mg/L Fe^{3+} + 10 mg/L O_3	0.0015 0.0021 0.0024	0.0021 0.0020 0.0028		0.22 ± 0.04	0.13 ± 0.22
	6 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.0031 0.0039 0.0030	0.0027 0.0026 0.0026		0.30 ± 0.05	0.18 ± 0.19
UF V A-C	Effluent	0.0157 0.0160 0.0163	0.0165 0.0164 0.0164	0.0170 0.0166 0.0168	1.64 ± 0.04	1.00 ± 0.02
	Effluent + UF	0.0156 0.0154 0.0157	0.0163 0.0161 0.0162	0.0164 0.0167 0.0161	1.61 ± 0.04	0.98 ± 0.05
	4 mg/L Fe^{3+}	0.0139 0.0138 0.0142	0.0145 0.0145 0.0145	0.0139 0.0139 0.0135	1.41 ± 0.04	0.86 ± 0.05
	4 mg/L Fe^{3+} +UF	0.0136 0.0131 0.0133	0.0139 0.0139 0.0141	0.0137 0.0132 0.0132	1.36 ± 0.04	0.83 ± 0.05
	4 mg/L Fe^{3+} + 2 mg/L O_3	0.0076 0.0078 0.0082	0.0082 0.0088 0.0082	0.0090 0.0093 0.0088	0.84 ± 0.06	0.51 ± 0.09
	4 mg/L Fe^{3+} + 2 mg/L O_3 + UF	0.0078 0.0077 0.0078	0.0078 0.0079 0.0077	0.0088 0.0088 0.0088	0.81 ± 0.05	0.49 ± 0.09
	4 mg/L Fe^{3+} + 6 mg/L O_3	0.0032 0.0036 0.0032	0.0029 0.0030 0.0034	0.0044 0.0043 0.0042	0.36 ± 0.06	0.22 ± 0.19
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF	0.0029 0.0027 0.0029	0.0029 0.0030 0.0027	0.0040 0.0038 0.0042	0.32 ± 0.06	0.20 ± 0.21
	4 mg/L Fe^{3+} + 10 mg/L O_3	0.0021 0.0016 0.0016	0.0014 0.0014 0.0014	0.0025 0.0022 0.0018	0.18 ± 0.04	0.11 ± 0.25
	4 mg/L Fe^{3+} + 10 mg/L O_3 + UF	0.0016 0.0017 0.0014	0.0012 0.0010 0.0014	0.0021 0.0022 0.0021	0.16 ± 0.04	0.10 ± 0.29

Table 38: Colour 436 of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

		Trial 1	Trial 2	Trial 3		
Name of experiment	Sample	Measured value [1/cm]	Measured value [1/cm]	Measured value [1/cm]	Mean value [1/m]	c/c_0
BW I A/C	Effluent	0.0192 0.0200 0.0189	0.0174 0.0176 0.0177		1.85 ± 0.11	1.00 ± 0.06
	Effluent + UF 1st permeate	0.0187 0.0190 0.0187	0.0159 0.0160 0.0156		1.73 ± 0.16	0.94 ± 0.15
	Effluent + UF 3rd permeate	0.0196 0.0186 0.0191	0.0163 0.0164 0.0165		1.78 ± 0.15	0.96 ± 0.14
	Effluent + UF 5th permeate	0.0193 0.0190 0.0194	0.0163 0.0166 0.0165		1.79 ± 0.15	0.97 ± 0.14
BW I B/D	4 mg/L Fe^{3+} + 6 mg/L O_3	0.0057 0.0050 0.0050	0.0037 0.0040 0.0037		0.45 ± 0.08	0.24 ± 0.24
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	0.0043 0.0044 0.0044	0.0037 0.0038 0.0036		0.40 ± 0.04	0.22 ± 0.15
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	0.0055 0.0040 0.0042	0.0040 0.0039 0.0037		0.42 ± 0.06	0.23 ± 0.21

	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	0.0050 0.0045 0.0044	0.0042 0.0042 0.0040		0.44 ± 0.03	0.24 ± 0.14
BW II	Effluent		0.0132 0.0130 0.0129	0.0154 0.0152 0.0170	1.45 ± 0.17	1.00 ± 0.12
BW II A/C	4 mg/L Fe^{3+}		0.0105	0.0131 0.0132 0.0140	1.27 ± 0.15	0.88 ± 0.24
	4 mg/L Fe^{3+} + UF 1st permeate		0.0100 0.0108 0.0099	0.0131 0.0128 0.0136	1.17 ± 0.17	0.81 ± 0.26
	4 mg/L Fe^{3+} + UF 3rd permeate		0.0109 0.0104 0.0104	0.0137 0.0131 0.0129	1.19 ± 0.15	0.82 ± 0.24
	4 mg/L Fe^{3+} + UF 5th permeate		0.0108 0.0107 0.0109	0.0146 0.0140	1.22 ± 0.19	0.84 ± 0.27
BW II B/D	4 mg/L Fe^{3+}+ 6 mg/L O_3		0.0027 0.0027 0.0028	0.0040 0.0039 0.0047	0.35 ± 0.09	0.24 ± 0.36
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate		0.0029 0.0024 0.0026	0.0040 0.0044 0.0041	0.34 ± 0.09	0.24 ± 0.37
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate		0.0033 0.0041 0.0041	0.0041 0.0040 0.0035	0.39 ± 0.04	0.27 ± 0.21
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate		0.0042 0.0035 0.0030	0.0044 0.0044 0.0044	0.40 ± 0.06	0.28 ± 0.27
BW III	Effluent	0.0179 0.0175 0.0179	0.0175 0.0172 0.0180		1.77 ± 0.03	1.00 ± 0.02
BW III A/D	4 mg/L Fe^{3+}	0.0145 0.0144 0.0141	0.0141 0.0143 0.0143		1.43 ± 0.02	0.81 ± 0.03
	4 mg/L Fe^{3+} + UF 1st permeate	0.0142 0.0149 0.0147	0.0135 0.0135 0.0145		1.42 ± 0.06	0.80 ± 0.06
	4 mg/L Fe^{3+} + UF 3rd permeate	0.0145 0.0145 0.0146	0.0148 0.0143 0.0152		1.47 ± 0.03	0.83 ± 0.04
	4 mg/L Fe^{3+} + UF 5th permeate	0.0149 0.0167 0.0153	0.0149 0.0157 0.0158		1.56 ± 0.07	0.88 ± 0.06
BW III B/E	4 mg/L Fe^{3+}+ 2 mg/L O_3	0.0092 0.0099 0.0091	0.0094 0.0090 0.0090		0.93 ± 0.03	0.52 ± 0.06
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	0.0083 0.0081 0.0096	0.0085 0.0089 0.0085		0.87 ± 0.05	0.49 ± 0.08
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	0.0088 0.0086 0.0084	0.0088 0.0088 0.0086		0.87 ± 0.02	0.49 ± 0.04
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	0.0088 0.0087 0.0087	0.0089 0.0090 0.0090		0.89 ± 0.01	0.50 ± 0.03
BW III C/F	4 mg/L Fe^{3+}+ 6 mg/L O_3	0.0044 0.0046 0.0044	0.0048 0.0047 0.0047		0.46 ± 0.02	0.26 ± 0.05
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	0.0039 0.0048 0.0038	0.0041 0.0050 0.0049		0.44 ± 0.05	0.25 ± 0.14
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	0.0047 0.0044 0.0046	0.0057 0.0042 0.0047		0.47 ± 0.05	0.27 ± 0.13

	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	0.0043 0.0043 0.0041	0.0046 0.0043 0.0047		0.44 ± 0.02	0.25 ± 0.07
BW III G	4 mg/L Fe^{3+}+ 10 mg/L O_3		0.0033 0.0032 0.0032		0.32 ± 0.01	0.18 ± 0.04
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate		0.0028 0.0033 0.0028		0.30 ± 0.03	0.17 ± 0.12
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate		0.0033 0.0033 0.0034		0.33 ± 0.01	0.19 ± 0.04
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate		0.0037 0.0042 0.0036		0.38 ± 0.03	0.22 ± 0.10

6.3.9 COD_f

Table 39: COD_f of Ruhleben secondary treated effluent with different combinations of Fe^{3+}-concentrations (0 - 6 mg Fe/L) and ozone dosages (0-10 mg O_3/L) – results of UF trials

		Trial A		Trial B		Trial C	
Name of experiment	Sample	Measured value [mg/L]	c/c_0	Measured value [mg/L]	c/c_0	Measured value [mg/L]	c/c_0
UF I A-C	Effluent	26.7	1.0	30.2	1.0		
	Effluent + UF	25.2	0.9	28.1	0.9		
	Effluent + 10 mg/L O_3	23.2	0.9	27.3	0.9		
	Effluent + 10 mg/L O_3 + UF	23.6	0.9	26.7	0.9		
	2 mg/L Fe^{3+}	25.5	1.0	29.3	1.0		
	2 mg/L Fe^{3+} +UF	25.2	0.9	27.7	0.9		
	2 mg/L Fe^{3+} + 10 mg/L O_3	24.6	0.9	26.7	0.9		
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	23.1	0.9	25.7	0.9		
	6 mg/L Fe^{3+}	23.1	0.9	28.0	0.9		
	6 mg/L Fe^{3+} +UF	23.3	0.9	27.0	0.9		
	6 mg/L Fe^{3+} 10 mg/L O_3	22.6	0.8	25.7	0.9		
	6 mg/L Fe^{3+} 10 mg/L O_3 + UF	22.4	0.8	25.2	0.8		
UF II A-C	Effluent	30.1	1.0	34.4	1.0	31.1	1.0
	Effluent + UF	29.1	1.0	32.3	0.9	28.3	0.9
	Effluent + 2mg/L O_3	29.7	1.0	34.2	1.0	29.9	1.0
	Effluent + 2mg/L O_3 + UF	27.8	0.9	32.0	0.9	27.6	0.9
	2 mg/L Fe^{3+}	29.2	1.0	33.1	1.0	28.4	0.9
	2 mg/L Fe^{3+} +UF	28.0	0.9	31.7	0.9	25.8	0.8
	2 mg/L Fe^{3+} + 2mg/L O_3	28.5	0.9	33.9	1.0	30.6	1.0
	2 mg/L Fe^{3+} + 2mg/L O_3 + UF	27.6	0.9	32.8	1.0	27.9	0.9

	6 mg/L Fe^{3+}	27.2	0.9	31.9	0.9	30.0	1.0
	6 mg/L Fe^{3+} +UF	26.6	0.9	30.2	0.9	26.2	0.8
	6 mg/L Fe^{3+} 2mg/L O_3	27.7	0.9	32.5	0.9	26.2	0.8
	6 mg/L Fe^{3+} 2mg/L O_3 + UF	26.5	0.9	31.4	0.9	25.2	0.8
UF III A-B	Effluent	27.8	1.0	31.5	1.0		
	Effluent + UF	27.6	1.0	27.6	0.9		
	2 mg/L Fe^{3+}	27.3	1.0	29.2	0.9		
	2 mg/L Fe^{3+} +UF	26.6	1.0	27.8	0.9		
	2 mg/L Fe^{3+} + 2mg/L O_3	27.4	1.0	28.5	0.9		
	2 mg/L Fe^{3+} + 2 mg/L O_3 + UF	26.0	0.9	28.4	0.9		
	2 mg/L Fe^{3+} + 4 mg/L O_3	26.5	1.0	25.1	0.8		
	2 mg/L Fe^{3+} + 4 mg/L O_3 + UF	26.0	0.9	26.7	0.8		
	2 mg/L Fe^{3+} + 6 mg/L O_3	26.4	0.9	28.6	0.9		
	2 mg/L Fe^{3+} + 6 mg/L O_3 + UF	25.7	0.9	26.6	0.8		
	2 mg/L Fe^{3+} + 8 mg/L O_3	25.6	0.9	27.1	0.9		
	2 mg/L Fe^{3+} + 8 mg/L O_3 + UF	25.0	0.9	25.6	0.8		
	2 mg/L Fe^{3+} + 10 mg/L O_3	25.3	0.9	25.9	0.8		
	2 mg/L Fe^{3+} + 10 mg/L O_3 + UF	24.8	0.9	25.6	0.8		
UF IV A-B	Effluent	29.1	1.0	30.0	1.0		
	Effluent + UF	27.4	0.9	27.5	0.9		
	6 mg/L Fe^{3+}	26.6	0.9	28.2	0.9		
	6 mg/L Fe^{3+} +UF	26.0	0.9	24.9	0.8		
	6 mg/L Fe^{3+} + 2 mg/L O_3	27.0	0.9	26.0	0.9		
	6 mg/L Fe^{3+} + 2 mg/L O_3 + UF	25.3	0.9	27.2	0.9		
	6 mg/L Fe^{3+} + 6 mg/L O_3	25.9	0.9	25.7	0.9		
	6 mg/L Fe^{3+} 6 mg/L O_3 + UF	24.8	0.9	25.9	0.9		
	6 mg/L Fe^{3+} + 10 mg/L O_3	25.0	0.9	23.9	0.8		
	6 mg/L Fe^{3+} + 10 mg/L O_3 + UF	23.8	0.8	24.9	0.8		
UF V A-C	Effluent	28.8	1.0	32.3	1.0	28.6	1.0
	Effluent + UF	27.2	0.9	28.0	0.9	27.9	1.0
	4 mg/L Fe^{3+}	27.5	1.0	30.1	0.9	28.5	1.0
	4 mg/L Fe^{3+} +UF	25.9	0.9	27.6	0.9	27.7	1.0
	4 mg/L Fe^{3+} + 2 mg/L O_3	27.8	1.0	28.9	0.9	27.5	1.0

	4 mg/L Fe^{3+} + 2 mg/L O_3 + UF	25.6	0.9	26.0	0.8	26.0	0.9
	4 mg/L Fe^{3+} + 6 mg/L O_3	26.2	0.9	27.6	0.9	26.7	0.9
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF	23.9	0.8	25.2	0.8	24.8	0.9
	4 mg/L Fe^{3+} + 10 mg/L O_3	24.8	0.9	25.4	0.8	24.0	0.8
	4 mg/L Fe^{3+} + 10 mg/L O_3 + UF	23.6	0.8	23.3	0.7	24.3	0.8

Table 40: COD_f of untreated Ruhleben secondary effluent and Ruhleben secondary effluent with 4 mg Fe^{3+}/L and different ozone dosages (0-10 mg O_3/L) – results of BW trials

		Trial 1		Trial 2		Trial 3	
Name of experiment	Sample	Measured value [mg/L]	c/c_0	Measured value [mg/L]	c/c_0	Measured value [mg/L]	c/c_0
BW I A/C	Effluent	32.2	1.00	28.8	1.00		
	Effluent + UF 1st permeate	30.8	0.96	27.2	0.94		
	Effluent + UF 3rd permeate	30.4	0.94	27.5	0.95		
	Effluent + UF 5th permeate	30.3	0.94	27.4	0.95		
BW I B/D	4 mg/L Fe^{3+} + 6 mg/L O_3	27.8	0.86	25.7	0.89		
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 1st permeate	27.0	0.84	23.6	0.82		
	4 mg/L Fe^{3+} + 6 mg/L O_3 + UF 3rd permeate	27.2	0.84	24.5	0.85		
	4 mg/L Fe^{3+} + 6 mg/L O_3+ UF 5th permeate	28.2	0.88	22.8	0.79		
BW II	Effluent			24.2	1.00	29.3	1.00
BW II A/C	4 mg/L Fe^{3+}			22.2	0.92	27.0	0.92
	4 mg/L Fe^{3+} + UF 1st permeate			20.3	0.84	26.2	0.89
	4 mg/L Fe^{3+} + UF 3rd permeate			21.2	0.88	26.3	0.90
	4 mg/L Fe^{3+} + UF 5th permeate			23.6	0.98	25.6	0.87
BW II B/D	4 mg/L Fe^{3+}+ 6 mg/L O_3			21.6	0.89	25.7	0.88
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate			19.7	0.81	22.6	0.77
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate			18.8	0.78	23.5	0.80

	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate			22.3	0.92	23.8	0.81
BW III	Effluent	29.7	1.00	28.2	1.00		
BW III A/D	4 mg/L Fe^{3+}	26.7	0.90	27.0	0.96		
	4 mg/L Fe^{3+} + UF 1st permeate	26.7	0.90	24.7	0.88		
	4 mg/L Fe^{3+} + UF 3rd permeate	26.3	0.89	25.4	0.90		
	4 mg/L Fe^{3+} + UF 5th permeate	27.0	0.91	25.6	0.91		
BW III B/E	4 mg/L Fe^{3+}+ 2 mg/L O_3	27.2	0.92	26.7	0.95		
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 1st permeate	26.1	0.88	25.7	0.91		
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 3rd permeate	25.6	0.86	25.6	0.91		
	4 mg/L Fe^{3+}+ 2 mg/L O_3 + UF 5th permeate	26.2	0.88	24.6	0.87		
BW III C/F	4 mg/L Fe^{3+}+ 6 mg/L O_3	25.9	0.87	23.4	0.83		
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 1st permeate	24.3	0.82	23.1	0.82		
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 3rd permeate	24.3	0.82	23.7	0.84		
	4 mg/L Fe^{3+}+ 6 mg/L O_3 + UF 5th permeate	23.8	0.80	23.9	0.85		
BW III G	4 mg/L Fe^{3+}+ 10 mg/L O_3			23.8	0.84		
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 1st permeate			21.8	0.77		
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 3rd permeate			22.8	0.81		
	4 mg/L Fe^{3+}+ 10 mg/L O_3 + UF 5th permeate			22.8	0.81		