CHALMERS

Analysis of the Membrane Alternatives Suitable for Kvarnagården Water Treatment Plant.

An Evaluation of Hollow Fiber Nanofiltration Membranes

Master of Science Thesis in the Master's Programme Geo- and Water Engineering

HJERPE KIM

OLSSON JONATHAN

Department of Civil and Environmental Engineering
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Examensarbete / Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2012-05

Department of Civil and Environmental Engineering
Division of Water and Environmental Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: +46 (0)31-772 1000

Cover:
Water intake at Lake Neden.

Department of Civil and Environmental Engineering Göteborg, Sweden

Abstract

Observed increases in the concentration of natural organic matter (NOM) in many parts of the world bring a new challenge for the water treatment plants utilizing surface water as a source for their water production. The water treatment plant (WTP) Kvarnagården in Varberg is in need of an additional microbial barrier as well as an improved reduction with respect to NOM substances and color. This report evaluates different membrane alternatives by using a multi criteria analysis based on economic, environmental and operational aspects. The membrane alternatives evaluated are nanofiltration, ultrafiltration and hollow fiber nanofiltration membranes. The report starts out with an extensive literature study where membrane technology and its different applications are explained. Detailed facts and input data about experiences of membrane technology were gained by a survey investigation where membrane manufacturers and water treatment plants participated. Since studies of membrane and fouling behavior have already been conducted at Lackarebäck WTP an experiment was carried out to assess the composition of the raw waters from the two different WTPs. In this way it was possible to assess what performance that could be expected of the membranes in Kvarnagården by comparing with the studies carried out at Lackarebäck. The experiment was performed in the water laboratory at Chalmers University using a nanofiltration membrane. In order to compare the membrane alternatives, different categories considered to have a significant importance in the decision of which membrane alternative to choose were established. The different membrane alternatives were then given scores according to how well they fulfilled each category. The categories that were used were; operational costs, purchase costs, global warming potential, recourse depletion, energy demand, footprint, stops in production and the quality of the permeate water. These categories were then weighted according to their relevance in membrane alternative decision. In addition to the multi criteria analysis different scenarios of where in the water process a membrane step could be implemented were considered. Three scenarios were evaluated where scenario 2a and 2b will be fed with water directly from the sand filters and scenario 3 will be fed with mixed raw water directly to the micro filter and the membrane step. It is concluded by the multi criteria analysis that the new type of HNF membrane seems to be the most promising alternative when all categories are considered. This alternative will be most beneficial if implemented in accordance with scenario 3. However, the positive effects of biofiltration as a pre-treatment will be lost in this scenario which could lead to an increased demand of cleaning and thereby chemical usage.

Key words: Drinking water treatment, Membrane technology, Natural organic matter, NOM, Nanofiltration NF, Ultrafiltration UF, Hollow fiber nanofiltration, Multi criteria analysis.

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1 Preface

In this study surveys to membrane manufacturers and water treatment plants regarding the performance of different membrane alternatives have been carried out from January to April 2012. The work has been done as a part of a study of the different membrane alternatives suitable for Kvarnagården Water Treatment Plant. Also in the study experiments regarding water quality parameters have been carried out at the water laboratory at Chalmers University of Technology. The project is carried out at the Department of Civil and Environmental Engineering and is connected to the company VIVAB, the company in charge of Kvarnagården Water Treatment Plant.

Main supervisor in this project has been Professor Olof Bergstedt and the co-supervisor has been Assistant Professor Thomas Pettersson. Contact person at VIVAB has been Alexander Keucken, R&D Engineer at Kvarnagården Water Treatment Plant. We would like to thank all of them for contributing with ideas and information, making this project possible.

Finally, the authors would like to thank Mona Pålsson for all her help regarding the experiments carried out in this study and Lars Ove Sörman for his help in setting up the experimental equipment.

Göteborg May 2012

Kim Hjerpe & Jonathan Olsson

2 Introduction

Potable water is essential to all life forms, and water with inadequate quality is a major cause for disease and mortality all around the world. The quality of a raw water sources is therefore of great importance in the production of safe and wholesome drinking water. Even though around 70 percent of the earth's surface is covered with water only around 1 percent is available as drinking water. Hence the protection of raw water sources is a major concern. Increased urbanization and industrialization as well as intensive agriculture often lead to increased risks of contamination of water sources. The urbanization also means that there are more and more people that are supplied with water from the same source. This fact shows to an even higher degree the importance of good quality raw water, since a contamination event in this case could fatally affect a large number of people. Recently, an additional threat especially to surface water has been noticed, the climate change with increased global mean temperatures affects the surface water in a number of different ways. This is something that must be addressed by municipalities and water treatment plants in order to ensure a reliable and safe drinking water supply. The main concerns associated with an increased mean temperature regarding drinking water production is the fact that the vegetative season is prolonged in many parts of the world, which leads to an increased production of natural organic matter (NOM) and also the risk of increased precipitation which leads to higher water levels and increased runoff to rivers and lakes but also droughts and water shortage can be expected. High concentrations of NOM in the raw water is a problem in drinking water production since the NOM colors the water and may also reduce the efficiency of some disinfection processes at the water works like UV disinfection. Yet another problem with increased NOM concentrations is that NOM together with Chlorine might react and form disinfection by products (DBP) which can be carcinogenic. An increased water level and increased runoff might also lead to higher microbial and pollution concentrations in the raw water. These new challenges must be dealt with in an efficient and sustainable way.

There are various options available in dealing with these new challenges, however, membrane technology is regarded as one of the most promising alternatives (Di Zio et al. 2005). It is mainly due to its ability to remove NOM and that it does not need any addition of chemicals during operation it is considered promising (Frimmel et.al 2004).The principle of membrane technology is that feed water is pressed through the membranes small pores, particles including contaminants larger than these pores will thereby be separated from the water and the produced permeate water will contain less particles and contaminants than previously. The membrane technology has a wide utility area and except for drinking water production the technology is also used in food and pharmaceutical production and waste water treatment among other. Membranes are divided in different categories depending on the pore size. The categories are microfiltration (MF), with the largest pore size, and then ultrafiltration (UF) follows, and finally nanofiltration (NF) and reverse osmosis (RO) has the smallest pore sizes. Depending on the prerequisites at each specific water treatment plant different membrane solutions are more beneficial. At some places for example where there are problems with salt intrusions in the ground water aquifers there might be a need to implement the RO process to lower the salt concentrations. Using membranes with very small pore sizes like NF or RO often requires some kind of pretreatment step to prevent the membranes from damage, this pre-treatment might be an MF membrane or some other type of filters to separate the larger particles before the actual membrane step. Generally, the tighter the membrane is the more pressure is needed to push the water through it. This means that MF generally needs less energy than UF, NF or RO, hence it is a balance between energy demand which is connected closely to costs and an acceptable water quality. The development of new membranes focuses a lot on energy efficiency while still maintaining good removal efficiency. The benefits of membrane processes are that they have a good capacity to remove a wide range of contaminants using less amounts chemicals than conventional processes. The membrane processes are also to a high extent automated processes which is time efficient in considering the need for personnel controlling the process (Di Martino et al. 2007).

3 Background

In Varberg, a municipality located around 70 km south of Göteborg on the Swedish west coast, most of the drinking water is produced by the WTP Kvarnagården. The raw water supply to this WTP is primarily surface water but before the intake surface water is mixed with ground water. The present treatment train at the WTP begins with an adjustment of the waters hardness, pH and alkalinity by using lime and carbonic acid. Thereafter the water is filtered through a sand filter and after that the water is mixed with chloramine and finally before distribution the water is subjected to UV light as a last microbial barrier.

One of the challenges that this WTP is facing is the need for an additional microbial barrier as well as a need to reduce color and NOM in the water. The present treatment at the WTP needs to be improved,   especially when future climate change is taken into account. Since the raw water source is surface water it is believed to be subjected to an increased load of NOM and possibly also increased amounts of microbial contamination. This is due to the fact that climate change might result in increased rain intensity in the specific area which will lead to higher water levels and runoff which in turn will lead to increased contamination of the raw water (IPCC 2007). To cope with these more challenging conditions the WTPs performance needs to be increased with respect to these factors.

There are numerous actions available to face these challenges, VIVAB the company that manages Kvarnagården WTP have primarily focused on membrane technology as the intended solution. Membrane technology is not a new technique but it is presently not in wide use in Swedish drinking water production. To cope with the challenges facing Kvarnagården, VIVAB have considered three different possible membrane alternatives. The first alternative is to use UF membranes as an additional microbial barrier together with a coagulant to remove color and NOM. The second option is to use NF membranes which will act as both a microbial barrier and remove color and NOM without the need for coagulation. The final alternative is to implement a new type of membrane sometimes called a cross over membrane or hollowfiber NF membrane (HNF), which is a membrane with a pore size equal to an NF membrane but with the design of an UF. This new type of membrane is believed to result in a less energy demanding operation of the water treatment process but with sufficient removal of contaminants. The energy use of the everyday operation of the plant is of great importance in the selection of which type of membrane to use. To evaluate the performance of the new membrane it is therefore interesting to compare its performance with the other membrane alternatives regarding some key parameters.

4 Aim

The aim of this study is to evaluate which membrane alternative that is most suitable for the water treatment plant Kvarnagården by using multi criteria analysis based on economic, environmental and operational aspects of each of the membrane alternatives ultrafiltration, nanofiltration and hollow fiber nanofiltration.

5 Method

As a start, a detailed description of the water treatment plant Kvarnagården and the different ideas of how to implement membrane technology in the existing plant is provided. In this section the different pilot trials and studies performed at the treatment plant will be described. The data material that was the basis for this section was provided by VIVAB. By conducting an extensive literature study regarding previous work in the field of membrane technology in potable water production the main part of the technical understanding of this field was acquired. This literature study is presented in the beginning of this report to provide a basic understanding of the different areas covered. The more detailed parts regarding the function of the different membrane alternatives on the market were acquired by a survey, where the major membrane manufacturers were approached by telephone as well as a questionnaire. To somewhat widen the perspective, different WTPs around the world utilizing membrane technology in full scale operations were also approached by telephone as well as with a similar type of questionnaire, however, with questions more adjusted for WTPs. Detailed information regarding the structure of the two different questionnaires can be reviewed in Appendix A. The results of the two questionnaires were compiled and used as a basis for calculations and estimations of the different categories that are a part of the multi criteria analysis (MCA) performed as a conclusion of which of the membrane alternatives that are most suitable for Kvarnagården WTP. Since more studies of membrane technology and fouling behavior have been conducted at Lackarebäck WTP in Göteborg, it was considered valuable to assess whether the raw water from the two different WTPs were similar in their composition regarding constituents associated with fouling problems.

Therefore an experimental analysis was conducted in this project. The aim of the experimental part was to measure different key parameters of the raw water from each WTP in order to assess whether the composition of the different raw waters could be considered similar. The experiments were conducted during two weeks in the water laboratory at Chalmers University of Technology. Parameters measured were DOC, turbidity, color, UV absorption and calcium for both water types. However, to get an indication of the fouling potential of each water type a filter house fitted with NF membranes was used to filter both types of water, see figure 1. By keeping a constant pressure of around 5 bar and measuring the time needed to filtrate 500 ml key parameters regarding the membrane function like flow and flux could be measured and calculated. The membranes used in each trial were of the same quality and size and were weighed before and after the filtration cycle. In this way the weight increase is measured before and after the filtration, this value is used as an indicator of the amount of fouling accumulated on each membrane. A detailed description of the experiments conducted in this study can be reviewed in Appendix B.

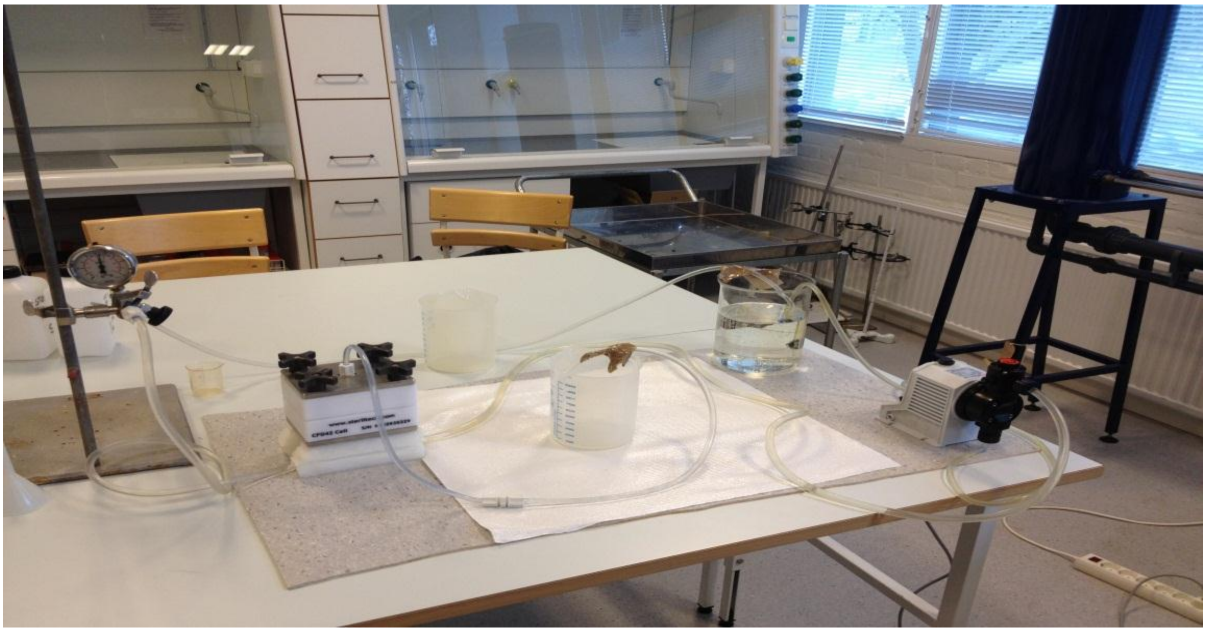

Figure 1. This figure shows the setup of the experimental filtration trials, using a filter house fitted with an NF membrane.

The different categories used in the MCA were chosen to cover most aspects associated with the decision of which membrane solution to apply. The estimations that were used as a basis for the MCA is carried out for each membrane alternative regarding energy demand, chemical use, global warming potential, resource use, expected area of the membrane system, the risks of stops in production due to technical failure of the system, the expected water quality of the water produced and the risk of DBP formation and finally estimations regarding the costs associated with the different membrane alternatives. For a membrane alternative to be considered a feasible alternative it has to fulfill basic standards for drinking water. The guideline values used were taken from Swedish Livsmedelverket (SLV FS 2011). After the MCA the different scenarios of implementation of the membrane technology in the existing plant will be addressed. To provide an estimation of which of these scenarios that could prove to be most beneficial.

6 Kvarnagården WTP

Kvarnagården WTP is located in the northern part of Varberg city. The raw water is taken from Lake Neden by a water intake in the southern part of the lake, see figure 2. Around the lake there are no industries or residential areas, no agricultural areas that may threaten the water quality. However, there is a road in connection to the most northern part of the lake which could affect the water quality, if an accident would occur. Hence, the water in the lake is considered relatively free from pollution and microbial contamination. However, since there are forested areas all around the lake the concentration of NOM and color are a problem and this is therefore the main treatment goal. From the raw water intake the water is lead through a tunnel down to Kvarnagården WTP. Before entering the WTP the lake water is mixed with ground water extracted from a nearby aquifer called Ragnhilds källa. The annual average flow that may be taken out from Lake Neden is around 300 l/s. From the aquifer the maximum allowed extraction is 80 l/s. However, presently only around 150 to 200 l/s is taken out from the lake depending on the season. Apart from these regulations there is also a requirement of the minimum water level in the lake which is 76,5 m, lower water levels than this requires pumping of water from the nearby lake Mäsen, which is at an elevation of 51 meters i.e. the water needs to be pumped up 25,5 meters and is therefore not preferred (VIVAB 2012).

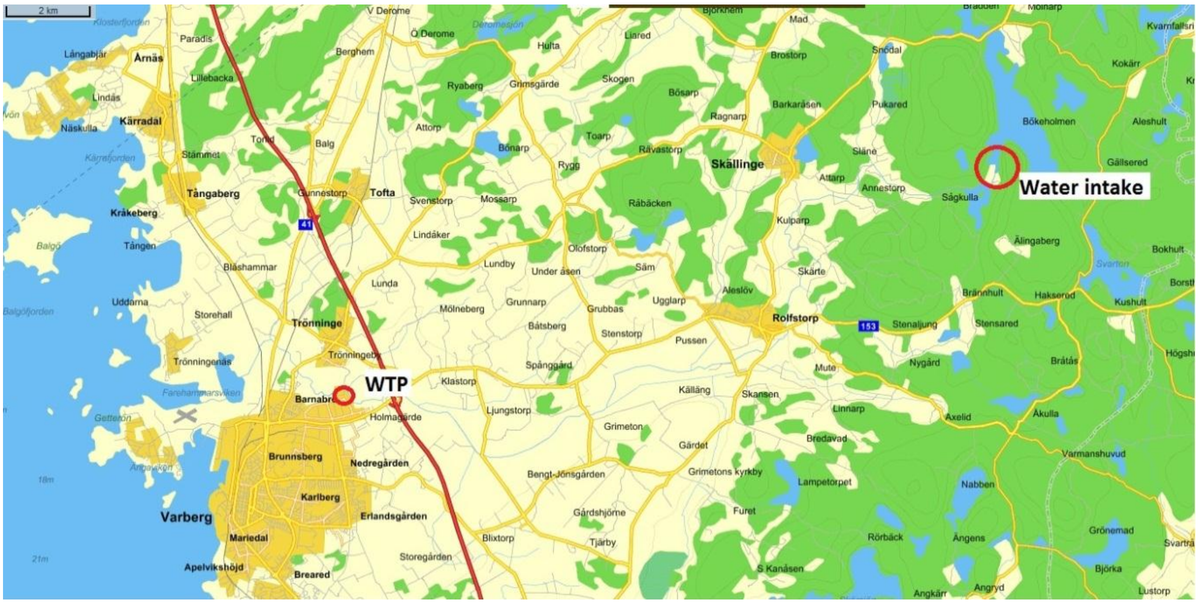

Figure 2. This figure shows the geographic locations of the water source, the water intake and Kvarnagården WTP.

As mentioned above the lowest acceptable level in Lake Neden is 76,5 meters, however, the intake at the WTP is located at an elevation of 8,8 meters. This means that there is positive potential energy of the incoming water. The potential energy is used by letting the water pass through a turbine at the intake before any treatment processes. This turbine has a maximum capacity of 200 liters per second. The mentioned elevations as well as the elevations of other important processes in the treatment are presented in table 1.

Table 1. Table 1 shows the elevations of different key points regarding the water treatment.

Location	Elevation (m above sea level)
Neden, lake	76,5
Excavation, bottom	9,25
Excavation, overflow	14,4
Sand filter, intake	13,1
Sand filter, outflow	12,4
Low reservoir 1, bottom	7,5
Low reservoir 1, overflow	10,5
Low reservoir 2-3, bottom	7,5
Low reservoir 2-3, overflow	10,5
Turbine, floor	8,8

The current treatment at Kvarnagården WTP starts with a reservoir where lime and carbonic acid is mixed with the raw water. This is done to adjust the waters hardness, alkalinity and pH, see figure 3. After that 10 parallel sand filters are installed, after the water is filtered it is lead to three reservoirs in a row, see figure 4. Chloramine is added to the water before it is pumped from the reservoirs through two parallel UV-light installations, which act as a microbial barrier. The chloramine is used to prevent microbial growth in the network (VIVAB 2012).

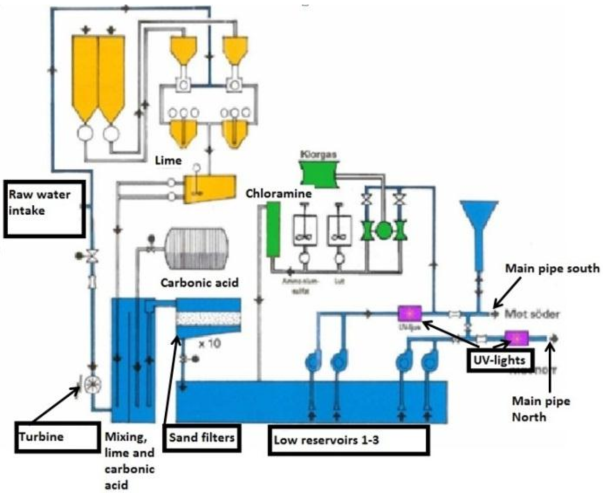

Figure 3. This figure illustrates the present water treatment process in Kvarnagården WTP.

The current average flow through the WTP is 176 liters per second of which 6 liters per second are used for the lime addition. However, during eight months it is possible to take out 300 l/s from the lake without lowering the water level below the limit where it has to be filled up from Lake Mäsen. During the summer months 200 l/s may be withdrawn without risking a too low water level in Lake Neden. At current operation around 570 MWh/year is produced

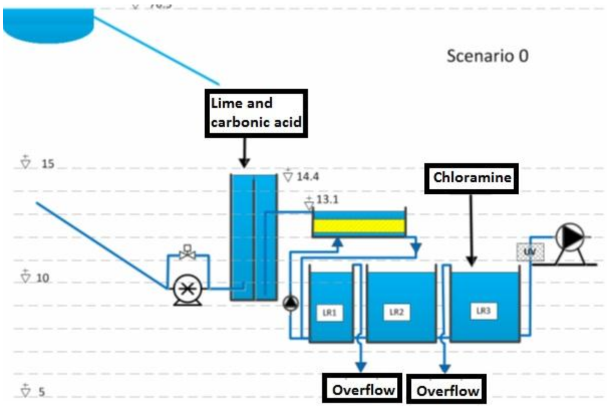

Figure 4. This figure shows a more conceptual view of the present treatment at Kvarnagården WTP.

by the turbine (VIVAB 2012).

However, since the regulation of the lakes water level allows a larger out flow than what the current turbine can handle there may be reason to invest in a new turbine with a higher capacity, preferably a turbine with a max efficiency at flows around 300 liters per second, see figure 5. This is due to the fact that it is possible to take out around 300 l/s during 8 months a year. During the summer months the out take from the lake according to the regulations can only be 200 l/s due to the increased evaporation during 4 warmer months. If these allowed flows instead would be taken out some of the water that passes through the turbine will have to be overflowed to the river Himleån adjacent to the WTP since the water demand only require treatment of around 176 liters per second. To make the most out of this overflow water an additional turbine could be installed in the overflow pipe, see figure 5. This could increase the energy production at the WTP even more. It is estimated by VIVAB that the energy production with this new higher flows and the upgrade with new turbines could be around 898 MWh/year, which is an additional 328 MWh/year compared to present system (VIVAB 2012).

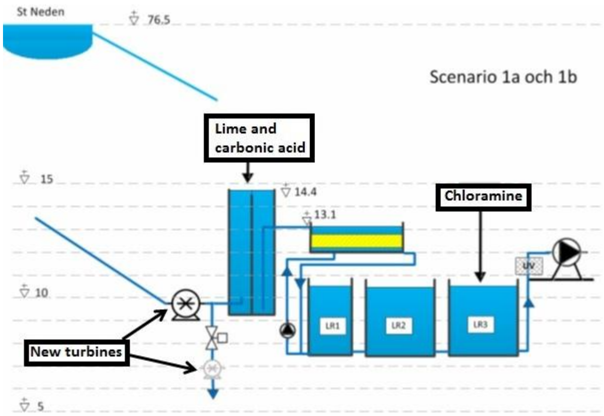

Figure 5. This figure shows the a conceptual view of the WTP with increased flow through the new turbines.

However, the WTP needs an upgrade in its treatment processes since increased NOM concentrations have been observed in the surface water at Lake Neden, also the WTP needs an additional microbial barrier according to the Swedish health administration (Livsmedelverket). The regulations regarding microbial barriers are based on the raw water source. Depending on the raw water source the microbial barriers recommended is between 1-3 barriers. However, in Kvarnagården two barriers of different kind is required (SLVFS 2001:30). For this reason membrane filtration will be implemented in some way at the WTP. There are currently three different scenarios of how the membrane technology may be implemented in the current treatment. These alternatives are called scenario 2a, scenario 2b and scenario 3. For both scenario 2a and b the membrane-filters will be fed with permeate from the sand filters. In case of UF the coagulation chemicals will be added prior to the membrane step continuously or temporarily in case of high NOM concentrations. The increase of hardness will be moved downstream of the UF to not interfere with the coagulation. Also in both scenarios it is assumed that a new turbine with a 300 liter per second capacity is installed.

In scenario 2a the membrane is fed from the first low reservoir with water from the sand filters, see figure 6. In this scenario low reservoir 1 is also used for backwash of the sand filters. After the membrane filtration lime and carbonic acid are added to the water for hardness, pH and alkalinity control in low reservoir 2. In low reservoir 3, chloramine is added and from there the water is pumped through the UV lights and thereafter distributed as before (VIVAB 2012).

In scenario 2b the membranes are fed directly from the sand filters and low reservoir 1 is in this case divided in two parts where half of it is used for backwash of the sand filters and the other half is used for permeate from the membranes, see figure 7. Hardness, pH and alkalinity control will then be performed in one half of low reservoir 1 and the rest of the treatment will be as in scenario 2a (VIVAB 2012).

In scenario 3 the fed water to the membranes is taken directly from the intake water and the flow and pressure is regulated by valves, see figure 8. The membranes and strainers for the membranes may then be put in the same area as the sand filters previous location, since these filters will not be used in this scenario. As for scenario 2a and b it is assumed that two new turbines are installed. The advantage in this scenario is that there may be no need to pump the water through the membranes since the potential energy of the incoming raw water may be used. However, the actual use of the potential energy from the lake has to be evaluated for each different membrane alternative. Even though the potential savings in energy associated with scenario 3, there are risks of pressure fluctuations in the incoming water in this setup. This might damage the processes and the membranes and lead to stops in the water production (VIVAB 2012).

To get an overview of the different membrane alternatives VIVAB has made calculations of what energy production and demands that the different scenarios if implemented may lead to, see table 2. The calculations of energy demand are based the values associated with an UF membrane for each scenario, values of energy demand are

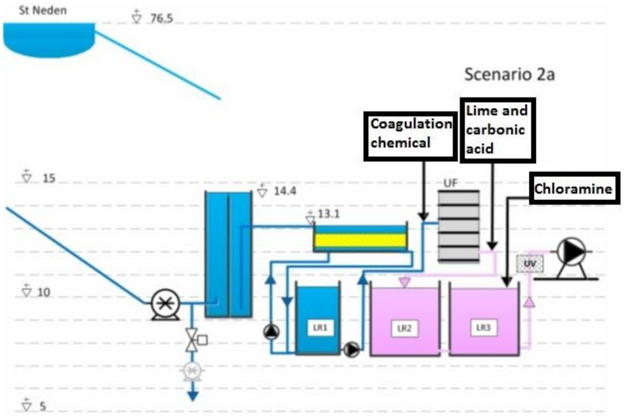

Figure 6. This figure show the conceptual setup in scenario 2a where the membranes are fed from the sand filters.

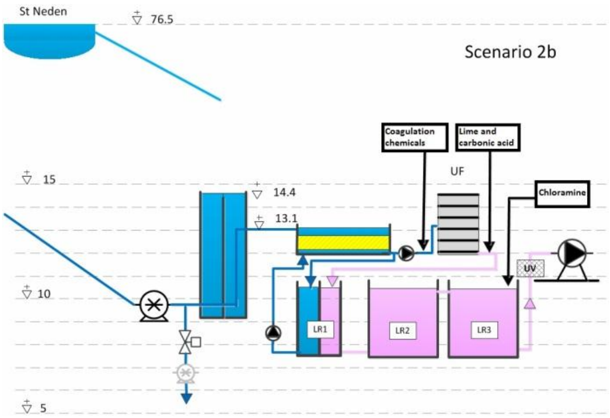

Figure 7. This figure shows the setup according to scenario 2b where the membrane are fed directly from the sand filters.

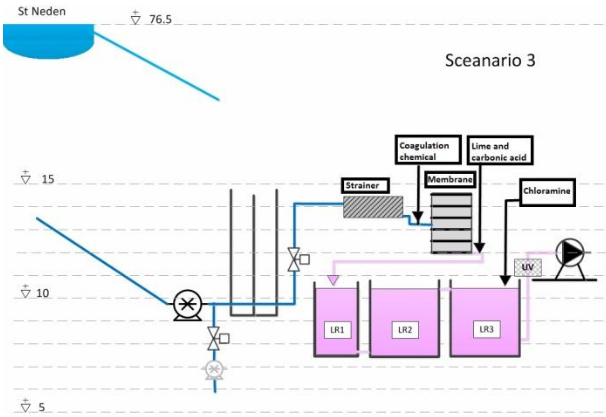

Figure 8. In this figure the setup in scenario 3 where the membranes are fed directly from the raw water by utilizing the potential energy of the lake can be reviewed.

therefore not representative for the use of NF or HNF alternatives.

Table 2. This table shows an overview of the energy production and demand associated with each scenario of implementation (VIVAB 2012).

Scenario	Energy (MWh/year)	Energy demand (MWh/year)
2a	855	163
extra turbine	43	-
2b	855	125
extra turbine	43	-
3	705	-
extra turbine	97	-

A number of different studies have been conducted regarding membrane alternatives at Kvarnagården WTP. The most extensive was a trial where an UF pilot plant was tested during almost one year from October 2010 to late September 2011. These trials showed that the water quality produced from these trials did meet the requirements of potable water and in many cases to a higher degree than present treatment at the WTP, see table 3. However, as can be seen in the table, also the mean values of the raw water fulfill the requirements for the most common parameters (VIVAB 2011).

Beginning in late 2011 pilot trials with the new type of HNF membranes were started at Kvarnagården WTP. In these pilot trials the new HNF membrane is fed directly with mixed raw water. The results from these trials are not yet complete. However, some preliminary results from November 2011 to February 2012 are available. These results are also presented in table 3 and compared to guideline values. The values shown in the table are mean values during the time period[1]. From this pilot trial it has also been shown that the observed fouling has been quite limited even though the membranes are fed with raw water without pre-treatment. The cleaning frequency of the membrane has been once every 7th day but scaled down to once ever 14th day without any indications of limiting pressure drops or irreversible fouling[2].

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[1] Alexander Keucken (R&D engineer Kvarnagården WTP) from an excel sheet retrieved through e-mail

[2] Alexander Keucken (R&D engineer Kvarnagården WTP) from e-mail correspondence 2012-05-21.

Table 3. This table shows the mean quality of the raw water of some common parameters and the results of the different pilot trails conducted at Kvarnagården WTP. Guideline values from SLV FS 2001 and LIVSFS 2005:10, are also shown as a comparison.

	Regulations for drinking water	Raw water Neden	UF trial Kvarnagården	HNF trial Kvarnagården
Color [mg/l Pt]	15	13,8	5,2	0,12
Turbidity [FNU]	0,5	0,17	<0,100	<0,121
TOC [mg/l]	5,5	3,2	2,3	0,7
Manganese [mg/l]	0,05	<0,01	<0,01	<0,02
Iron [mg/l]	0,100	0,027	<0,02	<0,02
Aluminum [mg/l]	0,100	-	0,023	-
Coli.bacterias [/100ml] (35°C)	Establ.	<1	<1	<1
E.coli bacterias	Establ.	<1	<1	<1

In another study, of the raw water of Kvarnagården and the efficiency of present treatment mainly focused on NOM characterization have been performed by (Lavonen et al. 2012). Some of the results from this study regarding Kvarnagården WTP are presented in chapter 8.3.

7 Possible effects on surface water due to climate change

The effects of climate change is rather hard to specify with accuracy, however, there are outcomes that are considered more likely. One of these effects, believed to occur due to climate change is drought. For rivers and lakes solely supplied by rain water drought has a severe effect on the water availability. This lack of water may lead to water shortage in a time period when the water demand is at its peak. Less runoff and rain water also means that contaminants will have a higher concentration relative to the water body, this is especially a problem for surface water bodies with a constant pollution source adjacent, for example where waste water treatment plants are located upstream of a raw water source. Droughts also lead to increased temperatures in the water which encourage microbial growth. Also chloride concentrations are increasing in surface water during droughts, depending on how severe the drought is and during how long time it forth goes the chloride concentration in the water might exceed the threshold value for drinking water production of 150 mg/l (Senhorst & Zwolsman 2005).

In order for drinking water treatment plants to maintain a safe drinking water production the temperature of the raw water needs to be below 25 degrees Celsius (Ramaker et al. 2005). This is important since a too high water temperature will result in extended microbiological growth. Another problem regarding climate change and longer dry periods is the fact that water consumption is often increased during these events, where at the same time the supply of raw water is lowest. During long dry periods contamination and pollution will reach higher concentrations in the surface water because of less dilution from runoff water. All these factors accumulated means that the challenges producing drinking water during dry periods is increased (Ramaker et al. 2005). One way of dealing with large seasonal variations in the supply of raw water is water storage, this concept is when water companies' use large surface water reservoirs to meet seasonal peak demands. Surplus water could also be stored in aquifers to meet the increased demand during dry periods (Ramaker et al. 2005).

Meteorology and weather patterns are closely connected to changes in surface water quality. Fresh water sources are of great importance to human society and changes in the climate have a large potential to severely affect fresh water resources. According to 2007 IPCC report heavy precipitation events have likely already increased over most areas and especially in Europe and Northern America. The frequency of short duration heavy rainfall events have probably already occurred and likely this trend has not yet reached its peak. Because of these shifting flow regimes, caused by changes in the climate, the chemistry, hydro morphology and ecology of water bodies will be altered (Whitehead 2009). This will especially be true for surface water sources where increased runoff transports more suspended solids, chemical substances and pathogens. Also adding to this problem, especially regarding the northern parts of Europe and North America, is the prolonged vegetative season due to the warmer climate that results in an increased production of NOM (Pardue et al. 2005; Delpla et al. 2009; Curriero et al. 2001). There is also a risk of failure in the water treatment plants, leading to outbreaks of water-borne disease, because of overloads in the treatment due to excessive precipitation (Kistemann 2002). Storm events like the ones mentioned above may be very troublesome to handle for water treatment plants using conventional treatment. Furthermore, most of the transports of DOC from catchments to the treatment facilities are taking place during these storm events (Fellman 2009). This fact together with the observed increase in NOM concentrations in natural waters during the past two decades caused by the reduction of acidic deposition is adding to the problem (Evans 2005).

8 Membrane technology

Membrane processes is a separation technique where the differences in the feed waters permeability is used as a separation mechanism. In the membrane process water is pumped towards and through the membrane surface resulting in a stream of treated water, called the permeate. The main advantage with membrane technology according to (Di Zio et al. 2005) is that this process requires less need for chemical agents than conventional systems. Furthermore, separation takes place by size exclusion which is less sensitive to changes in the feed water quality. The production of permeate is constant and permeate quality is fairly independent of feed water quality. The membrane process is also a quite compact process and quite easy to extend and automate comparing to conventional systems (Di Zio et al. 2005).

The pore size of membranes is usually divided into four sizes; microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). The suitable pore size depends on the specific requirements of the user. As table 1 shows smaller pores will be more efficient in their effect, but the need for added pressure, i.e. energy is proportional to the reduced pore size. The material of a membrane will influence factors like mechanical strength, fouling resistance, hydrophobicity, hydrophilicity and chemical tolerance (Pilutti et.

al 2012). The categorization between the four different classes of membranes is shown in table 4. The borders between the different filtration techniques are not absolute. Some manufacturers sell their membranes as UF even though the pore sizes more resembles an NF membrane and vice versa. Generally, membrane technology in water treatment is used to remove microbial contaminants such as bacteria, protozoa and virus and most membranes with pore sizes smaller than UF grant a good removal of these contaminants. In membrane technology also small colloids, dissolved organic matter may be removed, however, depending on the pore size. For RO the most common application is desalination of brackish or sea water.

Table 4. This table shows the differences between the membrane alternatives (Van der Bruggen et al. 2003).

	Microfiltration (MF)	Ultrafiltration (UF)	Nanofiltration (NF)	Reverse Osmosis (RO)
Permeability (l/h.m2.bar)	>1000	10-1000	1.5-30	0.05-1.5
Pressure (bar)	0.1-2	0.1-5	3-20	5-120
Pore size (nm)	100-10000	2-100	0.5-2	<0.5
Rejection:				
Monovalent ions	-	-	-	+
Multivalent ions	-	-/+	+	+
Small organics	-	-	-/+	+
Macromolecules	-	+	+	+
Particles	+	+	+	+
Separation mechanism	Sieving	Sieving	Sieving/charge effects	Solution-Diffusion
Applications	Clarification; Pretreatment; Removal of bacteria	Removal of macromolecules, bacteria and viruses	Removal of (multivalent) ions and relatively small organics	Ultrapure water; desalination

In membrane technology one of the hardest parameters to control is the virus removal. Since protozoa and bacteria are larger it is easier to measure how much that is rejected by the membrane. However, virus is harder to control because of their smaller size. This means that the WTPs has to trust the information provided by the manufacturers, and assume that if the membrane is intact for bacteria and protozoa it is also intact for virus (Humbert et al. 2011). There are three general field methods of measuring and monitoring the water during treatment; in situ, on-line and off-line. In situ means that a sensor is put in the water that is supposed to be measured, this means there is no sampling step. In on-line measurements however, a sample is needed, generally this sample is pre-treated and measured. The measurement is often done using an optical technique. Finally, the off-line method requires a spot-sampling step and after that an analytical method. These different tools may be used to determine the characteristics of the water in a fast way (Roig 2009). They are therefore useful when fast flow variations occur (Roig 2011). In drinking and waste water plants today in situ measurements are done for parameters such as temperature, pH, redox potential, conductivity, dissolved oxygen, free chlorine, total chlorine, total organic carbon (TOC), nitrates, nitrites, ammonia, turbidity and particle counts (Yang et al. 2009).

In a membrane process there must always be a driving force in order to make the water pass through the membrane. How this force is applied will also have a significant role for the membrane properties because it determines what particles will be able to pass. This force can be accomplished by a pure physical process where a pressure is added, it could be differences in concentrations or an electric field. In drinking water production a pressure is normally applied to the feed side of the membrane. An important property of membranes is the allowed trans-membrane pressure (TMP). The TMP is the pressure difference between the pressure at the feed side and the pressure at the permeate side (HOH 2012).

Membrane technology is not only used in the production of potable water, but also in medicine and food industry. Usually, the main cost of operating a setup of membrane modules is associated with energy consumption. Other costs in membrane operation are connected to the expected lifetime of membrane module as well as the chemical usage regarding chemical cleaning and use of coagulation chemicals. These two factors are very much dependent on the adjustment of the membrane operation to the specific conditions, i.e. the quality of the raw water. Water with unfavorable quality will increase the chemical usage and decrease the membranes life time (Busch & Marquardt 2009). Generally, the life expectancy of a membrane module is around five years, however, in a WTP study by (Laine et al. 2000) operations have been performed with the same modules since 1988 but still the water produced were of good quality. This indicates that even the earlier types of membranes actually worked longer than the five year life expectancy. Therefore, even though five years is the common life expectancy for membranes used in capital cost calculations it could be considered a conservative calculation.

In filtration processes, the pore size of the membranes affects the pressure that is needed to achieve a flux (specific flow [l/m^2*h]) of water over the membrane area that is sufficient. Therefore, MF needs the least pressure of the feed water while RO needs the most (Van der Bruggen et al. 2003). Most often the limiting factor of the operation of membrane processes is fouling which will be explained in more detail later in this chapter. However, fouling is the general definition of the blocking of pores in the membrane. This blocking may be due to various reasons and substances, however, the most common are organics, minerals, colloids, microbial contaminants and particles on the membrane surface (Flemming, 2002).

There are different perspectives regarding the development of membrane techniques, this is most likely due to the wide range of different fields that membranes may be used. Regulators most often seek to minimize the risk of human exposure to pathogens, while plant operators seek a more reliable method of providing integrity assurance, since current methods are not sufficiently sensitive to quantify microbial content of the water at a sufficient resolution. Membrane defects may occur at many different levels from manufacturing, shipping, installation and operation. A good quality assurance may prevent this in all stages (Johnson & MacCormick 2003).

There is a constant development of membrane technology, a leap forward in this development were the composite thin film (CTF) membranes. These membranes consist of a thin separating layer, the active layer which determines the membranes removal capacity, as well as one or more supporting layers that have a larger pore size than the active layer. The supporting layer is only used for stability and to improve the rigidity of the membrane and does not affect the permeability. These types of membranes are called asymmetric membranes and one of the main benefits associated with them is that they combine high flux with mechanical strength (Van der Bruggen et al. 2003).

Recovery is a commonly used parameter in membrane technology, the recovery of a full scale membrane installation is described as the ratio between the permeate stream and the feed stream. Since some water is used for cleaning of the membrane some of the feed water is usually lost as a concentrate stream that is sent to the waste water system. The recovery may vary between different WTPs and different membrane models, typically the recovery is affected by the quality of the feed water as well as the pre-treatment in the plant previous to the membrane process. Generally, the recovery of a full scale treatment ranges between 50 and 90 percent, however, typically it is above 80 percent. Usually it is beneficial from an energy and resource point of view to achieve as high recovery as possible (Van der Bruggen et al. 2003).

In a study made by The University of Central Florida in cooperation with the American Water Works Service Company Inc., five different membrane filters removal capacity were tested for five different species of microorganisms in a water treatment plant in St. Louis, MO, USA. The membranes tested were a cellulose acetate UF, a polysulfone MF, a cellulose acetate NF and two CTF NF membranes. The feed water in these trials was aluminum coagulated and settled water and finished plant water. The different microorganisms that were used in the experiment were Clostridium perfringens spores for bacteria rejection, MS-2 and PRD-1 phage for virus rejection and finally Cryptosporidium parvum oocysts and Giardia lamblia cysts for protozoa rejection. The results of the tests showed that the CTF NF provided a clearly better rate of disinfection than the cellulose acetate NF membranes. Somewhat surprising however, a cellulose acetate UF membrane rejected more than any of the other tested membranes. The interpretation of this fact is that cellulose acetate membrane rejection is a function of construction of the membrane element rather than the material of the membrane. Also observed in these tests was that one of the CTF NF membranes the smallest organisms MS-2 phage only past the membrane in two of seven occasions while the much larger Clostridium perfringens passed the same membrane on three of seven occasions. This indicates that the operation of the membrane could affect the rejection and that membrane filtration is not an absolute barrier and that it is important to control the process (Lovins et al. 2002). Yet another reason not to view membranes as an absolute barrier the fact that the median pore size is often larger than the nominal size given by the membrane manufacturers. Membranes may also be partially damaged and seals may leak, also some organisms might be able to pass a pore smaller than their normal size as they divide. There may also be growth on the clean side of the membrane (Ghayeni et al. 1999).

In a study by (Westrell et al. 2002) of the environmental impact of different types of drinking water production systems, it was found that the main environmental aspect in this area was the energy consumption. In this study three different drinking water production systems were tested; one alternative utilizing a conventional treatment with chemical precipitation, activated carbon and chlorination. The other two tested systems were methods of implementing one respectively two decentralized membrane filtration steps. The one membrane system was a system where an UF membrane was installed locally at the consumers. The last of the tested systems were a two-step decentralized membrane system utilizing an MF step for all water and an extra RO unit that were only implemented for the potable water. The energy use of the different systems showed that the conventional and the two step membrane system required relatively equal amounts of energy while the one step UF system required less energy. The quality of the water produced in the one step UF membrane system had a higher quality than the conventional system but a sufficient water quality could not be guaranteed in this system either. However, the quality of the water produced in the conventional system where found to be inferior, especially to the two step membrane system.

In a study performed by (Porcelli & Judd 2010) operational costs regarding energy demand was evaluated for a WTP utilizing an UF membrane. A clear pattern of the most energy consuming stages could be observed. Head loss pumping, heating and waste treatment was in general consuming the most energy. Backwash pumping and chemical consumption contributed with approximately 0,2 – 1,8 percent of the total energy consumption (Porcelli & Judd 2010).

8.1 Materials used in membrane technology

Most commonly drinking water membrane materials are manufactured from synthetic polymers. However, ceramic and metallic membranes are available as well. It is mainly the low cost of synthetic polymer membranes that made this material dominating in the market for drinking water membranes (USEPA 2005). The different materials used can vary significantly in chemical and mechanical properties. The varying properties could be burst pressure, oxidant tolerance, VOC tolerance, pH operating range and so forth. Another essential property for a membrane material is whether the membrane is hydrophilic or hydrophobic. A membrane which is hydrophilic means that it is attracting the water molecules, a hydrophobic membrane on the other hand repels the water molecules. If the material is water repelling or attracting has to do with the surface tension. When liquids have lower surface tension than a membrane the membrane will attract the liquid and it will spread on the membrane material. Whether the membrane consists of a material with hydrophilic or hydrophobic character will influence the wet-ability and applied pressure requirements of the feed flow to the membrane (Pilutti.M et.al, 2012).

8.1.1 Cellulose acetate

Cellulose acetate is mainly used for NF and RO membranes (US EPA). Cellulose acetate is derived through reaction between acetic anhydride, acetic acid and sulfuric acid. Cellulose acetate could be considered a hydrophilic material which is preferable as it decreases fouling. Other advantages with cellulose acetate as a membrane material are low cost, easy to manufacture and that it can made in all pore sizes. Among the disadvantages with this material is the narrow temperature range, narrow pH range, poor resistance to chlorine and the susceptibility to microbial attack. The temperature recommended by manufacturers of cellulose acetate membranes are a maximum of 30 degrees Celsius. This affects the flux properties of the membrane material due to the fact that higher temperatures lead to higher diffusivity and lower viscosity which increases the flux (Cheryan.M, 1998). The pH range is mainly troublesome when considering cleaning agents. The pH range for cellulose acetate membranes are usually restricted to pH 3-6 but should preferably be between pH 2-8. The life length of a cellulose acetate decreases more the more the pH interval is challenged. Life length of cellulose acetate membranes are also shortened by contact with chlorine. The cellulose acetate material tends to oxidize with chlorine resulting in opening of pores on the membrane surface (Cheryan.M, 1998). In the beginning, this is an advantage because it increases the water flux but in the long term it affects the life length. When chlorine is a commonly used chemical in the water industry cellulose acetates sensitivity to chlorine poses a big problem.

8.1.2 Polysulfone

Polysulfone is mostly used for MF and UF in membrane technology (HOH vattenteknik). The material is characterized by its high tolerability to different pH and temperature ranges. The pH can have a range between 1 to 13, and the temperature could be up to 75 degrees Celsius (Cheryan.M, 1998). Naturally this facilitates the cleaning procedures of the membrane to a high extent. Polysulfone also has a fairly good resistance to chlorine. However, long exposure to chlorine can damage the membrane film. The membranes made of polysulfone are easy to manufacture and are made in a range of different pore sizes. The disadvantages with polysulfone material used in membranes are the pressure limits and sensitivity to fouling. Polysulfone is a hydrophobic material which leads to more reaction with other solutes, consequently polysulfone is vulnerable to fouling (HOH vattenteknik).

8.1.3 Ceramic

Since membrane filtration processes are considered to be energy intensive there is a need for less energy demanding, low pressure alternatives. The membrane material is therefore of interest, since it has a significant effect on the energy demand. An interesting alternative in this respect are ceramic micro filters. Due to their physical properties, mechanical stability and resistance to chemicals studies have suggested that these types of membranes are superior to organic membranes especially regarding cleaning procedures (Weber et al. 2003). This is of importance especially considering NOM which is identified as a major contributor to membrane fouling (Yamamura et al. 2007). Because of the ceramic membranes tolerability to chemicals a lot of different chemicals may be used to clean them and therefore removal of fouling and the restoration of the membrane performance is improved. This indicates that ceramic membranes may very well be a good substitute to polymeric membranes in drinking water treatment (Lerch et al. 2005). The higher investment cost of ceramic membranes can be diminished by operating the ceramic membranes with higher fluxes and by considering their longer lifetime. However, one of the main disadvantages regarding ceramic membranes are the high concentration of metals observed in the permeate at low pH values and high coagulant doses. For a practical implementation it is therefore important to choose operating conditions that will comply with the regulations of metal concentrations in potable water production (Meyn & Leiknes 2010).

8.2 Operation strategies in membrane technology

The actual operation of the membranes is usually divided into two different types of methods, cross flow and dead end filtration. In dead end filtration the water flows orthogonally to the membrane and all water that is fed has to penetrate through the membrane surface. In a cross flow system on the other hand the water flows parallel to the membrane surface and feed water that is not passing the membrane to the permeate side is recirculated to the feed side again (Meier et al. 2006). The advantage with dead end mode is that it is a less energy demanding mode of operation, since no water needs to be recirculated. However, the dead end operation is considered to be more susceptible to fouling. In cross flow the fouling formation is somewhat prevented by the cross flow. The cross flow creates shear- and buoyancy forces at the membrane surface which can remove particles from the membrane surface and thereby limit the fouling of the membrane. However, there are times in cross flow operations where fouling occurs to an extent that the performance of the membrane is reduced. For both operational methods rejected particles will deposit on the membrane surface and finally the fouling layer will have grown to an extent where the performance of the membrane decreased below the acceptable level. At this point mitigating measures is required to restore the membrane performance (Meier et al. 2006).

8.3 Fouling and maintenance of membrane modules

Fouling is considered one of the main challenges in operating a membrane setup. The fouling decreases the flux of membranes and thereby its efficiency over time. There are ways of dealing with this fouling and the most common ones are to operate the membranes in cross flow, use regular backwashing and chemical or mechanical cleaning (Busch & Marquardt 2009).

There are many different ways to categorize fouling, one way is to categorize the fouling as reversible or irreversible fouling, where reversible fouling is defined as the fouling which is completely removed from the membrane by BW or CEB and irreversible fouling is defined as the fouling that is not removed by cleaning (Zhao et al. 2011). Irreversible fouling can be estimated as the difference between the initial TMP of the first operating cycle and the initial TMP of any subsequent operating cycle, assuming that cleaning is carried out between each cycle. The irreversible fouling may therefore be hard to measure during short run times of the filters, due to the fact that too little irreversible fouling have usually formed to be measurable with accuracy (Peldszus et al. 2011). Another way of categorizing fouling is by the origins of the fouling, most often three different origins can be observed. These origins are inorganic fouling, organic fouling and biological fouling. The way these different groups react with the membrane surface and causes fouling is different, attempts to mitigate fouling has to be developed with this in mind. Primarily the fouling of membranes is due to how large the repelling electrostatic forces between the membrane surface and the potential fouling particle are. These electrostatic forces are mainly affected by pH and the feed waters conductivity, but also the flow and pressure of the feed water against the membrane affects the amount of fouling that can be expected. The main objective to prevent fouling is to minimize the interaction between particles and membrane surface by controlling pressure, flow and by using a suitable pre-treatment prior to the membrane filtration. Theoretically, no fouling will occur as long as the hydrodynamic forces of the feed flow are lower than the electrostatic forces between the particles and the membrane. However, in practice fouling will occur and other measures have to be taken in order to clean and regain the membrane performance (Dahlberg et al. 2009).

8.3.1 Inorganic fouling

Inorganic fouling also called scaling occurs when the concentration of substances adjacent to the membrane surface is higher than one or more salts solubility. When the concentration reach this level the salts precipitates on to the membrane surface and causes scaling, this will decrease the membrane performance. Affecting the inorganic fouling is the ionic strength of the particles in the feed water, where a higher ionic strength will lead to increased saturation and in turn scaling. A higher pH of the water also leads to increased scaling because the higher pH value decreases the solubility of the salts which therefore easier coagulates on the membrane surface. Increased pressure and temperature are yet other causes of increased scaling due to the fact that the solubility is decreased (Dahlberg et. al. 2009).

8.3.2 Organic fouling

The main cause of organic fouling is NOM which is present in all natural surface water. NOM can be categorized in three different groups; hydrophobic, hydrophilic and transphilic (Dahlberg et al. 2009). Sometimes the organic part of the water is also defined as Protein like substances, humic or fulvic acid like substances and colloidal/particulate matter (Peldszus et al 2011). Even though many studies have focused on fouling mechanisms and the fouling composition there is still little agreement on the role of each of these fractions fouling potential. Many studies have reported humic substances as a major constituent of NOM controlling the rate and extent of fouling during filtration of surface water (Yuan & Zydney 1999; Li & Elimelech 2004). Also a study by (Aoustin et al. 2001) concluded that the major flux decline and irreversible fouling were due to the larger humic acid fraction. The hydrophobic fraction of NOM were according to (Nilson & DiGiano 1996) the main reason for flux decline in their study of the influence of hydrophobic and hydrophilic NOM fouling potential on an NF membrane. However, using resin fractionation of NOM (Cho et al. 2000) concluded that higher molecular weight (MW) particles of the hydrophilic fraction were the fraction most responsible for the flux decline. According to (Kennedy et al. 2005; Fan et al 2001) hydrophilic groups is the major reason for fouling. These studies also concluded that reversibility of the hydrophilic fouling was very low. In a study by (Peldszus et al. 2011) a setup with a polymeric UF membrane with a cut off of 400 kDa in laboratory scale size were run with surface water and surface water pre-treated in biofilters and the different groups; protein-like substances, humic and fulvic acid-like substances and colloidal/particulate matter were identified and evaluated according to their contribution to reversible as well as irreversible fouling of the membrane. In this study it was concluded that the protein content of the surface water were to a large extent correlated to the irreversible fouling formed on the membrane. This was suggested to partly be due to the concentration of protein in the raw water but also due to combined fouling layer between colloidal/particulate matter and the protein that were observed in the trials. This combined fouling was also observed to result in increased reversible fouling. In this study it was also observed that the reversible fouling caused by protein like substances had a tendency to become irreversible over time. Fouling due to humic substances were not observed in these trials, however, since the study utilized an UF membrane with a quite large pore size it is reasonable to believe that the fouling due to humic substances would have been higher if a tighter membrane had been used (Peldszus et al. 2011).

According to (Di Zio et al. 2004) a calcium rich water source will increase the fouling of the membrane. This is believed to be due to complex formation between calcium and organic matter, in turn these complexes tend to be deposited on to the membrane and thus leading to increased fouling. The reason for the increased fouling of the membrane due to the presence of Ca^{2+}, but also other divalent ions such as Mg^{2+}, is that these divalent ions reduce the electrical repulsion between NOM and negatively charged membranes. This increased fouling will lead to decreased flux and therefore also decreased performance of the membrane (Visvanathan *et al*. 1998; Hong & Elimelech, 1997; Yoon *et al*. 1998). This mechanism of fouling is considered to be the most important reason for membrane fouling (Amy & Cho, 1999; Gwon *et al.*, 2003). According to a study by (Cornelissen et al. 2006), there may be a threshold value of calcium in the feed water where calcium-NOM complexes start to form more rapidly. This calcium level is believed to be around 200 mg of calcium per liter. A correlation between flux decline and the percentage of calcium-NOM complex in the feed water was also observed in this study, which indicates that calcium and NOM pose a serious problem to the performance of membrane technology (Cornelissen et al. 2006). Although it has been shown through various studies that the presence of calcium (Ca) in raw water increases the fouling of membranes, studies also indicate that the NOM rejection is lower in the presence of calcium and it is suggested that this might be because calcium influence the ionic strength of the water (Schäfer et al. 2002). In raw water with high ionic strength, the presence of cations affects the molecular weight, the shape and the size of the humic substances in the solution. This leads to a neutralization of the surface of the NOM particles in the water, this in turn leads coiling of large NOM particles to smaller ones that are harder to remove by membrane processes, especially for UF membranes (Swift, 1989).

8.3.3 Biologic fouling

Biologic fouling is caused from living organisms. The living organisms that create this type of fouling are mainly bacteria but could also be derived from fungi or eukaryote organisms (Dahlberg et.al 2009). The membrane surface is considered a favorable environment for living organisms due to the accumulation of nutrients. Biologic fouling could be described as a dynamic process of microbial colonization and growth which leads to so called biofilms (Al-Amoudi & Lovitt 2007). However, the term biologic fouling is only used when the biofilm created causes an operational problem (Vrouwenvelder et.al 1998). The operational problems are most often flux reduction or pressure drops.

8.3.4 Fouling mitigation and cleaning

There are several methods of cleaning and mitigating fouling of membranes. Most commonly used are backwashing (BW), chemical cleaning (CEB) and cleaning in place (CIP) as well as different pre-treatment options.

Cleaning is used to restore the performance of membranes subjected to fouling, sooner or later every membrane has to be cleaned in order to restore its performance. UF alternatives use regular backwashes with water or water mixed with chlorine on a day to day basis to keep the membrane performance on an acceptable level. However, depending on the quality of the feed water, UF membranes also have to undergo chemical cleanings from time to time in order to keep a high enough flux through the membrane at reasonable feed pressures. It is important that these cleanings is effective against several types of fouling, but at the same time gentle towards the membrane material so that the chemicals used do not damage the membrane surface, membrane manufacturers specify the membranes resistance regarding temperature, pH range as well as a number of different chemicals. The purpose of the chemical cleaning is to restore the membrane to its original performance even though some irreversible fouling inevitably will occur. In these CEBs most often an acid chemical, a basic chemical and chlorine is used to remove different types of fouling from the membrane (Li & Elimelech, 2004). For NF alternatives regular BW and CEB is not used, when the spiral wound configuration does not permit back washing of water in the same way as an UF hollow fiber configuration. In NF alternatives cleaning is instead generally performed when the pressure drop exceeds 30 percent of the original value (Heinicke 2005). Although chemical cleaning is important in the restoration of membrane performance, it does not affect the composition of the fouling. The composition is dependent on the raw water properties as well as the efficiency of the eventual pre-treatment and will instead determine what cleaning chemicals that have to be used (Di Martino et al. 2007).

In a study by (Heinicke 2005) pilot trials with an NF system using an NF270 (DOW Filmtec) membrane different pre-treatment options impacts on membrane fouling were evaluated. The pilot trials were run for 19 months with two different scenarios simultaneously. In one of the scenarios biofiltration was used as pre-treatment before the NF membrane. In the second scenario a multi-media rapid filter was used as pre-treatment. In both scenarios a relatively fast pressure drop indicating fouling was observed. However, especially fast pressure drops was observed in the scenario utilizing the multi-media rapid filter as pre-treatment. Also in this scenario the permeability could not be fully restored by alkaline chemical cleaning. The conclusion of these trials was that biofiltration as a pre-treatment significantly reduced the development of pressure drop due to fouling in the NF membrane. Generally, the scenario using rapid filtration as pre-treatment showed 50 to 100 percent higher concentrations on all measured parameters. However, the biofilter reduced the NOM fraction which was hydrophobic, this fraction of NOM would otherwise have passed through an UF membrane. No single parameter was concluded to be the reason for the difference in pressure drop between the two pilot trials rather it was believed to be due to the combined effects of many factors. On one membrane from each pilot trial a destructive analysis was performed. This analysis showed that polysaccharides which constituted only a small fraction of the feed waters NOM, constituted more than half of the chromatographable DOC of the fouling layer. As a conclusion of these findings it is advisable to optimize the biofilter pre-treatment regarding the removal of polysaccharides (Heinicke 2005).

Rapid biofiltration has also been demonstrated to be an efficient pre-treatment method to reduce both reversible as well as irreversible membrane fouling by other studies (Hallé et al. 2009). This is believed to be due to the fact that biofiltration reduces the biopolymer concentration in the feed water of the membrane. This study showed that the reversible fouling increased proportionally with increasing biopolymer concentrations in the feed water. For the irreversible fouling however, no such correlation could be found and it was therefore suggested that the composition of the biopolymers in the water rather than the absolute concentration were the critical factor for irreversible fouling (Hallé et al. 2009).

Also other studies have observed that the use of biofiltration as a pre-treatment decreased the concentration of protein like substances in the water and thereby reduced both reversible and irreversible fouling. The longer contact time of the water with the biofilters the less fouling were observed in the membranes (Peldszus et al 2011).

In a study by (Vrouwenvelder et al. 2011) a membrane fouling simulator fed with the same water as the actual membrane is fitted with a very sensitive differential pressure drop transmitter. In the membrane fouling simulator a higher linear water velocity is promoting the formation of biofouling compared to the actual membrane setup. In this way early warnings of pressure drops in the NF membrane can be foreseen and countermeasures can be put in earlier.

8.4 Different designs of membrane modules

In this chapter the most common types of membrane designs are described and the advantages and disadvantages associated with each of these designs are evaluated.

8.4.1 Tubular membranes

Tubular membranes are one of the earliest designs of membrane equipment for industrial purposes (Cheryan.M, 1998). Tubular membranes could easiest be explained as pipes constructed of a membrane material. Water is most often fed inside the pipe and the water is then forced by pressure to penetrate the membrane surface. Due to the relatively large openings of these membranes they are not very susceptible to clogging as other types of membrane designs. Therefore tubular membranes might be appropriate when the feed water contains large particles. One disadvantage with this module is the relatively large area per unit in the pressure vessel (USEPA 2005).

8.4.2 Hollow fiber membranes

Hollow fiber membranes consist of long and narrow hollow strands packed densely together, see figure 9. Most often the hollow fiber design is used in UF membranes and is typically operated in dead end mode. However, many hollow fiber membrane modules may also be operated in cross flow mode. The material used could vary but the most common materials used are cellulose acetate, polyvinyl fluoride, polyacrylonitrile, polysulfone, polyethersulfone (USEPA 2005). How the fibers are bundled may differ between different manufacturers but in one of the most commonly used configurations the fibers are bundled together longitudinally with both ends embedded in resin, and enclosed in a pressure vessel. However, the hollow fibers could also be installed submerged in a basin or cell. In contrast to pressure driven hollow fiber membranes the submerged system is driven by vacuum. The ends are fixed and the hollow fibers are exposed to water in the cell. A vacuum is induced at the fiber walls where it is filtered outside in to the center of the membrane (Draft Guidelines for Drinking-water Quality Management for New Zealand, 2005).

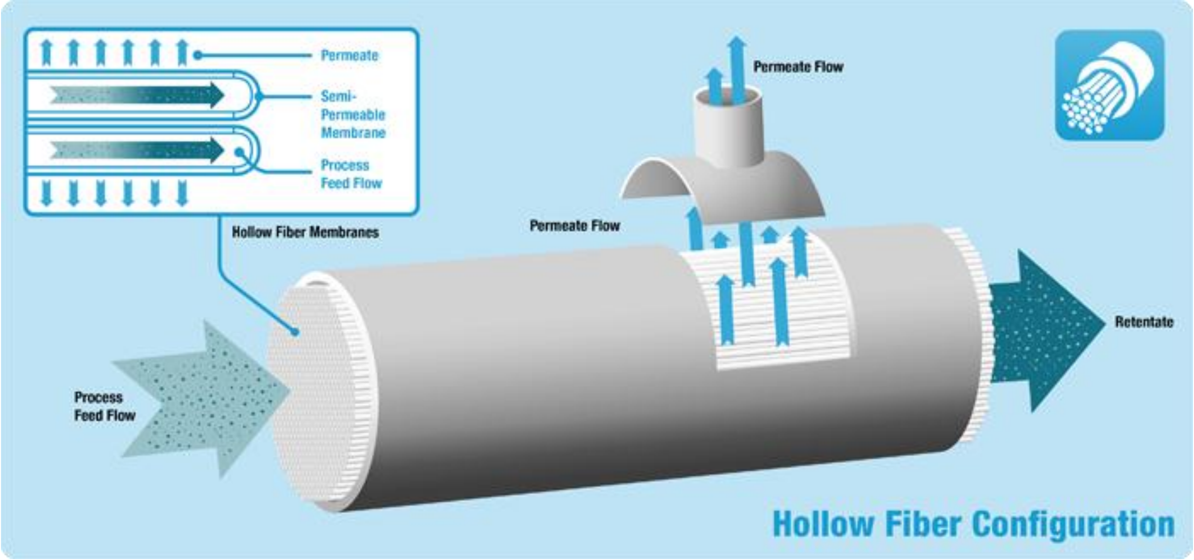


Figure 9. This figure shows an example of a hollow fiber module (Koch 2012).

Hollow fiber membranes do not only differ in design but could also be run in different ways. The modules could be operated as “inside-out” or “outside-in”. The terms are related to the direction of the water passing the membrane and the feed waters orientation in relation to the membrane surface (Pilutti.M Et. Al , 2012). When the water is induced to the inside of the fibers and flows through it to the outside of the membrane, it is referred to as inside-out flow. In contrast, when the water is added to the outside of the fiber and flows through the membrane to the inside it is called an outside-in flow. However, the risk for the fibers to be clogged is larger during inside-out flow than in outside-in flow. Therefore the quality of the feed water most often decides when to use which technique. In the outside-in flow the feed flow path is less defined, but the surface area for filtration per fiber is increased. An advantage with the hollow fiber design is that BW and CEB may be performed (USEPA 2005).

8.4.3 Spiral wound membranes

Spiral wound membranes are mostly associated with removal of dissolved organic solids and therefore NF or RO membranes are typically operated in cross flow mode. The membrane consists of flat-sheet membranes and feed separators wrapped around a hollow core, see figure 10. The two flat sheets are separated by a thin material usually, made of Vexar or polypropylene, glued together on three sides. The fourth side is fixed to the perforated tube (Cheryan.M, 1998). Water flows through the spiral wound membrane by adding pressure to the feed water that flows in between the feed spacers, the water then continues parallel to the membrane surface. Water that is pressed through the membrane is collected in the circular central core, and exit as a permeate (Koch, 2012). Water that has not passed through the membrane, called the concentrate then exits the element and either continues through an additional element or is recirculated to the feed side again (USEPA 2005).

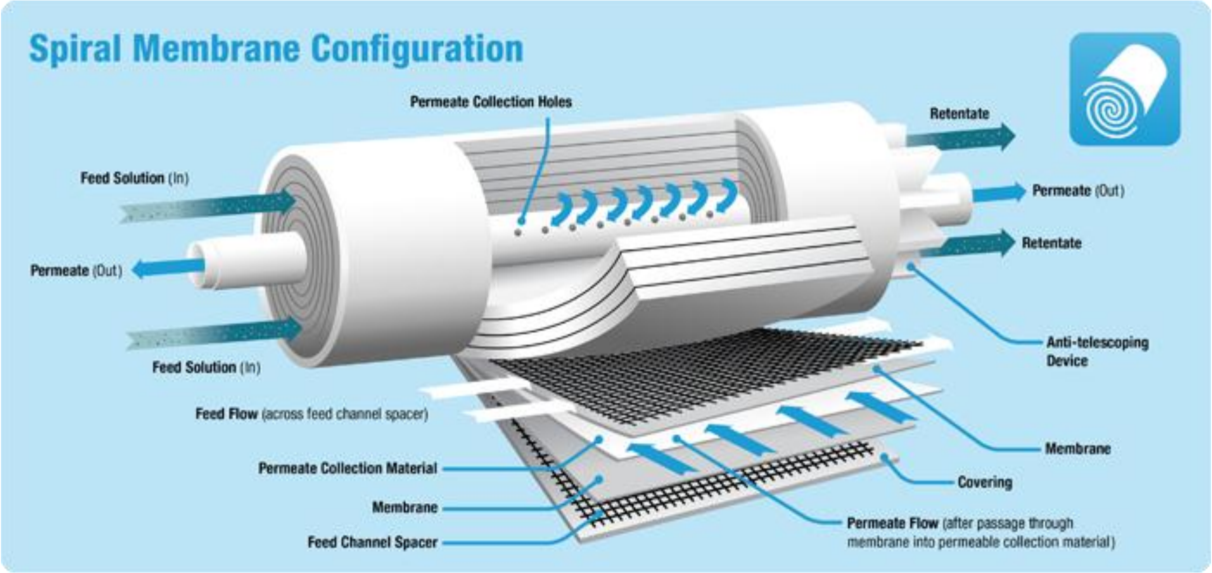


Figure 10. This figure show the basic design of a spiral wound membrane element design (Koch 2012).

Usually spiral wound membranes are made of cellulose acetate and triacetate blend or a thin film composite (Hydranatics, 2012). The composite membranes are more effective in rejecting particles at a lower operation pressure than the cellulose acetate membranes.

8.5 Ultra filtration applications

The common application of UF is to remove microorganisms, algae and pollen. Generally, RO or NF have been used as a mean to deal with high NOM concentrations in raw water, however, nowadays pretreatment such as direct coagulation or coagulation and flocculation in combination with UF have been successfully implemented at several WTPs. The driving force of this development has been the savings in energy connected to the latter technique (Meyn & Leiknes 2010). UF membranes used for drinking water production are techniques which have been more commonly used in recent years. Some of the advantages with the technique compared with a conventional system are the quality of the water, a more compact system, easier to operate, less maintenance, fewer chemicals and less production of sludge (Nakatsuka et al .1995). In the food industry UF membranes have been practiced for over 20 years. Gentle product treatment, high selectivity and lower energy use are some reasons for the wide usage of UF membranes in the food industry (Mohammad et al. 2011). According to a study of the performance of Aquasource UF membranes it was concluded that the technology is feasible for purposes such as clarifying groundwater and eliminating particles e.g. suspended solids and microorganisms. However, together with a coagulant, UF technology could also be used to treat surface water with relatively high loads of NOM as well as ground water contaminated with micro pollutants, like pesticides (Laine et al. 2000). UF filtration in combination with coagulation has been successfully implemented in several water treatment plants in Europe for example in Lausanne, Switzerland (Laine et al. 2000). Even though UF membranes have proven to be a reliable technique it is still not optimal. NOM fractions have molecule weights ranging from 1 kDa to 500 kDa. In comparison to UF membranes with pore sizes between 20 kDa and 200 kDa the smallest fraction of NOM will pass the membrane unless another treatment method like coagulation is not applied. Treatments combined with UF could as mentioned be coagulation but other methods have also been practiced such as PAC-or GAC adsorption and ozonation (Hongchen et al. 2011). The UF technology may also be used as a compliment to the conventional treatment (Laine et al. 2000).

In Norway there are successful full-scale examples of direct filtration of NOM using UF membranes. Polymeric porous membranes, works best in connection with some type of pretreatment like coagulation in order to minimize the fouling of the membrane (Cho et al 2006). Also Frimmel and colleagues concluded in a study of UF and NF rejection of NOM from different water sources that UF rejected a quite large quantity of all the organic matter even though NF as expected rejected even more of the organic matter (Frimmel et al. 2004). In this study the authors concluded that both UF and NF are well suited techniques to eliminate NOM, typical for raw water sources. However, NF removed most of the organic matter while UF mainly rejected the NOM with the largest molecular weight. This study also showed that some irreversible fouling of the UF membrane actually improved the NOM rejection, sometimes to a level similar to an NF membrane. This means that a somewhat better NOM rejection may be expected after some time of operation (Frimmel et al. 2004). UF membranes with a surface charge have been suggested to be more effective in dealing with fouling. In an experiment performed by (Cho et al. 2011) a thin film composite membrane which had a negative charge had better success in removing NOM than conventional UF membranes. Due to electrostatic exclusion and higher solute retention, decreased fouling could be accomplished.

8.6 Nanofiltration applications

NF membranes are initially a membrane type derived from RO membranes.
The RO membranes are an energy consuming technique and even though the permeate quality is good the energy consumption is a problem. In fact, the permeate result can sometimes be considered too well because it also removes nutrients that are considered healthy. The need for a less energy demanding product with lower rejection lead to the construction of NF membranes (Van der Brugge et.al. 2002) and the first NF membranes were available in the market in 1986 (Yayha et al. 1993). High surface charge, high density and pores in nanometer size are what NF is generally characterized by. Usually NF has a lower acceptable TMP than RO and therefore the design is more complicated (Bartel et al. 2008). NF membranes are made up by composite asymmetrical multilayers. Usually the outer layer is 1 μm thick and the inner 30 nm with a pore size of 3 nm to 10 nm (Gonsharuk et. Al. 2010).

Studies of NOM removal showed that NF led to a high rejection of NOM, generally more than 95 percent for all different water sources. The rejection of NOM by UF on the one hand was clearly dependent on the characteristics of the raw water (Frimmel et al. 2004).

Nanofiltration membranes are today mainly used for softening water, thus preventing the water from reacting with piping material (Bartels.et al, 2007). It is also used for removal of NOM and prevention of DBP formation. Pilot tests of three different modules have been carried out in Florida using groundwater and surface water as water sources. These tests displayed a reduction of NOM and DBP formation by over 90 percent (Duran & Dunkelberger, 1995).

The water treatment plant Mery-Sur-Oise is another example confirming the capacity of NF membranes. Mery-Sur-Oise supplies around 800 000 people living in northern Paris. The NF membranes were implemented due to problems with too high values of TOC. Since the implementation TOC levels have decreased from 1.8 to 0.67 mg/l. An additional result of this is that the chlorine levels also decreased, from 0.4 to 0.2 mg/l. The NF has also been able to reduce pesticides (Cyna et al. 2002). Besides the fact that both NF and UF alternatives works as a microbial safety barrier in the drinking water process, the NF alternative is also beneficial from other aspects as well. Since NF alternatives do not require supervision of the coagulation it is easier to automate the NF process. In a report by (Irvene et al. 2001) regarding the operational experiences from water treatment plants in Scotland it is said that the number of visits to the water treatment plants is significantly reduced due to automated processes associated with NF technology. In addition, the waste costs and chemical costs are reduced compared to conventional systems. A report written by (Mulford et al. 1999) also confirmed the reduced need for maintenance. The maintenance time spent was mainly due to cleaning of the membrane units.

On the other hand there are disadvantages such as energy consumption and the cost of replacing the membranes when needed (Irvene et.al. 2001). The increased consumption of energy associated with NF membranes compared to conventional water treatment plants is usually one of the most common arguments against NF membranes (Majamma et al. 2011). In a multi criteria analysis done by (Sombekke et al. 1997) a conventional WTP with ground water as raw water source was compared with an NF membrane system. An expert panel concluded that the conventional WTP had an energy impact of 50 percent while the NF membrane had an impact of 65 percent.

To save energy during operation with NF membranes (Thanuttamavong et al. 2001) concluded in a study that it is possible to operate the NF modules at very low pressure and produce good quality water with less energy use. In this study NF modules were operated at pressures below 0,5 bar and still produced potable water. However, this mode of operating NF membranes requires very large membrane surface to be able to produce any larger quantities of water since the flux is very low at these low feed pressures.

In NF filtration smaller particles will be removed, typically compounds with a molecular size of 300 Da or more. This makes NF suitable for removal of organic pollutants and color from surface water or groundwater but also to treat effluent of biologically treated waste water. Furthermore, the membrane material used in NF usually has a surface charge which is often good in a fouling perspective. The equilibrium between the charged membrane surface and the feed water yields an electric potential called the “Donnan potential”. This potential makes the NF able to contain and remove ions with a smaller size than the membrane pore size from the water (Van der Bruggen et al. 2003).

8.7 Hollow fiber nanofiltration

The membrane technology is a promising technique in many ways for the future production of drinking water. The fouling of the membranes has however, been a major problem for the continuous development of the technique. There are several WTPs using membranes today with no problems of fulfilling the drinking water regulations. However, chemical usage for cleaning and pre-treatments are necessary measures for many of the WTPs. Except the environmental and economic aspects of trying to reduce the consumption of chemicals, the discovery of DBPs forming as a result of chlorination have been leading motives to develop membrane technology even further. UF membranes cannot remove NOM without pre-treatment, such as coagulation. Removing NOM by the use of NF membranes can be achieved without coagulants but extensive pre-treatment is still needed due to limited cleaning capacity of the NF membranes. The removal of NOM using NF technique is also associated with very high energy consumption. Therefore, there is a need for new technique combining the advantages from UF and NF but without their negative side effects (Spenkelink et al. 2012).

In a report written by (Spenkelink et al. 2012) experiments were conducted on a so called ”cross over membrane” . The membrane was a hollow fiber nanofiltration membrane (HNF) from Pentair X-flow. It was tested on surface water from Yorkshire and compared with results of an existing conventional water treatment plant in Yorkshire. The current water process consisted of coagulation, flocculation, flotation, rapid gravity filtration and addition of hypochlorite. The water for the membrane experiment was screened through a 200 µm pre-filter before filtrated through the membrane. The experiment has been run since July 2011 and the parameters measured were turbidity, DOC, conductivity, pH, metals and DBP formation as trihalomethanes (THM) forming potential. Generally, the membrane experiment showed better results for all the parameters than the conventional system. The only exception was the color removal where the existing water process showed slightly better results. Removal of DOC was almost the same for both water processes but the membrane had a slightly better removal. Perhaps the most remarkable result was that the removal of THM was significantly better removed with the HNF membrane. The HNF membrane reduced the THMs 50 percent better than the existing water process (Spenkelink et al, 2012).

Since HNF membrane is a new technique it is not yet well tested. However, based on the experiments by (Spenkelink et. al. 2012) many of the previous flaws associated with NF membranes have been resolved in the HNF membrane. Thanks to the design of the membrane, hydraulic cleaning is now possible and thereby BW and CEB of the membrane can be performed regularly which have not been possible on spiral wound NF membranes. The membrane used in the experiment is made up of PES polymers which also makes it tolerant to chemicals and chlorine resistant. However, the membrane will not need any chemicals for coagulation or flocculation since the NOM is removed anyway. The expected specific energy use of this membrane according to the tests were between 0,2-0,4 kWh/m^3, this value is based on the performed pilot study of the HNF membrane. Another advantage with this membrane is that the reduction of conductivity in combination with no coagulants involved in the water process will create water clean enough to be returned directly to the surface water (Spenkelink et al, 2012).

9 Natural organic matter an increasing problem in potable water production

NOM in natural water is considered one of the main causes for fouling of membranes and is also associated with problems with taste and odor as well as formation of DBPs (Amy & Cho, 1999; Gwon *et al.*, 2003). NOM is also hard to remove successfully with conventional treatment processes and since NOM is present in all natural surface water it adds further to the problem. The concentrations of NOM in water vary depending on several different factors, for example the amount of rain, the temperature and what type of vegetation that is adjacent to the water. There are many different ways to categorize the NOM content of water, however, most often it may consist of hydrophobic humic and fulvic acids, hydrophilic acids, proteins, lipids, hydrocarbons and carbohydrates (Scott et al. 1998). The origin of all NOM is living and dead plants, animals and microorganisms, waste products from organism metabolism and from natural degradation of these different compounds (Chow et al. 1999). Due to the varied sources of NOM the structure of the molecules are very different and each source will provide a unique group of NOM. The removal of NOM in the production of potable water is important of many different reasons. One of the most important reasons is the fact that NOM may form harmful DBPs when residual NOM reacts with chlorine disinfectants. Another important aspect of NOM removal is to remove taste and odor problems that are associated with the presence of NOM in potable water. NOM may also lead to increased concentrations of metals in the drinking water which also could lead to problems with taste and odor but might also be harmful to humans in too high concentrations (Jarvis et al. 2008).

As previously mentioned an increased concentration of NOM has been observed in natural waters all around the world, especially in areas with a temperate climate. Increasing NOM levels in surface water seems to be related to global warming by changes occurring in the precipitation patterns. Another important factor may also be the decrease of acid rain because of regulations to industries. Even though this could be regarded as a positive development it does however, result in an increased concentration of NOM, since the acid rain speeds up the decomposition of organic matter. Surface water color and UV absorbance seems to increase to larger extent than TOC according to studies (Eikebrokk et al. 2004). This suggests that the characteristics of NOM are also changing and therefore also the treatability of the NOM may very well change. The covariance between rain intensity and NOM in discharge from forested sites is strong since increased rain intensity also leads to increased discharge from the upper parts of the soil profile where the concentration of organic matter is highest. Another effect connected to more intense rain events is decreased retention time in lakes which lead to less photochemical degradation of NOM. Decreased retention times also leads to less microbial degradation and decreased coagulation and sedimentation in lakes. There is an increased risk of seasonal variation of the surface water quality with respect to NOM. These variations is due to the fact that the concentrations of NOM will be much lower during warm and dry seasons and higher during periods with more rain and subsequently more runoff. Also more short term variations may occur when dry periods are followed by an intense rain event which seriously affects the water quality (Skjelkvale 2003; Eikkebrokk et al. 2004; Worrall 2004). Even though changes in climate and precipitation patterns are an important explanation to why the NOM concentration is increasing it may not be the sole reason. Another important factor in increasing NOM is changes in land use, large quantities of deciduous forest in the catchment of rivers and lakes may also be a contributing factor in increased NOM concentrations. Since litter from deciduous forest, especially from alder and birch, to a high degree contribute in the formation of NOM, the type of vegetation surrounding the water body is a key factor in the expected concentrations of NOM in the water. In the 1970-1980 in the Czech Republic a 50 percent decrease in forest cover was followed by a substantial decrease in NOM in adjacent water bodies. Also high terrestrial nitrogen concentrations will lead to increased production of biomass which in turn will encourage the production of NOM (Eikebrokk et al. 2004). High NOM concentrations in water bodies are most often associated with drainage from peat lands, shallow upland soils and watersheds with a high land/water ratio. Lower NOM concentrations on the other hand are found in areas with sparse vegetation, poorly developed organic soils and in areas dominated by large lakes. Studies show that spatial variation in NOM concentration was positively correlated with both molecular size and hydrophobicity (Vogt et al. 2004).

Some water works in the southern part of Norway have experienced a doubling and in some cases even a tripling of the raw water color during the past decade due to increases in the NOM concentration. This level of increase leads to increased risks of aesthetic problems as well as increased risks of the formation of DBPs and higher levels of inorganic and organic micro pollutants. Therefore more and more water treatment facilities have been obligated to introduce NOM removal processes in their treatment just to be able to comply with the present water quality regulations. Most treatment technologies are only capable of removing a fraction of the organic matter and there are also increased risks of biological growth in the distribution system due to the high raw water NOM concentration. Increased specific color in the visual light range (OD at 300-600 nm/mg C) as observed in regions with increased NOM in Norway implies that the increased NOM has a larger molecular weight now than what was observed previously (Eikebrokk et al. 2004). This might be positive since the NOM with high molecular weight is often removed easier by coagulation and membrane filtration. However, an increase of NOM in intermediate and small fractions poses a problem for WTPs using conventional treatment as well as systems with coagulation and UF membranes. In conventional treatment this often means an increased demand of chemical use, yet with an uncertain success rate. Often these increased NOM concentrations also lead to the formation of more DBPs. The higher concentration of NOM also leads to increases in biodegradable substances (BDOC) which may change bacteriological balance in the water as well as in the water treatment system (Korth et al. 2004). Since NOM is a potential food source for various microbial biota, residual NOM in the drinking water system may lead to re-growth of microorganisms in the drinking water system (Jarvis et al. 2008).

Studies show that a quite modest change in raw water color may lead to severe decreases in the membrane performance. From numerous pilot studies of the effects of an increase in raw water color by (Eikebrokk et al. 2002) it was shown that changes in raw water color level from 20 to 35 mg Pt/l resulted in severe consequences regarding the amount of BW, coagulant dosage and treatment capacity required in an UF membrane system. According to these pilot trials the increased color level would lead to increased amounts of back washes by a factor of

1.87. Coagulant doses and the amount of sludge produced increased by a factor of 1,64. The residual TOC in the treated water increased by a factor of 1,26. Finally the water treatment capacity and filter run time were found to decrease by a factor of 0,9 and 0,53 respectively (Eikebrokk et al. 2004)

The problem with NOM and the formation of disinfection by products (DBPs) is a serious problem in all drinking water treatment. DBPs are formed during the treatment when chlorine reacts with NOM and forms for example trihalomethanes (THMs), which are carcinogenic. One solution to this problem is to switch from chlorine to chlorine dioxide as disinfectant chemical. However, the use of chlorine dioxide as disinfectant may instead lead to formation of other types of by-products for example chlorite and chlorate, which may lead to hemolytic anemia even in low doses of exposure. Therefore, alternatives to these commonly used disinfectants would be beneficial. However, the choice of treatment is linked to a high degree to the characteristics of each specific surface water source. In conventional treatment coagulation is most often used to form flocs of the small NOM particles, however, in raw waters with a high concentration of NOM the flocs formed by coagulation is often very fragile and the NOM removal might be inefficient. This may have a negative effect on downstream processes for example filtration, where the small particles from broken flocs are clogging the filters faster and thereby reducing the filter run time. The normal way of dealing with such problems as elevated DOC levels is to increase the amount of added coagulant, however, this might lead to other water quality problems such as increased concentrations of metals in the water, and also increased costs of coagulants and waste disposal from the increased sludge production generated by the elevated coagulant dosage (Jarvis et al. 2008). Studies made by (Di Zio et al. 2004) conclude that membrane technology in many cases is a good and viable process to disinfect water, with a lower risk of DBP formation than conventional treatment.

9.1 Characterization of NOM

Due to the very varied composition of NOM in different water bodies it is important to try and determine what type of NOM the specific raw water is composed of in order to choose the most suitable removal method. It is therefore important to measure and determine the concentration and the characteristics of the NOM present in the raw water.

Generally, NOM is measured by total organic carbon (TOC), dissolved organic carbon (DOC), adsorption of UV-light (UV_{254}) or chemical oxygen demand (COD). However, there are other methods that may indicate the NOM concentration in water. Since NOM is the major reason for brownish or yellow coloration of water, measurements of color is also an indication of the amount of NOM in a sample (Uyguner et. al. 2007). The advantage with these general methods of measuring the NOM content of a sample is that they are all quite fast and easy methods and does not require any expensive equipment. However, the limit of these methods is that they only provide information regarding the amount of NOM in a sample, they do not specify the character of the NOM. Commonly used more sophisticated methods of NOM characterization includes SUVA, Fluorescence EEMs, HPSEC and FT-ICR-MS among others (Matilainen et. al. 2011).

9.1.1 TOC/DOC

Total organic carbon (TOC) and dissolved organic carbon (DOC) are common measurements of the amount of organic carbon present in for example a water sample. The TOC measures the sum of particulate carbon while DOC is the amount of organic carbon in the water after filtration through a 0,45 µm filter. TOC and DOC provide an idea of the amount of NOM present in a sample. It is also easy to use and may be measured online. However, it does not provide any information of the NOM characteristics, just an indication of the amount (Matilainen et. al. 2011).

9.1.2 Absorption of UV-light

The concentration of a certain compound may be determined by measuring the absorbance of UV-light at specific wavelengths. For NOM these specific wavelengths are considered to be between 220 and 280 nm. Different wavelengths are believed to identify different parts of the NOM content in the sample, i.e. different types of NOM compounds. The wavelength 220 nm is for example associated with carboxylic and aromatic groups in the NOM molecules. Even though UV at 254nm wavelength tends to be associated only with aromatic NOM molecules it may currently be used as a substitute for DOC measurements (Li et. al. 2009). Other important uses of the UV absorbance are ratios between absorbance at different wavelengths. The ratio between absorbance at 253 and at 203 was found to have a correlation with the formation of DBPs according to a study by (Kim & Yu 2007). However, a study by (Her et. al. 2008) mean that significant errors may occur at wavelengths between 220 and 230 nm due to interference from inorganic ions like nitrates and sulfates.

9.1.3 COD

Chemical oxygen demand (COD) is the amount of oxygen needed to decompose the organic material in a specific sample. Thereby the COD value gives an indication of the amount of organic material present in the samples, i.e. the NOM concentration (Matilainen et al. 2011).

9.1.4 Color

Color of natural water is due to different particles and substances of different origin. Among the most common reasons for coloration of water is presence of natural metallic ions like iron and manganese, humus and peat materials, plankton, weeds and industrial waste water. The common unit for measuring color of water is mg Pt/l. When utilizing color measurements a distinction is made between apparent color and true color. Apparent color is the color due to dissolved matter and suspended particles and true color is defined as the color of the water measured after the turbidity, i.e. suspended particles have been removed. The color of the water may provide an indication of the amount of NOM in the water, especially if the true color measurement is combined with a measurement of the waters iron and manganese concentration. A high value of color and low concentrations of metallic ions would therefore suggest a high NOM concentration in the water (Matilainen et al. 2011).

9.1.5 SUVA

The specific UV-absorbance (SUVA) is calculated by dividing the UV absorbance of a sample at 254 nm wavelength by the DOC concentration of the sample. This parameter describes whether the NOM in the sample is mostly hydrophobic or hydrophilic (Matilainen et al. 2011). Hydrophobic NOM is increasing the SUVA values, also terrestrial material, i.e. humic substances increase the SUVA value. Flocculation is an efficient removal method for water with high SUVA values. SUVA values above 4 indicate that the NOM present in the water is mainly hydrophobic and contains mostly aromatic material. However, SUVA values below 3 indicate that the NOM instead mainly consist of hydrophilic groups (Edzwald & Tobiason 1999). Hydrophobic molecules are often non polar molecules, while hydrophilic molecules tend to have higher polarity. There are researches linking the SUVA value to NOM removal by coagulation. There seem to be a good agreement between a high SUVA value and a good NOM removal by coagulation (Archer & Singer 2006;Bose & Reckhow 2007), i.e. coagulation tend to work better on hydrophobic molecules since they are non-polar when it is easier to alter the surface charge of the particles. Furthermore, hydrophobic particles tend to cluster together in a solution of water since the hydrophobic molecules and the water molecules strive to minimize the contact area between them. A correlation between SUVA-value and the formation of DBP may also exist, however, the result from different studies are somewhat inconclusive regarding this correlation (Matilainen 2011).

9.2 Fluorescence

Fluorescence is the phenomenon that occurs when a molecule absorbs energy, this causes an electron to become excited to a higher energy level. As the electron later returns to its normal state, energy is lost as light or fluorescence. Different molecular structures emits light in different manor and at different wavelength, thereby it is possible to identify certain substances. The organic compounds that absorb and reemit light in this way are called fluorophores (Mopper et. al. 1996). Presently, there are two different fluorescence groups associated with NOM. One of these groups has fluorescence properties similar to the fluorescence properties of protein. The other groups' properties are more equal to humic substances. The measurements of NOM fluorescence is a quite easy process, however, it does include very careful calibration of the instruments, and normalizing of the NOM fluorescence to a reference value in order to calibrate the signal intensity. Even though it is a promising technique there are however, some drawbacks with this technique, when the fluorescence does not provide information regarding the biochemical structure of NOM. Furthermore, it does not provide any information regarding the actual concentration of NOM in the sample and only a small fraction of the actual NOM contributes to the fluorescence of the sample. However, from the fluorescence there are different indices that may be used to quantify differences in the properties of samples. One of the most commonly used of these indices is the two dimensional fluorescence index (FI). This index provides information of the source of the NOM, i.e. if the NOM originates from a terrestrial or a microbial source. FI also provides information of the degree of degradation of the NOM in the sample, when it shows the relative contribution of aromatic or nonaromatic NOM. A FI value of 1,8 or higher indicates NOM derived from bacteria or algae, lower values of FI on the other hand indicates more terrestrially derived NOM, i.e. NOM from plants and soil organic matter. Often the fluorescence measurements of NOM are collected as three dimensional excitation emission matrices (EEM). By increasing the excitation wavelength successively and measuring the emissions, a so called EEM is constructed. This three dimensional matrix contains information of the composition, origin and processing of the NOM in the sample. According to (Chen et. al. 2003) peaks in the EEM at shorter excitation wavelengths (<250 nm) and shorter emission wavelengths (<350 nm) corresponds to aromatic proteins like tyrosine. Peaks occurring at longer excitation wavelengths (>280 nm) and longer emission wavelengths (>380 nm) is likely related to humic acid like organic material. Peaks with shorter excitation wavelengths (<250 nm) and longer emission wavelengths (>350 nm) are related to fulvic acid-like materials (Zhao et al. 2011). Due to the fact that fluorescence excitation and emission matrices are able to determine and quantify polysaccharides and proteins, humic and fulvic acid-like substances and colloidal or particulate matter with high sensitivity is one of the most promising techniques in determining low levels of organic substances in water (Henderson et al., 2009; Her et al., 2003; Kimura et al., 2004; Liu et al., 2007).

In the fluorescence technique other two dimensional indices may also be used, for example humification index (HIX) which is an indicator of the humic substance content or to which extent of humification the NOM in the sample is. Yet another two-dimensional index that can be derived from the EEM matrix is the freshness index (β:α). This index shows the relation between recently produced NOM and more decomposed NOM. In this index β represents the newly formed NOM while α represents the more decomposed fraction (Fellman et.al. 2010). Generally, an EEM matrix of a NOM sample shows five peaks of humic or protein like substances (Coble et al. 1990). The humic-like peaks are called A, C and M in the EEMs and the protein like peaks B and T. These peaks are believed to be linked to ecologically important features of the NOM. Peaks A and C exhibits emissions at long wavelengths and are referred to as “red shifted”, these peaks primarily originates from plant sources which are likely to be NOM of higher molecular weight. The M peak is on the other hand shifted blue since it emits emission with shorter wavelengths, this fraction of the NOM is of lower molecular weight than peaks A and C. The protein like peaks represents the NOM from microbial sources. These peaks have been found to have a strong correlation with the biodegradable DOC in the samples. Apart from previously discussed methods of evaluating the fluorescence of NOM molecules, also a method called parallel factor analysis (PARAFAC) may be used. This is a method where the fluorescent signature of NOM is divided into individual components and provides an estimation of each components relative contribution to the total NOM fluorescence (Fellman et. al.2010).

9.2.1 HPSEC

High pressure size exclusion chromatography (HPSEC) is a method where the NOM is fractioned based on molecular size. HPSEC is a development of the previous technology size exclusion chromatography (SEC). By comparing the result of a HPSEC with known molecular weight (MW) standards the molecular weight of the sampled NOM may be evaluated. The standard, most widely used for this purpose, is poly-styrene sulphonate (PSS). However, NOM in water are often more branched and cross linked than the PSS which means that this method only provides approximations of the MW and not the actual MW of the NOM (Matilainen et al 2011).

9.2.2 FT-ICR-MS

Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR-MS) is the latest method of NOM characterization. In this method thousands of ions are separated from each other and their molecular formula is determined with fairly high precision. By the FT-ICR-

MS the amount of double bonds in the NOM molecule groups can be determined. This in turn gives an indication of the reactivity of the NOM molecules. Groups containing double bonds are called unsaturated and are more reactive since they strive to become saturated. This affects the formation of DBPs since a large amount of unsaturated NOM molecules is more likely to react with disinfection substances. These groups identified by the FT-ICR-MS method also determine the surface charge of the NOM molecules and thereby also its ability to coagulate (Matilainen et al. 2011).

9.3 NOM characterization at KvarnagårdenWTP

In this chapter the results of the study by (Lavonen et al. 2012) regarding Kvarnagården WTP is presented.

The dissolved organic carbon (DOC) concentrations at different stages of Kvarnagården WTP with present treatment processes are presented in table 5. Also the specific UV absorbance at 254 nm wavelength ($SUVA_{254}$) which is a common measurement to characterize the NOM content of the water were measured at different stages in present treatment at Kvarnagården WTP, see table 5.

Table 5. This table shows the results of measurements carried out at different stages of the water treatment process at Kvarnagården WTP (Lavonen et al. 2012).

Stage at WTP	DOC value	$SUVA_{254}$ value
Surface water	3,0 mg/l	3,0
Mixed raw water	2,9 mg/l	2,7
Drinking water	2,9 mg/l	2,5
Total change %	-1%	-8%

Using high pressure size exclusion chromatography (HPSEC) and comparing with PSS standards, the size of the NOM particles were determined and presented as "Apparent Molecular Weight" (AMW). This method showed that the NOM in the raw water at Kvarnagården WTP had a peak concentration around 5000 Da (AMW) and three shoulders at 4000, 3000 and 1500 Da (AMW), see figure 11. The three different lines in the figure correspond to the different stages of the treatment at Kvarnagården WTP, i.e. surface water, mixed raw water and drinking water. In this figure it can also be seen that the largest reduction in concentrations of NOM occurs from when the surface water (black line in figure 11) is mixed with the ground water (red line in figure 11). The reduction from the mixed raw water to the drinking water (dotted line in figure 11) is much smaller. The largest reduction occurs at the peak concentration of around 5000 Da (AMW). Regarding the reductions of NOM in this case it is important to notice that it is only relative reductions and not absolute reductions of NOM that are measured.

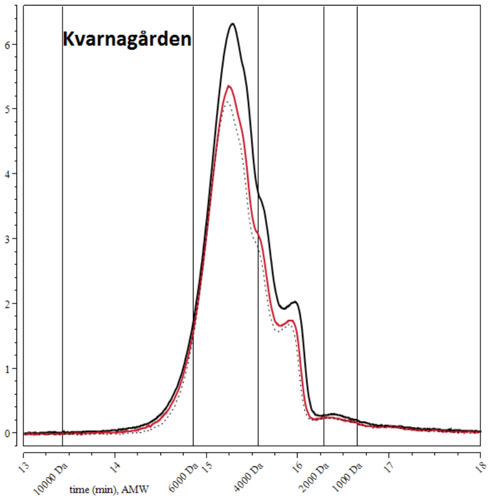


Figure 11. In this figure the results of the HPSEC of Kvarnagården water is presented, the black line correspond to surface water, red line to the mixed raw water and dotted line to the drinking water (Lavonen et al. 2012).

Using fluorescence spectroscopy the study by (Lavonen et al. 2012) produced EEMs of the different stages in Kvarnagården WTP, see figure 12. By these EEMs the character of the NOM may be established. However, the result of these EEMs is presently only preliminary and contains some disturbances, and they should not yet be used to draw any certain conclusions regarding the NOM composition of the water at Kvarnagården.

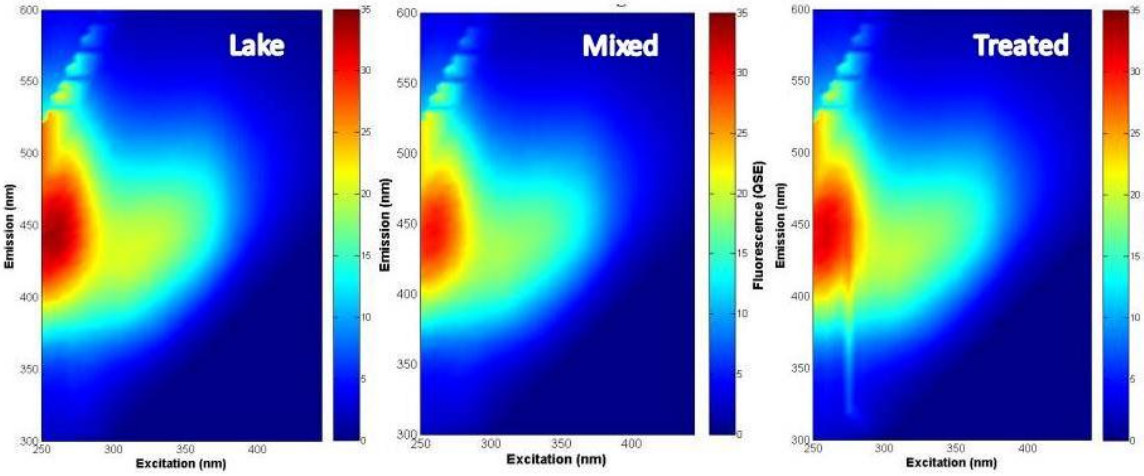


Figure 12. This figure shows the images of the EEMs of the different stages at Kvarnagården (Lavonen et al 2012).

Also derived from the fluorescence spectroscopy are the values of fluorescence index (FI), Humification index (HIX) and freshness index (β:α),the results are shown in table 6. These are different two-dimensional characterizations of the NOM composition of the water.

Table 6. This table shows the other compiled results of the fluorescence measurements performed (Lavonen et al. 2012).

	Lake	Raw	Treated
FI	1,8	1,8	1,8
HIX	8,8	8,1	8,2
β:α	0,53	0,53	0,53

By using FT-ICR-MS it could be observed that the current treatment at Kvarnagården WTP mainly removed saturated NOM with few oxygen containing compounds. This method also showed that 272 chlorinated compounds were formed during the treatment process, compounds with a higher O/C ratio and with more double bounds than what is naturally occurring (Lavonen et al. 2012).

10 Results and analysis

This chapter describes the results from the enquiries made to membrane manufacturers and water treatment plants operating membrane filtration setups. Also included in this chapter are the results from the analysis of the NOM characterization of the raw water in Kvarnagården as well as the results of the experimental part of the project.

10.1 Results questionnaire

In the questionnaire the questions were focused on the parts considered to have the greatest impact during operation of a WTP. The crucial parts considered were BW, CEB, pretreatment and treatment aims. The questionnaire results have been used to validate estimations, calculations and to see general routines among WTPs using membrane technology. Commonly occurring operational disturbances from the questionnaire have also been used when evaluating the operational aspects of using membranes. Twelve different WTPs participated in the questionnaire research, see Appendix A. Eleven of them were using UF membranes and one NF (Hollywood, Florida). The mean values of the results from the questionnaire are summarized in table 7. The table displays water flux; amounts of water spent on BW per square meter of membrane area and the energy consumption per cubic meter produced water.

Table 7. This table shows the compiled mean results of the performance of the UF plants and a NF plant.

	Membrane Area [m^2]	Mean permeate fluxes [l/m^2h]	Backflush per day [l/m^2]	Mean energy [kWh/m^3]
UF	21159	76	64	045
NF	14046	22,5	-	0,7

However, due to insufficient facts about amounts of chemicals used for pretreatment or CEB these parts of the water process could not be compared in numerical values. Instead a new table, see Appendix A, was constructed displaying what treatment aims, type of pre-treatment, chemicals used for CEB and whether air flushing is used in the process or not. The results are summarized in Appendix A. The operational routines differed between the WTPs which also were expected due to different raw water qualities. It is a fact that membranes work as a microbial barrier so this was assumed to be a treatment aim for all the WTPs. However, some WTPs had additional aims such as color removal, turbidity removal, TOC- removal, DOC-removal, odor removal and softening. With three exceptions, no WTPs used coagulants as pretreatment. The three exceptions were the WTPs in Heemskerk, Walpole and Inverness. Walpole and Inverness used Polyaluminumchloride while Heemskerk used ferric chloride as a coagulant. The pilot tests for the membrane modules which been done at Kvarnagården WTP in Varberg used Polyaluminumchloride as a coagulant as well. When estimating costs for future coagulant use in Kvarnagården the calculations were therefore based on the data of consumed coagulants at Inverness and Walpole water treatment plants. Three of the WTPs also used other pretreatments such as sedimentation, flocculation, rapid sand filtration and air stripping. Five of the WTPs did not use any pretreatment at all.

Earlier in this report the energy demand of different stages of the membrane process was discussed. It was mentioned that maintenance energy stage, including BW and CEB, is a minor part of the energy consumption if the whole WTP is considered. It was therefore mainly interesting with energy usages for operating WTPs since correlations for operational stages with energy usages otherwise cannot be seen. However, the varying consumption of energy between the WTPs indicated that some have considered the whole WTP and some not, see Appendix B. Consequently, any conclusions could not be drawn regarding correlations among operational routines and energy consumption. Most of the WTPs participating practiced CEB but some only used CIP, also referred to as recovery cleans. The chemicals used for CEB in the survey investigation were dominated by sodium hypochlorite. Air flushing was only used by three WTPs and the other did not practice it all.

10.2 Results Membrane manufacturers

In table 8 and 9 the input data of the performance of membranes from Dow Filmtec, Aquasource, Hydraunatics, Inge, Koch and Pall can be viewed. Table 8 compare NF information from manufacturers and table 9 compares UF information. The information and the input data from the membrane manufacturers have worked as a basis for many estimations and calculations in this report. Energy demand, chemical usage and operational aspects are estimations based on manufacturer results. Most of the manufacturers did not provide any facts about footprint so it needed to be calculated in some case. This was done by taking module design and size into consideration. The footprints were then adjusted to the required permeate flow in Kvarnagården. The information regarding foot print and the size of membrane elements and modules were provided by manufacturers, details regarding the values are presented in Appendix A.

Table 8. This table shows a summary of some of the information provided by membrane manufacturers.

	Dow filmtec	Hydranautics (ESNA)	Hydraunatics (Hydracore)	Koch
Active surface area [m2]	37	-	-	-
Product water flow [m3/day]	47,3	28-30,9	31,1	23,5
Maximum feed flow [m3/day]	15,9	3,6-17	17	-
Max. applied pressure [bar]	41	41,4	41,4	41,4
Max. pressure drop [bar]	1	0,69	0,69	-
pH range (operation)	3-10	3-10	2-11	4-10
Max. feed turbidity [NTU]	-	1	1	1

Table 9. This table shows a summary of the information regarding the UF alternatives provided by manufacturers.

	Aquasource	Hydraunatics	Inge	Koch	Pall	Mean UF
Feed pressure [bar]	1,5	1,5-5	1,5	1,3	1,5	1,81
Recovery [%]	95	93	95,5	89-91	95	93,7
pH range [-]	1 to 13	1,5 to 13	1 to 13	1 to 13	1 to 10	1,1 to 12,4
Mean flux [l/m2h] (at 20°C]	77	80	60-140	173,4	70	100
TMP range [bar]	0,7	0,3-0,8	0,1-1,5	0,17-2,7	0-3	1
MWCO [kDA]	20-50	150	100	100	150	20-150
Specific energy [kWh/m3]	0,08	0,1	0,04	0,05	0,14	0,082
Online factor [%]	89	94	97	97	95	94,4
Chlorine tolerability [ppm hour]	-	200000	200000	200000	-	200000
Temperature range [°C]	-	0-40	-	0-40	0-40	0-40
Bacteria rejection [log]	6	5	9	6	6	6,4
Protozoa rejection [log]	6	6	6	6	-	6
Virus rejection [log]	4	4	4	6	-	4,5

10.3 Analysis of NOM characterization

In this chapter the NOM characterization of the study performed by (Lavonen et al. 2012) is evaluated regarding its consequences for the implementation of membrane technology. The character of the NOM present in the raw water will affect the membrane fouling, the quality of the output as well as the success of an eventual coagulation step prior to the membrane filtration.

10.3.1 DOC

As was previously shown the DOC levels are hardly decreased during present treatment at Kvarnagården WTP which indicates that NOM are somewhat passing the treatment processes untreated and as a consequence of this there is a risk of DBP formation at the disinfection step. The conclusions that can be drawn from the DOC level is that there are NOM present in the raw water, however, no characteristics of the NOM are learned from this test.

10.3.2 SUVA

In Kvarnagården the SUVA value is around 3 in the incoming raw water, this value is the limit that indicates that the main part of the NOM particles are hydrophilic. SUVA values above 4 are considered to indicate hydrophobic NOM molecules which are most suitable to remove by coagulation. This means that the NOM composition of the raw water at Kvarnagården may be of a more hydrophilic character and therefore more troublesome to coagulate. This may pose a problem for the alternative using UF with coagulation. If the NOM molecules are less susceptible to coagulation, more coagulant chemicals may have to be used and there is a risk that NOM do not coagulate and pass through the UF membrane leading to increased formation of DBPs.

10.3.3 Fluorescence

In the fluorescence test of the water from Kvarnagården, EEMs were constructed and values for FI, HIX and β:α were calculated. The FI value at Kvarnagården (1,8) indicates NOM derived from microbial or algae origin. The main source of NOM in Lake Neden may therefore be microorganisms and algae and not so much caused by the terrestrial vegetation around the lake. The EEM of the raw water at Kvarnagården suggests that the NOM is primarily consisting of humic and fulvic acids. The EEMs of the mixed raw water and the drinking water suggests a decrease in humic acids from the raw water to the drinking water, the decrease however, is very small and the main change occurs when the lake water is mixed with groundwater. During treatment the fluorescence is instead somewhat increased, especially at the lowest excitation wavelengths and emission wavelengths around 450 nm. This suggests that the drinking water contains mainly of NOM with fulvic acid like characteristics and that these types of NOM pass through the treatment plant basically untreated. According to the EEM of the drinking water, there are indications of humic acid-like NOM still present after treatment. However, as previously mentioned these results are not yet fully certain and should therefore only be regarded as indications.

10.4 Results from the experimental

In this section the results of the experiments conducted in this study is presented and compared. This is done to estimate the raw waters composition and fouling potential.

10.4.1 Results Kvarnagården WTP

During a time of 4 hours and 9 minutes, 500 ml of permeate were produced. By this it was possible to calculate the permeate flow to 0.12 l/h, see table 10. The active area of the membrane were also measured to 0.006 m^2 and by dividing the permeate flow with the membrane area the flux of the membrane was calculated to 20 l/m^2h. The weight of the fouling were measured to 0,0055 g, see table 10.

Table 10. This table shows the results from the membrane filtration test using water from Kvarnagården WTP.

Measurement	Value
Permeate	500 ml
Time	4,15 h
Flow	0,12 l/h
Membrane area	0,006 m^2
Flux	20 l/m^2h
Weight fouling	0,0055 g

The DOC of the raw water and permeate water were measured, mean results of these measurements can be seen in table 11. The UV absorption at 254 nm wavelength was measured for the raw water and permeate, see table 11. By dividing the measured UV absorption by the DOC value a SUVA value were calculated for the raw water as well as the permeate. The mean turbidity and mean color of the raw water and permeate was measured for Kvarnagården using a Hach colorimeter, see table 11. The mean calcium concentrations of the raw water and permeate were also calculated, see table 11. Also shown is the rejection of the membrane of each parameter.

Table 11. This table shows the results from water quality measurements of the raw water and the permeate as well as the amount rejected by the membrane, i.e. the difference in concentration between the raw water and the permeate.

Water parameters	Kvarnagården raw water	Kvarnagården permeate	rejected
DOC (mg/l)	4,3	2,74	36%
UV_{254} (abs.)	9,6	2,4	75%
SUVA	2,23	0,8	-
Calcium (mg/l)	9,35	3,74	60%
Turbidity (FAU)	4	1	75%
Color (mg/l Pt-Co)	31	0	100%

The UV absorption was also measured at each wavelength between 220 and 280 nm, see figure 13. The absorption was clearly higher for the Raw water than for the permeate water, which shows that the membrane have rejected NOM at all different wavelengths.

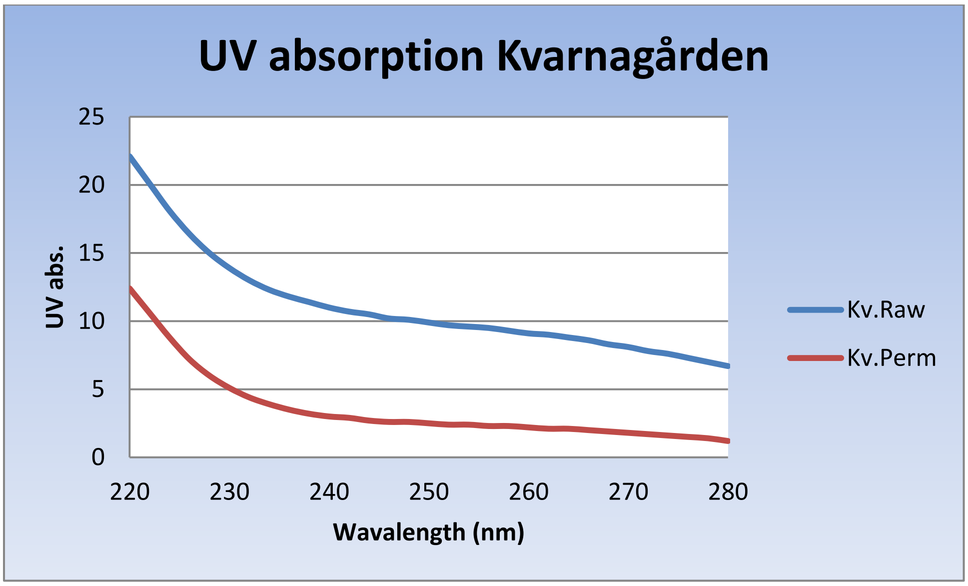


Figure 13. This figure shows the graph of the UV absorption between 220 and 280 nm of the raw water and the permeate water from Kvarnagården WTP.

The largest decreases in UV absorption as a percentage of the initial UV absorption of the raw water have occurred in the highest wavelengths, which indicates that the groups associated with these wavelengths are more efficiently removed in the membrane filtration, see figure 14. This may give an indication of which fraction of the NOM in the raw water that contains the smallest particles. In this case the fraction between 220 and 230 nm seems to be the smallest part. However, in this span the results could be affected by the nitrogen content of the raw water. Therefore the total nitrogen content of the water were measured to 0,54 mg/l for the raw water of Kvarnagården. The total nitrogen content of the permeate water were measured to 0,46 mg/l, this shows that the average reduction of nitrogen by the membrane is only around 15 percent. Therefore no valid conclusions could be drawn in this wavelength span. However, the largest reduction of UV absorption occurs at the larger wavelengths and according to these results the groups corresponding to these wavelengths can be associated with the NOM groups with the largest MW since they are removed to the highest degree.

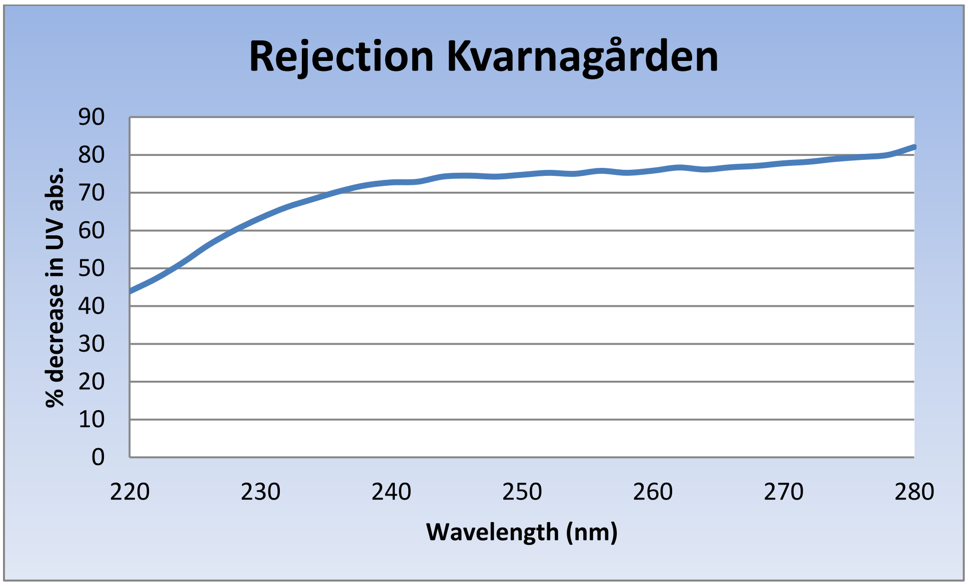


Figure 14. This figure shows the decrease in UV absorption after nanofiltration, indicates the removal of NOM.

10.4.2 Results Lackarebäck

When conducting the same tests for the raw water from Lackarebäck, the test took 6 hours and 30 minutes with the same active membrane area and applying the same pressure, see table 12. This lead to a flow of around 0,08 l/h and a flux of 12,8 l/m^{2}h. The weight of the fouling layer were measured to 0,0241g, see table 12.

Table 12. This table shows the results of the membrane filtration trials using water from Lackarebäck WTP.

Measurement	Value
Permeate	500 ml
Time	6,5 h
Flow	0.077 l/h
Membrane area	0,006 m^2
Flux	12,8 l/m^{2}h
Weight fouling	0,0241 g

The DOC and the UV absorption at 254 nm wavelength were measured also for the water from Lackarebäck WTP and its permeate, mean values of the measurements were then calculated. These values also provided the SUVA values of the raw water and permeate as explained above, see table 13. The calcium titration of the Lackarebäck water showed that the calcium levels in the raw water were around 11,5 mg/ l, and in the permeate around 4,6 mg/ l, see table 13. Finally, the turbidity and color were measured for both raw water and permeate. The last column in table 13 shows the percentage removed from raw water to permeate for each water parameter.

Table 13. This table shows the results of the measurements of water quality parameters for the raw water and the permeate water as well as the decrease.

Water parameters	Lackarebäck raw water	Lackarebäck permeate	rejected
DOC (mg/l)	5,54	2,09	62%
UV_{254} (abs.)	24	13,5	44%
SUVA	4,33	6,46	-
Calcium (mg/l)	11,5	4,6	60%
Turbidity (FAU)	3	1	67%
Color (mg/l Pt-Co)	26	0	100%

The UV absorbance of the raw water and permeate from Lackarebäck were also measured between 220 and 280 nm wavelength, results is presented in figure 15. The UV absorption is larger for the raw water than for the permeate which indicates that UV absorbing material have been removed in all measured wavelengths.

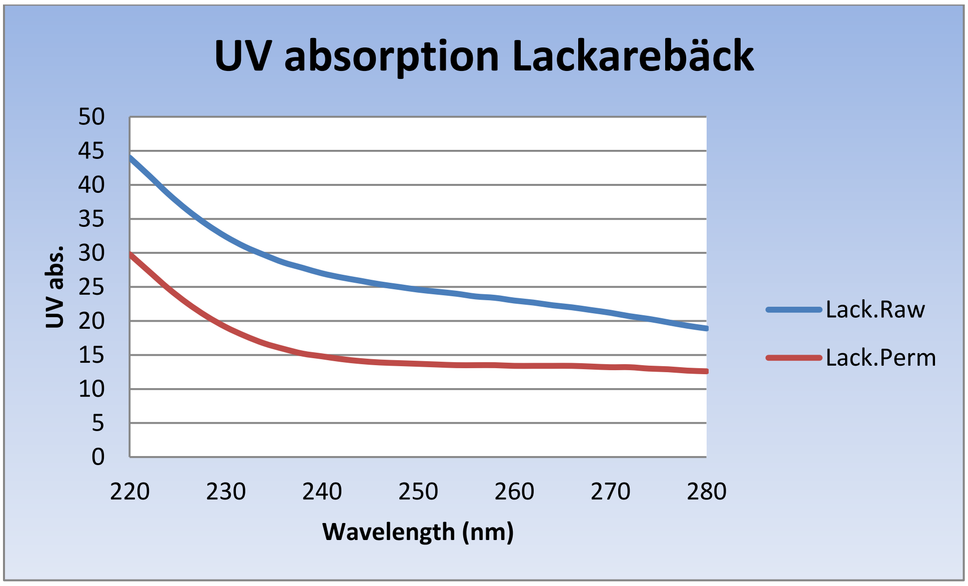


Figure 15. This figure shows the UV absorption of the raw water and the permeate water of Lackarebäck WTP.

The largest decrease of UV as a percentage of the original value for the raw water from Lackarebäck occurs around 240 nm wavelength and the largest rejection is around 45 percent, see figure 16. In the span between 220 and 230 nm, the decrease in UV absorption is the lowest which indicates small fractions. However, as previously mentioned the nitrogen content may have an effect in these wavelengths. The total nitrogen content of the raw water of Lackarebäck were 0,57 mg/l and for the permeate the total nitrogen content were on average 0,44 mg /l. This indicates that 23 percent of the total nitrogen in the raw water is removed by the membrane. Therefore, removal regarding NOM groups in this span cannot be concluded, since too much nitrogen is believed to pass through the membrane. However, in the span between 230 and 280 nm the largest decrease in UV absorption can be observed between 240 and 250 nm. This indicates that these fractions can be associated with the NOM groups with the largest molecular weight in this type of raw water.

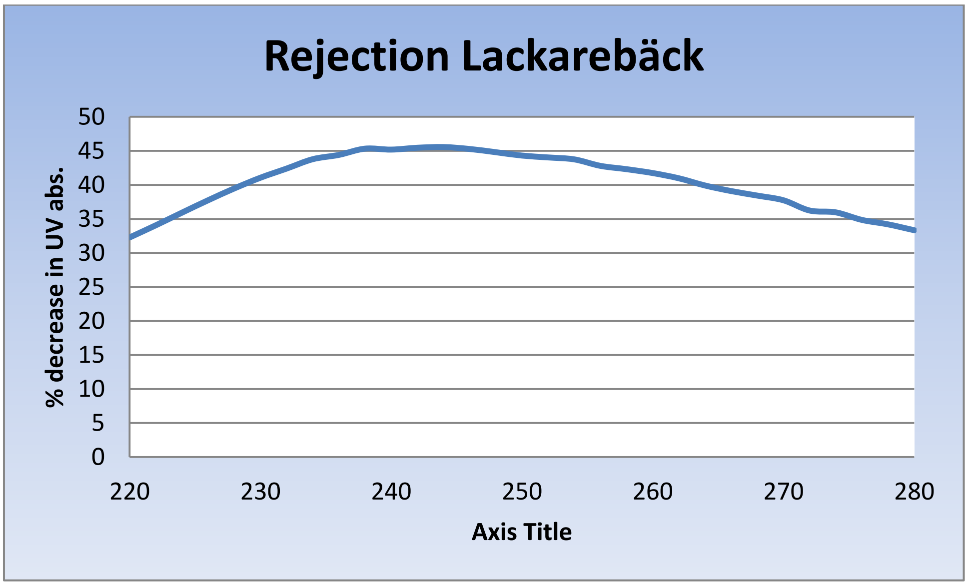


Figure 16. This figure shows the decrease in UV absorption between the raw water and the permeate water in Lackarebäck.

10.4.3 Comparison of results

The results show that the weight of the fouling layer produced when filtering the same amount of permeate applying the same feed pressure is larger in the water from Lackarebäck than the water from Kvarnagården, see figure 17. The weight of the fouling produced at the membrane filtered with water from Lackarebäck were around 4 times higher than the weight of the fouling produced on the membrane filtering raw water from Kvarnagården WTP. This suggests that the water in Lackarebäck has a higher fouling potential than that from Kvarnagården, at least when utilizing a hydrophilic membrane like the one used in this experiment. However, it is hard to draw any conclusions regarding the reversibility of the fouling measured. The irreversible fouling is formed during longer filtration times than what was used in this experiment and it is therefore hard to evaluate the extent of the irreversible fouling in this case.

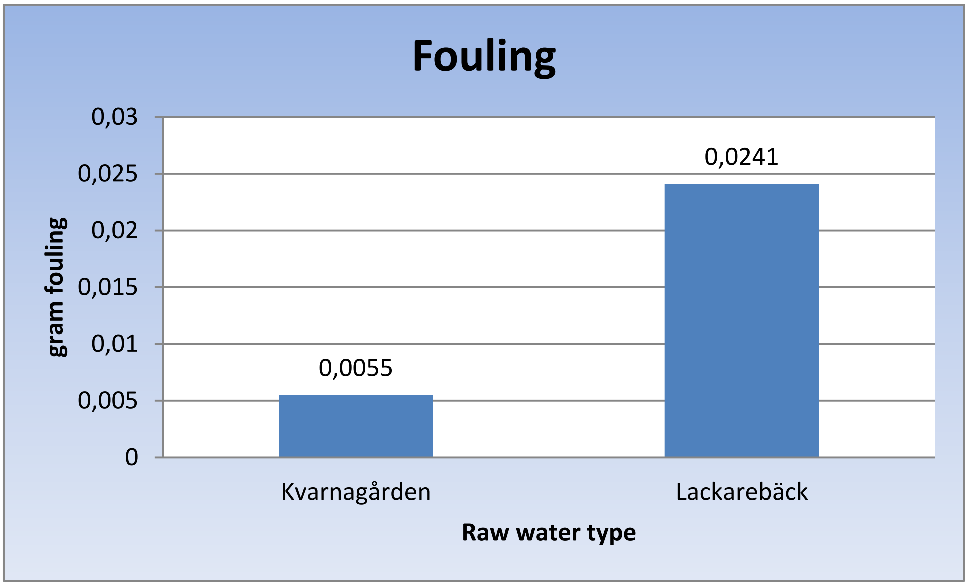


Figure 17. This figure shows a comparison in the fouling weight measured on each of the two membranes used in the filtration trials.

The measured DOC levels in these experiments showed that more DOC were rejected when filtering the water from Lackarebäck, see figure 18. The percentage removed during filtration of water from Kvarnagården and Lackarebäck were 36 percent and 62 percent respectively.

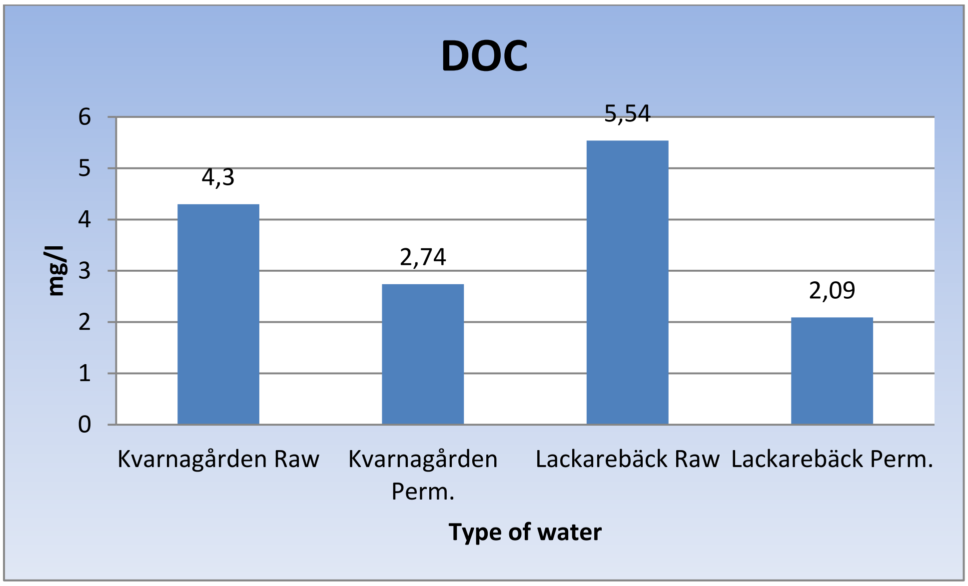


Figure 18. This figure shows comparisons between the DOC levels measured in raw water and permeate water from each of the WTPs.

The UV absorption at 254 nm of the two water types shows that the water from Lackarebäck contained a higher amount of particles associated with absorption at this specific wavelength, see figure 19. The decreases from raw water to permeate from Kvarnagården and Lackarebäck were 75 percent and 44 percent respectively.

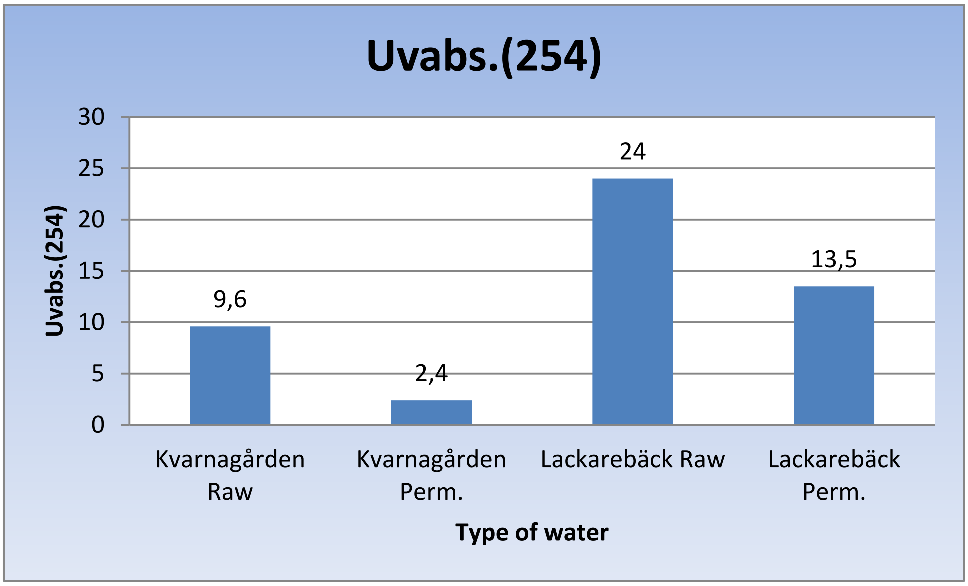


Figure 19. This figure shows the UV absoprtion at 254 nm wavelength of the raw water and the permeate of the two water types.

From the DOC and the UV absorption at 254 nm the SUVA was derived. A decrease of SUVA indicates as previously mentioned a selective removal of hydrophobic NOM. When considering the SUVA values derived through these experiments it is obvious that two different outcomes of the membrane filtration can be observed, see figure 20. While the SUVA decreases after the filtration of water from Kvarnagården, indicating a selective removal of hydrophobic NOM groups, the SUVA value derived from the measurements of the water from Lackarebäck is increasing which suggests that more hydrophilic fractions have been removed.

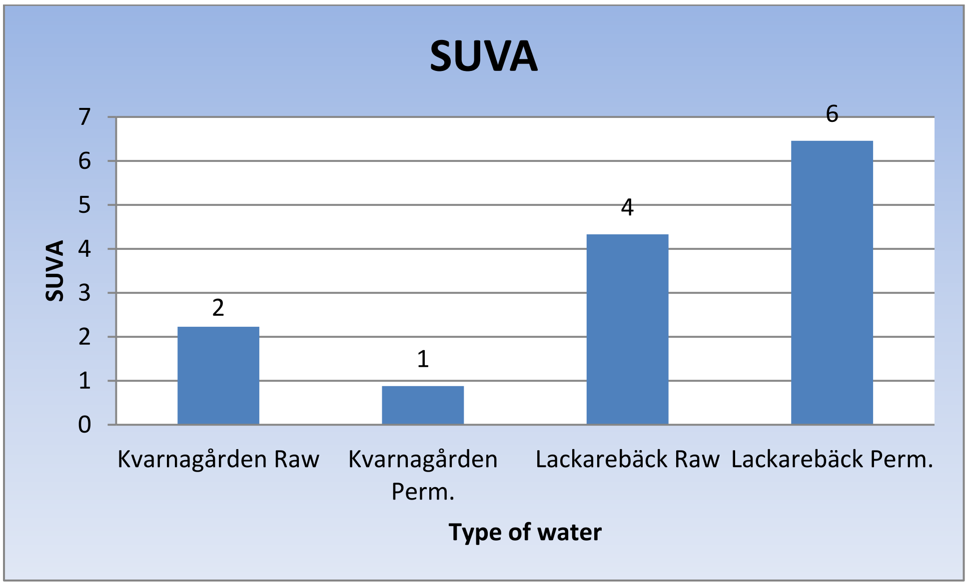


Figure 20. This figure shows a comparison between the tested waters SUVA values.

The turbidity measurements showed that the turbidity were a bit higher for the raw water of Kvarnagården, however, this difference is within the error margin of the test method and the two different raw waters can be considered quite similar in this matter. A slightly higher turbidity indicates that there are more suspended solids in the raw water at Kvarnagården than in Lackarebäck, see figure 21. After filtration both the water from Kvarnagården WTP and Lackarebäck WTP had a turbidity of 1 according to the colorimeter, which could be considered low due to the resolution of the colorimeter.

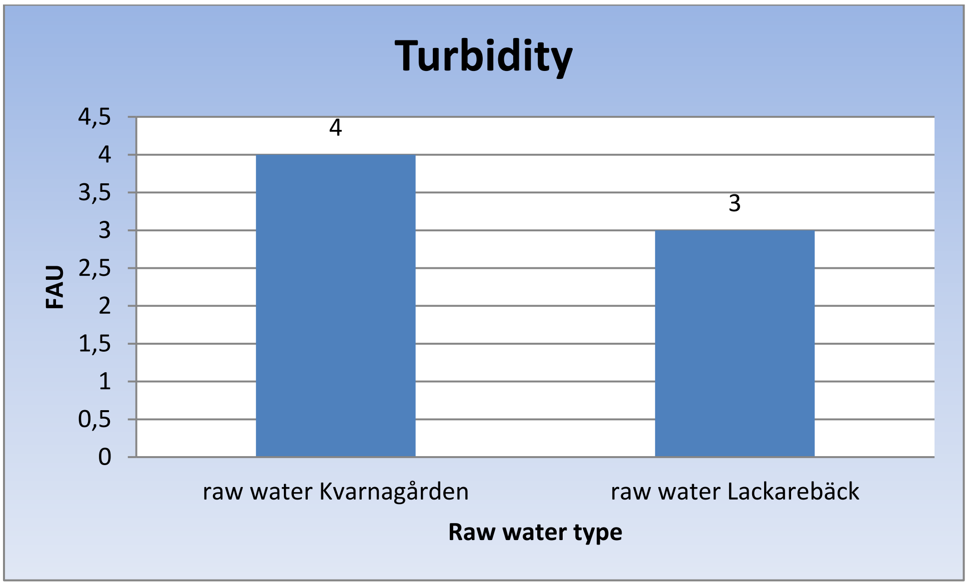


Figure 21. This figure shows the turbidity of the two raw waters tested.

Color measurements showed that also the color of the water was somewhat higher for Kvarnagården than for Lackarebäck, see figure 22. However, this difference is also within the margin of error of the test method which indicates no vast differences between the waters in this case. After filtration the permeate water of both water types had a color value of zero.

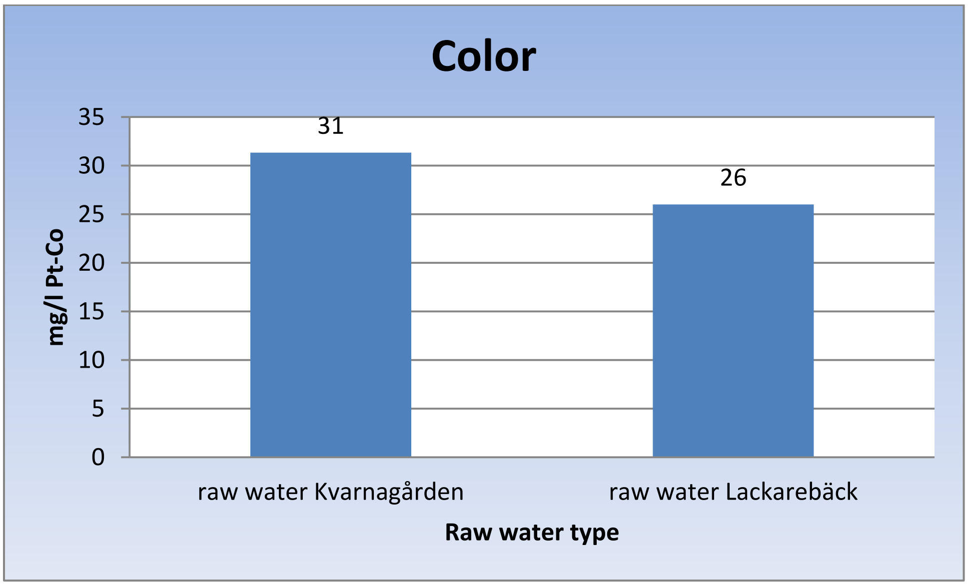


Figure 22. This figure shows the color measured for the two raw waters used in the trials.

The tests of calcium concentrations shows a higher concentration of calcium in the raw water at Lackarebäck than for Kvarnagården, see figure 23. This difference is larger than the error margin and therefore indicates that the average calcium concentration of the raw water at Lackarebäck WTP is higher than at Kvarnagården WTP. This could affect the amount of fouling produced in the two different membrane trials.

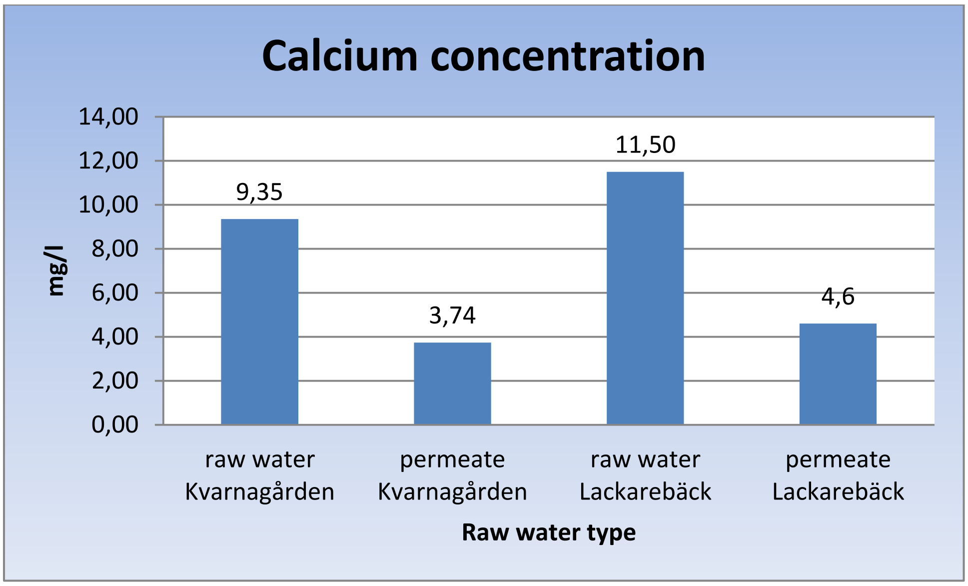


Figure 23. This figure shows the calcium concentration of the different water that was tested.

The UV absorbance measurements over the full spectra associated with NOM showed a higher absorbance of the water from Lackarebäck. This indicates that the concentration of NOM, although the curves are quite similar in shape, is higher in the raw water at Lackarebäck than at Kvarnagården, see figure 24.

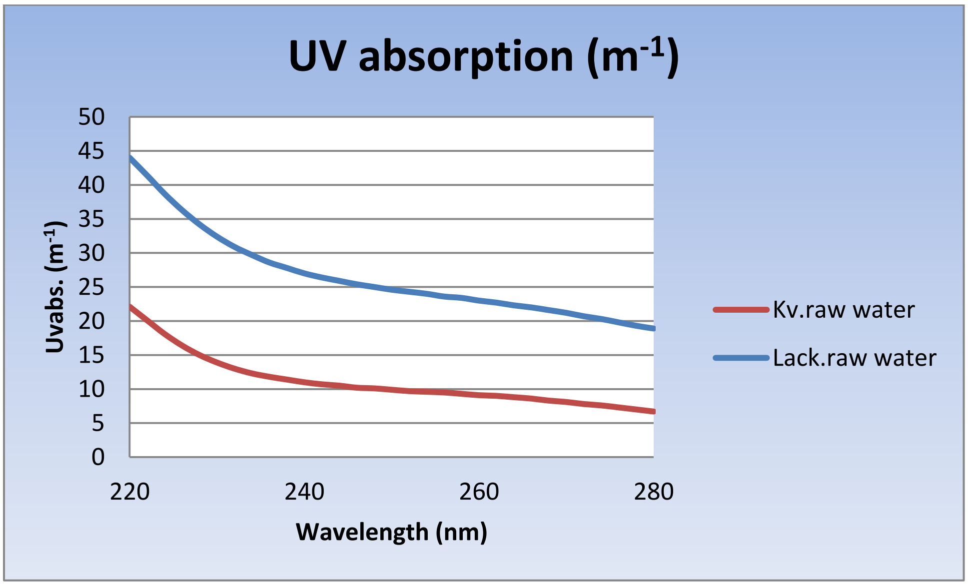


Figure 24. This figure shows the difference in UV absorption between the two raw waters tested, red line Kv.raw water is the raw water from Kvarnagården and the Blue line Lack.raw water represents the raw water from Lackarebäck.

However, when calculating the decrease in UV absorption between the raw water and permeate water of each type the differences between them becomes more obvious. The decrease of UV absorption of the water from Kvarnagården is significantly higher than that of the water from Lackarebäck. This indicates that more NOM has been removed in the trials with the water from Kvarnagården. Especially in the higher wavelengths it becomes more evident that the removal efficiency is diverting between the two types of water.

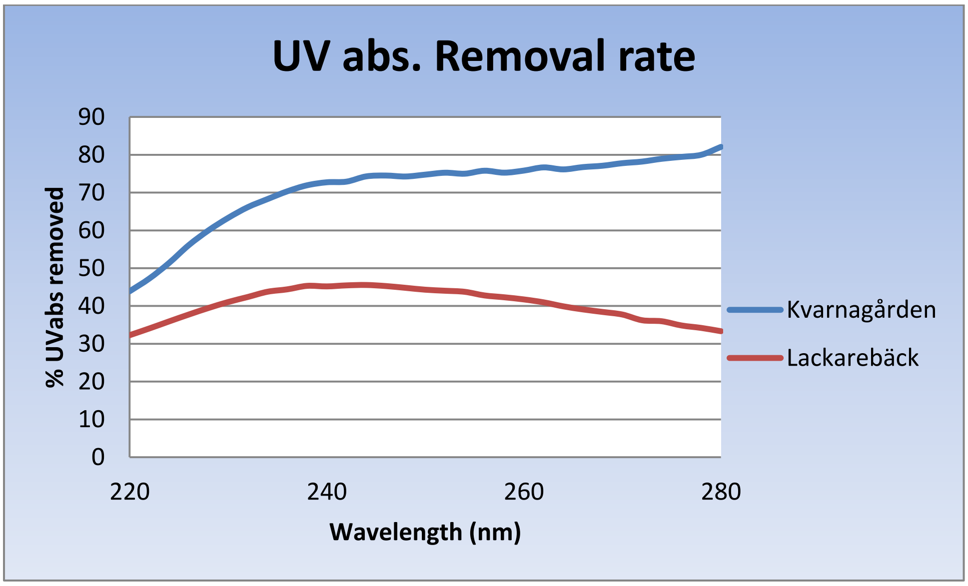


Figure 25. This figure shows the different decreases in UV absorption observed from raw water to permeate of each water type, indicating the NOM removal.

The quotient associated with DBP formation potential A_{253}/A_{203} was calculated for both samples, this calculation showed that the DBP formation potential of the raw water at Lackarebäck were slightly higher than for the water from Kvarnagården, see table .

Table 14. This table shows the UV absorption quotient between wavelengths 253 and 203, which indicates the potential of forming DBPs.

UV absorbance quotient	A_{253}/A_{203}
Kvarnagården raw water	0,322
Lackarebäck raw water	0,332

The higher Calcium concentration and the higher concentration of NOM in the raw water from Lackarebäck WTP is suggested to be the major cause of the higher fouling of the membrane filtered with water from Lackarebäck. This suggests that the fouling at Kvarnagården can be expected to be somewhat lower than at Lackarebäck. However, it is important to regard the fact that these results were obtained using a hydrophilic membrane. Some NOM compositions will attach better to hydrophobic membranes while other compositions of NOM attach better to hydrophilic membranes. Also since the tests were conducted during a relatively short time period, a couple of hours, it is hard to determine to what extent the fouling is reversible or not. As mentioned above irreversible fouling does not form during too short filtration times. The very low reduction UV absorption observed in the membrane trials of the water from Lackarebäck could indicate that the membrane was damaged in some way. However, as previously shown the DOC levels as well as the turbidity and color were significantly reduced when filtering the water from Lackarebäck. The indication of a better removal of NOM when filtering water from Kvarnagården could suggest that more organic fouling should have been present in the fouling of the membrane used. However, since the membrane trials were operated in cross flow mode one possible conclusion is that the NOM in the raw water from Kvarnagården was rejected by the membrane but did not attach to the membrane to the same extent as the NOM in the raw water from Lackarebäck did. Another possible explanation is that some other constituent of the raw water in Lackarebäck contributed more to the fouling than the organic part, i.e. that inorganic fouling occurred. Therefore an interesting additional experiment would be to assess the composition of the fouling of each of the membranes. However, due to lack of time and equipment this experiment could not be performed within timeframe of this project.

11 Estimations

In the following chapter estimations regarding energy use, chemical use, environmental impacts and operational aspects are performed. These estimations are used as a basis for the MCA later conducted.

11.1 Estimations of energy demand

Since one of the main costs associated with the operation of membrane technology is the cost of energy, the operational energy demand of different membrane solutions adjusted to their performance at Kvarnagården WTP was calculated. The specific energy demand of the UF and NF alternatives were retrieved trough questionnaires to manufacturers. However, Kochs UF and NF alternative and the NF alternative from Hydranautics had to be calculated from the recommended fed pressure and average permeate production per day, see Appendix C. The energy included in these values is the energy for raw water to pass through the membrane as well as BW and CEB of the membrane. However, in these values the pumping of water from reservoirs to the membranes is not included. This will instead depend upon which of the available scenarios of implementation that is chosen. Values shown here will be the additional energy demands for each membrane alternative.

As expected the UF alternatives display a lower specific energy than the NF alternatives, see table 15. The calculated mean value of all manufacturers UF alternatives is 0,084 kWh/m^3. The average value of the NF alternatives is 0,47 kWh/m^3. According to the manufacturer information the average NF membrane is therefore expected to be around five times more energy consuming than the average UF membrane. The last bar in the chart is the new HNF or crossover alternative and its expected specific energy demand.

Table 15. This table shows a summary of the different UF and NF alternatives specific energy demand (kWh/m^3) as well as their calculated mean values and the expected specific energy demand of the HNF alternative.

Membrane manufacturer	Specific energy demand (kWh/m^3)
Aquasource UF	0,08
Hydranautics UF	0,1
Inge UF	0,04
Koch UF	0,05
Pall UF	0,14
Mean value UF	**0,084**
Hydranautics NF	0,45
Koch NF	0,47
DOW Filmtec NF	0,49
Mean NF	**0,47**
Pentair Xflow HNF	0,3

Using the average values of the manufacturer information the expected energy use during a year considering the production in Kvarnagården WTP was calculated for each membrane alternative, see table 16. As expected the NF alternatives was most energy demanding while the UF alternatives was the least demanding. The HNF membrane is expected to be in between the two other alternatives, however, with a slight offset towards the NF alternatives energy use.

Table 16. This table shows the expected annual energy demand of each alternatives, calculated as a mean UF or a mean NF and with a production equal to Kvarnagården WTP.

Membrane alternative	Expected energy demand (MWh/year)
UF alternative	466
NF alternative	2609
HNF alternative	1665

To be able to economically evaluate these energy productions and demands they are multiplied by the cost of a kWh. The price chosen for this study is 0,987 SEK/kWh which was the mean price 2011 of one kWh provided by the company Varberg energi including taxes (Varberg energi 2012). With this price decided the costs of each of the alternatives could be evaluated and is presented in table 17.

Table 17. This table shows the expected cost of the energy demands of each scenario if the price of a kWH were the mean price of energy 2011.

Membrane alternative	Expected energy cost (SEK/year)
UF alternative	459 942
NF alternative	2 575 083
HNF alternative	1 643 355

11.2 Estimations of chemical usage

This section provides an estimation of the chemical use associated with each alternative. The calculation of coagulant demand only applies to the UF alternative, since none of the other alternatives utilizes direct coagulation. In the calculations of cleaning chemical usage, different calculations had to be carried out for each alternative, due to the fact that UF alternatives utilizes regular CEB while the NF alternatives is cleaned when pressure drops occur. For the UF alternatives the cleaning chemical estimations are based on the information provided by manufacturers. For the NF alternative the amount of cleaning chemicals needed could not be calculated from manufacturer data, since none of the contacted manufacturers provided any information regarding the chemical use as they did for the UF alternatives. However, assuming a similar fouling at Kvarnagården WTP as observed in the NF pilot trials of (Heinicke 2005) the NF membranes should be cleaned during 24 hours every two to four weeks with a 0,1 weight percent Sodium Hydroxide solution. The total amount however, is hard to estimate from this since the study did not specify how much sodium hydroxide that was used in each cycle. Therefore, the estimation of cleaning chemicals in the NF alternative is based on values from a study by (Bonton et al. 2012) where an NF plant in the northern part of the Canadian province of Quebec were investigated. For the HNF alternative it is hard to estimate the chemical usage since it has only just started to be tried out in pilot trials. However, since it has the same structure as an UF membrane but with a higher rejection it can be assumed to have at least the same but probably higher chemical usage as the UF alternative considering CEB chemicals. For these calculations however, the HNF alternative is assumed to use the same amount of CEB chemicals as the UF alternative. More detailed descriptions of calculations carried out in this section can be reviewed in Appendix D.

In the UF pilot tests conducted at Kvarnagården WTP the coagulant polyalumiumchloride (PAC) called Pluspac S 146 supplied by Feralco Nordic was used. The necessary amount of coagulant needed as a pretreatment for membrane filtration were not given from membrane manufacturers and therefore needed to be estimated. By using the questionnaire investigation of WTPs as a basis, the amount of coagulant needed could be assessed. Among the twelve answered questionnaires only six of them used coagulants as a pre-treatment. Of these six WTPs only two of them used PAC as a coagulant. These were the WTPs in Inverness (Scotland) and Walpole (Canada). Information regarding the average use of coagulant was only provided by Inverness WTP. The needed amount of coagulant was therefore based on the experiences of this WTP. The consumption of the coagulant for a year was calculated.

The total cost was based on price information provided from the company supplying the chemical, in this case Feralco Nordic. The permeate flux of drinking water was higher for Inverness than Kvarnagården and the required amount of coagulant was therefore scaled down to match the case for Kvarnagården WTP. The consumption of PAC for an UF membrane setup in Kvarnagården was estimated to be approximately 22 tonnes per year. Feralco Nordic made a quote on this estimation to a price of approximately 2135 SEK/tonnes (sales tax). There are three sales taxes in Sweden 25, 12 and 6 percent. According to the Swedish taxation agency, substances added intentionally to food during processing, preparation or treatments should have a sales tax of 12 percent (Skatteverket 2011). With a sales tax of 12 percent the price of PAC from Feralco Nordic will be 2391,2 SEK/tonnes. This result in a total cost of 52600 SEK per year, see table 18.

Table 18. This table shows the expected annual need of coagulant chemicals as well as the cost of this chemical use, only applies to the UF alternative.

Coagulant	Polyaluminumchloride
Consumption [tonnes/year]	22
Price [SEK/tonnes]	2391
Total price [SEK/year]	52600

To estimate the cost of purchasing the chemicals for CEB, data of which chemicals that were needed in the process were required. This information was provided from different membrane manufacturers for different outflow scenarios. The chemicals used in the CEBs of the pilot trials in Kvarnagården were citric acid, sodium hypochlorite and sodium hydroxide. The type of chemicals used, the amount needed and the recommended concentrations of the chemicals varied vastly between the different membrane manufacturers. The costs were calculated for three different manufacturers UF alternatives; Inge, Pall and Hydranautics. The recommended chemicals for CEB were sodium hydroxide and sulfuric acid for Inge; sodium hydroxide, sodium hypochlorite and hydrochloride for Hydranautics and sodium hydroxide, sodium hypochlorite and citric acid for Pall. The chemicals are bought at certain concentrations from suppliers and different strength of the solutions means the weight will vary due to the different densities of chemicals and water. During the UF pilot test carried out in Varberg the chemicals for the CEB were bought from the company Brenntag Nordic. Therefore the totals costs for purchasing chemicals for CEB have been based on price information from Brenntag Nordic.

The consumption and total price of sodium hydroxide are based on a mean value between the three membrane manufacturers. Since only Pall and Hydranautics had recommended use of sodium hypochlorite in their provided information, the calculations of total price and consumption is a mean value of the data from these two manufacturers. Calculations of the total price and consumption of citric acid is based on the information of the average use of acids by manufacturers' alternatives. The average total CEB chemical cost estimation for an UF alternative at Kvarnagården WTP is therefore around 250 000 SEK per year, with an expected chemical consumption around 47 tonnes per year, see table 19.

Table 19. This table shows the expected annual use of CEB chemicals and the expected cost of this chemical use.

Chemical use UF alternative	Sodium hydroxide (NaOH)	Sodium hypochlorite (NaOCl)	Citric acid	Average total UF alternatives
Consumption [tonnes/year]	12	27	8	47
Total price [SEK/year]	47 000	176 000	29 000	252 000

The estimation of chemical use of a Canadian NF plant where the specific use of cleaning chemical, sodium hydroxide, was 0,0042 kg/m^3. By multiplying this specific use with the annual production at Kvarnagården WTP, the estimation was provided, see table 20. However, the raw water from these two WTPs is somewhat different when the raw water of the Canadian WTP has a DOC of around 0,9 mg/l (Bonton et al. 2012), while the raw water at Kvarnagården WTP has a DOC value of around 3 mg/l. This indicates that the fouling and subsequently the chemical usage in Kvarnagården will be a bit higher than the estimate provided here. The fact that the estimate of the chemical use of NF may be a bit underestimated due to the lower DOC value of the raw water in the Canadian WTP may partly be the reason for the lower chemical consumption of this alternative. However, the cleaning of the UF alternatives utilizes chemicals on a day to day basis while the NF alternatives use chemicals at the most once a week and most often less. This is also one of the reasons for the somewhat lower consumption of cleaning chemicals of the NF alternative.

Table 20. This table shows the expected annual chemical use of the NF alternative as well as the cost associated with this usage.

Chemical use NF alternative	Sodium hydroxide (NaOH)
Consumption [tonnes/year]	23,3
Total price [SEK/year]	93 000

To conclude the chemical usage of the three alternatives the UF alternative will have the highest consumption when it utilizes both coagulant chemicals as well as cleaning chemicals. The NF alternative on one hand is estimated to have the lowest chemical use, see table 21. The HNF alternative is as mentioned before assumed to have a chemical usage equal to the CEB usage of the UF alternative and is estimated to be in between the two other alternatives.

Table 21. This table shows the summarized expected chemical costs of each of the membrane alternatives as well as the costs associated with each of the alternatives chemical use.

Total chemical use per alternative	UF alternative	NF alternative	HNF alternative
Chemical per year (tonnes)	69	23,3	47
Chemical cost per year (SEK)	305 000	93 000	252 000

11.3 Environmental aspects

In this section the different environmental aspects associated with the membrane alternatives will be considered. The different areas covered in this section are global warming potential, resource depletion and energy demand. Resource depletion will be evaluated by investigating the operational chemical use of the alternatives but also the material use is evaluated as a part of the resource depletion evaluation.

11.3.1 Global warming potential

The global warming potential (GWP) is taken into consideration by calculating the CO_2 and N_2O emissions associated with the transport of chemicals needed at the operation at Kvarnagården WTP during one year. For the HNF alternative, only the transport emissions equal to the UF alternatives use of CEB chemicals will be considered since this alternative do not use coagulant chemicals. More detailed information regarding the calculations carried out in this section can be reviewed in Appendix E.

The chemicals used for the pilot tests in Kvarnagården were bought from the company Brenntag Nordic and the coagulants from Feralco Nordic. The closest Brenntag Nordic warehouse is located in Borås which are approximately 80 kilometers from Varberg. Therefore, this distance was used in the calculation of emissions from transports of CEB chemicals. The coagulants are transported from a factory in Vetlanda, which is approximately 174 kilometers from Varberg. The distances between Varberg and both companies were doubled to consider the emissions produced by the trucks on their way back. For both the coagulant and chemical purchase a scenario with a heavy truck transporting the chemicals were assumed since the quantities needed to be transported are in such large volumes that light trucks would be an unreasonable alternative. The weight a truck is capable of loading was assumed to be 20 tonnes. The maximum weight capable for a truck was needed to be able to calculate how many times the trucks needed to drive the given distances in order to deliver the required amount of chemicals. The CO_2 emissions were calculated by a Microsoft Excel model made by Swedish EPA (Naturvårdsverket, 2011), see table 22. The N_2O emissions could be derived by guideline values produced by IPCC, who stated that a heavy truck as an average emits 0,0805g N_2O/ km. The emissions of N_2O were adjusted to CO_2 equivalents by multiplying the N_2O emission with 296, which is the global warming potential of N_2O compared to CO_2. The total GWP of each transport was then summarized, see table x.

Table 22. This table shows the annual emissions associated with transporting the chemicals required in UF from the chemical warehouse to the WTP.

Emissions UF alternative	CO_2 (g)	N_2O (g)	Total GWP (g CO_2 eq.)
Coagulant transport	103356	30,8	112473
CEB chemicals trans.	101520	30,4	110518

For the NF alternative the emissions is calculated in the same way as for the UF alternative, but using the weight of the chemicals needed in the NF alternative as a basis for the calculation. The results of these calculations are presented in table 23. The coagulant transport is not considered in the NF alternative since no coagulant chemicals are used.

Table 23. This table shows the expected emissions associated with the transport of the cleaning chemicals needed in the NF alternative.

Emissions NF alternative	CO_2 (g)	N_2O (g)	Total GWP (g CO2 eq.)
Cleaning chemical transport	50328	15	54768

The emissions associated with each alternative is then calculated by adding all emissions that are associated with each alternative, see table 24. In the UF alternative the emissions from both coagulant and CEB chemical transport is used. The NF alternative includes the calculations of GWP for the cleaning chemicals needed in the NF process. In the HNF alternative only the transport of CEB chemicals of equal amount as the UF alternative were used.

Table 24. This table shows the total expected annual global warming potential of each alternative.

Membrane alternative	Total GWP (g CO_2 eq.)
UF	222991
NF	54768
HNF	110518

11.3.2 Resource depletion

The resource depletion aspect is considered semi qualitative and focuses on the amount of material used in each of the alternatives. This means that the amount of membrane modules and their size is taken into account. The material used in each different alternative is quite similar and therefore only the amounts used will be regarded. Also the chemical usage of each alternative will be regarded in this section when this can be considered to be a resource depletion of a kind.

The number of modules needed in Kvarnagården WTP was calculated according to information regarding permeability and flux provided by membrane manufacturers, mean values of each alternative was then calculated, see figure 26. The NF alternative has the lowest average permeability as well as the smallest active membrane area per module which means that more modules were needed to produce sufficient amounts of permeate. The HNF alternative has a slightly higher permeability than NF but still requires far more modules than the UF alternative. However, the amount of modules is not representative of the actual material use since the modules of each alternative are not of the same size. Assuming that the modules of each alternative were quite similar regarding density, the total casing volume will provide an indication of which alternative that requires most material.

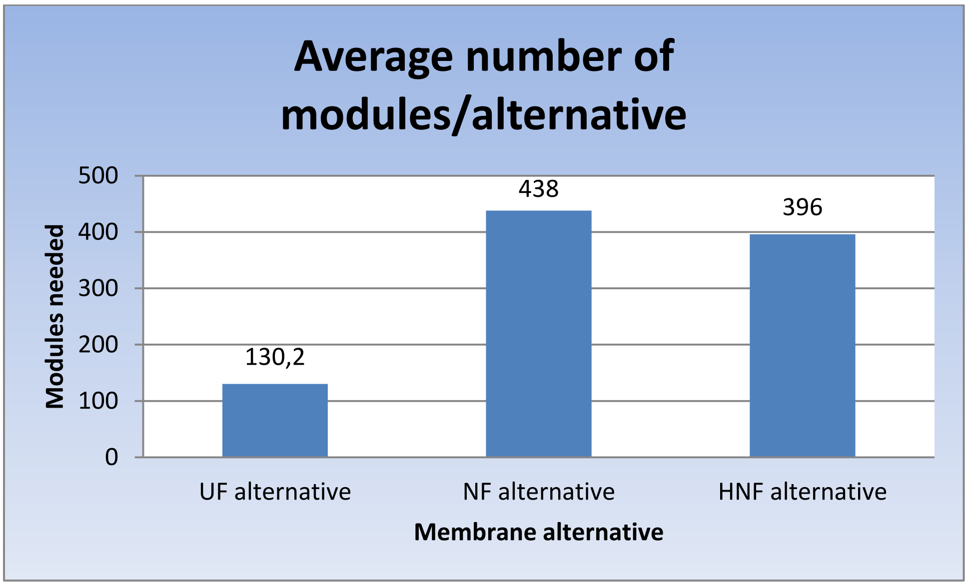
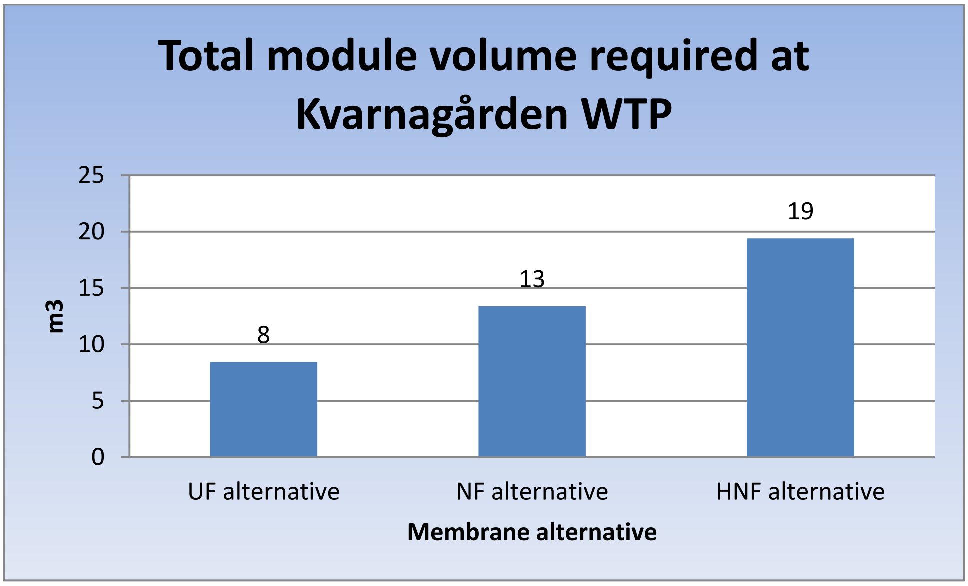


Figure 26 This figure shows a comparison of how many modules each alternative requires to produce the amount of permeate needed in Kvarnagården WTP.

Therefore, the mean volume of the casing of a module of each alternative were calculated and multiplied with the amount of modules required to produce the amount of permeate needed at Kvarnagården WTP. This value gives an indication of how much material that is needed for each alternative, see figure 27. This figure indicates that the UF alternative will be least resource demanding considering material use.



Figur 27. This figure shows the expected total module volume, which indicates the material needed for each alternative.

As mentioned before the chemical usage of the alternatives were higher for the UF alternative than for the NF alternative and slightly lower for the HNF alternative. Therefore, the alternatives can be regarded quite equal according to resource depletion.

11.3.3 Energy demand

The energy demand of each alternative were calculated in previous chapter and revealed as expected that NF required most energy input. However, in an environmental aspect the most important issue is how the energy is produced, not the actual energy usage. According to Varberg Energi, the energy company in Varberg, all energy they provide is guaranteed to be produced by renewable energy sources like wind and water (Varberg Energi 2012). With this in mind the energy consumption is less important in an environmental perspective, even though energy production in some way often can be associated with some kind of environmental impact. In this study the energy demand of the alternatives will therefore be of less importance than how the energy consumption affects the economic aspects.

11.4 Operational aspects

In this section the operational aspects of each alternative is evaluated. Included in this is the expected area that each alternative requires, i.e. the footprint of a full scale installation of each alternative. Also included in this section are the experiences of the WTPs that answered the questionnaire regarding unexpected stops in production due to technical problems associated with the membrane treatment step. Finally, the operational aspects regarding permeate quality was taken into account. Since all these alternatives are capable of removing microorganisms to a low enough level, the main focus have been on how efficient NOM is removed by the different alternatives and what risks there are of DBP formation. The basis for these estimations is the chapter NOM characterization as well as the results of the experiments carried out during this study.

11.4.1 Footprint

When investigating the footprint of different membrane setups a mean value of each membrane alternative was calculated from the footprints that were provided by the manufacturers. The footprints were adjusted to the required permeate flow at Kvarnagården WTP. However, far from all manufacturers provided information regarding the footprint and therefore the basis of these estimations were not completely satisfying, the manufacturer information regarding footprint used as a basis for this estimation is displayed in Appendix A. For the HNF alternative the footprint was assumed to be similar to the UF alternative due to the similarities of the module design and function. This investigation showed that the footprint was quite equivalent for the alternatives even though the NF alternative showed a slight advantage regarding the footprint, see figure 28. The reason for the somewhat smaller footprint of the NF alternative is probably due to the fact that the NF rack setup from Koch is very limited regarding footprint only 39 m^2 for a WTP with a capacity equal to Kvarnagården.

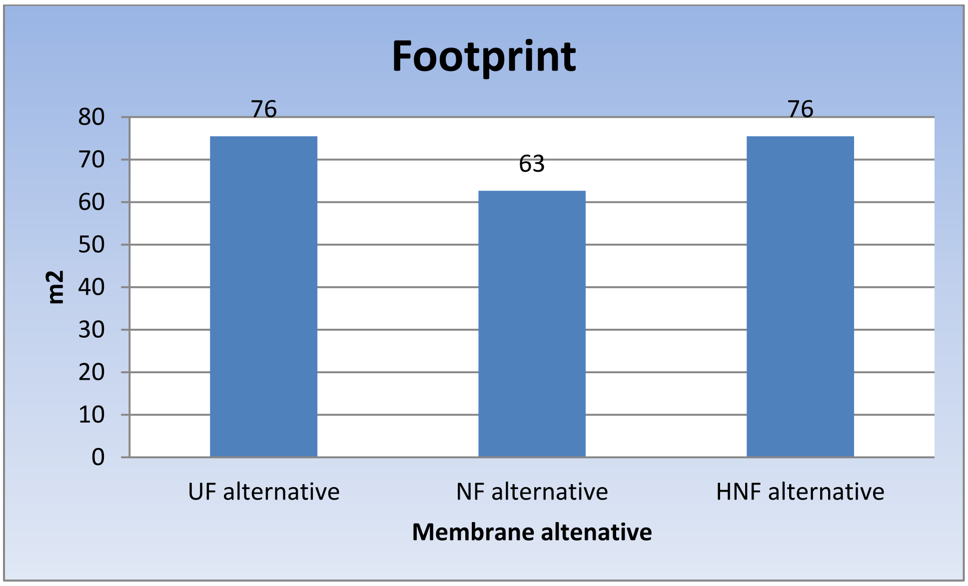


Figure 28. This figure shows the expected footprint of that can be expected regarding each alternative.

11.4.2 Risk of system failure

The questionnaire to WTPs revealed that the most common problems experienced at facilities using UF systems were filter breakage and valve failures. Other problems were communication losses of the computer systems. The WTPs utilizing NF systems experienced problems with shut downs of the system due to power failures. However, the information provided does not specify how often these problems occur and too few of the WTPs have provided an answer for any conclusions to be drawn regarding this aspect.

11.4.3 Permeate quality

The experimental stage of this report showed that the raw water used in Kvarnagården WTP and in Lackarebäck WTP were quite similar in composition, however, higher NOM concentrations and more fouling was observed in the tests of the raw water from Lackarebäck. Therefore, estimations of fouling potential carried out at Lackarebäck can be expected to be higher than what will be the case at Kvarnagården WTP. The main constituents of NOM in the raw water of Kvarnagården had a molecular size between 1500 and 5000 Da, comparing these values with the nominal molecular cut off of the different membrane alternatives, it shows that the NF and HNF with cut offs around 300 and 1500 Da respectively will remove most part of the NOM content in the water. The UF alternative on the other hand with a cut off between 80 000 to 150 000 Da will not be able to remove NOM without addition of coagulants. The efficiency of the coagulation is therefore of importance when considering the permeate quality of the UF alternative. As previously mentioned the SUVA values of the raw water in Kvarnagården may indicate that the NOM composition is somewhat troublesome to coagulate. Also the measurement of UV_{254} used to control the NOM concentration in the permeate water is not completely reliable when it focuses mainly on aromatic NOM molecules. If the NOM composition of the raw water is less aromatic there is a risk of miss judging the NOM concentrations in the UF permeate. However, according to the UV absorbance test performed on the raw water at Kvarnagården the highest concentrations of

NOM seems to be between 220 and 254 nm which corresponds to the more aromatic NOM groups. A more extensive NOM characterization like an EEM of the permeate water of an UF system with direct coagulation at Kvarnagården could probably shed more light on the actual performance of a system of this kind. What can be established is however, that there is an increased risk of inferior water quality and DBP formation connected to the UF alternative than for the NF and HNF alternatives.

11.5 Economy

In this section the total costs of each membrane alternative is evaluated, included in this calculation is the costs of energy demand and chemical use and the estimated purchase price. The estimated purchase price was provided by the manufacturers.

11.5.1 Operational costs

The estimated operational costs are the cost energy and chemicals during a year for each of the alternatives, see table 25. The operational costs of the NF alternative are by far the highest, even though this alternative has very low chemical costs. This indicates that the energy demand has a higher leverage on the operational costs. The lowest operational costs are associated with the UF alternative and the HNF alternative is estimated to have around one million SEK more per year in operational costs than the UF alternative.

Table 25. This table shows the total estimated annual operational costs associated with each alternative.

Estimated total operational costs	SEK/year
UF alternative	759 942
NF alternative	2 668 083
HNF alternative	1 895 355

11.5.2 Purchase cost

The price information provided by manufacturers were very diverse, when some manufacturers gave information regarding the cost of a full scale system others only provided information regarding the price of one module. In the price of a full scale system costs for piping, racks and computer systems are included, therefore comparisons between the different prices are not possible.

In table 26, the prices of a full scale system of the size of Kvarnagården WTP are shown for each of the membrane manufacturers that provided this information. These prices include piping, the rack, control system and installation. The cost is displayed in SEK but is recalculated from Euro using 8,99 EUR/SEK as exchange rate and from US dollar using 6,96 USD/SEK as exchange rate (Finansportalen 2012).

Table 26. This table shows the cost proposals by different manufacturers calculated in SEK.

Manufacturer	Total cost (SEK)
Aquasource UF	10 293 779
Inge UF	5 469 277
Hydranautics UF	2 143 372

For the NF alternatives price information were only provided regarding the cost of each element. Therefore additional costs of the system with piping racks and control systems will be an additional cost. However, information regarding this has not been acquired and therefore the purchase costs of the alternatives cannot be compared in the MCA. The prices per module acquired are however, presented in table 27. The values are recalculated from dollar using the same exchange rate as previously used 6,96 USD/SEK (Finansportalen 2012). Also in this table the price of the elements needed in Kvarnagården WTP is presented. The amount of elements needed are calculated from the manufacturer information regarding the nominal daily permeate flow of each element.

Table 27. This table shows the average prices of some of the different NF alternatives on the market.

Manufacturer	Price per module (SEK)	Elements needed	Cost for all membrane elements
DOW NF270	6629	322	2 134 538
Hydranautics ESNA LF2	6111	493	3 012 723

12 MCA

This section describes the structure of the MCA and is based on the results and conclusions drawn in previous chapter. Categories included in the MCA are the estimated operational costs associated with each membrane alternative in which both energy demand and chemical costs are included. The MCA also includes adverse environmental effects of each alternative and finally the conclusions of the operational aspects.

12.1 Weights

The subcategories are weighted from 0 to 5 according to their relevance in the decision making process regarding which membrane alternative is the most suitable in Kvarnagården WTP, see table 28. In the category of total costs there are two subcategories; operational costs including the cost of energy as well as the chemical costs, and the purchase costs. However, since no comparisons could be made according to the purchase price this category will not be assessed. The category environmental impacts include subcategories; global warming potential, resource depletion and energy demand. The subcategories in environmental impacts is weighted rather low, this is due to the relatively low amounts of transports. Regarding the resource depletion, also this category is weighted rather low due to the fact that quite similar material is used in each alternative and that the chemicals used is not rare. Regarding the environmental impact of the energy use it is considered less critical in the decision making due to the fact that the energy if bought from Varberg energi would be energy produced by renewable sources and therefore associated with low environmental impacts (Varberg Energi 2008). In the category operational aspects the subcategories footprint, stops in production and quality of permeate was considered. The footprint is an important factor, however the expected footprints of each alternative is quite similar which means that this subcategory will be of less importance in this case. As previously explained no conclusion could be drawn regarding the unexpected stops in production, therefore the weight of this subcategory will be zero. However, it is an interesting factor if enough information could be gathered. The quality of the permeate is an important factor. However, since it seems that each of the alternatives is able to satisfy the restrictions of potable water, this category is not regarded as the most important one.

Table 28. This table shows the weights of the different categories of the MCA.

Category	Sub category	Weight
Total costs	Operational costs	5
	Purchase costs	-
Environmental impacts	Global warming potential	1
	Resource depletion	1
	Energy demand	1
Operational aspects	Foot print	1
	Stops in production	-
	Quality of permeate	4

12.2 Score

In this section the estimations previously done is used as a basis for the scoring of each alternative. The alternatives are awarded points between 0 to 10, where 10 are considered the best and 0 the least favorable respectively. The scoring is supposed to reflect how well the alternatives perform in each category, see table 29. The score of the alternatives in each category is then multiplied with the weight of the category to produce a weighted score. The membrane alternative with the highest weighted score is considered to be the most favorable alternative to implement in Kvarnagården WTP.

Table 29. This table shows the score of the different alternatives regarding the different categories as well as the total score and weighted score.

Category	Sub category	Weight	UF alternative		NF alternative		HNF alternative	
			Score	Weighted score	Score	Weighted score	Score	Weighted score
Total costs	Operational costs	5	10	50	0	0	7	35
	Purchase costs	-	-	-	-	-	-	-
Environmental impacts	Global warming potential	1	5	5	7	7	6	6
	Resource depletion	1	2	2	4	4	3	3
	Energy demand	1	10	10	2	2	5	5
Operational aspects	Footprint	1	7	7	8	8	7	7
	Stops in production	-	-	-	-	-	-	-
	Quality of permeate	4	3	12	10	40	9	36
Total score			20	-	20	-	25	-
Total weighted score			-	86	-	61	-	92

The highest weighted score were awarded to the HNF alternative thanks to the fact that it performed relatively good in most categories while the other alternatives performed well in some categories and much worse in other. Therefore, if the HNF shows performances as expected it is considered the most favorable alternative to implement in Kvarnagården WTP. However, this is a rather new technology and there may yet be unforeseen technical difficulties associated with this alternative, even though its performance seems promising.

13 Sensitivity analysis

To evaluate the validity of the estimations carried out as a basis for the MCA it is important to conduct some kind of sensitivity analysis. However, many of the estimations are based on manufacturer information and are therefore hard to evaluate, when there are little insight in how these values are established by the manufacturers. This includes the energy demand, the chemical usage of the UF alternatives and the information regarding size and footprint of the membrane setups. In each estimation chapter however, the main drawbacks and uncertainties of the estimation are pointed out. However, for the chemical consumption of the NF alternative the estimation is based on the chemical usage of a Canadian WTP utilizing NF technology. As previously mentioned the raw water used by this WTP and the raw water used in Kvarnagården WTP are different regarding the DOC level. This will affect the fouling of the membrane and in turn also the amount of cleaning chemicals required. Therefore a sensitivity analysis was carried out regarding the consumption of chemicals in the NF membrane alternative.

The sensitivity analysis was performed by calculating a scaling factor from the DOC levels from the raw water used at the Canadian WTP and Kvarnagården WTP. The scaling factor was then multiplied with the specific use of chemicals and then multiplied with the total water production for a year in Kvarnagården, see table 30.

$$\frac{3}{0{,}9} * 0{,}0042 = 0{,}014\frac{kg}{m3}$$

Total water production at Kvarnagården:

$$\frac{176}{1000}\frac{m3}{s} * 60 * 60 * 24 * 365 = 5550336\frac{m3}{year}$$

Estimated consumption:

$$0{,}014\frac{kg}{m3} * 5550336\frac{m3}{year} = 77705\frac{kg}{year} = 77{,}7\ tonnes$$

Table 30. This table displays the previous estimated cleaning chemical consumption as well as the estimated chemical consumption adjusted to the different DOC values of the raw water.

	Consumption [tonnes/year]	Price change [SEK/year]
Previous consumption	23,3	93000
Consumption adjusted to DOC	77,7	396294

However, since there are no direct correlation between DOC level and the fouling potential of the membrane and thereby the chemical usage, the sensitivity analysis is only used as an indication of the sensitivity of the estimation. Therefore the estimation of chemical usage of the NF alternative believed to be somewhere in between these two estimations. This however, does not change the outcome of the MCA, since the NF alternative already were concluded to be the least favorable alternative. A much larger chemical consumption of the NF alternative would just further decrease the feasibility of this alternative.

14 Scenarios of implementing membrane technology in Kvarnagården

As explained in the chapter Kvarnagården water treatment plant there are three different scenarios of implementing the membrane technology in the current WTP. In scenario 2a and 2b the membranes will be fed with water from the sand filters and in scenario 3 the mixed raw water is directly fed to the micro filter and the membrane step. In this chapter the advantages and disadvantages associated with these scenarios are discussed. The main differences between the scenarios are the energy demand connected to each of the scenarios.

The additional energy demand associated with the implementation scenarios is shown in table 31. This energy demand corresponds mainly to the pumping of water from the reservoir to the membranes. Scenario 3 is not included in this table since it has to be calculated in a different way and does not necessarily lead to an increased energy demand. Instead it depends on whether the potential energy from the lake is enough to yield a high enough flux through the membranes.

Table 31. This table shows the additional energy demand not including the membrane stage associated with implementation scenario 2a and 2b.

Scenario	Additional energy demand MWh/year
Scenario 2a	160
Scenario 2b	86

The total energy demand of Scenario 2a and 2b for each membrane alternative is then calculated to provide an estimation of expected energy demand, see table 32. What has to be taken into account however, is the fact that energy is also produced in these two scenarios. Therefore, the demand presented in the table has to be compared with the amount of energy produced in the two scenarios.

Table 32. This table shows the total annual energy demand if the different alternatives were to be implemented according to scenario 2a or 2b.

Total energy demand (MWh/year)	UF	NF	HNF
Scenario 2a	627	2769	1825
Scenario 2b	552	2695	1751

The energy production in both these scenarios is 855 MWh/year with a possibility to utilize an extra turbine on the overflow water which would yield on average an additional 43 MWh/year. Taking this into account the UF alternative is the only alternative that can be implemented in one of these two ways and yield an energy surplus, see table 33.

Table 33. This table shows the demand or surplus of energy associated with the implementation of the alternatives according to scenario 2a or 2b, as well as the scenarios including an extra turbine on the overflow pipe.

Energy +/- (MWh/year)	UF	NF	HNF
Scenario 2a	+228	-1914	-970
Scenario 2a + turbine	+271	-1871	-927
Scenario 2b	+303	-1840	-896
Scenario 2b +turbine	+346	-1797	-853

For scenario 3 the pressure required at the fed side of the membrane as well as the pressure losses in pipes and micro filter determine whether energy can be taken out through a turbine or if energy has to be added by installing a feed pump. As seen previously the height of the lake is +76,5 meters and the inflow to the micro filter and the membrane is at an elevation of +14,1 meter, losses in the main pipe have been calculated and is 14,5 meters at a flow of 300l/s and 6 meter with a flow of 200 l/s and the loss in the micro filter has been assumed to be around 0,3 bar (VIVAB 2012). Available water height from the lake when pressure loss in pipes and micro filter has been accounted for is therefore 44,8 meters during 8 months, when a flow of 300 l/s can be utilized. In the summer months the outtake of water from the lake is limited due to larger evaporation and the minimum level of the lake, therefore during 4 months of the year only 200 l/s can be taken out. This means that the available pressure is increased due to the reduced pressure losses in the main pipe associated with a lower flow. The available pressure head during these 4 months are 53,3 meters.

For the UF alternatives the mean fed pressure is 1,81 bar, which is equal to a pressure of 18,4 meters of water. This means that between 26 and 35 meters of water pressure is available to take out through a turbine as an average during the year when using an UF alternative, see table 34.

The mean fed pressure of an NF cross flow membrane provided by manufacturers is 8,5 bar, this represents 86 meters of water pressure. Considering the 44,8 to53,3 meters of available water pressure, this means that additional energy has to be added to the feed side all year around in order to reach a high enough pressure on the fed side of the membrane. The amount of extra water pressure required is 41 m during 8 months of the year and 33 m during the summer, see table 34.

For the HNF alternative the necessary fed pressure is very close to the available height and the actual losses in pipes and pre-treatment has to be carefully tested in order to be certain whether the HNF membrane can be used without additional energy in this scenario. However, it shows that this scenario is possible to utilize with no or at least limited energy use, see table 34.

Table 34. This table shows the expected surplus or shortage in pressure head for each alternative implemented in accordance with scenario 3.

Scenario 3 pressure +/-	8 months per year	4 months per year
UF	26 m	35 m
NF	-41,16 m	-32,66 m
HNF	4,08 m	12,58 m

For scenario 3 this shortage or surplus pressure can be calculated to see the actual energy production or demand that the alternatives lead to. In these calculations the fed pressures shown above and the required flow of 176 l/s is used except for the NF alternative were also the recirculation flow of 83 l/s has to be taken into account. As shown in table 35, both the UF and HNF alternative have the potential to produce energy if implemented in accordance with scenario 3. The NF alternative on the other hand requires additional energy to be able to produce sufficient amounts of potable water.

Table 35. This table shows what the previously calculated pressure surplus or shortage leads to in terms of annual energy demand or production.

Scenario 3 Energy +/-	
UF	491 MWh/year
NF	-1137 MWh/year
HNF	107 MWh/year

As a conclusion table 36 shows the compiled results of the energy estimations for each scenario and alternative.

Table 36. This table summarizes the energy demand that can be expected with each alternative and scenario. A plus sign in front of the value indicates an energy production.

Energy demand (MWh/year)	UF	NF	HNF
Scenario 2a	+228	1914	970
Scenario 2b	+303	1840	896
Scenario 3	+491	1137	+107

The cost of the energy demand of each alternative and scenario is presented in table 37. However, since the UF alternative and HNF alternative in scenario 3 will provide an energy surplus rather than a demand the values presented in these cases will be the hypothetical profit if the energy were sold at the same price as it was bought, this is indicated with a plus sign in front of the value. The price used is the same as the previously used price from Varberg energi, 0,987 SEK/kWh (Varberg Energi 2012).

Table 37. This table shows the cost of each alternative in each scenario. A plus sign in front of the value indicates a profit rather than a cost.

Energy costs (SEK)	UF	NF	HNF
Scenario 2a	+225 000	1 889 000	957 000
Scenario 2b	+299 000	1 816 000	884 000
Scenario 3	+485 000	1 122 000	+106 000

By these estimations scenario 3 is the most favorable since the energy production is highest in the UF alternative and the demand of the NF alternative is lowest. Finally, scenario 3 is the only scenario where the HNF alternative can be expected to have an energy surplus, even though this has to be calculated with more accurate measurements in order to be established.

Although scenario 3 seems like the most favorable scenario in these calculations there are other aspects that need to be taken into account regarding the choice of scenario. The main concern regarding scenario 3 is that this setup might be subjected to large pressure fluctuations since the pressure in this case will be regulated by the water level in the lake. Large deviations in pressure might seriously damage the membranes, which mean that this scenario might not be able to implement in a safe enough way. However, a possible way to prevent these expected pressure fluctuations is to install a surge tank.

The second disadvantage regarding scenario 3 is the fouling potential associated with the placement of the membranes in the process train. In scenario 2a and 2b the raw water is pre-treated in the sand filters, which will have a positive effect on the amount of fouling that can be expected. Since the sand filters in Kvarnagården are believed to act as a biofilter the positive effects on the fouling formation that (Heinicke 2005) reported from his pilot studies in Lackarebäck WTP could also be achieved in Kvarnagården WTP by implementing scenario 2a or 2b. The results regarding fouling of the HNF trials presently performed at Kvarnagården WTP are of great importance in the decision of implementation scenario. If this pilot trial shows small or moderate fouling when fed with raw water directly the most favorable alternative regarding energy use will be scenario 3 if the surge tank is able to dampen the expected pressure fluctuations to a large enough degree.

15 Conclusion

As a conclusion the new type of HNF membrane seems to be the most promising alternative regarding water quality as well as operational costs. This is especially the case if this alternative is implemented in accordance with scenario 3 where the membrane is fed directly with mixed raw water and by using the potential energy of the incoming raw water. However, with this type of setup the positive effects of biofiltration as a pre-treatment might be lost which could lead to increased demand of cleaning and thereby also chemical usage. The results of the pilot trial is therefore of great importance in the choice of implementation scenario and membrane alternative. According to the preliminary results of the pilot trial the fouling seems to be very limited even though the membrane was fed with raw water directly. It is clear that the energy demand associated with the NF alternative makes this alternative quite unfavorable from an economic point of view. The UF alternative is a much more reasonable alternative considering the operational costs. However, the down side of this alternative is the higher demand of chemicals and the indication that the raw water at Kvarnagården could perhaps contain constituents of NOM that is hard to coagulate in an efficient way according to measured SUVA values. This together with the fact that only UV_{254} and DOC are used as indicators of NOM in the permeate water could result in an inferior water quality with potential formation of DBPs that is hard to detect. If the technique to detect and characterize the NOM content and the formation of DBPs would be improved at the WTPs, better knowledge could be acquired regarding the quality of the water produced. This could be important when it seems that around 270 new chlorinated compounds are formed during the current treatment process at Kvarnagården WTP. From an environmental point of view the UF alternatives more extensive chemical use including transports is an issue that cannot be neglected. Also the more extensive use of both cleaning and coagulation chemicals leads to increased volumes of waste water that have to be dealt with, which will increase the complete energy demand of this alternative even though this energy use is not directly associated with the alternative. Therefore, it seems likely that the HNF membrane could be a very feasible alternative to the two previous membrane alternatives when both of the main disadvantages associated with the previous alternatives are improved in this new membrane.

16 Discussion

This study aimed to provide an estimation of which membrane alternative that were most suitable to implement in Kvarnagården WTP and even though key parameters like energy demand and chemical usage could be estimated fairly accurately there are still important parameters that could not be estimated with enough accuracy, the fouling potential for example is hard to assess without membrane trials during longer time periods than what was possible in this study. The estimations carried out in this study are guiding values and are assumed primarily to enlighten differences between the membrane alternatives. To receive more detailed system designs a more formal inquiry to the membrane manufacturers has to be carried out. Information received for this study was not very detailed since the manufacturers did not prioritize a master thesis by students.

When the main part of the information regarding estimations were based on the surveys to manufacturers and water treatment plants, the result of this report was to a large extent dependent on the quality of the data that were retrieved through these surveys. When it was very hard to retrieve good quality information from both manufacturers and water treatment plants it is the authors opinion that the estimations could be performed with better accuracy if more information could have been retrieved. However, the method used is believed to reflect the necessary precautions and estimations that are associated with the decision of which membrane alternative to implement.

In the experimental part additional experiments would have been preferred when the UV absorption measurement indicated a very low rejection in the case for Lackarebäck which could indicate that the membrane used in this trial might have been damaged. However, other measurements like the rejection of color, turbidity, and DOC indicated that removal had occurred. Therefore it was hard to draw any certain conclusions regarding the similarities between the raw water from the two WTPs. This fact would be interesting to investigate further, for example regarding the composition of the fouling and perform more detailed analyzes of the NOM composition including fluorescence, FT-ICR-MS or HPSEC and try to find answers to why the UV absorption did not decrease much after the filtration with NF as well as evaluate which constituents in the water that resulted in the fouling from each specific water type. There seems to be a need for more knowledge regarding which constituents of the water and of NOM that contributes the most to the fouling of membranes. However, since different raw water and different membranes will provide different results regarding reversible and irreversible fouling it is hard to draw any general conclusions. Additional investigations regarding the NOM content of the permeate water and its reactivity, i.e. DBP forming potential from many different kinds of disinfectants could also be interesting since it is still somewhat unclear at the moment.

17 APPENDIX

APPENDIX A. QUESTIONNAIRE METHOD AND COMPLETE RESULTS

A.1 Questionnaire to WTPs

A.Treatment aims:
(Removal of NOM, ions , bacteria's, viruses etc.)

B.Pre-treatment options:

B.1 Coagulation:

B.2 Which coagulant do you use? :

B.3 Which concentration do you use? :

B.4 Which pH value do you use for coagulation? :

B.5 Do you use inline or standard coagulation? :

B.6 Do you use other pre-treatment options? (please specify) :

B.7 No pre-treatment options:

C.Membrane filtration (1):

General information

C.1 How large is the membrane surface area? m2

C.2 Which membrane module do you use?

C.3 Do you experience any unexpected stops in production due to technical failure of the membrane process? If yes what are the most common types of failures?

Filtration

C.4 Which flux do you aim for? L/ m^2h

C.5 What is the feed pressure? bar

C.6Which is the transmembrane pressure (TMP)? bar

Air flushing

C.7 Which air flushing interval do you use? Min

C.8 How long is the air flushing period? Min

D.Membrane filtration (2):

Back flush

D.1 Which back flushing interval do you
use? min

D.2 How long is the back flushing period? sec

D.3 How high is the back flushing flux? L/ m^2h

Chemical enhanced backwash

D.4 Which cleaning agent do you use?

D.5 Which back flushing interval do you
use? min

D.6 How long is the back flushing period
before chemical cleaning? sec

D.7 How long is the period for chemical
dosage? sec

D.8 How long is the residence time? sec

Membrane integrity

D.9 Which parameters do you measure to
prove the membrane integrity?

E.Energy demand:

E.1 What is the mean energy demand of the WTP to produce 1 m^3 potable water including all process steps?

E.2 What is the mean energy demand to produce 1 m^3 permeate in the membrane process?

E.3 What is the energy demand of the whole WTP during a year?

Table 1. This table displays the result of the questionnaire to the water treatment plants utilizing membrane technology.

	Treatment aims	Pretreatment	Chemical enhance back wash	Air flushing
Appleton, USA	TOC, softening, stabilization, filtration, flurodiation	Coagulation, sedimentation, flocculation and adding of lime	NaOH, NaOCl	None
Collingwood, Canada	Bacterias', viruses'	None	NaOCl for recovery clean	Yes
Grabs, Switzerland	DOC reduction, color, odour, turbidity	None	NaOCl	None
Halton, Canada	Bacterias', viruses, turbidity	Mesh grid	NaOCl	Yes
Heemskerk, Netherlands	Suspended solids, bacterias,viruses	Raw water strainers, coagulation, sedimentation, rapid sand filtration, GAC filtration	NaOCl	None
Hollywood, USA	Softening,organics	Acid addition	Clean in place twice a year (offline)	None
Inverness, Scotland		Coagulation	HCl and NaOCl	None
Maienfeld, Switzerland	Removal of turbidity and disinfection	Seat filter mesh	NaOCl	None
Männendorf, Switzerland	Micropollutants, DOC, AOC, color, odour, turbidity	Seat filter mesh	NaOCl	None
Periwinkle lane, England	Cryptosporidium barrier	Chlorination, airstripping	HCl and NaOH	None
Walpole, USA	Iron, manganese removal	Coagulation	Citric acid for recovery cleans	Yes

Table 2. This table displays typical performance values from the different water treatment plants that answered the questionnaire.

	Modules	Membrane area [m2]	Permetate Flux (l/m2h)	Liter/m2 backflush per day	Energy consumption Per m3 permeate [kWh/m3]
Appleton, USA	Koch membrane systems HF44	3233	110,4	69	0,60
Appleton, USA	Koch membrane systems HF50	556	501,2	60	0,60
Collingwood, Canada	GE A/B 500 series	27900	-	32	0,88
Collingwood, Canada	GE A/B 1000 series	7100	30	40	0,88
Grabs, Switzerland	Inge Dizzer plus 5000	1600	37,5	22	0,07
Halton, Canada	Zeeweed 1000 V3	90396	109	43	-
Heemskerk, Netherlands	Norit X-flow 8	30720	269	179	0,14
Hollywood, USA	Hydranautics ESNA-LF-LD	14046	22,5	-	0,7
Inverness, Scotland	Norit Hollow fibre SWL-150 FSF	20580	-	-	-
Maienfeld, Switzerland	Inge Dizzer XL 0,9 MB	1440	70	106	0,05
Manitowoc, Canada	Siemens/Memcor PVDF	67298	62,2	123	0,33
Männendorf, Switzerland	Inge Dizzer plus 5000	7380	55	13	0,43
Periwinkle lane, England	Norit X-flow S	1680	115	28	0,7
Walpole, USA	GE Zenon 500 C	1126	100	184	0,90

A.2 Questionnaire to manufacturers

The questionnaire to the manufacturers included questions regarding the information needed. However, most manufacturers that answered instead sent a system design including some of the information in this questionnaire. The manufacturers approached by telephone and mail were;

- Aquasource
- DOW Filmtec
- GE Osmonics
- Hydranautics
- Kalsep
- Koch Membrane Systems
- Inge AG
- Pall corporation
- Pentair X-flow
- Memcore US filters
- Microdyn Nadir
- Membrana
- HOH Vattenteknik
- Björks Rostfria
- Baga International
- Membranteknikk AS

The manufacturers that provided some kind of information were: Aquasource, DOW Filmtec, Hydranautics, Koch membrane systems, Inge AG, Pall Corporation, Pentair X-flow and Microdyn Nadir. However, not all of the information provided were detailed enough to be included in the evaluation performed in this study. For the UF alternatives the manufacturers that provided detailed enough information regarding the UF alternatives to be a part of the study were; Aquasource, Hydranautics, Inge AG, Koch Membrane Systems and Pall Corporation. The NF alternatives that could be included in the study were; DOW Filmtec, Hydranautics and Koch Membrane Systems. The questionnaire to the manufacturers is presented below:

A.General information about the membrane:

A.1 Membrane manufacturer:

A.2 Mambrane model:

A.3 Membrane material:

A.4 Length of module:

A.5 Diameter of module:

A.6 Membrane area per module:

A.7 Possible rack setups (number of modules):

A.8 Molecular weight cut off (MWCO) [Da]:

B.Information about mode of operation:

B.1 If dead end operation, inside out or outside in:

B.2 If cross flow, what is the suitable cross flow velocity:

B.3 Mean flux over the membrane in normal operating conditions [l/m^2*h]:

B.4 How long time may the mean flux be used during 24 hours:

B.5 What range of the feed pressure is suitable [bar]:

C.Other information about the membrane:

C.1 What is the expected trans membrane pressure (TMP) during normal operation [bar]:

C.2 What sizes are the different rack setups:

C.3 What is the required minimum distance between the racks:

C.4 What is the backwash (BW) frequency:

C.5 What is the BW duration and the BW volume during 24 hours:

C.6 What is the chemically enhanced backwash (CEB) frequency and for how long time will the membranes be out of operation:

C.7 How often does a cleaning in place (CIP) have to be carried out:

C.8 How long time will the membrane be out of operation, during a CIP:

C.9 What is the allowed pH range during CEB:

C.10 What is the allowed temperature range during CEB:

C.11 Chlorination tolerability [ppm*hours of free chlorine]:

C.12 Expected lifetime of the membranes:

C.13 What is the mean energy demand of one module producing one cubic meter of permeate, including BW,CEB and CIP:

C.14 What type of programmable logic controller (PLC) is used:

C.15 What type of pretreatment or strainer is used:

C.16 What type coagulant chemical is recommended:

C.17 What is the average cost of each membrane module:

D.Value provided by manufacturer:

D.1 What is the average water recovery of a module:

D.2 What is the average removal of virus:

D.3 What is the average removal of bacteria:

D.4 What is the average removal of protozoa:

D.5 What chemicals are used for CEB and CIP:

D.6 How many kilograms of these chemicals are used per m^3 permeate per year:

D.7 Are there any additional costs regarding the control system, for example license costs:

Additional results from membrane manufacturers

The results regarding the foot print and the size of the different membrane alternatives are presented in table 3. Only the manufacturers that provided some information that made it possible to evaluate the foot print of a full scale setup of a size equal to the size needed in Kvarnagården WTP were included in this table.

Table 3. This table shows the typical values of length and diameter of the membrane modules/elements of the different manufacturers as well as the expected foot print of a setup with a capacity equal to the requirements of Kvarnagården WTP.

Membrane manufacturer	Length of module/element (m)	Diameter of module/element (m)	Foot print Kvarnagården WTP (m^2)
Aquasource UF	1,884	0,324	83,5
Hydranautics UF	1,708	0,225	93
Inge UF	1,680	0,295	58
Koch NF	1,016	0,203	87
Koch NF (Mega Magnum)	1,549	0,457	39

APPENDIX B. PERFORMED EXPERIMENTS

The raw water used in the drinking water production in Göteborg is believed to be of a similar composition to that of the raw water used in Kvarnagården. To evaluate if this is in fact the case this study will also include an experiment where the composition of both raw waters are compared.

In the experimental part a small laboratory membrane filter house was used equipped with an NF membrane. By using a pump, a manometer and a valve a cross flow was created in the filter house and the pressure was kept between 4 and 5 bar. Part of the water passed by the membrane and was lead back to the container with the raw water, however, some water was filtered through the membrane and was lead to a container where the permeate water was gathered. The time it took to filtrate 500 ml was recorded using a stopwatch in order to evaluate which water that had the highest flux. To evaluate which of the two waters that had the most fouling potential the membranes used in each experiment were weighed before running the experiment. After running the experiment the membrane were dried in room temperature protected from contamination by a plastic cover, and when it was dry it was again weighed. Thereby the amount of fouling gathered on the membranes during filtration could be calculated. Tests were also carried out on each type of raw water as well as each type of permeate water. The tests carried out were color and turbidity, UV absorption in the spectra that is associated with NOM, furthermore, tests of the calcium concentration in the water were carried out. Finally, also the DOC of each raw water and permeate water were measured. These parameters were chosen to test because they can be associated with NOM concentrations and fouling potential.

All tests were repeated three times to make sure that the values were correct. The tests of color and turbidity of the raw waters will be compared to see whether there is compliance between them. The reason to test the same things on the permeate water is to see whether the membrane has worked properly and if there is any difference between the rejections of the membrane for a certain type of water. The calcium concentration of the water is connected to the amount of fouling that can be expected, thus it was interesting to evaluate whether there were any correlation between the calcium concentration and the amount of fouling that was found in the tests. The performed stages and equipment of the experiments is further explained in.

The UV absorption was measured in the spectra of 220 to 280 nm which is the spectra that is associated with the NOM particles in the water, also the quotient between the absorptions at wavelength 253/203 is considered to be interesting since they have a correlation to DBp formation potential. The components used in the experimental part are shown in table 4. For the turbidity the standard method 8237 Absorptometric Method using colorimeter were used. The accuracy of this measurement is +/- 2 FAU. Also for the color test the colorimeter were used together with the method 8025 APHA Platinum-Cobalt Standard Method. The accuracy of this method is +/- 10 mg/l pt co. The Calcium concentration tests were conducted according to the Swedish standard method SS 02 81 19. The calcium concentrations were then calculated by equation:

$X = 801{,}6 * V_{EDTA} * c$

Where:

V_{EDTA}= The amount of EDTA solvent used

c= Concentration of EDTA (0,01M)

The accuracy of this method is +/- 1 mg/l.

The UV absorbance was measured using a Shimadzu spectrophotometer, model UV-1800. The membrane used, DOW Filmtec NF270, is a Polyamide Thin-Film Composite membrane which is hydrophilic and a fairly high permeability (Mänttäri et al. 2003).

Table 4. This table displays the equipment used in the experimental part of this study.

Component	Brand	Model
Manometer	Fischer Scientific	
Pump	Iwaki	EP-A10
Valves	Fischer Scientific	
Filter house	Sterlitech	CF042
Membrane	DOW filmtec	NF270
UV spectrophotometer	Shimadzu	UV-1800
Colorimeter	Hach	DR/890

APPENDIX C. ENERGY CALCULATIONS

C.1 Energy calculations for UF

The recovery provided by manufacturers made it possible to calculate needed inflow corresponding with required outflow. The inflow to membrane process therefore needs to be equal to the total outflow from the permeate tank i.e. equal to out flow Qout and the backwash flow Qbw, see figure 1 below.

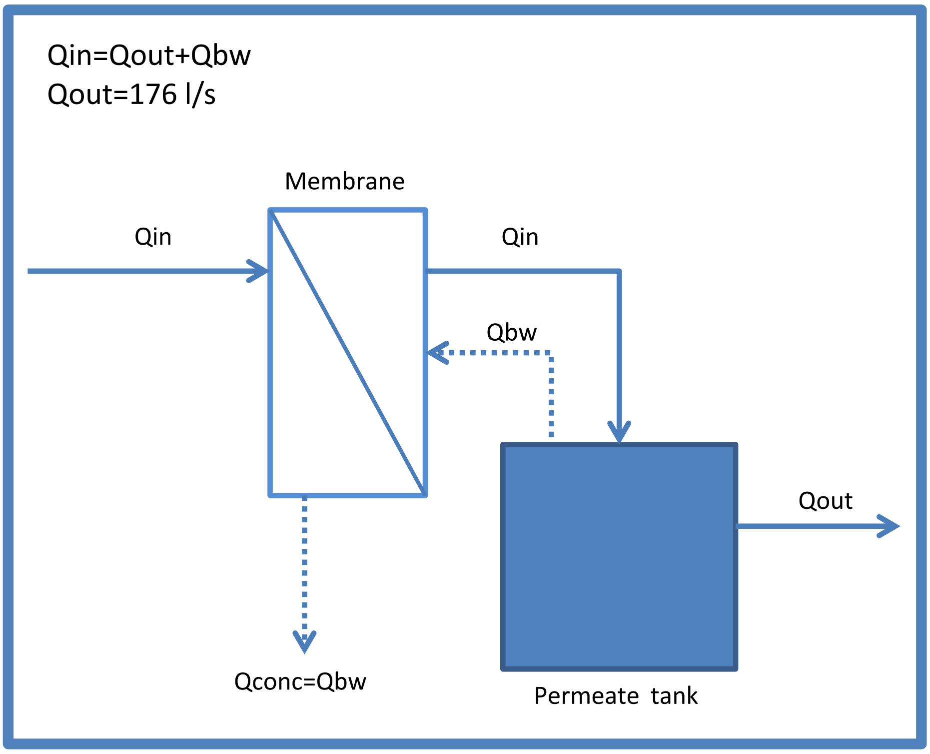


Figure 1. This figure shows the conceptual flows of the UF membrane setup.

The required inflow Qin is then calculated by dividing Qout by the recovery and Qbw is calculated by subtracting Qout from Qin, see equation X.

$$Qin = \frac{Qout}{Recovery} \qquad Qbw = Qin - Qout$$

After that the online factor (n) is calculated by calculating the hours the membranes do not produce water during a year due to BW, CEB and CIP the values for these factors are provided from manufactures, the online factor is then calculated by equation x.

$$n = 1 - \frac{hours\ out\ of\ operation}{hours\ per\ year}$$

When the online factor is calculated the total required membrane area (Ar) needed to produce the required amounts of permeate may be calculated. This calculation requires apart from the flow through the membranes (Qin) and the online factor (n) also a typical value of the membrane flux (J), this is calculated as a mean value of the typical fluxes provided by the manufacture information. The required area is then calculated by equation:

$$Ar = \frac{Qin}{J*n}$$

This area is then divided by the area of each module (Am) to determine the amount of modules that are needed (no). The value from this calculation is then rounded up to first nearby integer and the actual membrane area (A) is calculated by multiplying this integer with the area of each module (Am), see equation:

$$no = \frac{Ar}{Am} \qquad A = integer * Am$$

The required pump (P) effect is calculated in watts (W) by equation x from (Häggström 2006).

$$P = \rho * g * Q * H$$

Where

$\rho = density\ of\ water\ \ kg/m^3$

$g = gravitaional\ coefficient\ \ kg/s^2$

$Q = pumped\ flow\ \ m^3/s$

$H = required\ pump\ height\ m$

The pumped flow is the flow needed to be pumped through the membranes i.e. Qin. The required pump height is the height from the reservoir where the water resides up to the inflow of the membranes. However, an additional pressure is needed to reach the minimum required feed pressure of the membrane. These factors together make up the factor H in the equation. The minimum feed pressure on the membrane is different between different manufacturers. The same formula is used for both the feed pump and the back wash pump, however, for the BW pump the flow is Qbw and the required pump height will be different depending on the elevation difference between membrane and BW tank. The energy required during a year is then calculated by multiplying P with the amounts of seconds in a year, hereby the energy consumption is in the form kWh/year, see equation:

$$Energy\ demand\ \left(\frac{kWh}{year}\right) = P * 3600 * 24 * 365$$

Also the specific energy is calculated in kWh/m^3 by dividing the energy consumption during a second i.e. kW by the total amount of permeate produced in a second i.e. Qin, see equation:

$$Specific\ energy\ demand\ (\frac{kWh}{m^3}) = \frac{\frac{P}{1000}}{Qin}$$

In this way the annual energy operational costs may be calculated by multiplying the required energy with the average price of a kWh.

C.2 Energy calculations for NF

When calculating the energy demand of NF elements a setup with 7 NF elements in each pressure vessel is assumed. This is according to the setup used in the WTP of Hollywood Florida, see figure 2. By placing 7 consecutive membrane elements in a pressure vessel the energy requirements will be lower, due to a decreased need to recirculate the concentrate water. Each membrane element is fed with concentrate water from the previous element. Most of the studied NF elements had a recovery of 15 percent, therefore this value is used in the calculations. Knowing the required outflow means that all outflows from each element together needs to be equal to the required outflow (Qout). The inflow to the membrane pressure vessel, i.e. the first membrane, is the recirculation flow (Qrec) as well as the inflow (Qin). These two flows together has to be equal to the total outflow of the pressure vessel, i.e. Qout and Qrec. Since this is the case equal amounts of recirculation water exits and eneters the pressure vessel, i.e. Qin is equal to Qout. However, in the calculations of energy demand in cross flow mode the value of the recirculation flow is needed.

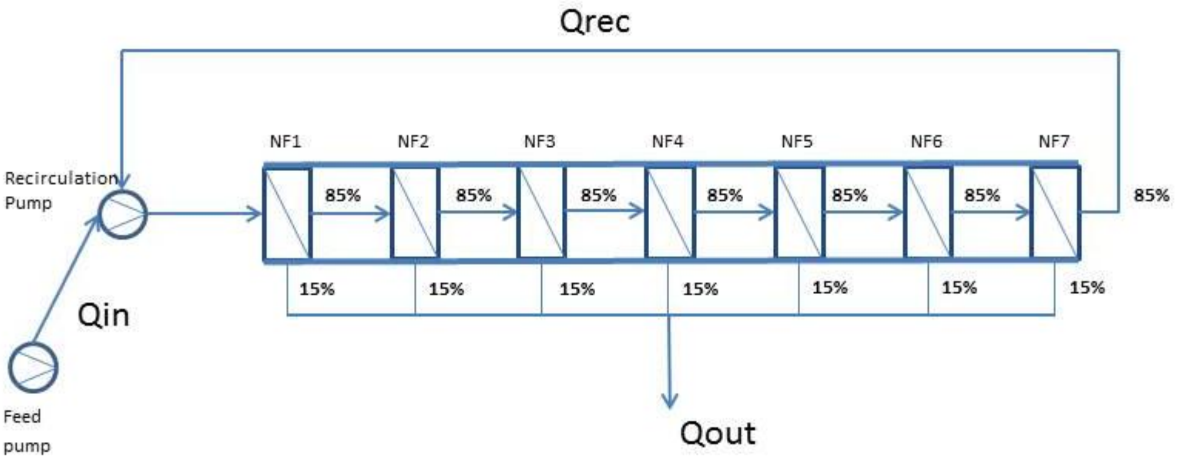


Figure 2. This figure show the conceptual flows of the NF setup with cross-flow.

The value of Qrec is calculated by equation:

$$(Qin + Qrec) * 0{,}15 + \left((Qin + Qrec) * 0{,}85\right) * 0{,}15 + \left((Qin + Qrec) * 0{,}85^2\right) * 0{,}15 + \left((Qin + Qrec) * 0{,}85^3\right) * 0{,}15 + \left((Qin + Qrec) * 0{,}85^4\right) * 0{,}15 + \left((Qin + Qrec) * 0{,}85^5\right) * 0{,}15 + \left((Qin + Qrec) * 0{,}85^6\right) * 0{,}15 = Qout$$

Where the sum of Qin and Qrec is first calculated, by adding all the outflows of each NF element together and put it equal to Qout. By knowing the required outflow Qout the value of (Qin+Qrec) is calculated to 259 l/s. Thereafter the value of Qrec is calculated by subtracting Qout=Qin=176 l/s from (Qin+Qrec). This yielded a Qrec of 83 l/s. After this all the amounts of water that required pumping in the system were established and the energy demand of each NF alternative could be calculated. The pump efficiency was assumed to be 75 percent as in the calculations performed in (VIVAB 2012). The equation used is the same as in the energy calculations of the UF alternatives:

$P = \rho * g * Q * H$

Where

$\rho = density\ of\ water\ \ kg/m^3$

$g = gravitaional\ coefficient\ \ kg/s^2$

$Q = pumped\ flow\ \ m^3/s$

$H = required\ pump\ height\ m$

Thereby, the pump energy needed could be established by using the feed pressure that was recommended by the manufacturers.

APPENDIX D. CHEMICAL CALCULATIONS

To calculate the chemical consumption for Kvarnagården the manufacturer information worked as a basis. Since the provided information was for a certain amount of modules and strength of chemicals it had to be recalculated to match the site specific conditions in Kvarnagården. The equations below show the typical methodology for the calculations.

$\rho(Water) = 1000\, kg/m3$

$\rho(Chemical) = XXX$

$Strength:$

$Chemical = A\%$

$Water = B\%$

$Density(Chemical) = A * \rho(Chemical) + B * \rho(Water)[kg/m3]$

$Weight = XXX\, kg\, /\, year$

$$Volume = \frac{Weight}{\rho(chemical)}$$

$Volume\ 1 = Strength(Chemical) * Volume$

$$Volume2 = \frac{Volume1}{Actual\ strength}$$

$$Volume/module = Volume2\ /\ Amount\ of\ modules = \frac{m3}{year} * module$$

$$Volume\ Varberg = Amount\ of\ modules\ needed\ at\ Varberg * \frac{Volume}{Module}$$

$Weight\ Varberg = Volume\ Varberg * \rho(Chemical)$

To calculate the cost of the chemical demand of each alternative the prices per kg were required. These prices were provided by Brenntag Nordic for each required chemical, see table 5.

Table 5. Shows prices provided by Brenntag Nordic

Chemical	Price [SEK/kg]	Min. supply .[kg]
Citric acid [$C_6H_8O_7$]	20	1000
Sodium Hydroxide [NaOH] (25%)	10	1000
Sodium Hydroxide [NaOH] (45%)	5,10	1160
Sodium Hypochlorite [NaOCl]	6,55	976
Hydrochloride [HCl] (34%)		927
Sulfuric acid [H_2SO_4] (96%)	3,45	1469

For the coagulation chemical cost calculation the price per kg coagulation chemical was needed, these prices were provided by Feralco Nordic, see table 6.

Table 6. Shows prices provided by Feralco Nordic

Coagulant	Consumption [ton/year]	Prise [SEK] (exl. Sales tax)
Polyaluminium Chloride (Pluspac S 1465)	22	2135

APPENDIX E. EMISSION CALCULATIONS

The parameters considered for transports were CO_2 and N_2O emissions. For the pilot tests chemicals were purchased from Feralco Nordic and Brenntag Nordic. If implementing membranes at Kvarnagården these two companies were therefore assumed to provide the chemicals. The nearest warehouses for Brenntag Nordic and Feralco Nordic made therefore up the basis for the distances traveled when considering emissions. The distances are showed in table 7 below. The N2O emission could be calculated with in data from EPA (1999). However, some assumptions had to be made in order to calculate the emissions. The assumptions made were that a heavy duty vehicle will be used and that the maximum load for this vehicle will be 20 tones.

The CO_2 emissions were calculated with a Microsoft Excel program, developed by Naturvårdsverket (2011). Also here the vehicle was assumed to be a light heavy duty vehicle. An additional assumption made in the programme was that the vehicle was diesel driven. The emissions were also here multiplied with the amount of times needed to transport the chemicals.

Table 7. This table displays the distances used in the calculation of the transport emissions due to the chemical usage.

Brenntag Nordic	Feralco Nordic
Varberg-Borås	Varberg-Vetlanda
80 km	174 km

Assumptions and calculations:

According to EPA (1999) a heavy duty vehicle consume approximately 0,05 N_20 g/mile.

$1\, mile\ =\ 1{,}609344\ km$

$Heavy\ duty\ vehicle: 0{,}05\ g/mile\ =\ 0{,}080467\ g/\ km$

$Max. vehicle\ load: 20\ ton$

$x * 20\ =\ amount\ of\ chemicals$

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