Reuse of Treated Wastewater in Industrial Symbiosis

by

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Preface

Ending my master's education with this thesis, has been a wonderful experience. To be able to combine my technical background with social interactions and insight into the world of water, has been a great joy! For trusting in me, I want to thank VA SYD, all the lovely people, which helped me and especially my supervisor Kerstin Hoyer, always looking out for me!

Having a place to work at in the Chemical Department at LTH, had a great influence on this thesis. Thank you to the department and particularly to Åsa Davidsson, supervising me, and always giving valuable comments and advise!

My family and friends all over the world. Despite the distances, your unconditional support means everything.

Hopefully this work can contribute and be part of the start of many new discoveries to reuse wastewater in the future!

Summary

Many regions around the world suffer from occasional or permanent droughts. Recent years have shown that although Sweden is not a water scarce country, it is vulnerable to dry periods. As drinking water is applied in not only households, but within agriculture and industries, this thesis explores the opportunities to achieve an improved management of water resources, by investigating the possibilities to reuse treated wastewater.

By collaborating with water associations and industries around Sweden, a categorization of the main water consuming applications within industries was established. These were found to be cooling water, boiler feed, the washing of vehicles and water for recreational purposes. The reuse within agriculture and directly at the wastewater treatment plant were also investigated although mainly through literature.

It was found that a large interest in the topic is present within the industries and the environmental incitement is strong. It was though also communicated that the environmental benefits alone will not be motivation enough, the economical incitement dominates, since drinking water is easily accessible at a relatively low cost.

Further, this study proposes processes, which could be installed in the wastewater treatment plant, to achieve the water qualities required by the industries. The proposed processes include activated carbon, reverse osmosis, nano-, micro- and ultrafiltration, ozonation and the disinfection processes ultraviolet light and chlorination. The instalment of nanofiltration showed a reduction or elimination of most substances, relevant for the categories for implementation. The remaining processes have abilities to reduce or eliminate some substances and it was further investigated if a combination of processes could be beneficial.

For a more holistic approach, the legal aspects and costs were looked into, with the conclusion that clarifying definitions about treated wastewater are needed, as it has the possibility not to be seen as waste, but as a bi-product of the treatment process. Depending on the classification, the possibilities of reusing treated wastewater change.

The range of costs is large, depending on mainly the process which needs to be installed at the treatment plant and the connecting pipe systems, since local differences may have large effects.

In conclusion, the reuse of treated wastewater does have potential and with the interest and motivation by industries, it seems like a promising option for the future of water.

Sammanfattning

Många regioner runtom i världen lider av tillfällig eller permanent torka. De senaste åren har visat att, även om Sverige inte är klassat som ett land med vattenbrist, är det sårbart för torra perioder. Dricksvatten tillämpas inte bara inom hushåll, utan även inom jordbruk och industri. Detta examensarbete utforskar därför möjligheterna att öka vattenresurshushållningen, genom att undersöka möjligheterna att återanvända behandlat avloppsvatten inom industrier och jordbruk.

Genom att samarbeta med vattenorganisationer och industrier runtom i Sverige etablerades en kategorisering av de viktigaste vattenförbrukande tillämpningarna inom industrier: kylvatten, pannvatten, tvätt av fordon och vatten för rekreationsändamål. Även återanvändningen inom jordbruk och inom avloppsreningsverket undersöktes genom litteratur.

Det visade sig att ett stort intresse för ämnet finns inom industrier och att miljötanken är stark. Eftersom dricksvatten i nuläget är lätt åtkomligt och jämförbart billigt, räcker inte miljötanken, men även de ekonomiska incitamenten måste förstärkas, då de är dominerande.

Vidare föreslår arbetet processer som skulle kunna installeras i avloppsreningsverket för att uppnå de vattenkvaliteter som krävs av industrierna. De föreslagna processerna innefattar aktivt kol, omvänd osmos, nano-, mikro- och ultrafiltrering, ozonering och desinfektionen genom ultraviolett ljus och klorering. Det visade sig att nanofiltrering kan medföra en reduktion eller eliminering av de flesta ämnen som är relevanta för kategorierna för att återanvända renat avloppsvatten. De återstående processerna har förmågan att minska eller eliminera vissa ämnen och det undersöktes vidare om en kombination av processer skulle kunna vara till nytta.

För ett mer holistiskt tillvägagångssätt undersöktes de juridiska aspekterna och kostnaderna, med slutsatsen att ett klargörande av definitioner om behandlat avloppsvatten behövs, eftersom det har möjlighet att inte ses som avfall, utan som en biprodukt av reningsprocessen. Beroende på klassificeringen, ändras möjligheterna för att återanvända renat avloppsvatten.

Kostnaderna är beroende av främst den process som behöver installeras i reningsverket för att uppnå de önskade kvalitetskraven, och anslutningsrörsystemen, eftersom lokala skillnader kan ha stora effekter.

Sammanfattningsvis har återanvändningen av behandlat avloppsvatten potential och med intresse och motivation från industrier, verkar det som ett lovande alternativ för vattnets framtid.

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List of abbreviations

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AOP – Advanced Oxidation Process

BAC – Biological Active Filter

BAF - Biological Aerated Filter

BOD – Biochemical Oxygen Demand

CEC – Compounds of Emerging Concern

CNM - Carbon Nanostructured Material

COD – Chemical Oxygen Demand

CSTR – Continuously Stirred Tank Reactor

DBP – Disinfection By-Products

DF – Disc Filter

DOC – Dissolved Organic Carbon

EBCT – Empty Bed Contact Time

GAC – Granular Activated Carbon

IWVA - Intermunicipal Water Company of the Veurne Region

MF – Microfiltration

NDN – Nitrification-Denitrification

NF - Nanofiltration

PAC – Powdered Activated Carbon

PE – Population Equivalent

pUF – Pressurized Ultrafiltration

RGSF – Rapid Gravity Sand Filter

RO – Reverse Osmosis

SBR – Sequencing Batch Reactor

sUF – Submerged Ultrafiltration

TDS – Total Dissolved Solids

TOC – Total Organic Carbon

TSS – Total Suspended Solids

UF – Ultrafiltration

UV – Ultraviolet Light

WHO – World Health Organization

WWTP – Wastewater Treatment Plant

1 Introduction

Water is a valuable resource and with an increase in areas experiencing permanent or reoccurring droughts, a sustainable approach to using water becomes more and more important. Although Sweden is not defined as a water scarce country, the past years have shown that it is not inviolable. Dry periods during the summer have caused for new solutions to be explored, of how water is being handled.

As of now, drinking water is being produced by treating surface- and groundwater to the required quality. After application, the produced wastewater is being treated within a system which is designed to treat it to a quality which protects the environment against over-fertilization and other negative impacts.

Drinking water is used for many purposes, as in households to flush toilets, for washing machines and showers. Further it is applied for processes within industries and agriculture. As a lot of energy is being used to treat water to drinking water quality, it is not always used for applications requiring that level. The applications water is being used for in industries and the according required qualities are investigated within this report. Further, the qualities are being analyzed and researched to find out if these are reachable within the wastewater treatment plant. By achieving the required qualities, a more circular water consumption could be achieved, relieving the pressure on the provision of drinking water.

1.1 Aim

This thesis is aiming at providing a practical summary of the potentials to use treated municipal wastewater in Sweden in different applications. Mainly the industrial symbiosis between the wastewater treatment plants and industries is investigated, but also other water requiring activities as irrigation in agriculture. The aim of this thesis is summarized as follows:

- To identify an interest and investigate the potentials for the reuse of treated wastewater from different parties relevant to the participating water associations
- To summarize the available techniques in order to achieve the adequate quality of water for the identified enforcements, where also the microbial risks will be taken into account
- To give an estimation and comparison of costs for the treatment and distribution of wastewater to the required quality, as well as an investigation of the legal perspectives.

2 Literature Review

The reuse of treated wastewater is being practiced around the world, mainly in areas struggling with a sufficient water supply. Applications for agricultural and industrial reuse are employed as well as groundwater recharge. Some selected examples from Europe and Israel are shortly being presented below.

2.1 Examples from other countries

Europe has a large potential of reusing wastewater and depending on the region, this potential becomes a necessity. For example, does more than half of Portugal's area suffer from a water deficit. A large interest of water reuse is in the agricultural sector and currently, the reuse is mainly applied in small fractions within agriculture and road construction. The tourist region of Algarve in southern Portugal has several projects for reuse, for example to irrigate golf courses.

Spain has more than 150 projects within the reuse of wastewater. In Vitória, in northern Spain, treated wastewater is being used to irrigate high-value crops. Between 1995 and 2004, 35,000 m^3 were supplied daily for the irrigation of 3,500 ha. These numbers were both set to be doubled within the following years (Angelakis and Durham, 2006).

In 2001, an investigative tour was done with a delegation from Australia, to visit and learn about water reuse within horticulture in Israel and California. The investigation compared the different systems and prioritized features in each location. It was found that Israel does not produce a high-quality effluent from wastewater treatment plants (WWTP's), and thereby restricting the possibilities of reuse. Nevertheless, Israel has been using systems where soil-less culture is being applied, meaning that issues concerning the soil are being avoided. Different from the Israeli system are the schemes in Monterey and Northern Adelaide in Australia, where a high quality in effluent water is focused on, to provide a flexibility when producing a wide range of horticultural crops (Feutrill et al., 2001).

2.1.1 Germany

As of 2014, 2 % of the German agricultural area was irrigated with treated wastewater, with the reasoning of Germany being a water secure country. In 2008, the German government acknowledged the water accessibility as being secured, when taking global warming into account. It was though also stated, that regionally occurring droughts may cause conflicts in water usage interests and especially the dry summer of 2015 was evidence, that Germany does need to take droughts into account and act accordingly, to avoid harvesting deficits. Germany has an annual precipitation rate of 450-1000 mm, which compared to other countries is quite high. Under normal circumstances, the precipitation is sufficient during vegetation periods (Seis et al., 2016).

An example of water reuse is being applied by the Wastewater Association in Braunschweig, which is managing a reuse scheme for wastewater. Biologically treated wastewater from households is being used for the irrigation of maize, wheat, sugar beets and rye. During the vegetation period, sludge from the WWTP is being added to the wastewater for irrigation. During the winter season, the sludge is being dewatered and stored, in order to be used as fertilizer during the summer in the greater Braunschweig area. The crops which are being irrigated/treated with the wastewater/sludge are being used as food or for energy production, e.g. biogas. The conducted study focuses mainly on the institutional boundaries and costs, rather than on the biological and chemical issues (Maaß and Grundmann, 2018).

To apply treated wastewater for the irrigation of agriculture, requirements that need to be met were set to be of hygienic, materialistic and micropollutant eliminating nature (Seis et al., 2016).

Another example is EUWA, which is a company treating industrial wastewater to be used within the beverage industry, e.g. breweries and juice production. The water from the treatment plant has gone through a biological and chemical treatment and is later being treated with ultrafiltration (UF). For this method, membranes are being installed modularly onto racks. The ultrafiltration removes entrained particles and represents at the same time a microbiological barrier. This is followed by a disinfection step to protect the storage in the proceeding filtration tank. This filtrate is then being processed by reverse osmosis (RO) to reduce the high and sometimes changing salt content to the drinking water limit (EUWA, 2018).

2.1.2 The Netherlands

The Netherlands are not considered to be a water scarce country, although regional water scarcity and costs may lead to a necessary reuse of domestic wastewater. Per year, the water abstraction is 400 m^3 per capita and the annual availability of water per person is 6000 m^3. Artificial aquifer recharge is a main barrier against pathogenic micro-organisms for the production of potable water and these areas are usually situated close to the shore line, which results in long transport routes from the raw water source in the cities, and thereby high costs. The requirements on the drinking water quality are high and The Dutch Government demands a limit of 1 infection, caused by contaminants, per 10,000 people/year.

With 24 % of the land being situated below sea level, the risk of saltwater intrusion when extracting groundwater, is large. It is suggested to use groundwater as drinking water, while reclaimed wastewater or surface water will provide for industrial purposes. The reclaimed wastewater has an expected constant quality, which is preferred in industries, compared to surface water, where changes in quality may occur more frequently. When comparing treated wastewater with sea water, the wastewater is more easily treated by RO, due to a lower salt content.

Dow Benelux B.V. in Terneuzen, a daughter company of The Dow Chemical Company, is a chemical company, with a daily water usage of 60,000 m^3. To produce the high-pressure boiler feed for the site, 7,500 m^3/d of wastewater from the Terneuzen community is being treated in an industrial water treatment plant. In the treatment plant, an integrated membrane system, where continuous microfiltration (MF) and a two stage RO system work to produce ultrapure water, is followed by a mix bed exchange, serving as a polishing step. The effluent from the WWTP has a total suspended solid (TSS) concentration of 1.8 mg/l, 0.5 mg/l of phosphorus and 3.5 mg/l of ammonium. Due to the concentration of 50 mg/l of chemical oxygen demand (COD), bio-fouling still occurs in the microfiltration and RO processes. Since the effluent is being used as boiler feed water, in which microbes do not survive because of the high temperature of 113 °C, the industrial process of Dow does not have higher requirements in water quality. The water is also preferable to sea water, which comes with a risk of corroding materials, resulting from the high salt concentration.

It has also been studied that a usage of reclaimed wastewater would be feasible in the agricultural sector. The Harnaschpolder WWTP was constructed in 2007 and has a capacity of

35,800 m^3/h. It is situated in the western, low lying part of The Netherlands and serves 1.3 million people. The effluent is being discharged, through a 2.5 km long pipe, into the North Sea and it has been discussed if this water could not instead be reused, due to the water scarcity in the region. Especially reusing the water for greenhouses in the area would be feasible as those contribute to the economical wealth in the region. A third of greenhouses in The Netherlands do not use soil to grow crops, the crops are instead being fixed within a substrate and are being fed by hydroponic solutions. This makes the soil aspect less and the conditions for the hydroponic substrate more relevant (Rietveld et al., 2011).

Rietveld et al., (2011) concluded that wastewater reuse in the industrial sector could be beneficial, especially as boiler feed, which is the largest water consuming section. The agricultural sector may also benefit from the reuse of treated wastewater, especially in greenhouses. Further studies are currently being conducted.

2.1.3 Belgium

Belgium is being considered as a water scarce country, due to the high density of population and in addition, the available natural water resources are low, approximately 820 m^3 per inhabitant and year. Guidelines were established in 2003 and since 2005, the reuse of water is a central part of the water resources management (Bixio et al., 2006).

The Veurne region is located in western Belgium, close to the French border. The Intermunicipal Water Company of the Veurne Region (IWVA) is responsible for providing drinking water as well as the wastewater treatment. The drinking water was for many years collected from a sand dune aquifer, it was though evaluated to be unsustainable, when the demand increased. To recharge the aquifer, effluent from the Wulpen WWTP was chosen as the water source. The IWVA region is considered as a water scarce region. Surface water is very limited, often brackish and only temporarily available, during the winter period. The recharge water has high quality requirements, since the aquifer is situated in a very sensitive environment. A RO system was implemented as a final treatment step, with a preceding UF membrane, to assure the water having accordingly low salt and nutrient contents. The influent to the tertiary treatment originates from municipal households and has undergone secondary treatment in the Wulpen WWTP. The study showed expected results for the infiltration water to the aquifer. The UF backwash water and RO concentrate are being discharged into the sea, with concentrations of nitrogen and phosphorus exceeding the requirements. Tests were conducted to investigate the possibilities of reducing these concentrations, the results are not covered within the report by Van Houtte and Verbauwhede, (2006).

2.1.4 France

In France, using wastewater to irrigate crops has been an applied method for almost a century. Especially around the region of Paris, this was the only way of eliminating the wastewater from the city until 1940. Since the early 1990s, local water deficits as well as the need to protect bathing waters and rivers from eutrophication resulted in a new interest in wastewater reuse. Since then, 30 projects for reuse have been conducted, 15 of those within agricultural irrigation, 9 for the irrigation of golf courses and 6 for the irrigation within cities. The main objectives with these projects are to overcome additional water stress due to decreasing rainfall, increasing tourism causing higher population numbers and the aim to reduce groundwater extraction, to also avoid seawater intrusion. To regulate the quality, French health authorities have set up guidelines, which basically follow the ones by the World Health Organization (WHO), with some exceptions. Additionally, every new project needs to be approved by the Ministry of Health and a continually monitoring is compulsory.

One of the largest reuse projects in Europe has been set up within the Clermont-Ferrand recycling scheme, where a 40 km long irrigation system is watering a 700 ha area of maize. To reuse industrial wastewater as cooling or process water after a substantial treatment, is also common in France (Bixio et al., 2006).

2.1.5 Israel

Israel is situated in a semi-arid region and with a nonsufficient water occurrence, the reuse of urban and industrial treated wastewater is highly relevant. Between 65-70 % of the treated water is being reused, mainly within the agricultural sector. This has been practiced since 1977 and according guidelines were established in 1978. The policy states that all treated wastewater should have the adequate quality, to be reused in agricultural irrigation for crops, vegetables and fruits, which should be able to be eaten raw and no effluent should be discharged into the sea (Feutrill et al., 2001; Icekson-Tal et al., 2003; Bixio et al., 2006).

The three largest reuse schemes are situated in central and northern Israel. Amongst these is the Dan Region WWTP, which has an inflow of 90 % domestic and 10 % industrial wastewater and treats the complete greater Tel Aviv metropolitan area. The catchment area is 220 km^2 and the treatment plant is designed for a 1.9 million population equivalent (PE), which includes the industrial input. The treated effluent is being led into recharge basins, which in their turn infiltrate the water into groundwater aquifers. In order to maintain aerobic conditions when recharging to the aquifer, a method where flooding is alternated with drying of the basins, is being adapted. The unsaturated zone of the aquifer is thereby contributing to the biological treatment of the water, where additionally ion-exchange, sedimentation and adsorption processes take place. The further below situated saturated zone also contributes, as viruses and bacteria are being destroyed, due to the long retention time. The treated water is being reused throughout Israel, up to 87 km distance from the infiltration basins, within agriculture (Icekson-Tal et al., 2003).

Israel's goal to reuse 100 % of the produced wastewater, is being worked towards by large research efforts and advances. To meet this goal, challenges such as the optimization of filtration and disinfection methods, saltwater intrusion into the aquifers when pumping for water and the monitoring in order to avoid fouling within the pipelines are in focus (Bixio et al., 2006).

2.1.6 United Kingdom

The United Kingdom is not considered as being water scarce, recent droughts have though had an effect on the usage of water and public as well as political awareness. Recycled wastewater has previously been led into rivers, to restore the flow and eventually contribute to the potable water usage. An example is the river Lee which in 1985 consisted of 60 % treated wastewater and provided North London with potable water. Similar projects have been done in the counties of Suffolk and Essex, where 40,000 m^3/day of water were discharged into the river and extracted further downstream to recharge the Hanningfield fresh water reservoir, which in its turn serves as a drinking water source (Paranychianakis et al., 2015).

A large project for wastewater reuse was conducted in London in 2000. The Millennium Dome, was for one year situated in eastern London and installed a wastewater reuse plant to treat greywater from the hand washing basins within, rainwater collected from the roof and groundwater from the aquifer situated below the Dome. The plant treated 500 m^3/day of treated grey and rainwater, which was being reused for non-potable purposes, to flush toilets and urinals on site. The project was initiated by Thames Water and the New Millennium Experience Company and it was presented as the first ‘in-building’ recycling plan. A biological aerated filter (BAF) followed by membranes was installed for the treatment of the greywater. These choices were based on the fact that water reused for toilet flushing needs to have a biochemical oxygen demand (BOD) content of 2 – 20 mg/l, and to keep within the frame, experiments were done, with synthetic wastewater having a BOD content of 59 mg/l. This resulted in the according treatment choices of a BAF filter and following membranes (Smith et al., 2000; Essays UK, 2003).

2.1.7 Denmark

Kalundborg Symbiosis is described as an organically-evolving project, since it combines the private and public sector. It started as a collaboration of a couple of entities and grew in size and scope over time. The mutual goal of water and waste resource reuse developed into further practices, resulting in a closed loop collaboration. The first collaboration was established in 1972 between Saint-Gobain Gyproc and Dansk Vedool (later becoming Statoil), when the flared-off gas from Vedool was reused to dry gypsum boards at Gyproc. The project expanded to 12 material exchanges by the end of the 1980’, with the municipality, Asnaes Power Station/DONG Energy and Novo Nordisk being additionally involved. In 2015, the Kalundborg Symbiosis Center involved 17 different companies exchanging resources via 30 projects. The projects are divided into categories, which are the disposal of waste, the supply of raw material, provision of services and the sale of a by-product (Branson, 2016; Valentine, 2016).

The system in Kalundborg includes water, as the wastewater and cooling water from a refinery are being used at the power plant. While the wastewater is employed for secondary purposes, the cooling water acts as feeding water for the boilers, which in their turn produce steam and electricity. The cooling water is also applied as input water within the desulfurization process. Kalundborg has a groundwater deficit, and the supplies have decreased, due to the industrial water consuming companies which expanded in size and water consumption. By optimizing the internal use and changing the source of water, from groundwater to surface water, improvements within the groundwater situation were made. Additionally, surface water was upgraded, to be treated to drinking water quality. These measures contributed to a diversified water supply system within the Kalundborg region, because of the close collaboration between several industries (Jacobsen, 2006).

2.1.8 Interreg 2 Seas

The 2 Seas Program is a EU-project between the four member states England, France, Belgium and The Netherlands with the objective to “develop an innovative knowledge and research based, sustainable and inclusive 2 Seas area where natural resources are protected and the green economy is promoted” (European Union, 2015). It is set to take place between 2014 and 2020 with an overall budget of 392 M€. Actions where developed, which include formulation, establishment, development, adoption, preparation of investment and the final investment. By acting on these, the specific objectives are worked towards, which are:

- To improve framework conditions for the delivery of innovation, in relation to smart specialization
- To increase the delivery of innovation in smart specialization sectors
- To increase the development of social innovation applications in order to make more efficient and effective local services to address the key societal challenges in the 2 Seas area
- To increase the adaption of low-carbon technologies and applications in sectors that have the potential for a high reduction in greenhouse gas emissions

- To improve the ecosystem-based capacity of 2 Seas stakeholders to climate change and its associated water-related effects
- To increase the adoption of new solutions for a more efficient use of natural resources and materials
- To increase the adoption of new circular economy solutions in the 2 Seas area (European Union, 2015).

Under the Interreg 2 Seas initiative, several projects are being worked on, such as the Nereus- and the F2AGRI projects.

Nereus

Nereus is a project, with a consortium of water companies, municipal organizations and research institutes, with the objective to increase the reuse of resources from wastewater. By improving the adaptation of technologies, both energy and water will be recovered from urban wastewater. Both demonstrational and institutional frameworks are being developed to not only implement resource recovering techniques but also to gain acceptance from the water consumers. To gain site specific information, feasibility studies were done providing the required data to install the techniques (Nereus, 2018c, 2018d).

A pilot plant is being built in Rotterdam, which will include the recovery and reuse of water, nutrients and energy. The collected municipal wastewater from an outer dyke area is first being stored in a buffer tank, where coarse materials settle, by positioning the supplying pipe at a high position. Before being pumped into the pilot, the wastewater passes a drum sieve at a rate of 2.5 m^3/h, where coarse particles are being removed. To remove particles, COD and phosphate from the wastewater, an electrocoagulation system is being used. In this process, iron and aluminum are added to the system to coagulate with these substances. The produced sludge is not being further processed on location, but options of fermentation and pyrolysis are being looked into in other plants (Nereus, 2018b).

Southern Water (England) has done a social study, where the acceptance from the public towards the reuse of treated wastewater was evaluated. The study was done in two steps with the first one being in-depth interviews with participants and the second was to interview 1000 consumers with computer assisted telephone interviews. The results showed high numbers in acceptation and understanding of water issues and their solutions (Southern Water, 2012).

In the residential area of the Nieuwe Dokken Gent in Belgium, is a pilot project by Nereus, where modern technologies are being used for the treatment of decentralized wastewater from households. The project is set to be in place by 2020 and by that time more than 90 % of the produced wastewater, 30,000 m^3, will be reused. The wastewater contains heat which will be retrieved, and the nutrients will be recycled as Nitrogen-Phosphorus-Potassium-fertilizer. The applied technologies to achieve the goals involve aerobic membrane bioreactors, which are used in the treatment of greywater as well as the effluent from the anaerobic treatment of the blackwater and kitchen waste. To recover the waste heat from the wastewater, a district heat pump is installed. Since the process chain between the wastewater source and treatment is small, a recovered heat performance with a coefficient of performance of more than 4-5 can be achieved, which covers one third of the total heat demand for sanitary water and central heating in the Nieuwe Dokken area (Nereus, 2018a).

F2AGRI

Interreg 2 Seas supports F2AGRI with 152 M€, for the development of solutions for the reuse of water within agriculture.

In Ardooie, situated in western Belgium, a 25 km long pipeline is being constructed underground, which will distribute treated wastewater from the vegetable processing company Ardo over 500 ha of agricultural land. This project with the participants of Flanders' FOOD, Howest, Inagro, Ghent University, VITO and Vlakwa has the aspiration to realize multi-sector projects for the agricultural and food industry (agri-food).

The company Ardo produces wastewater which is being purified and stored in a buffer basin since August 2018. The water volume is 150,000 m^3. The water will be pumped into the network via a neighboring pump house. The distribution will be done with 150 offtake points, with a pressure of 8 bar at each outlet point. The irrigation systems have to be connected to the respective hydrant. It was set to complete 11 km of pipeline in 2018 and 14 km in 2019.

By focusing on the development and demonstration of innovations in several fields, such as monitoring, sensors, energy management, automation, etc., and further stimulating innovation, this industry branch has been able to successfully join forces and since then approved 3 projects within the sustainable water use (Interreg, 2018).

2.1.9 Spain

The Life Wire Project started in 2013, was completed in 2017 and was co-funded by the Life Program of the European Commission. The main idea was to increase and boost the reuse of treated wastewater in industries, as an alternative to the usage of drinking water and to economic advantage and to protect the environment from exploitation of water resources. The demonstration site was set to El Baix Llobregat in Barcelona, which produces 300,000 m^3 of treated wastewater daily. The pre-existing treatment steps included coagulation, flocculation, MF (disc-filtration) and disinfection (UV-light). The proceeding prototype included ultrafiltration, carbon nanostructured material (CNM) and RO, each being able to operate individually and with a modifiable position. UF has the ability to reduce the turbidity with more than 80 % as well and shows a > 95 % reduction in microbiological parameters, although dissolved organic matter is only reduced by 15 %. The ceramic membranes in the UF treatment withstand intensive chemical cleanings and high pressures, without being damaged. It is also a dependable pretreatment for RO. Compared to UF, CNM provides a high removal rate of dissolved organic matter (25-90 %), but a low one in reduction of turbidity (10-40 %) and microbiological parameters. The RO treatment was situated as the final step of the pilot plant and is designed to allow dissolved salts separation, since the water has to fulfill strict requirements of salinity in order to be applied within industry. Since RO demands high amounts of energy (1-2 kWh/m^3), a well-functioning pre-treatment is essential. The prototype concluded, that the combination of CNM + RO was economically more feasible than UF + RO. The usage of UF or CNM meets the quality requirements for cleanings and reagents preparation and together with RO it would also be usable as process-, cooling- and boiler water. Although the operative costs are higher compared to the current treatment, it was considered as an alternative for the future (Life Wire, 2017).

3 Materials and Methods

3.1 Collaborations

This thesis is part of a project initiated by VA SYD to research the possibilities and limitations of reusing treated wastewater within industrial symbiosis in Sweden. A previous study by Persmark (2018) together with VA SYD investigated the four wastewater treatment plants Sjölunda, Ellinge, Källby and Södra Sandby and discovered an interest by industries, setting the basis for this thesis.

To create a Sweden-wide overview of possibilities in water reuse, seven other water associations participated in the project: Douglas Lumley (Gryaab), Tord Sonander and Liselotte Stålhandske (Hässleholms Vatten), Qing Zhao (Kalmar Vatten), Lars-Gunnar Johansson (Laholmsbuktens AV), Erika Lundström (Luleå Kommun), Hamse Kjerstadius (NSVA) and Henrik Nygren (Region Gotland). Each water association was responsible for the data collection in the respective regions and was free to conduct the interviews personally, via email or telephone.

The participating water associations represented the reference group for the project, together with representatives from industry (Sysav) and agriculture (The Federation of Swedish Farmers, LRF).

3.2 Interviews

The relevant industries to interview for the case of Sjölunda WWTP were chosen based on the annual drinking water consumption, and the proximity to Sjölunda.

The first contacts to the industries in Malmö, were established by the head of environment at VA SYD (Thomas Hulgaard-Person) to the head of environment at the respective industry. This was to make sure, that the appropriate person, having the needed knowledge of the industry would answer the questions and that the issue became anchored within the company. The industries interested in the project, provided according contacts.

To gain a sense of the industries, the interviews around Malmö were held in person, with some exceptions. This provided insight to the processes and further discussions.

The complete questionnaire (in Swedish) can be seen in Appendix 1, the prepared questions were divided into two categories, main and extra questions:

Main Questions:

- How much water is being used within the industry [m^3/year]?
- What applications is the water being used for? What quality does this water need to have?

Extra questions:

- Does the company reuse water internally at this moment? Does the company have plans to do so?
- What changes within the company can be expected over the next years? Are there plans to expand? Does the company expect challenges concerning water in the future?
- What regulations at the company need to be considered when reusing treated wastewater for the purposes stated previously?

3.3 Handling of results and demarcations

Since the objective was not to look at the companies per se, but to investigate general potentials to reuse treated wastewater, a categorization was done. This further grounds in the fact that the amounts of water used by the industries are relative to each case, meaning that small amounts in certain locations can have the same impact as large amounts somewhere else. It was therefore seen best, to anonymize the interviewed industries.

The water applications where divided into 7 categories, including WWTP's. That category was included, as drinking water is being used in processes and it should be investigated if the required water quality can be reached to use treated wastewater instead.

To gain knowledge about the identified categories and the according water qualities, a literature study was conducted. The processes to reach the water qualities were chosen as they were either proposed within the literature or had relevance concerning certain substances within the wastewater. Previous studies by Baresel et al., (2015) and the Secretary-General of the European Commission (2018a) about reusing treated wastewater in industry and agriculture have served as important references in this thesis. As this work focuses primarily on industry and agriculture, certain methods to treat wastewater have not been included, since the time did not allow for it. It should though be kept in mind, that further possibilities to reach the required water qualities exist and should be looked further into. The category of agriculture was researched solely through literature and not interviews, as the assumption was made that the water is used as irrigation. The treated wastewater is produced at municipal WWTP's and the reuse does not refer to industrial wastewater.

The legal aspects and costs were researched within literature and with explanatory help and guidance from VA SYD.

As drinking water is a large water sector, this thesis concentrates on the application within industries and agriculture. The direct drinking water usage in households was not investigated, since the requirements are very stringent, and it should rather be discussed if the discharge from the WWTP should be directly transported to the drinking water plant. Additionally, groundwater recharge is not further mentioned, as this is outside of the scope for this project.

The creation of the overview of previous studies was established together with Kalmar Vatten, since they are involved in a similar project, financed by Vinova, and being conducted simultaneously as this thesis. To exchange information and avoid overlaps in information, it was decided to collaborate.

4 Technical Background

The conventional WWTP is designed to treat water from different sources. Wastewater from households can be divided into two categories, where blackwater is the water from toilets and greywater all else wastewater, as showers, washing machines and sinks. To transport the water to the treatment plant, it is led through pipes, which in Sweden typically are designed to be combined, meaning that sewage and stormwater are transported through the same pipes, and thereby mixed. Separated systems are becoming more frequent, when updating or reconstructing pipe systems.

When the wastewater arrives at the WWTP, it is being led through several processes, which treat the water to a quality, dischargeable into nearby nature. The processes include screening, sedimentation, biological- and chemical treatment. To meet the requirements for discharged water, limiting amounts of nitrogen, phosphorus and organic matter, determine the design of the treatment plant, though additional substances can be found in the water. The WWTP is not designed to eliminate these sometimes dangerous chemicals, although a reduction or elimination can occur. To target these compounds, a tertiary treatment step could be installed, in addition to the already existing (Benstöm et al., 2016; Roccaro, 2018). It is expected that discharge limits for e.g. pharmaceuticals will be introduced in the future, which would result in WWTP's having to install further processes.

Treatment steps can differ in titling. The primary and secondary treatment steps in WWTP's are usually the mechanical, biological and could involve a chemical process. By adding further steps, differences in naming can occur, e.g. tertiary-, quaternary- or fourth treatment step. In this report, the tertiary treatment step describes a process added, after the conventional, already existing processes, at the WWTP.

The tertiary treatment can consist of different processes, acting on their own or in combination with other methods. Usually placed at the end of the treatment plant, the tertiary process is designed to remove targeted compounds, which could be pharmaceuticals, micro plastic, compounds of emerging concern (CEC's), chemicals for the protection of plants and materials and other toxic compounds. Processes to target these, are granular activated carbon, powdered activated carbon, biological active filter, ultrafiltration, ozonation, chlorination (disinfection) and ultraviolet light (disinfection), etc. RO and membrane filtration can also be considered, though do the enclosed costs connected with the energy supply often exceed the limitations (Baresel et al., 2015). Current Swedish WWTP's are rarely constructed with a tertiary treatment step to remove the targeted compounds, it is more common to have a polishing step, before discharging the water.

4.1 Granular Activated Carbon

Granular activated carbon (GAC) has been applied in the drinking water treatment industry for centuries but has also found its purpose in wastewater treatment and groundwater remediation. Its high adsorption area contributes to an accumulation of biofilm, which in its turn adsorbs organic molecules and molecules performing additional biological degradation. This process is called biological activated carbon (BAC) and it is a result of a biologically saturated GAC filter. Replacing parts of the BAC-filter with new GAC, results in biological functioning as well as new adsorption capacity. The sludge production for this technology is small, since the GAC-filter is replaced after a certain amount of time and re-activated. Different from other techniques, where a time period is set as a lifetime of a treatment, the deciding unit for GAC-filters is measured in volume of water per volume of GAC-filter [m^3_{water}/m^3_{GAC}] (Mulder, 2015; Benstöm et al., 2016; Moona et al., 2018).

Activated carbon is produced from materials as coconut shell, lignite, wood and petroleum residues, though the most common is volatile bituminous coal. To achieve a high effectiveness, it is activated by being exposed to high temperatures (1200 °C) and steam. With an average diameter of 0.5-4.0 mm, activated carbon possesses a large contact area, between 800-1200 m^2/g, which is its main advantage. The capacity to which a GAC-filter can absorb nutrients, is dependent on the type of active carbon, its production (carbonization) and the thermal activation (Benstöm et al., 2016).

Important factors when planning for a GAC-filter are dissolved organic carbon (DOC) and particulate organic matter. DOC is an expression for organic matter which can pass through a membrane with a pore size of 0.45 µm and it has a tendency of competing with the micropollutants for contact space of the filter, while particulate organic matter poses a risk of clogging it. Another important factor is the empty bed contact time (EBCT), which describes the residence time of the wastewater in an empty reactor, normally measured in minutes (Worch, 2012; Mulder, 2015; Benstöm et al., 2016).

The differing properties of the toxic compounds, for example, their size and charge, affects the adsorbing possibilities of the GAC-filter. An important factor is the competition for free adsorption spaces within a multicomponent system as wastewater. Compounds with a higher adsorbability could suppress those with a lower one, which during a longer time period could result in higher concentrations of the compounds with a lower adsorbability in the effluent, compared to the influent (Benstöm et al., 2016).

An advantage of GAC-filters is their ability to be ‘recycled’. When the filter has reached its maximum, it can be replaced and reactivated. Reactivation is usually done by the manufacturer and not within the WWTP. A complete reactivation is very important, since the residence time of the filter in the reactor can be immensely decreased otherwise. An over-reactivation should be avoided, where micropores can be burnt off, which leads to an increase of adsorption capacity for larger molecules and a decrease for small molecules (Worch, 2012; Mulder, 2015).

4.2 Powdered Activated Carbon

Powdered activated carbon (PAC) has, compared to a GAC-filter a larger contact area, due to its smaller particle size. A large advantage of PAC is, that it can be applied as a tertiary treatment at the end of the plant, but also during other treatment steps, for example in the biological stage, where it is added into an activated sludge process. With a high concentration of biomass at the granular surface, a further degradation of substances which were initially adsorbed is initiated. PAC is continuously undergoing a bio-regeneration, where the adsorbed species are biologically being degraded.

A disadvantage is the PAC being filtered out and remaining within the sludge. This depends on the position of retrieval of sludge and the use of PAC. The PAC will not likely be possible to separate from the sludge, for a reuse. The design of the WWTP is therefore decisive. As in GAC filters, the removal efficiency is also mainly controlled by DOC (Worch, 2012; Mulder, 2015).

4.3 Ultraviolet light

Ultraviolet light (UV) is a disinfection process, which is supposed to hinder the spread of waterborne diseases into the environment and further downstream applications. UV treatment does not produce any disinfection by-products (DBP's) and compared to ozonation, it requires a shorter exposure time for an effective disinfection. The main factors, affecting the UV process and its design are UV transmission, suspended solids, the flowrate, hardness of the water and the UV dose. Since the UV transmission is directly related to the TSS and the particle size, the disinfection performance is enhanced by a preceding filtration process. The UV-intensity, measured by the occurring UV light, correlates to the UV transmission; higher intensities are a result of a higher UV transmission. The dose at which UV needs to be provided is calculated by multiplying the UV intensity with the exposure time. To achieve disinfection of wastewater for reuse and discharge, microorganisms are not to be shielded from the UV light (Uslu et al., 2016; USEPA, 2018).

There are several types of UV lamps of the types low-pressure low output, low-pressure high output and medium pressure, out of which the low-pressure low output lamp is the most common, operating at a wavelength of 254 nm. Since the low-pressure low output lamp has a comparably low energy consumption, it is usually installed within the WWTP, where the outflow is discharged into surface waters. For plants with limiting space capacities, the medium pressure lamp would be more suitable, since its high output results in the use of fewer lamps. These lamps do though have a lower germicidal efficiency (USEPA, 2018).

It has been observed that UV light is ineffective for the elimination of antibiotic resistant E. coli (Sousa et al., 2017).

4.4 Advanced Oxidation Processes

The application of Advanced Oxidation Processes (AOP's) was first installed within the treatment of drinking water in the 1980s. Only later on were they found applicable for wastewater treatment as well. In an AOP, radicals are being formed, which can be either in the form of sulfate (SO_4^-) or hydroxyl (OH•). When added to the wastewater with an adequate quantity, these radicals have the ability to remove organic contaminants and inorganic compounds from the water. They also increase the biodegradability of the wastewater, which can be used in the pretreatment to a biological treatment. AOP's are usually not used as a disinfection method, caused by their very short half-life, which is in the range of microseconds. They are instead applied as a strong oxidizing agent, which deliberately destroys pollutants in the wastewater, into less or even non-harmful products. To determine and compare the oxidation potential of the different radicals, it is being measured with a saturated calomel electrode in Volt (V) (Deng and Zhao, 2015).

4.4.1 Ozonation

Ozone is a very reactive gas, which has a restricted solubility in water. When ozone is added to the wastewater, micropollutants are not being removed, but oxidized into other compounds, which remain in the effluent. The reaction can be caused directly, where molecular ozone oxidizes the micropollutants, or indirectly, when it is done by hydroxyl radicals. The hydroxyl radicals are being formed by the self-decomposition of ozone and have a much higher pollutant removal rate compared to the direct reaction. This is due to the indirect reaction, by hydroxyl radicals, having a non-selective attack on compounds, where molecular ozone is much more selective. The indirect reactions can also be called hydroxyl radical pathway, explained by the main reactive species being the hydroxyl radical. These radicals are formed by a series of chain reactions, involving an initiating, propagation and termination reaction. Since the reaction of the ozone molecule and the hydroxyl ion is relatively slow, the initiating step normally becomes the limiting step. It does though depend on further factors, where alkaline conditions for example promote a much faster reaction between the hydroperoxide ion (HO_2^-) and the ozone molecule, resulting in the generation of a hydroperoxyl radical, $HO_2^\bullet$. The hydroperoxyl radical is yet decomposed into another radical and a chain reaction propagates (Beltrán and Rey, 2018; Ikehata and Li, 2018).

There are different categories into which the aqueous molecular ozone reactions can be divided. The oxidation-reduction reaction is an oxygen transfer, moving from the ozone to the reactant. This reaction takes place, due to the high redox potential of ozone, which enables the oxidation of compounds such as iron, manganese, bromide and sulfides. The other reactions are dipolar cycloaddition reactions and electrophilic substitution reactions (Ikehata and Li, 2018).

The dosage of ozone is highly dependent on DOC although inorganic compounds, e.g. nitrite, can also influence the ozone demand. Since the treatment does not eliminate but produce intermediates, their new toxicity needs to be evaluated. A complete reduction of toxic compounds can therefore not be guaranteed; it has though been established that the biodegradability of the intermediates increases with ozonation (Mulder, 2015; Papageorgiou et al., 2017).

Due to its instability, ozone has to be produced at the WWTP. When it is being mixed into the wastewater, the basin needs to be airtight and a treatment for the produced emissions needs to be in place, since the ozone is still in gaseous form, it has to be treated accordingly. Proceeding the basin, a filter, e.g. sand or active carbon, has to be installed, to remove the produced biodegradable matter (Mulder, 2015).

4.4.2 UV-Hydrogen Peroxide (UV/H_2O_2)

The objective of the UV/ H_2O_2-process is to create hydroxyl radicals (•OH), which is an effective oxidant and a highly reactive species. By the addition of hydrogen peroxide (H_2O_2) into a system with UV-light, the hydroxyl radicals are generated.

$$H_2O_2 \overset{hv}{\rightarrow} 2 \bullet OH \tag{4-1}$$

$$H_2O_2 + \bullet OH \rightarrow H_2O + HO_2 \bullet \tag{4-2}$$

$$HO_2 \bullet + H_2O_2 \rightarrow H_2O + O_2 + \bullet OH \tag{4-3}$$

$$\bullet OH + \bullet OH \rightarrow H_2O_2 \tag{4-4}$$

$$\bullet OH + HO_2 \bullet \rightarrow H_2O + O_2 \tag{4-5}$$

$$HO_2 \bullet + HO_2 \bullet \rightarrow H_2O_2 + O_2 \tag{4-6}$$

Caused by the Haber-Weiss radical chain mechanism (1932), the photoinduced decomposition (4-1) acts as the starting point for a following sequence of reactions. The propagation steps (4-

2) and (4-3) produce a net reaction, correlating to the production of water and molecular oxygen by the decomposition of hydrogen peroxide (4-4), (4-5) and (4-6).

To design the system, the UV lamp potential has to be counterbalanced for hydroxyl radical production, energy usage, effective UV radiation output, life span and costs, in order to find the most appropriate lamp. The system can be installed into a batch reactor, a continuously stirred tank reactor (CSTR) or a tubular reactor. The batch reactor is characterized by the change of composition in the reactor content over time. When an equilibrium of the reaction has been reached, the content in the reactor is removed and replaced by a new batch. The CSTR is ideally perfectly mixed, with a homogenous reaction content, with the process only stopped if necessary. The flow through the reactor is characterized by the reactants present in the inflow and the products in the outflow. The tubular reactor, similarly to the CSTR, is also characterized by the continuous through-flow. It is designed as a plug flow, comparable to a series of batch reactors, where the content to be processed is being transferred from one to the next. The reactant mixture is received by the first reactor, from where it is moved on to the second reactor after a certain amount of time. By the time the mixture reaches the last reactor, it has been transformed into the final product.

To undergo a UV/H_2O_2 treatment, the inflow to the process should have low turbidity values, since the matter causing it (sand, clay, silt) has a large effect on the optical properties of the water to be treated, which affects the UV radiation transmission. DOC does similarly have an effect on the transmission, as it reduces the intensity of the UV radiation, which is important to the oxidation process. To maintain the •OH radical, bicarbonates and carbonates should be eliminated prior to the process, since these can absorb the UV radiation (Mierzwa et al., 2018).

4.4.3 Ozone –Hydrogen Peroxide

To control the taste and odor of water, the ozone-hydrogen peroxide process (O_2/H_2O_2) presents a low-cost alternative to the UV/H_2O_2 treatment as well as having a higher removal rate for some trace chemical constituents (USEPA, 2018).

The decomposition of ozone is accelerated by the addition of hydrogen peroxide, which leads to a higher concentration in hydroxyl radicals. To achieve the optimum stoichiometry, 2 mol of ozone per mol of hydrogen peroxide need to be added to the process. The contaminant degradation takes place as an indirect reaction with the hydroxyl radicals, unless the targeted contaminant possesses a very high reactivity against the molecular ozone (Ikehata and Li, 2018).

4.5 Membranes

There are two different configurations in which the membrane flow can function. With a direct flow, all of the water to be treated, is led through the membrane. In the cross-flow, a portion of the water, usually 90 – 95 % is being led through the membrane, while the remaining portion is used as a sort of ‘cleanser’ of the membrane, being led along the feed side, to remove the solids which were filtered out of the water, by the membrane (Voutchkov, 2013).

Membranes have many advantages. For instance, membranes can be tuned according to the required outcome. They can also be operated at low temperatures as well as pressures, as the hydrostatic force is the main factor. The material out of which a membrane is made, can vary, depending on the wanted robustness of the process. As membranes usually are constructed in a modular fashion, their exchange and/or maintenance is kept simple, as well as the scale-ups and downs, since modules can be added or removed. Membranes do though also pose some challenges, as for example the cleaning, which can be difficult or even impossible. Fouling can cause clogging, which reduces the performance capacity. Membrane degradation, which could be caused by fouling may lead to the need of a membrane replacement (Martins et al., 2017).

To avoid fouling and the proceeding clogging of a membrane, it needs to be backwashed. This can be done as needed, or in a set interval. Usually, backwashing occurs every 20-120 minutes and lasts for 30-60 seconds. The backwashing system can also be initiated when a certain trans-membrane pressure reaches a maximum threshold. The trans-membrane pressure is an expression for the difference between the feed pressure and the filtrate pressure of the pretreatment system, and it is directly correlated to the membrane flux, as it is the main pressure which drives the flow through the membrane (Voutchkov, 2013).

The backwash can be done with either water or air, or a combination of the two, but cleaning chemicals are not necessary to remove particulates. To remove accumulated organic deposits and biofilm, chemically enhanced backwash is required, which is normally required once or twice per day. Since membranes have a substantially smaller capacity to store micropollutants and other solids, compared to activated carbon, backwashing is a very important part of a membrane system. Membranes need to be backwashed of an average 30-50 more times compared to granular media filter cells (Voutchkov, 2013).

4.5.1 Reverse Osmosis

Reverse Osmosis (RO) is a pressurized membrane system, in which a membrane is able to separate water from solutes such as salts or low molecular weight organic materials. The pressure is necessary to counteract the natural osmosis force, where water with a lower concentration of a substance, moves towards water with a higher concentration. RO is primarily used for desalination but has also found its purpose in drinking- and wastewater treatment, because of its ability of high removal rates of micropollutants. The particle size which RO is able to remove ranges between 0.0001-0.001 µm, which includes viruses, bacteria and other micropollutants. Due to the high energy demand, RO is a costly alternative for micropollutant removal (Demeuse, 2009).

Different models for RO exist, as for example the S-D model, which distinguishing feature is the non-requirement of pores in the membrane. The model can be described in 3 steps, where the membrane first absorbs the product, for example a solvent (water) and a solute (salt). Within the membrane, the diffusion takes place and finally, the desorption from the membrane. Acting as the driving force is the chemical potential gradient from the upstream to the downstream side of the membrane (Ismail et al., 2019a).

The pretreatment for RO needs to be extensive. Screens to remove coarse and fine sands and micro-screens which filter out fine particulates and sharp objects which could harm the membrane, need to be in place (Voutchkov, 2013).

4.5.2 Ultra-, Nano- and Micro-Filtration

Ultrafiltration (UF) is not very different from RO, except for the pore size of the membrane, which is normally between 0.01-0.02 µm, and thereby the size of the particles, which the membrane can retain. UF uses the hydrostatic pressure to force the liquid through the membrane. UF is usually applied within research and industries to purify and concentrate macromolecules, for example protein solutions (Demeuse, 2009; Voutchkov, 2013).

UF membranes can benefit from PAC being added, since the PAC adsorbs dissolved low-molecular weight organic substances, which could cause fouling in a membrane. Nanofiltration (NF) does already have the ability to remove such small dissolved particles, using PAC additionally would also in this case reduce fouling on the membrane and a reduction of abrasion can be expected, which reduces the coating of the membrane surface. The combination of PAC together with a membrane technique, is called a hybrid process (Worch, 2012).

Another membrane process is microfiltration (MF), which is distinguished by the pore size being 0.04-0.1 µm (Voutchkov, 2013).

The fouling within UF, NF or MF treatment processes is explained by micropores plugging and a cake formation on the surface. In RO processes, the fouling is only caused by a cake formation on the surface of the membrane and not by the micropores plugging. Small particles create a substantially higher resistance on the filter cake than big particulates, leading to a more pronounced membrane fouling than detected by tests, such as the silt density index, which is a measure for the particulate fouling potential of saline source water (Voutchkov, 2013).

4.6 Trains

The combination of several tertiary treatment steps together with disinfection steps can result in reclamation technology trains, which are designed to achieve a higher water quality. When different treatment steps supplement each other, a higher quality of water can be expected, compared to the result achieved by the individual techniques. Trains can differ, depending on the wanted outcome. The requirements for industrial water usage are rarely the same as the ones for water in agricultural use and will be further presented in the results (Baresel et al., 2015).

5 Results

5.1 Interviews

The results from the interviews with the industries have been divided into seven categories:

- Cooling Water
- Recreational Purposes
- Cleaning of Vehicles
- Boiler Water
- Food Industry and Process Water
- Wastewater Treatment Plants
- Agriculture

The category wastewater treatment plant was added, not only for industries having their own treatment plants, but for the water-associations, also using water for processes. Since the interviews were done in different manners, depending on the water-organization, different answers were gathered. Many industries supplied one number for water consumption, but several applications, not stating how much water is going to what application. The categorization is the result of a subjective assessment of the gathered information.

In total out of all contacted industries, 38 replied with an interest and provided details about water applications and flows. Not all industries provided the same information, but the total water consumption which would be open to be replaced by treated wastewater, if it meets the quality requirements, was approximately 3.5 million m^3 annually, scattered over Sweden.

5.2 Wastewater Discharge Quality

Table 1 on the following page is a summary of the main information of each WWTP of the participating water associations. It shows the main features, the number of population equivalent (PE) it is designed for (alternatively the number of PE connected), the inflow and outflow, and the average concentrations of biological oxygen demand (BOD), nitrogen, phosphorus, COD and TSS in the discharge. The outflow was included, to show that it is not always the same as the inflow. The average values in the discharge were calculated to be 4.9 mg/l of BOD, 13.4 mg/l of total nitrogen, 0.2 mg/l of total phosphorus and 34.9 mg/l of COD. The maximum value for BOD is 9.7 mg/l, for total nitrogen 36 mg/l, for total phosphorus 0.3 mg/l and for COD 49 mg/l.

Metals which could be present in the outflow are e.g. mercury, cadmium, lead, nickel, chrome, copper and zinc for the values where though not always stated in the environmental reports.

Detailed information about further discharge qualities was obtained for Sjölunda WWTP, where an average of 310 mg/l of chloride was added to the wastewater in the WWTP between 2017 and 2018 (VA SYD, 2018a). In 2015, 57 mg/l of calcium, 11.9 mg/l of magnesium, total organic carbon (TOC) of 10.5 mg/l and DOC of 10.2 mg/l were measured in the effluent from the WWTP (VA SYD, 2018b).

Table 1 – WWTP's of the participating water associations and information about flows, recipient and outflowing BOD, Tot-N, Tot-P, COD and TSS (Kalmar WWTP, 2015; Laholmsbuktens VA, 2015; Hässleholms Vatten, 2017a, 2017b, NSVA, 2017f, 2017g, 2017h, 2017i, Region Gotland, 2017a, 2017b, 2017c; VA SYD, 2017; Wellsjö, 2017; Hässleholms Vatten, 2017c; NSVA, 2017a, 2017b, 2017c, 2017d, 2017e).

Water Association	**WWTP**	**PE**	**Inflow [m^3/d]**	**Outflow**						
				Recipient	**Q [m^3/d]**	**BOD [mg/l]**	**Tot-N [mg/l]**	**Tot-P [mg/l]**	**COD [mg/l]**	**TSS [mg/l]**
VA SYD	Sjölunda	550 000	142 560	Öresund	N.A.	9	13	0.3	46	N.A.
Gryaab	Ryaverket	763.064 (connected)	378 158	Göta älvs and Nordre älvs estuary	N.A.	7.6	7.2	0.22	41	2.4
Kalmar Vatten	Kalmar	100 000	16 192	Kalmarsund	16 192	3.7	12.7	0.14	43	6.3
Laholmsbuktens VA	Västra Strandens	143 000	32 787	Laholmsbukten	32 787	2.8	6	0.29	N.A.	N.A.
Hässleholm	Hästveda ARV	3 400	691	Lillasjön	691	4.7	18	0.11	26	N.A.
Hässleholm	Vinslöv	5 450	691	Vinnö å	691	9.7	36	0.26	49	N.A.
Hässleholm	Vittsjö	2 150	636	Emmaljungaån	326	1.6	9.2	0.06	40	N.A.
NSVA	Ekebro	14 300	4 000	Bjuvbäcken	4 000	6	10.8	0.16	N.A.	N.A.
NSVA	Ekeby	3500 (connected)	1 510	Bökebergsbäcken	1 409	7.3	18.7	0.13	N.A.	N.A.
NSVA	Kågeröd	1494 (connected) + 875 PE industry	2 400	Vegeå	N.A.	3.1	10.6	0.2	N.A.	N.A.
NSVA	Kvidinge	2 400	329	Rönne å	329	8	27	0.31	N.A.	N.A.
NSVA	Lundåkra	38 600	19000	Öresund	N.A.	3.3	7.4	0.24	N.A.	N.A.
NSVA	Nyvång	28 000	7 500	Humlebäcken	N.A.	3.1	10.6	0.23	N.A.	N.A.
NSVA	Öresundsverket	54 208	125 000	Öresund	54 208	2.1	8.7	0.35	16.5	N.A.
NSVA	Röstånga	773 (connected)	500	Lilla Bäljane å	N.A.	3.4	15.9	0.2	17.4	N.A.
NSVA	Svalöv	3780 (connected)	1 250	Svalövsbäcken	N.A.	4.6	11.4	0.07	N.A.	N.A.
NSVA	Torekov	13000 (connected)	5 400	Skälderviken	N.A.	3.8	8.2	0.13	N.A.	N.A.
Gotland	Klintehamn	10000 designed for (normally max 4500)	3 120	Baltic Sea	3 112	6	23 597 kg/year	0.15	410 804 kg in 2017	N.A.
Gotland	Slite	1 900	1536.2	Baltic Sea	1 536	4.2	13 111 kg/year	0.22	179 188 kg in 2017	N.A.
Gotland	Visby	60 000	9 072	Baltic Sea	9 065	3.9	9.8	0.19	2 226 666 kg in 2017	N.A.
Luleå	Uddebo	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

Baresel et al., (2015) propose required main effluent qualities as monthly average for the reuse of wastewater in agriculture and industry. The numbers shown in Table 2 are based on a pilot system at Henriksdal WWTP in Stockholm, focusing on the removal of e-coli, helminth ova eggs, viruses, TSS, total dissolved solids (TDS), turbidity, BOD_5, nitrogen, phosphorus and color.

Table 2 – Quality requirements for the reuse of wastewater in industries and agriculture and the range and average values for the participating WWTP's (Baresel et al., 2015).

Parameter	**Industry**	**Agriculture**	**Range in discharge from participating WWTP's**	**Average in discharge from participating WWTP's**
BOD_5 [mg/l]	< 5	< 8	1.6 – 9.7	4.9
COD [mg/l]	< 30	< 40	16.5 - 49	49
Tot-N [mg/l]	10	20	6 - 36	13.4
Tot-P [mg/l]	1	2	0.06 – 0.35	0.2
TSS [mg/l]	2	5	2.4 – 6.3	4.4

It should be noted that the numbers in Table 2 are average results. Different regions might require more stringent qualities of the water, while others are more tolerable to substances remaining in treated wastewater. Additionally, the individual water applications in industries, may differ to the proposed ones in Table 2, which has to be kept in mind. To target pharmaceutical residues in the effluent could also become relevant for e.g. recreational purposes. The criteria distinguish between acute and chronic effects of the residues. The acute describing the injury to an organism within 24-96 hours, while the chronic defines the continuous exposure of an organism over a longer period of time, more than 96 hours (Baresel et al., 2015). Pharmaceuticals are not within the scope of this thesis, but should be kept in mind for future research in wastewater reuse.

5.3 Water employment

The identified categories to reuse treated wastewater in industries, come with individual water quality requirements, described in the following chapters. The examples for applications apply to the results found in this work and other additional applications may exist in other industries.

5.3.1 Cooling water

Cooling water is used in several industries within the manufacturing of products, food-production, gas-production, powder production and in laboratories.

There are two main types of cooling water systems. In the 'once through cooling water system', water passes through heat exchangers, without decreasing or increasing in volume. The 'recirculating evaporative cooling water system' describes the transfer of process heat, which is first being adsorbed by the water, in order to be transferred by evaporation. The circulation of this water causes losses by the evaporation, which are being replaced by makeup water (Sharma and Sanghi, 2013).

The two strategies to employ cooling water differ in water consumption. While the closed looped process uses high amounts of water, the water is normally extracted and discharged into the same recipient. A closed looped system requires small amounts to operate, the losses which are being replaced with makeup water, will though not be returned to the recipient. While the once through cooling process may have a withdrawal rate of 76,000 – 190,000 liters/MWh and a water consumption of 1,000 liters/MWh, the closed looped system has a withdrawal rate of 2000-2300 liters/MWh with a consumption of 2000 liters/MWh (Kohli and Frenken, 2011).

Cooling water does not have to be drinking water quality, the amount of particles and substances within it, can though have a large effect on the efficiency, which is expressed by the heat transfer coefficient (Xu et al., 2016).

Engineers Edge, (2019) describes the heat transfer coefficient as "the proportionality coefficient between the heat flux and the thermodynamic driving force for the flow of heat (i.e., the temperature difference, ΔT)" and it is being measured in W/m^2K. The transfer coefficient is sensitive to fouling within the pipe, and only 0.25 mm thickness of fouling can have a decrease of the coefficient of 31.2 %, causing for losses. Fouling can be caused by mineral salts, organic particles or microbes which are influenced by the operation conditions, the quality of the water and the characteristics of the heat exchanger (Xu et al., 2016).

The water and system can further be affected by the hardness of the water, which could contribute to scaling. Calcium salts contribute to inverse solubility, which means that the precipitation increases with water temperature. Magnesium can together with high silica levels result in a magnesium-silicate scale within the heat exchangers. Except for acting as a nutrient for biofilm, phosphate has the ability to provide corrosion protection, when present with less than 4 mg/l and a pH between 7-7.5. This is explained by phosphate being an anionic inhibitor. If though present with more than 20 mg/l, and more than 1000 mg/l of calcium, there is a risk for calcium-phosphate scaling. If nitrates and/or nitrites are present with more than 300 mg/l, they are able to provide mild steel corrosion control and can contribute to a reduction in stainless steel cracking (San Diego Water Authority, 2009).

5.3.2 Recreational Purposes

The usage of water for recreational purposes has a broad spectrum. The categorization includes irrigation of gardens of housing companies and of football fields. Leaking pond-systems, currently being filled up with drinking water might use treated wastewater instead. Harbor basins, in risk of freezing during the winters could use treated wastewater, to prevent this from happening. The focus is thereby rather on the temperature of the wastewater discharge, instead on the amount of water. The cleaning of streets within cities as well as pipes transporting water was also suggested to be done, with water not being of drinking water quality.

Baresel et al., (2015a) suggest including recreational purposes under the broader spectrum of agricultural reuse, including the usage of water in parks, irrigation of landscapes and golf courses.

In 1997, the World Health Organization and the United Nations Environment Programme segregated recreational water reuse from agricultural, where emphasis was being put on the degree of body contact of the water and the recipient. For applications with aesthetic priority, the amount of nutrients within the water is important, to avoid for example eutrophication (Helmer and Hespanhol, 1997).

The Urban Waste Water Directive states that “Wastewater discharged in ‘sensitive areas’ (vulnerable to the effects of nutrient inputs) are subject to stringent requirements concerning effective treatment” (Naturvårdsverket, 2008) and, since this category of water usage will be in direct contact with valuable ecological areas and human interaction, the water quality needs to be secured. Although most applications, as dams and harbors are not designed to be used for bathing or other activities where people or animals would be at immediate risk of being in direct contact with the water, it has to be considered, that accidental consumption and/or skin contact with the water might occur. The aimed for quality of the water was therefor set to be bathing water in this report.

The EU Directive 2006/7/EC (2006) was issued for the protection of bathing waters and states several indicators to protect the environment. The cyanobacterial risks need to be closely monitored, as these may pose a risk to the health of the environment. Macro-algae and/or marine phytoplankton also need to be monitored and their acceptability and health risks as well as the adequate management need to be investigated. The bathing water also needs to be monitored for foreign pollution, as plastic, glass and rubber, though these should have been removed during the wastewater treatment (European Parliament and of the Council of European Union, 2006).

One example of reusing treated wastewater for recreational purposes is being done in Denmark. The project consists of discharging treated wastewater from the Mølleå WWTP to restore the quality of the recipients, which consisted of several following lakes, connected by Mølleå outside of Copenhagen. The WWTP receives wastewater from 4 municipalities and the discharge is being pumped 4 km to Kalvemosen. The plant is designed so that even with heavy rainfalls, all water reaching Kalvemosen is being treated to the right quality, and the rest is discharged into Öresund. Kalvemosen is the first link of water bodies being connected and flowing into Furesøen, an international natural and Natura 2000 area (Miljøministeriet Naturstyrelsen, 2012).

With the following discharge requirements, the project was successful:

- Tot-N: 2.5 mg/l (> 10 °C), 6.0 mg/l (< 10 °C)
- Tot-P: 0.04 mg/l
- pH: 7-8
- BOD_5: 3.5 mg/l
- Temperature: 25 °C
- Bacteria: requirements for bathing water conditions (Miljøministeriet Naturstyrelsen, 2012).

According to Heinicke and Eriksson, (2015), to be classified as an 'excellent' bathing water quality, the accepted amount of E. coli per 100 ml is 250, or 100 intestinal enterococci. The limit for the water body to be classified as 'good' is 500 E. coli per 100 ml and 200 enterococci. The bathing water directive does not state an acceptable risk to be infected with a gastrointestinal infection, but the risk lies at 3 % in water with 'excellent' quality and at 5 % in water with 'good' quality.

5.3.3 Cleaning of vehicles

To clean vehicles is a water consuming aspect in several different industries. City departments, hospitals, energy and food-producing companies, powder and petroleum manufacturing industries have stated an interest. This describes washing with additional chemicals, instead of washing without, which would rather be sorted under recreation.

The water quality required to clean vehicles may vary between industries and the individual objectives. In general, the water should not contain high level of minerals causing the hardness of the water, since this will prevent soap from lathering as well as it causes the buildup of scale. To avoid hard water, it should not contain more than 17.1 mg/l of calcium and magnesium. TDS should not exceed 50 mg/l, since these can cause spots on the vehicle as the water evaporates. The pH of the water should be close to 7, as higher values cause alkaline conditions, resulting in toxicity of the water and lower values cause acidic conditions, which can lead to corrosion, due to the high supply of hydrogen ions (Corbisiero, 2017).

To clean vehicles of different sizes, a high pressure system with a capacity of 20-180 bar is required (Kärcher, 2019). To operate a pressure system with more than 200 bar, a special education is needed, whereas pressure systems starting at 25 bar are under the regulations by the Swedish Work Environment Authority (Arbetarskyddsstyrelsen, 1994).

The high-pressure system may generate steam and foggy conditions. To increase the effect of the cleaning system, chemicals are sometimes added to the water, which together with disconnected particles can cause risks for the airways (Arbetarskyddsstyrelsen, 1994).

The risk of legionella is always present in water supply systems, non-regarding of the origin of the water and cannot be ruled out by the WWTP. Aerosols pose a risk in high pressure systems, since these might carry substances which are harmful to humans and the environment (Kunz and Bainczyk, 2014).

Aerosols are solid or liquid particles, within a large variety of size, which are suspended in a gas. They are normally not characterized in their individual state, but as a population, where important characteristics are the size distribution, chemical composition and the shape of the particles (Boucher, 2012).

If there are substances in the water which might cause allergic reactions, these have to be accordingly marked as Figure 1, showing that there is a risk for internal injuries of the airways to the left and a risk when breathing in, having skin contact or consumption of a product, shown to the right (European Parliament, 2008; Arbetsmiljöverket, 2018).

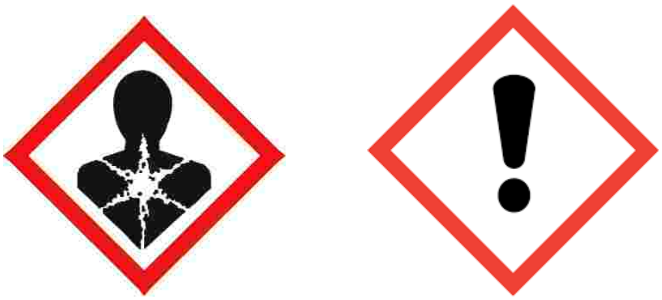


Figure 1 – Left: Pictogram to warn for caution of inhaling a substance. (European Parliament, 2008), right: Pictogram to warn for caution of inhaling, having skin contact or consumption of a substance (Arbetsmiljöverket, 2018).

5.3.4 Boiler Water

Product manufacturing, waste treatment and energy producing industries have stated that a boiler water process is in place, which uses drinking water, previously treated within a RO system at the industry. Industries have also been asked if an internal symbiosis would be relevant, since the resources often are in place already. One such example is to reuse process water from the industry, alternatively investigating what quality of water the RO process could treat, without excessive additional energy consumption and thereby costs. This way, treated wastewater or even water from earlier in the wastewater treatment process could be an alternative for the RO process producing boiler water.

A proposed boiler water quality was established by Suárez et al., (2015), which states that a pH value of 7-10, conductivity of < 40 µS/cm, COD < 10 mg O_2/l, TOC < 4 mg O_2/l, BOD_5 1-50 mg O_2/l, $Ca^{2+} < 0.4$ mg/l and TSS of 0.5 - 10 mg/l presents the water quality, satisfying the boiler requirements.

5.3.5 Food Industry and Process Water

The food industry comes with strict regulations, depending on the product. What type of food and its processing conditions play an important role, as does the preparation method, being the final step within the household (Barbera and Gurnari, 2018).

Several food industries have participated to this report, with a strong motivation for alternatives in water usage. Since the used water is mostly in direct contact with the product with drinking water quality requirements, they will not be further discussed in this report. Although WWTP's have the ability to treat wastewater to a high standard, this comes though with high costs and was not seen as relevant in this report. Similarly, industries with a sensitive production, where the water quality may have a direct influence on the product, will not be further investigated. To treat the water at the WWTP to an individual standard, was not judged as being feasible as part of this project. Waste treatment sites, energy production and powder production are industries, which use water in processes, where the product is in direct contact with the used water. Although these products might not to be consumed by animals or humans, they are greatly impacted in quality by slight changes in the water composition.

5.3.6 Wastewater Treatment Plants

Table 3 on the following page is a summary of available information concerning the two main water consuming processes within WWTP´s, backwashing of filters, e.g. disc-filters and sedimentation, and polymer preparation. Polymers, normally a metal salt, are used as a helping coagulant to improve the separation of particles in the WWTP. They are usually transported to the WWTP from an external location and are diluted on site. The polymer acts supporting to the precipitant added to the wastewater (Svenskt Vatten, 2007). Polymers are further being applied within the sludge treatment (VA SYD, 2017a). Filters in the WWTP may clog, due to substances in the wastewater. To avoid or counteract clogging, a backwashing system is usually installed, which cleans the filter (Svenskt Vatten, 2007). Other processes within the plants might also have an effect, as sanitary facilities for the staff. Sjölunda WWTP, treating approximately 142,560 m^3/d, had a total water consumption of 5,275,495 m^3 in 2017 (VA SYD, 2017b). Kalmar WWTP, with an annual usage of 24,880 m^3, discharges 16,192 m^3/d of treated wastewater (Kalmar WWTP, 2015).

Table 3 – Processes connected to the drinking water consumption in WWTP's (Kalmar WWTP, 2015; Laholmsbuktens VA, 2015; Hässleholms Vatten, 2017a, 2017b, NSVA, 2017f, 2017g, 2017h, 2017i, Region Gotland, 2017a, 2017b, 2017c; VA SYD, 2017; Wellsjö, 2017; Hässleholms Vatten, 2017c; NSVA, 2017a, 2017b, 2017c, 2017d, 2017e).

Water Association	**WWTP**	**Filters**	**Precipitation**
Malmö	Sjölunda	Bio-Filter	Iron-Sulphate
Gothenburg	Ryaverket	Disc-Filters	Iron-Sulphate
Kalmar	Kalmar	N.A.	
Laholmbuktens VA	Västra Strandens	N.A.	Iron-Chloride
	Busör	N.A.	Polyaluminium-Chloride
Hässleholm	Hästveda	Pre-Sedimentation, Bio-Filter	Aluminum-Chloride
	Vinslöv	Pre-Sedimentation, Bio-Filter	Iron-Chloride
	Vittsjö	N.A.	N.A.
NSVA	Ekebro	Bio-Filter	Iron-Chloride
	Ekeby	Bio-Filter	Iron-Chloride
	Kågeröd	N.A.	N.A.
	Kvidinge	N.A.	Iron-Chloride
	Lundåkra	Pre-Sedimentation, Bio-Filter	Aluminum-Chloride
	Nyvång	Bio-Filter	Iron-Chloride
	Öresundsverket	Sand-Filter (polishing)	Iron-Chloride (if bio-step not sufficient)
	Röstånga	N.A.	Iron-Chloride
	Svalöv	Pre-Sedimentation, Bio-Filter	N.A.
	Torekov	N.A.	Polyaluminium-Chloride
Gotland	Klintehamn	N.A.	Iron-Sulphate
	Slite	Pre-Sedimentation	Iron-Sulphate
	Visby	MBBR	Iron-Sulphate
Luleå	Uddebo	MBBR	N.A.

5.3.7 Agriculture

The reuse of treated wastewater in agriculture differs from other applications in the sense that not only the water is of interest, but also important nutrients, such as phosphorus and nitrogen. The hygienic quality is the main aspect when reusing water to irrigate crops (Baresel et al., 2015).

Depending on the type of crop and their sensibility, the water requirements differ. Potatoes and maize have a high sensitivity towards the water supply, compared to cabbage, with a low sensitivity (FAO, 1992).

More detailed guidelines for the reuse of water in agriculture depend on the type of crop and its consumption. The risks have been divided into biological (bacteria, helminth eggs, viruses, etc.) and chemical (heavy metals, pesticides and substances of sanitary interest) categories by FAO, (1992). Table 4 shows the guidelines for irrigating crops which will either be consumed without further treatment or not consumed at all. Crops which are to be consumed without further processing are recommended to undergo a secondary treatment as well as a filtration and disinfection step. To irrigate crops, which are not being consumed, no recommendation for processes is given by FAO, (1992).

Table 4 – Guidelines for the irrigation water quality, for crops which are not further treated and crops which will not be consumed (FAO, 1992).

Type of crop	**BOD [mg/l]**	**E.coli [numbers/100 ml]**	**Helminth eggs [numbers/l]**	**TSS [mg/l]**
Consumption without further treatment	< 10	14	1	-
Not for consumption	< 30	200	-	30

The soil in which the crops grow can also be affected by different irrigation water types, as the physicochemical parameters may change, which has an effect on the fertility and productivity. Factors which might have an impact are pH, organic matter, nutrients, salinity, contaminants and microbial diversity in the water (Jaramillo and Restrepo, 2017).

5.4 Technical solutions

Table 5 shows the five main industrial categories for the reuse of wastewater and their individual main quality requirements. WWTP's are not included, as the quality requirements for processes in the WWTP are not as clearly defined. The distinction between recreational and agricultural purposes should also be noted, as these are not to be equalized. The introduced treatment processes and their qualitative capabilities of removing relevant substances can be seen and although phosphorus and nitrogen are also highly relevant for biofilm growth in cooling water systems, these are not marked as such in the table, since without a biofilm produced, nutrients for its growth are not considered. This should though be further investigated. Marked with a minus (-), means that the substance is not being removed while the plus (+) stands for a certain or complete removal. Empty cells mean that no relevant information was found. The numbers in brackets indicate the references.

Table 5 – Wastewater reuse applications with the according substances and treatment processes (EPA, 1999 (1); LeChevallier and Au, 2004 (2); US Environmental Protection Agency, 2009 (3); Grote, 2012 (4); Baresel et al., 2015 (5); Deng and Zhao, 2015 (6); Miehe et al., 2017 (7); Naturvårdsverket, 2017 (8); USEPA, 2018 (9); Edefell, Ullman and Bengtsson, 2019 (9); Ismail, Khulbe and Matsuura, 2019b (10); Tappwater, 2019 (11)).

<table>
<tr><th></th><th colspan="2"></th><th colspan="4">Washing of Vehicles</th><th></th></tr>
<tr><th></th><th colspan="3">Recreational</th><th></th><th colspan="3">Cooling Water</th></tr>
<tr><th></th><th colspan="2"></th><th>Agriculture</th><th></th><th colspan="3">Agriculture</th></tr>
<tr><th></th><th colspan="7">Boiler Water</th></tr>
<tr><th></th><th>Tot-N</th><th>Tot-P</th><th>Bacteria
Viruses</th><th>Ca/Mg</th><th>Particles</th><th>Turbidity</th><th>Salts</th></tr>
<tr><td>GAC</td><td>-
(9)</td><td>-
(9)</td><td>-
(11)</td><td>-
(11)</td><td>+
(5)</td><td>+
(3)</td><td>-
(11)</td></tr>
<tr><td>PAC</td><td>-
(8)</td><td>-
(8)</td><td>-
(8)</td><td>-
(8)</td><td>+
(5)</td><td></td><td>-
(8)</td></tr>
<tr><td>MF</td><td></td><td></td><td>+
(2)</td><td></td><td>+
(2)</td><td>+
(2)</td><td></td></tr>
<tr><td>UF</td><td></td><td></td><td>+
(2)</td><td></td><td>+
(5)</td><td>+
(5)</td><td></td></tr>
<tr><td>NF</td><td>+
(10)</td><td>+
(10)</td><td>+
(2)</td><td>+
(10)</td><td>+
(5)</td><td>+
(5)</td><td></td></tr>
<tr><td>RO</td><td>+
(9)</td><td></td><td>+
(2)</td><td></td><td>+
(5)</td><td>+
(5)</td><td>+
(10)</td></tr>
<tr><td>AOP</td><td>-
(6)</td><td>+
(together with a filter)
(7)</td><td>+
(7)</td><td></td><td></td><td>-
(4)</td><td>+
(4)</td></tr>
<tr><td>UV</td><td></td><td></td><td>+
(1)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Cl</td><td></td><td></td><td>+
(2)</td><td></td><td></td><td></td><td></td></tr>
</table>

All proposed treatment options have in common that the pre-treatment is very important. To not disturb the processes, emphasis is mostly put on turbidity and TSS remaining in the wastewater after the conventional treatment steps. While activated carbon, micro-/ultra-/nano-filtration and RO reduce turbidity, the efficiency of these processes is decreased, by too much turbidity in the water. Filters are clogged at a faster rate and require more frequent backwashing or a replacement. AOP processes are also affected, as turbidity and TSS hinder the reactions from occurring (Grote, 2012). Ozonation, as part of AOP, partly removes bacteria, as aerobic bacteria spores are not removed, but heterotrophic bacteria are. To achieve a successful ozone-production, a rest of nitrogen in the wastewater is beneficial, and although ozonation does not reduce ammonia-nitrogen, it can nitrify it (Miehe et al., 2017).

UV light as a disinfection method has the advantage of not requiring a large amount of space, and there is no residual effect which needs to be handled in a following treatment step. The dosing needs though to be right, as a low dosage may not effectively inactivate certain viruses and spores. A well-functioning pre-treatment is necessary, to avoid fouling of tubes and a reduction in efficiency. To achieve the best result, TSS should be reduced as much as possible during previous treatment as it might absorb the UV radiation and shield embedded bacteria (EPA, 1999).

To treat the wastewater to a quality which is safe as bathing water, chemical oxidation, usually through chlorination, or UV-treatment is normally carried out. To achieve a high inactivation-rate, it is important that the water has gone through the right pre-treatment and is left with a low number of particles. When chlorinating water with a high number of particles, a higher dosage of chlorine is needed. Furthermore, organisms protected by flocs can surpass the treatment without being inactivated. The same goes for UV-radiation, where the barrier effect is decreased by particles remaining in the water after pre-treatment. Therefor a filtering process should be installed before a chlorination or UV process. This could be done by a disc filter with a pore size of 10-20 µm, a sand filter or by reconstructing the WWTP and complementing the biological treatment step by including a membrane bioreactor (Heinicke et al., 2015).

Activated carbon as in GAC and PAC reduces turbidity and TSS. Since its main focus when applied in WWTP's is to reduce micropollutants, and TSS is not favorable for that process, it should be further discussed if activated carbon on its own is a feasible solution when treating wastewater to be reused.

The combination of processes is in many cases a possibility. To achieve a reduction in toxicity of the wastewater discharge, ozonation should be followed by a filter, which could be a sand-filter, a membrane or activated carbon. Not only GAC could be applied, but also PAC, which is able to remove oxidation by-products after the ozonation process (Bourgin et al., 2018).

Baresel et al., (2015a) have developed process trains for both industrial and agricultural reuse of wastewater, which together achieve an optimal nutrient and solid reduction. The limits for substances remaining in the water after treatment, were defined by reviewing regulations and standards for the regions of interest (e.g. Australia, China, USA, Western Europe, etc.), effluent qualities and reuse alternatives. Therefore, they might differ for Swedish WWTP's. The trains for industrial reuse follow a conventional biological treatment step with a sequencing batch reactor (SBR) containing a nitrification-denitrification (NDN) process. The trains differ by either applying submerged ultrafiltration (sUF) or pressurized ultrafiltration (pUF) as well as either ozonation or UV:

Train 1: SBR (NDN) → pUF → UV → Cl

Train 2: SBR (NDN) → sUF → O_3 → Cl

Train 3: SBR (NDN) → sUF → UV → Cl

Table 6 visualizes the results obtained through the study, showing that all trains meet the limiting requirements for the chosen substances (Baresel et al., 2015).

Table 6 – Removal rates of treatment trains for the reuse of wastewater in industries. (Baresel et al., 2015).

	NH_4	Tot-P	COD (/10)	BOD	Turbidity	TSS
Limit (mg/l)	**1**	**1**	**3**	**5**	**1**	**2**
Train 1	0.75	0.25	3	2	0.1	1
Train 2	0.75	0.25	3	3	0.2	2
Train 3	0.75	0.25	3	3	0.25	2

To meet the requirements for the reuse of wastewater in agriculture, the biological treatment with an SBR system is followed by either a rapid gravity sand filter (RGSF) or a disc filter (DF). The disinfection step is in both trains a UV treatment (Baresel et al., 2015):

Train 1: SBR → RGSF → UV

Train 2: SBR → DF → UV

As for industrial reuse, the agricultural trains follow a biological pre-treatment and Table 7 shows the remaining concentrations in the wastewater after each process-train. Each train fulfills the quality requirements and the study concluded that the main difference is the use of either a RGSF or a DF. While a RGSF uses a larger amount of energy, the disc filter requires a higher polymer dosage (Baresel et al., 2015).

Table 7 - Removal rates of treatment trains for the reuse of wastewater in agriculture (Baresel et al., 2015).

	NH4	Tot-P	COD (/10)	BOD	Turbidity	TSS
Limit (mg/l)	**5**	**2**	**4**	**5**	**2**	**5**
Train 1	4.5	2	3.5	5	0.5	1
Train 2	4.5	2	3.5	5	2	2

The Drinking Water Quality Regulator for Scotland (DWQR) has also produced an overview of the existing barriers and their ability to remove different compounds. The whole table can be seen in Appendix 2. While coagulation/flocculation shows to be partly effective on bacteria and viruses, it performs effectively when removing turbidity and coarse particles. The preferred technique to remove bacteria, viruses, turbidity, coarse particles, pesticides and aluminum are membranes. Slow sand filtration also produces good results, removing bacteria, viruses and turbidity to a high amount (DWQR, 2016).

To ensure that treated wastewater is safe to use, concerning microbial risks, a multiple barrier system, as used in drinking water treatment, is an option. To install multiple barriers means that if one should fail, it will be compensated by the remaining, effectively functioning barriers. This ensures a minimal risk that harmful contaminants should pass by the barriers and affect the environmental and human life. The processes might also be dependent on each other, for example, a granular filtration process not reducing turbidity and particles efficiently, might reduce the removal efficiency of the proceeding disinfection process (LeChevallier and Au, 2004).

5.5 Legal aspects

The legal aspects concerning the reuse of treated wastewater are affected by different areas of the legal system. The Swedish Environmental Protection Agency (Naturvårdsverket) requires that when reusing treated wastewater, it needs to be classified, either as waste, a product or a bi-product, shown in Figure 2. A product is defined by being consciously produced within an industry and the main objective of the industry is to produce this product. When a rest-product is being produced, which is a product, not specifically aimed to being produced, it is classified as either a bi-product or waste. Waste is being defined as an object or substance, which the owner disposes or is obligated to dispose of. For an object or substance to be called a bi-product, it has to be produced in a process, where the main objective is not to produce this object or substance. A bi-product can also be directly used, without further processes needed and it will be used in a manner, which is environmentally and health wise acceptable and does not conflict with the law or constitutions (Miljöbalken 15 kap 1 §) (Naturvårdsverket, 2019).

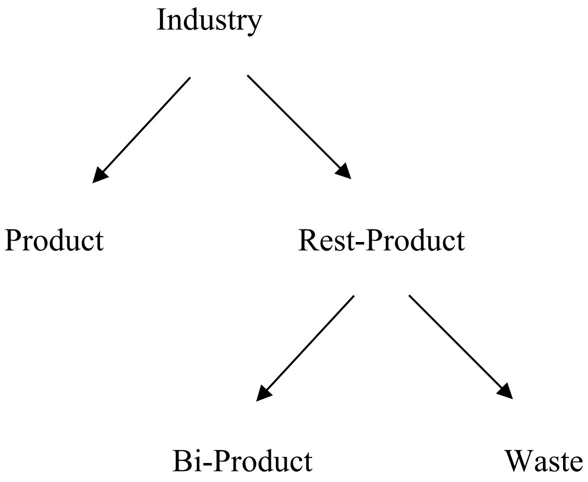


Figure 2 – Production pyramid of an industry.

According to the Waste Framework Directive (2008/98/EC), article 6, a waste-product can become a bi-product by going through an end-of-waste procedure. For this to happen, the following conditions have to be met:

a. the substance or object is commonly used for specific purposes
b. there is an existing market or demand for the substance or object
c. the use is lawful (substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products)
d. the use will not lead to overall adverse environmental or human health impacts (European Union, 2008).

The conditions are cumulative, meaning that all requirements need to be fulfilled for waste to be classified as a bi-product. If a rest-product does not meet the requirements, it is always to be classified as waste. A bi-product is not included in the waste legislature, and thereby the same chemical legislation as for a newly produced product is applied, which might include Reach and CLP (regulation for classification, marking and packaging). If the bi-product is to be used internally at the industry, it is exempted from certain parts of the chemical legislation. Exemptions might include the duty of registration, if the product is not exported or placed on the market. Concerning placing a bi-product on the market, Reach, article 3, pt12 describes it as the delivering or providing to a third party, against payment or for free (Naturvårdsverket, 2019).

5.5.1 Reach

Reach is a regulation by the EU, standing for the registration, evaluation, approval and limitation of chemicals. It has been adapted to improve the protection of human and environmental health from risks caused by chemicals. The regulation also increases competition between chemical industries in the EU and promotes alternative methods for hazard assessment of products to decrease animal testing. Reach includes all chemical substances and puts the burden of proof on the industries, which have to identify and handle the risks coming with the substances they produce and market within the EU (ECHA, 2019).

Article 12.1 of the Reach-regulation requires industries to state information about acute and chronicle toxicity in water environments for fish, algae and other water living plants. Available information about the toxicity for soil living micro- and macro-organisms and other environmentally relevant organisms like birds, bees and plants needs to be included. If the production of the substance/product has an inhibitory effect on the organisms' activity, the possible impact by a WWTP should be mentioned. Furthermore, Article 12.3, dealing with the persistency and biodegradability of substances, requires that the potential of each substance to biodegrade in relevant parts of the environment, either through biological degradability or other processes as oxidation or hydrolysis, has to be stated. If available, the half-times for degradation have to be included, as well as the substances', or relevant elements' potential to degrade in the WWTP (European Union, 2006).

5.5.2 EU Directive

In 2018, a proposal was made by the European Commission to implement a regulation for the reuse of water in industries. This proposal describes the need for legislation, due to the high level of water scarcity in many parts of Europe as well as the resource that is treated wastewater. The proposal claims that one third of Europe is experiencing water stress and due to population growth and climate change this stress will continue to increase. The proposition was perceived with an interest by the European Council and the commission was encouraged to work on a legal frame for the reuse of water in the European Parliament resolution. This acts as a follow-up of the European Citizens Initiative Right2Water, which started in 2012, and in remark of the Committee of the Regions "Effective water management system: an approach to innovative solutions" from December 2016 (Puigarnau, 2018; Secretary-General of the European Commission, 2018b).

The proposal refers to Directive 91/271/EEG, concerning the discharge quality for WWTPs, which precedes further treatment, before being reused. These requirements are:

- BOD – 25 mg O_2/l
- COD – 125 mg O_2/l
- TSS – 35 mg/l (PE > 10.000), 60 mg/l (PE 2.000 – 10.000)
- Tot-P – 2 mg/l (PE 10.000 – 100.000), 1 mg/l (PE > 100.000)

- Tot-N – 15 mg/l (PE 10.000 – 100.000), 10 mg/l (PE > 100.000) (Council of the European Communities, 1991).

The discharge limits by the Swedish Environmental Agency are a bit more stringent, according to SNFS 1994:7:

- BOD_7 - 15 mg O_2/l of,
- COD_{Cr} - 70 mg O_2/l for (can be exchanged for TOC)
- Tot-N - 10 mg/l (PE > 100.000), 15 mg/l (PE 10.000-100.000) (Naturvårdsverket, 1994).

5.5.3 Irrigation

The Californian Title 22 benchmark technology has been the guiding instruction for the unrestricted irrigation, due to its high rate of successful projects, which alone in the United States have exceeded 400. The concept is the base for the development of tertiary treatment steps as coagulation, flocculation, sedimentation, filtration and disinfection treatment steps to achieve the limit of 100 fecal coliforms per 100 ml of treated wastewater (Bixio et al., 2006).

While the Californian Title 22 solely suggests monitoring the total coliform count, assessing the microbiological quality, the WHO includes the monitoring of intestinal nematodes. Pathogens are very difficult to monitor but the WHO advises a limit of less than 1000 coliforms per 100 ml, as well as less than 1 intestinal nematode egg per liter (Angelakis and Durham, 2006).

The guidelines for irrigation water are divided into three categories, for unrestricted irrigation, which is the usage of water to irrigate crops without health risks, including crops which are eaten raw (Bixio et al., 2006), restricted irrigation, as highly mechanized and labor intensive, and localized (drip) irrigation, which concerns high- and low-growing crops. The guidelines also propose measures to be taken, to protect workers, consumers and the local community from health risks. Risks include excreta-related pathogens and toxic chemicals. Since cooking does not eliminate all toxic chemicals present in the crop, health protection measures are to be taken in the wastewater treatment, crop restriction, produce washing, disinfection, cooking, etc. It is also suggested that workers and consumers, who are in contact with the crops are to use personal protective equipment.

To make decisions regarding irrigation with treated wastewater, the main considerations according to the WHO are:

Policy – is the project encouraged/discouraged? Which clearly defined policies exist?

Legislation – Which rights and obligations do the stakeholders hold? Are the legislative aspects clearly defined?

Institutional Framework – Which organization/institution/agency has the authority for decision making on local/regional/national level? Are the responsibilities clearly stated?

Regulations – Which regulations exist and do they meet the wastewater use objectives (protection of human and environmental health, produce quality, conservation of nutrients and water, etc.) (WHO, 2006)?

5.5.4 Bathing Water

Since 2000, Sweden follows the EU Water Framework Directive, and since 2008, a directive for the marine environment was adopted. This includes the directives 76/160/EEC and 2006/7/EC for bathing waters, with Article 1.2 stating “(a) "bathing water" means all running or still fresh waters or parts thereof and sea water, in which: - bathing is explicitly authorized by the competent authorities of each member state, or (b) bathing is not prohibited and is traditionally practiced by a large number of bathers” (European Environment Agency, 1975).

The required quality for inland waters according to the European Environment Agency can be seen in Table 8, detailed information about the quality requirements can be found in Appendix 3:

Table 8 – Quality requirements for inland waters. (European Environment Agency, 1975)

Parameter	Excellent Quality	Good Quality	Sufficient Quality	Reference Methods of Analysis
Intestinal enterococci (cfu/100 ml)	200	400	330	ISO 7899-1 or ISO 7899-2
Escherichia coli (cfu/100 ml)	500	1000	900	ISO 9308-3 or ISO 9308-1

If the bathing water does not meet the required values for a sufficient quality, it is labeled as ‘poor’.

Since 2011, bathing water profiles need to be produced (article 6), which include “the identification and assessment of pollution that might affect bathing water and impair bathers’ health” and the potential of proliferations of cyanobacteria, macro-algae and/or phytoplankton. The complete bathing water profile is found in Appendix 4.

As the definition for treated wastewater yet has to be established, the IPPC Directive (Integrated Pollution Prevention and Control, 96/61/EC) should be taken into account. In Annex III of the directive, a list of the main polluting substances to regard for fixing emission limit values can be found. This includes, amongst others, persistent hydrocarbons and persistent and bioaccumulable organic toxic substances, metals, materials in suspension, substances contributing to eutrophication and substances which have an unfavorable influence on the oxygen balance (and can be measured using parameters such as BOD, COD, etc.). As the WWTP may be able to reduce or eliminate polluting substances, this also concerns upstream conditions, contributing to the amount of substances reaching the WWTP (European Union, 1996).

5.5.5 Swedish Work Environment Authority

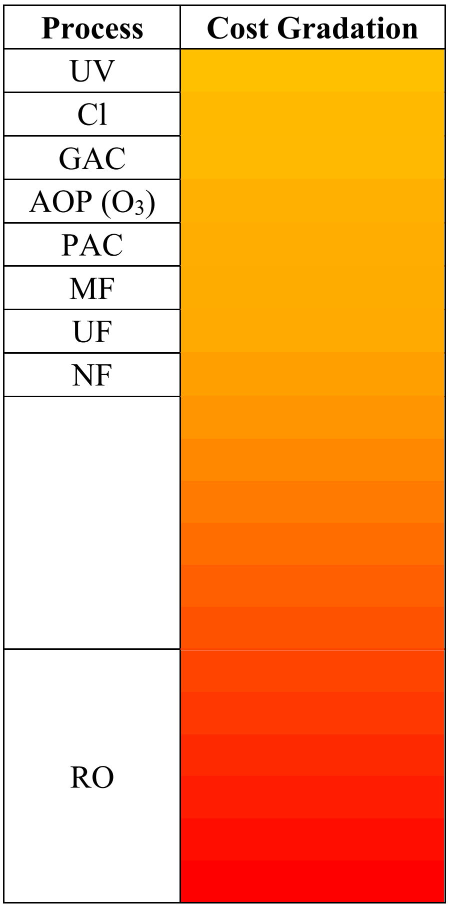
The Swedish Work Environment Authority (Arbetsmiljöverket) does not state specific requirements concerning the water quality when using treated wastewater in industrial applications. The document ‘chemical rules’ and the ‘chemical work environment risks’ apply when working with water. The chemical rules state that a prolonged exposure of substances, normally not classified as dangerous, may cause problems. The §5 explains how to investigate and evaluate the chemical risks in a work environment, where first the chemical risk sources need to be identified together with their dangerous properties and what rules apply. The next step is to identify dangerous situations and the according measures to be followed, in order to avoid these. If the risk sources are unknown, an assessment needs to be done, for any type of chemical risk source which could occur and prepare measures for these. Protection measures are explained by 28, 29, 30 §§, explaining the usage of eye-protection, eyewash and emergency-showers, when working with risk substances (Arbetsmiljöverket, 2018).

When working with a high-pressure jet, the according constitution AFS 1994:54 has to be followed. This applies when cleaning or cutting with stationary, transportable or mobile high-pressure equipment, which has a higher-pressure system than 25 bar. Since spraying of the jet may occur, eye injuries are a security risk, as particles and aerosols could come off the object to be cleaned or dangerous substances in the spray-water can cause harm (Arbetarskyddsstyrelsen, 1994).

5.6 Costs

The calculation of costs for the project of reusing treated wastewater is generated by many different factors. The processes, which need to be installed come with individual costs, depending on the size of the plant, the amount of water to be treated, required discharge quality, inflow quality, location, maintenance varieties, costs of replacements, personnel costs, etc. Table 9 shows a very approximate cost gradation of the processes, which in total may range between 1 – 15 SEK/m^3 for the operational costs. This is visualized by the range from yellow to red, going from minor to larger costs. The input to the table does though vary and the colors do not represent exact numbers and should be handled cautiously. The table was constructed by combining the numbers found within literature. Plappally and Lienhard V, (2013) calculated approximately 9 – 15 SEK/m^3 for RO, Guo et al., (2014) made the approximation of 2.5 SEK/m^3 for UF, Mulder, (2015) estimates 2.7 SEK/m^3 for GAC, 1.8 SEK/m^3 for ozonation together with a sandfilter and 2 SEK/m^3 for PAC. Heinicke et al., (2015) state that a UV process costs 0.13 – 0.25 SEK/m^3, although these numbers do not include the instalment of the process. It should be noted that these numbers were converted from different currencies, and the gradation is based on approximations, with the goal to visualize that there are differences in costs for the processes. Approximations include the assumption that MF, UF and NF are in the same range, though increase in cost with decrease in pore size.

Table 9 – Gradation of costs for each proposed treatment process (Plappally and Lienhard V, 2013; Guo et al., 2014; Heinicke et al., 2015; Mulder, 2015).



Process	Cost Gradation
UV	
Cl	
GAC	
AOP (O_3)	
PAC	
MF	
UF	
NF	
RO	

In Sweden, the “VA-taxa” describes the tariff to be payed by costumers for being connected and provided by the water system. This includes the supply of drinking water, wastewater treatment and stormwater drainage (VA SYD and Lunds Kommun, 2018). The tariff is calculated so that no profit is being made and its usage is divided into infrastructure and consumption fees. Infrastructure fees cover the costs for connecting new costumers and the consumption fee covers the costs to operate the plant. The fees also cover capital costs for investments on the main pipe system, WWTP’s and other plants. These are in their turn affected by factors as climate change, increasing the need for improving processes (VA SYD, 2019). Currently, when including all Swedish municipalities, the average tariff is 48.61 SEK/m^3, with the lowest value of 21.6 SEK /m^3 in Solna (Stockholms län) and the highest value of 78.7 SEK /m^3 in Högsby (Kalmar län). These values are applicable to Swedish households but not to industries, where different systems apply (Svenskt Vatten, 2018). The Swedish Water Services Act (Vattentjänstelagen) is in place to secure water supply and sewage in a bigger context in regard to the protection of human and environmental health. This includes that the water association is not obligated to provide water to industries, fire departments or other operations and in case of a water shortage, households paying the tariff are to be provided before all else. To provide water to industries should be seen as a usual business transaction, and therefore non-specific tariffs exist (Svenskt Vatten, 2017).

To connect industries with treated wastewater instead of drinking water, new piping systems need to be constructed, which can vary in costs, depending on many factors. The type of landscape has a great effect, since densely populated areas exert a larger pressure, caused by streets and buildings, compared to sparsely populated areas. The density of a location also contributes to the pollution within the ground, increasing with density of the city. Drinking water pipe systems are constructed as a pressurized system and it should be further examined if this is the case also for reused wastewater, as the prize for the system varies compared to a gravity driven system. Local geotechnical aspects have to be considered, and especially what material the ground is made up of. The volumes of water to be transported through the pipes and the slope at which the pipes will be constructed also have an effect on the costs. Regional aspects should also be considered, especially since further north in Sweden, the pipes have to be put deeper into the ground, due to very low temperatures causing frost, compared to more southern locations. The costs to build a piping system to connect the WWTP’s with the industries may vary between 5,000 SEK/m (arable, simple recovery) and 50,000 SEK/m (high-traffic inner-city street) (Personal interview with Jimmy Andersson, VA SYD, 2019).

The Secretary-General of the European Commission (2018a) as well as Baresel et al. (2015a) have proposed costs together with processes for a reuse of treated wastewater in different applications. As the approximations do not state the exact usage of water, for example the type of industry or individual quality requirements, they are not included in this thesis.

6 Discussion

In the project of investigating the reuse of wastewater, it becomes clear that no exact answer can be given to the questions posed. Many factors are involved, and the discussion starts at the WWTP, where a clarification of treated wastewater needs to be established. As of today, it is classified as waste, since wastewater in itself is the disposal of waste. The role of a WWTP should therefore be investigated. Is the WWTP a waste handling institution or does it produce a product, which is treated wastewater, together with biogas and sludge, which are further being used to produce energy or to fertilize within agriculture? The WWTP collects a waste product and treats it to a standard at which it should not be harmful to release into the environment, which can be defined as deactivating a toxic substance, while seizing the outcomes of that process. Especially when discussing the reuse of wastewater, it should be defined if the role of a WWTP is to treat wastewater, or to provide water of a certain quality to a costumer, by using available (recyclable) material, which in this case is the wastewater. Throughout history, the objective of the WWTP has been changing. As wastewater was originally collected to get removed from the households, it was later treated, since the untreated discharge into the environment was causing harm. As the WWTP's have become more advanced, by introducing new processes to benefit the human and natural environment, it could be discussed if further redefinitions are in place. When looking at the objective to treat wastewater, it seems that the discharge as well is a waste-product, which the treatment plant needs to dispose of. When regarding the WWTP as taking advantage of wastewater to produce a new product, while biproducts emerge as well, it could be seen as an industry, producing a costumer-adapted product which could counteract a scarcity in the sector. As the Waste Framework Directive (2008/98/EC), article 6, describes how a rest-product becomes a bi-product, the conditions by wastewater discharge to be fulfilled, should be further discussed. The first condition of the substance commonly being used for specific purposes is achieved, as the wastewater discharge could be applied for specific applications. The second condition as to if an existing market exists is also fulfilled, as water is a valuable resource and the demand thereafter has increased due to recent, more regularly happening droughts. With the proposed processes to achieve the required qualities to be reused, the wastewater discharge could be able to fulfill the technical requirements for the specific purposes, which describes the third point for waste to become a bi-product. The fourth and last condition is that the substance will not have a negative effect on environmental or human health. This could also be achieved by installing the according processes. The definitions to treat wastewater discharge not as waste, but as a bi-product, would therefore be fulfilled. Furthermore, to reuse the water directly at the WWTP, it would be exempted from certain parts of the chemical legislation, including the duty of registration, posing an attractive option.

6.1 Interviews

The process of interviewing and collecting data about the interest of industries to use a different kind of water instead of drinking water showed a large motivation. Environmental issues are omnipresent when speaking with industries and the willingness to take part of action was big. An interesting observation was industries contributing with suggestions and ideas about the water consumption, as for example to discuss the possibility to use a different kind of water to treat with RO, before being applied as boiler water. Industries with large water consumptions and therefor also discharge, have treatment steps installed, to reach a water quality which can be disposed of into the environment instead of transporting the water to the local WWTP. It was therefore discussed if the water discharged by the industries could be reused internally first, before looking into other solutions. To use the water already in the industry could be a first step towards reuse, before using drinking water or treated wastewater from the municipal WWTP. The economical incitement is though not as strong yet, since drinking water is easily available and comes at a comparable low cost. To install new treatment steps or redesign the water systems in industries, need a strong economical incitement as the environmental benefits alone are not feasible for the companies. The option for collaboration between industries and WWTP was expressed by industries considering internal symbiosis. The will to explore opportunities is counteracted by the gap in knowledge, which could be filled by working together with local or regional water organizations.

6.2 Quality Requirements

When comparing water quality requirements for the different applications with the current discharge quality by the WWTP's, it becomes visible that existing treatment steps need to be changed or updated, or additional treatment steps need to be installed. When comparing the quality requirements by Baresel et al., (2015) with the effluent qualities by the WWTPs, the requirements being fulfilled are the nitrogen- and phosphorus values for agriculture. Since these substances are beneficial within agriculture but not as part of discharge into the environment, it highlights the difficulties within this project, as what to focus on. The water and nutrients reusable from a WWTP can be of great use in one sector but cause damage in another. If treated wastewater can be used in agriculture and fulfills the requirements for that use, it needs to be evaluated what happens in case of an unplanned incident. Could that water still be discharged into the ordinary recipient or are there other measures to not harm valuable nature? As of now, treated wastewater is usually discharged into a water body close to the WWTP, which is examined to be fit to act as a recipient with the lowest environmental impact aimed for. It should be examined to what extent the environmental impact is affected with a lower or different water quality discharge. Furthermore, current systems of discharging treated wastewater might be part of a larger eco-system and the holistic approach to a re-application is therefore important.

Continuing on that note, the possibility to generate several qualities within the WWTP should be examined. Depending on the industries around, and their individual quality requirements, it could be feasible to have a system, where water is extracted from different locations of the treatment plant and receives the treatment it needs to be further used in industries. This is though very dependent on the WWTP, the surrounding industries, required water qualities, volumes of water required, distance between, volumes of water being treated, future prospects. etc. To update a WWTP to co-operate with industries is a long-term project. An alternative could be to investigate variable, modular treatment steps, with the possibility to adapt for future flows and quality requirements. When planning for the future, the WWTP could have the ability to adapt for minor changes and not be designed for the current time and conditions, but rather flexible towards future collaborations and changes.

With WWTP's having a water consumption of their own, these are a first opportunity to reuse the treated wastewater within. Applications as filters and the preparation of polymers are in need of water and with the availability on site, this seems like an important opportunity. As Sjölunda WWTP treats approximately 142,560 m^3/d (52,034,400 m^3/y) and has a drinking water consumption of 5,275,495 m^3/y, almost 10 % of the treated wastewater could cover the annual water consumption. These numbers should though be further investigated, since the drinking water consumption is measured at the inlet and the exact usage of water is not stated, as leakages might occur. As for Kalmar WWTP, only 0,4 % of the discharge could cover the water consumption. As the quality needed for filter backwashing or the preparation of polymers have not been further analyzed in this report, they require further studies.

6.3 Recreational Purposes and Agriculture

To reuse the treated wastewater for recreational purposes is a broad category and has been distinguished from agricultural reuse in this report. That separation is explained by the need for nutrients within agriculture and the lack thereof in recreation. As the pond- and harbor systems are mentioned as possible recipients, eutrophication and other impacts by nutrients should be avoided. Since direct human or environmental contact cannot be excluded, bacteria, viruses and pesticides should be inactivated or removed from the discharge. The impact by micro-pollutants as pharmaceuticals should be kept in mind, this report does though not go further into that field. Agriculture poses the possibility to not only reuse treated wastewater, but also nutrients, meaning that the water might be taken from an earlier process in the WWTP, which further could relieve following process capacities. The feasibility of extracting water from the WWTP, to seize nutrients as phosphorus and nitrogen could be further researched. The biological treatment step, designed to reduce BOD and nitrogen, would play an important role. In case of a post-precipitation step, it could be further investigated if the possibility to use the water entering that process and seize the remaining phosphorus could exist. A disinfection step should be installed for that discharge as well, which depends on the type of crop to be irrigared.

To reuse treated wastewater as irrigation for agriculture also comes with seasonal requirements. In Sweden, irrigation and nutrients are not required during the whole year and it could be further looked into, if storing systems for farmers would be a feasible solution.

The recreational applications requirements by Miljøministeriet Naturstyrelsen, (2012), of Tot-N being 2.5 – 6 mg/l, Tot-P of 0.04 mg/l and BOD of 3.5 mg/l are partially or not met, by the current WWTP's as these are not operated to meet these values. Some of the WWTP's looked into in this report do meet the required BOD values, but for the most part, the limits to reuse current discharge for recreational purposes are not reached. It is also not clearly stated to what extend this would be legally acceptable. As WWTP discharge is directed into the environment already now, and although it is usually led to a waterbody not endangering human or environmental health, it can be discussed to what extent that discharge is environmentally acceptable. When looking at current WWTP's and their discharge, it should be considered that the plants have discharge limits which need to be achieved. It could be the case, that WWTP's have the ability to treat the water to additional qualities, but since they are not obligated to do so, and without further incitement do not make the most of the processes.

6.4 Industries

To reuse treated wastewater as cooling water, it should contain as little calcium salts and magnesium as possible to avoid scaling in the heat exchangers. Currently, the discharge of Sjölunda WWTP contains 57 mg/l of calcium and 11.9 mg/l of magnesium and it should be examined how the system would be affected by these concentrations. As cooling water is sensible to fouling, since it significantly increases the losses, it should be further analyzed as to how big the impact would be with the current discharge. The disinfection of water is also important, as employees might come in contact with the water when maintaining the system, but also to not promote growth of bacteria, which could be fed by nutrients. As remaining phosphorus in the water can act protecting against scale, this could be an option to not remove from the wastewater discharge. In order for the phosphorus to work, bacteria and substances feeding of it, should not remain in the water, as these could grow.

To clean vehicles, emphasis is put on the lack of minerals and solids within, as well as the disinfection of the water. Sjölunda WWTP does meet the limiting value by Corbisiero, (2017) of 17.1 mg/l of magnesium in the discharge, the same limit for calcium is though not met. The water should also be well disinfected, since the risk of human interaction with the water is large. Depending on the washing system, this risk might become larger, when handling the washing by hand. Aerosols carrying bacteria or viruses can occur in open or closed system, a closed system being a washing system where the car drives into and is being washed by an automatic system.

The case of using water as boiler fee is very interesting, as it requires an ultraclean quality. By treating drinking water to that quality themselves, industries are in control and held accountable of reaching the required limits. As RO systems require more energy with increasingly polluted water to clean, it would be interesting to look into how the relationship, between for example polluted water and energy consumption, develops. It could further be discussed to where it would be most beneficial to invest the required energy. Could it be an option to clean the water at the WWTP to a certain degree, which would be able to be used by the RO system, without large energy and connected cost increases? Or could another option be, to apply additional energy and costs for the RO system, which could act relieving to the WWTP? Furthermore, since the boiler feed in some industries is only a small percentage of the total water consumption, the feasibility needs to be investigated.

6.5 Processes

When deciding for a process, which could be installed to reach new water qualities, required by the industries, there are many options and combinations which could act similarly to each other. A feature that all applications have in common is the need of disinfection, and mainly bacteria and viruses need to be inactivated or removed. This is achieved by membranes, ozonation, UV-treatment and chlorination. The reduction of particles and TSS is also important for all categories which activated carbon and membranes can achieve. To reduce other important compounds nanofiltration poses as an option of most substances reduced. To combine ozonation with NF covers all substances and the discharge could be used within all applications. To produce cooling water, ozonation together with a GAC process could be able to produce the right quality of water, as it is important that no salts are left in the discharge, which ozonation is able to remove. MF and UF could be options to produce water for the washing of vehicles, it has though to further be analyzed if these are also able to remove minerals as calcium and magnesium.

The treatment trains proposed by Baresel et al., (2015a) and the achieved qualities by them meet the requirements for industry and agriculture. Although the category industry, in this case, stands for a broad range of applications, they are in the range of the categories in this report. The cleaning of vehicles could be an option with the trains, although more information about minerals would be required. Recreational purposes could also be an application after the trains, with the water being disinfected and low in nutrients. Cooling water can also be further explored, as the degree to which fouling would occur, is an important factor. All three trains consist of filtration and several disinfection steps, which could act as a multi-barrier system.

The trains developed for agriculture also meet the requirements by Baresel et al., (2015a). They include disinfection and a filter, which this report has not further discussed. Both proposed trains with an RGSF or DF together with UV as disinfection reach the required values. The limit for phosphorus was set to 2 mg/l and depending on the objective with reuse of water in agriculture, it would be further interesting to investigate how much phosphorus would be possible to regain from the WWTP.

Since the quality requirements for the identified applications have many similarities, it could be possible for WWTP's to meet several requirements, by installing certain processes. As previously mentioned, ozonation together with nanofiltration could be able to reduce all relevant substances for a water reuse in industries and recreation.

6.6 Costs and Transport

The transport of water from the WWTP to the industry is a large contributor to the feasibility of reusing treated wastewater. The connected construction works are substantial, if a new pipe system needs to be installed. Depending on many factors, the costs are variable, and it would be beneficial to find solutions with as little impact as possible. Since the industries are as well connected to the drinking water plant, these might serve as a backup solution, in case the WWTP is unable to deliver the right amount or quality of water. When considering industries with large water consumptions, this will also have an effect on the drinking water plant, which might become over-dimensioned. All these factors might differ between each WWTP and the location in Sweden.

Activated carbon has a lower cost per m^3 than filtration methods or RO. The pre-treatment and actual outcome after the process have though a very different quality, and depending on the application of the water, might or might not be sufficient. It can be observed that with a higher substance reduction possibility come increasing energy demands and thereby costs. This cannot be said for every process but when looking at disinfection processes, UV and chlorination have high abilities to reduce bacteria and viruses and a comparable low cost. It has though not been found out if these are also applicable to reduce further substances. Nanofiltration has the ability to remove most particles, this comes though at higher costs. To recommend the right process to reuse wastewater is therefore highly dependent on the individual requirements and possibilities of the WWTP's. The processes might as well differ in installation and operation costs, as some might be cheaper to install but more expensive to operate, and vice versa.

To cover the costs of realizing the project, is also dependent on local circumstances. Since drinking water is as easily available at a comparable low cost, the industries need a large incitement to contribute. As mentioned earlier, the environmental benefits alone are in most cases not sufficient enough to contribute to such a drastic change. The VA-tariff states that it covers the costs for improving a WWTP towards climate change. Therefore, it should be clarified what objective the project of reusing treated wastewater follows. Considering water being a scarce resource might not have the same meaning in Sweden as in other, struggling countries. And although regions in Sweden do struggle with water supply, this might not be the case for all municipalities. It should be investigated if the VA-tariff does cover the costs to update the WWTP's and if that would be the case for the whole country, or just for municipalities with proven water scarcity.

Connecting to costs and feasibility, each case of WWTP and industry should be further investigated regarding how the water will be transported and where to place the possibly needed additional treatment step. A WWTP with several water consuming industries in close proximity might not be able to fulfill several different water qualities. It could be an option to place the treatment step to reach the individual water qualities, at the industries, instead of at the WWTP. Since industries might move or close down, this option lacks in flexibility. Furthermore, the costs and legal aspects should be thoroughly examined, as the accountability has to be clear.

7 Conclusions

The potential to reuse treated wastewater within industries or agriculture is large, as the environmental incitement is present, and industries are eager to contribute to a sustainable future. However, the current comparable low cost of drinking water counteracts the environmental prospects, as the economic feasibility still needs to be established.

The main categories for reusing treated wastewater were identified as being boiler water, the washing of vehicles, recreational purposes, cooling water, wastewater treatment plants and agriculture. Each category has certain quality requirements and by introducing new treatment steps to the WWTP's, these are able to be achieved. Depending on local and regional aspects, processes could be installed, to target specific substances. All identified water reuse applications have in common that a disinfection of the water is essential, and the amount of total suspended solids should be reduced to a minimum. The proposed techniques to achieve the water qualities are activated carbon, membranes, advanced oxidation processes (ozonation), chlorination and UV-treatment. The combination of processes is an option and the similarities between the quality requirements of the applications may result in achieving several qualities with the same processes. Except for a water reuse within agriculture, all other identified quality requirements could be achieved by installing an ozonation together with a nanofiltration process at the WWTP. It was observed that there is a correlation between operational costs and removal efficiency, and the spectrum ranges between 1 – 15 SEK/m^3 of treated wastewater.

Many possibilities exist to reuse treated wastewater and to do so, the legal aspects have to be in order, including the definition of wastewater discharge. Defined as a waste-product, it needs to be handled according to the waste directive. If it fulfills the requirements to instead be classified as a bi-product, it would fall under the according legislation. The definition of wastewater discharge being a waste or a bi-product must therefore be defined, before being able to further implement solutions.

Finally, the reuse of treated wastewater could be a contributing step towards a more sustainable water usage and by working together to find solutions for implementation, this could become part of a viable future!

8 Future Work

During this thesis, many questions arose and the need for further research became clear. Examples of questions that this thesis was not able to answer but would be interesting to further look into are:

- What water quality would be required for the preparation of polymers and for backwashing filters within wastewater treatment plants?
- How does the efficiency of a reverse osmosis process change with different inflow water qualities and how would the feasibility be affected?
- How is a cooling water system affected by a combination of particles within the water? Do combinations exist, which would not decrease the efficiency, but still contain particles?
- Could it be possible to seize nutrients from the wastewater, to reuse in agriculture, without compromising human and environmental health? What would happen to the nutrients if the water went through a disinfection process?
- Under what legislation does treated wastewater fall? Could it be possible to define it as a bi-product instead of a waste-product?

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Luleå Vatten – Erika Lundström, February – April 2019

Hässleholms VA – Tord Sonander, Liselotte Stålhandske, February – April 2019

Gotlands Vatten – Henrik Nygren, February – April 2019

NSVA – Hamse Kjerstadius, February – April 2019

Appendix 2 – Treatment methods for reducing selected compounds and substances.

Treatment Methods

	Bacteria	**Cysts**	**Viruses**	**Turbidity**	**Al**	**Ammonia**	**Fe/Mn**	**Nitrate**	**Pesticides**
Coagulation/Flocculation	+	+	+	++	++		++		
Sedimentation				+	+		+		
Gravel filter/Screen				+	+		+		
Rapid sand filtration	+	+	+	++	+		+		
Slow sand filtration	++		++	++	+		+		
Chlorination	++		++			++			
Ozonation	++	+	++						++
UV	++	+	++						
Activated Carbon									+
Ion Exchange						+		++	
Membranes	++	++	++	++	++		++	++	++

(DWQR, 2016)

Appendix 3 – Assessment and classification of bathing water according to the European Environment Agency, (1975), including descriptions of how to reach or how to improve the bathing water qualities.

Bathing water assessment and classification

1. Poor quality Bathing waters are to be classified as ‘poor’ if, in the set of bathing water quality data for the last assessment period (1), the percentile values (2) for microbiological enumerations are worse (3) than the ‘sufficient’ values set out in Annex I, column D.

2. Sufficient quality Bathing waters are to be classified as ‘sufficient’: 1. if, in the set of bathing water quality data for the last assessment period, the

percentile values for microbiological enumerations are equal to or better (4) than the ‘sufficient’ values set out in Annex I, column D; and

2. if the bathing water is subject to short-term pollution, on condition that:

(i) adequate management measures are being taken, including surveillance, early warning systems and monitoring, with a view to preventing bathers' exposure by means of a warning or, where necessary, a bathing prohibition;

(ii)adequate management measures are being taken to prevent, reduce or eliminate the causes of pollution; and

(iii)the number of samples disregarded in accordance with Article 3(6) because of short-term pollution during the last assessment period represented no more than 15 % of the total number of samples provided for in the monitoring calendars established for that period, or no more than one sample per bathing season, whichever is the greater.

3. Good quality Bathing waters are to be classified as ‘good’: 1. if, in the set of bathing water quality data for the last assessment period, the

percentile values for microbiological enumerations are equal to or better (4) than the ‘good quality’ values set out in Annex I, column C; and

2. if the bathing water is subject to short-term pollution, on condition that:

(i) adequate management measures are being taken, including surveillance, early warning systems and monitoring, with a view to preventing bathers' exposure, by means of a warning or, where necessary, a bathing prohibition;

(ii)adequate management measures are being taken to prevent, reduce or eliminate the causes of pollution; and

(iii)the number of samples disregarded in accordance with Article 3(6) because of short-term pollution during the last assessment period represented no more than 15 % of the total number of samples provided for in the monitoring calendars established for that period, or no more than one sample per bathing season, whichever is the greater.

4. Excellent quality Bathing waters are to be classified as ‘excellent’:

1. if, in the set of bathing water quality data for the last assessment period, the percentile values for microbiological enumerations are equal to or better than the ‘excellent quality’ values set out in Annex I, column B; and

2. if the bathing water is subject to short-term pollution, on condition that:

(i) adequate management measures are being taken, including surveillance, early warning systems and monitoring, with a view to preventing bathers' exposure, by means of a warning or, where necessary, a bathing prohibition;

(ii)adequate management measures are being taken to prevent, reduce or eliminate the causes of pollution; and

(iii)the number of samples disregarded in accordance with Article 3(6) because of short-term pollution during the last assessment period represented no more than 15 % of the total number of samples provided for in the monitoring calendars established for that period, or no more than one sample per bathing season, whichever is the greater. (European Environment Agency, 1975)

Appendix 4 – The bathing water profile according to the European Environment Agency, (1975), explaining the requirements to be classifies as 'good', 'sufficient' or 'poor' bathing water quality.

The bathing water profile

1. The bathing water profile referred to in Article 6 is to consist of:

(a) a description of the physical, geographical and hydrological characteristics of the bathing water, and of other surface waters in the catchment area of the bathing water concerned, that could be a source of pollution, which are relevant to the purpose of this Directive and as provided for in Directive 2000/60/EC;

(b) an identification and assessment of causes of pollution that might affect bathing waters and impair bathers' health;

(c) an assessment of the potential for proliferation of cyanobacteria;

(d) an assessment of the potential for proliferation of macro-algae and/or phytoplankton;

(e) if the assessment under point (b) shows that there is a risk of short-term pollution, the following information:

—the anticipated nature, frequency and duration of expected short-term pollution,

—details of any remaining causes of pollution, including management measures taken and the time schedule for their elimination,

—management measures taken during short-term pollution and the identity and contact details of bodies responsible for taking such action,

(f) the location of the monitoring point.

2. In the case of bathing waters classified as 'good', 'sufficient' or 'poor', the bathing water profile is to be reviewed regularly to assess whether any of the aspects listed in paragraph 1 have changed. If necessary, it is to be updated. The frequency and scope of reviews is to be determined on the basis of the nature and severity of the pollution. However, they are to comply with at least the provisions and to take place with at least the frequency specified in the following table.

Bathing water classification	**‘Good’**	**‘Sufficient’**	**‘Poor’**
Reviews are to take place at least every	Four years	Three years	Two years
Aspects to be reviewed (points of paragraph 1)	(a) to (f)	(a) to (f)	(a) to (f)

In the case of bathing waters previously classified as ‘excellent’, the bathing water profiles need be reviewed and, if necessary, updated only if the classification changes to ‘good’, ‘sufficient’ or ‘poor’. The review is to cover all aspects mentioned in paragraph 1.

3. In the event of significant construction works or significant changes in the infrastructure in or in the vicinity of the bathing water, the bathing water profile is to be updated before the start of the next bathing season.

4. The information referred to in paragraph 1(a) and (b) is to be provided on a detailed map whenever practicable.

5. Other relevant information may be attached or included if the competent authority considers it appropriate. (European Environment Agency, 1975)

Appendix 5 – Popular Science Summary

The Reuse of Treated Wastewater in Industrial Symbiosis

Greta Bürger

Drinking water is currently used for many applications, which do not require as high of a quality. At the same time, treated wastewater is discharged into the environment without being further used. To connect those two topics, this thesis, in collaboration with VA SYD, explores the possibilities for a more conscious water usage.

The reuse of treated wastewater has been done in several countries around the world. These regions suffer from occasional or permanent droughts, and recent years have shown that even northern Europe can experience water shortages. Sweden does not suffer from water scarcity, but reoccurring droughts, have caused for discussions around the usage of drinking water.

With the help from seven other water associations around Sweden, this thesis looked into, if industries have the possibility and motivation, to use another type of water than drinking water, with a focus on treated wastewater. It was found, that there is a great interest and industries are eager to rethink their water usage. As not all processes in industries have the same water quality requirements, it was further looked into, how these differ. The seven main water reuse possibilities are cooling water, recreational purposes, cleaning of vehicles, boiler water, food industry and process water, wastewater treatment plants and agriculture. As wastewater treatment plants are not designed for the reuse of treated wastewater, additional processes need to be installed to achieve the required qualities. Since wastewater is defined as waste, so is treated wastewater. In order to be able to reuse the water, an end-of-waste procedure could be a solution to re-classify wastewater as a bi-product of an industry. This would enable the water to be reused for other purposes, instead of being discharged into the environment.

The costs to go through with a wastewater reuse project, depend on the location of reuse and the required water quality. To install processes and connect the wastewater treatment plant with the industry can range greatly, due to regional, local and individual circumstances. Industries work towards environmentally benefitting solutions but without an economical benefit of reusing treated wastewater, it seems unlikely for them to contribute to the investment. Drinking water is comparably cheap and easily available in Sweden and for industries to invest in the project, more benefits need to become clear.

Concluding, it was found that industries in Sweden have noticed the water issues and the dry summers during the past years. This has contributed to more awareness and environmental thinking around their water usage. As processes exist to fulfill the quality requirements of the industries, the reuse of wastewater could become a valuable option in the future.