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The municipal wastewater treatment plant of the future – A water reuse facility

Evaluation of a full-scale tertiary treatment system for removal of pharmaceuticals and recovery of water at the WWTP Stengården in Simrishamn, Sweden

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Summary

Climate change and the ongoing pollution of the aquatic environment will lead to a further increased pressure on natural water resources and an increased shortage in access to clean water in many regions of the world. The Water Framework Directive has established a framework for integrated water management in Europe to tackle these problems, a recent evaluation indicates that less than half of the EU's water bodies are in good status, even though the deadline for achieving this was 2015. For wastewater and other waste stream handling, a paradigm shift from end-of-pipe solutions to circular approaches must be the way forward. Sewage and other wastes should be considered as valuable resources that can be turned into valuable commodities in resource facilities that provide services to a sustainable society, e.g. reuse of water.

In 2015 the municipality of Simrishamn at the coast of Hanöbukten, took an initiative to do concrete actions for the water environment in the gulf and the Baltic sea. Together with IVL Swedish Environmental Research Institute, Simrishamn decided to start a project for the design, implementation and evaluation of a full-scale plant for removal of micropollutants such as pharmaceuticals and hormone disturbing substances. This ambition came true within a VINNOVA funded programme, Challenge Driven Innovation, stage 3 - Implementation of innovations in full scale and through a decision by the City council for the investment in a full-scale demonstration plant. As the region, including Simrishamn municipality, have been facing water shortage in recent years, it was decided to also evaluate the possibility to reuse the treated water by infiltration to the ground water. For this, an advanced treatment was added to the existing wastewater treatment plant (WWTP) with a design most suitable for evaluation and demonstration. The plant was up and running in the beginning of 2019 and the evaluation period ended in September the same year.

Over the existing WWTP, the evaluation showed that the removal efficiencies for pharmaceuticals is generally poor. This is in line with previous reported results from other Swedish WWTPs. Considering concentrations of pharmaceuticals in the effluent of the WWTP and the targeted wastewater reclamation, an additional treatment of the effluent becomes necessary.

The evaluation of the implemented three parallel advanced treatment systems consisting of only activated carbon (GAC), ozonation combined with sand filter, and ozonation combined with activated carbon clearly shows an added removal effect for pharmaceuticals but also other pollutants. This agrees with previous studies of these systems and especially that the combination of ozonation with activated carbon stands out as the most efficient treatment system. The pre-treatment with microfiltration (by disc-filtration), common for all advanced treatment systems, further implies an important part for a robust operation of the tertiary treatment system and for the overall removal efficiency.

Evaluation of the reusability of the treated water also showed positive results. The removal of pharmaceuticals, endocrine disrupting substances and antibiotics was almost 100 % and indicates that the water could be reused, e.g. by recharging to the groundwater. If the water is recharged to the groundwater, a long-term follow-up is recommended. Addition of a disinfection of the final effluent as an extra barrier for reused water, e.g. UV-treatment, is also recommended. Online sensors for monitoring and control of e.g. ozone doses requirements could be considered for improved and real-time follow-up of the treatment system. As the treatment consisting of microfiltration, ozonation and activated carbon was shown to be the most efficient configuration, the other treatment existing lines may eventually be converted to this operational mode as well.

Sammanfattning

Klimatförändringar och utsläpp av förorenande ämnen till vattenmiljön kommer att öka trycket på de naturliga vattenresurserna och leda till ökad brist på rent vatten i många regioner i världen. För att hantera dessa problem har EU:s ramdirektiv för vatten inrättat en rambeskrivning för integrerad vattenförvaltning i Europa. En ny utvärdering visar att mindre än hälften av EU: s vattendrag har god status, trots att tidsfristen för att uppnå detta var 2015. För avloppsvatten krävs ett paradigmskifte från linjära lösningar till cirkulära metoder. Avlopp och annat avfall bör betraktas som resurser som kan förvandlas till värdefulla varor i resursanläggningar som tillhandahåller tjänster till ett hållbart samhälle, exempelvis återvinning av vatten.

2015 tog Simrishamns kommun vid Hanöbuktens kust ett initiativ för att genomföra konkreta åtgärder för vattenmiljön. Tillsammans med IVL Svenska Miljöinstitutet beslutade Simrishamn att starta ett projekt för att designa, implementera och utvärdera en fullskalig anläggning för avlägsnande av mikroföroreningar som läkemedelsrester och hormonstörande ämnen ur det kommunala avloppsvattnet. Denna ambition gick i uppfyllelse inom ett VINNOVA-baserat program, Utmaningsdriven Innovation, UDI, etapp 3 - Implementering av innovationer i fullskala och genom ett beslut i fullmäktige om att investera i en fullskalig demonstrationsanläggning. Eftersom regionen, inklusive Simrishamn kommun, har upplevt vattenbrist de senaste åren beslutades att också utvärdera möjligheten att återanvända det behandlade vattnet genom infiltration till grundvattnet.

Utvärderingen av det befintliga reningsverket visade att effektiviteten för avskiljning av läkemedel i allmänhet är dålig. Detta är i linje med tidigare rapporter från andra svenska avloppsreningsverk. Med tanke på koncentration av läkemedel i avloppsvatten från det befintliga reningsverket och en eventuell återvinning av avloppsvattnet, är en utökad behandling av avloppsvattnet viktig.

Fullskaleanläggning som uppfördes under 2018 och stod färdig i januari 2019 består av tre parallella avancerade behandlingsystem; ett som endast består av granulerat aktivt kol (GAC), ett med ozonering i kombination med sandfilter och ett bestående av ozonering i kombination med aktivt kol. De tre systemen visar en tydlig avskiljning av läkemedel men även av andra föroreningar. Detta överensstämmer med tidigare studier av dessa system och särskilt att kombinationen av ozonering med GAC framstår som det mest effektiva behandlingsystemet. Förbehandlingen med mikrofiltrering (utgör en viktig del för en robust drift men bidrar även till avskiljningen av oönskade ämnen över systemet som helhet.

Den utökade utvärderingen av det behandlade vattnet för återvinningsändamål visade också goda resultat. Avlägsnandet av läkemedel, hormonstörande ämnen och antibiotika var nästan hundraprocentig och indikerar att vattnet bör kunna återanvändas, exempelvis genom infiltration till grundvattnet.

Om vattnet infiltreras till grundvattnet för produktion av dricksvatten rekommenderas en längre uppföljning av detta vatten. Desinfektion av det återvunna vattnet som en extra barriär för återanvänt vatten, exempelvis UV-behandling, rekommenderas också. Online-sensorer för övervakning och kontroll av exempelvis ozondosen kan övervägas för förbättrad realtidsuppföljning. Eftersom den avancerade reningen bestående av mikrofiltrering, ozonering och granulerat aktivt kol (GAC) visade sig vara den mest effektiva konfigurationen, bör de andra befintliga behandlingslinjerna (GAC utan ozonering samt sandfiltrering efter ozonering istället för GAC) också ställas om till denna uppställning.

1 Introduction

1.1 Background and motivation

Today's society is facing a variety of environmental issues and problems with climate change as the most acknowledged one. It is important to understand that various environmental parameters are strongly interconnected and affect each other. Climate change and the ongoing pollution of the aquatic environment will for example further increase pressures on natural water resources and lead to increased shortage in access to clean water in many regions of the world. An increased urbanization and consumption and lifestyle patterns may be main underlaying causes and only a decoupling of environmental degradation and resource use from economic growth will facilitate a sustainable society. In the case of the aquatic environment, the problems that require proper attention may be divided into two dimensions: water pollution (quality matter) and management of freshwater resources (quantity matter). Even so the Water Framework Directive has established a framework for integrated water management in Europe to tackle these problems, a recent evaluation indicates that less than half of the EU's water bodies are in good status, even though the deadline for achieving this was 2015 (EC 2019).

Both professional fishermen and an interested public have, for several years, reported on problems they observed in the Hanöbukten on the east coast of Skåne, south of Sweden. These have been such serious things as, for example, injured fish, falling fish stocks and oxygen deficiency in the bottom water. These observations were taken most seriously and led to several investigations. Already in 2013, the Marine and Water Authority published a survey of the environment in the Hanöbukten, but without being able to pinpoint any crucial causes of the problems reported (The Swedish Agency for Marine and Water Management, SwAM, 2018).

Several of the pharmaceuticals accumulate in the ecosystems and in accordance with a report by HELCOM on pharmaceutical concentrations and effects in the Baltic Sea (UNESCO and HELCOM, 2017), pharmaceuticals are among the major emerging pollutants, making it a common challenge to the countries around the Baltic Sea. Even if treated wastewater is discharged to recipients with high dilution such as marine environments, an advanced purification of wastewater to remove micropollutants may be necessary. This because these persistent substances have a long residence time and can be detected in surface water far out in the Baltic Sea and filtering organisms, such as blue mussels (Swedish EPA, 2017).

For wastewater and other waste stream handling, a paradigm shift from end-of-pipe solutions to circular approaches must be the way forward. Sewage and other wastes should be considered as valuable resources that can be turned into valuable commodities in resource facilities that provide services to a sustainable society. At the same time, contaminants collected by the sewage can be removed from the circular use of resources.

The removal of micropollutants has gained increasing attention during the last years with many activities going on even in Sweden. Especially the removal of pharmaceutical residues and the risk of antibiotic resistant bacteria (ARB) is currently under discussion. Much focus has been on inland recipients as concentrations of pharmaceutical residues easily can exceed predicted no-effect concentrations. However, long residence times of pharmaceuticals and their detection in filtering organisms, such as blue mussels, and open waters imply that pharmaceuticals can accumulate even in recipients with large water turnover such as the Baltic Sea (Swedish EPA, 2017).

Moreover, wastewater reclamation, the reuse of treated wastewater, has been identified as one of the most significant approaches to be integrated in water management. Demands of different water uses such as drinking water, consumption for agricultural and industrial use, which all consume substantial quantities of water, could be meet using reclaimed water. While access to fresh water is getting more costly due to environmental pollution, climate change and increased demand on water resource, the use of reclaimed water provides a decreases stress on natural water resources by implementing a circular management approach. At the same time, micropollutants that need to be removed from sewage anyhow in order to stop the diminishing of the aquatic environment, can be taken care of.

In the recent years, the Swedish Österlen region, including Simrishamn municipality, has been facing such challenges of water shortage, especially during dry summer months with intensive tourist pressure on the region. Depending on limited groundwater resources and an increased water demand, the municipalities are looking for new approaches to reduce the use of drinking water for various applications (e.g. industries) or to support used groundwater sources by circular water management including wastewater reclamation and aquifer recharge.

1.2 General objectives of the project

To meet these challenges described in background, in 2015 the municipality of Simrishamn took an initiative to move from words to concrete actions for the water environment in the Hanöbukten and the Baltic sea. Together with IVL, they decided to start a project for the design, implementation and evaluation of a full-scale advanced treatment for removal of micropollutants such as pharmaceutical and hormone disturbing substances from treated wastewater. This ambition came true within a VINNOVA founded programme, Challenge Driven Innovation, stage 3, implementation of innovations in full scale. The VINNOVA- IVL-Simrishamn funded project had the title “The municipal wastewater treatment facility of tomorrow – a production unit for resources”.

The original aim of this project was to demonstrate and evaluate a full-scale system for tertiary post treatment of pharmaceutical residues from the municipal wastewater treatment plant (WWTP) Stengården in Simrishamn. With the expanding issue of water shortage around the world, in addition to evaluation of the performance for removing pharmaceutical residues, the project additionally evaluated the potential of creating a reusable water through the installed tertiary treatment. Since the start-up of the project, water scarcity has also hit the south eastern part of Sweden including the coast of Hanöbukten. With the aim to meet this new challenge, the project was extended to also include the evaluation of the possibility for wastewater reclamation.

In addition to the advanced treatment for micropollutant removal, the VINNOVA project also included other actions such as the test and evaluation of co-digestion of sludge and fish slaughter waste, test and evaluation of anammox technology for energy efficient removal of nitrogen and a subproject for optimisation of the activated sludge process. The results of those sub-projects are not included in this report.

1.3 Stengården wastewater treatment plant

The Stengården WWTP was originally built in 1972 for treatment of municipal and industrial wastewater. Since then, the plant has successively been expanded and modernized. In 1995, the WWTP was rebuilt for nitrogen purification with pre-denitrification. In 1998, sludge reed beds were built to treat the produced sewage sludge. About 7 000 households are connected to the

WWTP in addition to several industries including fish industries, wine industry, food companies and chemical industry. In recent years, the load from industries has decreased significantly but the total flowrate is rather constant around 2 250 000 m^3/year, corresponding to an average value of 270 m^3/hour.

Due to leakage (infiltration to wastewater piping) and stormwater connected to the sewer system, the average flowrate during the period between October to March is roughly 350 m^3/h. The contribution of other water than wastewater is estimated to be as much as 50% of the total flow treated at the WWTP. The actual design of Stengården WWTP is for 1 455 m^3/h (Q_{dim}) with a maximal flow of 2 265 m^3/h (Q_{max}). Expressed in load as Biochemical oxygen demand (BOD), the plant is originally designed for 87 000 pe (70 g BOD_7/person and day as standard in Sweden) with a current average load of < 10 000 pe. Both actual flows and loads indicated oversized process volumes, which results in higher retention times of the wastewater in the WWTP. This may also affect removal efficiencies of various pollutants.

Current regulatory limits for the treated wastewater are defined as 10 mg/L BOD_7 as quarterly mean value, 0.3 mg TP (total phosphorous)/L as yearly mean and quarterly guideline, and 12 mg TN (total nitrogen)/L as yearly mean guideline (no limit). The incoming wastewater is first screened before it enters the sand trap. The sand trap is aerated as also Al-based precipitation chemical (PAX 15) is added. The biological treatment takes place in four parallel lines without primary sedimentation. Within biological treatment, nitrified water from the aerated zone is recirculated back to the inlet anoxic zone of the biological treatment. Sludge separation takes place in six sedimentation basins. Excess sludge is transferred to reed beds for mineralisation and, if reed beds cannot be used, dewatered and transported to an incineration in Malmö. The treated wastewater is discharged into the Baltic Sea just south of Simrishamn using an outlet pipe of about 400 m from the shoreline with an outlet depth of about 10 meters (Figure 1.1). The WWTP has also an option for a chlorine disinfection of the effluent before it is discharged to the Baltic Sea.

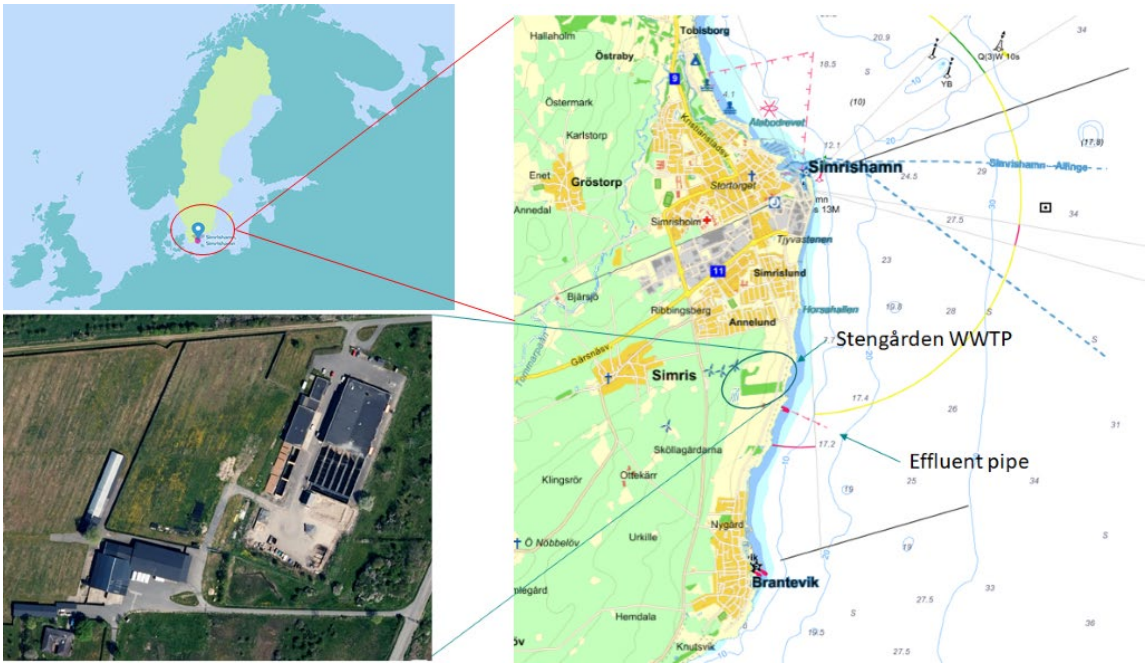

Figure 1.1 Location of Stengården WWTP, Simrishamn.

With respect to the defined guidelines and regulatory limits the treatment facility at Stengården WWTP performs generally acceptable. Considering the facility's environmental report for year 2018, only an operational disturbance that shut down half of the facility during February caused higher pollutant concentrations than normal in the effluent. Generally, BOD_7 was below 5 mg/L and TP below 0.2 mg/L for most of the year. TN was mostly below 12 mg/L despite the period of operational problems. However, better treatment performance during the last month of 2018 with TN of < 6mg/L implied that the guideline value of 12 mg TN/L for the yearly average was not exceeded. Average reductions obtained for BOD_7, TP and TN were 94%, 95% and 66%, respectively.

As complement to the existing activated sludge process at Stengården WWTP, the advanced treatment system implemented by Simrishamn municipality consists of three different treatment trains in parallel. It is the first full-scale system of its kind in Sweden. The system is installed in a new building, exclusively dedicated for the demonstration plant. The design of the plant is made with high focus on testing and demonstration resulting in an impressive facility, not only in the perspective of performance but also for testing and demonstration, including guided tours for delegations, project groups, the public (e.g. school classes).

1.4 Project organization and management

The evaluation of the full-scale plant Stengården in Simrishamn, Sweden, is the third stage of a VINNOVA program, Demand Driven Innovation (Swedish: UtmaningsDriven Innovation, UDI). During UDI phase two of the UDI program year 2013-2015, we have evaluated partial solutions that will lead to a production plant for water that, after removal of pharmaceutical residues, metals and other priority substances, can be recycled for different purposes. Bioenergy can be produced from sewage and organic waste; phosphorus and other nutrients can be returned in its pure form.

Based on the positive pilot results, the third phase of the UDI, demonstration, was started up 2015. The project in phase 3 aimed to demonstrate in full-scale the use of three steps in series for removal of pharmaceuticals and reuse of water by three parallel advanced treatment systems: 1/ only activated carbon (GAC), 2/ ozonation combined with sand filter (O3SF) and 3/ ozonation combined with activated carbon (O3GAC). All 3 configurations were pre-treated by microfiltration, MF (by disc-filtration). The sand filtration and GAC filtration after ozonation are biological polishing treatment steps based on surfaces (sand and GAC) for biological growth. The quality of the treated water was carefully evaluated for removal of pharmaceuticals and for water reuse and the process was optimized from a resource efficiency point of view.

The project group for the advanced treatment implementation and evaluation at Stengården WWTP consisted of IVL Swedish Environmental Research Institute, The municipality of Simrishamn, Xylem Water Solutions, Nordic Water and the Swedish University of Agricultural Sciences (SLU). There were more partners involved in the project during construction and installation. Some partners that originally were part of the project group was not involved in the full-scale installation and evaluation phase. This report focusses on the evaluation of the demonstrated full-scale polishing treatment step at Stengården for removal of pharmaceuticals and water reuse. In addition to this demonstration of the tertiary treatment system, subprojects on biogas production, resource efficient removal of nitrogen by use of anammox technology and optimization of the secondary treatment step at Stengården was carried out but not reported here.

2 Project Methodology

2.1 Circular water management

The current project has focused on an approach the project team often referred to as "The wastewater treatment plant of tomorrow – a resource facility to serve a sustainable society". With respect to the earlier mentioned challenges that require proper attention (see 1.1), the approach of wastewater reclamation used in the project targets both water pollution (quality matter) and management of freshwater resources (quantity matter). With water being a limited resource that naturally has been recirculated an endless number of times, the increased use and deterioration of water by humans has created an imbalance in the circular water cycle. Shifting from end-of-pipe solutions to circular approaches, as suggested by the project, must be taken into consideration as a future, sustainable solution.

Figure 2.1 illustrates the overall scheme of wastewater reclamation and interlinks between various water using and polluting sectors. Water as one of the most valuable resources should be cleaned from contaminants and reused for various purposes such as irrigation, industrial use or groundwater recharge at first. As today's WWTP are only designed for removal of easily degradable organic pollutants and nutrients, advanced treatment is required as a complement to remove micropollutants. The "regained" water quality after advanced treatment helps to save natural water resources by reduced use of these for purposes that instead can be fulfilled by reclaimed water. Recycling of reclaimed water to natural water resources is another way of restoring natural ecosystem balance and securing access to clean water to society.

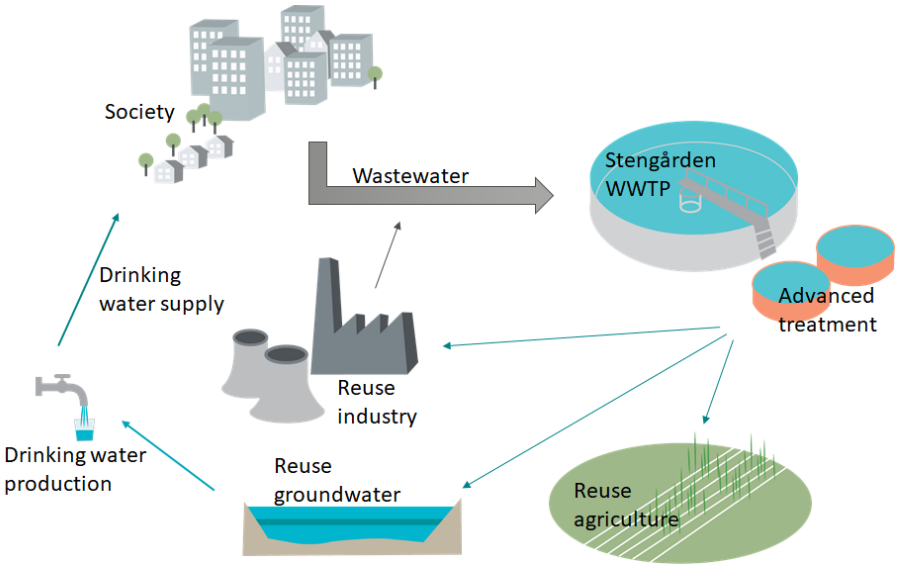

Figure 2.1 Schematic illustration of the targeted water management scheme by the project.

To establish sustainable circular systems for different resources is one of the overall goals for Simrishamn municipality. The reuse of water is just one of these circular systems. Related to the sewage handling, circular sludge handling is another focus area of the municipality.

2.2 Selected advanced treatment

The selected advanced treatment systems to complete Stengården WWTPs existing treatment process consist of a microfiltration (MF) as first additional process step for removal of suspended material from the current WWTP effluent. The filtered water is then going to three different treatment configurations. The first line consists of a granular activated carbon (GAC) filter only. The second and third train have an ozone oxidation (O_3) as the first process followed by 2 parallel sand filtration (SF) units respectively two parallel GAC-filters (2.2).

The setup with three parallel advanced treatment trains was chosen to facilitate full-scale comparison of these three technology combinations. All trains can be operated with constant or dynamic flow with the latter linked to the inflow to the WWTP. The design flow of the advanced treatment is 300 m^3/h (in total for three lines with 30 m^3/h for internal use). At higher flows the excess of 300 m^3/h is discharged to the Baltic Sea already after the already existing treatment. This design flow was decided based on flow rate evaluation revealing that most of the flow could be treated with this design while at the same time not installing unused treatment capacity that requires maintenance. From the start, an additional treatment of the final effluent in the already existing disinfection process at Stengården WWTP was thought of but not included in the overall process evaluation.

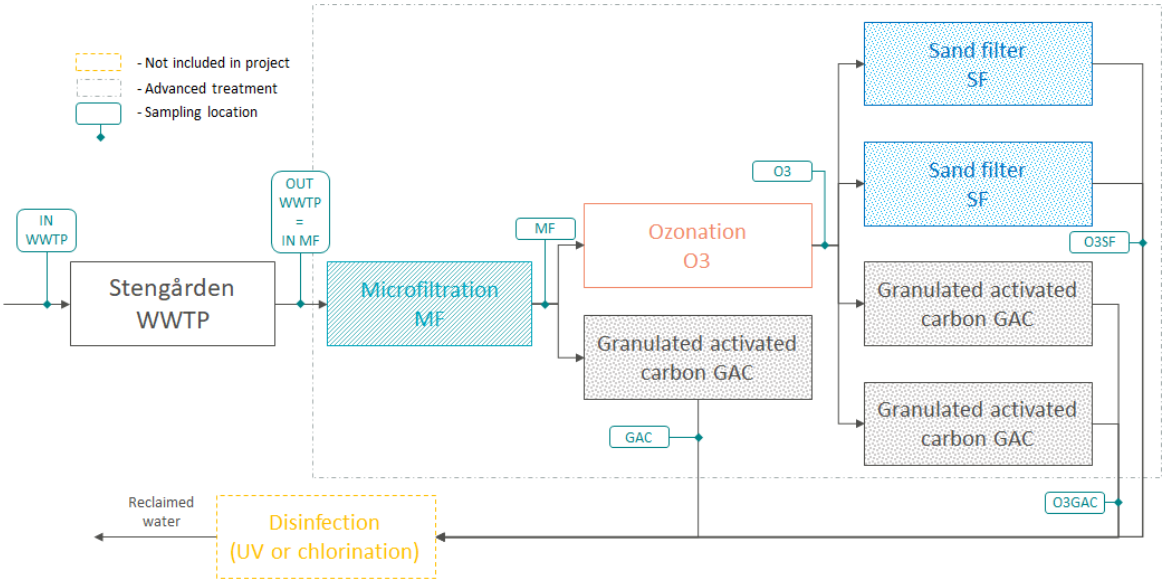

Figure 2.2 The three parallel tertiary treatment systems demonstrated in full scale at Stengården WWTP.

The implemented advanced treatment systems were selected based on extensive pilot studies in the "ReUse-project" performed by IVL and Xylem at the R&D-facility Hammarby Sjöstadsverk (www.hammarbysjostadsverk.se) during 2011-2015 (Baresel et al., 2015a, b) but also in the two first stages of the Vinnova funded project. These projects demonstrated that the right technologies can be efficiently combined to meet various regulations and requirements and guarantee that the solutions work reliably. The novelty in the ReUse-project, however, was the approach to shift focus from individual processes to treatment systems while not losing single process performance. This implied an overall system optimization based on the whole system assessment that guaranty best value-for-money. This included a combined assessment of treatment performances, environmental impact and life cycle cost of several treatment systems of different plant sizes based on state-of-the-art technologies and archiving various wastewater reuse quality requirements. Results of the

extensive assessment of treatment performances, environmental impact (LCA) and life cycle cost (LCC) of several treatment systems including the three configurations applied at Stengården WWTP are provided by Baresel et al. (2015a, b; 2016; 2017a, b; 2019) and Lazic et al. (2016a, b; 2017a, b). The combination of microfiltration, ozonation and sand or GAC filters was one of the most efficient combinations to achieve reclaimed water qualities. The assessment of life cycle cost (LCC) for different treatment configurations was based on performance test with pilot-scale installations and actual data from full-scale installations. These cost calculations showed that the advanced treatment can be achieved at a relatively low cost of <0.5 SEK/m^3 including investment and operational costs for larger installations but that an efficient advanced treatment can also be implemented at smaller (>10 000pe) facilities (Baresel et al. (2015a; 2017a).

In specific, the following technologies were implemented in full-scale (2.2.1 – 2.2.3).

2.2.1 Microfiltration (MF)

The microfiltration, MF, consists of a DynaDisc filter from Nordic water, consisting of multiple filter discs with a nominal pore size of 10 µm. The water to be filtered flows via the inlet channel into the rotor drum and then flows by gravity into the filter disc segments through openings in the drum and passes through the filter media. Suspended solids are separated and accumulated on the inside of the filter cloth. When the water level inside the filter rotor increases to a pre-set point, the filter rotor starts rotating and the backwash of the filter media starts. The high-pressure backwash spray removes the accumulated suspended solids inside the filter. The suspended solids are then discharged via the reject pipe. The discs are submerged to approximately 65 % and the water level of the filtrate is maintained by a level tank.

Figure 2.3 Nordic water DynaDisc-filter.

The Nordic water DynaDisc-filter features a well-proven and highly effective filtration process that has been used worldwide in many full-scale installations.

2.2.2 Ozonation (O_3)

The estimated water quality after the disk filter used for the design of the ozonation unit were 10 mg DOC/L, ≤1.5 mg BOD7/L, 6-7 mg SS/L, ≤7 mg TN/L, ≤0.5 mg TP/L and very low iron.

The implemented ozone system is feed with oxygen, produced by a Pressure Swing Adsorption (PSA) oxygen separator which also includes a filter and storage tanks. The ozone generation unit itself is of the compact type SMOevo. High voltage is applied inside the generator to break-up oxygen molecules that re-form into ozone molecules. As this process also creates waste heat, this heat has to be removed by cooling water passing through the vessel. Important process parameters, e.g. cooling water flow, gas flow, ozone concentration, pressure and temperature, are permanently controlled via the integrated PLC. The ozone introduction system consists of 8 diffusers inside the contact tank to ensure an efficient ozone transfer into the water. To quantify the ozone concentration in the gas phase, a WEDECO HC 400+ is used as process analyzer which makes it possible to calculate an ozone transfer mass balance. A local programmable Siemens logic controller (PLC) provides independent operation of the ozone generation system. Connected to the PLC is a spectral sensor (WTW NiCaVis 705 IQ) in the ozone inlet for not only UVT measurement, but also for Nitrite, COD. By this the ozone dose control can be set by the following different methods:

1) Adjustment of ozone production related to water flow
2) Adjustment of ozone production related to ozone concentration in offgas
3) Adjustment of ozone production related to spectral sensor readings

Figure 2.4. WEDECO Ozone Generator Type SMOevo 460.

A safety device to monitor the ozone concentration in the ambient air provides an alarm signal in case of ozone gas leak and automatically turns down the system in emergency cases. The included ozone destruct system removes non-dissolved gas and converts any residual ozone present to oxygen using catalytic material.

Figure 2.5 Full-scale installation of the ozonation system.

2.2.3 Granular activated carbon (GAC) and Sand filtration (SF)

Both technologies have been supplied by Nordic Water and are based on the company's well-known up-flow, continuously moving bed filter system that is designed to use different filter medias and media depths for various applications and configurations. In the current configuration, two DynaSand filter and three DynaSand Carbon filters (one alone and two in combination with ozonation) were installed.

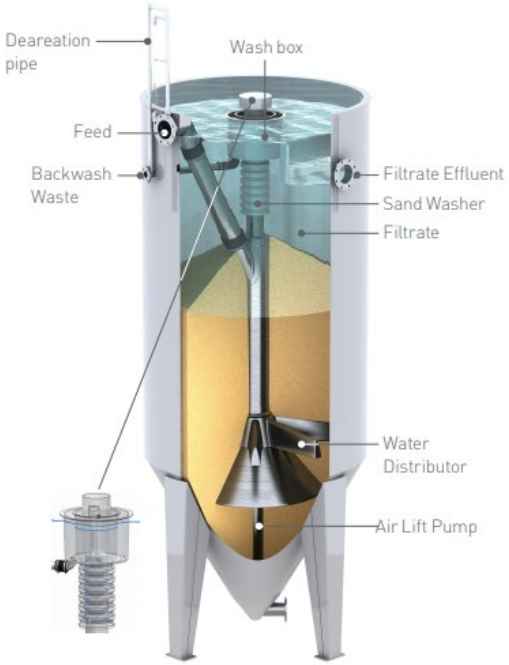

Figure 2.6 Schematic illustration of the installed DynaSand and DynaSand Carbon filters.

The function of the different filters is basically the same. Untreated water enters near the top of the filter and is lead down in the center of the filter to the bottom. The water is then evenly distributed into the filter media through the distribution arms. The treated water leaves the filter at the top. Unlike conventional backwashed sand filters, DynaSand most of the time operates with a continuous backwash, as a fraction of the filtrate is used to clean the filter media from impurities. The key mechanism behind the bed movement is injection of air near the bottom of the filter in the air-lift pump, which generates a drag that in turn elevates dirty bed material up into the sand washer.

Continuous moving filters represent a totally mixed bed volume in comparison to conventional backwashed filters that were used in preceding pilot studies (Baresel et al., 2015a). The more well-defined sorption zone as in conventional filter systems is not available. Instead a more evenly distributed sorption effect will take place throughout the whole filter bed height. To what extend this affects the adsorption performance of the filter compared to traditional filters has not been looked at in the current project. Another aspect not investigated yet is the performance of different GAC-filter types as biological filter subsequent to ozonation. DynaSand Carbon filters have previously been used as adsorption filters in drinking water production. For the removal of pharmaceuticals from wastewater, the technology has been investigated e.g. at German WWTPs (e.g. Rietberg WWTP, 2013). The study at Rietberg WWTP also indicated that the used filter technology is affected by certain activated carbon characteristics such as particle size and density.

At Stengården WWTP, two different types of bed material are used in the filters: conventional sand and granular activated carbon (GAC). By using GAC as filter media it is possible to adsorb micropollutants such as pharmaceutical residues. Principally, the adsorption in DynaSand Carbon does not differ from other activated carbon filters. However, the effect of elevated oxygen concentrations from the previous ozonation on the biological activity in the filter has not been studied as for conventional GAC filters (Baresel et al., 2015a).

The continuous filtration used within DynaSand filters reduces footprint and makes it resistant to high loading of suspended solids. This achieved without any extra strain on the wash water treatment stage. No clean water or wash water storage tanks are required in DynaSand, and normally redundancy of filter system is not required. The continuous backwash increased on the other hand the use of backwash water that has to be returned to the main treatment process and thus increases the internal load. Therefore, other operation principles to further boost the overall efficiency may be possible. Operating intermittently, meaning that during certain periods of time there is no air injection into the air-lift pump and therefore the bed is stationary, is one option.

Figure 2.7 Two of the five Dynasand filters after installation

After an initial period with problems monitoring the movement and circulation of the sand and activated carbon, all filters were complemented with an automated monitoring and control tool called Sand-Cycle (BW Products). Sand-Cycle has originally been developed to provide better insight in the performance of any type of continuous sand filtration system. It uses RFID tags that are added to the filter bed, where they follow the sand/carbon movement through the filter. The signal of the tags passing certain detection points provides information like circulation speeds and filter bed homogeneity.

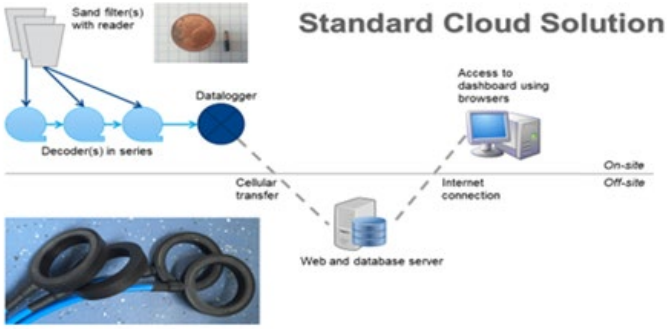

Figure 2.8 Automated monitoring and control tool Sand-Cycle.

Bed turnover is determined by averaging all measured ID-tags over a 4-hour period, and is expressed in mm/min. The homogeneity of the filter is calculated by the spread between mean and standard deviation, i.e. the more ID-tags that move within similar time intervals the more homogeneous the bed. The volume of the active bed is estimated from the number of unique ID-tags that passed the last day.

2.3 Water quality targets for water reuse

As the project targets wastewater reclamation to various reuse applications groundwater recharge, quality targets meeting the minimum requirements for such water reuse have to be accomplished by the treatment processes at Stengården WWTP. In 2018, the European Commission put forward a proposal for a regulation setting EU-wide standard that reclaimed water would need to meet in

order to be used for agricultural irrigation and groundwater recharge (COM/2015/614). While this harmonization is welcomed by most, critics stress that contaminants of emerging concern, antibiotic resistance spread, and possible risks associated with advanced treatment were inadequately addressed (e.g. Rizzo et al., 2018). The added problem of transformation products has not been considered according to Rizzo et al. (2018).

The new EU-standards for reclaimed water, however, were not at place when the current project was planned and implemented. Therefore, water quality requirements as defined by the previous ReUse-project on wastewater reuse (Baresel et al., 2015a) were used. The ReUse-project mapped the global non-potable reuse quality standards and guidelines to identify compounds of interest and synthesize global reuse quality targets for different reuse applications. This included different regulations and guidelines from different countries. From the review of various regulations and standards, effluent quality targets for the considered reuse alternatives were defined as shown in table 2.1

Table 2.1 Required main effluent qualities as monthly average for the different reuse applications (modified from Baresel et al., 2015a).

Parameter	Unit	Irrigation in agriculture	Industrial use	Groundwater Recharge
Microbiology				
Total Coliforms	/100 ml	2.2	2.2	2.2
Max Total Coliforms	/100 ml	23	23	23
Solids				
Total Suspended Solids	mg/L	5	2	5
Organic & Inorganic				
BOD_5	mg/L	<8	<5	<5
COD	mg/L	<40	<30	<30
Total Nitrogen	mg/L	20	10	<10
Ammonia Nitrogen	mg/L	5	1	1
Nitrate Nitrogen	mg/L	10	5	10
Organic Nitrogen	mg/L	5		5
Total Phosphorus	mg/L	2	1	1

The presented parameters in the table above only provide an indication of the required quality of the reclaimed water. The project further included analyses of several other micropollutants as described in the next section. For several of these pollutants, no maximum concentrations are defined. As late as in June 2019, the Council of the EU agreed on the general approach of water reuse (EU 10278/19), but only for agricultural irrigation and defined limits are less and weaker than the one defined in the Reuse project. For the comparison of the results from the evaluation of the reused water we have used Swedish drinking standards which are stricter than for industrial, irrigation and ground water recharge.

As ozonation was proposed as one of the treatment technologies for advanced treatment, analyses of bromide and bromate were performed and bromate concentrations in the effluent water compared to the recommend drinking water standard of 10 µg/l.

The Swedish chemical and microbiological permission limits for drinking water is shown in the Appendices 6.2.

2.4 Contaminants, sampling, analysis methods and online monitoring

Common parameters including BOD_7, TP and TN, ammonium and a number of metals were monitored at Stengården WWTP by means of 24h-composite samples analysed by an external commercial laboratory (Synlab). In addition to the external analyses, analyses for operational follow-up were also performed internally at the Stengården WWTP by means of colorimetric methods using a spectrophotometer and standard cuvette tests.

For the evaluation of the treatment performance of the advanced treatment (polishing step), both composite (weekly and 24h) and grab samples were used. Collection of grab and composite samples was performed by onsite samplers (ISCO 6712, Portable Sampler) directly connected to refrigerators with options for various interval sampling and local cooling. The placement of the different samplers is indicated in figure 2.9. Grab samples could also be collected by manual samplers and at different valves. Sampling intervals varied depending on long-term evaluation or shorter campaigns, e.g. when investigating ozone dose-response relationships.

Figure 2.9 Sampling valve station for collecting grab samples.

For weekly composite samples, the sample taps were kept running and continuously flooding glass beakers (figure 2.9). Via PVC and silicone tubing, the automated samplers took sample water from the glass beakers into a larger container inside the fridge. The sampling point into Stengården WWTP (IN WWTP) was sampled through the already set-up monitoring sampling by Stengården, taking continuous flow-proportional 24h-samples. A representative weekly sample was then manually mixed. Depending on the substance/variable to analyse, the sample water was after finished week sampling transferred to new plastic bottles (polypropylene) and frozen or refrigerated before being sent for analysis at the laboratories, depending on the analysis to be made. Some analyses such as ozone residual and nitrite were conducted directly onsite at the time of measurement. In between sampling sessions, equipment was thoroughly cleaned with detergent and rinsed in the respective sample tap water. Tubing and other equipment in contact with sample water inside the sampler was regularly cleaned with distilled water through programming the samplers to take single samples in between. When grab samples were collected, each sample tap was beforehand let open at high flow during at least two minutes.

In addition to standards contaminants (BOD, P, N, SS, etc.) a series of additional emerging pollutants were investigated in the project. These include

- Pharmaceutical residues including antibiotics and hormones,

- Nonyl phenols, octyl phenols and ethoxylates (OV-18e),
- Per- and Polyfluoroalkyl Substances (PFAS),
- Phthalates (OV-4b),
- Polychlorinated biphenyls,
- Microplastics,
- Antibiotic resistant bacteria (ARB),
- and a number of chemical parameters with bacterial and pesticide extension according to the Swedish drinking water standard.

The appendices 6.4 includes a complete list of all monitored parameters. Pharmaceuticals, PFAS, microplastics, phenols and many standard parameters were analyzed by IVL Swedish Environmental Research Institute. Bacteriological analyses including antibiotic resistance were performed by the Swedish University of Agricultural Sciences. All other analyses including for example drinking water standard parameters were done by ALS Scandinavia.

All analyses were performed according to existing standards and only for analyses of pharmaceuticals, microplastics and antibiotic resistance a brief description of the methods is provided.

2.4.1 Pharmaceuticals

Pharmaceuticals were analysed using aliquots of 100 to 200 mL thawed composite samples that were spiked with 50 µL internal standard carbamazepine-13C15N (2000 ng/mL) and ibuprofen-D3 (2000 ng/mL). One millilitre of 0.1 wt% ethylenediaminetetraacetate (EDTA-Na2) dissolved in methanol:water (1:1) was added. Prior to extraction using solid phase extraction (SPE) cartridges (Oasis HLB, 6 mL, Waters), the sample was shaken. Cartridges were conditioned with methanol followed by Milli-Q (MQ) water. Thereafter, the samples were applied to the columns at a flow rate of two drops per second. The substances were eluted from the SPE cartridges using 5 mL methanol followed by 5 mL acetone. The supernatants were transferred to vials for final analysis on a binary liquid chromatography (UFLC) system with auto injection (Shimadzu, Japan). The chromatographic separation was carried out using gradient elution on a C18 reversed phase column (dimensions 50 × 3 mm, 2.5-µm particle size, XBridge, Waters, UK) at a temperature of 35°C and a flow rate of 0.3 mL/ min. The mobile phase consists of 10 mM acetic acid in water.

2.4.2 Microplastics

Microplastic particles (correct term is microlitter particles comprising microplastics and non-synthetic anthropogenic material such as textile fibers) were analyzed by following method (Magnusson et al., 2016) commonly used in screenings in Nordic countries as standards for microplastic analyses are not yet established. The water samples were filtered through filters with a mesh size of 300, 100, and 20 µm and the material collected on the filters was analyzed with a Nikon SMZ18 stereo microscope (7.5 - 135 times magnification). All microplastic particles were counted and divided into two groups according to their shape—plastic fragments and plastic fibers. The term microplastics or plastic particles refer to both groups. In addition to the microplastics, also non-synthetic fibers of anthropogenic origin were counted. This included textile fibers of for example cotton, but not cellulose from toilet paper. Samples of incoming water were treated with 1M KOH overnight in order to reduce the amount of organic matter.

A mass determination was performed for the incoming untreated wastewater sample. For each of the three filter sizes (300, 100 and 20 µm) 10 particles or fibers were randomly selected. The volume

of the particle or fiber were calculated with the help of Nikon´s NIS-Elements Imaging Software. Following assumptions were made: fibers were classified to be either rectangular or cylindrical. For a rectangular fiber the volume was calculated with the formula: $V = l \times b \times h$, where l is the length of the fiber, b is the width of the fiber and the thickness, h, was set to 2 µm. For a cylindrical fiber the volume was calculated with the formula: $V = \pi \times r^2 \times l$, where r is the measured thickness of the fiber divided by two and l is the measured length. For fragments with a shape similar to a sphere the volume was calculated with the formula $V = (4 \times \pi \times r^3)/3$ and for fragments with a more flat shape the formula $V = A \times h$ was used, where A corresponds to the area of the object as measured by the NIS-Elements Imaging Software and h is the thickness of the particle; measured if possible otherwise estimated.

The mass of the particles was calculated with the formula mass = density * volume. The density of plastic particles was set to 1 mg/mm^3, since the most common plastic particles are made of polypropylene (PP) and polyethylene (PE), which both have a density just below 1 g/cm^3, while most of the other plastic materials have a density just above 1 g/cm^3. The most commonly used material in plastic fibers is polyethylene terephthalate (PET), with a density of 1.38 g/cm^3 and this was used as density for all the plastic fibers identified. The density of cotton is 1.5 g/cm^3, and this was used for all non-synthetic fibers.

2.4.3 Bacteria, antibiotic resistant bacteria

For analysis of antibiotic resistant bacteria (ARB) 1-4 litre samples were collected in sterile bottles and were cold stored until analysed. Water samples for ARB analyses was depending on assumed concentration either serially diluted (Buffered NaCl with Tween) or filtered over 45 µm filters. Diluted samples were then plated, or filters transformed to agar plates for bacterial enumeration. For detection of extended beta lactamase (ESBL) producing *E. coli* and other *Enterobacteriaceae* (*Klebsiella* spp., *Enterobacter* spp., *Citrobacter* spp, *Pseudomonas* spp and *Acinetobacter* spp.) CHROMagar^{TM}ESBL was used and in parallel for enumeration of total number of the bacteria the same media without antibiotic supplement was used (CHROMagar ^{TM}Orientation). For enumeration of vancomycin resistant *Enterococcus* spp., allowing differentiation of *E. faecalis* and *E. faecium* from other enterococci, CHROMagar ^{TM} VRE was used, with and without antibiotic supplement. All plates were incubated for 24 hours at 37 °C before counting of typical colonies. Presumptive *E. coli* was confirmed by indole test and antibiotic resistant *E. coli* was also plated on CHROMID Carba Smart (bioMérieux) and presumptive *E. facalis* and *E. faecium* confirmed by growth in 6.5% NaCl in Brain Hearth Infusion (BHI), tested being Pyrrolidonyl Arylamidase (PYR) positive with antibiotic resistant *E. facalis* and *E. faecium* also plated on CHROMID VRE (bioMérieux).

2.4.4 Bromate/Bromide

Bromide was analyzed on a Dionex anion-chromatograph. The sample was led with a carbonate eluent through an anion exchange column where the ions are separated. The eluent conductivity was reduced by a suppressor and the anions are then detected with a conductivity detector.

Bromate was analyzed on a Dionex anion-chromatograph. The sample was led with a potassium hydroxide eluent through an anion exchange column, where the ions were separated. Eluent strength increased gradually through a gradient generator to provide the best separation in the shortest time. The eluent conductivity was reduced by a suppressor and the anions were then detected with a conductivity detector. Analyses were performed at the IVL laboratory in Gothenburg.

2.5 Sampling campaigns (SC)

The evaluations have been conducted in the period from April to September 2019. During this period the incoming sewage flow to Stengården WWTP was 66 – 384 m^3/h (average ± standard deviation: 218 ± 39 m^3/h). A number of sampling campaigns (SC) were performed for the evaluation of different aspects.

2.5.1 SC1 – Removal of pharmaceuticals at ozone dose 8 mg/L

A first week composite sampling campaign was carried out 2019-04-04 – 2019-04-12 to assess the functionality of the automated samplers and evaluate the efficiency of removal of pharmaceutical residues including antibiotics at a constant dosage of 8 g ozone/m^3. The incoming flow rate to Stengården WWTP was in the range 262-294 m^3/h, with an average value of 276 ± 11 m^3/h based on averaged day values with 24 h resolution. The flow over the ozonation was constant at 160 m^3/h. Samples were collected as 50 ml every 30 minutes for the sampling points of IN MF, O3SF, O3GAC, GAC.

2.5.2 SC2 - Ozone dose-response behavior

During 2019-04-29 – 2019-04-30, shorter tests with different ozone dosages were run and different variables analysed in grab samples before and after the ozone tank (MF and O3) to determine an ozone dose-response curve. The incoming flow rate to Stengården WWTP varied in the range 174-247 m^3/h with an average value of 216 ± 31 m^3/h based on averaged hourly values with 3-8 h resolution (00:00-06:00, 06:00-09:00, 09:00-16:00, 16:00-24:00). The flow over the ozonation was fixed at 160 m^3/h. Evaluated ozone doses were 3, 6, 8 and 12 g/m^3, tested in random order. Samples were collected as grab samples, allowing for flow proportional adjustment of the facility between ozone doses (>120 min) as well as over the ozone tank (52 min between MF and O3). Sampled variables include: pharmaceutical residues (including antibiotics at the dosage of 8 g/m^3), remaining ozone, nitrite, bromate, UVA, UVT and dissolved organic carbon (DOC).

2.5.3 SC3 - Removal of microplastics and pharmaceuticals at ozone dose 6 mg/L

Sampling of microplastics was conducted as a week composite sampling 2019-05-09 – 2019-05-16 with 50 ml sample taken every 30 minutes for IN MF and O3GAC. IN WWTP was sampled as described above. The ozone dose was 6 g/m^3. The incoming flow rate to Stengården WWTP varied between 147-520 m^3/h with an average value of 225 ± 71 m^3/h based on averaged hourly values with 3-8 h resolution. The flow over the ozone tank was 160 m^3/h. All sampling containers and equipment in contact with sample water was beforehand rinsed twice with distilled water. All exposed surfaces were covered in clean aluminium foil and a 100% cotton laboratory coat was worn during the whole procedure. A procedural contamination control sample was created by simulating the sampling process through connecting identical tubes to the tap for normal drinking water. This sample was then handled and analysed identically to the other samples to enable representative quantification of potential contamination levels and establishment of the limit of detection for microplastic analyses.

2.5.4 SC4 – Removal om pharmaceuticals at ozone dose 4 mg/L

A week composite sampling evaluation period was performed between 2019-06-24 – 2019-07-01 for the analysis of pharmaceutical residues, antibiotics, hormones and microbiology at an ozone dosage of 4 g/m^3. The incoming flow rate varied between 131 and 267 m^3/h with an average of 191 ± 39 m^3/h based on averaged hourly values with 3-8 h resolution. The flow over the ozone tank was adjusted from 160 to 150 m^3/h before sampling start to minimize occasions where the inflow to the ozone tank would be affected due to seasonal flow reasons. Samples were flow proportionally collected at the sampling points IN WWTP, IN MF, O3SF, O3GAC, and GAC.

2.5.5 SC5 – Production of a reusable water at ozone dose 6 mg/l

A week composite sampling evaluation period was conducted during the period 2019-08-27- 2019-09-03 for an assessment of the potential to create reusable water. The evaluation was performed at an ozone dosage of 6 g/m^3 and the following extended choice of substances were analysed at O3GAC: pharmaceutical residues including antibiotics, hormones, per- and polyfluorinated alkyl substances (PFAS), standard drinking water parameters (including metals), pesticides, microbiology, polycyclic aromatic hydrocarbons (PAH), phenols, etoxilates, polychlorinated biphenyls (PCB) and phthalates. The incoming flow rate varied between 38 and 322 m^3/h with an average of 166 ± 80 m^3/h based on averaged hourly values with 3-8 h resolution. The flow over the ozone tank was adjusted from 150 to 120 m^3/h before sampling start to minimize occasions where the inflow to the ozone tank would be affected due to seasonal flow reasons. Samples were flow proportionally collected at the sampling points IN WWTP, IN MF, O3GAC.

2.5.6 Other sampling campaigns

Several special sampling campaigns were conducted to investigate levels and dynamics of bromate through the whole WWTP and tertiary treatment with different ozone dosages. These were performed both as grab samples (2019-05-28), day composite sample (2019-06-12) and week composite sample (2019-08-27 – 2019-09-03) at the following sampling points: IN WWTP (not all at all occasions), MF, O3 and O3GAC. The level of suspended solids was also analysed at IN MF and after each filter to monitor the functionality of the filters (2019-05-28 & 2019-07-01). Samples were collected as grab samples.

Grab samples during different ozone dosages were collected 2019-07-15 – 2019-07-16 for the analysis of antibiotic resistant bacteria. The incoming flow rate varied between 172 and 288 m^3/h with an average of 227 ± 52 m^3/h based on averaged hourly values with 3-8 h resolution. The flow over the ozone tank was 150 m^3/h. A follow-up was conducted 2019-09-03 – 2019-09-04 for an additional analysis of antibiotic resistant bacteria. The incoming flow rate during this occasion varied between 66 and 322 m^3/h with an average of 187 ± 96 m^3/h based on averaged hourly values with 3-8 h resolution. The flow over the ozone tank was 120 m^3/h.

3 Results

3.1 Treatment efficiency at Stengården WWTP

The following sections provide results for the removal of various contaminants in the Stengården WWTP without any additional advanced treatment for micropollutant removal. In addition, current loads to the recipient, the Baltic Sea, and risk assessment of these loads are presented.

3.1.1 General treatment performance

Table 3.1 shows averages for incoming and outgoing concentrations of common parameters analyzed in samples collected during sample campaigns SC3 and SC4 and analyzed at IVL. As the table indicates, an effective removal of standard pollutants was achieved during the evaluation period. It can also be noticed that defined effluent limits were not reached for Biological oxygen demand (BOD) and total phosphorous (TP). However, effluent limits for those are set as yearly mean and quarterly guideline, respectively. Concentrations of suspended material were still high, which illustrates the need for an extra microfiltration preceding the advanced treatment. These parameters are regularly and standardly measured at Stengården WWTP and when considering these historical data, removal efficiency of standard pollutants is varying but generally good, table 3.1.

Table 3.1 Concentrations of standard parameters at Stengården WWTP (average, based on two samples collected during SC3 and SC4).

Parameter	IN WWTP	OUT WWTP	Removal efficiency
Total Nitrogen TN (mg/L)	39	6.3	84%
Ammonia NH4-N (mg/L)	19.1	2.8	85%
Total Phosphorous TP (mg/L)	5.8	0.41	93%
Suspended solids SS (mg/L)	208	98	53%
Biological oxygen demand (5 days) BOD5 (mg/L)	75	12.5	83%
Chemical oxygen demand COD (mg/L)	345.5	32.5	91%

3.1.2 Microplastics

The analysis results for the mapping of microplastics during sampling campaign 3 (May 9 – 16) are shown in Table 3.2. A very effective removal of microplastics for all analyzed particle ranges (> 300 µm; >100 µm and > 20 µm) from the wastewater and transfer to the sludge phase is observed at the Stengården WWTP. An explanation for the higher removal rates than compared to other studies (e.g. Magnusson and Wahlberg, 2014; Magnusson et al., 2016) is most likely that the actual load to the Stengården WWTP is much lower than the design load (Q_{actual} <<< Q_{dim}; see section 1.3), which implies longer retention times and settling of most microplastics.

Most detected microplastics was non-synthetic fibers with about <80% abundance for the largest (>300 µm) and smallest (>20 to < 100 µm) particle size ranges. For microplastics of size between 100 and 300 µm, non-synthetic fibers accounted for about 50%. Plastic fibers accounted for about 20 percent in the largest and smallest particle sizes but about 50% in the medium size range. Other fragments made up 50% in the medium size range but were insignificant in the other two size ranges.

Table 1.2 Microplastics concentrations in the incoming sewage and the effluent of the treatment plant.

Microplastics particles/m^3 Fibres, non-synthetic fibres, fragments	**IN WWTP**	**OUT WWTP**	**Removal %**
>300 µm	210 000	1000	99.5
100-300 µm	64 000	3750	94.1
20-100 µm	426 000	1250	99.7
Total	**700 000**	**6 000**	**99.14**

The total calculated mass of microplastics in the inflow of the WWTP is 640 kg/yr while only 5 kg/yr are emitted to the Baltic Sea. It should however be noted that this mass calculation is based on simplifications including the assumed uniformity of particle sizes. Further, the estimated mass only includes microplastic particles larger than 50 µm.

Microplastics that is removed from the treatment process with the waste sludge are either accumulated in the sludge reed beds or are destroyed when the sludge is undergoing thermal treatment (see 1.3). To what extent further spreading of microplastics from sludge reed beds takes place is difficult to estimate from this dataset.

3.1.3 Pharmaceutical residues

The evaluation of the advanced treatment on the removal of pharmaceutical residues from wastewater has been done during all sampling campaigns. For the assessment of the situation in the main treatment process at the Stengården WWTP samples were collected in campaigns 3 and 4 (SC3 & SC4).

3.1.3.1 Concentrations, loads and removal efficiency

Table 3.3 shows the average concentrations of hormones, pharmaceuticals and antibiotics in the influent and effluent of the Stengården WWTP. Only substances that could be quantified are presented. For the whole list of analyzed substances, please see the appendices. Hormone concentrations were below detection limits in the WWTP effluent. For estrone (E1) a very good removal was achieved in the existing treatment process. For estradiol (E2) and Ethinylestradiol (EE2) no removal efficiency was calculated as only level of quantification (LOQ) or detection (LOD) could be provided by that analyses and actual concentrations may thus be any value below these limits.

Removal efficiencies for pharmaceuticals were generally poor with several substances indicating an increase over the existing treatment process, i.e. negative reduction. This may have several explanations as investigated by Baresel et al. (2017). First, the complex wastewater matrix can reduce the recovery during sample preparation and affect the signal during pharmaceutical analysis. For example, high concentrations of other organic material in influent wastewater imply that certain pharmaceuticals are "observed" at lower concentrations than in the treated effluent wastewater. Further, some pharmaceuticals, metabolized in the human body, return to the structure of the parent compound during the treatment process and, therefore, quantified to larger extent in effluent wastewater. Some substances may also interact with free ions from the matrix and form chelate complex, which result in reduced recovery and detection.

Table 3.3 Average concentrations of hormones, pharmaceuticals and antibiotics in the influent and effluent of the Stengården WWTP (SC3 & SC4; only substances that could be quantified are presented). The LUSKA study is shown as reference for substances also included in that study.

Substance	IN WWTP (ng/L)	OUT WWTP (ng/L)	Removal efficiency	LUSKA (2017)
Hormones				
E1 (estrone)	37	2	>95%	48%
E2 (17β-estradiol)	4.85	2	-	
EE2 (17α-ethinylestradiol)	2.5	2	-	
Pharmaceuticals				
Amlodipine	125	37.5	-	
Atenolol	585	735	-26%	
Bisoprolol	160	185	-16%	
Caffeine	26 500	190	>99%	
Carbamazepine	260	435	-67%	80%
Citalopram	275	380	-38%	41%
Diclofenac	1320	1700	-29%	-5%
Fluoxetine	22	25.8	-17%	
Furosemide	3750	3950	-5%	
Hydrochlorothiazide	2300	3350	-46%	
Ibuprofen	5050	237.5	95%	94%
Ketoprofen	155	223	-44%	
Metoprolol	2150	3100	-44%	-11%
Naproxen	2350	780	67%	64%
Oxazepam	3700	7600	-105%	-19%
Paracetamol	4	4	-	
Propranolol	98.5	154	-56%	
Ramipril	61.00	41	-	
Ranitidine	57.5	86	-50%	
Risperidone	3.5	3.5	-	
Sertraline	240	97.5	59%	85%
Simvastatin	650	130	-	
Terbutaline	3	3	-	
Warfarin	27	17.6	35%	
Antibiotics				
Ciprofloxacin	26	6.8	>74%	100%
Claritromycin	28	10	-	
Clindamycin	7	36.7	-424%	
Doxycycline	110	110	-	
Erythromycin	175	119	32%	
Fusidic acid	16	16	-	
Linezolid	7.5	7.5	-	
Metronidazole	15.3	12.5	18%	
Moxifloxacin	2.5	2.5	-	
Norfloxacin	6.5	6.5	-	
Rifampicin	18	18	-	
Sulfamethoxazole	178	100.5	44%	64%
Tetracycline	162.5	157.5	-	
Trimetoprim	26.25	26.3	-	-20%
xxx – Average based on LOQ (Level of Quantification) and/or LOD (Level of Detection) values			≥80%	≥80%
			≥40 - <80%	≥40 - <80%
xxx – Average partly based on LOQ and/or LOD values			≤40%	≤40%

The table indicates that most of the analyzed antibiotics are below LOQ or LOD already in the influent to the WWTP. However, removal efficiency for quantifiable antibiotics indicate a poor removal except for Ciprofloxacin and Sulfamethoxazole.

Comparing removal rates with a mapping performed in 2017 within the LUSKA -project (Svahn and Björklund, 2017) shown similar trends but both higher and lower removal efficiencies. It must be noted not only few of the considered substances in this project were included in LUSKA and information about LOD and LOQ is not available.

From the average concentrations of various pharmaceuticals and the total flowrate of 350 000 m^3/year, the total discharges mass of pharmaceuticals can be estimated. Considering only the average values of 3.3 solely based on quantified concentrations and not considering Caffeine, a total of 8 kg of pharmaceuticals are entering the Stengården WWTP annually. The same amount of 8 kg of pharmaceuticals is emitted to the Baltic Sea each year with the effluent from the WWTP. This indicate no average removal effect in the current WWTP. The LUSKA-project estimated that about 10 kg of pharmaceuticals are emitted.

3.1.3.2 Comparison of levels against other WWTP

Table 3.4 shows a comparison of average levels of pharmaceuticals, antibiotics and with reference levels from various previous screenings that IVL has participated in. The reference levels are based on the median value of the respective substance. As the number of available reference levels continuously increases, presented values may change over time. For substances where an average value is based on only values below LOD or LOQ, no comparison has been made. Currently, the reference values consist of more than 30 measurement occasions at more than 14 Swedish treatment plants. It should be noted that these analyzes are based on different measurement occasions, different sampling frequency, different load cases and that analyzes have been carried out by different laboratories with different detection limits and quality. However, reference values can still give an indication of how the situation at Stengården WWTP is in a broader perspective.

All levels of hormones in the incoming wastewater at the Stengården WWTP were below average levels compared to other Swedish WWTPs. Many pharmaceuticals and two of the detectable antibiotics occur in significant higher concentrations than in other Swedish WWTPs. Possible reasons may be emissions from a relatively high number of residential homes and the hospital in Simrishamn. This may be supported by the very much higher concentrations of oxazepam that also has been observed especially in the effluent from residential home facilities in other studies (IVL, unpublished data). Table 3.4 further indicates higher effluent concentrations for a number of substances. Especially for substances that at the same time occur in lower concentrations in the influent compared to other WWTPs (e.g. Atenolol and Naproxen), this indicate a poorer removal efficiency of these substances at the Stengården WWTP. However, as this evaluation is only based on few measurement campaigns, results should be considered with care.

Table 3.4 Average concentrations of hormones, pharmaceuticals and antibiotics in the influent and effluent of the Stengården WWTP compared to other screenings at Swedish WWTPs (values based on LOD/LOQ above reference values are not considered). 100% means same levels as in other Swedish wastewaters, lower and higher than 100% imply lower or higher levels at Stengården WWTP compared to the refence, respectively.

Substance	IN WWTP (ng/L)	Compared to reference IN WWTP	OUT WWTP (ng/L)	Compared to reference OUT WWTP
Hormones				
E1 (estrone)	37	99%	2	<80%
E2 (17β-estradiol)	4.85	<35%	2	-
EE2 (17α-ethinylestradiol)	2.5	<25%	2	-
Pharmaceuticals				
Amlodipine	125	-	37.5	<79%
Atenolol	585	33%	735	131%
Bisoprolol	160	100%	185	168%
Carbamazepine	260	79%	435	95%
Citalopram	275	153%	380	90%
Diclofenac	1320	186%	1700	238%
Fluoxetine	22	251%	25.8	99%
Furosemide	3750	214%	3950	304%
Hydrochlorothiazide	2300	144%	3350	231%
Ibuprofen	5050	96%	237.5	153%
Ketoprofen	155	42%	223	99%
Metoprolol	2150	154%	3100	177%
Naproxen	2350	68%	780	217%
Oxazepam	3700	1038%	7600	390%
Paracetamol	4	<1%	4	<27%
Propranolol	98.5	167%	154	128%
Ramipril	61.00	555%	41	-
Ranitidine	57.5	37%	86	48%
Risperidone	3.5	<21%	3.5	<23%
Sertraline	240	600%	97.5	184%
Terbutaline	3	<27%	3	<15%
Warfarin	27	270%	17.6	352%
Antibiotics				
Ciprofloxacin	26	24%	6.8	<69%
Claritromycin	28	<78%	10	<42%
Clindamycin	7	<74%	36.7	122%
Erythromycin	175	583%	119	1082%
Moxifloxacin	2.5	-	2.5	<33%
Sulfamethoxazole	178	1195%	100.5	3350%
Tetracycline	162.5	<71%	157.5	-
Trimetoprim	26.25	8%	26.3	28%
				≥130%
				110 – 130%
				≤110%

3.1.3.3 Risk assessment for pharmaceutical emissions

Besides the risks for accumulation of pharmaceuticals and other emerging pollutants in the eco-systems of the Baltic sea, an assessment of risks for the nearest recipient, the Hanöbukten, has been performed based on toxicological studies and risk ratio and based on limit values for recipient status classification.

In table 3.5, a risk assessment of the recipient and an assessment of additional treatment requirements have been compiled. The risk assessment is based on the risk ratio, the so-called. EC/PNEC-ratio in the recipient. A high risk of unwanted effects is considered to exist if the risk ratio is 1 or higher. In the interval 0.1–1, the risk is defined as moderate, and a risk ratio <0.1 implies a low risk. The calculation is done according to the following equation.

$$\text{Risk ratio } \left(\frac{EC}{PNEC}\right) = \frac{WWTP\ effluent\ \times Safety\ factor}{NOEC \times Dilution}$$

where EC (Environmental Concentration) is the concentration in the WWTP effluent (WWTP OUT or IN MF) divided by the dilution of the effluent in the recipient. PNEC (Predicted No Effect Concentration) is based on NOEC (No Effect Concentration) which corresponds to the concentration that is the limit when toxic effects on the aquatic environment start according to the literature and a safety factor that considers the uncertainty in the ecotoxicological studies present in the literature. NOEC and safety factors have been updated within a recent project and are reported in Ågerstrand (2019). There are many different studies on effects, but no comprehensive database, which means that these values are constantly changing and need to be constantly updated as new toxicological studies are performed. The safety factor for each substance is chosen depending on the amount of toxicological data available. According to the risk assessment rules in the REACH regulation (ECHA guidance on chemical risk assessment; echa.europa.eu), the safety factor for 2 acute tests and a chronic test at three different trophic levels shall be 100. The safety factor for one acute test and 2 chronic tests at three different trophic levels. is 50. The safety factor for 3 chronic tests at three different trophic levels is 10. If there are no chronic tests, a safety factor 1000 has been used. For Citalopram and Oxazepam, the effect value is also based on a LOEC (Lowest Observed Effect Concentration) and thus an additional evaluation factor of 2 has to be used to compensate for the uncertainty, which must be considered in the risk assessment.

Information about the dilution of the discharged wastewater in the Hanöbukten is not available to the project. However, considering the general bathometry, flow conditions etc., the dilution conditions outside Simrishamn are exceptionally good and reach probably 1 000 times quickly. However, at what distance from the outlet pipe this high dilution is reached is difficult to say without more detailed investigations. Therefore, a dilution of 100 times was assumed in the risk assessment.

Levels of pharmaceutical residues in the receiving coastal water are not available as such analyses were not included in the project. However, detection limits are generally often much higher than levels in the recipient. Of the analyzed substances, most have a PNEC lower than the detection limit for the analytical method. A further development of analytical methods is required to be able to measure levels at the same level as PNEC.

For the hormones (estrone, estradiol and ethinyl estradiol) and some other substances, no effect assessment was made as measured levels were generally lower than the detection or quantification limit. An assessment of risks and purification needs based on LOD or LOQ would give a misleading picture. For Metronidazole, no assessment was made as relevant NOEC and safety factors have not been defined yet for this substance.

Table 3.5 Compilation of risk assessment and additional treatment requirements at Stengården WWTP. PNEC is the Predicted No Effect Concentration.

Substance	IN WWTP (ng/L)	OUT WWTP (EC) (ng/L)	PNEC (µg/L)	Risk ratio (-) Effluent	Risk ratio (-) Recipient (100x dilution)	Treatment required for risk ratio <1 in recipient	Treatment required for 80% reduction WWTP IN-OUT
Pharmaceuticals							
Amlodipine	125	37.5	0.01				
Atenolol	585	735	32	0.02	0.00		84%
Bisoprolol	160	185	35.6	0.01	0.00		83%
Carbamazepine	260	435	2.5	0.17	0.00		88%
Citalopram	275	380	0.000075	5070	51	98%	86%
Diclofenac	1320	1700	0.05	34	0.34		84%
Fluoxetine	22	25.8	1.16	0.02	0.00		83%
Furosemide	3750	3950	0.156	25.32	0.25		81%
Hydrochlorothiazide	2300	3350	1000	0.00	0.00		86%
Ibuprofen	5050	237.5	102	0.00	0.00		
Ketoprofen	155	223	2	0.11	0.00		86%
Metoprolol	2150	3100	2.59	1.20	0.01		86%
Naproxen	2350	780	15	0.05	0.00		40%
Oxazepam	3700	7600	0.01	760	7.6	87%	90%
Paracetamol	4	4	46				
Propranolol	98.5	154	0.228	0.68	0.01		87%
Ramipril	61.00	41	100				-
Ranitidine	57.5	86	0.002	43	0.43		87%
Risperidone	3.5	3.5	5.8				
Sertraline	240	97.5	0.0094	10.4	0.10		51%
Simvastatin	650	130	0.2				
Terbutaline	3	3	240				
Warfarin	27	17.6	11	0.00	0.00		69%
Antibiotics							
Ciprofloxacin	26	6.8	0.064				
Claritromycin	28	10	0.04				
Clindamycin	7	36.7	0.014	2.62	0.03		>96%
Doxycycline	110	110	0.0369				
Erythromycin	175	119	0.02	5.95	0.06		71%
Fusidic acid	16	16	0.5				
Linezolid	7.5	7.5	8				
Metronidazole	15.3	12.5	-				76%
Moxifloxacin	2.5	2.5	0.125				
Norfloxacin	6.5	6.5	0.022				
Rifampicin	18	18	0.064				
Sulfamethoxazole	178	100.5	0.118	0.85	0.01		65%
Tetracycline	162.5	157.5	0.482				
Trimetoprim	26.25	26.3	0.5	0.00	0.00		80%

Table 3.5 shows that Citalopram and Oxazepam have a calculated risk ratio in the recipient of >1, thus a high risk of influencing the recipient. Four other substances have a risk ratio between 0.1 and 1 which implies moderate risk. It should be noted that the safety factor for the two substances with high risk is very high (≥1000) due to the absence of chronic effect studies. If considering the undiluted effluent instead, the risk of effects is assessed as high for 9 substances and as moderate for another 4 substances.

As part of the classification of chemical status in water bodies is an assessment of levels of particularly pollutants. In the latest issue of HVMFS 2013:19 (The Swedish Agency for Marine and Water Management, SwAM, 2015), two pharmaceuticals (Ciproflaxin and Diclofenac) and two hormones (Estron and Ethinyl estradiol) are included in the list of particularly pollutants. To classify the chemical status of a recipient as Good, the levels of these pharmaceuticals in the recipient must be lower than the respective limit values. If the discharge of wastewater leads to the limit being exceeded, advanced treatment of the effluent to remove these substances must be implemented, otherwise permits for discharge to the recipient cannot be granted.

In table 3.6, calculated recipient levels of pharmaceuticals included in the list of special pollutants have been compared with the respective applicable limit values in HVMFS 2013:19. As shown in the table, PNEC for Estron (E2) and Ciprofloxacin are about twice lower than the respective limit valuesin HVMFS 2013:19, but for Diclofenac and Ethinyl estradiol (EE2), the current limit values are five and 2.3 times lower than PNEC-values, respectively. With an assumed dilution factor of 100, the content of Ciprofloxacin in the recipient is much lower than both PNEC and the HVFMS-limit. For EE2 and E2, the PNEC and limit values are so low that it is not possible to determine whether their emissions in purified wastewater will lead to an exceedance of PNEC and/or the HVFMS limit value. Analysed values were below the level of detection or quantification and even if the table indicates that the limit for EE2 may be exceeded, this is solely based on that average EE2 values are based on detection and quantification limits; actual concentrations may be much lower. The estimated concentration of Diclofenac in the recipient is, however, exceeding the limit value. Assuming a dilution of 1000x instead, the HVFMS-limit will not be exceeded.

Table 3.6. Assessment of emissions based on limit values in HVMFS 2013:19 (SWAM 2013).

Substance	Calculated concentration in recipient incl. dilution of 100x, µg/L	PNEC, µg/L	Risk ratio in recipient	Analytical detection limit, µg/L	Limit in coastal waters according to HVFMS 2013:19, µg/L	Percentage of limit value used, %
Ciprofloxacin	<0.000068***	0.064	<0,001	0.001	0.1*	<0.1%
Diclofenac	0.017	0.05	0.34	0.004	0.01**	170%
EE2	<0.00002***	0.000016	<1.25	0.002	0.000007**	<285%***
E2	<0.00002***	0.00004	<0.5	0.002	0.00008**	<20%***

* - maximal allowed concentration
** - as yearly average
*** - based on values <LOD/LOQ

3.1.3.4 Advanced treatment requirements to improve effluent quality

To achieve a risk ratio <1 for all substances analyzed in the nearest recipient, an additional treatment would be required that achieves a removal efficiency of 98% for Citalopram and 87% for Oxazepam. Citalopram then becomes the dimensioned substance.

Despite the risk quotas in the recipient being <1 for most of the analyzed substances, an advanced treatment of wastewater to lower levels is justified as persistent pharmaceutical substances have a long residence time and are observed in surface waters far out at sea in the Baltic Sea. Also filtering organisms, such as blue mussels, can accumulate pharmaceutical substances also in recipients with large water turnover (Swedish Environmental Protection Agency, 2017).

When considering the HVFMS-limits as presented in table 3.6, an additional treatment of the Stengården WWTP effluent may be required for Diclofenac in case of a maximum dilution in the Hanöbukten of 100 times.

For a defined removal requirement of 80% for individual substances considering the entire treatment plant, as e.g. is required in Switzerland, an additional treatment of most substances would be needed as indicated in the last column of table 3.5. For those substances with a negative reduction over the Stengården WWTP (table 3.3), a very high removal efficiency would be required, in most cases higher than 80%. However, this target definition does not consider the recipient's sensitivity and needs, or that different substances may cause different effects in the recipient. Using such a target definition for pharmaceuticals would imply that a treatment would be required also for substances, which are considered not to have any negative environmental effect in the recipient. This would on the other hand consume resources and creating unnecessary negative environmental effects by the treatment as such.

3.1.4 Bacteria, antibiotic resistant bacteria

The mapping of bacteria over the Stengården WWTP included two sampling occasions of the incoming wastewater and samples collected in the effluent. Most of the bacteria covered by the methods were detected in the untreated wastewater (extended spectrum β-lactamase (ESBL) producing *Escherichia coli*, *Klebsiella* spp, *Enterobacter* spp., *Citrobacter* spp. and *Pseudomonas* spp. as well as vancomycin resistant *Enterococcus faecium* and *faecalis*). The bacterial concentrations in the untreated wastewater was not significantly different between the two occasions (July and September) or over the two days sampling campaigns. However, the effluent from Stengården held lower bacterial concentrations in September, i.e. a higher reduction was achieved (Table 3.7). Figure 3.1 shows bacterial concentrations in the incoming and outgoing wastewater to Stengården WWTP.

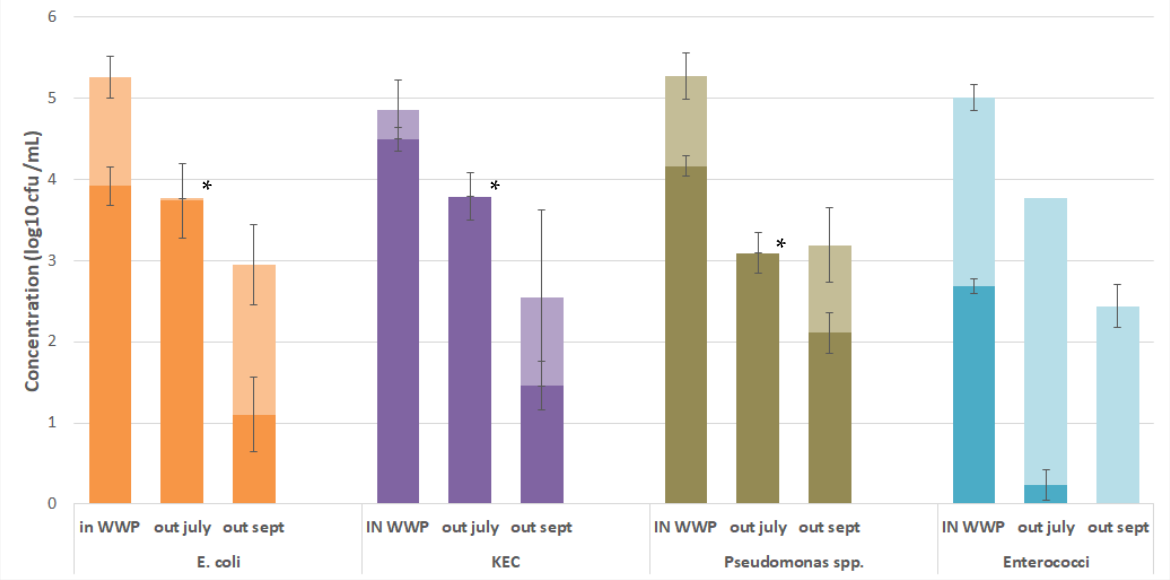

Figure 3.1 Bacteria concentrations (log_{10} cfu/mL) in wastewater in to and out from Stengården WWTP showing the total population together with the antibiotic resistant fraction. For outgoing concentrations in July, except for enterococci, only the resistant population was enumerated (marked *).

The fraction of antibiotic resistant population made up in average 54 to 80% of the total bacterial population (Figure 3.1) with vancomycin resistant *E. faecalis* and *E. faecium* having the lowest fraction of resistant bacteria. The reduction of bacteria concentrations over the conventional treatment process ranged from 0.7 to 3 log_{10} (table 3.7). The antibiotic resistant bacteria (ARB) were

in general reduced to the same degree as the total bacterial population except for vancomycin resistant *E. faecalis* and *E. faecium* (VRE) that were reduced to the extent that they in the second campaign were not detected (detection limit 1 $\log_{10}$ cfu/mL) after the conventional wastewater treatment.

Table 3.7. Reduction of bacteria by the main treatment process at the Stengården WWTP for the two sampling campaigns. # mark significant reduction (alpha 0.05).

	Reduction over WWTP (log10 cfu)	
	Total population	**Resistant population**
E. coli	-1.7#	-0.7
	-2.2#	-2.7#
KEC*	-	-0.8#
	-1.8#	-3#
Pseudomonas spp.	-	-0.8#
	-2.2#	-2.1#
E. faecalis* and *E. faecium	-1.0#	-2.6#
	-2.6#	> -1.6

**Klebsiella, Enterobacter, Citrobacter*
 # significant reduction

Repeated sampling (n=46) at the MF sampling point showed, similar to wastewater out from Stengården, different mean concentrations at the two sampling occasions but no difference in-between samples taken at various times during 2-day sampling campaign. These results indicate low fluctuation in bacterial concentration in the system, which implies that flow proportional sampling may not necessary for determining bacteria concentrations. The difference in concentrations after the WWTP between sampling occasions were consistent over the sampling points in the system.

3.2 Performance of the advanced treatment

The following sections provide information about treatment performance of the three implemented advanced treatment systems for removal of micropollutants from the Stengården WWTP effluent.

3.2.1 Removal efficiency for micropollutants

3.2.1.1 Microplastics

Table 3.8 shows removal efficiency of microplastics over the advanced treatment system comprising microfiltration, ozonation and granular activated carbon filter. The MF-O3-GAC treatment system removes additionally about 80% of all microplastics. As microplastics removal in the main process of the WWTP already was extremely efficient (see Table 3.2), total removal over the WWTP including the advanced treatment is almost 100%. Due to contamination of samples during sampling and processing, complete microplastic-free samples are very hard to obtain. Both the environment when sampling and atmospheric deposition imply that sample contamination is almost impossible to avoid despite very strict and careful sampling procedures. Control sampling repeating the same sampling procedure but filling samples bottles with distilled water can provide an indication of the sample contamination. Control samples taken at Stengården WWTP indicated a contamination of samples with up to 500 particles per cubic meter for the largest and medium size range (>300 µm and >100-<300 µm, respectively), and up to 80 particles per cubic meter for the smallest size range (between 20-100 µm).

Table 3.8. Microplastics removal in the advanced treatment at Stengården WWTP.

	Microplastics particles/m^3		Removal efficiency	
Fibres, non-synthetic fibres, fragments	IN MF	O3GAC	O3GAC	WWTP Total
>300 µm	1000	670	33%	99.7%
100-300 µm	3750	560	85.2%	99.1%
20-100 µm	1250	110	91.1%	99.97%
Total	**6 000**	**1 340**	**77.8%**	**99.8%**

3.2.1.2 Pharmaceutical residues

Hormones were removed efficiently already in the main treatment (Table 3.5) and concentrations in the water entering the advanced treatment processes were all below detection limits. Therefore, no hormones could be detected in any of the collected samples out from the three different advanced treatment systems.

Table 3.9 provides removal efficiencies for pharmaceutical substances that could be quantified before and after the advanced treatment systems. For the treatment combination O3GAC, samples were collected through all 3 constant dose sampling campaigns (SC1, SC3 and SC4). For GAC only and O3SF, analyses were performed in SC1 and SC4 only. From the table it becomes obvious that the GAC-filter alone has the lowest overall removal efficiency for pharmaceutical residues. In addition, the removal efficiency varies significant between the two sampling occasions. The removal efficient during SC1 was significantly higher than during the later SC4. This may partly be explained by a reduced adsorption capacity of the GAC-filter during one-month operation between the two sampling dates. Compared to earlier studies, the GAC-filter removal capacity is, however, significantly lower than expected. An increase of several substances over the GAC-filter may further indicate a significant desorption of previously adsorbed substances. Thus, even other aspects, such as varying loads and operational issues, may be possible reasons for this as a similar effect can be observed for SC4 for O3SF and O3GAC (table 3.9). While the load to the advanced treatment and the overall treatment efficiency in the conventional treatment between the two campaigns naturally varies, no clear extreme or other cause that could explain potential disturbances was observed in the analyses. However, since the evaluation is based on weekly composite samples, short-term disturbances that may change the water composition significantly or that can disturb the performance of the advanced treatment, are difficult to detect. Whatever the cause of a potential disturbance might have been, it becomes clear from table 3.9 that the technology configuration comprising of ozonation and activated carbon seems to handle this in the best way with very high removal rates for most analysed substances.

Table 2. Removal efficiencies over the advanced treatment lines at sampling campaigns SC1, SC3 and SC4 (only substances that could be quantified are presented; average DOC concentration was 7.5 mg/L).

	Removal efficiency						
	GAC only		O3SF		O3GAC		
			SC1	SC4	SC1	SC3	SC4
Substance	SC1	SC4	8 mg O_3/L	4 mg O_3/L	8 mg O_3/L	6 mg O_3/L	4 mg O_3/L
Pharmaceuticals							
Atenolol	93%	78%	98%	-19%	100%	99%	>95%
Bisoprolol	84%	58%	98%	-20%	>99%	98%	93%
Carbamazepine	>83%	-29%	>88%	49%	>88%	>96%	>88%
Citalopram	77%	-44%	>99%	13%	>99%	97%	89%
Diclofenac	44%	-329%	100%	54%	100%	96%	79%
Fluoxetine	73%	14%	>95%	-18%	>95%	>98%	>87%
Furosemide	59%	-72%	>99%	87%	>99%	98%	>96%
Hydrochlorothiazide	94%	64%	100%	-25%	100%	99%	93%
Ibuprofen	32%	-735%	90%	>76%	90%	>97%	33%
Ketoprofen	52%	-192%	66%	-35%	87%	91%	52%
Metoprolol	91%	77%	98%	-20%	100%	99%	95%
Naproxen	63%	-150%	100%	38%	>99%	98%	>77%
Oxazepam	58%	-123%	78%	-41%	95%	94%	70%
Propranolol	93%	59%	>99%	48%	>99%	>99%	>98%
Ramipril	25%	-445%	>94%	-41%	>94%	67%	-77%
Ranitidine	96%	>92%	>99%	>92%	>99%	>99%	>95%
Sertraline	83%	-29%	>98%	26%	>98%	>98%	>90%
Warfarin	17%	-422%	>92%	>84%	>92%	>94%	>84%
Antibiotics							
Claritromycin	-8%	39%	>77%	84%	>77%	73%	88%
Erythromycin	1%	22%	>98%	84%	>98%	53%	84%
Sulfamethoxazole	41%	45%	>94%	>84%	>94%	78%	>84%
Trimetoprim	>88%	>92%	>88%	74%	>88%	>89%	>95%

Results further indicate that the performance of the combination ozonation with sand filter (O3SF) shows a very good removal efficiency at the first sampling campaign with an ozone dose of 8 mg/L while the performance is significant lower in SC4, half the ozone dose and one month later. This may be explained either by the lower ozone dose that is not sufficient to oxidizes most of the substances or similar problems in the filter unit as for the GAC-filter only (see above).

The combination of ozonation and GAC-filter has the highest removal efficiency and only a slight efficiency decline is observed between SC1, SC3 and SC4. This decline may hover be due to either successively lower ozone doses applied or decrease of performance of the GAC-filter. The overall removal efficiency of the treatment line O3GAC is however extremely good even at the lowest ozone dose and after several months of operation and potential disturbance (SC4). This agrees with recent results from a study at the Detmold WWTP, Germany, showing that lower ozone dosages combined with GAC have good removal performance (Austermann-Haun et al., 2018).

3.2.1.3 Bacteria, antibiotic resistant bacteria

In the advanced treatment the filtration did not affect the bacterial concentrations and differences in concentrations out from MF were mainly reflecting the ingoing concentration that differed between the occasions (table 3.10). The whole system was sampled at two occasions running at an ozonation rate of 6 mg O_3/L. The effect of ozonation at this rate was small nor did the following filtration in sand or GAC filter have any major effect on the reduction (figure 3.2). The

concentration of bacteria in the effluents (O3GAC, O3SF and GAC) were thus most often not reduced compared to the concentrations in to the advanced treatment.

Table 3.10. Change in bacterial concentration (log_{10} cfu) over the steps in the advanced treatment process at the Stengården WWTP. Asterisks (*) mark significant reduction (alpha 0.05).

	E. coli		KEC[a]		*Pseudomonas* spp.		*Enterococcus* spp.[b]	
Process	**total**	**resistant**	**total**	**resistant**	**total**	**resistant**	**total**	**resistant**
Filtration	+0.1	-0.5	-	-0.3	-	-0.1	-0.3	-
	0.0	+0.2	0.0	+0.2	-0.4	-0.1	+0.1	-
Ozone 4 g/L	+0.2	-0.2	-	-0.5	-	-0.2	-0.2	-
Ozone 6 g/L	-0.2	-0.4	-	-0.5	-	-0.4	-0.4	-2.0*
	-0.9*	+0.4	-0.7	+0.6	-0.6	+0.7	-0.4	-
Ozone 8 g/L	0.0	-0.3	-	-0.2	-	0.0	-0.7	-
Ozone 12 g/L	> -4.0*	> -2.2*	-2.6*	-2.6*	-0.9*	-1.5*	-2.7*	> -2.0*
Ozone 24 g/L	> -2.3*	> -2.2*	> -3.3*	-2.6*	-	-2.0*	-3.3*	> -2.0*
O3SF	-0.2	-1.5*	-	-0.7	-	-0.8*	0.0	-
	+0.2	-0.6	-0.1	-1.3	1.2	-1.5*	-0.5	-
O3GAC	-0.1	-0.3	-	-0.3	-	-0.7	0.0	-
	-0.1	-0.6	-0.3	-1.3	-0.8	-1.7*	-0.5	-
GAC	0.0	-0.2	-	0.0	-	-0.5	-0.1	-
	-0.5	+0.8	-0.6	+0.3	-0.3	0.0	-1.9*	-

a) Klebsiella, Enterobacter, Citrobacter

b) E. faecalis and *E.faecium*

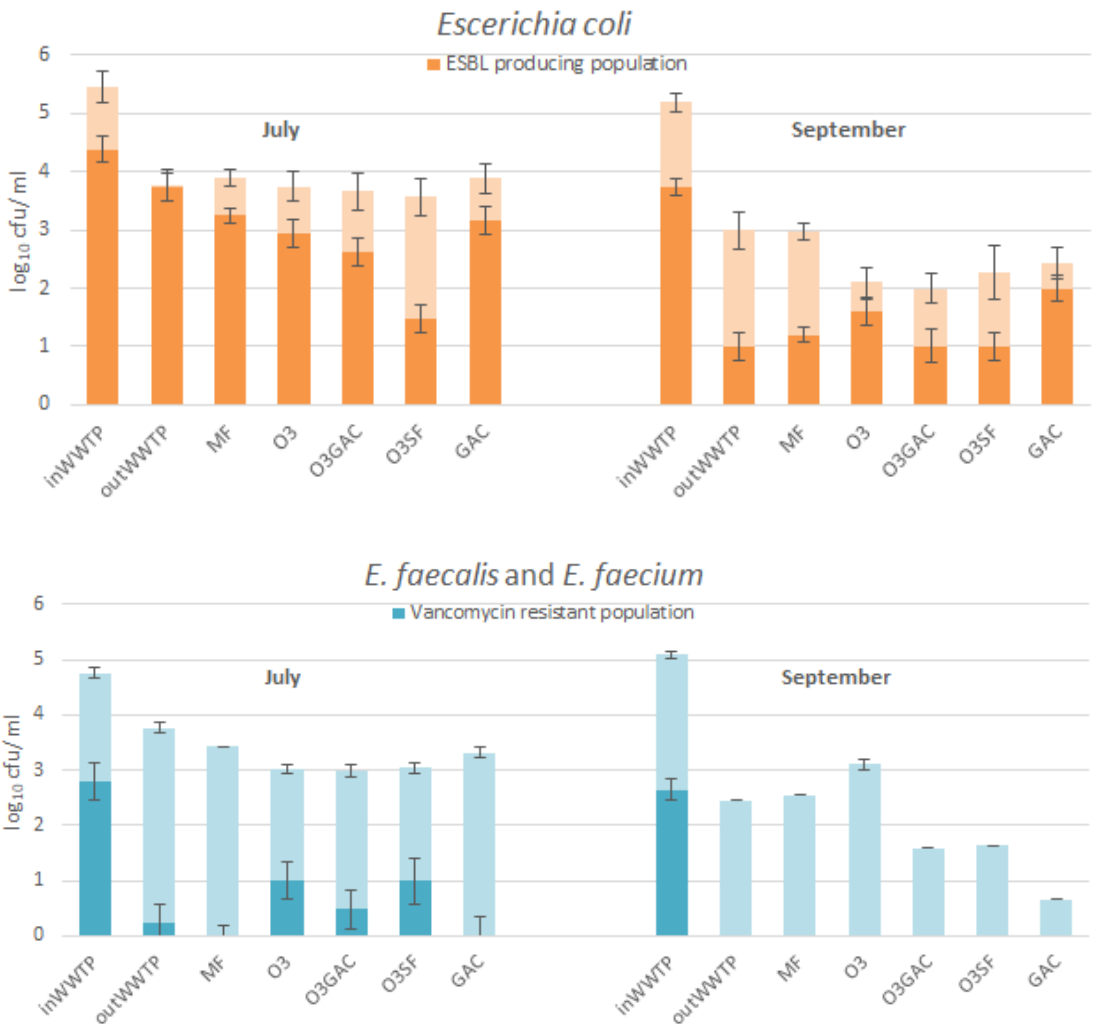

Figure 3.2 Concentrations (log_{10} cfu/mL) of *Escherichia coli* (a) and *E. faecalis* and *E. faecium* (b) out from the different treatment steps in the advanced treatment at ozone dose 6 mg/L. Shaded part of the bar constituting the antibiotic resistant fraction.

Testing effect of ozone doses, little reduction of bacteria was observed at doses 4-8 mg O_3/L with no correlation to ozone doses. Increasing the ozone dose to 12 and 24 mg O_3/L however had a significant effect as no bacteria could be detected (detection limit 1-10 cfu/100 mL). This corresponded to more than a 2-4 log_{10} reduction in bacterial concentrations, depending on incoming bacteria concentrations. Due to that detection limits were met; no conclusions can be drawn about differences in removal of bacteria at doses 12 and 24 mg O_3/L. An ozone dose of 6 mg O_3/L, which was tested at two occasions, had rather large variation in bacteria reduction effect. Such variations are most likely explained by other parameters of the water affecting the ozonation effect, such as varying DOC-levels that ranged from 7.5 to 10 mg/L. Even with high removal of bacteria by the ozonation at 12 and 24 mg O_3/L, bacteria were detected in the effluent from the different filters, i.e. bacterial concentrations had increased after the filtration. For example, *E. coli* was present in concentrations 1.0 - 1.6 log_{10} cfu per mL whereas KEC were present in concentrations 1.5 - 3.1 log_{10} cfu per ml with marginally better results for the highest ozonation doses.

When the system was operated at a constant dose of 6 g O_3/L, the activated carbon filter alone resulted in similar concentrations in the effluent or, as for enterococci, performed better compared to when combined with ozonation. Enterococci in general and antibiotic resistant enterococci (VRE) in particular showed the largest reduction of the studied bacteria. VRE were present in concentrations 1.0-2.5 $\log_{10}$ cfu per mL in the raw wastewater whereas only randomly present in samples after the conventional treatment and below detection in samples after the advanced treatment.

Even so, relatively high ozone doses above 8 mg O_3/L (1.1 mg O_3/mg DOC) provide a good bacterial removal, such high ozone doses are not necessary for the removal of pharmaceutical residues (see 3.2.3) and would imply an significant increase of the risk for the production of formation and by products during ozonation. In addition, operational cost would increase significantly. From table 3.10 it also becomes clear that the biological activity in the filter subsequent to the ozonation may imply an increase in bacterial levels. Therefore, more efficient technologies for the final removal of bacteria such as i.e. UV disinfection should be implemented downstream of the biofiltration system.

3.2.1.4 Other pollutants

Collected samples during the sampling campaigns were also analyses for standard parameter to investigate if their concentrations may affect or be affected by the advanced treatment. Results shown in Table 3.11 indicate that the advanced treatment also has an additional polishing effect on common pollutants with highest added removal effect on ammonium, and BOD. Also phosphorous is removed with additional up to 40% based on the effluent concentrations from the main treatment process. In general, observed removal affects here somewhat lower in the GAC only system compared to the other treatment systems. Based on earlier tests (e.g. Baresel et al., 2015a, 2017; Sehlén et al., 2015), this may have several explanations. Combinations with ozonation can break up organic bound nutrients and carbon, which then can be degraded in the following filter. Increased oxygen concentrations in the effluent from the ozonation also supports a biological activity in the filters. In the GAC only system, only a biological breakdown of carbon and nutrients can take place. The performance may however be lower than in filters connected to effluent from ozonation as increased oxygen levels are available and nutrients and carbon have not been transformed to easier degradable forms.

Table 3. Added removal efficiency of various common pollutants by the advanced treatment.

	Removal in % over treatment			
Parameter	**MF**	**O3SF**	**O3GAC**	**GAC**
Suspended solids	70	<25	<25	<10
Ammonium	-	95	94	52
Total Nitrogen	-	0-15	0-15	0-15
Total Phosphorous	-	<35	<35	<30
BOD5	-	0-50	0-50	0-50
COD	-	0-25	0-25	0-20

3.2.2 Comparison of advanced treatment systems

Table 3.12 shows removal efficiency of the complete treatment at Stengården WWTP including the main treatment and the newly implemented advanced treatment lines at SC4. The partly high negative reduction in the main treatment imply that some pharmaceuticals cannot be removed in all treatment setups. With the exception for Ramipril, the combination of the main treatment

process completed with microfiltration, ozonation and activated carbon filter is the only system that shows very efficient removal of all analyses pharmaceuticals.

Table 3.12. Removal efficiencies over the complete WWTP including advanced treatment lines at sampling campaign 4, ozone dose 4 mg/L (only substances that could be quantified are presented).

	Removal efficiency WWTP incl.		
Substance	**GAC**	**O3SF**	**O3GAC**
Pharmaceuticals			
Atenolol	91%	52%	>98%
Bisoprolol	81%	45%	97%
Carbamazepine	39%	76%	>94%
Citalopram	38%	62%	95%
Diclofenac	-76%	81%	91%
Fluoxetine	70%	59%	>95%
Furosemide	30%	95%	>99%
Hydrochlorothiazide	86%	50%	97%
Ibuprofen	89%	100%	99%
Ketoprofen	-40%	35%	77%
Metoprolol	88%	36%	98%
Naproxen	78%	95%	>98%
Oxazepam	-17%	26%	84%
Propranolol	80%	75%	>99%
Ramipril	-94%	50%	37%
Ranitidine	>92%	>92%	>96%
Sertraline	84%	91%	>99%
Warfarin	-33%	>96%	>96%
Antibiotics			
Claritromycin	-	-	-
Erythromycin	7%	81%	81%
Sulfamethoxazole	58%	>90%	>90%
Trimetoprim	>93%	77%	>96%

For the removal of microplastics, a comparison of the different advanced treatment system was not performed as already the main treatment process achieved a removal efficiency of >99%. The microfiltration is probably responsible for the additional removal effect observed (see 3.2.1.1). As this treatment step is common to all advanced treatment lines, the same additional removal capacity may be assumed for all lines.

Regarding removal of bacteria, antibiotic resistant bacteria, no significant advantage of one of the three advanced treatment lines could be identified. A separate disinfection by e.g. UV-light is recommended.

Considering other pollutants, a slightly better performance of the advanced treatment lines that combine ozonation with filter could be observed. This may, as discussed, be explained by the advantageous effect of oxidation and subsequent biological filtration.

3.2.3 Ozone dose – response curve

Figure 3.3 shows results from the test with various ozone doses to investigate to which degree pharmaceutical residues with different chemical structure can be oxidized at different conditions. During sampling Campaign 2 (SC2), ozone doses of 3, 6, 8 and 12 mg/L were tested. With a relative low average DOC of 7.5 mg/L during the test period, this corresponds to 0.4, 0.8, 1.1 and

1.6 mg O_3/mg DOC, respectively. It can be seen from the figure that an increasing ozone dose gives an increased removal effect for investigated substances. The reduction is consistent with what was reported in previous studies (e.g. Baresel et al., 2015c). It can also be noted that a reduction of 80% over the ozonation step is only achieved at an ozone dose of 8 mg/L (1.1 mg O_3/mg DOC) for the average of substances that could be quantified in the test. For Oxazepam and Ketoprofen, even higher doses would be required to achieve an 80% reduction.

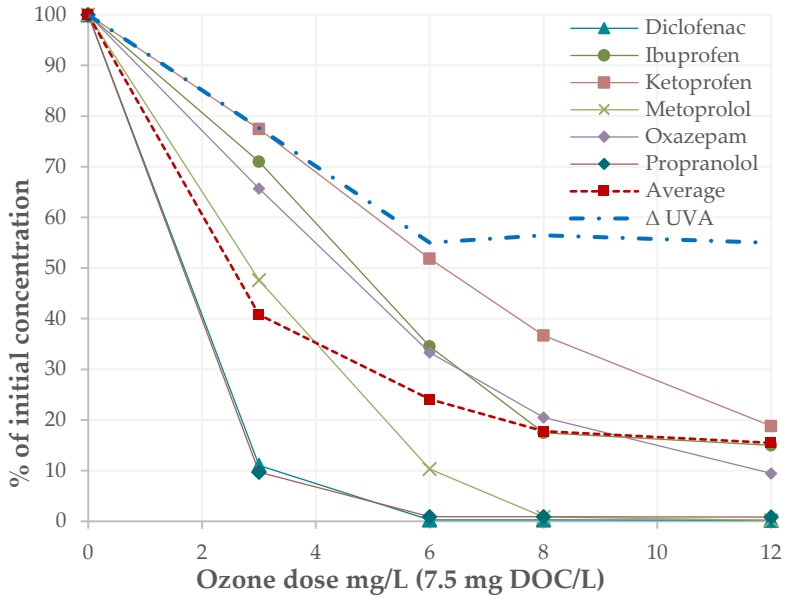

Figure 3. Dose-response relationship for the removal of selected pharmaceutical substances as % of substance remaining after treatment.

3.2.4 Bromate formation and handling

With regard to potential by product formation, bromide and bromate levels were investigated during the ozone dose-response test (SC2) to ensure that no carcinogenic bromate products are produced during ozonation or that they are removed in the advanced treatment. Thus, bromide and bromate levels in incoming and outgoing water from the ozone unit (sampling MF and O3) were examined at the different ozone doses. The bromide levels prior to ozonation and the bromate levels after ozonation are most significant in this experiment because the predominant risk of conversion of bromides to bromates in reaction with ozone. Figure 3.4 provides results of the bromate analysis during the dose-response test.

Obviously, there is a clear increase of bromate formation with increasing ozone dose. While there is no wastewater related threshold for bromate, the recommended drinking water standard of 10 µg/L (WHO Guidelines for Drinking-water Quality, WHO/SDE/WSH/05.08/78) is exceeded already at the lowest ozone dose. Bromide concentrations on the other hand were stable at 0.15 mg/L before and after ozonation.

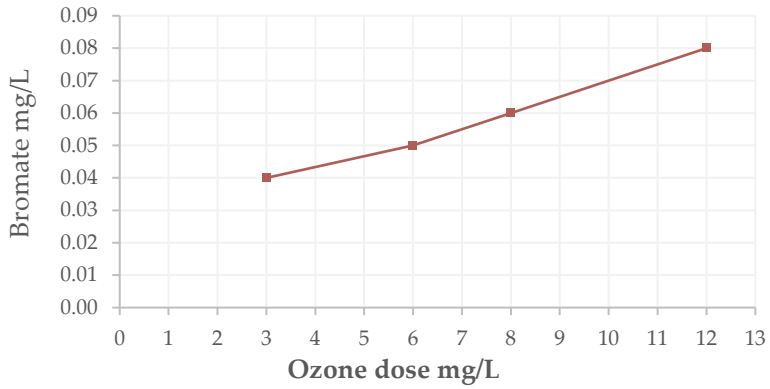

Figure 3.4 Bromate concentrations after ozonation during dose-response tests. Important to note that the bromate concentration in the incoming wastewater to Stengården WWTP are already on a very high level with values >0.02 mg/L.

Even though the drinking water standard was not the defined target to achieve, the obtained results were much higher than expected. Therefore, an additional analysis of one incoming wastewater sample was performed. In the inflow to the Stengården WWTP a concentration of 0.024 mg/L was determined for bromate, i.e. already here the recommended drinking water standard is exceeded. Seawater intrusion or incineration facilities in the region might explain these high levels but no further information is available. Bromide concentration were about the same as around the ozonation. Thus, high bromate levels in the incoming wastewater may be more important than the actual bromate formation during ozonation and their source and mitigation may be focus of future investigations.

Results from the last sampling campaign including Bromate analyses in the sampling point O3GAC, i.e. in the effluent of the GAC-filters following ozonation, showed a concentration of < 5 µg/L which would imply levels below recommend drinking water standards. Unfortunately, no analyses of related samples for IN WWTP or O3 were performed and thus it is not known if the GAC filter or lower incoming Bromate concentrations are the reason for this. A more extensive evaluation for bromate over a longer period is recommended for a better understanding of the Bromate situation at Stengården WWTP.

3.2.5 Capability to produce reusable water

Comparing average target levels of various pollutants specified in Table 2.1 it can be observed that the effluent from the "reuse" Stengården WWTP fulfills requirements for the three reuse categories industrial reuse, irrigation and groundwater recharge, except for a few parameters, e.g. bacteria, where an additional reduction would have been required.

The analytical results from the sampling campaign CS5 for production of a reusable water for infiltration to the groundwater are shown in Appendices 6.3. As seen from the results the produced water by the combination disc filter-ozonation and granular activated carbon show low concentrations of almost all analysed parameters. In Appendices 6.2 you will find a comparison with the standard for Swedish drinking water. For many of the analysed organic parameters there is no limits set in the drinking standard to compare with but as seen from tables for pharmaceutical substances, PFAS, PAH`s, phenolic substances, ethoxylates, phthalates, PCB`s and other organic substances the results showed that pesticide concentration in the reclaimed water are below detection limits. The same is true for glyphosate and its metabolite AMPA. Analyzed PFAS, PAH, PCB and phthalates levels are also below detection limit. As discussed, hormones, pharmaceuticals and antibiotics are removed in the advanced treatment and especially the combination of

microfiltration, ozonation and active carbon. Analyses in the reclaimed water did thus not show any detectable levels of these substances.

Sodium and chloride concentrations are relatively high, which may be caused by inflow of seawater into the sewer network. The concentrations are, however low in respect to health and taste aspects. However, bromate concentrations are currently too high if considering the recommended standard for drinking water as target. Even here, sources for the high incoming levels to the WWTPs are yet to be determined in order to facilitate efficient abatement.

As far as microbiology is concerned, levels of bacteria are too high in the current reclaimed water. However, disinfection using UV-light of the final effluent should ensure that this quality parameter can be fulfilled (see figure 2.1). The use of ozonation for disinfection is not recommended as it requires high ozone dosage to guarantee a complete removal of bacteria. UV-treatment is a well-established treatment for final disinfection with a higher efficiency and lower cost than other methods.

3.3 Operational aspects

To ensure stable flow conditions over the ozone tank in the tertiary treatment system, the flow was initially set to a constant flow of 160 m^3/h (40 m^3/h to each filter following ozonation). Due to low flowrates of incoming water to Stengården WWTP, the flowrate was adjusted to 150 m^3/h (37.5 m^3/h to each filter following ozonation) in late June and to 120 m^3/h in mid-July (30 m^3/h to each filter following ozonation).

3.3.1 Ozonation and energy use

The ozonation unit was automatically shut down several times due to variation in the power grid. This was also observed during other installation in Sweden and should by now be a well-known problem. A technical upgrade of the power cabinet can solve the problem.

The ozonation could further not be used during a shorter period as consumables for the safety sensors that have to be replaced on a regular basis were not available. This may seem like a minor problem but illustrates that operation and maintenance routines have to be established and implemented for a continuous operation.

A simple evaluation of the energy use for ozonation revealed that energy savings related to applied ozone doses are only in a limited way possible. Most of the components used in the installation have a minimum working effect which implies that they use about the same energy even if less ozone is dosed. This is especially true for very low ozone doses while energy demands can increase significantly at higher ozone doses. The use of variable frequency drive (VFD) could further reduce the basic power consumption.

In general, power consumption for ozone generation is proportional to the mass ozone produced and can be expressed in KWh/kg ozone produced or via the actual applied ozone dose to W/m^3 treated wastewater. In this project, the ozone system design was based on reduced dependencies on consumables/commodities delivered. Thus, auxiliaries as an air-cooled chiller for cold water generation, to supply the ozone generator, as well as onsite oxygen production by means of a pressure swing adsorption (PSA) system were included. This imposed a limitation of the turn down behaviour of the overall system. For larger WWTP plants with higher flows and higher

power demands, turn down operation and resulting operational savings should be considered in the design stage.

The energy use during the evaluation period July-September 2019 is described below and some findings could be mention:

- In general, for the treatment, the energy consumption is rather low, during the evaluation period July-August approximately 0,4 kWh/m^3 of treated water.

- As the ventilation and compressor for feeding the PSA-unit (oxygen production unit) with air works regardless the treated water volume, the energy consumption during low flow is relatively high. During the evaluation period July-August, the mean treated volume was 3256 m^3/day which resulted in a energy consumption of 0.39 kWh/m^3. As a reference, the 6 May 2020, the humidity and temperature was relatively low and the flowrate high. The energy consumption was then calculated to be approximately 0,24 kWh/m^3.

- The energy could roughly be divided in three 4 parts: Compressor for feeding air to the PSA-unit for oxygen production (27 % of total energy consumption), Ozone generator 28 %), Humidity control in building (19 %) and Pumps and other energy usage 25 %), see table 3.13.

- As the system is constructed, the compressor feeding the oxygen production unit with air is working full-time, regardless the need of ozone. A system that run the compressor relatively to the need of ozone should consume slightly less energy. There might also be potential energy savings by the use of ventilation directly connected to the open surface of the Dynasand filters that reduces the humidity in the building.

The evaluation of the implemented three parallel advanced treatment systems consisting of only activated carbon (GAC), ozonation combined with sand filter (O3SF), and ozonation combined with activated carbon (O3GAC) clearly shows an added removal effect for pharmaceuticals but also other pollutants. This agrees with previous studies of these systems and especially that the combination of ozonation with activated carbon (O3GAC) stands out as the most efficient treatment system. The pre-treatment with microfiltration, MF (by disc-filtration), common for all advanced treatment systems, further implies an important part for a robust operation of the tertiary treatment system and for the overall removal efficiency.

Tabell 3.13. The energy consumption and treated volume during the evaluation period July-September 2019.

Month	Running time (h)	Volumes treaded by ozonation (m^3)	Volume per day (m^3/d)	Energy consumption (kWh): Com-pressor	Ozone generator	Humidity control	Pumps + other	Total energy consumption (kWh)	(kWh/m^3)
July	705	96917	3126	11160	11280	7750	7145	37335	0.39
August	715	89765	2896	11160	11440	7750	12422	42772	0.48
September	667	116140	3746	10800	10672	7500	9828	38800	0.33
Total:	2087	302822	9768	33120	33392	23000	29395	118907	0.39
Mean	**696**	**100941**	**3256**	**11040**	**11131**	**7667**	**9798**	**39636**	**0.39**

3.3.2 Filter operation

During the initial phase of the evaluation period it became clear that a more efficient method of controlling the turnover in the sand and GAC-filters was required for an efficient filter monitoring and control. One of the reasons for this was according to the supplier the relatively low ceiling, which made it difficult to perform the usual manual measurement. The Sand-Cycle technology described in section 2.2 was therefore implemented as an alternative to the conventional method. The technology has been tested before (e.g. Gardermoen WWTP, Norway) but this is the first time it has been implemented in full-scale in Sweden. Sand-Cycle generates data continuously and gives everyone in the project group on-line access to real-time sand conversion data (Figure 3.5).

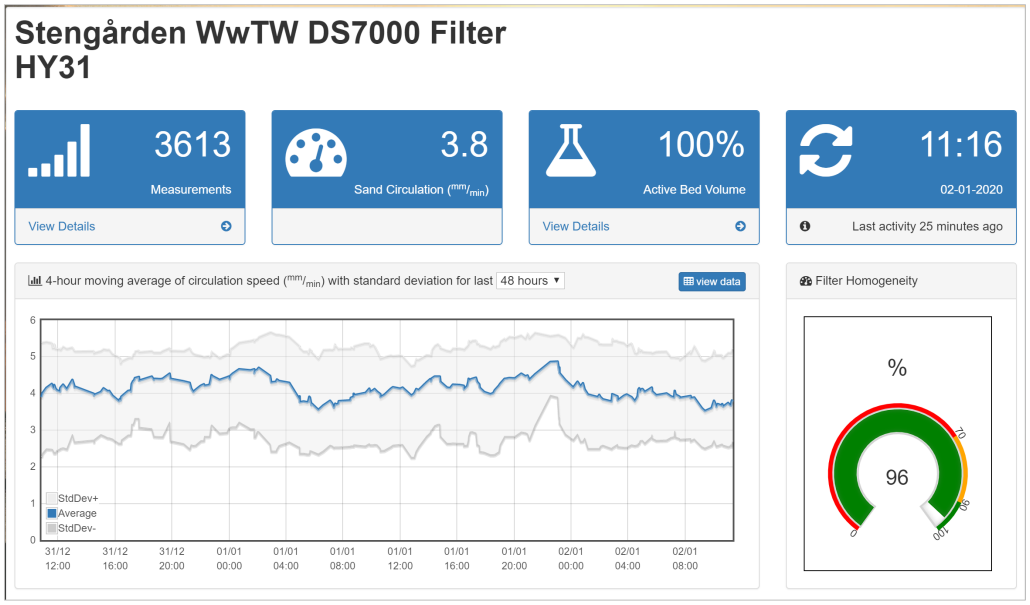

Figure 3.5. Sand-Cycle use at Stengården WWTP.

The first measurements from the Sand-Cycle system were obtained at the end of June 2019. In continuous operation mode of the filters, the system indicated a good and as expected performance of all filters with homogeneous filter beds. However, in intermittent operation of the filters, which originally was planned for to reduce the amount of backwash water, the Sand-Cycle measurements did not agree with manually measured values. This can be explained by the fact that the Sand-Cycle system was originally developed for continuous sand movement. However, based on experience from this project, the system is under further development.

The evaluation of the bed turnover did also not reveal any deviations during sampling campaign 4 (SC4) that could explain that all filters had a poorer performance during this period.

3.3.3 Dynamic ozone dose control

During the startup and evaluation periods, various measurements were performed in order to asses which parameter could be used to monitor and control the ozone dose dynamically towards actual loads. For this, collected samples for analyses of pharmaceuticals have also been analyzed for other parameters such as residual ozone, DOC and UVT. Additionally, the installed online water flowmeter, the spectral sensor for UVT, nitrite and COD measurement in the inlet to the ozonation and the offgas ozone sensor were used in the evaluation. Ozone dose control has two main drivers. One being to use as low ozone doses as possible in order to minimize the risk of

transformation products such as bromate (see Figure 3.4). Another common driver is to reduce energy use for ozonation.

Online DOC-levels in the influent to the ozonation were tested as control parameter with minor success. One reason was that the online readings exceeded actual values determined by control samples by more than 25% during the evaluation period. DOC sensors are known to be more sensitive to changes in the water matrix and sensor maintenance. Both require frequent cleaning and matrix calibration if the DOC-reading is used for monitoring and control. Evaluation over the whole evaluation periods show that online readings match verification measurements towards the end of the evaluation period, which indicates that a more stable sensor operation was achieved. However, the main reason for not using incoming DOC as control parameter for ozone dose control is that analyses of DOC shows low correlation with pharmaceutical concentrations based on the collected samples during the different campaigns.

The same is true for nitrite in the incoming water to the ozonation. Even though the online readings matched verification measurements quite well, a distinct correlation of nitrite in the inflow to the ozonation to measured concentrations of pharmaceutical could not be observed. Nitrite concentrations after ozonation decreased according to measurements with increasing ozone dose.

UV transmittance of the water (UVT %) can also be expressed as UV absorbance (UVA) per cm but is often also referred to as Spectral Absorption Coefficient (SAC). Measurements during installation and startup suggested a correlation of SAC to DOC as SAC = 1.08 × DOC, which did not seem to be correct based on verification measurement. This may partly be due to false online readings of the DOC as discussed above. Further, the use of UVT or UVA in the influent to or effluent from the ozonation did not indicate any clear correlation to pharmaceutical residues in the treated water. However, the change of UV over the ozonation, i.e. ΔUVA seems to be a potential control parameter. This was also shown during ozone dose response tests (see Figure 3.3). Considering the current installation of only one UV-sensor in the influent to the ozonation, an addition UV-senor would be required after ozonation in order to use this control option.

Most of the time, the ozone dose was directly correlated to the water flow. Even so, being the easiest control option with least requirements in equipment and maintenance effort, such a control cannot account for varying concentration of pharmaceuticals in the water. A throughout mapping of concentrations variations during days, weeks and seasons could maybe facilitate to establish an empirical relationship between water flow and concentrations that could be used for ozone dose control. At low flows, concentrations are generally higher due to more concentrated flows while high water flows often means dilution of pollutants. Thus, at high flows added ozone per cubic meter could be less than at low flows. The current technology provider Xylem has developed a controller to reduce the ozone dosage based on the flow signal and dilution rates to avoid overdosing. However, changes in the water matrix over seasons and other factors would make such a control unreliable.

Measurements of residual ozone in the off-gas from ozonation indicated varying concentrations with very high levels of ozone (> 5 g/Nm^3) during the initial startup phase. Even though most of the time residual ozone in off-gas was below 1 g/Nm^3, variations indicate that an overdosing of ozone occurs during periods when using a water flow related ozone control. High off-gas ozone concentrations may, however, not only indicate fewer organic pollutants in the wastewater but can also indicate a poor ozone transfer from the added ozone gas to the water phase. Considering a well function ozone transfer in the current system, the off-gas residual ozone could be used to adjust ozone doses as secondary control parameter next to the primary flow control. An additional

online sensor for measuring residual ozone in the effluent from the ozonation (water phase) could together with off-gas measurements provide indication of actual consumed ozone and thus provide a better monitoring and control.

In summary, considering the current installed online measurement equipment, a water flow-based ozone dose of e.g. 6 mg/L backed up with an adjustment of the base dose depending on residual ozone in the off-gas of e.g. <0.3 g/Nm^3 is recommended. An additional online residual ozone measurement in the effluent from the ozonation would provide an even better adjustment and control of dosed ozone. Further studies using ΔUVA at Stengården WWTP are recommend if a control towards actual concentrations of pharmaceuticals in the water is intended. However, this would also require the installation of a second UV-sensor in the effluent from the ozonation.

3.3.4 Costs for the production of a reusable water

The total investment cost for the building, the equipment and the installation were approximately 30 MSEK. To be added to the investment cost for the water reuse plant in Simrishamn are costs for UV-treatment of the reclaimed water (approx. 0.5 MSEK), piping to area for infiltration and infiltration arrangements. The running costs are estimated to approximately 1 SEK per cubic meter produced water including investment and operational costs based on previous studies (Baresel et al., 2015s; 2017a).

Actual costs for the wastewater reclamation in Simrishamn could be divided in pay-off for investment costs (CAPEX), operational costs (OPEX; personnel, maintenance and energy cost). The investment costs are summarized in table 3.13. As seen from the table, less than 1/3 of the costs are related to the equipment. As the facility is designed as a demonstration site accessible for guided tours and includes an advanced humidity control (ventilation), extra costs arose.

The operation costs, excluding costs for energy, for the period June 2019 – April 2020 is shown in table 3.14. As could be seen from the table 1/3 of the costs is for personnel, 1/3 for exchange of granular activated carbon (GAC) and 1/3 is other costs (materials, service).

As shown in table 3.15, the total costs for the period July-September 2019 for investment, running and energy is totally 365 784 SEK. During this period 302 822 m^3 was treated by the combination of microfiltration, ozonation and post treatment over Dynasand filters. The treatment cost is 1,21 SEK/m3 (approx. 0,12 Euro/m^3).

To be noticed, the volume used for the cost per cubic meter is the volume that has been treated by ozonation. The volume treated by the granular activated carbon filter without pretreatment with ozonation is not included (20 % of the flow). Most of the costs is not related to the ozonation step so if the volume treated by the single filter, the cost per cubic meter will reduced approximately 20 %. In addition, the period for calculation was July-September, which represents a low flow period, approximately 20 % lower than the estimated mean value for a full year. In summary, as most of the costs are independent the treated volume and the volume that could be treated is approximately 40 % higher than shown by calculation in table 4.3, a recalculation should end up in a cost per cubic meter of 0,86 SEK, equal to 0,09 Euros per cubic meter.

Table 3.13 Investment costs, pay-off time and costs per month due to pay off time.

Costs for	Cost (SEK)	Pay-off-time (Years)	Cost per month (SEK/month)
Equipment			
Discfilter, Ozon generator, Dynansand filters	7 100 000	25	23 667
Building			
Building for the equipment including ventilation	12 457 858	80	12 977
Installations (material + commision):			
Electricity and control	1 505 921	30	4 183
Piping	576 790	50	961
Ventilation	1 233 077	30	3 425
Process	4 269 473	30	11 860
Planning and project management:	2 815 903	30	7 822
Other costs:	22 750	30	63
Total costs	**29 981 772**		**64 958**

Table 3.14 The operation costs, excluding costs for energy, for the period June 2019 – April 2020. As could be seen from the table, 1/3 of the costs is for personnel, 1/3 for exchange of granular activated carbon (GAC) and 1/3 is other costs (materials, service).

Running cost for 11 months (June 2019 - April 2020)	**Costs 11 months:**	**SEK/Month**
Personell	124146	11286
Materials		0
Ozon- and oxygen sensors for warning system	14405	1310
Lubricants	3000	273
Service		0
PSA-equipment	28544	2595
Compressor for ozonation equipment	18100	1645
Pumps	5000	455
Exchange of GAC every second year:	137000	12455
Total costs	**330195**	**30018**

Table 3.15 Total treatment costs during the evaluation period July-September 2019.

Total costs (Investment+Running) Jul-Sep 2019, 302 822 m^3	**Costs for 3 months (SEK)**	**Costs per m^3 (SEK/m^3)**
Investment cost	194874	0.64
Running cost energy not included	90053	0.30
Energy (0,68 SEK/kWh), 118 907 kWh,	80857	0.27
Total costs:	**365784**	**1.21**

4 Discussion

4.1 Removal of pharmaceuticals, microplastics and bacteria

The removal efficiency of standard pollutants at Stengården WWTP without advanced tertiary treatment was generally good. Results also indicate that a very good removal of microplastics and hormones takes place already in existing treatment processes of the WWTP. The removal efficiencies for pharmaceuticals were, however, generally poor with several substances even indicating an increase over the existing treatment process, i.e. negative reduction. This is in line with previous reports results from other Swedish WWTPs (e.g. Allard and Wahlberg, 2017; Habagil et al., 2020). Calculated removal efficiencies and loads to the recipient are further in line with previous studies (Svahn an Björklund, 2017). Compared to other Swedish WWTPs, some pharmaceuticals including antibiotics occur in significant higher concentrations in the inflow to the Stengården WWTP. Possible reasons may be emissions from a relatively high number of residential homes and the hospital in Simrishamn but further research on this topic is recommended. Simrishamn municipality has the 5th oldest population in Sweden, which may affect the consumption of pharmaceuticals including antibiotics. The comparison with other Swedish WWTPs further indicates higher effluent concentrations for a number of substances at Stengården WWTP that at the same time occur in lower concentrations in the influent compared to other WWTPs. This may indicate a poorer removal efficiency of these substances at the Stengården WWTP. However, as this evaluation is only based on a limited evaluation period, results should be considered with care.

For some pharmaceuticals, a need for an advanced treatment to remove these substances was indicated. However, this only for an assumed low dilution and for effect concentrations including high safety factors assumed. Further, considering the measured concentration of pharmaceuticals in the effluent of the WWTP, the general goal to decrease the load to the Baltic sea with unwanted substances, and the targeted wastewater reclamation, the additional advanced treatment of the effluent becomes necessary.

The evaluation of the implemented three parallel advanced treatment system consisting of only activated carbon (GAC), ozonation combined with sand filter (O3SF), and ozonation combined with activated carbon (O3GAC) clearly shows an added removal effect for pharmaceuticals but also other pollutants. This agrees with previous studies of these systems and especially that the combination of ozonation with activated carbon (O3GAC) stands out as the most efficient treatment system (Baresel et al., 2015a). This is explained by the combination of several efficient removal technologies in this combination. The pre-treatment with microfiltration (MF), common for all advanced treatment systems, further implies an important part of the overall removal efficiency. The conversion of all treatment lines to the combination of microfilter, ozonation and activated carbon is recommended.

An aspect that has not been studied earlier is the effect of the continuous backwash of the activated carbon filter. Even though the evaluation of the filter indicates a good treatment performance and operational stability, effects on the long-term capacity of the activated carbon, i.e. the lifetime, and thus the economic impact of the GAC-operation need further consideration. The positive effect of an established biology in the active carbon filter as reported by Baresel et al. (2015a, 2017) was not

investigated in this project. To what extend the continuous backwash is affecting this enhancing effect, is for example yet unclear.

Another aspect that may be importance for the long-term sustainability of the advanced treatment is the implementation of findings regarding possible monitoring and control strategies for the ozonation. Similar to previous studies (e.g. Sehlén et al., 2015), a more dynamic control of ozone-doses towards actual pollutant loads may provide an improved overall performance of the system.

For long-term evaluation of operational stability and economic feasibility, the continuous follow-up over the whole lifetime of the implemented system is recommend. As one of the first full-scale installation of its kind, valuable information can be gathered and provided to society. The technologies used were proven in full-scale and the operators were capable to operate the system after training.

Concentrations of antibiotic resistance bacteria in untreated wastewater were in line with previously reported levels in Sweden of ESBL producing *E. coli* (Kwak et al., 2015) and presence of enterococci positive for VRE (Iversen 2002). Even if the removal of pharmaceuticals were poor in the conventional treatment, the major part of bacterial removal was achieved there. For all bacteria, both resistant and total population, a higher reduction in Stengården WWTP was achieved in September when the flow rate was in average lower. Of the studied ARB, vancomycin resistant enterococci (VRE) showed the highest reduction over the system similar to observations of conventional WWTPs by Iversen et al. (2002). Enterococci were also more sensitive to ozonation than *Enterobacteriaceae* as also reported by Luddekke et al. (2015).

The present and the mentioned studies (Kwak et al., 2015; Iversen et al., 2002) observed no selection for antimicrobial resistance by conventional treatment, and the current study not for advanced treatment either. This contrasts other findings (Alexander et al., 2016; Luddekke et al., 2015), which suggest that ozonation may select for antibiotic resistance. Reported effect from ozonation range from a 2 $\log_{10}$ reduction of *E. coli* and enterocoocci with 0.9 g O_3/g DOC, 18 min (Alexander et al., 2016) and around a 1 $\log_{10}$ reduction with 0.73 O_3/g DOC, 20 min (Luddeke et al., 2015). However, these references studying the ozonation effect over a long time period, encountered large variability. Luddeke et al. (2015) studied a similar system with ozonation followed by sand or GAC filtration and could not, similar to this study, see any contribution from the filters in reducing ARB. Longer retention time in the conventional wastewater treatment system seem to reduce ARB and general population of studied bacteria. Since effects from increased ozonation may not be cost efficient other measures to reduce ARB, e.g. a final treatment step may give better effluent quality regarding bacteria.

4.2 Production of reusable water

The evaluation of the reusable water showed good results. The removal of pharmaceuticals, hormone disturbing substances and antibiotics was almost total and indicates that the water could e.g. be recharged to the groundwater. Appendices 6.2 Swedish limits for drinking water provides a comparison of measured concentrations of various parameters compared to Swedish chemical and microbiological permission limits for drinking water. Even though direct potable water uses or fulfilling drinking water standards has not been a project goal, the comparison shows that these limits are meet or only slightly exceeded except for chloride and bacteria. The first caused by the high salt content in the wastewater probably caused by seawater leakage into the sewer. The bacteria levels were not targeted by the project but can be reduced by a proposed disinfection (see Figure 2.2).

The period for evaluation of reusable water was limited. If the water produced is recharged to the groundwater aquifer and is supposed to serve as a drinking water, an extended long-term follow-up period is recommended. In general, the effects and substances from analysis of Microtox, YES/YAS (standardized tests to measure the estrogenic and androgenic effects of water), N-Nitrosodimethylamine (NDMA) and 1,4-Dioxane are easily removed by the combination of ozonation and GAC (Baresel et al., 2015a). Still, during a long-term follow-up-period those analysis could be considered. Further, due to the results for bromate during the evaluation period for production of a reusable water indicated too high concentrations, bromate should also be followed-up. In this context, more focus on the mitigation of upstream bromate sources may be needed.

Results from the evaluation period show that an effective disinfection of the reclaimed wastewater is necessary as bacteria levels are too high. This is in agreement with the expectations (figure 2.2) and the use of an already existing disinfection process could be considered. The use of well-known standard UV- treatment may be considered as alternative. To provide a safe reclamation of the treated wastewater, some kind of real-time monitoring or frequent analysis of the reused water is recommended

4.3 Economic aspects

The total investment cost for the building, the equipment and the installation were approximately 30 MSEK or 3 MEuros (see 3.3.4). To be added to the investment cost for the water reuse plant in Simrishamn are costs for UV-treatment of the reclaimed water (approx. 0.5 MSEK), piping to area for infiltration and infiltration arrangements. By a recalculation of the flow measured during the evaluation period to a 40 % higher expected mean value (see 3.3.4) the running costs are estimated to be approximately 0,9 SEK (0,09 Euro) per cubic meter produced water which includes investment and operational costs, see table 4.1. It seems realistic to assume that the real cost is somewhere in between, approximately 1 SEK/m^3 or 0,1 Euro/m^3. This is equal to the calculated cost based on previous studies of 1 SEK/m^3 (Baresel et al., 2015s; 2017a). Compared to other technologies for production of water in water scarcity areas, e.g. desalination, this cost should be considered as relatively low.

Table 4.1 Total running costs based on the figures from the evaluation period and recalculated to a 40 % higher mean value of the flow (see 3.3.4)

Total costs (Investment+Running) Recalculated values to 40 % higher volume compared to the volume during the evaluation period.	**Costs per m^3 (SEK/m^3)**
Investment cost	0.46
Running cost (energy not included)	0.21
Energy (0,68 SEK/kWh)	0.19
Total costs:	**0.86**

For the aim of production of fresh water, these costs should be set in perspective to the cost for the production of fresh water using desalination. The plant in Simrishamn has a capacity of producing 6000 m^3 reusable water per day. As a comparison, the desalination plant in Sandviken (island of Öland) has a capacity of 3000 m^3 water per day and the investment cost was 85 MSEK (excluding piping) and specific treatment cost per cubic meter produced water, investment cost included, is 4.80 SEK/m^3 (Skoglund et al., 2019). The running costs (energy, service, chemicals, future replacement of membranes) for the first years of operation (2018 and 2019) was estimated to 3,2 SEK/m^3 Another example is the desalination plant in Kvarnåkershamn (island of Gotland) with a capacity of 5000-7500 m^3 per day. The investment cost was approximately 220 MSEK and the

estimated specific cost is 40 SEK/m³ produced water which includes investment in piping (Sjöstrand et al., 2019). The high unit cost of desalination is partly caused by a higher energy price on the island and by the long pipelines needed to reach the end-users.

4.4 Energy demand

The power demand for running the wastewater reclamation facility is roughly estimated to 67 kW during maximum capacity (270 m³/h). The power demand is divided as follows: PSA-unit for production of oxygen (as supply for the ozone unit) 16 kW, the ozone unit 16 kW, pumps 20 kW, dehumidification unit 5 kW and a future UV-light treatment for disinfection 10 kW. With 24 hours per day and 365 days, the energy demand is 590 000 kWh/year. At this maximum flowrate, the water volume produced is 2 Mm³/year which results in 0.32 kWh/m³. This value is in the same range as calculated from the evaluation, see below. It should be noted that the actual flowrate will in periods be lower than 270 m³/h and as a result both the total produced volume and the total energy demand will be lower.

The actual energy demand for the evaluation period July-September was 118 907 kWh for water being treated by ozonation followed by Dynasand filtering, 100 941 m³, see table 3.13. This gives an energy demand of 0,39 kWh/m³.

As discussed for the costs per cubic meter, see 3.3.4, the addition of the flow that today is only treated by granular activated carbon without pretreatment with ozonation, would increase the treated volume by 20 % without almost any additional extra demand for energy. This is also true for an estimated higher volume during a full year compared to the volume treated during the evaluation period July-September when the flow is relatively low, and the humidity control equipment has to run on full capacity. If the evaluation had covered a full year, approximately a 20 % higher mean flow would be expected without a higher energy usage. In total, approximately 40 % higher flow could be estimated to be treated in the future during a full year without any significant higher energy use.

Recalculation of the energy demand of 0,39 kWh/m³ to running of the plant a full year period and with all 5 Dynsand filters included in the recalculation would result in approximately 40 % less consumption equally to 0,23 kWh/m³. This is closed to a calculation in April 2020 that showed a energy demand of 0,24 kWh/m³. In April 2020 the flow was at the high side and the humidity in the building was relatively low due to low temperatures on both air and water which gives lower energy demand for air condition.

It is not easy to find figures for the energy demand for running desalination plants on water from the Baltic sea (0.7 % salinity), but an energy demand of 0.6 – 2.5 kWh/m³ could be estimated (Pinto and Marques, 2017). Those figures give a net saving of energy by using the system based on ozonation of 0.3 – 0,4 kWh/m³ or 2-6 times less compared to desalination. In the near future, there should be figures on energy demand from the desalination plant at Kvarnåkershamn, Gotland (2019). During April and May 2020, the energy demand for desalination of brackish water at the Sandviken, Öland (Borgholm Energi), was 1,5 kWh/m³ produced tap water.

5 Conclusions and recommendations

The evaluation of both the treatment conditions for removal of pharmaceuticals and to produce reusable water showed good results. The removal of pharmaceuticals, hormone disturbing substances and antibiotics was almost total and indicates that the water could be recharged to the ground water. The most efficient treatment configuration was the combination of microfiltration, ozonation and activated carbon.

Considering the current installed online measurement equipment, a water flow-based ozone dose of e.g. 6 mg/L backed up with an adjustment of the base dose depending on ozone residual in the off-gas of e.g. <0.3 g/Nm^3 is recommended. An additional online ozone residual measurement in the effluent from the ozonation would provide an even better adjustment and control of dosed ozone. Further studies using ΔUVA at Stengården WWTP are recommend if a control towards actual concentrations of pharmaceuticals in the water is intended. However, this would also require the installation of a second UV-sensor in the effluent from the ozonation.

If the water is recharged to the groundwater for drinking water propose, a long-term follow-up is recommended as a complement to those results. Addition of a disinfection of the final effluent as an extra barrier for reused water is also strongly recommended, e.g. by UV-treatment. Online sensors for monitoring and control of e.g. ozone doses requirements and effluent quality could also be considered for improved follow-up of the treatment system.

As the treatment consisting of microfiltration, ozonation and activated carbon was shown to be the most efficient configuration, the other treatment lines may be converted to this successful operational mode

The cost for treatment with this combination during July-September was 1,21 SEK/m^3. Recalculation on a full year basis shows an estimated cost of 0,86 SEK/m^3. It seems realistic to assume that the real cost is somewhere in between, approximately 1 SEK/m^3 or 0,1 Euro/m^3. Compared to other technologies for production of water in water scarcity areas, e.g. desalination, this cost most be considered as relatively low.

The energy demand for treatment with this combination during July-September was 0,39 kWh/m^3. Recalculation on a full year basis shows an estimated energy demand of 0,23 kWh/m^3. It seems realistic to assume that the real energy demand is somewhere in between, approximately 0,3 kWh/m^3. Compared to other technologies for production of water in water scarcity areas, e.g. desalination, this energy demand most be considered as relatively low.

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6 Appendices

6.1 Analytical results from SC5, production of a reusable water

In addition to the analysis micropollutants shown in part 3.2.1, analytical results from the sampling campaign CS5 for production of a reusable water for infiltration to the groundwater are shown here (pharmaceutical residues, antibiotic substances, PFAS, PAH`s, phenolic substances, ethoxylates, phthalates, PCB`s and other organic substances). For the analyse of hormone disturbing substances, all 3 substances showed values lower than the detection limit 1 ug/l.

Table 6.1 Analytical results from the analyse of pharmaceutical residues.

Substance	Mode of action	Out OCF [ng/L]
Amlodipine	*Antihypertensive*	<14
Atenolol	*Antihypertensive*	12
Bisoprolol	*Antihypertensive*	6
Caffeine	*Stimulant*	<50
Carbamazepine	*Sedative*	<25
Citalopram	*Antidepressant*	17
Diclofenac	*Anti-inflammatory*	110
Fluoxetine	*Antidepressant*	<1
Furosemide	*Diuretic*	100
Hydrochlorothiazide	*Antihypertensive*	72
Ibuprofen	*Anti-inflammatory*	<11
Ketoprofen	*Anti-inflammatory*	33
Metoprolol	*Antihypertensive*	58
Naproxen	*Anti-inflammatory*	30
Oxazepam	*Sedative*	750
Paracetamol	*Analgesic*	<1
Propranolol	*Antihypertensive*	<3
Ramipril	*Antihypertensive*	20
Ranitidine	*Antiulcer*	<3
Risperidone	*Antipsychotic*	<1
Sertralin	*Antidepressant*	<3
Simvastatin	*Lipid-regulating*	<2
Terbutaline	*Asthma medication*	<1
Warfarin	*Anticoagulant*	<3

Table 6.2 Analytical results from the analyse of antibiotic substances.

Substance	[ng/L]
Amoxicillin	---
Ampicillin	<24
Benzylpenicillin	<5
Ciprofloxacin	<1
Clarithromycin	5
Clindamycin	<1
Doxycycline	<3
Erythromycin	27
Fusidic acid	<9
Linezolid	<3
Metronidazole	<1
Moxifloxacin	<2
Norfloxacin	<2
Rifampicin	<32
Sulfamethoxazole	33
Tetracycline	<60
Trimethoprim	<1

Table 6.3 Concentrations of metals in treated water for water reuse by infiltration to ground water from sampling campaign CS5.

Parameter	Unit	Value
Ca	mg/l	107
Fe	mg/l	0.0356
Mg	mg/l	9.19
Na	mg/l	194
Al	µg/l	80.8
As	µg/l	0.783
Cd	µg/l	0.0119
Cr	µg/l	0.345
Hg	µg/l	<0.002
Mn	µg/l	11.6
Sb	µg/l	0.253
B	µg/l	61.6
Se	µg/l	<0.5
Cu	µg/l	1.68
Pb	µg/l	0.328
Ni	µg/l	3

Table 6.4. Other inorganic parameters in treated water for water reuse by infiltration to ground water from sampling campaign CS5.

Parameter	Unit	Value
Total hardness	°dH	17.1
Smell at 20°C		Non
Smell, kind of at 20°C		----------
Turbidity	FNU	1.2
Conductivity	mS/m	155
pH		7.8
nitrite	mg/l	0.36
Color	mgPt/l	20.8
CODMn	mg/l	5.84
ammonium	mg/l	0.164
nitrate	mg/l	21.4
fluoride	mg/l	0.33
chloride	mg/l	286
sulphate	mg/l	77.6
bromate	µg/l	<5.0
CN total	mg/l	<0.005

Table 6.5 PFAS11 in treated water for water reuse by infiltration to ground water from sampling campaign CS5.

Parameter	Unit	Value
PFBA	ng/L	< 0.63
PFPeA	ng/L	2
PFHxA	ng/L	2.5
PFHpA	ng/L	0.98
PFOA	ng/L	< 0.2
PFNA	ng/L	0.43
PFDA	ng/L	0.16
PFBS	ng/L	1.2
PFHxS	ng/L	< 0.1
PFOS	ng/L	0.61
6:2 FTS	ng/L	1.8

Table 6.6 Organic substances in treated water for water reuse by infiltration to ground water from sampling campaign CS5.

Parameter	Unit	Value
bensen	µg/l	<0.20
1,2-dikloretan	µg/l	<0.750
tetrakloreten	µg/l	<0.20
trikloreten	µg/l	<0.10
summa tetra- och trikloreten	µg/l	<0.20
triklormetan (kloroform)	µg/l	<0.30
tribrommetan (bromoform)	µg/l	<0.20
dibromklormetan	µg/l	<0.10
bromdiklormetan	µg/l	<0.10
summa trihalometaner	µg/l	<0.35
bens(b)fluoranten	µg/l	<0.0040
bens(k)fluoranten	µg/l	<0.0020
benso(ghi)perylen	µg/l	<0.0030
indeno(123cd)pyren	µg/l	<0.0030
PAH, summa 4	µg/l	<0.0060
bens(a)pyren	µg/l	<0.0020
aldrin	µg/l	<0.0050
dieldrin	µg/l	<0.010
heptaklor	µg/l	<0.010
heptaklorepoxid	µg/l	<0.010
cis-heptaklorepoxid	µg/l	<0.010
trans-heptaklorepoxid	µg/l	<0.010
atrazin	µg/l	<0.050
desetylatrazin	µg/l	<0.050
desisopropylatrazin	µg/l	<0.050
bentazon	µg/l	<0.050
BAM (2,6-diklorbensamid)	µg/l	<0.050
bitertanol	µg/l	<0.050
boskalid	µg/l	<0.050
cyanazin	µg/l	<0.050
2,4-D	µg/l	<0.050
2,4-DP (diklorprop)	µg/l	<0.050
dimetoat	µg/l	<0.050
diuron	µg/l	<0.050
etofumesat	µg/l	<0.050
fluroxipyr	µg/l	<0.050
imidakloprid	µg/l	<0.050
isoproturon	µg/l	<0.050
klopyralid	µg/l	<0.050
kloridazon	µg/l	<0.050
kvinmerak	µg/l	<0.050
MCPA	µg/l	<0.050
MCPP (mekoprop-isomerer)	µg/l	<0.050
metalaxyl (isomerer)	µg/l	<0.050
metamitron	µg/l	<0.050
metazaklor	µg/l	<0.050
metribuzin	µg/l	<0.050
pirimikarb	µg/l	<0.050
propyzamid	µg/l	<0.050
terbutylazin	µg/l	<0.050
metsulfuronmetyl	µg/l	<0.050
sulfosulfuron	µg/l	<0.050
tifensulfuronmetyl	µg/l	<0.050
tribenuronmetyl	µg/l	<0.050
glyfosat	µg/l	0.338
AMPA	µg/l	0.571

Table 6.7. Organic substances (PAH`s, phenolic substances, ethoxylates, phthalates and PCB`s)) in treated water for water reuse by infiltration to ground water from sampling campaign CS5.

Parameter	Unit	Value
naftalen	µg/l	<0.100
acenaftylen	µg/l	<0.010
acenaften	µg/l	<0.010
fluoren	µg/l	<0.020
fenantren	µg/l	<0.030
antracen	µg/l	<0.020
fluoranten	µg/l	<0.030
pyren	µg/l	<0.060
bens(a)antracen	µg/l	<0.010
krysen	µg/l	<0.010
bens(b)fluoranten	µg/l	<0.010
bens(k)fluoranten	µg/l	<0.010
bens(a)pyren	µg/l	<0.020
dibenso(ah)antracen	µg/l	<0.010
benso(ghi)perylen	µg/l	<0.010
indeno(123cd)pyren	µg/l	<0.010
PAH, summa 16	µg/l	<0.19
PAH, summa cancerogena	µg/l	<0.040
PAH, summa övriga	µg/l	<0.15
PAH, summa L	µg/l	<0.10
PAH, summa M	µg/l	<0.080
PAH, summa H	µg/l	<0.045
oljeindex	µg/l	<50.0
fraktion >C10-C12	µg/l	<5.0
fraktion >C12-C16	µg/l	<5.0
fraktion >C16-C35	µg/l	<30.0
fraktion >C35-<C40	µg/l	<10.0
4-tert-oktylfenol	µg/l	<0.010
4-tert-OF-monoetoxilat	µg/l	<0.010
4-tert-OF-dietoxilat	µg/l	<0.010
4-tert-OF-trietoxilat	µg/l	<0.010
4-nonylfenoler (tekn blandning)	µg/l	<0.100
4-NF-monoetoxilat	µg/l	<0.100
4-NF-dietoxilat	µg/l	<0.100
4-NF-trietoxilat	µg/l	<0.100
PCB 28	µg/l	<0.00014
PCB 52	µg/l	<0.00014
PCB 101	µg/l	<0.00014
PCB 118	µg/l	<0.00014
PCB 138	µg/l	<0.00014
PCB 153	µg/l	<0.00014
PCB 180	µg/l	<0.00014
PCB, summa 7	µg/l	<0.0010
dimetylftalat	µg/l	<1.0
dietylftalat	µg/l	<1.0
di-n-propylftalat	µg/l	<1.0
di-n-butylftalat	µg/l	<1.0
di-iso-butylftalat	µg/l	<1.0
di-pentylftalat	µg/l	<1.0
di-n-oktylftalat (DNOP)	µg/l	<1.0
di-(2-etylhexyl)ftalat (DEHP)	µg/l	<1.0
butylbensylftalat	µg/l	<1.0
di-cyklohexylftalat	µg/l	<1.0
di-iso-decylftalat (DIDP)	µg/l	<10
di-iso-nonylftalat (DINP)	µg/l	<10
di-n-hexylftalat (DNHP)	µg/l	<1.0

6.2 Comparison with Swedish limits for drinking water

In the table below the limits for Swedish drinking water is listed together with the results from evaluation of the SC5 sampling campaign for production of a reusable water.

Table 6.8 The Swedish permission limits for drinking water published (SLVFS 2001:30, H90).

Element/substance	Unit	Analysed concentration	Limit for drinking water
Ca	mg/l	107	100
Fe	mg/l	0.0356	0.1
Mg	mg/l	9.19	20
Na	mg/l	194	100
Al	µg/l	80.8	100
As	µg/l	0.783	10
Cd	µg/l	0.0119	5
Cr	µg/l	0.345	50
Hg	µg/l	<0.002	1
Mn	µg/l	11.6	50
Sb	µg/l	0.253	5
B	µg/l	61.6	1000
Se	µg/l	<0.5	10
Cu	µg/l	1.68	200
Pb	µg/l	0.328	10
Ni	µg/l	3	20
Odour at 20°C		none	weak
Turbidity	FNU	1.2*	0.5
Colour	mgPt/l	20.8	15
Conductivity	mS/m	155	250
pH		7.8	7.5 - 9
nitrite	mg/l	0.36	0.1
CODMn	mg/l	5.84	4
ammonium	mg/l	0.164	0.5
nitrate	mg/l	21.4	20
fluoride	mg/l	0.33	1.5
chloride	mg/l	286	100
sulfate	mg/l	77.6	100
bromate	µg/l	<5.0	10
CN total	mg/l	<0.005	0.05
bensen	µg/l	<0.20	1
1,2-dichloretan	µg/l	<0.750	3
sum trihalometane	µg/l	<0.35	50
PAH, sum of 4	µg/l	<0.0060	0.1
bens(a)pyren	µg/l	<0.0020	0.01
aldrin	µg/l	<0.0050	0.03
dieldrin	µg/l	<0.010	0.03
heptachlor	µg/l	<0.010	0.03
heptachlor epoxid	µg/l	<0.010	0.03
pesticides, single	µg/l		0.1
pesticides, total	µg/l		0.5
vinylchlride (teoretical estimated)	µg/l		0.5

Microbiology			
Cultivated microorg.22°C, 3 days	CFU/ml	10600	10
slow growing bacteria´s 22°C	CFU/ml	15 700	5000
coliform bacteria´s 35°C	CFU/100 ml	>200	Shown
E.Coli <1 CFU/100ml 1 1 ERJA	CFU/100 ml	>100	Shown
actinomyceter	CFU/100 ml	<1	100
intestinala enterococks	CFU/100 ml	190	Shown

6.3 Required effluent qualities for different reuse

Table 6.9. Required main effluent qualities as monthly average for the different reuse applications (modified from Baresel et al., 2015a) and compared with the results from the evaluation of production of reusable water by use of the combination microfiltration-ozonation (6 mg/l) -granular activated carbon, SC5.

Parameter	Unit	Analysed concentration, SC5	Irrigation in agriculture	Industrial use	Groundwater Recharge
Microbiology					
Total Coliforms	/100 ml	>200	2.2	2.2	2.2
Max Total Coliforms	/100 ml	>200	23	23	23
Organic & Inorganic					
BOD_5	mg/L	*	<8	<5	<5
COD	mg/L	5,8	<40	<30	<30
Total Nitrogen	mg/L	5,5	20	10	<10
Ammonia Nitrogen	mg/L	0,16	5	1	1
Nitrate Nitrogen	mg/L	4,8	10	5	10
Organic Nitrogen	mg/L		5		5
Total Phosphorus	mg/L	0,08	2	1	1
Total Suspended Solids	mg/L	2,4	5	2	5

*/ No analyze result provided but COD value indicates that BOD5 should be well below the limits for all 3 usage areas.

6.4 Analytical packages

Substances measured within each analytical package are presented in the following tables.

Package 1. Estrogenic hormones. Analyses performed by IVL Swedish Environmental Research Institute.

Substance	Mode of action
Estrone (E1)	Hormone
B-Estradiol (E2)	Hormone
Ethynylestradiol (EE2)	Hormone

Package 2. Common pharmaceuticals. Analyses performed by IVL Swedish Environmental Research Institute.

Substance	Mode of action
Amlodipine	Antihypertensive
Atenolol	Antihypertensive
Bisoprolol	Antihypertensive
Caffeine	Stimulant
Carbamazepine	Sedative
Citalopram	Antidepressant
Diclofenac	Anti-inflammatory
Fluoxetine	Antidepressant
Furosemide	Diuretic
Hydrochlorothiazide	Antihypertensive
Ibuprofen	Anti-inflammatory
Ketoprofen	Anti-inflammatory
Metoprolol	Antihypertensive
Naproxen	Anti-inflammatory
Oxazepam	Sedative
Paracetamol	Analgesic
Propranolol	Antihypertensive
Ramipril	Antihypertensive
Ranitidine	Antiulcer
Risperidone	Antipsychotic
Sertraline	Antidepressant
Simvastatin	Lipid-regulating
Terbutaline	Asthma medication
Warfarin	Anticoagulant

Package 3. Antibiotics. Analyses performed by IVL Swedish Environmental Research Institute.

Substance	Mode of action
Amoxicillin	
Ampicillin	
Benzylpenicillin	β-Lactam
Ciprofloxacin	Fluoroquinolone
Clarithromycin	Macrolide
Clindamycin	Lincosamide
Doxycycline	Tetracycline
Erythromycin	Macrolide
Fusidic acid	Fusidane
Linezolid	Oxazolidinone
Metronidazole	
Moxifloxacin	Fluoroquinolone
Norfloxacin	Fluoroquinolone
Rifampicin	Antimycobacterial
Sulfamethoxazole	Sulfonamide
Tetracycline	Tetracycline
Trimethoprim	Folic acid antagonist

Package 4. Microplastics. Analyses performed by IVL Swedish Environmental Research Institute.

Particle type and size ranges	Size ranges	Mass estimation (y/n)
Plastic fiber	300. 100. 50 µm	Y
Non-synthetic fiber	300. 100. 50 µm	Y
Synthetic fragments	300. 100. 50 µm	Y

Package 5. Per- and Polyfluoroalkyl Substances (PFAS). Analyses performed by IVL Swedish Environmental Research Institute.

Substance
PFBA
PFPeA
PFHxA
PFHpA
PFOA
PFNA
PFDA
PFBS
PFHxS
PFOS
6:2 FTS

Package 6. Drinking water standard parameters with bacterial and pesticide extension (DV-4). Analyses performed by ALS Scandinavia.

Parameter
Ca
Fe
Mg
Na
Al
As
Cd
Cr
Hg
Mn
Sb
B
Se
Cu
Pb
Ni
total hardness
odor at 20 ° C
smell. species at 20 ° C
turbidity
conductivity
pH
nitrite
color
CODMn
ammonium
nitrate
fluoride
chloride
sulphate
bromate
CN total
benzene
1,2-dichloroethane
tetrachlorethylene
trichloroethene
total tetra- and trichloroethene
trichloromethane (chloroform)
tribromethane (bromoform)
dibromochloromethane

bromodichloromethane
sum of trihalomethanes
benzo (b) fluoranthene
benzo (k) fluoranthene
benzo (ghi) perylene
indeno (123cd) pyrene
PAH. sum 4
benzo (a) pyrene
aldrin
dieldrin
heptachlor
heptachlor
cis heptachlorepoxide
trans heptachlorepoxide
atrazine
desetylatrazin
desisopropylatrazin
bentazone
BAM (2,6-dichlorobenzamide) Bitertanol boscalid cyanazine 2,4-D 2.4-DP (dichloropropylene) dimethoate diuron ethofumesate fluroxypyr Imidacloprid isoproturon clopyralid chloridazon quinmerac MCPA MCPP (mechoprop isomers) metalaxyl (isomers) metamitron metazachlor metribuzin pirimicarb propyzamide terbuthylazine metsulfuron methyl sulfosulfuron thifensulfuron methyl tribenuron glyphosate

AMPA culturable microorganisms.22 ° C. 3 days slow-growing bacteria 22 ° C coliform bacteria 35 ° C E.Coli actinomycetes intestinal enterococci clostridium perfringens. prospective microspongesorobenzamide) Bitertanol
boscalid
cyanazine
2,4-D
2.4-DP (dichloropropylene)
dimethoate
diuron
ethofumesate
fluroxypyr
Imidacloprid
isoproturon
clopyralid
chloridazon
quinmerac
MCPA
MCPP (mechoprop isomers)
metalaxyl (isomers)
metamitron
metazachlor
metribuzin
pirimicarb
propyzamide
terbuthylazine
metsulfuron methyl
sulfosulfuron
thifensulfuron methyl
tribenuron
glyphosate
AMPA
culturable microorganisms.22 ° C. 3 days
slow-growing bacteria 22 ° C
coliform bacteria 35 ° C
E.Coli

actinomycetes
intestinal enterococci
clostridium perfringens. prospective
microsponges

Package 7. Nonyl phenols. octyl phenols and ethoxylates (OV-18e). Analyses performed by ALS Scandinavia.

Parameter
285/5000
4-tert-octyl phenol
4-tert-OF-monoetoxilat
4-tert-OF-dietoxilat
4-tert-OF-trietoxilat
4-nonylphenols (technical mixture)
4-NF monoetoxilat
4-NF dietoxilat
4-NF trietoxilat
4-tert-octyl phenol
4-tert-OF-monoetoxilat
4-tert-OF-dietoxilat

Package 8. Phthalates (OV-4b). Analyses performed by ALS Scandinavia.

Substance
dimethyl phthalate
diethyl phthalate
di-n-propyl phthalate
di-n-butyl phthalate
di-iso-butyl phthalate
di-pentylftalat
di-n-octyl phthalate (DNOP)
di- (2-ethylhexyl) phthalate (DEHP)
butyl benzyl
di-cyklohexylftalat
diiso-decyl phthalate (DIDP)
diiso-nonylphthalate (DINP)
di-n-hexyl phthalate (DNHP)

Package 9. Waterpack 7. oil GC-FID and PAH16. Analyses performed by ALS Scandinavia.

Parameter
naphthalene
acenaphthylene
acenaphthene
fluorene
phenanthrene
anthracene
fluoranthene
pyrene
benzo (a) anthracene
chrysene
benzo (b) fluoranthene
benzo (k) fluoranthene
benzo (a) pyrene
dibenzo (ah) anthracene
benzo (ghi) perylene
indeno (123cd) pyrene
PAH. sum 16
PAH. sum of carcinogens
PAH. sum of others
PAH. Sum L
PAH. sum M
PAH. sum H
Oil index
fraction >C10-C12
fraction >C12-C16
fraction >C16-C35
fraction >C35-<C40

Package 10. Polychlorinated biphenyls (OV-2aQ PCB7). Analyses performed by ALS Scandinavia.

Parameter
PCB 28
PCB 52
PCB 101
PCB 118
PCB 138
PCB 153
PCB 180
PCB. sum 7

Package 11. Other parameters.

Parameter	Analytical lab (IVL. ALS or SLU)
Total suspended matter	IVL
E.coli (% resistant)	SLU
KEC	SLU
Acinetobacter	SLU
Fecaelis/faecium	SLU
NO2-N	IVL
NO3-N	IVL
NH4-N	IVL
Tot P	IVL
Tot N	IVL
COD	IVL
BOD5	IVL
DOC	IVL
Bromide	IVL
Bromate	IVL and ALS
UVA	IVL
UVT	IVL
Rest ozone	IVL

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