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Optimization of Galtneset Reverse Osmosis plant

Optimization of the RO process for a reduced permeate flow and testing the performance using computational program WAVE.

Master’s thesis in Environmental Engineering

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Gothenburg, Sweden 2023

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ENVIRONMENTAL ENGINEERING

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MASTER'S THESIS ACEX30

Optimization of Galtneset Reverse Osmosis plant

Master's Thesis in the Nordic Master's Programme Infrastructure and environmental engineering

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Degree Project, ACEX30 Department of Architecture and Civil Engineering
Chalmers University of technology, 2023

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ABSTRACT

Desalination using Reverse osmosis process at Galtneset water treatment plant situated in Træna municipality located in the Nordland County on the coast of Helgeland, Norway has been facing operational challenges. One reason is due to its overdesigned process configuration with a greater production than required and secondly due to its old and outdated design, currently the plant has been shut down. It is required for the plant to start working and producing drinking water to meet the water demand for in periods of high consumption in the winter and in the summer months when the surface water reservoir is not being able to meet the required water demand.

Two scenarios are investigated and modelled using computational software WAVE (Water Application Value Engine), where in first case the number of membrane elements are reduced, and the effect of Trans membrane pressure (TMP) and flux are evaluated for two cases of permeate flow of 23 and 11.5 m^3/h at different temperature ranges. Similarly, in the second case the effect of feed flow on the TMP and flux is investigated. Using these two scenarios, the best possible operating conditions for a normal permeate production as well as reduced permeate production are evaluated, and suggestions are made for improvements accordingly.

Additionally, to check the change of TMP at different seawater concentration the TMP changes are detected by modelling the process for three different salinity range 32000<35000<40000 mg/L. This controlled system helps to back up the suggestions for selecting the best possible operating conditions. Additionally, normalization of the reverse osmosis data is done to help troubleshoot any potential problems in the process.

ACKNOWLEDGEMENT

This project is the final documentation of my Master Thesis to graduate with the Nordic´s master's degree in environmental engineering at both Norwegian University of Science and Technology (NTNU) and Chalmers University. The topic was suggested by Marius Møller Rokstad from NTNU who together with Thomas Pettersson from Chalmers supervised my work.

I would like to express my gratitude to Marius, who despite the physical distance, they provided unwavering support and guided me every step of the way, while also helping me communicate with the municipality. Additionally, I extend my sincere appreciation to Thomas, who consistently championed my best interests throughout this time and additionally also helping me in communicating with the professionals of the WTP. Their invaluable assistance helped me untangle complex issues and navigate through challenges that arose during my project.

I would like to thank Frank Persson, who has been my examiner and have guided me with knowledge and support, which has been a major help to me.

I also thank professionals from Træna municipality, Andres Budde and Rune Gustavsen for supporting me with all possible data from the Water treatment plant.

This thesis is dedicated to my family; my mother, my brother and my late father who always encouraged me to do my best and have supported me in every way. Also, to my beloved Nordic family Lu and Maggie for always being by my side, taking care of me during my master and making me feel at home.

Lastly, it wouldn't be fair if haven't thanked my lovelies Rowdy and Willow for giving me so much love and always making me happy.

Sumanna Kakoti

18.08.2023

Gothenburg, Sweden

ABBREVIATIONS

RO	Reverse osmosis
WTP	Water treatment plant
TMP	Trans membrane pressure
J_w	Water flux
Q_p	Permeate flow
Q_i	Feed water flow
Q_c	Concentrate water flow
A	Wetted surface area
C_o	Permeate water concentration
C_i	Feed water concentration
C_c	Concentrate water concentration
P_i	Permeate Pressure
P_f	Feed Pressure
P_c	Concentrate Pressure
LMH	Liters per square meter and hour l/m^{2}hr (Unit of flux)
Kw	Constant
Π	Osmotic pressure
SEC	Specific energy consumption
t/T	Temperature
TCF	Temperature correction factor
TDS	Total dissolved solids
TOC	Total organic carbon
K_w	Membrane permeability coefficient
NPF	Normalized permeate flow
aNDP	Average net driving pressure
NSR	Normalized salt rejection
NPD	Normalized pressure differential

SDI	Silt density Index
NF	Nanofiltration
TSS	Total suspended solids
α	Pressure Coefficient
β	Temperature coefficient
K	Constant based on characteristic of the membrane material
δ	Pore diameter
L	Length of membrane element
ɳ	Viscosity of water
$E_{a,w}$	Activation energy for water flux
R	Gas constant

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1. INTRODUCTION

Desalination is a process to treat water with high salt concentration, such as seawater, by removing the salts and minerals from it. It also refers to treating low-salinity water (salt concentration<15,000 ppm), known as brackish water and the processes are either membrane based, like Reverse osmosis (RO), or thermal based such as multi-effect distillation and multi-stage flash distillation (Alhaj & Al-Ghamdi, 2019). The treatment process of desalination and its supply network are dependent on different factors, such efficiency, ion concentration, costs efficiency, and flexibility (Al-Nory et al., 2014).

Desalination plant production and operation can be optimised by engineers by having a thorough understanding of the physical characteristics of a reverse osmosis membrane (Najdawi & Neptune, 2022). The optimization of plant production and operation can help meet the demand for clean water, minimize maintenance and energy cost and ensure smooth operation(Al-Nory et al., 2014). Mathematical and computational models can assist in resolving these systems' optimisation parameters, enabling significant advancements (Najdawi & Neptune, 2022). Any effort that improves clean water production inevitably contributes to the demand for clean water which indirectly betters the quality of life for many (Ulf Jeppsson, 1996).

1.1. Background

Træna municipality, located in the Nordland County on the coast of Helgeland, Norway, around the Artic circle, consist of more than 418 islands, islets and reefs and out of which human settlement is limited to four islands namely Husøya , Selvær , Sanna and Sandøy(Træna kommune, 2023). Husøya is the main administrative island of Træna municipality (Træna kommune, 2023).The water supply in the municipality is provided by three treatment plants; Husøy nanofiltration plant (NF), Galtneset seawater desalination plant and Selvær desalination plant (Træna. The Husøy nanofiltration plant and Galtneset seawater desalination plant is administered by Husøy waterworks (Van Sui Cer, 2022). The source of water to the to the Husøy Nanofiltration plant is provided by two sources of raw water, one from the freshwater collected from surface runoff from the neighbouring island Sanna and the Husøy raw water reservoir (Van Sui Cer, 2022).

Water supply based only on fresh water has at times been challenging for Træna municipality, since access to fresh water is limited, and highly dependent on rainfall as shown in Figure 1-1. When cyanobacteria (blue-green algae) were also discovered in the raw water reservoir on Husøy, the supply of fresh water became even more unstable since water from the raw water reservoir cannot be used in certain periods of the year. Galtneset water treatment plant was therefore built in 2003 (Norconsult AS, 2022)

Both water treatment plants supply to the same distribution network (Van Sui Cer, 2022). Husøy water treatment plant (WTP) produces water which is stored into an reservoir located at a higher elevation close to the treatment plant (Van Sui Cer, 2022). Thereafter, the water is distributed to the distribution network using gravity flow, while Galtneset WTP pumps water directly into the distribution network (Van Sui Cer, 2022).

The water production takes place preferably from Husøy WTP since there are lower energy costs to produce drinking water from fresh water versus salt water (operating pressure of 6 and 50 bar, respectively). But in periods of high consumption in the winter and in the summer months, when the river water reservoir may contain cyanobacteria, the water supply is only from Galtneset (Norconsult AS, 2022).

Galtneset seaweater desalination plant is a desalination plant using reverse osmosis technology. The water treatment process in the water treatment plant: the raw water from the intake passing through a sand filter, a screen filter, pressure pumps, RO membranes, UV, marble filter and on to output pumps as shown in both Figure 1-2(a) and Figure 1-2(b). The water treatment plant has two parallel lines and currently is producing approximately 460 m^3/day (20.9 m^3/h) of clean water per line, giving a total capacity of the plant producing 920 m^3/d (41.8 m^3/h) for 22 hours of operation (Van Sui Cer, 2022). However, the maximum capacity of the plant is to produce 506 m^3/d (23 m^3/h) in one line of operation. Thus, giving a total production of 1012 m^3/d (46 m^3/h) when both the lines are in operation.

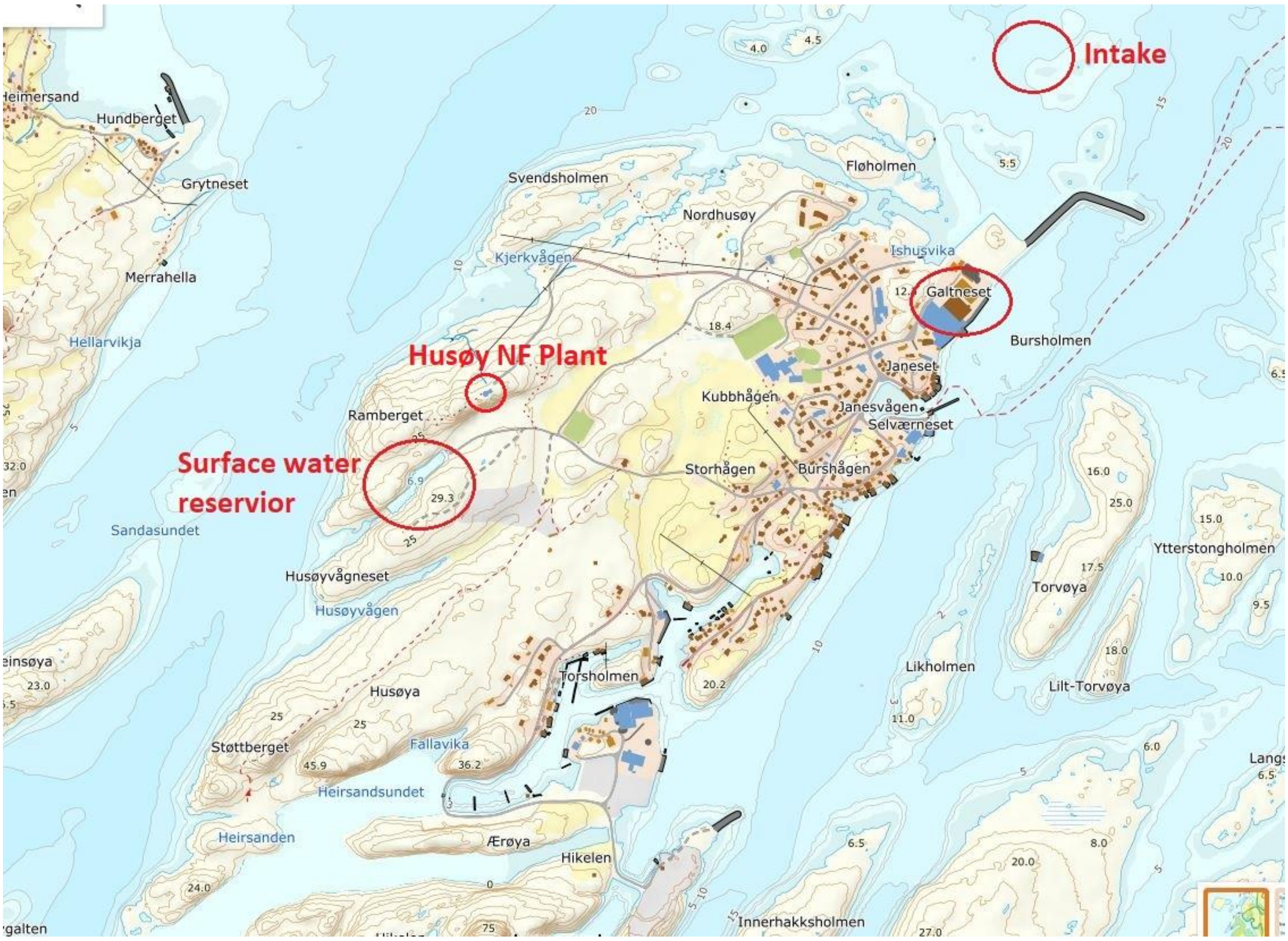


Figure 1-1: Location of the WTP at the island of Husøya (Kartverket .no, 2023)

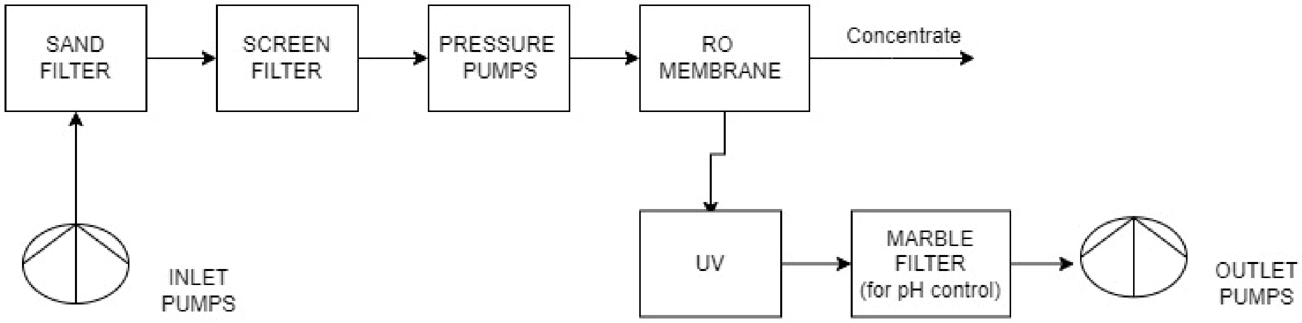


Figure 1-2: Flow diagram of Galtneset RO treatment process

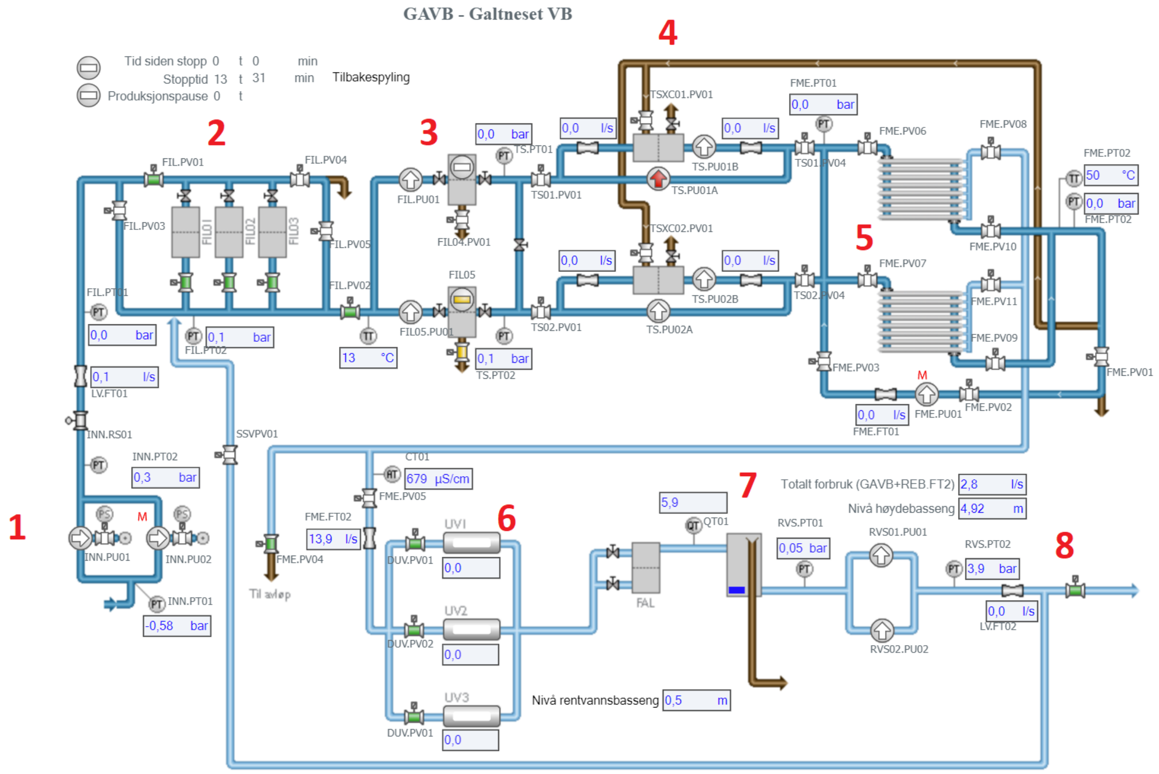


Figure 1-3: Schematic of RO Galtneset treatment process

Table 1-1: Process description

Element Number	Description
1	Inlet Pump
2	Sand Filter (3 units)
3	Screen filter (2 units)
4	Energy recovery devices (2 units)
5	Membrane units (2 units)
6	UV units (3 units)
7	Marble filter (1 units)
8	Outlet pump

A master plan for Træna's water and sewage systems were created in 2021 by Norconsult A/S in Bodø. This refers to a potential switch from employing the Galtneset desalination plant as the primary plant to existing Husøy nanofiltration facilities for drinking water, depending on assumptions stated in the master plan (Norconsult AS, 2022).

1.2. Problem description

The Galtneset water treatment facility is newer and in better shape than the Husøy NF plant, but because of the outdated management system, and also faces several difficulties, e.g., unnecessary alerts that could have been prevented by updating the control system (Van Sui Cer, 2022). The outdated management system also calls for extensive operational supervision (Van Sui Cer, 2022).

Additionally, the intake pipe, being located at a shallow depth, is prone to heavy fouling causing the diameter to lessen and more pressure required by the pump to suck up raw water from the sea (Van Sui Cer, 2022). Also, there has been reported issues of the intake pump to stop alarming the system as greater portion of the water is being used up by the Pelagia fish factory, resulting in very little water for the RO plant, since both the municipal RO plant and Pelagia AS share the same intake pipeline (Van Sui Cer, 2022). The flux through the membranes have also been reported to be less than that of the criteria of 12-17 LMH (L/m^2h).

Furthermore, ordering membranes takes a while, which can be problematic if an emergency arises (Van Sui Cer, 2022). Prior to that, the current production requirements of the water treatment plant have also been reduced since the fishing company Pelagia stopped buying water from the municipality (because they could produce water themselves at a lower cost) (Norconsult AS, 2022). Thus, only one line out of two is in operation today. However, even with only one line operating the production of clean water is greater than the consumption. The reason for this is because the water is produced in the WTP only when its needed. This is usually when there is increased consumption or when the altitude of the surface water reservoir, that is a water source to the Husøy NF plant is low (Van Sui Cer, 2022). Therefore, now since the membrane system in the WTP is overdesigned, the municipality has been aiming ways to minimize the water production to approximately half of what it is producing as of now. Thereby, optimize the process design for a reduced permeate flow of 11.5 m^3/h, that had been currently designed for producing a permeate of 23 m^3/h without compromising on the efficiency of the whole treatment process.

1.3. Aims and objective

The aim of the thesis is to create an information basis on the optimization of the performance (permeate pressure, flux and salt rejection) of the RO treatment plant for the current operating permeate flow of 23 $m^{3/}h$ as well as a reduced permeate flow of 11.5 m^3/h , using RO computational modelling software WAVE (Water Application Value Engine) at different seawater temperature. Thereafter, create process models for both the permeate flows and run the simulation to test the performance of the system.

To achieve a lower permeate flow the model will be simulated using WAVE considering two different scenarios and test the efficiency of the system for each of the scenarios:

- Scenario 1: Reducing the number of membrane modules from 6 to 4 and 3.
- Scenario 2: Lowering the feed flow.

Since the seawater salinity is not constant, another aim of this thesis is to evaluate the results for TMP and flux, for a control system for three ranges of salinity, 32000<35000<40000, mg/L. The design models based on different salinity are set up and modelled using the program WAVE. This is done to check the effects of change in salinity on those parameters and thereby investigate if the performance of the process.

Finally, based on the results the aim is to create a normalized data for the RO process. Where the calculated real time normalised data from the process is compared to the reference data, to investigate any fouling, scaling, or membrane damage problems in the process and thereby suggest improvements.

1.4. Limitations

One limitation of this thesis is the availability of real time data for modelling. The data used in this thesis are either obtained via literature search or provided by the water treatment plant. Since, the Water treatment plant has been shut down and not in operation currently due to having a less optimised process and change in water demand. It was not possible to model for the current conditions since the present operating conditions were unknown. The values used in this thesis were primarily the standard values used by the WTP for operation, which does not give an accurate picture of how the treatment plant is operating in present day.

Additionally, to set up normalized data the baseline values were also not available, therefore the standard values from obtained from model were taken. Also, due to the lack of measured data the temperature correction factor (TCF) required to calculate aNDP was assumed to be equal for both the baseline and measured value, which is not true for a real case scenario.

Another limitation of this thesis is not being able to set up the data for energy consumption for the results obtained in different scenarios in the model due to technical issues with the program and time constraints. The results for energy consumptions would have helped to make better conclusions for an effective process.

Limited data and information were available in the form of literature to make comparison analysis for RO processes in cold climate region. Most of them primarily was from the warmer regions.

There is a level of slight uncertainty in the results and data of scenario 2, when modelling the reduced feed flows at different temperatures. Since, due to a runtime technical error in the WAVE program causing the program to crash and lose all the data, some models had to be redesigned and restimulated by inserting all inputs from the beginning. This caused some variation in the results compared to the results obtained from previous simulations.

Another, limitation of the model WAVE was not having the flexibility to able to change the feed flow and by and permeate flow flexibly. To achieve this in the model, it had to be done changing the recovery, then checking the feed flow and then simulating results. This process was lot of time taking since the recovery is being changed in defining the RO in step 4 figure 3-7 and then returned to step 2 to check the feed flow.

Lastly, not being able to visit the project site physically and analyse the site-specific problems, the operation and tools for the thesis is another limitation that needs to be addressed.

2. LITERATURE REVIEW

2.1. Osmosis

Osmosis is a natural process that occurs when two solutes of different concentration are separated by a semi-permeable membrane and the high solute concentrated solution will tend to become more diluted due to migration of solvent (e.g., water) through the membrane from the other low concentrated side, building up an osmotic pressure (π) as shown in figure 2-1 (Puretec.com, 2023). This increase in osmotic pressure happens because the water molecules during the movement from low concentration to high concentration exert pressure on the membrane (Ismail et al., 2018). This is because the semi-permeable membrane is a membrane that allows only molecules up to a specific size (e.g., H_2O) to pass through it and stop larger molecules from passing (Ismail et al., 2018).

2.2. Reverse Osmosis

Reverse osmosis in the inverse of the osmosis process. In this process, a certain pressure is applied on the side with higher solute concentration. This allows the water to pass through the semipermeable membrane while restricting the salts and ions to pass (Ismail et al., 2018). The process is clearly explained in figure 2-1 below.

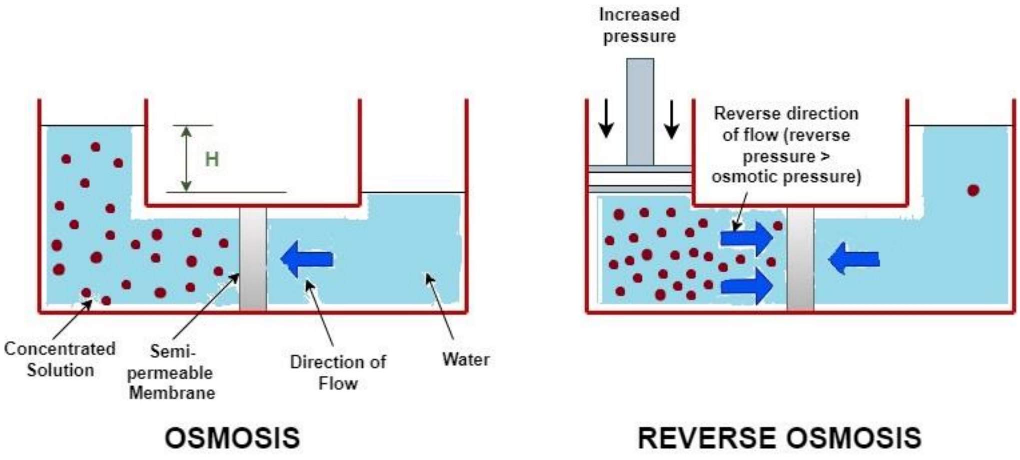


Figure 2-1: Diagrammatic representation of process of Osmosis and Reverse Osmosis

2.3. Terminology in reverse osmosis process and design criteria

The common terms used in describing and evaluating the RO technology are listed below (K. L McMordie Stoughton et al., 2013):

- **Feed water**: The supply water from the intake that is fed into the RO system.

- **Permeate:** The part of the feed water that passes through the membrane (cleaning process) or series of membranes.

- **Concentrate:** The part of feed water that does not pass through the membrane or is strained in the membrane. Typically contains higher concentration of salts, ions and impurities.

- **Water Flux:** Water flux in a RO process is the rate of permeate water production, this also can be expressed as the rate of water flow per unit area of a membrane. The design water flux in seawater RO membranes for FilmTec^{TM} membrane elements (type used in Galtneset) as suggested by the membrane manufacturer Dupont (Dupont, 2023) is about 12-17 L/m^{2}h (LMH).

$$J_w = \frac{Q_p}{A} \qquad 2.1$$

  Where, J_w is the flux, Q_p ***is*** the permeate flow and A is the effective membrane area.

- **Recovery Rate**: Ratio of permeate flow to the total feed water flow. The recovery rate of as system is highly dependent on the feed water concentration and the RO pre-treatment steps (Puretec.com, 2023).The ideal TMP of the RO membranes for an stable operation is 35-45 bar (Lenntech.com, 2023).
  Recovery is often fixed at highest level while making calculations and modelling a system to achieve maximum permeate flow. Additionally, for FilmTec^{TM} membranes a standard element test for a test time of 20 minutes conducted by the membrane manufacturer Dupont the recovery was reported to be 15% (Dupont, 2023).

$$R\% = \left(\frac{Q_p}{Q_i}\right) * 100 \qquad 2.2$$

  Where R is the recovery and Q_p and Q_i are the permeate and feed flow respectively.

- **Salt rejection**: Percentage of concentration of constituents (total dissolved solids) that has been removed in the permeate water. The performance of the system is improved by a higher salt rejection rate (Raphael A. Afonja, 2015). In case when the concentration of particles in the permeate is high, thus the system has a lower salt rejection rate, might indicate that the membrane either needs to be cleaned or replaced (Puretec.com, 2023).

$$Salt\ rejection\ \% = \left(\frac{C_i - C_o}{C_i}\right) * 100 \qquad 2.3$$

  Where, C_i is the concentration of water in the feed and C_o is the concentration of water in the permeate.

- **Trans membrane pressure** (TMP): The pressure difference between the feed stream and the permeate stream is known as TMP. It is also defined as the pressure required to push the water through the RO membrane.

$$TMP = P_i - P_p \qquad 2.4$$

Where P_i is the feed pressure and P_p is the permeate pressure.

2.4. Factors affecting the RO process

In a reverse osmosis process the key performance parameters are the permeate flow rate and the salt rejection. The product flow rate is defined similar to that of the production rate, whereas the salt passage rate is described previously in section 2.3. They are mostly impacted by variable factors like pressure, temperature, recovery, and salt concentration in the feed water (Ibrahim S. Al-Mutaz et al., 2001). A description summary for the relationship between the factors influencing the RO performance is shown in table 2-1 below.

Table 2-1: Relationship of RO perfomace

Increasing	Permeate flow	Salt rejection
TMP	↑	↑
Temperature	↑	↑
Recovery	↑	↓
Feed salt concentration	↓	↓
Increasing ↑ Decreasing↓		

2.5. Membrane Configuration

The most common types of membrane configuration are Spiral wound and hollow fibre (Butt et al., 1997):

Spiral Wound: In spiral wound configurations modules flat sheets of membranes are wrapped around the permeate collection tube (Butt et al., 1997). This configuration help produce flow channels for permeate and feed water (Butt et al., 1997). Feed spaces are places between the flat sheet membrane and are usually made of netting type of material. This feed spaces promote the turbulent flow in the feed water helping the water to move through the membrane (K. L McMordie Stoughton et al., 2013).

Hollow fibre: Hollow fibre systems are a collection of small membrane tubes placed collectively in a pressure vessel (Butt et al., 1997). The permeate from the tubes are collected at the centre of the fibres and the concentrate brine is produced on the outside as shown in (K. L McMordie Stoughton et al., 2013).

It is important to understand the type and geometry of membrane configuration since it plays an important role in the performance of a membrane filtration system, which impact the feed flow pattern (Angelo Basile et al., 2015). Membrane configurations influence the distribution of flow and design of feed spacers create turbulence between the channel and prevent fouling (Angelo Basile et al., 2015). Since in thesis, the effect of lowering feed flow is studied, and the membrane configuration used is a spiral wound membrane, it is important to consider the membrane module configuration to investigate any fouling issues between the spacers.

2.6. Cross flow Membrane technology

In this type of membrane filtration, the feed stream is pressurized, and it flows parallel to the membrane surface (Raphael A. Afonja, 2015). The filtered permeate passes through the membrane surface and leaves behind the rejected particles. Rather than accumulating on the membrane surface, as is the case for dead-end membranes, the particles are swept away by the concentrate stream, since there is a continuous flow across the membrane surface as shown in figure 2-2 below (DuPont, 2023b).

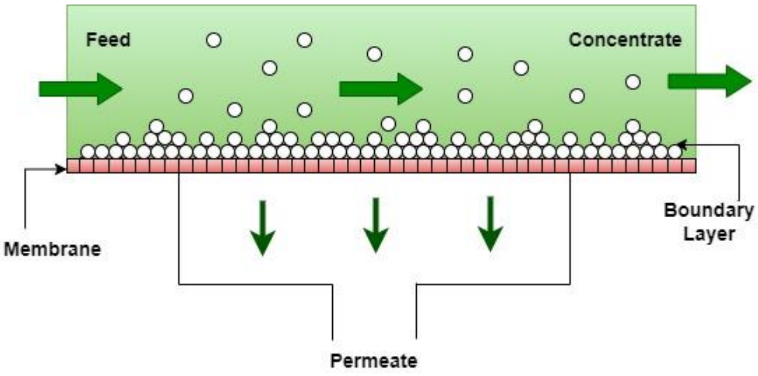


Figure 2-2: Schematic representation of a cross-flow RO process *Click or tap here to enter text.*

2.7. Scaling

Scaling is a phenomenon in a reverse osmosis and nanofiltration membrane processes where the sparingly salts within the membrane surface reach concentrations beyond their solubility limit and accumulate/precipitate to form a dense layer on the membrane surfaces (Matin et al., 2019). It is one the main factor contributing to lowering the efficiency of the process, as it causes the decrease of flux through the membrane. Scaling can be prevented by frequent membrane cleaning or addition of anti-scalants. The addition of the anti-scalant prevents scaling in the membrane by chemically reacting with the salts to lower the precipitation levels (DuPont, 2023b).

2.8. Fouling

Fouling in the context of water treatment and membrane processes, such as reverse osmosis (RO) refers to the accumulation and deposition of undesirable substances on the surface of membranes (Ismail et al., 2018). This fouling can result in reduced system performance and increased operational costs (DuPont, 2023b). There are different types of fouling in membrane processes namely particulate fouling that are caused by silt clay or sediments, scaling (refer section 2.7), organic fouling that is caused by organic matter, biofouling that is caused by microorganisms and colloidal fouling that is caused by colloidal particles (P. Hoornaert, 1984)

2.9. Salinity

Salinity is defined as the measure of dissolved solids in water. It can also be defined as the total salts in the water (US EPA, 2023). Salinity, however, is a strong contributor to the conductivity of water. Salinity is important input parameter for RO process since the salinity determines the flux through the membrane and thus the process performance is hugely dependent on the salinity (Aladwani et al., 2021). Salinity in seawater is dependent on the depth of seawater. Salinity decreases with increasing depth (*Lab 5.1 – Ocean Data Lab*, 2023).

2.10. SDI index

The most commonly utilized measure for predicting fouling potential in reverse osmosis (RO) operations is the silt density index (SDI), which is used to evaluate and minimize fouling(Yoo et al., 2021). It calculates the amount of time needed to filter a constant volume of feed water (500 ml) through a typical microfiltration (MF) membrane with a pore size of 0.45 m and a diameter of 47 mm in a dead-end filtration mode at constant pressure (207 kPa) (Ouyang et al., 2022; Wei et al., 2012). The SDI value is represented by the difference between the first time and the time of a second measurement, often 15 minutes later (after silt built up) (Wei et al., 2012).

2.11. Basic reverse osmosis relation

The equation below shows how the concentration of dissolved salts in solution can be connected to the osmotic pressure, π, of a solution (Ibrahim S. Al-Mutaz et al., 2001). This is important because the pressure required for the process of reverse osmosis to happen, should be greater than that os osmotic pressure (Ismail et al., 2018).

$$\pi = 1.19\,(t + 273) * \Sigma\,(mi) \qquad 2.5$$

Where, π = osmotic pressure in psi, t is the temperature in °C, and Σ (mi) is the sum of molal concentration of all constituents in a solution. An approximation for π may be given by the relationship below (Ibrahim S. Al-Mutaz et al., 2001):

$$\pi = \frac{0.0385 * C(t+273)}{1000-(\frac{C}{1000})} \qquad 2.6$$

where C is the total dissolved solids (TDS), mg/L (ppm). The TMP across the membrane can be given by (Ibrahim S. Al-Mutaz et al., 2001) :

$$\text{TMP}=\left(\frac{J_w}{K_w}\frac{x}{A}\right) + \Delta\pi \qquad 2.7$$

where , Jw is the water flux through the membrane, $\Delta\pi$ is the difference in osmotic pressure across the membrane, A is the membrane area, x is the membrane thickness and K_w is the membrane permeability coefficient for water typical values of the membrane permeability coefficient for different RO membrane materials (Okamoto & Lienhard, 2019):

- Cellulose Acetate (CA) membranes: average: 0.8 L/(m².h.bar)
- Thin-film Composite (TFC) membranes: average: 3 L/(m².h.bar)
- Polyamide (PA) membranes: average: 4 L/(m².h.bar)
- Polyethersulfone (PES) membranes: average: 3 L/(m².h.bar)
- Polyvinylidene fluoride (PVDF) membranes: average 2.5 L/(m².h.bar)

2.12. Calculating the efficiency and cost

Efficiency in a reverse osmosis process is usually calculated to assess how effectively the system removes impurities, including dissolved salts and contaminants, from a feed water source to permeate water (Ismail et al., 2018). It is the ratio of permeate flow rate to feed flow rate, given in percentage. The efficiency of a reverse osmosis is calculated using the formula (Ismail et al., 2018):

$$Efficiency(\%) = (1 - (Q_p - Q_i)) * 100 \qquad 2.6$$

Also, the energy consumption of the RO process is a critical factor in determining its efficiency and cost. To calculate the specific energy consumption (SEC) at an operating TMP and feed flow rate of water through the RO system can be given by (Xavier Bernat et al., 2010).

$$SEC\left(\frac{kWh}{m^3}\right) = \frac{Energy\ consumption(kWh)}{Q_p\ (m^3)} \qquad 2.7$$

2.13. Normalization of data in reverse osmosis process

A method for converting a system's actual performance into a format that can be compared to a reference performance is defined as data normalisation. This reference performance could be the system's designed performance or the measured starting performance (Singh & Singh, 2020). Normalization of data is very important when there are variable data, which means that one parameter affects the other parameter. In reverse osmosis systems normalization of data is necessary to compare the membrane performance regardless of changes in the operating conditions and check if the system is stable or developing problems (Puretechwater.com, 2023). It also helps to troubleshoot any potential problems. Thus, the normalized data will measure the direct condition of the RO system and show the actual performance and health of the RO system (Puretechwater.com, 2023).

The process of performing a normalization of data involves a few steps (Singh & Singh, 2020):

- Collect operating data
- Normalize the data
- Trending the normalized data over time
- Comparing the values to a baseline. In RO systems the baseline is considered as a startup values, in cases when the RO membrane is new or freshly cleaned.

Three important parameters that are normalized in the RO process to monitor and trend are (Puretechwater.com, 2023) :

Normalized permeate flow (NPF): It can be used to monitor issues such fouling membrane deterioration and other issues by measuring the amount of permeate water that the RO is producing (Puretechwater.com, 2023). In case if NPF drops 10% to 15% below the baseline value or the reference value then this might indicate fouling or scaling of RO membranes (Puretechwater.com, 2023). Increase in NPF determines the damage of the RO membrane.

$$NPF = Q_i * \left(\frac{Baseline\ aNDP}{aNDP}\right) * \left(\frac{Baseline\ TCF}{TCF}\right) \tag{2.8}$$

Where aNDP is the average net driving pressure and TCF is the temperature correction factor is given by:

$$aNDP = \left(\left(\frac{P_i+P_p}{2}\right) - \left(\frac{C_i+C_o}{2}\right)\right) - P_p \tag{2.9}$$

Where, P_i and P_p are the feed and permeate pressure and C_i and C_o are the feed and permeate concentration of water respectively.

$$TCF = EXP\ (2640 * \left(\left(\frac{1}{298}\right) - \left(\frac{1}{273 - Feed\ temperature\ in\ celcius}\right)\right)) \tag{2.10}$$

- Normalized Salt rejection (NSR): The RO membrane's ability to reject salts is indicated by its NSR (Puretechwater.com, 2023). A good RO membrane should reject particles with a percentage of 97% to 99%; a membrane is considered "bad" if its RO rejection drops to 90% or less (Puretechwater.com, 2023). The NSR is defined as:

$$NSR = 100(\left(Salt\ passage * \left(\frac{Q_i}{Baseline\ Q_i}\right) * TCF\right) * 100) \tag{2.11}$$

Where salt passage is given by:

$$Salt\ passage = 1 - salt\ rejection \qquad 2.12$$

- Normalized pressure differential (NPD): Differential pressure is the TMP of a membrane. Thus, NPD is a measurement of the pressure drop that occurs as feed water moves through the system's element flow channels (Puretechwater.com, 2023). It gives information about how clean the feed water spacer is on the membrane and therefore the if the NPD increases by 15-25% of the differential value, the membrane is required to be cleaned (Puretechwater.com, 2023).

$$NPD = Pressure\ drop * \frac{Baseline\ Q_{average}}{Q_{average}} \qquad 2.13$$

And

$$Average\ flow = Q_{average} = \frac{Q_i + Q_c}{2} \qquad 2.14$$

3. MATERIALS AND METHODS

3.1. Input data from the Galtneset water treatment plant

Membrane: The Galtneset waterworks has two membrane lines, each containing six membrane modules, which are connected in parallel by o-rings. In total there are 12 membranes in two of the membrane rigs as shown in figure 3-1, however in present day only one rig consisting of 6 elements are in operation. The membrane is of thin film composite membrane also known as FilmTec^{TM} of the type SW30XLE440i. These types of membrane are specifically used for seawater desalination with low energy consumption (Dupont, 2023). These membrane modules have an area of 40.9 m^2 each and the thickness of the membrane of 0.03077 m^2. These membranes are spiral wound membranes with cross flow configuration.

Figure 3-1: RO membrane units in Galtneset

Production: For a normal operation of 22 hours (2 h cleaning) per day, the plant is designed to produce a permeate flow of approximately 23 m^3/h in every line of the membrane. The permeate flow of 23 m^3/h is also the maximum capacity for one unit of membrane containing 6 elements. Therefore, the plant has the capacity to produce approximately 46 m^3/ h, when both lines are in operation. However, since only one line consisting of 6 membranes are in operation today due to change in water demand since the Pelagia built their own water treatment plant. Additionally, currently in practice the permeate flow is reported to be slightly lower than that of the designed flow of 23 m^3/h, and is usually reported to be around the range of 19.8-21 m^3/h for one line in operation (Van Sui Cer, 2022). Therefore, the permeate production is currently reported to be around 21 m^3/h (460 m^3/d) as mentioned in section 1.1.

Intake: The water source is seawater from the sea north of Galtneset as shown in figure 1-1 . The intake line is approximately 700 m long at approximately 12 m depth and with a diameter of Ø600 mm (Norconsult AS, 2022). This intake line is being shared with the water treatment plant for Pelagia AS.

The intake line ends in an intake pumping station with 12 pumps, of which two pumps are municipal pumps for the municipal RO plant and the other pumps are for the fish industry Pelagia AS(Norconsult AS, 2022). The pumps have the capacity to pump seawater at 80 m^3/h. However, in present day the flow from the intake is operated at 54 m^3/h.

Pre-treatment: The water is pre-treated in three units of sand filters running in parallel. Thereafter, it passes through another screen filter of pore size 50 µm. Temperature of the feed water is measured using a temperature sensor that is installed right after the sand filters.

Pressure pumps: The pump system in the water treatment plant consist of several pumps which pumps the water throughout the process train and the pumps are less flexible in design. This is because the pumps are not technically flexible to regulate the speed based on the requirements of flows. Before the raw water (seawater) enters the reverse osmosis membranes, the raw water is pressurized by the high-pressure pump of 60 bar and the pressure drop is estimated to be 10 bars across the membrane. However, the pressurised pump is designed to provide a pressure of 52-60 bar and is in practice currently providing a constant pressure of 54 bar (Norconsult AS, 2022). The variation in feed pressure from the pump for the year 2022 are presented in Figure 3-2. In the figure 3-2 it can be seen that from the end of August to the month of December the WTP has experienced frequent stops.

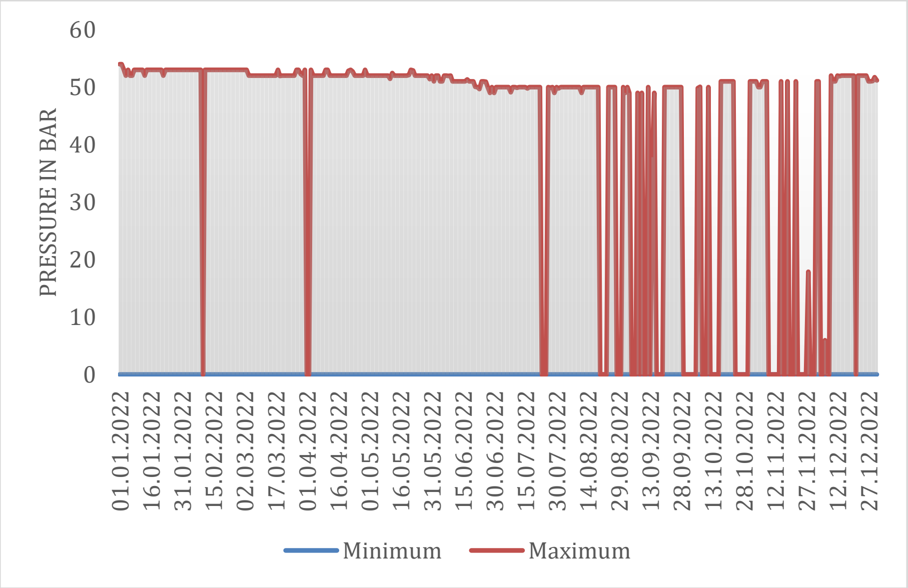


Figure 3-2: Yearly TMP data recorded at Galtneset in the year 2022

3.2 Raw water quality

Galtneset does not have any seasonal monitoring of the salinity at the feed water stream. However, some reference values from different literature can be investigated for having an understanding of the salinity, and other water quality parameters and are presented in table 3-1 It must be considered that the salinity measurements presented in table 3-1 are not indicative of the salinity of feedwater at Galtneset, since the salinity measurements may vary depending on the depth. However, these values might give an understanding of the range of water quality of the seawater in Træna. Additionally, the measurements for the salinity and TOC measurements of the seawater from Galtneset WTP are not available.

Table 3-1: Water quality parameters for seawater

Parameter	Quantity	Units	Source
Turbidity	0.2	NTU	(Van Sui Cer, 2022)
pH	8		(Van Sui Cer, 2022)
Colour	2	Pt-Co	(Van Sui Cer, 2022)
Salinity	34920	mg/L	Norwegian sea (Elizabeth Jones & Melissa Chieric, 2019)
	37600	mg/L	Atlantic sea (DuPont, 2023b)

The temperature of the feed water is recorded by the temperature sensor as shown in figure 3-3, placed after the sand filter shows that the temperature during the period of the year 2022 the lowest temperature recorded was approximately 5◦C .The average seawater temperature at Husøya, Nordland over the year is 5.5°C (seatemperature.org, 2023). The monthly seawater variation in temperature for the seawater near Husøya shows a minimum temperature of 3°C and maximum of 15°C see Appendix A . This temperature is lower than that of the minimum temperature recorded by the temperature sensor at the WTP see Appendix A .

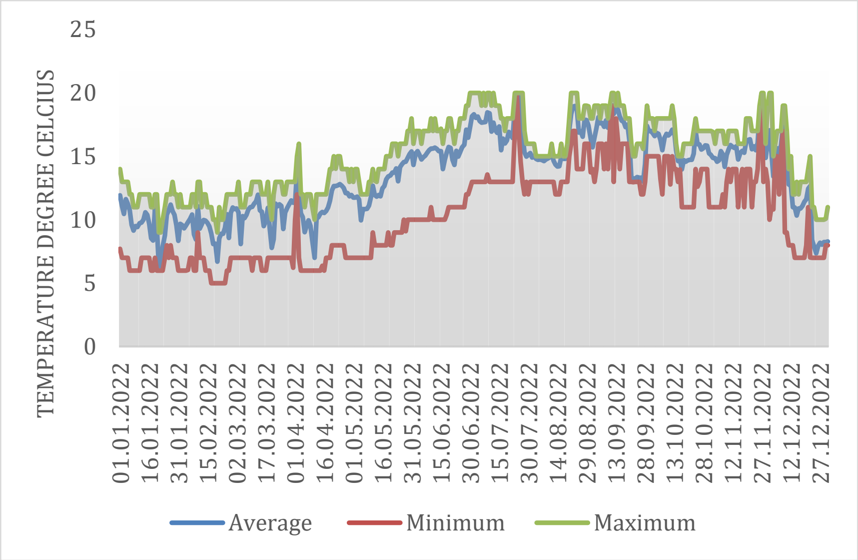


Figure 3-3: *Temperature recorded in the sensor for the year 2022*

3.3. WAVE (Water treatment design software)

The Water Application Value Engine (WAVE) is a new modelling software program offered by Dupont. Three technologies—ultrafiltration, reverse osmosis, and ion exchange resin—are combined into one comprehensive platform through this program (DuPont.com, 2023). This can be used to design as well as simulate different scenarios of the operation of the water system with membrane processes (Dupont.com, 2023).

This is a calculation engine that has the capacity to run different membrane process designs with accuracy which provides flexibility of using these three technologies (DuPont.com, 2023). It also provides an option to define the system-feed or net-product flow rate and also multiple unit operation combinations that can be modelled using this program (Dupont.com, 2023). The program also takes into account changes in the density, temperature, water composition and water compressibility when calculating the mass balances for flows and volume (DuPont.com, 2023). Thus, the program is compact and easy to use and allows to create a design quickly.

Modelling the RO process using the WAVE program involves different steps:

- Defining the user and project information
- Specifying the treatment process or combination of treatment process
- Specification of feed flowrate or the product flow rate in a system design. In this step it should be noted that the flow rates should be specified for one membrane element. For instance, if the net permeate flow is 20 m^3/h for a 6 membrane unit. The input permeate flow rate to be given in the program is 3.3 m^3/h per membrane unit.
- Defining the feed water characteristics. In this step the feed water type (Wastewater, seawater, well water etc.) and subtypes are characterized, and then different chemical parameters, as listed below, are defined:

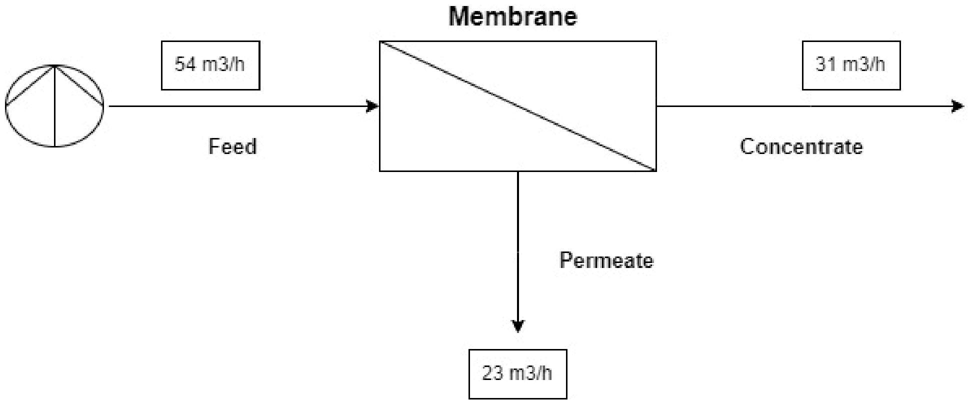
  - Salinity (Concentration of different ions Chloride Cl^-, Sulfate SO_4^{2-} , Sodium Na^+, Magnesium Mg^{2+}, Potassium K^+ and Calcium Ca^{2+})
  - pH
  - Temperature range (Maximum, design and minimum)
  - Turbidity
  - Total organic carbon (TOC)
  - SDI

  In case if any chemicals are added, based on the project requirement pH adjustment is done accordingly to the feed.
- Defining the RO system based on the number of passes, specifying the temperature for which is being designed, the desired system recovery and membrane characteristics.
- Simulation of the RO system and creating summary report.

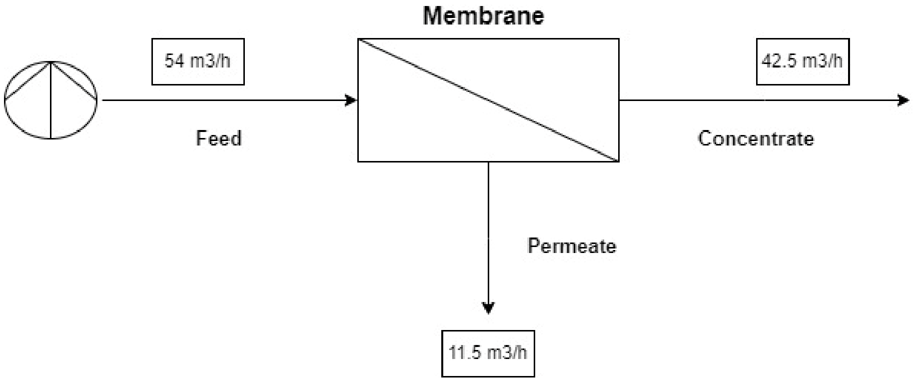
However, when designing the RO treatment using WAVE, some of the parameters such as the flux, feed flow or the product flow are not variable and are constant for each simulation. Therefore, it is necessary to understand the method used for modelling the scenarios in this thesis. The modelling procedure used is shown in figure 3-4 below:

3.3. Inputs to set up RO system design in WAVE

In this thesis, initially a RO system design will be simulated using the design feed flow and permeate flow, the pressure and flux will be calculated for a recovery rate of 40% for different temperature ranges. The initial design feed and permeate flow for current operation of the Galtneset WTP is shown in figure 3-4(a). Thereby, the flows that will be designed to run the simulation to for a reduced permeate flow of approximately half that of 23 $m^{3/}$/h (11,5 m^3/h) as shown in figure 3-4(b).



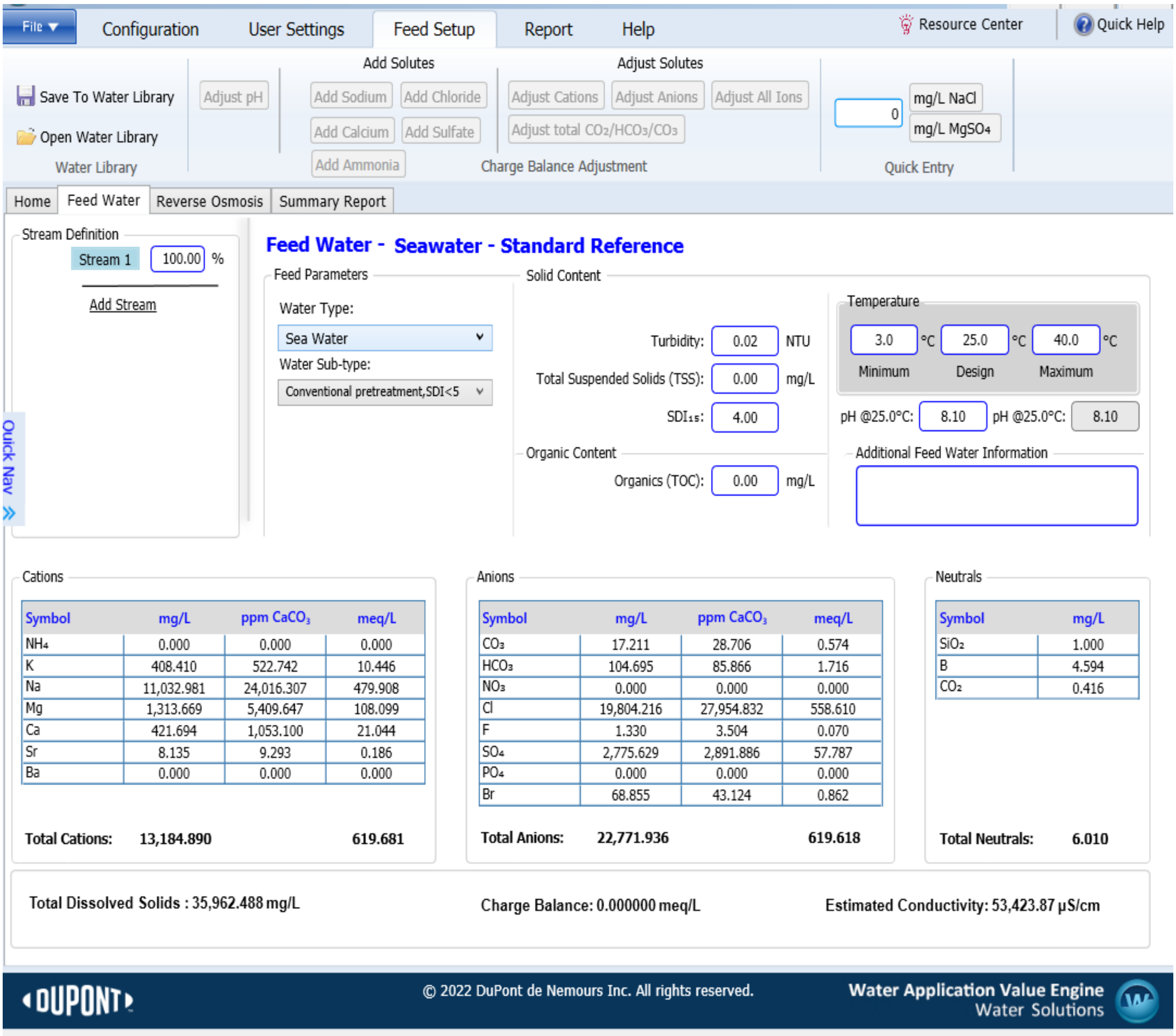
(a)



(b)

Figure 3-4: Figure representing the different flows(feed, Permeate and concentrate) in the system that were modelled for in considering two cases (a)Operating flow (b) Reduced flow

The feed water characteristics are defined for a standard seawater salinity of approximately 35 000 mg/L and the concentrations of the ions are adjusted to standard value for the salinity from (DuPont, 2023b) as shown in figure 3-5. The input values for the TSS is set at 0.2 NTU (Van Sui Cer, 2022), temperature range (minimum, design, maximum) 3°C < 25°C < 40°C, the pH of 8.0 and SDI index < 4 (Van Sui Cer, 2022).



Stream Definition: Stream 1 100.00 %

Feed Water - Seawater - Standard Reference

Feed Parameters

Water Type: Sea Water

Water Sub-type: Conventional pretreatment,SDI<5

Solid Content

Turbidity: 0.02 NTU

Total Suspended Solids (TSS): 0.00 mg/L

SDI_{15}: 4.00

Organic Content

Organics (TOC): 0.00 mg/L

Temperature

Minimum 3.0 °C; Design 25.0 °C; Maximum 40.0 °C

pH @25.0°C: 8.10 pH @25.0°C: 8.10

Additional Feed Water Information

Cations

Symbol	mg/L	ppm $CaCO_3$	meq/L
NH_4	0.000	0.000	0.000
K	408.410	522.742	10.446
Na	11,032.981	24,016.307	479.908
Mg	1,313.669	5,409.647	108.099
Ca	421.694	1,053.100	21.044
Sr	8.135	9.293	0.186
Ba	0.000	0.000	0.000

Total Cations: 13,184.890 619.681

Anions

Symbol	mg/L	ppm $CaCO_3$	meq/L
CO_3	17.211	28.706	0.574
HCO_3	104.695	85.866	1.716
NO_3	0.000	0.000	0.000
Cl	19,804.216	27,954.832	558.610
F	1.330	3.504	0.070
SO_4	2,775.629	2,891.886	57.787
PO_4	0.000	0.000	0.000
Br	68.855	43.124	0.862

Total Anions: 22,771.936 619.618

Neutrals

Symbol	mg/L
SiO_2	1.000
B	4.594
CO_2	0.416

Total Neutrals: 6.010

Total Dissolved Solids : 35,962.488 mg/L

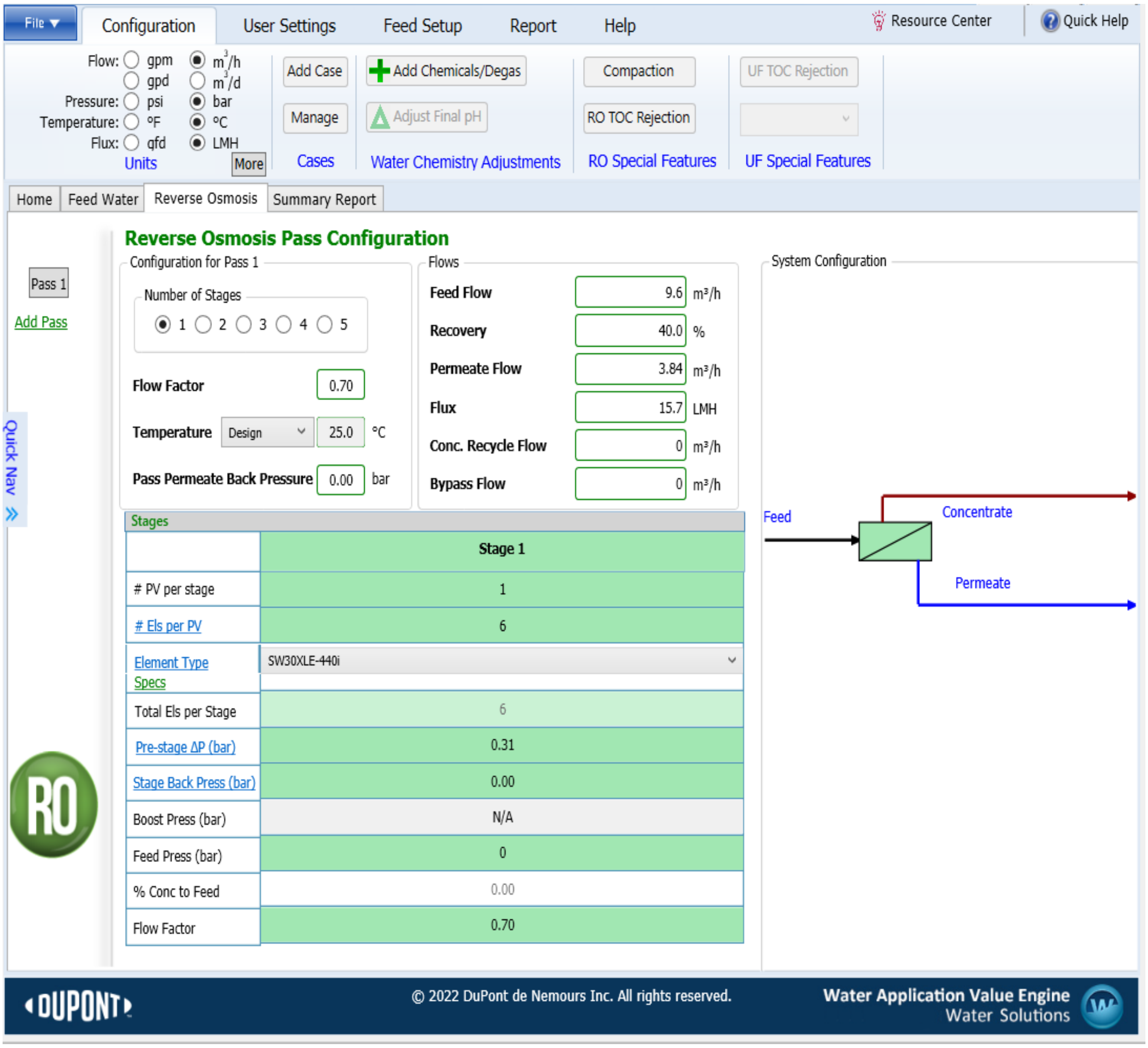
Charge Balance: 0.000000 meq/L

Estimated Conductivity: 53,423.87 µS/cm

Figure 3-5: Input feed water characteristics for a salinity of 35000 mg/L provided in WAVE model for modelling scenario 1 and 2

For defining the RO process a single pass RO system was designed for the membrane SW30XLE440i. A single pass RO system is the system where the permeate produced by one membrane unit is the final permeate water and it does not flow to another membrane unit for filtration (Ismail et al., 2018).

The simulation results were obtained by changing different number of elements and specifying different temperatures as shown in figure 3-6. In this step the flux can be changed by changing the recovery ratio of the system. The report was then generated by simulating the design.



Units: Flow: ○ gpm ● m³/h; ○ gpd ○ m³/d; Pressure: ○ psi ● bar; Temperature: ○ °F ● °C; Flux: ○ gfd ● LMH

Reverse Osmosis Pass Configuration

Configuration for Pass 1

Number of Stages: ● 1 ○ 2 ○ 3 ○ 4 ○ 5

Flow Factor 0.70

Temperature Design 25.0 °C

Pass Permeate Back Pressure 0.00 bar

Flows

Feed Flow 9.6 m³/h

Recovery 40.0 %

Permeate Flow 3.84 m³/h

Flux 15.7 LMH

Conc. Recycle Flow 0 m³/h

Bypass Flow 0 m³/h

System Configuration

Stages

	Stage 1
# PV per stage	1
# Els per PV	6
Element Type Specs	SW30XLE-440i
Total Els per Stage	6
Pre-stage ΔP (bar)	0.31
Stage Back Press (bar)	0.00
Boost Press (bar)	N/A
Feed Press (bar)	0
% Conc to Feed	0.00
Flow Factor	0.70

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Figure 3-6: Defining the RO systems input parameters in WAVE at a constant recovery of 40% and at standard temperature of 25°C for a 6 element membrane.

3.4. Description of modelling process used in WAVE

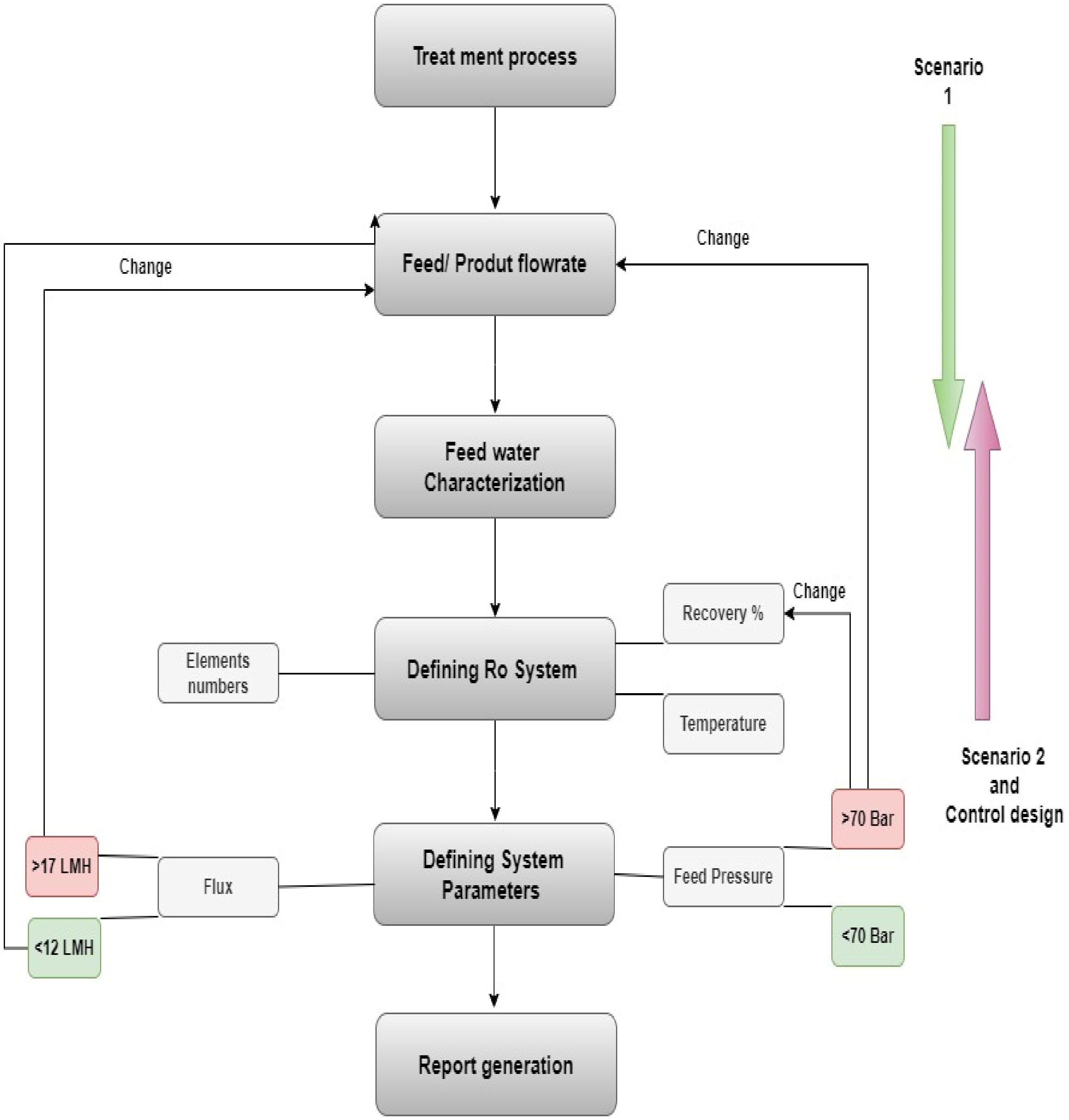


Figure 3-7: Modelling procedure for scenario 1 and 2

The modelling procedure for this thesis, using WAVE, is done initially by identifying the treatment process of a single stage reverse osmosis process. Then identifying the product water flow rate for both the cases when modelled for 23 m^3/h and 11.5 m^3/h . While modelling scenario 1 where the number of membrane elements are reduced, the results for the flux and the TMP are generated at the permeate water flow rate for both the cases with 23 m^3/h and 11.5 m^3/h. In this scenario, the feed water characteristics for the salinity is kept constant whereas the element numbers and temperature are changed for each model. The recovery rates for the processes were also kept constant, and the flux and TMP were recorded accordingly.

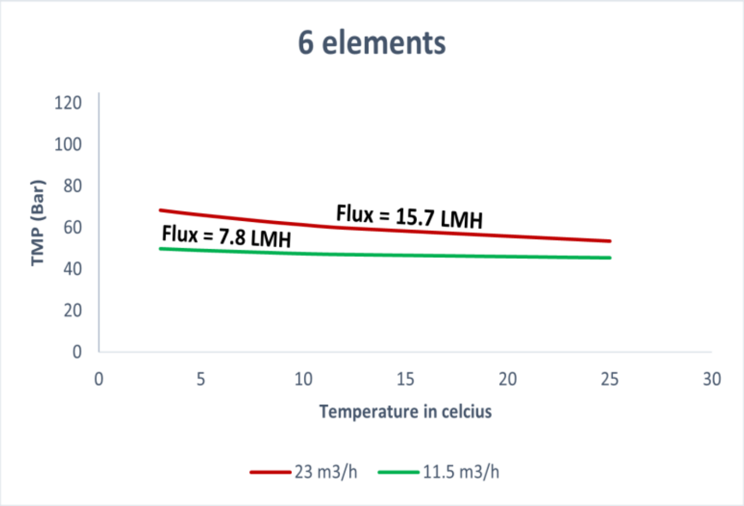
While modelling for scenario 2 where the feed flow is being reduced, the process is modelled for two different permeate flow rates, as mentioned above. In this case, keeping the salinity and water characteristics constant, the RO system was defined for a 6-element system and the standard temperature at 25°C. However, the recovery initially kept at 40% and then was changed to adjust and obtain results for different feed flows in the model. Since, it is not possible to adjust flexibly both the feed flow and the permeate flow simultaneously in WAVE, it can be done only by increasing or decreasing the recovery ratio in the reverse direction. For a RO process to be operating under the criteria and not exceeding the required flux or TMP, figure 3-7 gives the idea on what parameters in the model needs to be changed in different steps.

However, while modelling for the scenario 1 and 2 the flux and the TMP were not limited to a range based on the criteria in the model. Thus, the TMP and flux obtained from the results after simulating the model were recorded and the best possible operating conditions were studied based on the results.

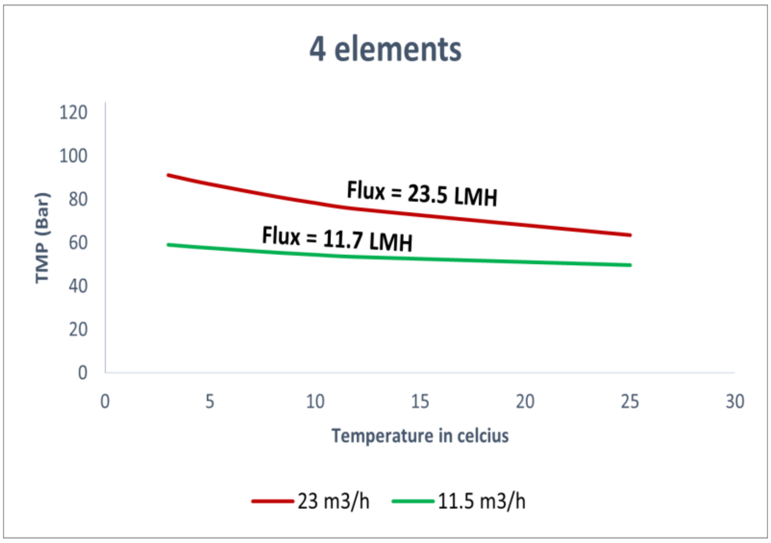
4. RESULTS

4.1. Scenario 1: Results for 6, 4 and 3 elements at different temperatures

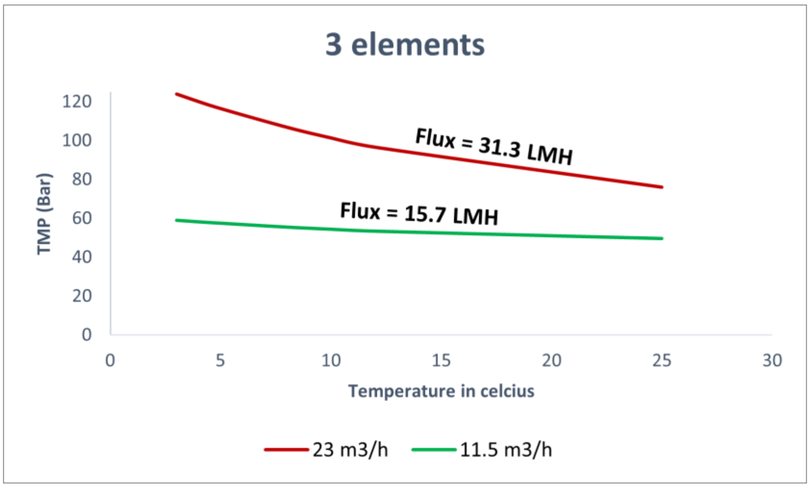
The system was designed two permeate water flow rate shown in the figure 3-4. Keeping the recovery ratio constant, the system was designed for seven different temperatures range. The pressure in the permeate stream, by default in the WAVE program is assumed as 0 bar. Therefore, the feed pressure is same as the TMP in the results. The results are presented in figure 4-1 below where the flux recorded are mentioned along with the plots in each case.



(a)



(b)



(c)

Figure 4-1: Results for the WAVE simulation results for (a) 6 membrane elements (b) 4 membrane elements (c) 3 membrane elements

The results show that as the temperature decreases, the TMP increases for every membrane element, since the flux is kept constant throughout the simulation for different temperature ranges. It can be also seen from figure 4-1(a) that at design temperature of 25°C the TMP / Feed pressure is around 53 bar. This can be verified with the RO plants operating feed pressure of 54 bars (refer section 3.1), that is same as the TMP of the process as the permeate pressure is very low. Therefore, the TMP is almost equivalent to the feed pressure. This gives the information that the plant operation has been designed at the design temperature of 25°C. It is also seen that the pressure exceeds the maximum design pressure of 60 bar at temperature lower than 12 degrees. At the average seawater temperature of approximately 5°C the feed pressure is almost 66 bars for a constant permeate flux of 15.7 LMH. However, when the permeate, flow is reduced to 11.5 m^3/h the feed pressure required for each temperature is around a range of 45-49 bar, which is quite lower than the operating pressure of the RO treatment plant of 54 bar. However, the flux for a recovery of 40 % in this case was 7.8 LMH which is lower than the design criteria of 12-17 LMH. Thus, with regards to the TMP reducing the number of elements is possible to achieve a lower permeate flow.

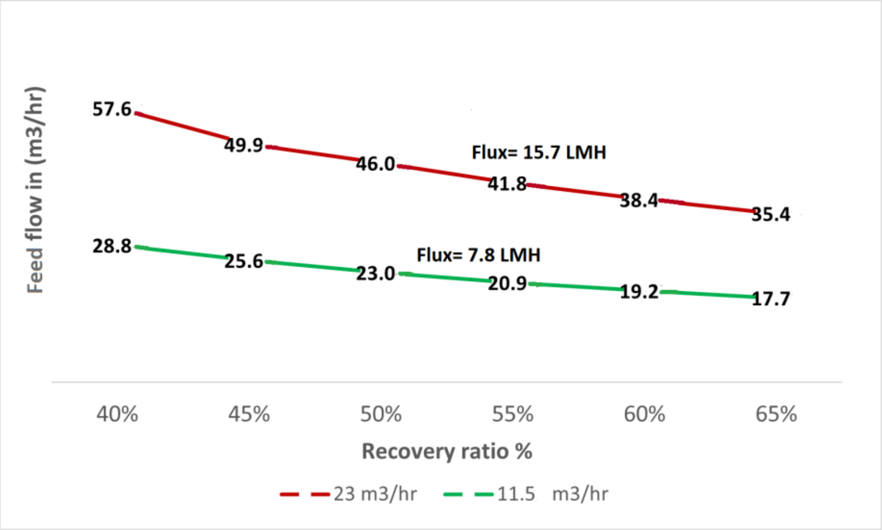
From figure 4-1 (b) and (c) it is evident that when the number of membrane elements are reduced, the TMP increases in normal operation with a flow of 23 m^3/h. The design feed pressure for 4 and 3 elements in operation were both greater than the operating feed pressure of 53 bar. Additionally, the flux was 23.48 LMH for 4 membrane elements and 31.3 LMH for 3 membrane elements, which is much higher than the criteria of 12-1 LMH. Therefore, it needs to be adjusted.

On the other hand, the permeate pressure at 11.5 m^3/h was when designed for 4 membrane element the permeate pressure was approximately 50 bar for design temperature and 55 bar for temperature at 5 degrees and operating at a constant flux of 11.7 LMH, which is acceptable as it is just slightly lower than the criteria. The pressure also didn’t exceed more than 60 bars at the lowest temperature of 60 bar.

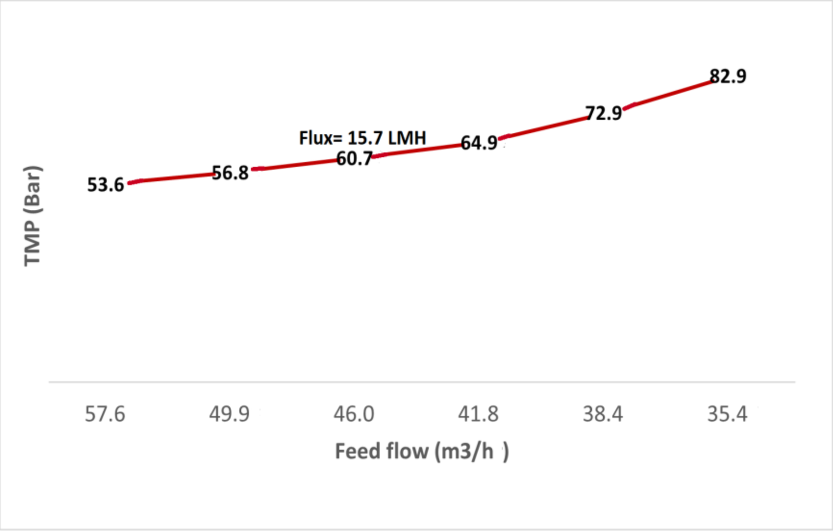
When designing for 6 membrane in operation the TMP obtained at standard temperature of 25°C was almost same as that of current operating TMP of Galtneset at 54 bar as shown in figure 3-2 for a permeate flow of 23 m^3/h flow. However, from figure 4-1, the results for the TMP when modelled at lower temperatures than 25°C for a 6-element membrane model were all greater than 54 bar.

4.2. Scenario 2: Lowering the feed flow.

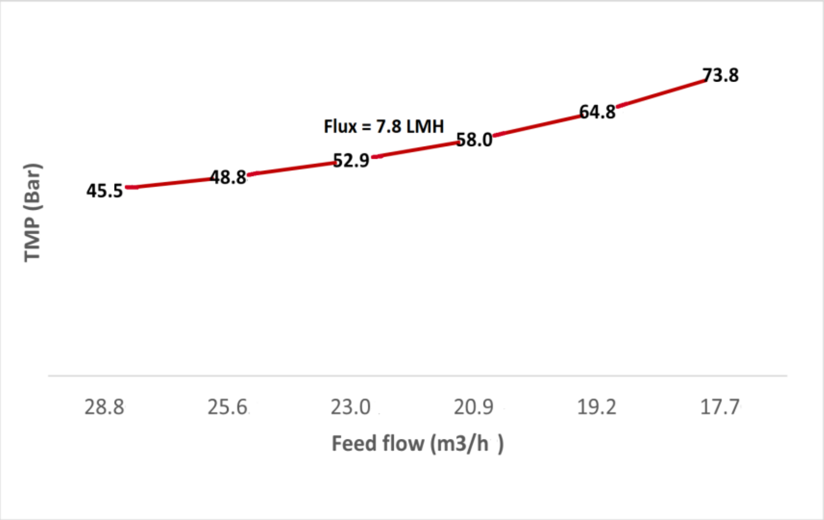
The feed flow was lowered by changing the recovery ratio of the system, since it was not possible to run the design with different feed flows and calibrating at a constant permeate flow. Therefore, the recovery ratios were changed first, and the corresponding feed flows were recorded as shown in figure 4-2(a). The feed flow was lowered for 6 different recovery ratios, for two different operational permeate flows, and then the results ae presented in the figure 4-2(a) and the pressure at corresponding flows are presented in figure 4-2 (b)and (c).



(a)



(b)



(c)

Figure 4-2: WAVE simulation results for (a) Recovery vs feed flow (b) Feed flow vs TMP at 23 m^3/h (c) Feed flow vs TMP at 11.5 m^3/h

From figure 4-2 (b) it is evident that when feed flow is being lowered the recovery of the process is increased. However, the TMP also increases as the feed flow is decreased due to the increased recovery of the system. This can be seen at figure 4-2 (b) and (c), where with each lowered feed flow and the TMP obtained at that respective feed flow corresponds to different recovery as shown in figure 4-2(a).

The pressure increased from approximately 53 to 83 bar when the feed flow was reduced from 57.6 to 35.6 m^3/h. Similarly in case of modelling for 11.5 m^3/h permeate flow, the TMP increased from 45-73 bar as the flow was reduced. It is evident from figure 4-2 that a lowered feed flow could possibly help achieve a lower permeate flow with comparatively lower TMP than an operating TMP of 54 bar and lower flux. Further, the TMP results for modelling at a feed flow of 57.6 and 25 m^3/h at different temperatures are presented in figure 4-3.

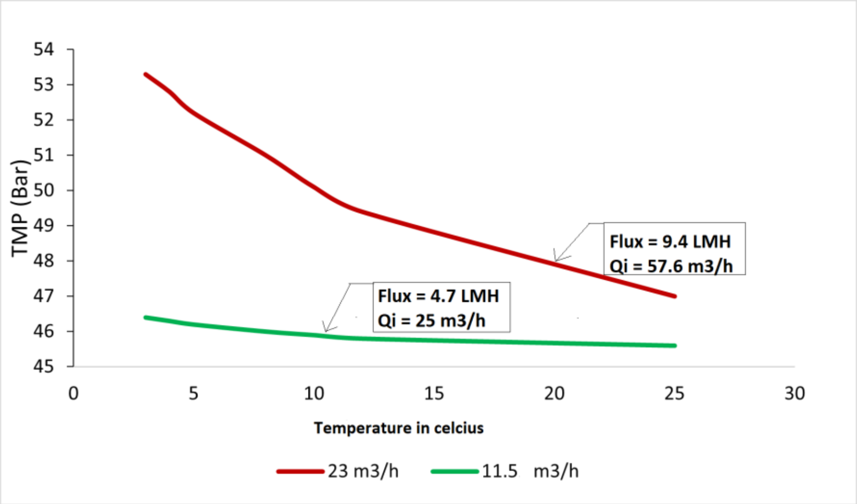


Figure 4-3: Results for TMP at a feed flow of 57.6 and 25 m^3/h in different temperatures

4.3. Modelling for a control process

The results for the different salinity concentrations modelled, to check the effect of the process for a change in salinity on the flux and TMP and thereby achieve a lower permeate flow are presented in table 4-1 below.

The flux was seen to be constant for the two flows at all the salinity concentrations. The TMP for the reduced flow is quite lower than the current operating TMP of 54 bar. The feed water salinity after balancing the charge of the cations and anions concentration has highly increased, as shown in Table 4-1.

Table 4-1: Results for different salinity measurements at design temperature 25°C

		23 m^3/h		11.5 m^3/h	
Seawater salinity (mg/L)	**Conductivity (µS/cm)**	**TMP (bar)**	**Salt rejection %**	**TMP (bar)**	**Salt rejection %**
32000 (32880 with balanced charged)	49370	49.5	99.5	42.0	99.0
35000 (35963 with balanced charged)	53423	53.6	99.6	49.8	99.0
40000 (41099 with balanced charged)	60071	60.7	99.5	52.3	99.0

4.4. Results for Normalization of data

The results for the Normalization of reverse osmosis data are presented in table 4-2. This was done to compare the real performance parameters of a system into a normalized form and compare it with the baseline values. The baseline data are generally the data obtained after the first operation after a new membrane installation or the data recorded just after membrane cleaning.

However, since the baseline values were not recorded at Galtneset, these data were assumed to be same as the values obtained from modelling in WAVE for a standard membrane operation at 25°C for a salinity of 35 000 mg/L. Additionally, another assumption made was that the baseline temperature and measured temperature used to calculate the normalized values were assumed to be the same.

Furthermore, in calculating the NPF, NSR and NDP the baseline permeates flow for the system is assumed as 23 m^3/h as shown in table 4-2. However, the calculated normalized permeate flow data given shows that the permeate flow is 22.8 m^3/h in present operating condition.

Also, since an ideal salt rejection for RO membrane is 95-99% (Puretec.com, 2023), the baseline salt rejection was assumed to be 99%. To verify this, the salt rejection was calculated after modelling in WAVE for the standard operation as mentioned above.

The permeate salinity was found to be around 1.7 mg/L which gives approximately 99% salt rejection. Therefore the baseline for the salt rejection is considered to be 99% as shown in table 4-2.

Table 4-2: Results for the Normalization of data

Parameter	Calculated	Baseline	Units	Remarks
NPF	22.8	23.0	(m^3/h)	>10-15% baseline value
NSR	97.3	99.0	(%)	>90%
NPD	54.7	39.0	(Bar)	< 15-25% baseline value

5. DISCUSSION

5.1. Scenario 1

One of the first steps, to reduce the permeate flow for an overdesigned RO membrane WTP, is to reduce the number of membranes in operation. Since reducing the number of membrane results in less effective area available for osmosis, thus resulting in the lesser production of water. However, a reverse osmosis process is much more complicated, since manipulating one parameter results in changing of another. It can be seen from figure 4-1 that as the permeate flow is halved , the TMP and flux have also reduced. The TMP for both the flows increased at lower temperature. It is evident that temperature plays an important role in the process of reverse osmosis, and reverse osmosis is works more effectively in higher temperatures. Thus, it makes the optimization process for Galtneset much more challenging due to its location in the cold Nothern-Atlantic climate, when most of the models and operation strategies are designed for the standard temperatures of 25 degrees. In Appendix A the surface seawater temperature for different months in Husøya can be seen, ranging from a minimum of 4°C to a maximum of 16°C. However, the actual temperature of the feed might be a bit higher than this temperature, since the intake water is being taken for 12 m depth of the sea. Thus, designing the RO process for a standard temperature range of 25°C, cannot be considered accurate. Therefore, considering an average range of temperature of 10-15°C, the TMP is seen to be increasing for every reduction in the number of RO elements in operation.

This can be understood from the basic reverse osmosis relation for the TMP or ΔP, which refers that the TMP being directly proportional to the flux and inversely proportional to the effective area available for membrane filtration. However, for a recovery rate of 40% to get a reduced permeate flow the TMP for each case of reducing elements is calculated to be less under the criteria of <70 bar. Therefore, it gives the information that the RO process could be run at around a TMP of 60 bars when operated with a reduced number of membrane elements. Furthermore, for a permeate flow of 23 m^3/h, the reduction of elements is not seen to be effective as for every reduction the TMP increased than the criteria of 70 bar.

At a recovery ratio of 40%, the flux for permeate flow of 11.5 m^3/h is seen to be increasing when changing from 6 to 3 elements in operation. It is also seen that the flux is less than the acceptable recommended range of 12 LMH. However, in some cases, low flux rates using membrane technology could be used to focus on achieving high water quality, minimizing fouling and extending membrane lifespan(Othman et al., 2021) For example, some water treatment plants, such as The Tuas Desalination Plant in Singapore operate with a considerably low flux of 75 LMH to produce a permeate of 5418 m^3/h (Sara Charco Iniesta, 2016). (DuPont, 2023c; Sara Charco Iniesta, 2016). This flux of operation is much less than that of Galtneset RO plant, if being operated at the lowest flux of 7.8 LMH to produce a permeate of 11.5 m^3/h. Additionally,, in the cases where a higher flux was obtained, the flux can be lowered by lowering the feed flow rate (Ismail et al., 2018) and the effects of lowering feed flow is evaluated while discussing scenario 2 in section 5.2.

However, the membrane elements in Galtneset as shown in figure 3-1 is not flexible to adjust the operation of only certain number of elements. Therefore, to reduce the number of elements in operation the plant has to install valves between the membrane elements. On the other hand, the other set of membrane modules is not put into operation. Thus, having a flexible train operation such as in The Carlsbad Desalination Plant in California, USA, which is equipped with multiple RO trains, each containing a set of membrane modules and where the number of operating trains can be adjusted based on the current water demand (Water-technology.net, 2023).

5.2. Scenario 2

In the WAVE model the feed flow can be changed by changing the recovery rate, while keeping the permeate flow constant. figure 4-2(a) shows that to lower the feed flow, the recovery rate needs to be increased. This corresponds to the table 2-1 and recovery equation in section 2-3, that shows that as the recovery of the process is increased, the permeate flow increases and salt passage increase. However, it can be seen from the figure 4-2 (b) and (c) that as the feed flow is lowered the TMP increases, which is not an ideal case for an efficient RO process. To produce a permeate of 23 m^3/h, the required feed flow should be around the range of 50-58 m^3/h. Furthermore, to produce a permeate at 11.5 m^3/h the feed flow could be lowered to 21 m^3/h with a recovery of 55%. Even though to maintain a stable operation in a desalination plant the recovery is limited in a range of 35-45% (Lenntech.com, 2023), higher recovery was taken in the model to evaluate the effects of having lower feed flow in the system. However, the results from the model in figure 4-2 (c) represents that at a feed flow of 23 m^3/h with recovery 50 %, the TMP is almost equal to the current operational TMP of 53 bar, but with a lower flux of 7.8 LMH. This lower flux can be considered acceptable, as RO treatment plants can operate on lower fluxes as discussed in section 5-1. Additionally, the model can be simulated for lower feed flow and recovery in case of reduced permeate flow of 11.5 m^3/h.

Also from figure 4-3, it can be seen that the TMP in case of permeate flow of 11.5 m^3/h and reduced feed flow of 25 m^3/h was lower than 53 bar even at very low temperatures. However, in case of a permeate flow of 23 m^3/h the TMP at lower is almost equal to that of 53 bars. However, the results for at standard temperature 25 degrees does not match with the results in figure 4-2. This was because of the technical runtime error in the WAVE program resulting in the crashing of the program and as a result the values obtained from the models that were redone again were slightly different than the previous ones.

The challenge in lowering the feed flow in the system is that the pump used in the RO process in Galtneset does not have the flexibility to easily change the flow. Therefore, other alternatives have to be adopted to lower the feed flow. Following are some of the methods that can be used to lower the feed flow:

- Flow control valves: Flow control valves are specialized valves designed to regulate the flow rate of fluids through pipes or channels. They are used to control the speed or volume of fluid passing through the valve, providing accurate and adjustable flow control. These valves are essential in various industries where precise control of fluid flow is required thus can be effectively used in water treatment process (R. Keith Mobley, 2000).
- Variable speed pumps: Another option could be by installing a variable speed pump motor which helps to adjust the speed of pumps or motors and thus regulate the flow in the pipes (Ahmed et al., 2022).

5.3. Control process with salinity range 32000<35000<40000 mg/L

Designing a controlled system with different salinity ranges, is very important in a reverse osmosis system. This is because, the water quality such as salinity of seawater it provides crucial information about the quality of the water being treated and its potential impact on the efficiency and effectiveness of the RO system (Ibrahim S. Al-Mutaz et al., 2001). Therefore, a control system based on salinity is important to understand if the designed operating parameters are acceptable for operation of a RO process, in case the salinity of seawater changes. The raw water quality plays an important role in the RO performance, as it affects the TMP and recovery (Zubair et al., 2023).

High salinity levels in the feed water can lead to the formation of scales and fouling on the RO membrane's surface. Thus, salinity measurements help identify whether the feed water has a propensity for scaling and fouling, allowing operators to implement appropriate preventive measures (Ismail et al., 2018).

From table 4-1, it is evident that the increase in seawater salinity increases the TMP. To have an energy efficient system with a lower TMP, it is important to monitor the Realtime seawater salinity over the period of a year to establish the required TMP for operation, since the conductivity of seawater changes with temperature. Installing a conductivity meter in the feed stream, right after the pressure pump is necessary to have an overview and establish a real-time control system. However, results from the WAVE modelled for different salinity concentration shows that the TMP required for obtaining a lower permeate flow is less than the TMP at current operation, which is approximately 50 bars. Thus, from figure 4-2(c) it can be said that lowering the feed flow to 25 m^3/h would be effective and thus the required TMP would be approximately 50 bars.

Furthermore, to have a more efficient process and helping the system not to shut down due to lack adequate flow in the feed stream, recycling of the concentrate stream can be done. Recycling a portion of the concentrate or reject stream back into the feed can effectively reduce the overall feed flow rate. This approach maintains the desired recovery rate while lowering the amount of new feed entering the system (Al-Ghamdi, 2017; Watertreatmentguide.com, 2023).

Recycling a portion of the concentrate stream, the effective concentration of impurities in the feedwater increases thus to counteract the negative effects of higher impurity concentrations in the feedwater, the overall feed flow rate to the RO system can be reduced (Al-Ghamdi, 2017).Thus this would allow the RO system to continue effectively removing impurities and producing clean permeate in case of low flow (Al-Ghamdi, 2017). However, in case if recycling is done the feed water salinity should be regularly measured. Thus, installing a conductivity meter would be useful in this case.

5.4. Normalization of RO Data

The results from the Normalized data cannot be established as accurate as they are based on the set of assumptions as explained in section 4-4. However, the data might give us some insights about the problems in the RO process, even though the baseline values are taken from the model in general operation. From table 4-2, it can be seen that the NPF has not dropped more than 10-15 % therefore it indicates that there is no damage to the RO membrane. Since the NSR id also greater than 90% it indicates that the RO membrane is performing well in rejecting the salts and indicate no fouling or scaling in the membrane. In the case of NPD, the NPD is 29% greater than the baseline value. This shows that the spacers (the feed spaces in the spiral wound membrane) between the membrane are plugged, since the spacers are very thin and therefore, they are susceptible to plugging. Plugging in a membrane happens when the solids are clogged and restrict the water to pass through it and thus it causes increase in the resistance to flow and increase in TMP (Fujioka et al., 2020). This means that the membrane needs to be cleaned. However, it is highly unlikely not have a dropped NPF and having an increasing NPD, since the clogging would result in the reduction of permeate flow. On the contrary, in the case when the results shows that the decrease in NPF and unchanged NDP, it's because the feed water spacer hasn't been clogged by fouling and scaling problems yet (Fujioka et al., 2020). The results obtained for the normalized data does not correspond to the theory. Thus, it cannot be taken to derive conclusions about the problems in the process. This might be due to the lack of data and assumptions made for the calculations. However, it can be assumed that there is no or little problem with fouling or scaling, as well as any damage to the membrane, since there is no drastic change in permeate flow and quality while in operation and thus can be said that as of now, the performance of the RO membrane ok. However, it is necessary to redo the calculations for the normalized data to investigate actual cause of reduction of permeate flow from 23 m^3/h to a current operating permeate flow 19.8-21 m^3/h. This also gives the information that the permeate flow right after the membrane cleaning is greater and then it lowers over time until the next cycle cleaning.

6. CONCLUSIONS AND FUTURE WORK

The aim of the thesis to optimize the RO process for a reduced flow of 11.5 m^3/h from 23 m^3/h. To achieve this, the RO process was modelled using WAVE (Water application value engine). The process was modelled for different scenarios, as well as modelled for a control system, and then to evaluate the existing process was investigated using Normalization of data. The first scenario considered reducing the number of membrane elements and testing the performance in different temperatures for two different permeate flows. The second scenario considered investigating the performance of the system by reducing the feed flow similarly for the two different flows.

6.1 Conclusions

Two ideal conditions could be concluded for operation for considering the scenarios.

- Reducing membrane element numbers both 4 or 3 would be ideal for a reduced permeate flow of 11.5 m^3/h and for a permeate flow of 23 m^3/h 6 membrane element being ideal. However, in this case the TMP required would be around 60 bars, which is greater than the operating TMP of 54 bars.
- Lowering the feed flow from 54 m^3/h to 25 m^3/h would give an TMP of 49 bars, which is lower than the operating TMP of 54 bars. On the other hand, not much difference in the TMP was seen in case where feed flow is lowered to achieve a permeate flow of 23 m^3/h.

Therefore, the best possible solution for Galtneset would be to lower the feed flow for achieving a permeate flow of 11.5 m^3/h. Additionally, a control system with different salinity ranges were modelled to investigate the TMP change for the different salinity and found out that the TMP for all three cases were below the current operating TMP in case of a reduced flow. Normalization of the RO data was done to investigate fouling, scaling or any membrane damage. However, since the Normalized data were calculated based on some assumptions due to lack of data. Therefore, the normalized data for NPF,NSR and NPD lack accuracy.

6.2 Future Work

6.2.1. Case study: Sorek Desalination Plant, Israel

The Energy consumption of the Galtneset desalination plant can be reduced by recovering energy from the pressure recovery devices similar to the one in Sorek Desalination Plant. This might help to both cut down the high-water cost and by using the energy to provide TMP to the membranes.

The Sorek Desalination Plant is one of the largest seawater desalination plants in the world (IDETechnologies.com, 2013). It is located south of Tel Aviv and has a capacity of producing 150 million cubic meters of fresh permeate water every year (IDETechnologies.com, 2013).

One of the key techniques used at the Sorek Desalination Plant, to optimize the permeate flow and overall efficiency, is advanced energy recovery technology. The plant employs a technology called

Pressure Centre Energy Recovery (PX) developed by IDEXX Solutions (Tal, 2018). The PX technology focuses on maximizing energy efficiency in the RO process, by using pressure exchangers to recover energy from the high-pressure concentrate stream.

This recovered energy is then used to assist in pressurizing the incoming feed water, reducing the energy consumption required to drive the RO process (Tal, 2018). Below is an explanation about how the PX technology works (Tal, 2018):

- Pressure Exchangers: Pressure exchangers are devices that transfer pressure energy from the concentrate stream (high-pressure side) to the feed water stream (low-pressure side) without mixing the two streams. This energy transfer helps pressurize the feed water, reducing the energy needed from the high-pressure pumps.
- Energy Recovery: By utilizing pressure exchangers, the Sorek Desalination Plant is able to recover a significant amount of the hydraulic energy that is typically lost in the concentrate stream. This recovered energy is used to increase the pressure of the incoming feed water, enabling the RO membranes to operate more efficiently.
- Lower Energy Consumption: The recovered energy from the concentrate stream allows the high-pressure pumps to work more efficiently, resulting in lower energy consumption for the entire RO process. This, in turn, contributes to the optimization of the permeate flow rate and overall water production.

The adoption of the Pressure Centre Energy Recovery technology at the Sorek Desalination Plant has helped to achieve high water recovery rates, reduce energy consumption, and optimize the permeate flow while maintaining water quality standards (Tal, 2018). The plant's success in incorporating advanced energy recovery techniques serves as an example of how innovation can contribute to more sustainable and efficient water treatment processes.

However, this technology has been actively used in increasing the permeate flow for higher production at low energy. Possibilities of using technologies such as pressure exchangers and recovery devices to lower the permeate flow in Galtneset could be an interesting field to look upon in future.

It’s hard to say if this solution is a solution worth implementing to the system but it could be a source of interest for a better sustainable energy efficient process.

6.2.2 Data Collection and specific energy calculation

One of the major limitations in this thesis was the lack of real time recorded data from Galtneset, which made some calculations and modelling scenarios based on couple of assumption as it is discussed in section 1.4 above. Thus, another future work for Træna municipality could be to focus on recording and measuring the data on the raw water concentrations, flows, TMP, possible fouling or scaling and temperature of the raw water. This could help to aid and improve future work to improve their process based on scientific methods.

Additionally, due to the technical difficulties faced as mentioned in section 5.2 while modelling in the WAVE program during this thesis. Also, along with the data collected, as mentioned above by the municipality could also help to calculate and evaluate the energy consumption to test the efficiency of the process based on costs. Furthermore, also investigate the energy consumption by using recovered energy from pressure recovery devices as suggested in section 6.1.1 above, to establish an efficient process.

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APPENDIX

Appendix A. Seawater temperature in Husøya (seatemperature.org, 2023)

Entity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min °C	**4.1**	**4.5**	**3.6**	**4.2**	**5.3**	**8.7**	**11.7**	**10.8**	**10**	**8.5**	**6.3**	**4.7**
Max °C	**7**	**5.8**	**5.9**	**6.9**	**10.2**	**14.8**	**15.8**	**15.9**	**13.6**	**11.9**	**11**	**9.3**

Appendix B. Mathematical models for RO processes

B.1. Mathematical model for water flux depended on temperature.

The model is based on the principles of thermodynamics and fluid mechanics. It considers the effect of temperature and pressure on the driving force of the RO process, which is the difference in chemical potential between the feed solution and the permeate (Ismail et al., 2018).

An empirical formula describing the relationship between temperature, pressure, and RO performance can be described using the following equation (Lakner et al., 2020):

$$\ln K_w = \ln K_{w,0} - \frac{E_{a,w}}{R} * \frac{1}{T}$$

where K_w is the mass transfer coefficient, R is the gas constant, T is the temperature, $E_{a,w}$ is the activation energy for water flux .

B.2. Model for water flux temperature dependence

Temperature correction factor (TCF) is used to describe the permeate flux with temperature. It is given by the relation(Ibrahim S. Al-Mutaz et al., 2001) :

$$TCF = exp(K * \left(\frac{1}{273 + t}\right) - \frac{1}{298}))$$

Or,
$$TCF = a^{(t-25)} = \frac{flux\ at\ t \circ C}{flux\ at\ 25 \circ C}$$

Where, K is a constant characteristic for a given membrane material, and t is feed water temperature in degrees Celsius and a is constant between 1.024 and 1.03(Ibrahim S. Al-Mutaz et al., 2001).

B.3. Transmembrane transition model

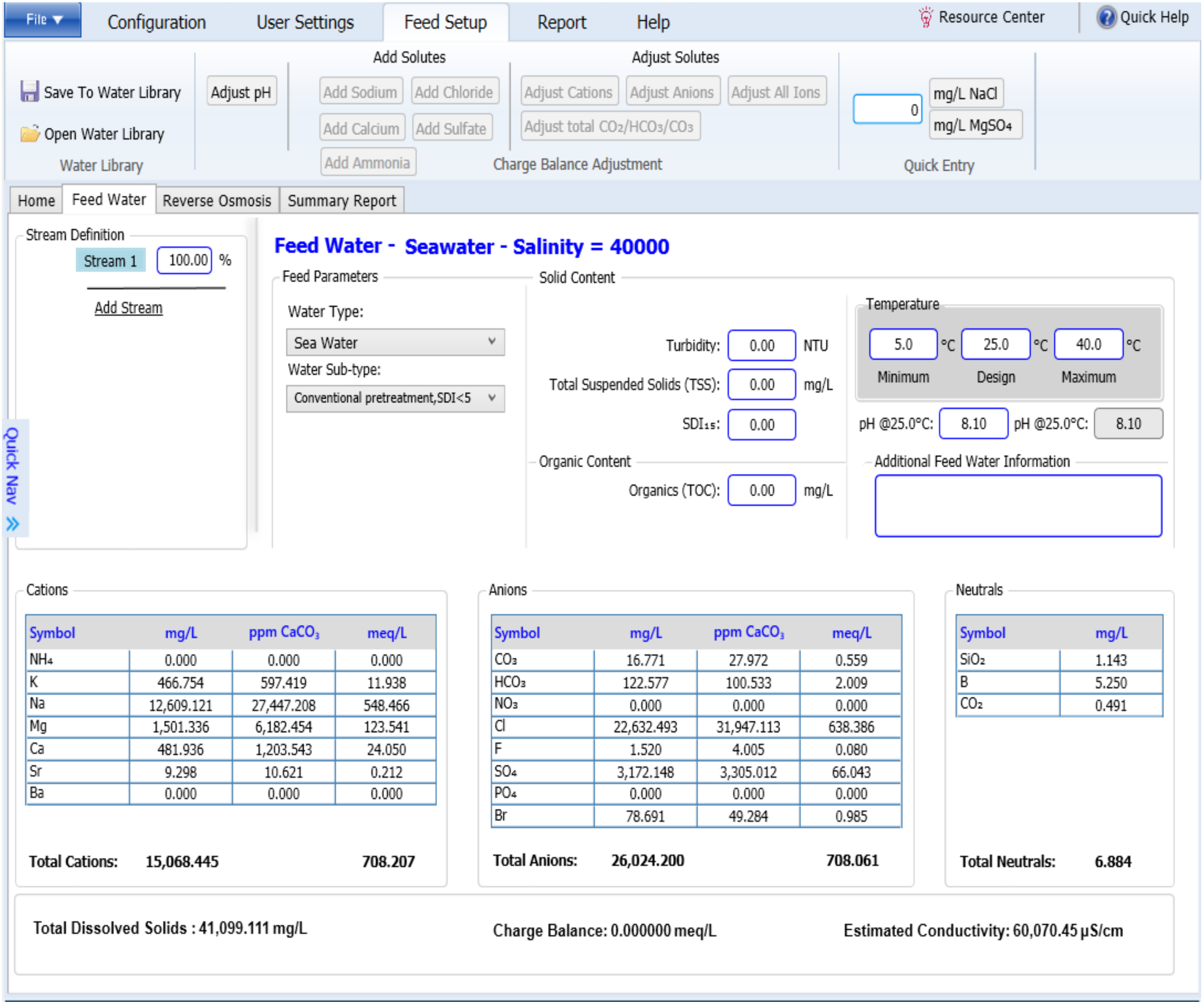
The Transmembrane transition model is an Arrhenius-type temperature dependent model. Assuming the pores in the membranes to be cylindrical, the main flow resulting from TMP is described by the Poiseuille-law and is based on individual pores (Lakner et al., 2020).

$$Flux = (\pi\delta) * \frac{TMP}{128\, \eta L}$$

where $\delta \geq 0$ is the pore diameter, L is the length, and η is the viscosity of the liquid (water).

Appendix C. WAVE

C.1. Feed water characterization for salinity 32000 mg/L used in the model to design the control process based on salinity



Stream Definition

Stream 1 100.00 %

Feed Water - Seawater - Salinity = 40000

Feed Parameters

Water Type: Sea Water

Water Sub-type: Conventional pretreatment,SDI<5

Solid Content

Turbidity: 0.00 NTU

Total Suspended Solids (TSS): 0.00 mg/L

SDI_{15}: 0.00

Organic Content

Organics (TOC): 0.00 mg/L

Temperature

Minimum	Design	Maximum
5.0 °C	25.0 °C	40.0 °C

pH @25.0°C: 8.10 pH @25.0°C: 8.10

Additional Feed Water Information

Cations

Symbol	mg/L	ppm $CaCO_3$	meq/L
NH_4	0.000	0.000	0.000
K	466.754	597.419	11.938
Na	12,609.121	27,447.208	548.466
Mg	1,501.336	6,182.454	123.541
Ca	481.936	1,203.543	24.050
Sr	9.298	10.621	0.212
Ba	0.000	0.000	0.000

Total Cations: 15,068.445 708.207

Anions

Symbol	mg/L	ppm $CaCO_3$	meq/L
CO_3	16.771	27.972	0.559
HCO_3	122.577	100.533	2.009
NO_3	0.000	0.000	0.000
Cl	22,632.493	31,947.113	638.386
F	1.520	4.005	0.080
SO_4	3,172.148	3,305.012	66.043
PO_4	0.000	0.000	0.000
Br	78.691	49.284	0.985

Total Anions: 26,024.200 708.061

Neutrals

Symbol	mg/L
SiO_2	1.143
B	5.250
CO_2	0.491

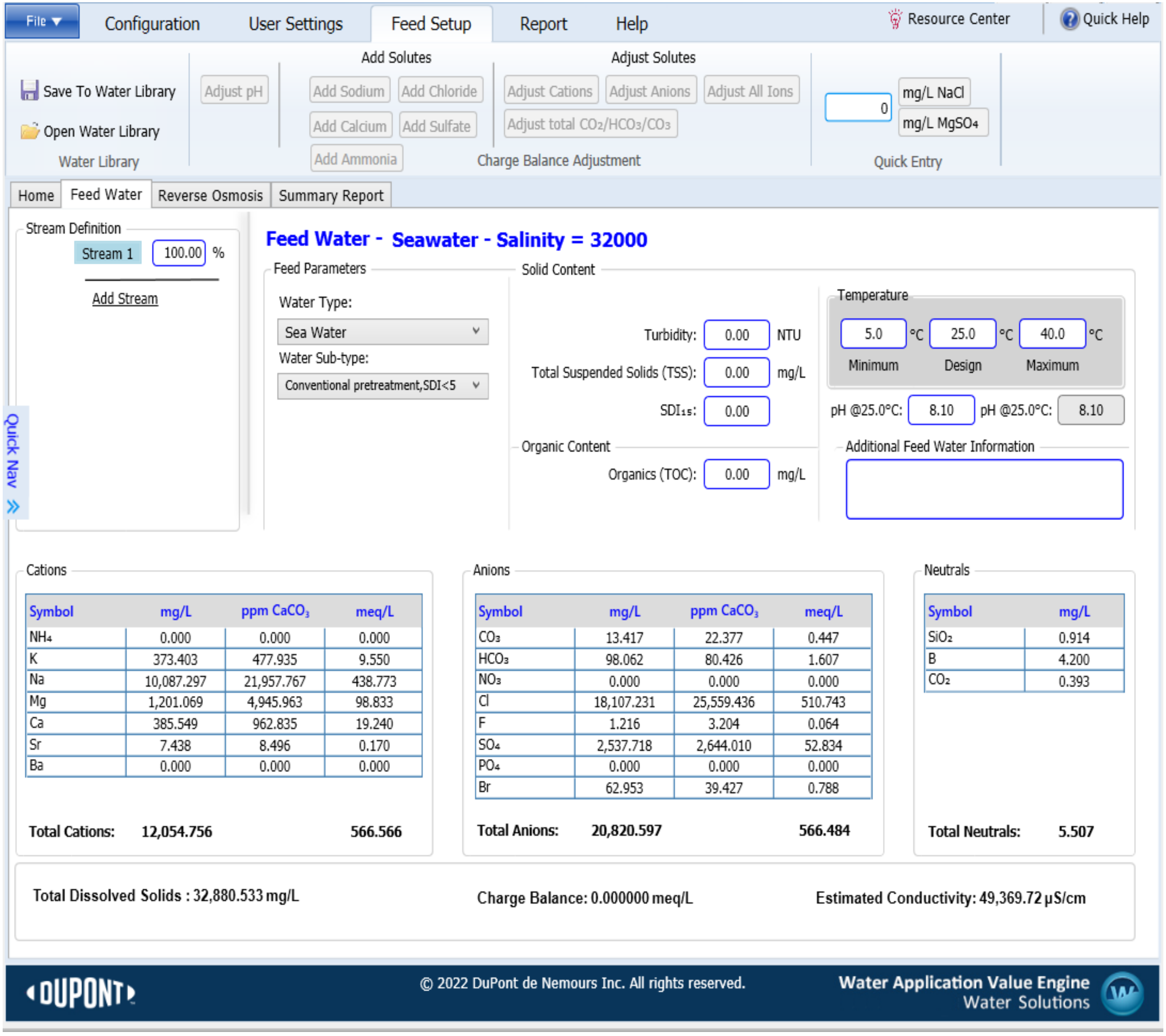
Total Neutrals: 6.884

Total Dissolved Solids : 41,099.111 mg/L

Charge Balance: 0.000000 meq/L

Estimated Conductivity: 60,070.45 µS/cm

C.2. Feed water characterization for salinity 40000 mg/L used in the model to design the control process based on salinity



Feed Water - Seawater - Salinity = 32000

Stream Definition: Stream 1 100.00 %

Quick Entry: 0

Feed Parameters

Water Type: Sea Water

Water Sub-type: Conventional pretreatment,SDI<5

Solid Content

Turbidity: 0.00 NTU

Total Suspended Solids (TSS): 0.00 mg/L

SDI_{15}: 0.00

Organic Content

Organics (TOC): 0.00 mg/L

Temperature

Minimum 5.0 °C; Design 25.0 °C; Maximum 40.0 °C

pH @25.0°C: 8.10

pH @25.0°C: 8.10

Additional Feed Water Information

Cations

Symbol	mg/L	ppm $CaCO_3$	meq/L
NH_4	0.000	0.000	0.000
K	373.403	477.935	9.550
Na	10,087.297	21,957.767	438.773
Mg	1,201.069	4,945.963	98.833
Ca	385.549	962.835	19.240
Sr	7.438	8.496	0.170
Ba	0.000	0.000	0.000

Total Cations: **12,054.756** **566.566**

Anions

Symbol	mg/L	ppm $CaCO_3$	meq/L
CO_3	13.417	22.377	0.447
HCO_3	98.062	80.426	1.607
NO_3	0.000	0.000	0.000
Cl	18,107.231	25,559.436	510.743
F	1.216	3.204	0.064
SO_4	2,537.718	2,644.010	52.834
PO_4	0.000	0.000	0.000
Br	62.953	39.427	0.788

Total Anions: **20,820.597** **566.484**

Neutrals

Symbol	mg/L
SiO_2	0.914
B	4.200
CO_2	0.393

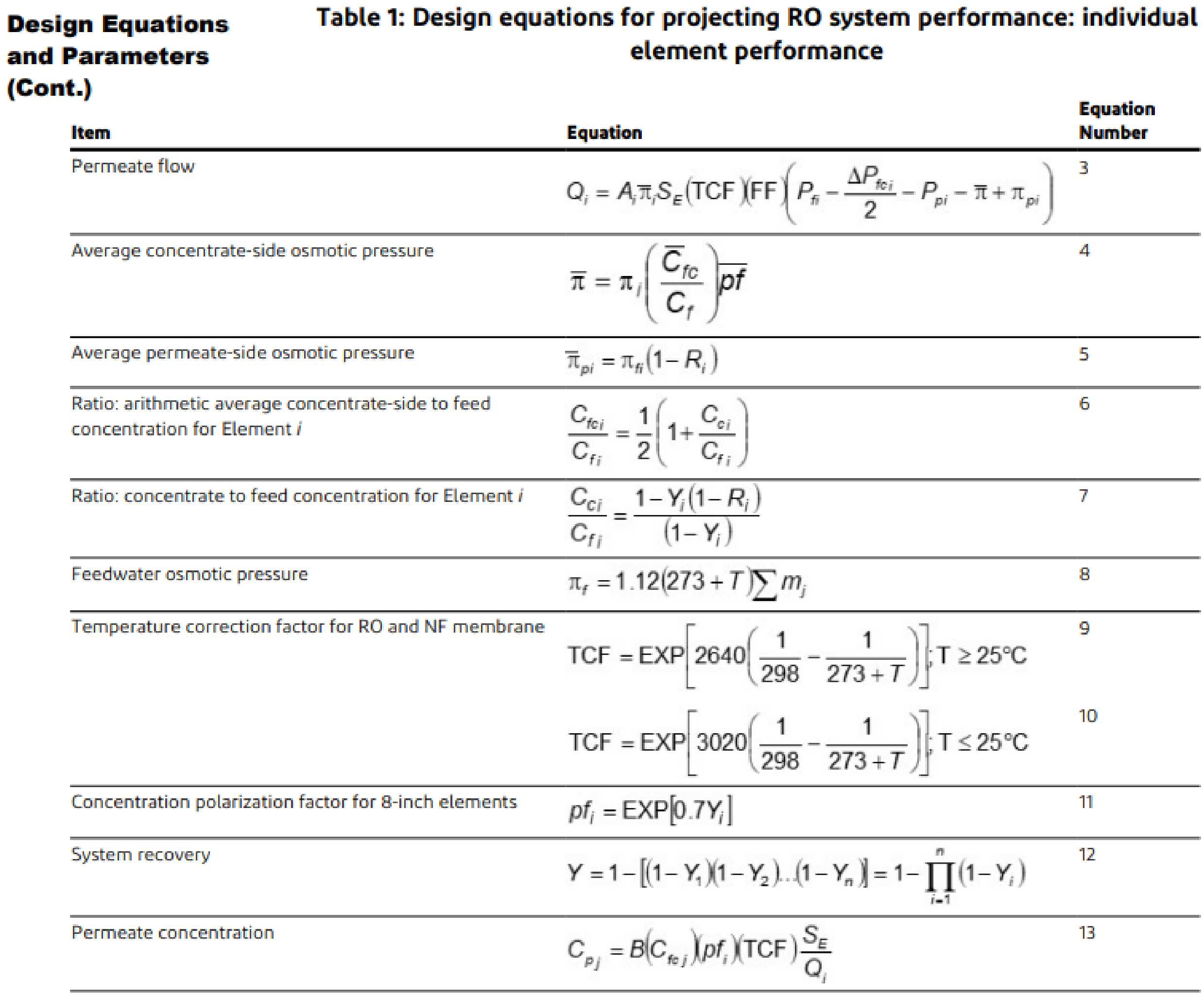
Total Neutrals: **5.507**

Total Dissolved Solids : 32,880.533 mg/L

Charge Balance: 0.000000 meq/L

Estimated Conductivity: 49,369.72 µS/cm

Appendix D. System design equations used in WAVE that gives information about the principles used for calculating different parameters (DuPont, 2023a)



Design Equations and Parameters (Cont.)

Table 1: Design equations for projecting RO system performance: individual element performance

Item	Equation	Equation Number
Permeate flow	$Q_i = A_i \pi_i S_E (\text{TCF})(\text{FF})\left(P_{fi} - \frac{\Delta P_{fci}}{2} - P_{pi} - \overline{\pi} + \pi_{pi}\right)$	3
Average concentrate-side osmotic pressure	$\overline{\pi} = \pi_i \left(\frac{\overline{C}_{fc}}{C_f}\right)\overline{pf}$	4
Average permeate-side osmotic pressure	$\overline{\pi}_{pi} = \pi_{fi}(1 - R_i)$	5
Ratio: arithmetic average concentrate-side to feed concentration for Element *i*	$\frac{C_{fci}}{C_{fi}} = \frac{1}{2}\left(1 + \frac{C_{ci}}{C_{fi}}\right)$	6
Ratio: concentrate to feed concentration for Element *i*	$\frac{C_{ci}}{C_{fi}} = \frac{1 - Y_i(1 - R_i)}{(1 - Y_i)}$	7
Feedwater osmotic pressure	$\pi_f = 1.12(273 + T)\sum m_j$	8
Temperature correction factor for RO and NF membrane	$\text{TCF} = \text{EXP}\left[2640\left(\frac{1}{298} - \frac{1}{273 + T}\right)\right]; T \geq 25°\text{C}$ $\text{TCF} = \text{EXP}\left[3020\left(\frac{1}{298} - \frac{1}{273 + T}\right)\right]; T \leq 25°\text{C}$	9 10
Concentration polarization factor for 8-inch elements	$pf_i = \text{EXP}[0.7Y_i]$	11
System recovery	$Y = 1 - [(1 - Y_1)(1 - Y_2)\ldots(1 - Y_n)] = 1 - \prod_{i=1}^{n}(1 - Y_i)$	12
Permeate concentration	$C_{pj} = B(C_{fcj})(pf_i)(\text{TCF})\frac{S_E}{Q_i}$	13