Ammonium Removal by Reverse Osmosis Membranes

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The greater the difficulty, the more the glory in surmounting it.

-Epicurus-

Preface

This report is the result of my research project for my graduation from the Sanitary Engineering Section as a Master student of the Water Management Department at Delft University of Technology. It indicates the end of a fascinating journey that has led to great professional and personal enrichment and growth.

The long days spent in the pilot plant, battling with the installation, trying to make it work, the times of disappointment for not being able to do my experiments due to operational problems and the happiness of getting good results are going to be a valuable experience that simply give me impetus to fly even higher.

I would like to sincerely express my gratitude to Prof. Walter van der Meer for his weekly supervision and for his help on problems that arose during this project. In addition, a special word of thanks to my supervisor in the company Dr. Bastiaan Blankert for his patience and guidance the last months. His tireless assistance and his triggering points resulted to the completion of this research. I would like to thank Mr. Harmen van der Laan for his trust on me from the beginning. Thank you for your advice, your support and our discussions. Moreover, I want to thank Dr. Bas Heijman and Mr. Amir Haidari for giving their feedback during this project.

A special thank also goes to Oasen for giving me the opportunity to work in the pilot plant of the company and deal with real problems. Many thanks to the operators in the treatment plant “De Hooge Boom” for their help.

Furthermore, I would like to express my unreserved gratitude to my parents, the persons who inspire me most in my life and are always there for me. Thank you so much! Last but not least, I want to thank my friends for supporting me and encouraging me all this period.

Athina Chrysovergi
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*A*bstract

The insufficient prediction of ammonium permeability through RO membranes by calculation software in combination with the high ammonium concentrations in ground water result to the waste of money and time by the drinking water treatment companies. This research is focused on the parameters that affect ammonium permeability by reverse osmosis membranes in an attempt for some general conclusions to be derived and less or no testing experiments to be necessary in the future.

During this research project three different reverse osmosis membranes were tested: XLE-440, Espa2max and LG BW 440 R. Artificial, water that composed in the pilot plant, was used during the experiments.

Three parameters were investigated for their influence on ammonium removal: the ration between monovalent anions and monovalent cations (molar ratio), the ionic strength and the pH. In order to check the results of each parameter, three groups of experiments were done. In each group, one of the above parameters was changing while all the other characteristics of the feed water were kept the same.

Results show that the higher the molar ratio, the higher the ammonium permeability of the 3 RO membranes. XLE has the highest ammonium permeability while LG and Espa2max show approximately similar results. Sodium removal was also checked and it was proved that LG has a strange behavior with ammonium.

Regarding the ionic strength, XLE show higher ammonium permeabilities at higher ionic strengths while ammonium permeability of Espa2max and LG was not affected by the increasing ionic strength. Besides, comparison between raw water and artificial water took place. Despite the fact that the solutions had similar characteristics, the permeability of ammonium had a decreasing trend at higher ionic strength when raw water was used while with artificial water the changes in ionic strength did not affect the permeability. The strange behavior of raw water is considered to be caused due to the supersaturation of $CaCO_3$.

Finally, the pH, when it ranges between 4.9 and 8.3, seems to have no influence on ammonium permeability in case of Espa2max and LG, in contrast to XLE where the changes in ammonium permeability are significant. These changes do not depend on the fraction of ammonia which is found to be negligible until the pH of 8.2.

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1.1 General Introduction

1.1.1 Oasen

Oasen NV, a Dutch water company, tries to achieve its goal to provide the inhabitants with pristine drinking water of impeccable quality. The company supplies water to the municipalities in the East of Zuid-Holland operating 7 drinking water treatment plants.

1.1.2 New treatment concept

The company wants to introduce a new treatment concept where RO membranes will treat the feed water without any pre-treatment. This concept will be applied first in the treatment plant “De Hooge Boom” while until 2025 other plants such as De Put, Lekkerkerk and Ridderkerk will follow. The aim of the company is that in the coming decades all its 7 drinking water treatment plants will operate with RO membranes without any pre-treatment.

1.1.3 Kamerik

The treatment plant “De Hooge Boom” is located near Kamerik. It is a conventional drinking water treatment plant, with a production capacity of 300m^3/h. The treatment procedure that has been following in the plant can be found in Figure 1.

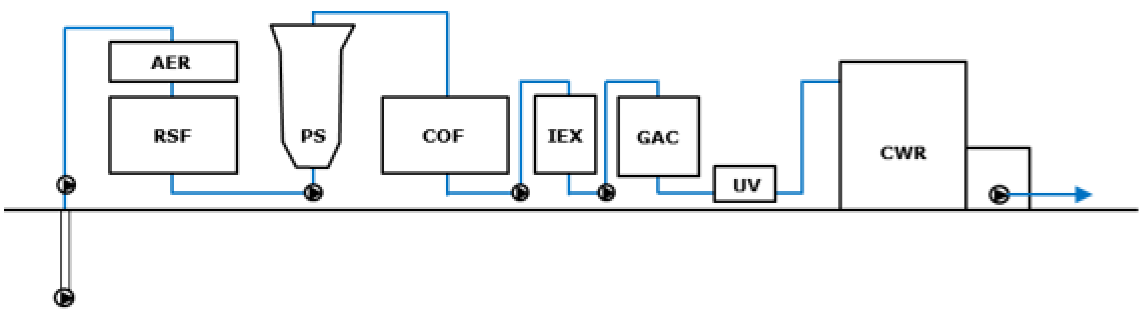

Figure 1:The treatment process in Kamerik (AER=aeration, RSF= rapid sand filtration, PS=pellet softening, COF= carry-over filter, IEX= ion exchange, GAC= granular activated carbon, UV= disinfection, CWR=clear water reservoir) (Oasen, Project specific information:Kamerik).

However, the existing plant has reached its End-of-Life and the company wants to rebuild a new treatment plant in this location. It is supposed that this will be achieved at the end of 2018. The plans for the new plant constitute of a completely different treatment procedure based on more advanced and high-tech technologies. The treatment processes that are estimated to be applied in the new treatment plant can be seen in Figure 2.

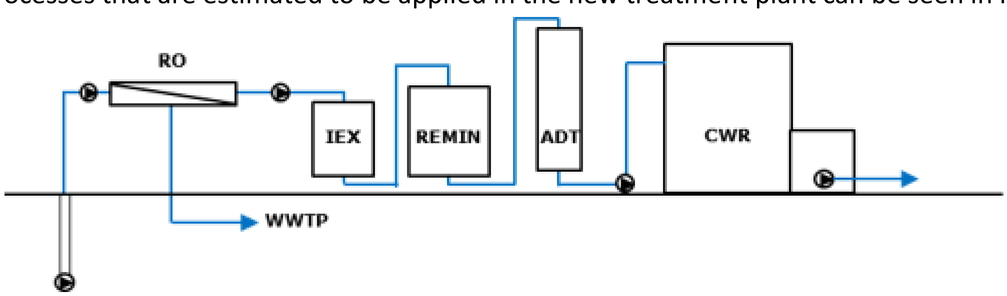

Figure 2: The treatment process of the new concept in Kamerik (RO= reverse osmosis membrane filtration, WWTP= waste water treatment plant, IEX= ion exchange, REMIN= remineralization, ADT=aeration and degasification tower, CWR=clear water reservoir) (Oasen, Project specific information:Kamerik).

1.2 Problem definition

The raw water of all the treatment plants of Oasen is anaerobic with high concentration of ammonium which ranges between 0.8-7.2 mg/l. These levels exceed the limitation of 0.2mg/l of ammonium concentration as set by Dutch law.

Oasen has its own limitation which is much stricter than the Dutch Standards. According to the company, the ammonium concentration of drinking water should be less than 0.03mg/l in an attempt to achieve its goal for the production of pristine drinking water of impeccable quality. A so low ammonium concentration in the permeate leads to no formation of nitrite and subsequently, permeate with low nutrients.

Figure 3 presents the average of ammonium concentration in feed water of the treatment plants the last three years as well as the standards that are set by Oasen and the Dutch legislation.

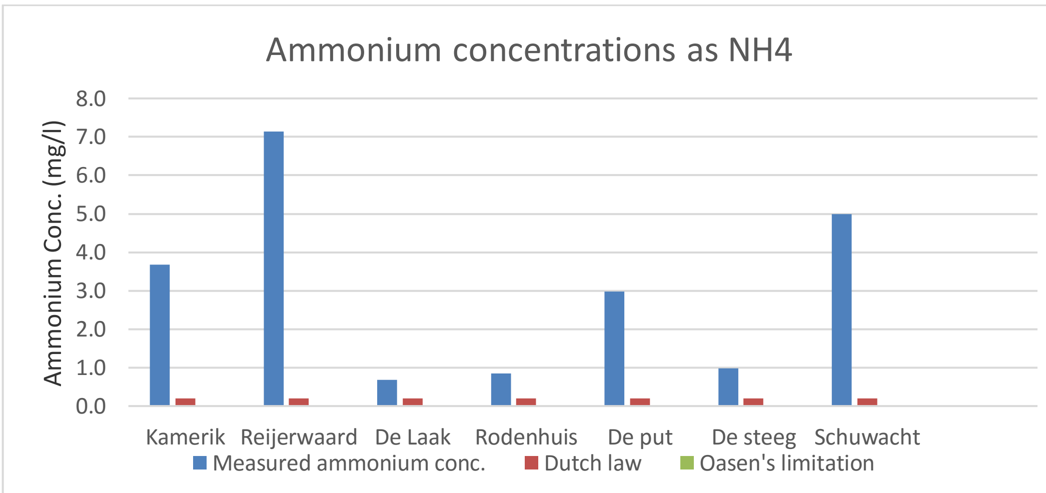

Figure 3: Ammonium concentrations in feed water at the treatment plants in comparison with the standards of the Dutch law and Oasen.

1.2.1 Challenge of ammonium

The main problem that Oasen faces as far as ammonium is concerned is its insufficient rejection by RO membranes. Previous research (Gragt, 2015) that has already been done in the past has shown that the low allowable ammonium concentration that Oasen wants to have in the permeate cannot be achieved by RO membranes.

In general, there are two factors that characterize a membrane: A and B. "A" is the water permeability in L/m^2hbar while "B" is the salt permeability coefficient (in this case ammonium) in L/m^2h. High water permeability means that there is low energy consumption while low ammonium permeability indicates high ammonium rejection. Unfortunately, membranes with higher A tend to have high B and vice versa. Consequently, when two membranes are compared it can be said that one is better than the other when it has low B and high A.

The challenge to produce water with ammonium concentration in the permeate less than 0.03mg/l has not be achieved despite the variety of the experiments that was done in the company in the past, making clear the weakness of the membrane.

1.2.2 Calculation software

Due to the fact that companies want to have a better overview of the membrane that they are going to use in the plants, calculation software have been developed.

There is a variety of calculation software in the market which is used by drinking water companies in order for the best membrane and the primarily design to be chosen. These software are provided by the manufacturers. Specific characteristics of raw water are input in the software and the dimensioning of the RO system as well as the best membrane that is suitable for the treatment of the water are predicted.
It is considered that it is very convenient for drinking water companies to use these software and know about the results before applying the membrane in the plant. However, it is estimated by Oasen, after two-year-research, that some limitations are dominant and lead to unreliable results. The most important are:

- The calculation software takes into account a wide variety of water types, membranes and operational conditions and try to give the estimated results. However, focusing on a specific feed water matrix would give rejection results that are not accurate.
- Each software has its own formulas and internal parameters that are used in order to estimate the rejection. However, they are not known to the companies and cannot be found. This leads to the fact that a comparison between different membranes from different manufacturers is not desirable as the assumptions that are taken into account are different.

1.2.3 Research about the rejection of ammonium by calculation software

Previous research has been done by Oasen for the ammonium permeability through RO membranes. The results from the experiments were compared with the results of the calculation software using the same characteristics of feed water. This comparison is depicted in Figure 4. The figure is a "parity plot" where the black line indicates the region of the projection software's prediction while the dash line indicates a difference of a factor ten for ammonium passage through the membranes. The colorful spots correspond the measurement points of the different membranes. As it can be seen, the measured values for the ammonium permeability of the tested RO membranes are higher than the predicted by the software. What is more, it can be noticed that the deviation between the measured and the predicted value is different for different manufacturers (Laan, et al., 2015).

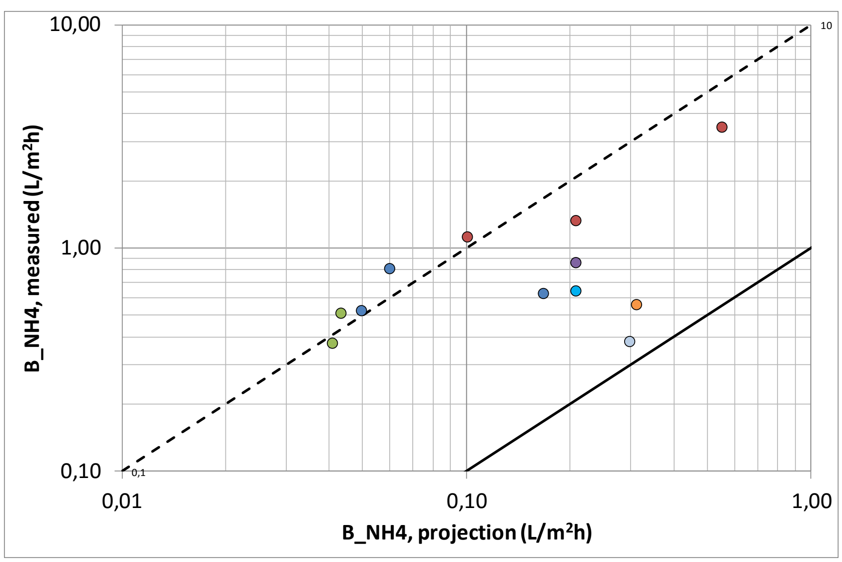

Figure 4: Comparison between the predicted ammonium permeability by projection software and the measured ammonium permeability (Laan, et al., 2015).

Based on the abovementioned results, it can be clearly seen that it is not possible to have precise prediction by using the projection software.
Finally, it can be summarized that a new treatment concept is planned to be applied by Oasen to its treatment plants. This concept is basically the treatment of water with RO membranes and without pre-treatment. It is

considered that Kamerik will be the first treatment plant where this concept will be applied and the coming years the other plants will follow.
However, the insufficient ammonium removal by RO membranes is the main problem that Oasen faces in this attempt. Due to the fact that the prediction by the manufacturers cannot be trusted, performance tests should be done in order for the membranes to be selected. Since the main parameter that influences the performance of the membranes is the water matrix, intensive testing protocols should be done each time to select the proper membrane. However, this is time-consuming and expensive. Hence, it is desirable to better understand the performance of the membranes under simple water matrixes. In this way, the process design can be improved and the desirable results can be achieved.
The performance of the membranes is going to be tested by changing some parameters of the solution. These parameters will be the ionic strength and the ratio between the monovalent anions and the monovalent cations as well as the pH and the membrane characteristics.

1.3 Research Question

Taking into account the problem, the main research question for this thesis is:

- *How do the different pH and concentration of ions in the feed water influence the ammonium rejection by different RO membranes?*

In order to answer it, the following sub-questions should be set firstly. Some of them follows:

- Which is the role of the +/- ratio of the ions and the ionic strength on the ammonium rejection?
- Are there any differences between artificial water and raw water as far as the ammonium removal is concerned?
- What are the parameters that influence the abovementioned differences (if there are)?
- Does pH affect ammonium removal by RO membranes?
- What is the influence of the precipitation of $CaCO_3$ on ammonium removal?
- Are there any differences on ammonium removal by different RO membranes?

2. Theory

2.1 Ammonium

In aqueous solutions ammonia can be found in two chemical species. The following equation describes this interaction:

$$NH_3 + H_2O(aq) \leftrightarrow NH_4^+ + OH^-$$

As it can be seen from the equation above, gaseous or un-ionized form (NH_3) and the ionized form (NH_4^+) are present in the water. The pH of the solution plays an important role on this aqueous ammonia equilibrium. An increase in the pH leads to the increase of the hydroxide ion concentration and the equilibrium shifts towards the NH_3. On the other hand, when the pH drops, the ammonia molecules are converted into ammonium ions (Thurston, et al. , 1981).

It should be mentioned that ammonium removal from RO membranes is a topic that is not investigated deeply in the past. There is almost no literature about it. Consequently, the results will be evaluated using the general laws about ion permeation through RO membranes.

2.2 Transport through membranes

2.2.1 General

The transport through the porous or non-porous membranes depends on the diffusion flow (v) and the convective flow (u). Considering an ion i, its flux through the membrane can be derived by the following equation:

$$J_i = c_i * (v_i + u)$$

where: J_i= the flux of component i
c_i= the concentration of component i
v_i= diffusion flow
u=convective flow

For porous membranes the contribution of the convective flow plays the most important role to the permeation process while for non-porous membranes this term is negligible due to the absence of pores and the only parameter that influences the transport is the diffusion flow (Mulder, 2012).

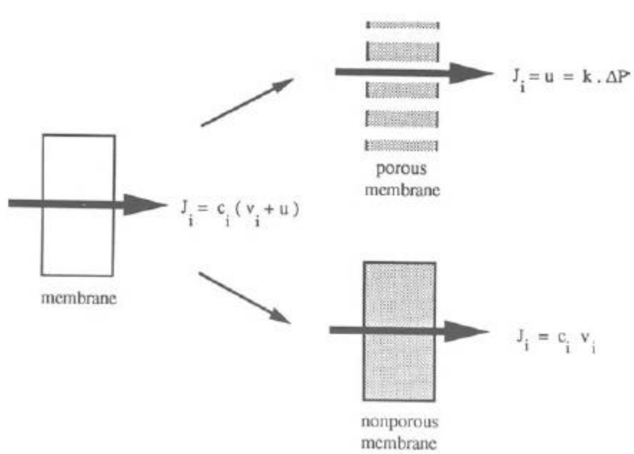

Figure 5: Transport through porous and non-porous membranes (convective and diffusive flow) (Mulder, 2012)

The transport of the solutes and the solvent through membranes is described by a variety of models. This description can be classified into two approaches: the phenomenological approach which is based on irreversible thermodynamics and the mechanistic approach (Mulder, 2012), (Wang, et al., 2014), (Mehdizadeh, 1990).
According to the phenomenological approach, the membrane is considered as a "black box" and there is no information about the separation processes that take place. As far as the mechanistic approach is concerned, information about the separation are given based on the membrane characteristics and parameters (Mehdizadeh, 1990), (Mulder, 2012). Besides, a more specified subdivision can be made in this approach in order for the permeation of different species through the membranes to be described. The first is the pore flow model which is referred to porous membranes and the second is the solution diffusion model which is used for dense and non-porous membranes like RO membranes. According to the pore flow model, the permeants with molecular size bigger than the pore size are rejected by the membrane in contrast to the permeants with smaller size that can penetrate through the pores (Wijmans, et al., 1995). On the other hand, in the solution diffusion model diffusion plays the most important role for the transport of water and salts.

2.2.2 Solution Diffusion Model

2.2.2.1 General Description and assumptions

In the solution diffusion model it is assumed that the solute and the solvents are firstly dissolved in the non-porous surface layer of the membrane and then they are molecularly diffused through it down a concentration gradient in an uncoupled manner. (Paul, 2004), (Yaroshchuk, 1995), (Soltanieh, et al., 1981), (Lonsdale, et al., 1965). Finally, at the permeate side they dissolve again from the membrane into the permeate. The separation of the solvent and the solute depends on their difference in solubility and diffusivity (Wang, et al., 2014).
Four assumptions should be taken into consideration for the solution diffusion model:

1. The membrane should be non-porous.
2. The solvent and the solute are dissolved in the non-porous layer and after that they diffuse across it.
3. The diffusion of the solvent and the solute is down in an uncoupled manner depending on their own chemical potential.
4. The concentration (activity) and pressure gradients are only responsible for the chemical gradients across the membrane (Wang, et al., 2014).
5. The fluids and the membrane material in the interface are in equilibrium with each other in order for a continuous chemical potential through the membrane to be achieved (Wijmans, et al., 1995).

2.2.2.2 Electrochemical Potential

The electrochemical potential plays an important role on the solution diffusion model, the Donnan effect and the Nernst-Planck equation as their concepts are derived by the electrochemical potential's equation. This equation is shown below:

$$\mu = \mu_i^0 + RTln(\gamma_i c_i) + v(p - p_i^0) + z_i F\Phi$$

where μ_i^0= the chemical potential of pure ion (i) at a reference pressure of p_i^0

γ_i= the activity coefficient
c_i = the molar concentration of ion i
p= the pressure
v= the molar volume of ion i
z_i= the valence of the ion i
F= the Faraday constant
ϕ= the electrostatic potential (Wijmans, et al., 1995)

However, the electrical potential is neglected from the solution diffusion model as there is the assumption of electro-neutrality. This means that the last term from the above equation is not taking into account and only the driving forces of pressure and concentration are dominant. This is the chemical potential and is given by the following equation:

$$\mu = \mu_i^0 + RTln(\gamma_i c_i) + v(p - p_i^0)$$

According to the solution diffusion model the pressure within the membrane is uniform only the concentration gradient influences the chemical potential (Wijmans, et al. 1995). A schematic overview of the transport of one-component solution through a membrane is depicted at Figure 6.

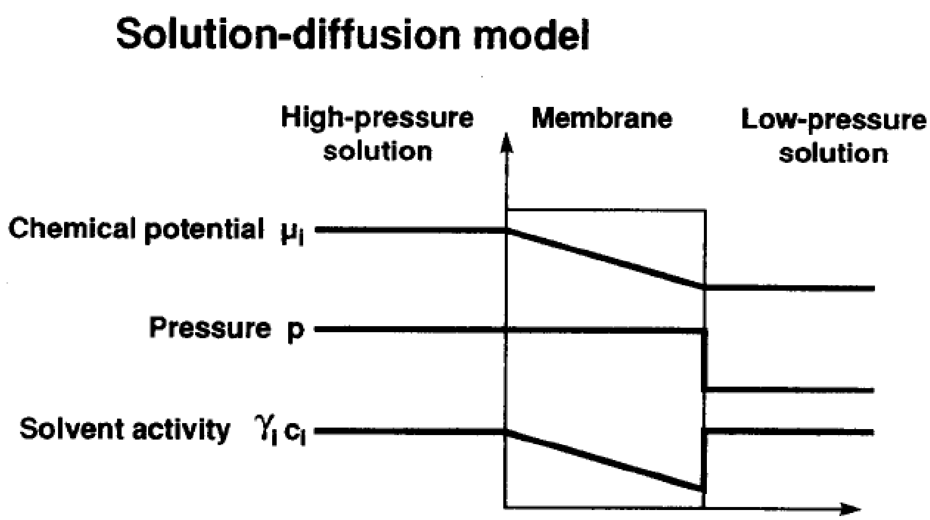

Figure 6: Schematic overview of the permeation of an one-component solution through a membrane (Wijmans, et al., 1995).

2.2.2.3 Flux

Due to the chemical gradient that is described at Figure 6, there is flux passing through the membrane. The total flux is determined to be the sum of the water flux (Jw) and the solute flux (Js). For the water flux Henry's law and Fick's first law of diffusion are used in order for its equation to be derived.

$$J_w = A(\Delta p - \Delta\pi)$$

where: A= the water permeability
Δp= transmembrane pressure difference
Δπ= osmotic pressure difference across the membrane

As far as the solute flux is concerned, only the Fick's law is taken into account because the driving force of pressure is negligible and only the driving force of concentration influences the chemical potential.

$$Js = Jw * Cp = B * (Cf - Cp)$$

where: B=the solute permeability
C_f= the concentration of the solute in the feed side
C_p= the solute concentration at the membrane surface on the permeate side

"B" value is calculated using the following equation:

$$B = \frac{J_w C_p}{(C_f - C_p)}$$

Finally, based on the above equations regarding the two fluxes (solute and solvent) it is clear that the water flux depends on the applied pressure across the membranes while the salt flux is independent of the pressure.

2.2.2.4 Rejection

Except from the flux there is another factor that characterizes the membrane performance. It is the rejection which shows the ability of the membrane to separate the solutes from the solvents. Two kind of rejections can be found, the observed and the real. Their equations are given below:

$$Ro = 1 - \frac{c_p}{c_f}$$

where: c_p= the concentration of the solute in the permeate
c_f = the concentration of the bulk feed

The real rejection is given by the same equation but instead of the concentration of the bulk feed, the concentration from the membrane surface is used. However, in the solution diffusion model the real rejection is calculated by the use of the water flux and the permeability of the salt (B_value) (Wang, et al., 2014), (Mulder, 2012).

$$Rr = \frac{J_w}{J_w + B}$$

2.2.2.5 Why the solution diffusion model

As it is mentioned before in the solution diffusion model the membrane is considered to be non-porous and consequently no convection flow takes part. However, Sherwood et al. indicated that there are imperfections in the membranes which means that both diffusion and convection are present during the transportation of the solutes and the solvent, the so-called solution diffusion imperfection model. The same research was also conducted by Yaroshchuk on 1995 who tried to develop a more consistent approach.

Kocbec (2016) show in her research that the rejection of ammonium, when Espa2max is used, increases at increasing flux while the passage decreases. This results to the fact that the transport of the ions is achieved by diffusion and hence the membranes can be characterized as non-porous.

Based on these results, it is decided that diffusion is the main mechanism for the transport of ions for the membranes that are going to be used in this research and therefore, they can be characterized as non-porous. Hence, the solution diffusion model can be taken into account.

2.2.3 The Donnan Potential

The Donnan Potential in one of the effects that influences the salt passage through the membranes. The concentration difference as well as the fixed charge of the membrane are the driving forces for ion transport regarding the Donnan effect (Mulder, 2012). As a monoatomic cation, ammonium is considered to be affected by the Donnan Potential. It refers only to the points on the surface of the membrane which are in equilibrium with the solution and not to the whole membrane. What is more, the Donnan effect refers both to the charge of the membrane and the charge in the solution.

The presence of a charged membrane in a charged solution results to the creation of a dynamic equilibrium. In this research the RO membranes that are going to be used in the experiments are negatively charged.

On the boundary layer of the negatively charged membrane there is a layer of counter-ions which can be assumed that are bound to this layer. These counter-ions are not penetrated into the membrane but they are hold there due to the Donnan effect. Only a small amount of the counter-ions can penetrate the membranes. However, due to the electro-neutrality that should take place, an amount of co-ions will also flow towards the membrane.

Taking into account that the charge density (X) of the membrane is constant according to the equation below:

$$\sum_{i=1}^{n} z_i c_i = -X \ (for\ 0 \leq X \geq \Delta x)$$

As well as the occurrence of electro-neutrality in the solution which is given by the following equation:

$$\sum_{i=1}^{n} z_i c_i = 0$$

And that there is no overall electrical current that passes through the membrane which can be expressed by the equation below:

$$I = \sum_{i=1}^{n} F z_i c_i = 0$$

where: F= Faraday constant

And finally taking into account the chemical potential equation, it can be summarized that the following equation indicates the relation between the concentrations of the solute in the membrane and in the water with the valence of the solute.

$$\frac{c_m}{C_w} = \exp(-\frac{z_i F}{RT}\Delta\psi)$$

where: c_m= the concentration of the solute in the membrane
c_w = the concentration of the solute in the water (solution)
z_i= the valence of the ion
$\Delta\psi$= the Donnan potential

However, the term $-\frac{F*\Delta\psi}{RT}$ is constant, so the above equation can be simplified to the following equation:

$$\frac{c_m}{c_w} = k^z$$ (Bowen, et al., 1996), (Wallace, 1967)

Bason et al. have found in their research that the higher the ionic strength of the solution the weaker the Donnan effect resulting to the increase of the permeability of the ions. In addition, the salinity of the solution influences the salt rejection based again on the Donnan potential. In general, the more diluted a solution is (lower salinity), the higher the Donnan potential and hence the permeability goes down (Bason, et al., 2011). Finally, the presence of divalent ions in the solution has as an outcome the decrease of the Donnan effect because these kind of ions at the membrane surface lower the repulsive force that is produced (Bartels, et al., 2005).
As it is explained at the beginning of this sub-chapter, the Donnan effect refers not only to the charge in the solution but also to the charge of the membrane. Due to the fact that Donnan Potential is difficult to be understood, a simple example is described below to show how the charge of the membrane influences ions transport through it.
It is considered that a negatively charged membrane (R^-) comes in contact with a dilute sodium chloride (NaCl) solution. The ions of Na^+ and Cl^- and the water molecules will diffuse from the solution phase to the membrane phase. At equilibrium, the amount of Na^+ ions that will diffuse to either side should be the same with the amount of Cl^- ions.

More specifically:

$$[c_{Na^+}]^m * [c_{Cl^-}]^m = [c_{Na^+}] * [c_{Cl^-}]$$

where m indicates the membrane phase. Taking into account the electro neutrality:

$$[c_{Na^+}]^m = [c_{Cl^-}]^m + [c_{R^-}]^m$$

Combining the two previous equations and if [c_{Na}+] = [c_{Cl}-] and the solution is dilute the following equation can be derived:

$$[c_{Cl^-}]^m = \frac{[c_{Cl^-}]^2}{[c_{R^-}]^m}$$

It can be noticed that the stronger the charged membrane, the more effective the Donnan Potential. What is more, as it is also described above, the higher the feed concentration the weaker the Donnan Potential (Mulder, 2012).

2.2.4 The Nernst Planck equation

Based on the solution diffusion model where the solute and the solvent are diffused through the membrane and taking into account that RO membranes are considered to be non-porous, an equation should be used to describe the transport of ions through the membranes. What is more, the fact that the membranes are charged should be considered as the electrostatic force which is applied between the charged membrane and the ions in the solution influences their transport through the membrane (Ong, et al., 2002).

$$J_i = -D_{i,m}\,[\frac{dc_i}{dx} + \frac{Fz_ic_i}{RT}\frac{d\psi}{dx}]$$

where: Ji= the ion flux
$D_{i,m}$= the diffusivity of the chemical species
c_i= the molar concentration of the species
z_i= the valence of the species
F= the Faraday constant
R= the gas constant
T= the absolute temperature
ψ= the electrical potential (Ong, et al., 2002).

The equation above shows that the first term refers to diffusion, and the last to electrical potential. Except from the concentration gradient there is another driving force, the electrical potential gradient. The effect of this gradient depends on the charge of the ions. Besides, the concentration of the solutes inside the membrane is taken into account based on the fact that this equation applies to the transport through the membranes.

2.2.4.1 Mobility of ions

The mobility of ions plays an important role on the transport of solutes through the membranes. It is determined by the ion's drift velocity and the external electric field. The external electric field depends on the ionic radius. Combining these relations, it can be summarized that the smaller the ionic radius of an ion the smaller its mobility in the solution (Koneshan, et al., 1998). Hence, the radius of the ions significantly influences the mobility of the ions. The radius of the chemical components that are going to be used in this research can be found at Table 1.

Table 1: Ionic radius of components (Nightingale Jr, 1959).

Ionic Compounds		Ionic Radius (nm)
Calcium	Ca^{2+}	0.099

Chloride	Cl^-	0.181
Sodium	Na^+	0.095
Ammonium	NH_4^+	0.148

Table 1 shows that the radius of Cl^- is bigger than the radius of the other cations hence its mobility is greater in the solution. The electrical potential gradient is the outcome of this difference in anions and cations mobility which has as a result the acceleration of the cations and the slowdown of the anions as the same number of cations and anions should be transferred (Pages, et al., 2013), (Laan, et al., 2015). Figure 7 depicts a schematic overview of the acceleration and the retardation of the ions and cations.

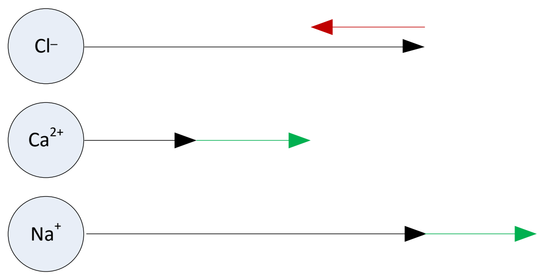

Figure 7: Schematic overview of the effect of the electrical field on the mobility of the ions (Laan, et al., 2015).

It should be mentioned that the divalent ions are more easily rejected by the membrane than the monovalent ions (Pages et al. 2013). Taking into account that the RO membranes are dense enough and capable to retain monovalent ions, it means that the retention of the divalent ions will be better.

2.2.5 Influence of pH

Another factor that influences the salt passage and consequently ammonium passage is the pH. Mänttäri et al. have researched about the influence of the pH on the salt passage as a result of the membrane material.
An increase in the pH results in an increase of salt passage because the membrane is not so dense. This effect is based on the characteristics of the membrane skin layer and more specifically on the chemical nature of the polymer chains in the abovementioned layer. This happens because when the pH increases, the charges of the polymer chains start to repel each other and consequently make the surface of the membrane more hydrophilic and looser (Mänttäri, et al., 2006).
Except from the influence of the pH on the membrane material which results to the influence of the salt passage through the membrane, pH also affects the ammonia equilibrium. As it is explained at Chapter 2, in aqueous solutions ammonia can be found in two chemical species: the gaseous or un-ionized form and the ionized form (ammonium ion). This interaction is shown at the reaction below:

$$NH_3 * H_2O(aq) \leftrightarrow NH_4^+ + OH^-$$

Increasing the pH has as a result the increase of the hydroxide ion concentration, thus the increase of the NH_3 concentration. On the other hand, when the pH decreases, the amount of the ammonium ions in the solution is bigger and hence the permeability of the overall ammonium is less compared to the previous situation (Thurston, et al., 1981).
The relation between the un-ionized ammonia and the ammonium ion is described by the following equilibrium expression:

$$K_{\alpha} = \frac{[NH_3][H^+]}{NH_4^+}$$

The rise of one unit in pH results to the increase of the above ration by 10-fold (Erickson, 1985). Consequently, it can be summarized that pH influences a lot the ammonium permeability of RO membranes.

2.2.6 Supersaturation of CaCO3

2.2.6.1 General

Calcium carbonate is considered to be one of the most common compound for scaling of RO membranes. Scaling is an undesirable effect that is tried to be avoided during filtration procedure as it has several outcomes. The increase of the energy consumption and the more frequently need for chemical cleaning as well as the decrease of the lifespan of the membrane are some of the most important results of scaling (Van de Lisdonk, et al., 2001). As far as the operation of the membranes is concerned, when scaling occurs, the permeability decreases while the pressure drop across the element increases (Tzotzi, et al., 2007).
Scaling is not going to be studied in this research, however, due to some strange results that are found during the experiments, the supersaturation of $CaCO_3$ will be researched more deeply as it is supposed that the formation of $CaCO_3$ results to changes on the ratio, the pH and the total ionic charge.

2.2.6.2 Solubility Product

In artificial water that is used during the experiments as well as in raw water, there is a great amount of HCO_3 and Ca^{2+}. However, these two react to each other and $CaCO_3$ is produced. The reaction is described by the following equation (Wojtowicz, 1998):

$$Ca^{2+} + HCO_3 \rightarrow CaCO_3\ (s) + H^+$$

In order to be checked if $CaCO_3$ will precipitate or not, its solubility product should be found. The solubility product K_{sp} is defined below:

$$K_{sp} = [Ca^{2+}][CO_3]$$

If the product of the ions (Ca^{2+} and CO_3) exceeds the solubility product, the water is supersaturated with respect to $CaCO_3$ while when it does not exceed the water is under saturated with respect to $CaCO_3$ (Panthi, 2003). It should be mentioned that when a solution is supersaturated, it does not indicate that there will be scaling for sure (Tzotzi, et al., 2007).

2.3 Background information

Previous research (Kocbek, 2016) has been done in Kamerik about ammonium removal. Based on these results, the membranes will be flushed with the solutions for at least 45min before the first samples will be taken.
In addition, the amount of ammonium that is contained in the feed water does not affect its permeability. Hence, it is decided that the concentration of NH_4^+ will be 10mg/l in all the solutions.

3 Material and Methods

3.1 Introduction

Several experiments were performed in the pilot plant to investigate the ability of RO membranes to remove ammonium. The pilot plant is located next to the drinking water treatment plant, which is called “De Hooge Boom”. The feed water of the pilot plant is the same with the feed water of the drinking water treatment plant and is considered to be anaerobic groundwater.

3.2 Description of the pilot unit

The installation that was used is the Single Element Unit (SEU8”) and is partly automated. The set-up consists of two parallel 8” pressure vessels which are suitable for a single standard 8” RO membrane element. A photo of the pilot unit is represented at Figure 8 while a simplified overview of the configuration can be found at Appendix C.

Figure 8: The installation that is used during the experiments in Kamerik.

There are two pumps in the unit. The first is located at the beginning of the process before the cartridge filter and the other just before the membrane. During the experiments the pumps were operating automatically.

The valves that are also depicted at the same Figure, were operated automatically or manually. This is the reason why the unit is not completely automated. Despite the fact that the unit has two pressure vessels, only one of them can be used each time. According to which one will operate, the corresponding valves should be switched on.

Except from the valves, the rest unit is automated while a variety of sensors records the measurements. All the data are represented on the screen which is located on the right side of the installation (Oasen, 2015).

3.2.1 Circulation mode

The aim of the experiments is to evaluate the performance of the membranes during different recoveries. A variety of recoveries tried to be achieved which cannot be done only by one element. This was the reason of the circulation mode. The water was recirculated in the recirculation loop and the whole procedure tried to resemble the procedure of a full-scale installation.

The feed flow, the recirculation flow and the concentrate flow were calculated manually based on the flux and the recovery that should be achieved and they were input in the system. During the 15% recovery, which is the recovery of the element, the feed water was flushed through the membrane producing the permeate and the concentrate which left the system. In order for higher recoveries to be achieved (system recoveries), the recirculation mode was under operation. During this mode, part of the concentrate returned back at the beginning of the process where it was mixed up with a specific amount of feed water each time depending on the desirable recovery.

3.2.2 Recirculation Tank

Artificial water was used during the experiments. For this reason, a recirculation tank was necessary. The tank was located next to the unit and was connected with it with three different hoses. The feed water, which was the artificial water that was collected in the tank was connected to the unit while the permeate and the concentrate were returned back to the tank. In this way, the same type of water could be used for the experiment.
Due to the fact that the temperature of the water plays an important role on the results of the experiments, it was decided that the feed water should retain a temperature of 11.6^{o}C during the experiments. This was achieved by the operation of a cooler which was connected with the tank. Besides, the water flow that was produced in the tank due to the cooler, was supposed to act as a mixer and helped the chemicals to dissolve better.

3.2.3 Sample procedure

To determine the ammonium recovery by the RO membranes, ammonium concentration was measured in feed water and permeate. The sampling was done manually and the procedure that was followed is described below:

- The sampling bottles were flushed with feed water or permeate, depending on which sample should be taken. The volume of water that was used for this flushing was at least three times the volume of the sample line.
- During the sampling, the time and the date were noted. Each time three bottles were filled with permeate and three with concentrate. These bottles had the same timestamp and were taken with a deviation of ±5min from this timestamp.
- During the interval between sampling and measurements, the samples were stored in the fridge.
- Responsible for the measurements was the lab which should receive the samples within 1 day (Oasen, 2015).

3.3 Type of tested membranes

3.3.1 Tested membranes

Three different 8" RO membranes were used for the experiments. These membranes are: Espa2max from Hydranautics, XLE-440 from DOW and LG-BW-440 from LG Chem. All of them are 8" membranes with an active membrane area of 41m^2. More characteristics about them can be found at Appendix B.

3.3.2 Procedure before and after the performance test

Before the experiments, the membrane elements were flushed with drinking water at a feed flowrate of 3-10 m^3/h and a recovery of 15%, which is the recovery of the element, for at least twelve hours. During this period, the conductivity of the permeate was checked in order to ensure that there is no leakage (Oasen, 2015).
What is more, before the beginning of each experiment, the membranes were flushed with the artificial solution for at least one hour and after this time the samples were taken.
After the experiments, the membranes were preserved in a bisulfite solution. During preservation drinking water was used while sodium bisulfite (7.5L/h, 30-40w% $NaHSO_3$) was dosed in the feed. The dosing continued until the

conductivity in the concentrate is 3500-4000μS/cm. The unit was operating at a feed water flow rate of 10-14 m^3/h, a concentrate flow rate of $1m^3/h$ and a recirculation flow rate of $12m^3/h$. After their preservation the membranes were placed in a sealed plastic bag and were stored in the pilot plant (Oasen, 2015).

3.4 Tested water types

Different artificial solutions were composed for the experiments. The experiments can be separated in 3 parts.

Molar ratio

In the first part the only parameter that was changed was the molar ratio. It is the ratio between the monovalent anions and the monovalent cations and can be defined by the equation below:

$$Molar\ ratio = \frac{monovalent\ anions\ [-]}{monovalent\ cations\ [+]}$$

This ratio ranged between 1:1 and 5:1. During the conduction of this group of experiments only the ratio was changed and the pH, the ionic strength and the temperature was tried to be kept constant. More specifically, the pH was 7.2 with a deviation of ±0.2, the temperature was 11°C and the ionic strength was 20mM.

Ionic strength

In this group the only parameter that was changed was the ionic strength. This was achieved by changing the recovery of the system. Different ionic strengths were applied so its influence on ammonium removal can be evaluated. The equation that describes the ionic strength is given below:

$$I = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2$$

where: I=the ionic strength
z_i= the valence of the ion
c_i= the molar concentration of the ion

The same ionic strengths were applied to all the different molar ratios for all the membranes.

pH

At the end, it was checked how the pH affects ammonium removal. The molar ratio that was taken into account here was the 3:1 because this is the molar ratio of the raw water in Kamerik. The solutions that were checked had different pH which fluctuate between 5 and 8, the same molar ratio,3:1, the lowest and the highest ionic strength and finally the same temperature. What is more, the extremes were also studied which were the molar ratios of 1:1 and 5:1 with the lowest and the highest pH values and ionic strengths. Appendix G has analytical tables about the abovementioned values. Using the results, the supersaturation of $CaCO_3$ in the solutions was investigated.

3.5 Chemicals

The feed water of the unit should have different characteristics each time because the parameters that affect ammonium removal should be checked. The production of different water solutions was achieved by using chemicals. A variety of chemicals were added in the recirculation tank which was filled with aerated RO permeate. The concentration of each chemical was calculated according to the molar ratio that should have been achieved. More specifically, the chemicals that were dosed in the tank are the following:

- NH_4Cl (ammonium chloride)
- $NaHCO_3$ (sodium bicarbonate)
- NaCl (sodium chloride)
- $CaCl_2$ (calcium chloride)

Except from the above chemicals acid (HCl) and base (NaOH) were dosed in the solutions for the correction of the pH. Their concentration was calculated at the beginning so no change on the molar ratio or the ionic strength would occur.

3.6 Software

ROSA (Reverse Osmosis System Analysis) design software was used during the experiments for the calculation of the osmotic pressure of the solutions as well as the saturation index.

The osmotic pressure should be found as it is necessary for the calculation of the water and ammonium permeability. ROSA is a helpful tool that can find the osmotic pressure of the solution by inputting the concentration of the chemicals that are dosed.

In addition, due to the great salinity of some solutions especially when the pH is high, there is the risk of precipitation of $CaCO_3$ which will cause scaling. In order to prevent this situation, the LSI was checked before each experiment.

It should be mentioned that even if LSI>0, it is possible that there will be no scaling on the membranes. This is why all the planned experiments were conducted despite the warning of the design software. However, the pressure drop was monitored during the experiments because in case of a significant increase they should be terminated.

4 Results and Discussion

The results of the experiments, that were conducted in the pilot plant in Kamerik, are going to be presented in this chapter. A detailed description of them will follow in an attempt to explain clearly the parameters that influence ammonium removal by RO membranes.

4.1 Parameters Affecting Ammonium Permeability

There is a variety of parameters that affect ammonium passage through RO membranes. Three of these are going to be researched in this dissertation: molar ration, ionic strength and pH. The results are depicted below and are discussed thoroughly. In addition, a comparison with sodium permeability is done based on the fact that both ammonium and sodium are cations and have quite similar ionic radius.

4.1.1 Molar ratio

Figure 9 shows the ammonium permeability of 3 different RO membranes at different molar ratios. The molar ratios change from 1:1 to 5:1. An increase in ammonium permeability is shown with increase in molar ratios. All the membranes have an increasing trend of ammonium permeability, albeit with different magnitude.
The lowest rejection is noticed at XLE, indicating the highest permeability to ammonium. LG and Espa2max have approximately the same ammonium permeability until the molar ratio of 4:1. Then, there is a difference at molar ratio of 5.

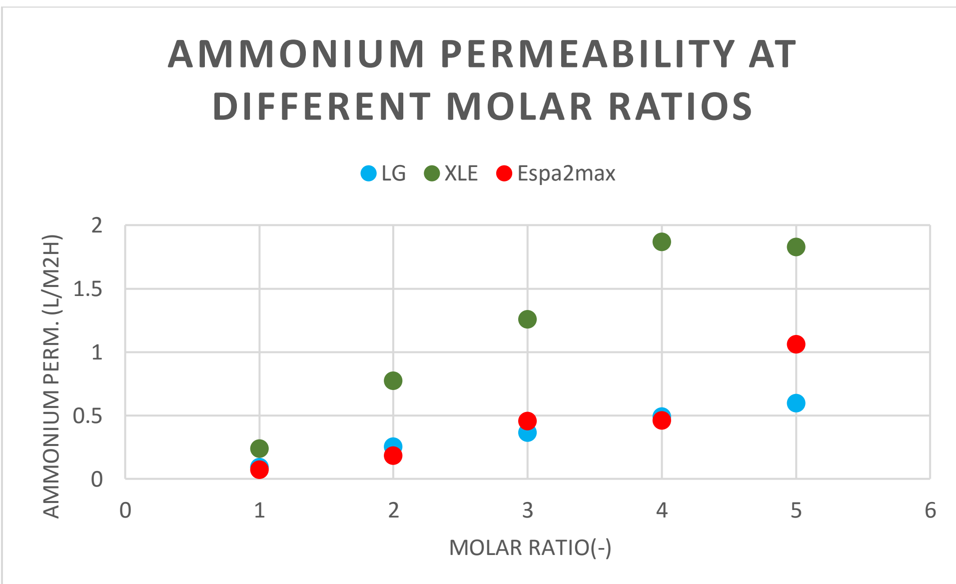

Figure 9: Ammonium permeability at different molar ratios and 15% recovery for the 3 RO membranes.

Nernst Planck equation and Donnan effect can adequately describe the increasing ammonium permeability at increasing molar ratios. As far as the former is concerned, the positive charge of ammonium leads to its acceleration in the membrane compared to the other ions. What is more, as the feed concentration goes higher and the molar ratio increases, the electrical potential is changed. These changes affect ammonium removal in the permeate as it can be seen at Figure 9.
In terms of the Donnan effect, due to the negatively charged membranes, ammonium cations are attracted by them. The higher the molar ratio, the weaker the Donnan effect. This results to a greater amount of ammonium cations that penetrate the membrane.
It should be mentioned here that when the molar ratio increases, the Ca^{2+} concentration increases. Ca^{2+} does not affect the molar ratio as it is defined only by the monovalent anions and cations but it is necessary to be added in

the solution if the abovementioned ratios should be composed. However, as it is mentioned at Chapter 2, the presence of divalent ions in the solution decreases the Donnan effect resulting to the increase of ions concentration in the permeate. In this case, the increasing molar ratios are accompanied with the increase of the concentration of Ca^{2+} decreasing the performance of the membranes.
In addition, at Figure 9, LG and Espa2max seem to have the same ammonium permeability at different molar ratios. Taking this into account, sodium permeability is decided to be checked in order to see if the two membranes behave the same. Sodium is selected because it is a cation as ammonium and they have similar ionic radius. The results are presented below:

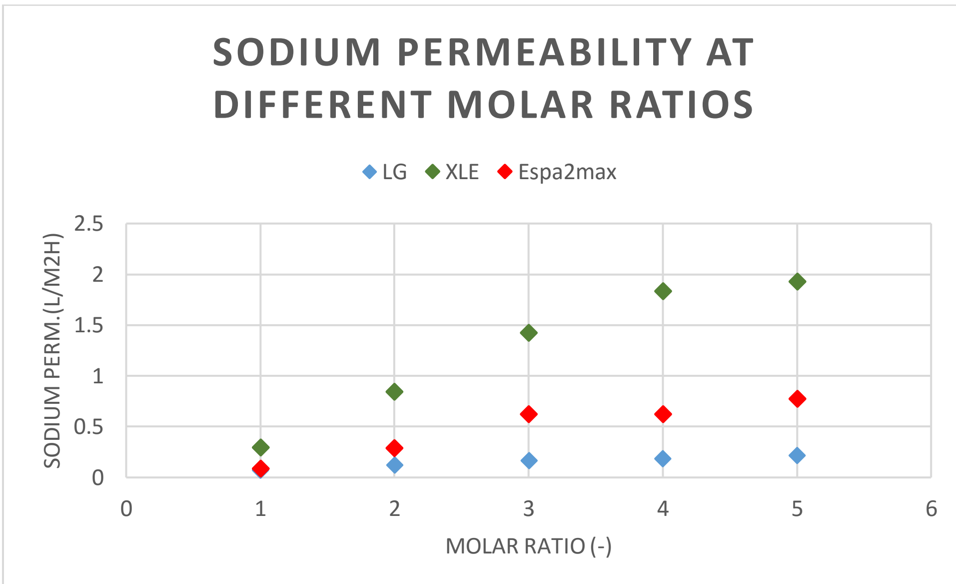

Figure 10: Sodium permeability at different molar ratios and 15% recovery for the 3 RO membranes.

Figure 10 presents sodium permeability at different molar ratios for 3 RO membranes. An increasing trend is noticed for all the membranes at increasing molar ratios. However, the magnitude of this increase differs for each membrane.
XLE seems to have the lowest sodium rejection of all the 3 membranes while LG has the highest. Figure 10 shows that sodium permeability differs between LG and Espa2max which is not the case for ammonium permeability. More specifically, sodium permeability is lower for LG than for Espa2max. Taking into account these results, LG can be considered as the densest membrane of the all the 3 membranes, while XLE is the less dense compared to the other two.
Another interesting observation is that the measurements seem to have a linear relation for each membrane. This means that any given change of the molar ratio will lead to a corresponding change to sodium permeability.
Due to the strange behaviour of ammonium a detailed comparison is done for each membrane and the results are shown at Figures below:

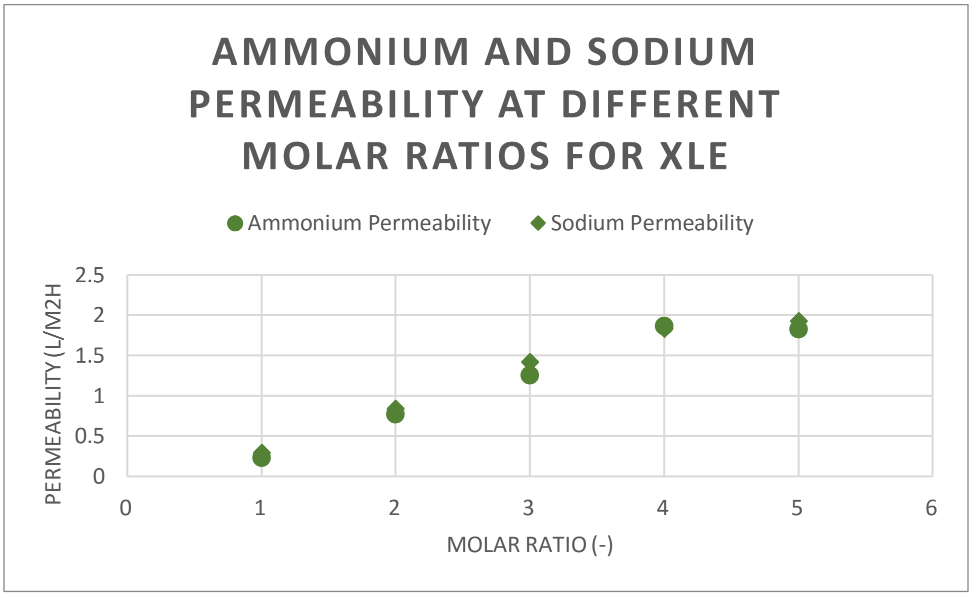

Figure 11: Ammonium and sodium permeability at different molar ratios and 15% recovery for XLE.

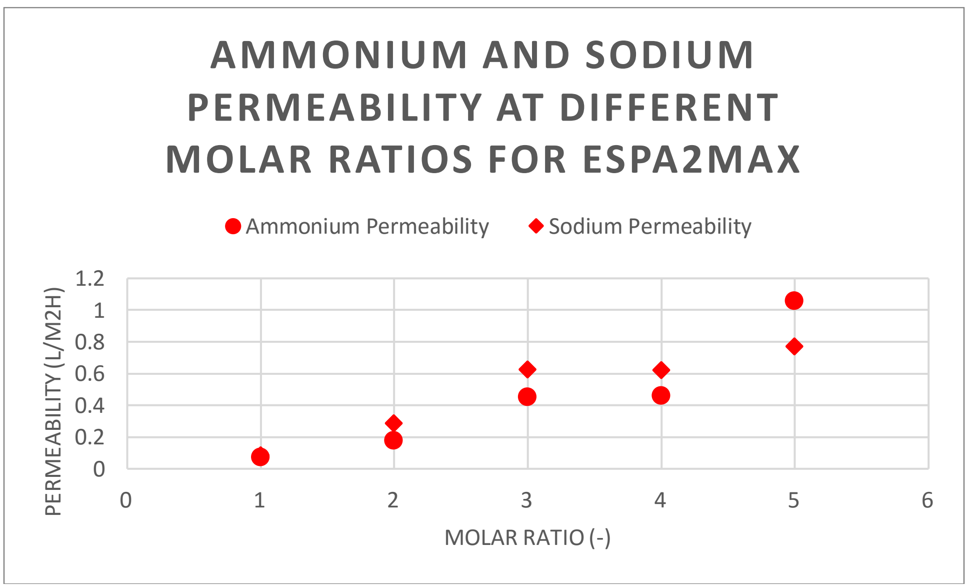

Figure 12: Ammonium and sodium permeability at different molar ratios and 15% recovery for Espa2max.

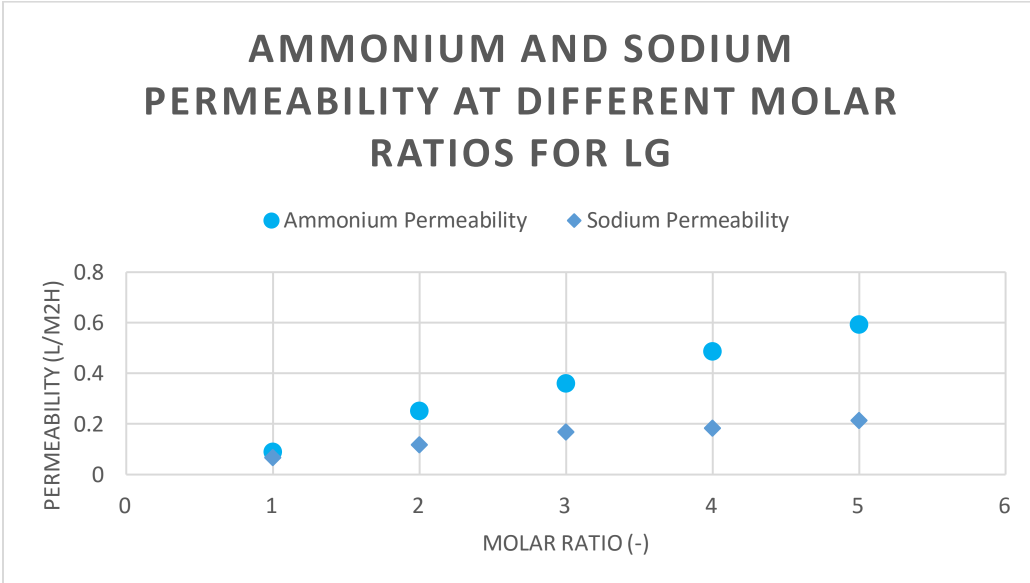

Figure 13: Ammonium and sodium permeability at different molar ratios and 15% recovery for LG.

It can be concluded that LG has a particularity with ammonium permeability. Despite the fact that there is a noticeable difference between LG and Espa2max as far as sodium permeability is concerned, things are not the same for ammonium where the two membranes behave in a similar way.

4.1.2 Ionic Strength

Ionic strength is another parameter that is studied in this thesis project. Experiments are conducted for each molar ratio applying different ionic strengths. The change in the ionic strengths is achieved by changing the recoveries in the system. Table 2 shows the recoveries that were applied and which ionic strengths represent. More detailed calculations about the relation between recoveries and ionic strengths can be found at Appendix H.

Table 2: Recoveries that are applied during the experiments and the corresponding ionic strengths.

Recovery	**15%**	**40%**	**42%**	**47%**	**50%**	**53%**	**56%**	**59%**	**60%**	**62%**	**68%**	**70%**
Ionic str.	0.024	0.033	0.034	0.038	0.040	0.043	0.045	0.049	0.050	0.053	0.063	0.067

Figure 14 presents the results of ammonium permeability at increasing ionic strengths. It can be noticed that the trends are different for the 3 membranes. For XLE, the higher the ionic strength, the higher the ammonium permeability. However, ammonium permeability seems to be stable at increasing ionic strength for LG and Espa2max.

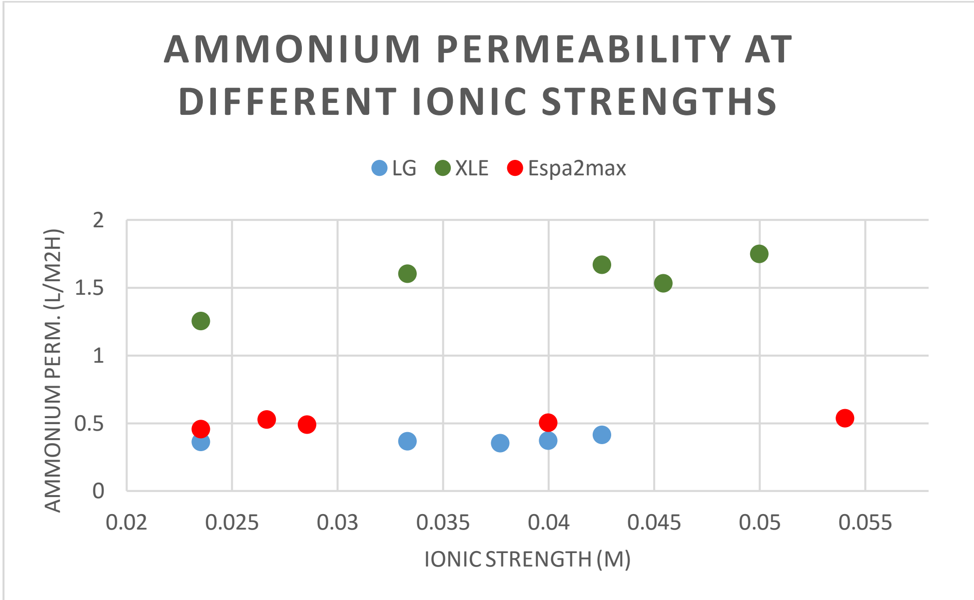

Figure 14: Ammonium permeability as a function of ionic strength at 3:1 molar ratio for the 3 RO membranes.

The pattern that XLE follows can be described by the Donnan effect which is thoroughly explained at Chapter 2. In general, as ionic strength increases, the Donnan effect becomes weaker and more ammonium ions flow towards the membrane.

Probably Espa2max and LG are not influenced so much of the change on ionic strengths as far as ammonium permeability is concerned.

Again, it is important to mention that LG and Espa2max have similar ammonium permeabilities as the ionic strength increases. Hence, sodium permeability is checked again to observe if the consideration that LG has a strange behaviour with ammonium is the same here.

At Figure 15 sodium permeability as a function of ionic strength is plotted for the three RO membranes. The figure shows that sodium permeability is approximately constant at increasing ionic strengths for the three RO membranes. Even XLE does not seem to influence sodium permeability as the ionic strength becomes bigger which was the case for ammonium.

Calculations are done in order to check the difference between ammonium and sodium permeability. The results which are shown at Table 3 reveal that sodium permeability for Espa2max is around 30% higher than ammonium permeability and only at the highest ionic strength the difference between the two components seems to be negligible. On the other side, LG shows a strangely behaviour for ammonium as it is observed during the experiments when the different molar ratios were applied. The difference between ammonium and sodium permeability is quite high. Finally, XLE has also considerable differences between sodium and ammonium permeability.

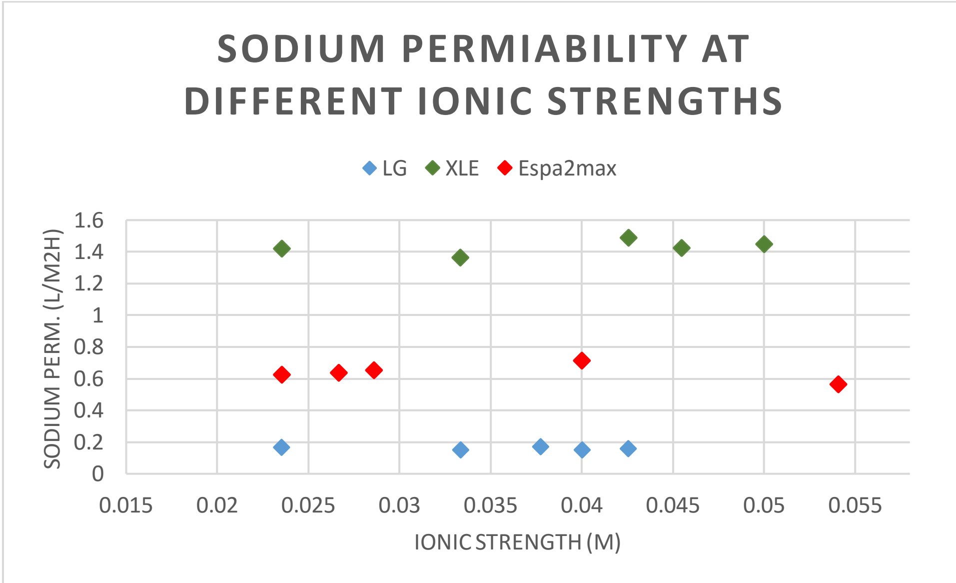

Figure 15: Sodium permeability as a function of ionic strength at 3:1 molar ratio for the 3 RO membranes.

Table 3: % difference between ammonium and sodium permeability for the 3 RO membranes at molar ratio of 3:1.

Differences between ammonium and sodium permeability						
Ionic strength		0.0235	0.0333	0.0377	0.0400	0.0426
LG	B_NH4+	0.3603	0.3648	0.3516	0.3700	0.4156
	B_Na	0.1682	0.1534	0.1706	0.1536	0.1604
	% difference	53.31%	57.94%	51.49%	58.49%	61.40%
Ionic strength		0.0235	0.0333	0.0426	0.0455	0.0500
XLE	B_NH4+	1.2557	1.6047	1.6706	1.5311	1.7494
	B_Na	1.4222	1.3659	1.4903	1.4272	1.4496
	% difference	-13.26%	14.88%	10.79%	6.78%	17.14%
Ionic strength		0.0235	0.0267	0.0286	0.0400	0.0541
Espa2max	B_NH4+	0.4545	0.5273	0.4880	0.5013	0.5349
	B_Na	0.6251	0.6398	0.6564	0.7131	0.5645
	% difference	-37.56%	-21.32%	-34.52%	-42.25%	-5.53%

At Figure 14 and 15, ammonium permeability was checked for the solutions with 3:1 molar ratio as this corresponds to the molar ratio of raw water in the treatment plant. However, it is interesting to check how ammonium behaves when an increasing ionic strength is applied at solutions with different molar ratios.

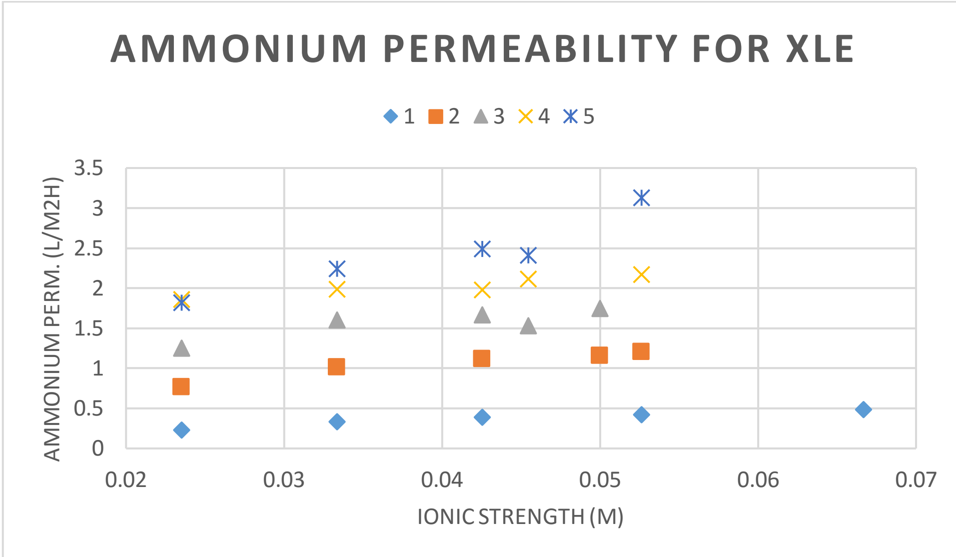

Figure 16: Ammonium permeability as a function of ionic strength at different molar ratios for XLE.

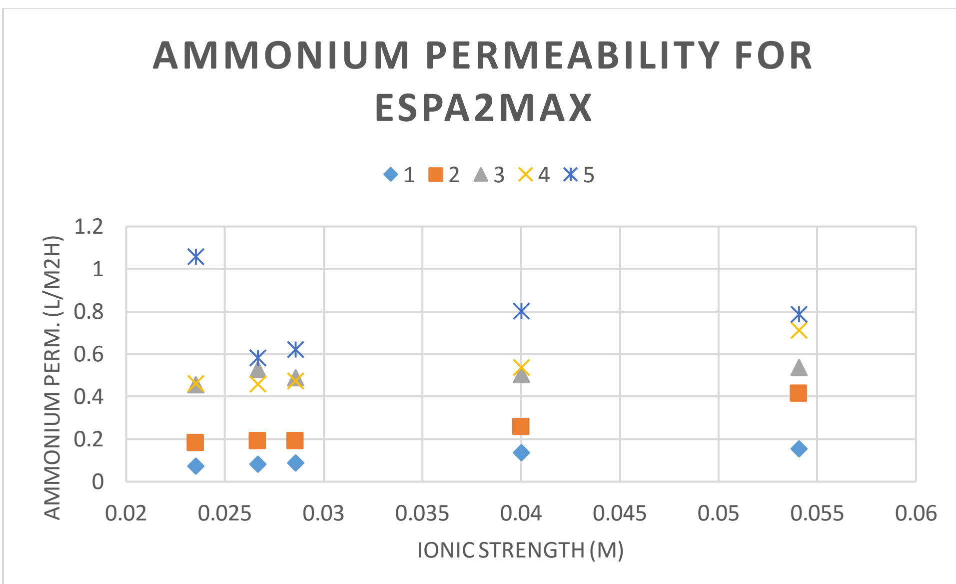

Figure 17: Ammonium permeability as a function of ionic strength at different molar ratios for Espa2max.

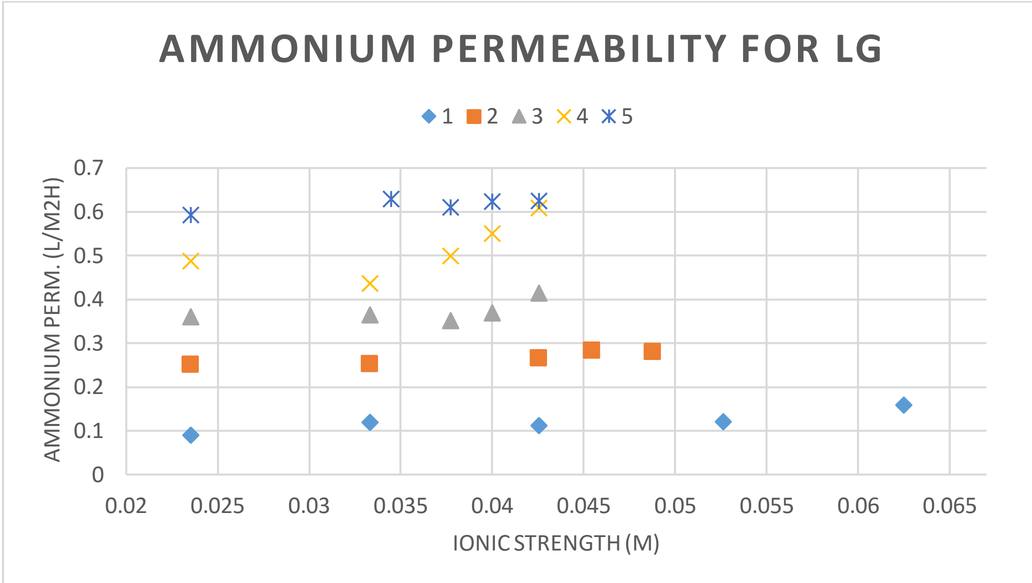

Figure 18: Ammonium permeability as a function of ionic strength at different molar ratios for LG.

Probably there should be a measurement error during the experiments for Espa2max at molar ratio 5:1 and recovery 15%. At Figure 17, ammonium permeability is higher at the lowest ionic strength and then a reasonable trend follows.

At Figures 16-18, the same conclusions can be derived for the three membranes. The higher the molar ratio, the higher the ammonium permeability. This conclusion is according to the initial estimations based on the theoretical background. However, as far as the ionic strength is concerned, the results from the measurements are different from the initial estimations. Based on the Donnan effect the higher the ionic strength the weaker the Donnan effect, therefore more ammonium can pass through the membrane. This happens with XLE but not with LG and Espa2max where the permeability of ammonium is almost the same at increasing ionic strengths.

4.1.2.1 Differences between raw water and artificial water

A comparison between artificial water and raw water is done to check if there are any significant differences. The same membrane (Espa2max) is used and the solutions have the molar ratio of 3:1.

Figure 19 shows the ammonium permeability at an increasing ionic strength using raw water and artificial water. Ammonium permeability of the former has a decreasing trend while the ionic strength increases. On the other hand, the changes of ammonium permeability, when artificial water is used, are negligible at increasing ionic strength.

Besides, despite the fact that the operating conditions where the same during the experiments and the characteristics of the feed solutions (molar ratio and pH) were the same, Figure 19 shows that the rejection of ammonium is lower when using artificial water than the rejection when using raw water.

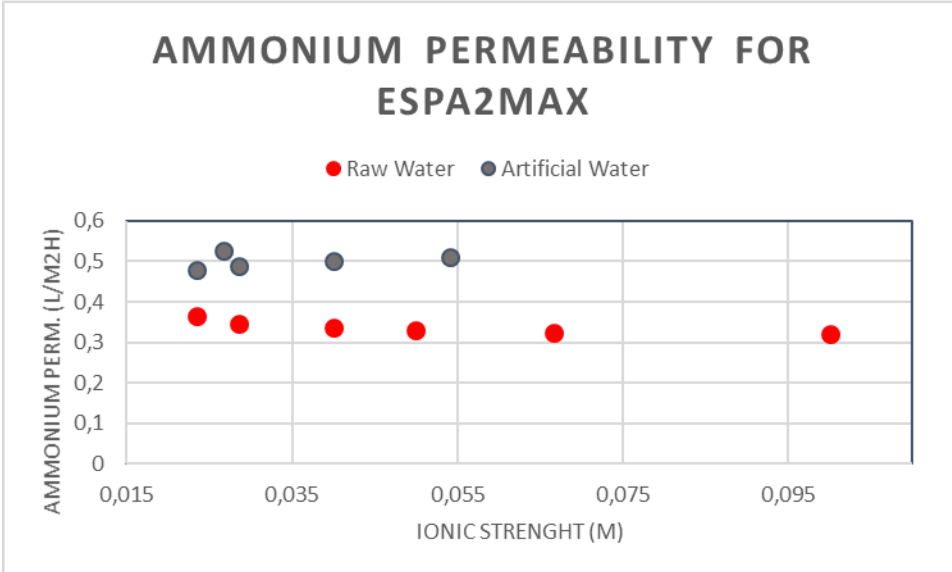

Figure 19: Ammonium permeability as a function of ionic strength for artificial water and raw water.

It is assumed that some of the reasons of these results are the following:

- Presence of other inorganic components in raw water. The artificial solutions that are used in the experiments contain specific components which were considered to be the most important for this research. These inorganic components are NH_4^+, Cl^-, Na^+, HCO_3^- and Ca^{2+}. However, in raw water there is a variety of inorganic components that compose the final solution such as iron, manganese and sulphate. Their presence in the feed solution maybe affects permeability of ammonium. This behaviour is not going to be investigated in the thesis project.
- Supersaturation of $CaCO_3$. The supersaturation of $CaCO_3$ is going to be further analysed in an attempt to explain the reasons of this discrepancy.

4.1.2.2 Supersaturation of CaCO3

Supersaturation of $CaCO_3$ is a parameter that is assumed to be responsible for the different patterns of ammonium permeability that are shown at Figure 19. The solubility constants of raw water and artificial water are calculated in order to be checked how saturated the solutions are. More details about the calculations can be found at Appendix I.

Table 4:Supersaturation of CaCO3 as a function of ionic strength for artificial water.

Artificial Water					
Ionic str. (M)	0.023	0.027	0.029	0.04	0.05
% saturated	51.3	57.5	62.4	73.2	145.4

Table 5: Supersaturation of CaCO3 as a function of ionic strength for raw water.

Raw Water			
Ionic str. (M)	0.016	0.035	0.056
% saturated	626	2477	4805

Tables 4 and 5 show the percentage of saturation of raw water and artificial water at increasing ionic strengths. The higher the ionic strength, the more saturated the solutions are. It is interesting to mention that raw water is a lot more saturated compared to artificial water.

CO_3 concentration is higher in raw water that in artificial water. This is an outcome of the high concentration of HCO_3 in raw water. More specifically, in raw water the HCO_3 concentration ranges between 350mg/l to 833mg/l at ionic strengths that range between 0.016M and 0.056M. On the other hand, in artificial water concentrations of HCO_3 range between 91mg/l and 102mg/l at ionic strengths between 0.023M and 0.05M.

Based on the results above, the raw water is supersaturated and gets more supersaturated as ionic strength increases. In general, this means that microcrystals could be formed and precipitation could occur resulting to the decrease of permeability. However, this is not the case here as the experiments last for 1 hour, a rather small time period for precipitation to occur. The main reason here seems to be that the supersaturation of $CaCO_3$ results to the decrease of Ca^{2+} concentration in the permeate which results to the decrease of the molar ratio. As it is found from Subchapter 4.1.1, the lower the molar ratio the lower the ammonium permeability. Therefore, could be a good explanation why ammonium permeability of raw water at increasing ionic ratios decreases.

4.1.2.3 Differences between 4" and 8" membrane using artificial water

The difference between artificial water and raw water leaded to the desicion to check what is going on if artificial water is checked using the same membrane (Espa2max) but with different diameters (one with 4" diameter and one with 8" diameter).

Figure 20 shows the comparison between the results that are obtained by this research when Espa2max with 8" diameter is used and the results from Kocbek's research where Espa2max of 4" diameter was used.

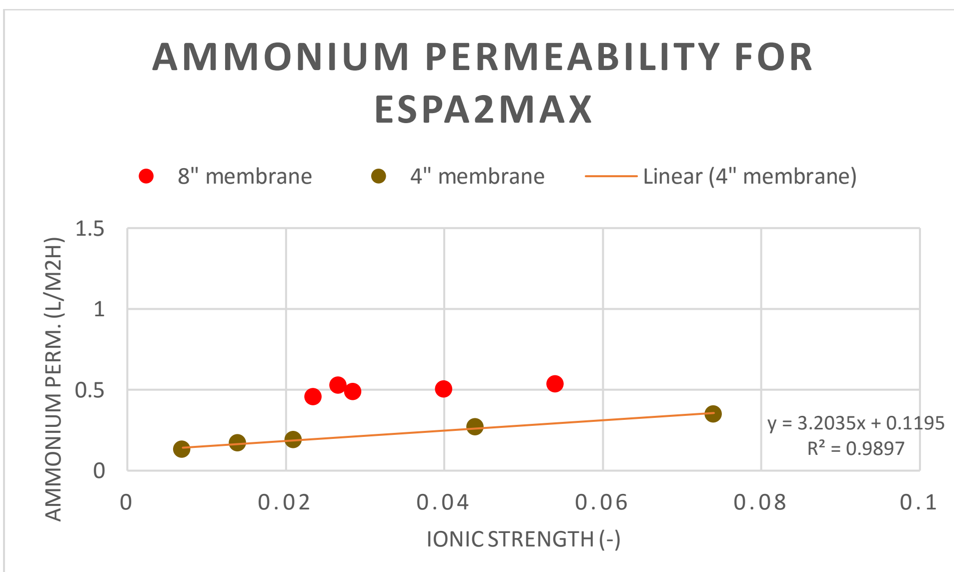

Figure 20: Ammonium permeability as a function of ionic strength for 4" and 8" Espa2max.

Ammonium permeability increases at increasing ionic strength for the 4" Espa2max while no significant changes are noticed on ammonium permeability for 8" Espa2max. The difference between the 4" and 8" membrane on ammonium permeability is checked.

Taking into account the equation of the trend that Kocbec found and using the ionic strengths that were applied during the experiments with the 8" membrane, the ammonium permeability can be found. Then the difference in the permeability between the 2 membranes can be calculated.

Table 6: % difference of ammonium permeability between 4" and 8" Espa2max.

Ionic strength	0.0235	0.0267	0.0286	0.0400	0.0541
B_NH4+ for 4"	0.1949	0.2049	0.2110	0.2476	0.2927
B_NH4+ for 8"	0.4545	0.5273	0.4880	0.5013	0.5349
%	57.12%	61.14%	56.76%	50.60%	45.29%

It is obvious that the permeability of the 8” membrane is significantly higher than of the 4” membrane. The differences between the two solutions are that in case of the 4” membrane, the ionic strength was increased during the experiments by adding salts (calcium and/or sodium chloride) at the permeate while in case of the 8” membrane ionic strengths were changed by changing the recoveries of the system.

4.1.3 pH

It has been mentioned in Chapter 2 that pH influences ammonium permeability by affecting the characteristics of the membrane skin layer as well as by affecting the fraction of ammonia (NH_3^+/NH_4^+). Experiments were conducted to check if these considerations can be proved.
During the experiments, pH ranged between 4.8 and 8.2 while all the other parameters were stable (molar ratio, ionic strength, temperature and flux). The molar ratio of 3:1 was tested since this is the molar ratio of the raw water in the Kamerik. The results for the 3 RO membranes are presented at Figure 21.
Figure 21 shows that when pH ranges between 4.8 and 8.2 there is no significant change on ammonium permeability for LG and Espa2max. Only XLE seems to have a different behavior at increasing pH. More specifically, at lower pH ammonium permeability is high, it decreases until pH of 7.4 and then it increases again.

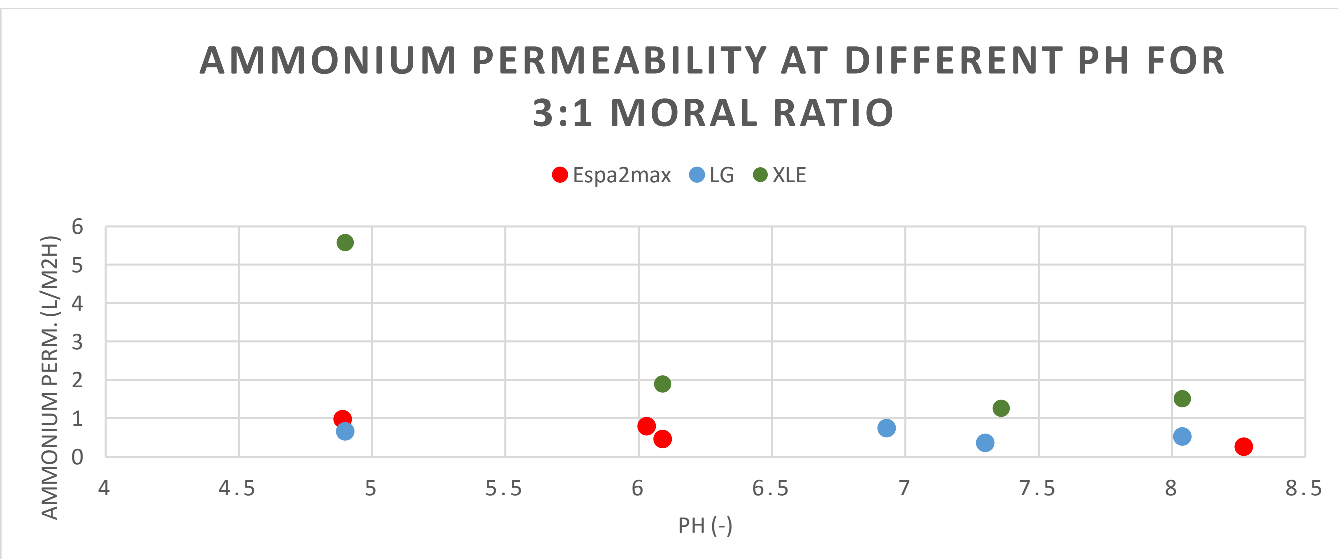

Figure 21: Ammonium permeability as a function of pH at 3:1 molar ratio for the 3 RO membranes.

In order to investigate more how pH affects ammonium passage through the membrane, the NH_3/NH_4^+ ratio should be checked. Then the conversion of ammonium to ammonia can be found and its effects on ammonium passage can be derived.

4.1.3.1 The NH3/NH4+ ratio in the solutions

It is interesting to check the NH_3/NH_4^+ ratio of the solutions that are used for the experiments. Based on this ratio, it will be checked if the dissociation of NH_4^+ influences the passage or not.

Ammonium is converted to ammonia while the pH increases. In order to check if this conversion influences ammonium passage through the membrane, the NH_3/NH_4^+ ratio is calculated and then it is plotted against the passage of ammonium.
Unfortunately, ammonia and ammonium cannot be separately measured in the lab, hence, the results indicate both the concentration of ammonium and ammonia in the solution. However, the NH_3/NH_4^+ ratio can be calculated and then the percentage of the NH_3 in the solution can be found.
Ammonium dissociated reversibly to ammonia as it is shown below:

$$[NH_4^+] \leftrightarrow [NH_3] + [H^+]$$

K_a value should be calculated. Ka value is temperature dependent. Due to the fact that only K_a value at 25°C is provided in the literature, the K_a value at 11°C should be found. The equation that will be used follows:

$$\log\left(\frac{Ka'}{Ka}\right) = \frac{\Delta H^0}{R}\left(\frac{1}{T} - \frac{1}{T'}\right)$$

where: Ka= dissociation constant at 25°C
Ka'= dissociation constant at 11°C
ΔH^0= difference in heat of formation ΔH^0 between product and substrate
T= temperature in K for 25°C
T'= temperature in K for 11°C (Dissociation constant - explanations, Ka-values, and examples, 2016)

Table 7: Enthalpy change of NH4+ , NH3 and H+ (Dissociation constant - explanations, Ka-values, and examples, 2016).

Components	ΔH^0 (kJ/mol)
NH_4^+	-133.26
NH_3	-80.83
H^+	0

The overall ΔH^0 is 52.43kJ/mole based on Table 7.
Taking into account the above equation as well as that K_a at 25°C is $5.6*10^{-10}$ (ScienceGeek.net, 2016), K_a' at 11°C is calculated to be $5.13*10^{-11}$. Eventually, NH_3/NH_4^+ ratio can be found based on the following equation:

$$K_\alpha = \frac{[NH_3][H^+]}{[NH_4^+]}$$

where: $[H^+]= 10^{-pH}$

Table 8 shows the fraction of NH_3

Table 8: Fraction of ammonia as a function of pH.

The fraction of NH_3 in the solution at different pH								
pH	4.9	6.03	6.09	6.93	7.3	7.36	8.04	8.27

f_{NH3}	0%	0.01%	0.01%	0.04%	0.10%	0.12%	0.56%	0.96%

The calculated fraction of ammonia should be plotted against the ammonium passage in order to check if ammonium dissociation influences the passage. Table 9 presents the results for the 3 different RO membranes.

Table 9: Fraction of ammonia and ammonium passage as a fraction of pH.

The fraction of ammonia at different pH								
pH	4.9	6.03	6.09	6.93	7.3	7.36	8.04	8.27
f_{NH3} calc.	0.00%	0.01%	0.01%	0.04%	0.10%	0.12%	0.56%	0.96%
NH_4 Passage XLE	18.22%		6.92%			4.79%	5.50%	
NH_4 Passage LG	2.58%		2.82%		1.42%		2.10%	
NH_4 Passage Espa2max	3.78%	3.15%		1.96%				1.06%

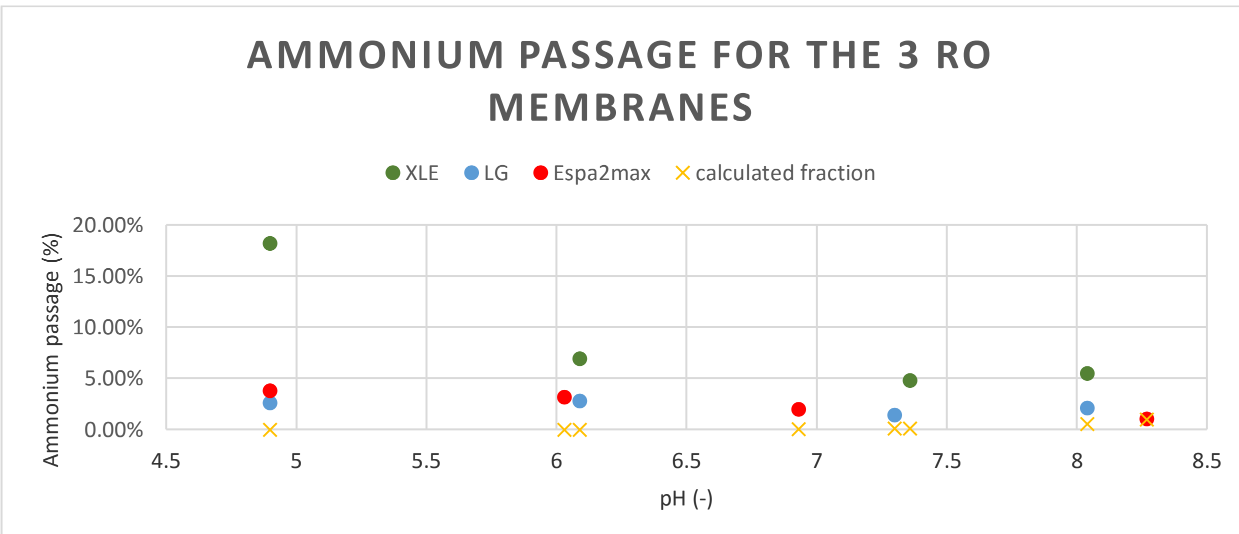

Figure 22: Ammonium permeability as a function of pH for the 3 RO membranes.

Table 9 shows that the fraction of ammonia increases at increasing pH. However, this increase can be considered as negligible since it does not exceed the percentage of 0.96%. Consequently, until pH of 8.3 a very small amount of ammonium is converted into ammonia.

In addition, Table 9 and Figure 22 present ammonium passage at increasing pH. The results contain both ammonium and ammonia concentration as the lab cannot measure the two components separately.

For Espa2max, the higher the fraction of ammonia the lower the passage of ammonium through the membrane. However, the results of LG are vague as there is a fluctuation of ammonium passage at an increasing pH and not clear conclusion can be derived. As far as XLE is concerned, quite high passage is found at lower pH. As the pH increases, ammonium passage decreases until the pH reaches the value of 7.4 and then it goes up again. However, the different behaviours of the 3 RO membranes is not considered to be affected by NH_3/NH_4^+ ratio as the amount of ammonia in the solution is negligible until the pH of 8.3.

5 Conclusion

A variety of conclusions about ammonium removal by RO membranes can be drawn by this thesis project. These conclusions are categorized below:

Molar ratio

The higher the molar ratio the higher the ammonium permeability through the three RO membranes. According to Donnan effect and Nernst Planck equation this behaviour is reasonable.

Despite the fact that the three membranes show an increasing trend at increasing molar ratio, their magnitude is different. XLE has the lowest rejection of all while LG and Espa2max seem to have similar ammonium permeability. Focusing on XLE, its lowest ammonium permeability was expected as XLE is supposed to be a not so dense RO membrane. However, the similarity between LG and Espa2max is quite strange as LG is considered to be denser membrane than Espa2max, therefore it's ammonium permeability should be lower. This consideration confirmed when sodium permeability is checked for LG and Espa2max. Based on these results, LG has a strange behaviour with ammonium.

Ionic strength

The measurements of XLE show that the higher the ionic strength, the greater the ammonium permeability through the membrane. When ionic strength increases, the Total Dissolved Solids (TDS) increase and hence the salinity increases. This results to the fact that Donnan effect is getting weaker and has as an outcome the increased concentration of ammonium in the permeate.

However, Espa2max and LG show another behaviour. Ammonium permeability is not affected by the increasing ionic strength for these two membranes. Based on the results, the trends of the two membranes do not change as the ionic strength increases.

Again, LG has a strange behaviour with ammonium as its results are similar to the results of Espa2max. When sodium permeability is checked, there is a discrete difference between LG and Espa2max as far as ammonium permeability is concerned.

pH

Based on the experiments, when pH ranges between 4.9 and 8.3 ammonium permeability is affected only for XLE. LG and Espa2max are not influenced by the change of pH (when it ranges between 4.9 and 8.3

The fraction of ammonia at the abovementioned pH range is negligible as it is calculated to be less than 1%. Hence, the dissociation of ammonium does not affect ammonium permeability.

Supersaturation of $CaCO_3$

It is interesting to mention that different results are observed after testing raw water and artificial water with the same molar ratio and the same membrane (Espa2max). In case of raw water, ammonium permeability decreases when the ionic strength increases while when artificial water is used, ammonium permeability is not affected by the increasing ionic strength.

It is considered that one of the reasons for the difference between raw water and artificial water is the supersaturation of $CaCO_3$. Raw water is found to be very supersaturated compared to artificial water which is supersaturated only when the highest ionic strength is applied. The supersaturation of $CaCO_3$ results to the decrease of molar ratio and hence the ammonium permeability falls. This could be one of the explanations that ammonium permeability decreases when raw water is used.

Different RO membranes

Ammonium permeability is higher for XLE due to the fact that it is an open RO membrane. It is easier for the ions to pass through the membrane as due to its structure they cannot be easily retained in the membrane.

LG and Espa2max have similar results as far as ammonium removal is concerned. It can be derived by the experiments that LG reacts in a strange way when it comes in contact with ammonium ions. Despite the fact that it is a dense membrane, ammonium permeability is quite high. This does not happen with sodium permeability where a discrete difference between LG and Espa2max is obvious.

6 Future Research

The present research accomplished the goals to answer its research questions and derive some valuable conclusions. However, it gave food for future research in the field of reverse osmosis membranes and ammonium removal.

A detailed investigation should be done regarding the reasons that contribute to the differences in permeability between raw water and artificial water. The different trends as far as the ammonium permeability is concerned, result to considerations that there are parameters that affect the passage of ammonium through the membranes. In additions, more experiments about ammonium removal by 4” and 8” membranes could be conducted in order to reveal the main factors that caused the already discussed results.

Another important observation in the present project is the strange behaviour of LG membrane with ammonium. A detailed research based on the manufacturers point of view could give the answer to this question.

Finally, due to the fact that no relation is found between the range of the pH and ammonium rejection when LG and Espa2max are tested, experiments with solutions with pH higher than 8.2 should be done. In this way, the ratio of NH_3/NH_4^+ can be thoroughly researched and a better relation between the pH of feed solutions and ammonium permeability can be derived.

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Appendix A: General Theory

Ammonium

The World Health Organization (1986) has set that ammonium concentration in drinking water should not excess the 0.2mg/l. This regulation is followed by the Dutch law too. However, Oasen has its own standard which is 0.02 mg/l as it wants to achieve its goal to produce pristine drinking water of impeccable quality.

The question that raises is why ammonium standards are so low and if this component is dangerous for human health. Ammonium can become toxic to humans when its concentration is higher than the capacity to detoxify (World Health Organization, 1986). However, it is not carcinogenic and there is no evidence that it results in long-term ill effects.

For humans exceeded ammonium concentration in water in typical pH values (6.5-9.5) is not directly harmful. The most significant concern is the possibility for nitrite ions to be formed under oxidative conditions and nitrate is considered to be toxic for humans (Takó, 2012). Consequently, sufficient ammonium removal by water treatment should be taken place in order for the undesirable effects to be eliminated.

The question that raises is what happens to ammonia when it comes in contact with water. Ammonia dissolves in water and forms ammonium (NH_4^+) and hydroxyl (OH^-) ions. This reaction is characterized by the equilibrium constant K_B= 1.78*10^{-5} (at 25^{o}C) while different parameters such as temperature, pH and the concentration of dissolved salts in the water, influence the degree of ionization (World Health Organization, 1986).

Membranes

The access to clean drinking water is an indefeasible human right. Taking into account the statement of the famous Thomas Malthus that the increase in population and in water demand are following an arithmetic and a geometrical ratio, respectively, (Maltus, 2006), (Lee, et al., 2011), it can be summarized that the water scarcity is going to be a huge problem the coming years. Consequently, new water resources should be found. This necessity combined with the continuous attempt of the developed countries to produce drinking water with high quality conclude to the fact that more advanced technologies should be used in the water treatment industry as the conventional are not sufficient enough.

One of these advanced technologies, which has been flourished the last decades is the use of membranes for the production of drinking water. There are a lot of advantages that membrane separation processes offer such as simple process, applicable to different fields using the same principles, compact technology, high selectivity, no phase change (Soltanieh et al., 1981), which make them an appealing solution for drinking water companies.

Reverse Osmosis Membranes

In case of brackish and saline water, which is the main focus of this thesis project, the membrane that should be used in order for the desirable results to be achieved should has some specific characteristics. These are listed below:

- High water permeability
- Low salt permeability
- Thermal stability
- Resistance to microorganisms
- Chemical stability under conditions with extreme pH values (Riley, et al., 1977)

Reverse osmosis membranes (RO) contribute to the abovementioned requirements and consequently they are preferred for the treatment of brackish and saline feed water.

More specifically, using the scanning electron microscopy (SEM) for RO membranes no pores are identified. The membrane acts as a perm-selective medium where the water molecules permeate it while the salt molecules are rejected (Yoon, 2016), (Soltanieh, et al., 1981). Many types of dissolved and suspended solids are rejected by RO

membranes while they are the only membranes that can remove monovalent ions such as ammonium and sodium (Greenlee, et al., 2009).
Nowadays, they are not only used for the production of potable water but also in the industry for many different processes. It should be mentioned that RO membranes are mainly preferred for desalination due to their high salt rejection.

Thin Film Composite membrane

The thin film composite membrane is a type of RO membrane material which is used in membrane sheets. It consists of layers of different materials, each one with different characteristics, that are combined in order to improve performance of the membrane.
Generally, three layers are placed one of the top of the other. The first layer is the ultra-thin aromatic polyamine top layer which is formed by interfacial polymerization of meta-phenylenediamine (MDP) and trimesoyl chloride (TMC) (Wang, et al., 2014) and where the selectivity for the membrane is provided. Below this layer it can be found the porous ultrafiltration layer which supports the abovementioned layer. There is almost no resistance to mass transfer in this layer. Finally, below the porous ultrafiltration support layer is placed a non-woven support fabric which is responsible for the mechanical stabilization of the membrane structure (Dalwani, 2011), (Vrentas, et al., 2002). A schematic overview of the thin film composite membrane material is presented at Figure 24.

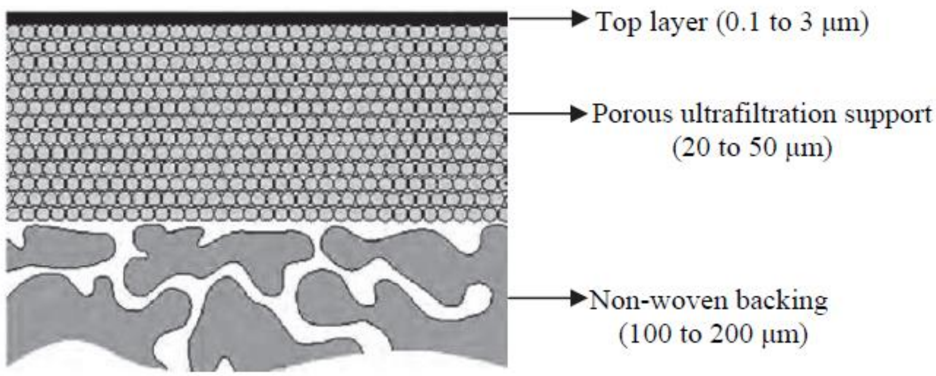


Figure 23: Schematic overview of a thin film composite membrane material (Dalwani, 2011)**.**

Spiral wound module

The spiral wound modules are constituted by two layers of thin film composite semi-permeable membranes materials while between them a highly microporous, incompressible backing material is placed. The layers are glued from their three sides and are wound spirally around the main pipe (Tolba, et al., 1999).
The feed water is transported parallel along the central pipe while the permeate flows radially towards it and is collected in it. A schematic overview of the spiral wound module is depicted at Figure 25.

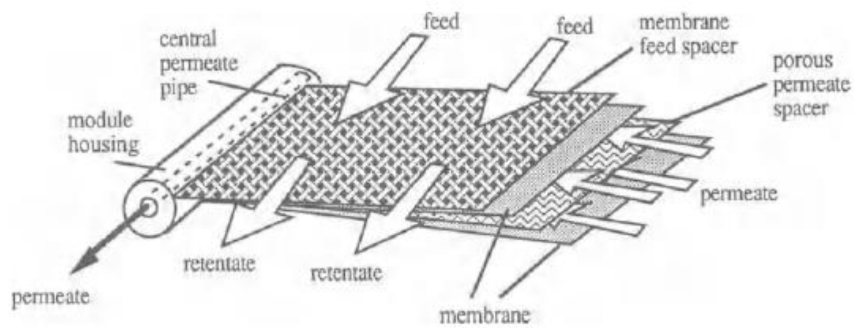


Figure 24: Schematic overview of the spiral wound module (Mulder, 2012)**.**

Appendix B: Membranes data sheets

High Rejection

Brackish Water Reverse Osmosis (RO) Element

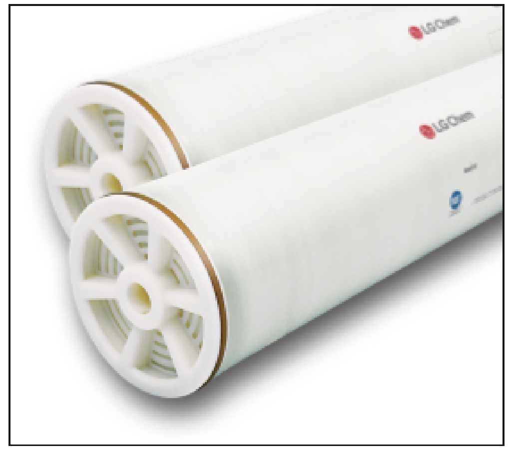
LG BW 440 R

LG Chem

Overview

LG Chem's brackish water RO membranes lower the cost of desalination by improving energy efficiency and productivity. These thin-film nanocomposite (TFN) membranes feature benign nanomaterials incorporated into the thin-film polyamide layer of a composite membrane. This innovative patented and patent-pending technology significantly increases membrane permeability while offering superior salt rejection.

- Matches industry-standard flux and rejection
- Easy to retrofit existing systems
- Well suited for low quality feed water or varying operating conditions

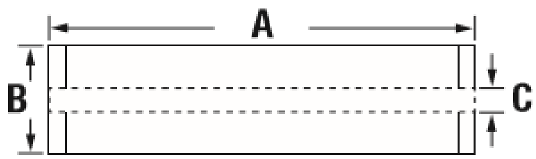


Product Specifications

Configuration: 8-inch spiral wound
Membrane Polymer: Thin-film nanocomposite (TFN) polyamide

Product Number	Permeate flow rate m^3/d (gpd)	Minimum NaCl Rejection %	Stabilized NaCl Rejection %	Active Membrane Area m^2 (ft^2)	Feed Spacer mil
LG BW 440 R	43.7 (11,550)	99.5	99.6	41 (440)	28

Note: The above values are normalized to the following conditions: 2,000 ppm NaCl, 15.5 bar (225 psi), 25°C (77°F), pH 8, 15% recovery. Permeate flows for individual elements may vary +/- 15%.



Part Number	Length A	Element O.D. B	Perm Tube I.D. C	Weight kg (lbs.)
LG BW 440 R	1016 mm (40 in.)	200 mm (7.9 in.)	28.6 mm (1.125 in.)	16.4 (36)

Operating Specifications

For more information and operating guidelines, visit www.LGwatersolutions.com

Max. Operating Pressure:	41 bar (600 psig)
Max. Chlorine Concentration:	< 0.1 ppm
Max. Operating Temperature:	45°C (113°F)
pH Range, Continuous (Cleaning):	2-11 (2-12)
Max. Feedwater Turbidity:	1.0 NTU
Max. Feedwater SDI (15 mins):	5.0
Max. Feed Flow:	19 m^3/h (85 GPM)
Max. Pressure Drop:	1.0 bar (15 psig)

NanoH$_2$O

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Rev. B (08.15)

Product Data Sheet

DOW FILMTEC™ XLE-440 Element

Description

Ideal for: reverse osmosis plant managers and operators dealing with controlled-pre-treatment and seeking high-quality permeate water at low operating costs.

DOW FILMTEC™ XLE-440, the lowest pressure DOW FILMTEC™ RO element:

- Provides lower energy costs and more productivity, especially in cold waters
- Minimizes equipment CAPEX in designs with savings in elements and pumping due to the 440 ft² active area
- Delivers the most effective cleaning performance, robustness and durability due to its widest cleaning pH range (1-13) tolerance and the support of FilmTec technical representatives

Product Type

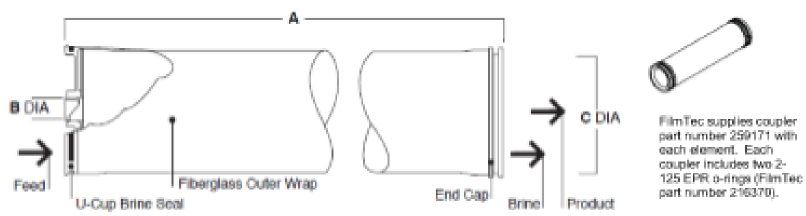
Spiral-wound element with polyamide thin-film composite membrane

Product Specifications

DOW FILMTEC™ Element	Active Area (ft²)	Active Area (m²)	Feed Spacer Thickness (mil)	Permeate Flow Rate (GPD)	Permeate Flow Rate (m³/d)	Typical Stabilized Salt Rejection (%)	Minimum Salt Rejection (%)
XLE-440	440	41	28	14,000	53	99.0%	97.0%

1. Permeate flow and salt (NaCl) rejection based on the following standard test conditions: 2,000 ppm NaCl, 125 psi (8.6 bar), 77°F (25°C), pH 8, 15% recovery.
2. Flow rates for individual elements may vary but will be no more than ±15%.
3. Stabilized salt rejection is generally achieved within 24-48 hours of continuous use; depending upon feedwater characteristics and operating conditions.
4. Sales specifications may vary as design revisions take place.
5. Active area guaranteed ± 5%. Active area as stated by Dow Water & Process Solutions is not comparable to nominal membrane area often stated by some manufacturers. Measurement method described in Form No. 609-00434.

Element Dimensions



DOW FILMTEC™ Element	A (in.)	A (mm)	B (in.)	B (mm)	C (in.)	C (mm)
XLE-440	40.0	1,016	1.50 ID	38 ID	7.9	201

1. Refer to Dow Water & Process Solutions Design Guidelines for multiple-element applications. 1 inch = 25.4 mm
2. Element to fit nominal 8-inch (203-mm) I.D. pressure vessel.

Operating and Cleaning Limits

Maximum Operating Temperature [a]	113°F (45°C)
Maximum Operating Pressure	600 psig (41 bar)
Maximum Element Pressure Drop	15 psig (1.0 bar)
pH Range, Continuous Operation [a]	2 – 11
pH Range, Short-Term Cleaning (30 min.) [b]	1 – 13
Maximum Feed Silt Density Index (SDI)	SDI 5
Free Chlorine Tolerance [c]	< 0.1 ppm

[a] Maximum temperature for continuous operation above pH 10 is 95°F (35°C).

[b] Refer to Cleaning Guidelines in specification sheet 609-23010.

[c] Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure. Since oxidation damage is not covered under warranty, Dow Water & Process Solutions recommends removing residual free chlorine by pretreatment prior to membrane exposure. Please refer to technical bulletin "Dechlorinating Feedwater" for more information.

Additional Important Information

Before use or storage, review these additional resources for important information:

- Usage Guidelines for DOW FILMTEC™ 8" Elements
- System Operation: Initial Start-Up

Regulatory Note

These membranes may be subject to drinking water application restrictions in some countries; please check the application status before use and sale.

Product Stewardship

Dow has a fundamental concern for all who make, distribute, and use its products, and for the environment in which we live. This concern is the basis for our product stewardship philosophy by which we assess the safety, health, and environmental information on our products and then take appropriate steps to protect employee and public health and our environment. The success of our product stewardship program rests with each and every individual involved with Dow products—from the initial concept and research, to manufacture, use, sale, disposal, and recycle of each product.

Customer Notice

Dow strongly encourages its customers to review both their manufacturing processes and their applications of Dow products from the standpoint of human health and environmental quality to ensure that Dow products are not used in ways for which they are not intended or tested. Dow personnel are available to answer your questions and to provide reasonable technical support.

DOW FILMTEC™ Membranes
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http://www.dowwaterandprocess.com

Notice: The use of this product in and of itself does not necessarily guarantee the removal of cysts and pathogens from water. Effective cyst and pathogen reduction is dependent on the complete system design and on the operation and maintenance of the system.

Form No. 609-00245, Rev. 2
August 2015

Membrane Element ESPA2 MAX

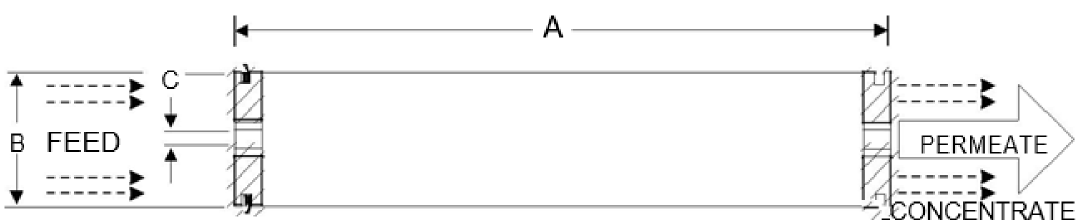
Performance	Permeate Flow:	12,000 gpd (45.4 m^3/d)
	Salt Rejection:	99.6% (99.5% minimum)
Type	Configuration:	Spiral Wound
	Membrane Polymer:	Composite Polyamide
	Membrane Active Area:	440 ft^2 (40.8m^2)
Application Data*	Maximum Applied Pressure:	600 psig (4.14 MPa)
	Maximum Chlorine Concentration:	< 0.1 PPM
	Maximum Operating Temperature:	113 °F (45 °C)
	pH Range, Continuous (Cleaning):	2-10.6 (1-12)*
	Maximum Feedwater Turbidity:	1.0 NTU
	Maximum Feedwater SDI (15 mins):	5.0
	Maximum Feed Flow:	75 GPM (17.0 m^3/h)
	Minimum Ratio of Concentrate to Permeate Flow for any Element:	5:1
	Maximum Pressure Drop for Each Element:	15 psi

* The limitations shown here are for general use. For specific projects, operating at more conservative values may ensure the best performance and longest life of the membrane. See Hydranautics Technical Bulletins for more detail on operation limits, cleaning pH, and cleaning temperatures.

Test Conditions

The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:

1500 PPM NaCl solution
150 psi (1.05 MPa) Applied Pressure
77 °F (25 °C) Operating Temperature
15% Permeate Recovery
6.5 - 7.0 pH Range

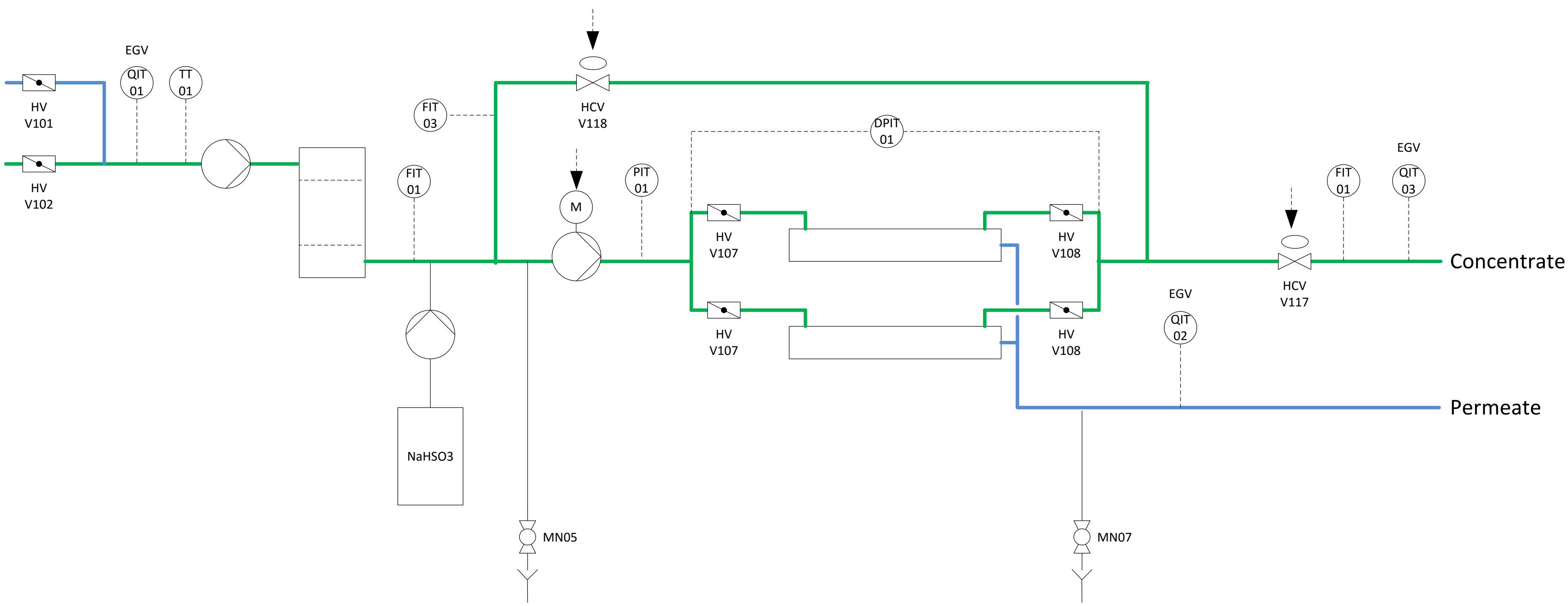


A, inches (mm)	B, inches (mm)	C, inches (mm)	Weight, lbs. (kg)
40.0 (1016)	7.89 (200)	1.125 (28.6)	36 (16.4)

Notice: Permeate flow for individual elements may vary + or - 15 percent. Membrane active area may vary +/-4%. Element weight may vary. All membrane elements are supplied with a brine seal, interconnector, and o-rings. Elements are enclosed in a sealed polyethylene bag containing less than 1.0% sodium meta-bisulfite solution, and then packaged in a cardboard box.

Hydranautics believes the information and data contained herein to be accurate and useful. The information and data are offered in good faith, but without guarantee, as conditions and methods of use of our products are beyond our control. Hydranautics assumes no liability for results obtained or damages incurred through the application of the presented information and data. It is the user's responsibility to determine the appropriateness of Hydranautics' products for the user's specific end uses. 11/03/15

Appendix C: Schematic overview of the configuration of the unit (Oasen, Membrane Test Protocol, 2015)



Where:

Variable	Unit	Type	Tag
Feed flowrate-in (Q_{in})	m^3/h	Endress+Hauser 10W50-UA0A1AA; Range: 0.5 – 18m3/h	FQIT-01
Concentrate flowrate-out (Q_{put})	m^3/h	Endress+Hauser 10W25-UA0A1AA; Range: 0 – 18m3/h	FQIT-02
Circulation flowrate (Q_R)	m^3/h	Endress+Hauser 10W50-UA0A1AA; Range: 0.5 – 18m3/h	FQIT-03
Conductivity Feed	µS/cm	Endress+Hauser	QIT-01

		CLS21D-C1E1; Range: 0.01 -20mS/cm	
Conductivity Concentrate	µS/cm	Endress+Hauser CLS21D-C1E1; Range: 0.01 -20mS/cm	QIT-01
Conductivity Permeate	µS/cm	Endress+Hauser CLS15D-B1M1; Range: 0.1 -200µS/cm	QIT-03
Feed pressure (P_F)	bar	Endress+Hauser PTC31-A1C11MI; Range: 0-25bar	PIT-03
Permeate pressure (P_P)	bar	Endress+Hauser PTC31-A1C11PI; Range: 0-10bar	PIT-04
Pressure drop (ΔP)	bar	Endress+Hauser PDM55-INP1; range: 0-2.5 bar	DPIT-01

Appendix D: Settings

Target settings					
Name of the membrane	ESPA2MAX				
Membrane Area (m2)	40.88	40.88	40.88	40.88	40.88
Element Recovery	15%	15%	15%	15%	15%
System Recovery	15%	25%	30%	50%	80%
Filtration flux (l/m2h)	25	25	25	25	25
Permeate frow rate (m3/h)	1.02	1.02	1.02	1.02	1.02
Feed flow rate (m3/h)	6.81	4.09	3.41	2.04	1.28
Concentrate flow rate (m3/h)	5.79	3.07	2.38	1.02	0.26
Recirculation flow rate (m3/h)	0.00	2.73	3.41	4.77	5.54

Target settings					
Name of the membrane	LG				
Membrane Area (m2)	40.88	40.88	40.88	40.88	40.88
Element Recovery	15%	15%	15%	15%	15%
System Recovery	15%	40%	53%	62%	68%
Filtration flux (l/m2h)	25	25	25	25	25
Permeate frow rate (m3/h)	1.02	1.02	1.02	1.02	1.02
Feed flow rate (m3/h)	6.81	2.56	1.93	1.65	1.50
Concentrate flow rate (m3/h)	5.79	1.53	0.91	0.63	0.48
Recirculation flow rate (m3/h)	0.00	4.26	4.89	5.16	5.31

Target settings					
Name of the membrane	XLE				
Membrane Area (m2)	40.88	40.88	40.88	40.88	40.88
Element Recovery	15%	15%	15%	15%	15%
System Recovery	15%	40%	53%	62%	68%
Filtration flux (l/m2h)	25	25	25	25	25
Permeate frow rate (m3/h)	1.02	1.02	1.02	1.02	1.02
Feed flow rate (m3/h)	6.81	2.56	1.93	1.65	1.50
Concentrate flow rate (m3/h)	5.79	1.53	0.91	0.63	0.48
Recirculation flow rate (m3/h)	0.00	4.26	4.89	5.16	5.31

Appendix E: Results from the experiments regarding different molar ratios and ionic strengths

I. Espa2max

1:1 molar ratio

Input			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53,489	0,56
NaHCO3-	168	84,0057	2,00
NaCl	1013	58,4397	17,33
HCl		36,458	0,18
pH	7,16		

Total Concentration (mmol/l)	
NH4+	0,56
HCO3-	2,00
Cl-	18,07
Ca2+	
Na+	19,33

Sensors EU					
Recovery	**15%**	**25%**	**30%**	**50%**	**63%**
Feed flow rate (m3/h)	6,55	4,09	3,41	2,04	1,27871
Concentrate flowrate (m3/h)	5,79	3,07	2,38	1,02	0,46
Circulation flowrate (m3/h)	0,25	2,73	3,41	4,77	5,537097
Feed pressure (bar)	7,34	9,53	9,69	9,82	8,48
Pressure drop (bar)	0,17286	0,16171	0,16106	0,1598	0,163201
Permeate pressure (bar)	0,09	0,15	0,15	0,14	0,10871
Conductivity Feed (µS/cm)	2056,09	2042,7	2034,93	1981,44	1891,65
Conductivity concentrate (µS/cm)	2170,97	2478,81	2618,48	3381,88	4102,912

Conductivity Permeate (µS/cm)	12,76	12,29	13,03	18,87	32,48194
Feed Temperature (oC)	11,58	11,54	11,48	11,51	11,55903

Feed Analysis						
		15%	25%	30%	50%	80%
NH4+	(mg/l)	8,82846	9,90952	10,41663	13,05262	18,9047
HCO3-	(mg/l)	96,807	106,445	114,802	140,727	190,503
Cl-	(mg/l)	572,5012	619,9459	681,7207	857,0358	1240,757
Ca2+	(mg/l)					
Na+	(mg/l)	439,9333	492,8667	523,1667	639,7667	852,9
EC	(mS/m)	184,7	204	216	268	371
pH		7,19	7,21	7,3	7,34	7,47

Ionic Balance (feed analysis)	1,89	2,76	2,22	2,07	0,02

Feed Analysis						
		15%	25%	30%	50%	80%
NH4+	(mmol/l)	0,49	0,55	0,58	0,72	1,05
HCO3-	(mmol/l)	1,59	1,74	1,88	2,31	3,12
Cl-	(mmol/l)	16,15	17,49	19,23	24,18	35,00
Ca2+	(mmol/l)					
Na+	(mmol/l)	19,14	21,44	22,76	27,83	37,10
EC	(mS/m)	225	222	227	281	403
pH		7,19	7,21	7,3	7,34	7,47

Permeate Analysis						
		15%	25%	30%	50%	80%
NH4+	(mg/l)	0,03403	0,03191	0,03612	0,07071	0,14366
HCO3-	(mg/l)	4,819	4,575	5,063	5,307	6,039
Cl-	(mg/l)	2,46538	2,00718	2,40307	3,71384	6,11931
Ca2+	(mg/l)					

Na+	(mg/l)	2,024	1,954667	1,709333	3,219	4,898333
EC	(mS/m)	1,06	1,06	1,1	1,6	2,66
Ph		5,46	5,37	5,44	5,54	5,79

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,00	0,00	0,00	0,00	0,01
HCO3-	(mmol/l)	0,16	0,16	0,16	0,16	0,16
Cl-	(mmol/l)	0,09	0,09	0,09	0,09	0,09
Ca2+	(mmol/l)					
Na+	(mmol/l)	0,09	0,09	0,07	0,14	0,21
EC	(mS/m)	1,02	1,06	1,16	1,63	2,8
pH		5,48	5,52	5,57	5,76	6,19

Ratio					Initial ratio
15%	**25%**	**30%**	**50%**	**80%**	
0,90	0,87	0,90	0,93	1,00	1;1

Ionic strength					Initial Ionic strength
15%	**25%**	**30%**	**50%**	**80%**	
18,68	20,61	22,22	27,52	38,13	20

Results of the permeability and rejection					
Recoveries	**15%**	**25%**	**30%**	**50%**	**80%**
Jw (l/m2h)	18,59	24,95	25,19	24,95	20,03
B_value (ammonium) (l/m2h)	0,0719	0,0806	0,0877	0,1359	0,1533
Rejection (ammonium)	0,9961	0,9968	0,9965	0,9945	0,9924
B_value (sodium) (l/m2h)	0,0859	0,0993	0,0826	0,1261	0,1156
Regection (sodium)	0,995399	0,996034	0,996733	0,994968	0,994257

2:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53,489	0,56
NaHCO3-	168	84,0057	2,00
NaCl	307,4	58,4397	5,26
HCl		36,458	0,09
CaCl2	555	110,978	5,00
pH	7,17		

Total Concentration (mmol/l)_Input	
NH4+	0,56
HCO3-	2,00
Cl-	15,91
Ca2+	5,00
Na+	7,26

Sensors EU					
Recovery	**15%**	**25%**	**30%**	**50%**	**63%**
Feed flow rate (m3/h)	6,81	4,09	3,41	2,04	1,27
Concentrate flowrate (m3/h)	5,79	3,07	2,38	1,02	0,38
Circulation flowrate (m3/h)	0,00	2,73	3,41	4,77	5,52
Feed pressure (bar)	9,53	9,50	9,63	9,62	8,90
Pressure drop (bar)	0,17	0,16	0,16	0,16	0,16
Permeate pressure (bar)	0,10	0,09	0,09	0,09	0,08
Conductivity Feed (µS/cm)	1614,88	1604,21	1589,63	1542,45	1455,32
Conductivity concentrate (µS/cm)	1744,98	1917,89	2014,82	2562,68	1968,58
Conductivity Permeate (µS/cm)	11,05	12,34	13,02	18,04	32,09
Feed Temperature (oC)	11,36	11,40	11,34	11,40	11,44

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**

NH4+	(mg/l)	8,43332	9,09332	9,80603	12,40547	17,34802
HCO3-	(mg/l)	112,179	120,597	131,15	164,029	226,31
Cl-	(mg/l)	422,8645	453,9712	489,5306	618,8992	876,2997
Ca2+	(mg/l)	128	144	150	194	304
Na+	(mg/l)	150,7	174,1	175,5667	249,7333	379,4667
EC	(mS/m)	142,2	157	169,8	210	275
pH		7,22	7,26	7,31	7,33	7,49

Ionic Balance (feed analysis)	-0,36	0,48	-0,29	1,08	4,21

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,47	0,50	0,54	0,69	0,96
HCO3-	(mmol/l)	1,84	1,98	2,15	2,69	3,71
Cl-	(mmol/l)	11,93	12,81	13,81	17,46	24,72
Ca2+	(mmol/l)	3,19377214	3,592993662	3,742702	4,840561	7,585209
Na+	(mmol/l)	6,56	7,57	7,64	10,86	16,51
EC	(mS/m)	142,2	157	169,8	210	275
pH		7,22	7,26	7,31	7,33	7,49

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mg/l)	0,0606	0,06823	0,0732	0,12517	0,32434
HCO3-	(mg/l)	4,636	4,819	3,965	4,331	5,856
Cl-	(mg/l)	1,81932	2,39201	1,96548	3,05582	6,68758
Ca2+	(mg/l)	<0,5	<0,5	<0,5	<0,5	<0,5
Na+	(mg/l)	1,723	2,059333	2,1	2,98	5,911667
EC	(mS/m)	0,95	1,05	1,06	1,45	2,84
pH		5,44	5,44	5,44	5,51	5,66

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,00	0,00	0,00	0,01	0,02
HCO3-	(mmol/l)	0,08	0,08	0,06	0,07	0,10
Cl-	(mmol/l)	0,05	0,07	0,06	0,09	0,19
Ca2+	(mmol/l)	<0,01	<0,01	<0,01	<0,01	<0,01
Na+	(mmol/l)	0,07	0,09	0,09	0,13	0,26
EC	(mS/m)	0,95	1,05	1,06	1,45	2,84
pH		5,44	5,44	5,44	5,51	5,66

Ratio					Initial ratio
15%	**25%**	**30%**	**50%**	**80%**	
1,96	1,83	1,95	1,74	1,63	2;1

Ionic strength					Initial Ionic strength
15%	**25%**	**30%**	**50%**	**80%**	
16,78	18,62	19,55	25,53	38,12	20

Results of the permeability and rejection					
Recoveries	**15%**	**25%**	**30%**	**50%**	**80%**
Jw (l/m2h)	24,95108	24,95108	25,19569	24,95108	21,65892
B_value (ammonium) (l/m2h)	0,180591	0,188631	0,189495	0,25432	0,412652
Rejection (ammonium)	0,992814	0,992497	0,992535	0,98991	0,981304
B_value (sodium) (l/m2h)	0,288573	0,298665	0,305021	0,30133	0,342762
Regection (sodium)	0,988567	0,988172	0,988039	0,988067	0,984421

3:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)

NH4Cl	30	53,489	0,56
NaHCO3-	168	84,0057	2,00
NaCl	137,33	58,4397	2,35
HCl		36,458	0,01
CaCl2	554,89	110,978	5,00
pH	7,26		

Total Concentration (mmol/l)_Input	
NH4+	0,56
HCO3-	2,00
Cl-	12,92
Ca2+	5,00
Na+	4,35

Sensors EU					
Recovery	**15%**	**25%**	**30%**	**50%**	**63%**
Feed flow rate (m3/h)	6,19	4,09	3,41	2,04	1,29
Concentrate flowrate (m3/h)	5,26	3,07	2,38	1,02	0,52
Circulation flowrate (m3/h)	0,00	2,73	3,41	4,77	5,54
Feed pressure (bar)	7,92	9,17	9,36	9,39	7,37
Pressure drop (bar)	0,11	0,17	0,17	0,17	0,17
Permeate pressure (bar)	0,08	0,15	0,15	0,15	0,10
Conductivity Feed (µS/cm)	1454,41	1533,87	1528,82	1483,22	1448,23
Conductivity concentrate (µS/cm)	1388,17	1824,87	1935,31	2478,26	779,03
Conductivity Permeate (µS/cm)	10,69	17,47	18,09	22,94	32,37
Feed Temperature (oC)	11,49	11,28	11,24	11,22	11,26

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mg/l)	8,68	9,18	10,00	13,20	15,20

HCO3-	(mg/l)	91,00	58,00	62,00	73,00	102,00
Cl-	(mg/l)	430,00	480,00	500,00	590,00	840,00
Ca2+	(mg/l)	166	186	194	269	336
Na+	(mg/l)	86,00	96,80	95,70	122,00	158,00
EC	(mS/m)	158	147	158	201	261
Ph		6,8	6,52	6,53	6,61	6,79

Ionic Balance (feed analysis)	-1,12	-0,49	-0,72	1,62	-0,88

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,48	0,51	0,55	0,73	0,84
HCO3-	(mmol/l)	1,49	0,95	1,02	1,20	1,67
Cl-	(mmol/l)	12,13	13,54	14,10	16,64	23,70
Ca2+	(mmol/l)	4,14	4,640950147	4,840561	6,711912	8,383652
Na+	(mmol/l)	3,74	4,21	4,16	5,31	6,87
EC	(mS/m)	225,00	222	227	281	403
pH		6,80	6,52	6,53	6,61	6,79

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mg/l)	0,17	0,19	0,19	0,26	0,42
HCO3-	(mg/l)	<10	<10	<10	<10	<10
Cl-	(mg/l)	<3	<3	3	4	6
Ca2+	(mg/l)	<0.5	<0.5	<0.5	<0.5	<0.5
Na+	(mg/l)	2,3	2,42	2,43	3,39	4,6
EC	(mS/m)	1,41	1,48	1,53	1,86	2,76
pH		5,13	5,13	5,07	5,1	5,16

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**

NH4+	(mmol/l)	0,01	0,01	0,01	0,01	0,02
HCO3-	(mmol/l)	<0.16	<0.16	<0.16	<0.16	<0.16
Cl-	(mmol/l)	<0.09	<0.09	<0.09	<0.09	<0.09
Ca2+	(mmol/l)	<0,01	<0,01	<0,01	<0,01	<0,01
Na+	(mmol/l)	0,10	0,11	0,11	0,15	0,20
EC	(mS/m)	1,41	1,48	1,53	1,86	2,76
pH		5,13	5,13	5,07	5,1	5,16

Ratio					Initial ratio
15%	**25%**	**30%**	**50%**	**80%**	
3,23	3,07	3,21	2,95	3,29	3;1

Ionic strength					Initial Ionic strength
15%	**25%**	**30%**	**50%**	**80%**	
17,21	18,89	19,60	25,36	33,31	20

Results of the permeability and rejection					
Recoveries	**15%**	**25%**	**30%**	**50%**	**80%**
Jw (l/m2h)	22,75	24,95	25,20	24,95	18,82
B_value (ammonium) (l/m2h)	0,4545	0,5273	0,4880	0,5013	0,5349
Rejection (ammonium)	0,9804	0,9793	0,9810	0,9803	0,9724
B_value (sodium) (l/m2h)	0,6251	0,6398	0,6564	0,7131	0,5645
Regection (sodium)	0,9733	0,9750	0,9746	0,9722	0,9709

4:1 ratio

Input			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53,489	0,56
NaHCO3-	168	84,0057	2,00
NaCl	54,35	58,4397	0,93

HCl		36,458	0,00
CaCl2	604,8	110,978	5,45
pH	7,165		

Total Concentration (mmol/l)Input	
NH4+	0,56
HCO3-	2,00
Cl-	12,39
Ca2+	5,45
Na+	2,93

Sensors EU					
Recovery	**15%**	**25%**	**30%**	**50%**	**63%**
Feed flow rate (m3/h)	6,81	4,09	3,41	2,04	1,29
Concentrate flowrate (m3/h)	5,79	3,07	2,38	1,02	0,60
Circulation flowrate (m3/h)	0	2,73	3,41	4,77	5,58
Feed pressure (bar)	9,33	9,32	9,49	9,45	6,63
Pressure drop (bar)	0,16911	0,16129	0,16075	0,15967	0,17
Permeate pressure (bar)	0,1	0,09	0,15	0,09	0,07
Conductivity Feed (µS/cm)	1524,82	1516,35	1507,88	1464,48	1449,90
Conductivity concentrate (µS/cm)	1601,07	1766,72	1863,02	2362,86	577,69
Conductivity Permeate (µS/cm)	11,67	12,85	13,53	18,23	25,37
Feed Temperature (oC)	11,39	11,38	11,33	11,32	11,44

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mg/l)	8,84	9,45	10,30	13,30	14,30
HCO3-	(mg/l)	121	128,00	135,00	159,00	194,00
Cl-	(mg/l)	470	440,00	470,00	550,00	640,00
Ca2+	(mg/l)	185	209	220	289	324
Na+	(mg/l)	70,1	78,60	81,70	104,00	113,00

EC	(mS/m)	165	141	153	181	218
pH		7,12	7,26	7,29	7,4	7,49

Ionic Balance (feed analysis)	-2,47	-0,14	-0,37	1,56	0,64

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,49	0,52	0,57	0,74	0,79
HCO3-	(mmol/l)	1,98	2,10	2,21	2,61	3,18
Cl-	(mmol/l)	13,26	12,41	13,26	15,51	18,05
Ca2+	(mmol/l)	4,62	5,21	5,49	7,21	8,08
Na+	(mmol/l)	3,05	3,42	3,55	4,52	4,92
EC	(mS/m)	165,00	141,00	153,00	181,00	218,00
pH		7,12	7,26	7,29	7,4	7,49

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mg/l)	0,16	0,17	0,19	0,28	0,44
HCO3-	(mg/l)	<10	<10	<10	<10	<10
Cl-	(mg/l)	<3	<3	<3	3	5
Ca2+	(mg/l)	<0.5	<0.5	<0.5	<0.5	<0.5
Na+	(mg/l)	1,71	1,95	2,01	2,89	3,98
EC	(mS/m)	0,97	1,04	1,14	1,52	2,04
pH		5,5	5,58	5,39	5,49	5,62

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,01	0,01	0,01	0,02	0,02
HCO3-	(mmol/l)	<0.06	<0.06	<0.06	<0.06	<0.06
Cl-	(mmol/l)	<0.08	<0.08	<0.08	<0.08	<0.08

Ca2+	(mmol/l)	<0,01	<0,01	<0,01	<0,01	<0,01
Na+	(mmol/l)	0,07	0,08	0,09	0,13	0,17
EC	(mS/m)	165	1,04	1,14	1,52	2,04
pH		7,12	5,58	5,39	5,49	5,62

Ratio					Initial ratio
15%	**25%**	**30%**	**50%**	**80%**	
4,31	3,68	3,75	3,44	3,72	4;1

Ionic strength					Initial Ionic strength
15%	**25%**	**30%**	**50%**	**80%**	
18,62	19,66	20,78	26,11	29,64	20

Results of the permeability and rejection					
Recoveries	**15%**	**25%**	**30%**	**50%**	**80%**
Jw (l/m2h)	24,95	24,95	25,20	24,95	16,88
B_value (ammonium) (l/m2h)	0,4599	0,4571	0,4735	0,5366	0,5358
Rejection (ammonium)	0,9819	0,9820	0,9816	0,9789	0,9692
B_value (sodium) (l/m2h)	0,6239	0,6348	0,6355	0,7132	0,6162
Regection (sodium)	0,9756	0,9752	0,9754	0,9722	0,9648

5:1 molar ratio

Input			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53,489	0,56
NaHCO3-	168	84,0057	2,00
NaCl	18,1	58,4397	0,31
HCl		36,458	0,01

CaCl2	633,7	110,978	5,71
pH	7,17		

Total Concentration (mmol/l)_Input	
NH4+	0,56
HCO3-	2,00
Cl-	12,30
Ca2+	5,71
Na+	2,31

Sensors EU					
Recovery	**15%**	**25%**	**30%**	**50%**	**63%**
Feed flow rate (m3/h)	6,81	4,03	3,41	2,04	1,28
Concentrate flowrate (m3/h)	5,79	3,06	2,39	1,02	0,39
Circulation flowrate (m3/h)	0,00	2,75	3,41	4,77	5,54
Feed pressure (bar)	9,39	8,84	9,42	9,32	8,57
Pressure drop (bar)	0,16	0,16	0,16	0,16	0,16
Permeate pressure (bar)	0,09	0,12	0,13	0,08	0,14
Conductivity Feed (µS/cm)	1467,83	1457,21	1452,70	1389,32	1300,59
Conductivity concentrate (µS/cm)	1402,96	1499,45	1593,57	1923,75	2487,69
Conductivity Permeate (µS/cm)	11,96	13,35	13,74	17,20	28,97
Feed Temperature (oC)	11,45	11,43	11,43	11,42	11,51

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mg/l)	5,21	9,64	9,91	11,82	19,12
HCO3-	(mg/l)	93,09	99,37	108,09	142,62	222,97
Cl-	(mg/l)	386,91	418,72	451,81	552,30	904,39
Ca2+	(mg/l)	191,17	216,03	253,10	346,23	476,77
Na+	(mg/l)	48,43	52,37	55,61	75,37	102,47
EC	(mS/m)	125,60	134,00	145,10	174,96	281,69

Ph		7,14	7,14	7,20	7,47	7,52

Ionic Balance (feed analysis)	-0,50	0,15	1,08	3,29	0,14

Feed Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,29	0,53	0,55	0,66	1,06
HCO3-	(mmol/l)	1,53	1,63	1,77	2,34	3,65
Cl-	(mmol/l)	10,91	11,81	12,75	15,58	25,51
Ca2+	(mmol/l)	4,77	5,39	6,32	8,64	11,90
Na+	(mmol/l)	2,11	2,28	2,42	3,28	4,46
EC	(mS/m)	125,60	134,00	145,10	174,96	281,69
Ph		7,14	7,14	7,20	7,47	7,52

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mg/l)	0,211	0,231	0,239	0,367	0,669
HCO3-	(mg/l)	4,331	3,965	4,087	4,331	5,307
Cl-	(mg/l)	1,967	2,246	2,275	3,060	5,530
Ca2+	(mg/l)	0,051	0,061	0,050	0,085	0,149
Na+	(mg/l)	1,452	1,624	1,659	2,266	3,759
EC	(mS/m)	1,000	1,090	1,100	1,410	2,440
Ph		5,350	5,320	5,310	5,670	5,660

Permeate Analysis						
		15%	**25%**	**30%**	**50%**	**80%**
NH4+	(mmol/l)	0,01	0,01	0,01	0,02	0,04
HCO3-	(mmol/l)	1,52	0,06	0,07	0,07	0,09
Cl-	(mmol/l)	10,91	0,06	0,06	0,09	0,16
Ca2+	(mmol/l)	0,00	0,00	0,00	0,00	0,00
Na+	(mmol/l)	0,06	0,07	0,07	0,10	0,16

EC	(mS/m)	1,00	1,09	1,10	1,41	2,44
Ph		5,35	5,32	5,31	5,67	5,66

Ratio					Initial ratio
15%	**25%**	**30%**	**50%**	**80%**	
5,19	4,78	4,89	4,55	5,29	5;1

Ionic strength					Initial Ionic strength
15%	**25%**	**30%**	**50%**	**80%**	
16,96	18,91	21,37	28,20	41,13	20

Results of the permeability and rejection					
Recoveries	**15%**	**25%**	**30%**	**50%**	**80%**
Jw (l/m2h)	24,97	23,62	25,05	24,95	21,66
B_value (ammonium) (l/m2h)	1,0571	0,5812	0,6197	0,7998	0,7858
Rejection (ammonium)	0,9594	0,9760	0,9759	0,9689	0,9650
B_value (sodium) (l/m2h)	0,7719	0,7558	0,7703	0,7734	0,8249
Regection (sodium)	0,9700	0,9690	0,9702	0,9699	0,9633

II. XLE

1:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	1008.1	58.4397	17.25
CaCl2			
HCl		36.458	0.297
pH	7.18		

Total Concentration (mmol/l)

NH4+	0.56
HCO3-	2.00
Cl-	18.11
Ca2+	
Na+	19.25

Sensors EU					
Recovery	**13%**	**40%**	**53%**	**62%**	**70%**
Feed flow rate (m3/h)	6.62	2.56	1.93	1.65	1.28
Concentrate flowrate (m3/h)	5.79	1.53	0.91	0.63	0.39
Circulation flowrate (m3/h)	0.21	4.26	4.89	5.16	5.54
Feed pressure (bar)	4.62	5.75	5.98	6.26	6.03
Pressure drop (bar)	0.22	0.20	0.20	0.20	0.20
Permeate pressure (bar)	0.09	0.10	0.10	0.08	0.08
Conductivity Feed (μS/cm)	1942.98	1889.48	1843.23	1795.50	1735.98
Conductivity concentrate (μS/cm)	2160.91	2953.76	3556.70	4168.69	4907.19
Conductivity Permeate (μS/cm)	30.63	37.14	41.24	41.24	41.24
Feed Temperature (oC)	11.48	11.41	11.46	11.43	11.49

Feed Analysis						
		13%	**40%**	**53%**	**62%**	**70%**
NH4+	(mg/l)	8.67	11.42	13.61	16.75	20.29
HCO3-	(mg/l)	100.59	129.75	167.51	197.82	238.51
Cl-	(mg/l)	572.16	697.11	881.86	1092.28	1298.28
Ca2+	(mg/l)					
Na+	(mg/l)	343	464	540	722	899
EC	(mS/m)	165.8	221	274	335	402
Ph		7.38	7.48	7.57	7.78	7.68

Ionic Balance (feed analysis)	-2.39	1.15	-3.38	-1.72	-0.30

Feed Analysis						
		13%	40%	53%	62%	70%
NH4+	(mmol/l)	0.48	0.63	0.75	0.93	1.12
HCO3-	(mmol/l)	1.65		2.75	3.24	3.91
Cl-	(mmol/l)	16.14	19.66	24.88	30.81	36.62
Ca2+	(mmol/l)					
Na+	(mmol/l)	14.92	20.18	23.49	31.41	39.10
EC	(mS/m)	165.8	221	274	335	402
pH		7.38	7.48	7.57	7.78	7.68

Permeate Analysis						
		13%	40%	53%	62%	70%
NH4+	(mg/l)	0.0988	0.15	0.212	0.28	0.44
HCO3-	(mg/l)	4.697	5.551	5.307	5.92	6.89
Cl-	(mg/l)	5.97	8.15	11.21	13.87	21.24
Ca2+	(mg/l)					
Na+	(mg/l)	4.902	6.95	9.08	11.15	16.5
EC	(mS/m)	2.21	3.19	4	4.94	7.32
Ph		5.78	5.84	5.89	6.03	6.07

Permeate Analysis						
		13%	40%	53%	62%	70%
NH4+	(mmol/l)	0.01	0.01	0.01	0.02	0.02
HCO3-	(mmol/l)	<0.16	<0.16	<0.16	<0.16	<0.16
Cl-	(mmol/l)	<0.09	<0.09	<0.09	<0.09	<0.09
Ca2+	(mmol/l)					
Na+	(mmol/l)	0.21	0.30	0.39	0.48	0.72
EC	(mS/m)	2.21	3.19	4	4.94	7.32
pH		5.78	5.84	5.89	6.03	6.07

Ratio					Initial ratio
13%	**40%**	**53%**	**62%**	**70%**	
1.16	0.94	1.14	1.05	1.01	1;1

Ionic strength					Initial Ionic strength
13%	**40%**	**53%**	**62%**	**70%**	
16.59	20.24	25.93	33.19	40.38	20

Results of the permeability and rejection					
Recoveries	**13%**	**40%**	**53%**	**62%**	**70%**
Jw (l/m2h)	20.30	25.20	24.95	24.95	21.94
B_value (ammonium) (l/m2h)	0.2340	0.3353	0.3948	0.4242	0.4863
Rejection (ammonium)	0.9886	0.9869	0.9844	0.9833	0.9783
B_value (sodium) (l/m2h)	0.2944	0.3831	0.4267	0.3914	0.4101
Rejection (sodium)	0.9857	0.9850	0.9832	0.9846	0.9816

2:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	306.8	58.4397	5.25
HCl		36.458	0.35
CaCl2	443.9	110.978	4.00
pH	7.24		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	14.16

Ca2+	4.00
Na+	7.25

Sensors EU					
Recovery	**13%**	**40%**	**53%**	**61%**	**62%**
Feed flow rate (m3/h)	6.63	2.56	1.93	1.59	1.65
Concentrate flowrate (m3/h)	5.79	1.53	0.91	0.61	0.63
Circulation flowrate (m3/h)	0.18	4.26	4.89	5.35	5.16
Feed pressure (bar)	4.47	5.49	5.62	5.63	5.82
Pressure drop (bar)	0.22	0.20	0.20	0.21	0.20
Permeate pressure (bar)	0.07	0.10	0.10	0.10	0.10
Conductivity Feed (µS/cm)	1607.40	1564.44	1525.25	1485.82	1487.89
Conductivity concentrate (µS/cm)	1714.64	2290.61	2705.70	3076.39	3116.89
Conductivity Permeate (µS/cm)	40.24	41.24	41.24	41.24	41.24
Feed Temperature (oC)	11.55	11.50	11.52	11.61	11.59

Feed Analysis						
		13%	**40%**	**53%**	**61%**	**62%**
NH4+	(mg/l)	8.84	11.87	14.71	16.86	17.10
HCO3-	(mg/l)	105.41	133.041	165.55	185.32	192.15
Cl-	(mg/l)	474.79	582.6	728.20	843.85	867.23
Ca2+	(mg/l)	130.6	182.4	230.93	261.03	273.63
Na+	(mg/l)	157.80	212.17	272.97	304.83	318.93
EC	(mS/m)	150.7	195.9	244	270	279
pH		7.33	7.57	7.59	7.61	7.62

Ionic Balance (feed analysis)	-1.25	0.37	0.96	0.86	0.38

Feed Analysis						
		13%	**40%**	**53%**	**61%**	**62%**
NH4+	(mmol/l)	0.49	0.66	0.82	0.93	0.95
HCO3-	(mmol/l)	1.73	2.18	2.71	3.04	3.15

Cl-	(mmol/l)	13.39	16.43	20.54	23.80	24.46
Ca2+	(mmol/l)	3.26	4.55	5.76	6.51	6.83
Na+	(mmol/l)	6.86	9.23	11.87	13.26	13.87
EC	(mS/m)	225.00	225.00	227.00	403.00	281.00
pH		7.33	7.57	7.59	7.61	7.62

Permeate Analysis						
		13%	40%	53%	61%	62%
NH4+	(mg/l)	0.32	0.46	0.63	0.78	0.79
HCO3-	(mg/l)	5.19	7.015	5.876	5.612	5.92
Cl-	(mg/l)	7.67	11.59	15.66	18.02	18.7
Ca2+	(mg/l)	0.36	0.368	0.46	0.498	0.51
Na+	(mg/l)	6.16	8.465	10.65	12.83	13.29
EC	(mS/m)	2.91	4.28	5.51	6.46	6.61
pH		5.71	5.7	5.94	5.95	5.94

Permeate Analysis						
		13%	40%	53%	61%	62%
NH4+	(mmol/l)	0.02	0.03	0.03	0.04	0.04
HCO3-	(mmol/l)	0.08	0.11	0.10	0.09	0.10
Cl-	(mmol/l)	0.22	0.33	0.44	0.51	0.53
Ca2+	(mmol/l)	0.02	0.02	0.03	0.03	0.03
Na+	(mmol/l)	0.27	0.37	0.46	0.56	0.58
EC	(mS/m)	2.91	4.28	5.51	6.46	6.61
pH		5.71	5.7	5.94	5.95	5.94

Ratio					Initial ratio
13%	40%	53%	61%	62%	
2.06	1.88	1.83	1.86	1.89	2;1

Ionic strength					Initial Ionic strength
13%	**40%**	**53%**	**61%**	**62%**	
17.75	23.35	29.50	34.87	33.54	20

Results of the permeability and rejection					
Recoveries	**13%**	**40%**	**53%**	**61%**	**62%**
Jw (l/m2h)	20.74	25.20	24.95	23.91	24.95
B_value (ammonium) (l/m2h)	0.7712	1.0158	1.1164	1.1598	1.2085
Rejection (ammonium)	0.9641	0.9612	0.9572	0.9537	0.9538
B_value (sodium) (l/m2h)	0.8423	1.0470	1.0130	1.0505	1.0849
Rejection (sodium)	0.9610	0.9601	0.9610	0.9579	0.9583

3:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4+	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	125.64	58.4397	2.15
HCl		36.458	0.305
CaCl2	554.89	110.978	5.00
pH	7.202		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.02
Ca2+	5.00
Na+	4.15

Sensors EU					
Recovery	15%	40%	53%	56%	60%
Feed flow rate (m3/h)	6.81	2.56	1.94	1.81	1.51
Concentrate flowrate (m3/h)	5.79	1.53	0.91	0.85	0.60
Circulation flowrate (m3/h)	0.00	4.26	4.89	5.02	5.30
Feed pressure (bar)	5.37	5.94	6.06	5.65	5.52
Pressure drop (bar)	0.20	0.20	0.20	0.20	0.20
Permeate pressure (bar)	0.30	0.66	0.65	0.58	0.52
Conductivity Feed (µS/cm)	1484.02	1449.46	1415.10	1421.37	1389.93
Conductivity concentrate (µS/cm)	1632.91	2112.23	2509.85	2433.50	2821.07
Conductivity Permeate (µS/cm)	35.35	45.42	56.15	46.95	70.55
Feed Temperature (oC)	11.60	11.59	11.56	11.53	11.62
Feed Analysis						

		15%	40%	53%	56%	60%
NH4+	(mg/l)	9.60	11.19	13.83	14.80	16.11
HCO3-	(mg/l)	91.62	128.40	155.49	162.56	180.68
Cl-	(mg/l)	394.38	555.89	670.96	711.80	784.85
Ca2+	(mg/l)	165.83	255.13	280.8	299.73	343.23
Na+	(mg/l)	86.6	120.57	141.10	144.90	160.00
EC	(mS/m)	127.3	175.6	211	236	243
pH		7.36	7.5	7.56	7.61	7.6

Ionic Balance (feed analysis)	-0.05	0.81	-0.56	-0.66	-0.12

Feed Analysis						
		15%	40%	53%	56%	60%
NH4+	(mmol/l)	0.53	0.62	0.77	0.82	0.89
HCO3-	(mmol/l)	1.50	2.10	2.55	2.66	2.96
Cl-	(mmol/l)	11.12	15.68	18.93	20.08	22.14
Ca2+	(mmol/l)	4.14	6.37	7.01	7.48	8.56
Na+	(mmol/l)	3.77	5.24	6.14	6.30	6.96
EC	(mS/m)	127.30	175.60	211.00	236.00	243.00

Permeate Analysis						
		15%	40%	53%	56%	60%
NH4+	(mg/l)	0.46	0.67	0.86	0.91	1.17
HCO3-	(mg/l)	4.76	5.12	5.18	6.47	5.86
Cl-	(mg/l)	7.36	10.32	12.88	13.73	17.87
Ca2+	(mg/l)	0.57	0.67	0.8	0.84	1.01
Na+	(mg/l)	4.67	6.2	7.88	8.34	9.75
EC	(mS/m)	2.94	3.92	4.83	5.1	6.48
pH		5.67	5.7	5.76	5.85	6.04

Permeate Analysis						
		15%	40%	53%	56%	60%
NH4+	(mmol/l)	0.03	0.04	0.05	0.05	0.06
HCO3-	(mmol/l)	0.08	0.08	0.08	0.11	0.10
Cl-	(mmol/l)	0.21	0.29	0.36	0.39	0.50
Ca2+	(mmol/l)	0.01	0.02	0.02	0.02	0.03
Na+	(mmol/l)	0.20	0.27	0.34	0.36	0.42
EC	(mS/m)	2.94	3.92	4.83	5.10	6.48
pH		5.67	5.70	5.76	5.85	6.04

Ratio					Initial ratio
15%	40%	53%	56%	60%	
2.94	3.03	3.11	3.19	3.20	3;1

Ionic strength					Initial Ionic strength
15%	40%	53%	56%	60%	
16.74	24.56	28.20	29.89	33.60	20

Results of the permeability and rejection					
Recoveries	15%	40%	53%	56%	60%

Jw (l/m2h)	24.95	25.20	25.20	23.37	22.34
B_value (ammonium) (l/m2h)	1.2557	1.6047	1.6706	1.5311	1.7494
Rejection (ammonium)	0.9521	0.9401	0.9378	0.9385	0.9274
B_value (sodium) (l/m2h)	1.4222	1.3659	1.4903	1.4272	1.4496
Rejection (sodium)	0.9461	0.9486	0.9442	0.9424	0.9391

4:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	46.17	58.4397	0.79
HCl		36.458	0.09
CaCl2	604.83	110.978	5.45
pH	7.202		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	12.34
Ca2+	5.45
Na+	2.79

Sensors EU					
Recovery	**15%**	**40%**	**53%**	**56%**	**62%**
Feed flow rate (m3/h)	6.81	2.54	1.93	1.83	1.64
Concentrate flowrate (m3/h)	5.79	1.52	0.91	0.80	0.63
Circulation flowrate (m3/h)	0.00	4.24	4.89	4.99	5.13
Feed pressure (bar)	5.21	5.30	5.36	5.51	5.55
Pressure drop (bar)	0.20	0.20	0.20	0.20	0.20
Permeate pressure (bar)	0.09	0.02	0.08	0.08	0.03

Conductivity Feed (µS/cm)	1454.62	1415.75	1383.95	1372.25	1351.66
Conductivity concentrate (µS/cm)	1593.06	2076.69	2455.26	2592.73	2835.44
Conductivity Permeate (µS/cm)	33.66	44.97	53.91	56.68	63.82
Feed Temperature (oC)	11.57	11.64	11.54	11.53	11.55

Feed Analysis						
		15%	**40%**	**53%**	**56%**	**62%**
NH4+	(mg/l)	8.74	11.96	14.65	15.31	16.77
HCO3-	(mg/l)	87.41	112.42	141.76	153.60	176.11
Cl-	(mg/l)	379.14	492.20	639.38	681.21	796.14
Ca2+	(mg/l)	182.53	264.07	303.67	343.10	75.73
Na+	(mg/l)	61.05	84.34	93.55	103.77	114.30
EC	(mS/m)	131.40	163.20	213.00	224.00	257.00
pH		7.24	7.32	7.46	7.55	7.61

Ionic Balance (feed analysis)	0.12	1.78	-0.32	0.75	-15.66

Feed Analysis						
		15%	**40%**	**53%**	**56%**	**62%**
NH4+	(mmol/l)	0.48	0.66	0.81	0.85	0.93
HCO3-	(mmol/l)	1.43	1.84	2.32	2.52	2.89
Cl-	(mmol/l)	10.70	13.88	18.04	19.22	22.46
Ca2+	(mmol/l)	4.55	6.59	7.58	8.56	1.89
Na+	(mmol/l)	2.66	3.67	4.07	4.51	4.97
EC	(mS/m)	131.40	163.20	213.00	224.00	257.00
pH		7.24	7.32	7.46	7.55	7.61

Permeate Analysis						
		15%	**40%**	**53%**	**56%**	**62%**
NH4+	(mg/l)	0.61	0.89	1.08	1.19	1.35
HCO3-	(mg/l)	4.45	4.88	5.06	5.12	5.67
Cl-	(mg/l)	6.73	10.06	12.22	13.16	15.06

Ca2+	(mg/l)	0.76	0.91	1.12	1.14	1.27
Na+	(mg/l)	4.19	5.23	6.63	6.95	8.32
EC	(mS/m)	2.73	3.93	4.47	4.89	5.32
pH		5.50	5.53	5.84	5.83	6.00

Permeate Analysis						
		15%	**40%**	**53%**	**56%**	**62%**
NH4+	(mmol/l)	0.03	0.05	0.06	0.07	0.07
HCO3-	(mmol/l)	0.07	0.08	0.08	0.08	0.09
Cl-	(mmol/l)	0.19	0.28	0.34	0.37	0.42
Ca2+	(mmol/l)	0.02	0.02	0.03	0.03	0.03
Na+	(mmol/l)	2.66	0.23	0.29	0.30	0.36
EC	(mS/m)	2.73	3.93	4.47	4.89	5.32
pH		5.50	5.53	5.84	5.83	6.00

Ratio					Initial ratio
15%	**40%**	**53%**	**56%**	**62%**	
3.86	3.63	4.17	4.05	4.29	4;1

Ionic strength					Initial Ionic strength
15%	**40%**	**53%**	**56%**	**62%**	
16.74	23.21	27.77	30.67	19.40	20

Results of the permeability and rejection					
Recoveries	**15%**	**40%**	**53%**	**56%**	**62%**
Jw (l/m2h)	24.95	24.79	24.95	25.20	24.74
B_value (ammonium) (l/m2h)	1.8640	1.9858	1.9853	2.1141	2.1696
Rejection (ammonium)	0.9305	0.9258	0.9263	0.9226	0.9194
B_value (sodium) (l/m2h)	1.8363	1.6390	1.9044	1.8094	1.9433
Rejection (sodium)	0.9314	0.9380	0.9291	0.9330	0.9272

5:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	6.43	58.4397	0.11
HCl		36.458	0.6
CaCl2	633.68	110.978	5.71
pH	7.2		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	12.69
Ca2+	5.71
Na+	2.11

Sensors EU					
Recovery	**15%**	**40%**	**53%**	**56%**	**62%**
Feed flow rate (m3/h)	6.81	2.56	1.93	1.83	1.6321212
Concentrate flowrate (m3/h)	5.79	1.53	0.91	0.8	0.6260606
Circulation flowrate (m3/h)	0	4.26	4.89	4.99	5.1439394
Feed pressure (bar)	5.8	6	5.47	5.59	5.54
Pressure drop (bar)	0.20203	0.20162	201	0.20041	0.20
Permeate pressure (bar)	0.77	0.74	0.11	0.11	0.11
Conductivity Feed (µS/cm)	1427.8	1390.45	1357.84	1345.67	1323.7709
Conductivity concentrate (µS/cm)	1555.27	1974.32	2332.95	2456.75	2678.7342
Conductivity Permeate (µS/cm)	34.03	39.79	48.97	51.73	58.170606
Feed Temperature (oC)	11.6	11.69	11.69	11.67	11.702424
Feed Analysis					

		15%	40%	53%	56%	62%
NH4+	(mg/l)	9.58	11.61	13.32	14.98	16.12
HCO3-	(mg/l)	90.28	117.00	150.85	162.32	181.41
Cl-	(mg/l)	373.69	494.83	636.72	701.42	771.35
Ca2+	(mg/l)	193.67	284.87	333.63	374.73	416.70
Na+	(mg/l)	48.29	67.00	75.91	83.33	90.60
EC	(mS/m)	122.40	168.60	215.00	228.00	240.00
pH		7.53	7.62	7.70	7.71	7.75

Ionic Balance (feed analysis)	0.28	1.90	0.26	0.71	0.90

Feed Analysis						
		15%	**40%**	**53%**	**56%**	**62%**
NH4+	(mmol/l)	0.53	0.64	0.74	0.83	0.89
HCO3-	(mmol/l)	1.48	1.92	2.47	2.66	2.97
Cl-	(mmol/l)	10.54	13.96	17.96	19.79	21.76
Ca2+	(mmol/l)	4.83	7.11	8.32	9.35	10.40
Na+	(mmol/l)	2.10	2.91	3.30	3.62	3.94
EC	(mS/m)	225.00	222	227	281	403
pH		7.53	7.62	7.7	7.71	7.75

Permeate Analysis						
		15%	**40%**	**53%**	**56%**	**62%**
NH4+	(mg/l)	0.65	0.95	1.21	1.31	1.82
HCO3-	(mg/l)	4.58	5.19	5.55	5.06	5.80
Cl-	(mg/l)	6.45	8.71	11.33	12.27	13.64
Ca2+	(mg/l)	0.85	1.03	1.26	1.30	1.44
Na+	(mg/l)	3.46	4.59	5.83	6.17	6.98
EC	(mS/m)	2.46	3.43	4.07	4.53	5.06
pH		5.83	5.86	5.92	5.95	6.15

Permeate Analysis						
		15%	**40%**	**53%**	**56%**	**62%**
NH4+	(mmol/l)	0.04	0.05	0.07	0.07	0.10
HCO3-	(mmol/l)	1.48	0.08	0.09	0.08	0.09
Cl-	(mmol/l)	10.54	0.25	0.32	0.35	0.38
Ca2+	(mmol/l)	0.02	0.03	0.03	0.03	0.04
Na+	(mmol/l)	2.10	0.20	0.25	0.27	0.30
EC	(mS/m)	122.40	3.43	4.07	4.53	5.06
pH		7.53	5.86	5.92	5.95	6.15

Ratio					Initial ratio
15%	**40%**	**53%**	**56%**	**62%**	
4.57	4.46	5.06	5.04	5.12	5;1

Ionic strength					Initial Ionic strength
15%	**40%**	**53%**	**56%**	**62%**	
16.99	23.93	28.89	32.15	35.58	20

Results of the permeability and rejection					
Recoveries	**15%**	**40%**	**53%**	**56%**	**62%**
Jw (l/m2h)	24.95	25.20	24.95	25.20	24.61
B_value (ammonium) (l/m2h)	1.8242	2.2460	2.4930	2.4145	3.1322
Rejection (ammonium)	0.9319	0.9182	0.9092	0.9126	0.8871
B_value (sodium) (l/m2h)	1.9259	1.8531	2.0757	2.0147	2.0530
Rejection (sodium)	0.9283	0.9315	0.9232	0.9260	0.9230

III. LG

1:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	1008.1	58.4397	17.25
HCl		36.458	0.297
pH	7.18		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	18.11
Ca2+	
Na+	19.25

Sensors EU						
Recovery		**15%**	**40%**	**52%**	**54%**	**68%**
Feed flow rate (m3/h)		6.82	2.56	1.93	1.64	1.28
Concentrate flowrate (m3/h)		5.79	1.53	0.92	0.75	0.41
Circulation flowrate (m3/h)		0.00	4.27	4.89	5.16	5.54
Feed pressure (bar)		14.23	13.92	13.49	12.15	12.27
Pressure drop (bar)		0.16	0.16	0.16	0.16	0.16
Permeate pressure (bar)		0.09	0.09	0.09	0.12	0.08
Conductivity Feed (µS/cm)		1961.26	1889.20	1845.83	1837.83	1762.93
Conductivity concentrate (µS/cm)		2236.49	3010.96	3580.95	3663.70	4921.00
Conductivity Permeate (µS/cm)		7.33	8.87	10.29	11.22	17.00
Feed Temperature (oC)		11.30	11.32	11.32	11.34	11.40
Feed Analysis						
		15%	**40%**	**53%**	**62%**	**68%**
NH4+	(mg/l)	8.39	12.66	15.42	14.34	18.80
HCO3-	(mg/l)	112.00	134.20	166.66	178.00	238.33

Cl-	(mg/l)	530.00	744.80	1006.47	942.57	1185.00
Ca2+	(mg/l)					
Na+	(mg/l)	396.00	534.00	587.00	617.00	940.27
EC	(mS/m)	176.00	231.00	274.21	293.00	411.00
pH		7.34	7.35	7.52	7.59	7.53

Ionic Balance (feed analysis)	0.90	0.72	-4.73	-1.87	4.61

Feed Analysis						
		15%	**40%**	**53%**	**62%**	**68%**
NH4+	(mmol/l)	0.47	0.70	0.85	0.79	1.04
HCO3-	(mmol/l)	1.84	2.20	2.73	2.92	3.91
Cl-	(mmol/l)	14.95	21.01	28.39	26.59	33.43
Ca2+	(mmol/l)					
Na+	(mmol/l)	17.23	23.23	25.53	26.84	40.90
EC	(mS/m)	176	231	274.21	293	411
pH		7.34	7.35	7.52	7.59	7.53

Permeate Analysis						
		15%	**40%**	**53%**	**62%**	**68%**
NH4+	(mg/l)	0.03	0.06	0.07	0.08	0.14
HCO3-	(mg/l)	4.33	5.06	5.55	6.03	6.65
Cl-	(mg/l)	1.13	1.50	1.44	1.57	2.92
Ca2+	(mg/l)					
Na+	(mg/l)	1.06	1.42	1.94	2.17	3.14
EC	(mS/m)	0.62	0.79	0.88	0.96	1.46
pH		5.94	5.69	5.81	5.9	5.93

Permeate Analysis						
		15%	**40%**	**53%**	**62%**	**68%**

NH4+	(mmol/l)	0.00	0.00	0.00	0.00	0.01
HCO3-	(mmol/l)	0.07	0.08	0.09	0.10	0.11
Cl-	(mmol/l)	0.03	0.04	0.04	0.04	0.08
Ca2+	(mmol/l)					
Na+	(mmol/l)	0.05	0.06	0.08	0.09	0.14
EC	(mS/m)	0.62	0.79	0.88	0.96	1.46
pH		5.94	5.69	5.81	5.9	5.93

Ratio					Initial ratio
15%	**40%**	**53%**	**62%**	**68%**	
0,95	0,97	1,18	1,07	0,89	1;1

Ionic strength					Initial Ionic strength
15%	**40%**	**53%**	**62%**	**68%**	
17,24	23,57	28,76	28,57	39,64	20

Results of the permeability and rejection					
Recoveries	**15%**	**40%**	**53%**	**62%**	**68%**
Jw (l/m2h)	25.20	25.27	24.71	21.69	21.28
B_value (ammonium) (l/m2h)	0.0904	0.1203	0.1127	0.1217	0.1597
Rejection (ammonium)	0.9964	0.9953	0.9955	0.9944	0.9926
B_value (sodium) (l/m2h)	0.0676	0.0674	0.0819	0.0766	0.0712
Rejection (sodium)	0.9973	0.9973	0.9967	0.9965	0.9967

2:1 molar ratio

Input			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	306.8	58.4397	5.25
HCl		36.458	0.35

CaCl2	443.9	110.978	4.00
pH	7.24		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	14.16
Ca2+	4.00
Na+	7.25

Sensors EU						
Recovery		**15%**	**40%**	**53%**	**57%**	**59%**
Feed flow rate (m3/h)		6.81	2.56	1.93	1.51	1.65
Concentrate flowrate (m3/h)		5.79	1.53	0.91	0.65	0.68
Circulation flowrate (m3/h)		0.00	4.26	4.89	5.32	5.16
Feed pressure (bar)		13.73	13.44	13.35	11.37	12.74
Pressure drop (bar)		0.16	0.16	0.16	0.16	0.16
Permeate pressure (bar)		0.10	0.09	0.09	0.07	0.08
Conductivity Feed (µS/cm)		1596.21	1550.06	1511.99	1495.59	1487.26
Conductivity concentrate (µS/cm)		1746.70	2296.58	2711.12	2886.69	2982.31
Conductivity Permeate (µS/cm)		7.04	8.31	9.57	11.13	10.72
Feed Temperature (oC)		11.37	11.45	11.39	11.53	11.39
Feed Analysis						
		15%	**40%**	**53%**	**57%**	**59%**
NH4+	(mg/l)	8.93	11.80	14.70	16.59	17.06
HCO3-	(mg/l)	101.00	135.00	166.00	175.90	184.46
Cl-	(mg/l)	460.00	600.00	730.00	803.90	818.40
Ca2+	(mg/l)	134.00	184.00	239.00	250.80	253.20
Na+	(mg/l)	128.00	204.00	271.00	282.40	289.00
EC	(mS/m)	153.20	201.00	243.00	258.00	257.00

pH		7.22	7.33	7.41	7.44	7.44

Ionic Balance (feed analysis)	-1.88	-0.43	1.22	0.04	0.16

Feed Analysis						
		15%	**40%**	**53%**	**57%**	**59%**
NH4+	(mmol/l)	0.50	0.65	0.81	0.92	0.95
HCO3-	(mmol/l)	1.66	2.21	2.72	2.88	3.02
Cl-	(mmol/l)	12.98	16.93	20.59	22.68	23.09
Ca2+	(mmol/l)	3.34	4.59	5.96	6.26	6.32
Na+	(mmol/l)	5.57	8.87	11.79	12.28	12.57
EC	(mS/m)	153.20	201.00	243.00	258.00	257.00
pH		7.22	7.33	7.41	7.44	7.44

Permeate Analysis						
		15%	**40%**	**53%**	**57%**	**59%**
NH4+	(mg/l)	0.09	0.12	0.16	0.22	0.20
HCO3-	(mg/l)	5.58	4.70	4.88	5.46	4.88
Cl-	(mg/l)	0.99	1.23	1.45	1.69	1.94
Ca2+	(mg/l)	0.11	0.12	0.13	0.13	0.14
Na+	(mg/l)	0.60	0.97	0.95	1.23	1.17
EC	(mS/m)	0.64	0.66	0.81	2.69	0.91
pH		5.63	6.03	5.53	5.87	5.57

Permeate Analysis						
		15%	**40%**	**53%**	**57%**	**59%**
NH4+	(mmol/l)	0.00	0.01	0.01	0.01	0.01
HCO3-	(mmol/l)	0.09	0.08	0.08	0.09	0.08
Cl-	(mmol/l)	0.03	0.03	0.04	0.05	0.05

Ca2+	(mmol/l)	0.00	0.00	0.00	0.00	0.00
Na+	(mmol/l)	0.03	0.04	0.04	0.05	0.05
EC	(mS/m)	0.64	0.66	0.81	2.69	0.91
pH		5.63	6.03	5.53	5.87	5.57

Ratio					Initial ratio
15%	**40%**	**53%**	**57%**	**59%**	
2.41	2.01	1.85	1.93	1.94	2;1

Ionic strength					Initial Ionic strength
15%	**40%**	**53%**	**57%**	**59%**	
17.03	23.51	29.88	32.45	31.90	20

Results of the permeability and rejection					
Recoveries	**15%**	**40%**	**53%**	**57%**	**59%**
Jw (l/m2h)	24.95	25.20	24.95	21.07	23.73
B_value (ammonium) (l/m2h)	0.2512	0.2530	0.2664	0.2831	0.2804
Rejection (ammonium)	0.9900	0.9901	0.9894	0.9867	0.9883
B_value (sodium) (l/m2h)	0.1182	0.1200	0.0877	0.0922	0.0965
Rejection (sodium)	0.9953	0.9953	0.9965	0.9956	0.9960

3:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	125.64	58.4397	2.15
HCl		36.458	0.31
CaCl2	554.89	110.978	5.00
pH	7.202		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.02
Ca2+	5.00
Na+	4.15

Sensors EU						
Recovery		15%	40%	47%	50%	53%
Feed flow rate (m3/h)		6.81	2.56	1.46	1.66	1.93
Concentrate flowrate (m3/h)		5.79	1.53	0.77	0.83	0.91
Circulation flowrate (m3/h)		0.00	4.26	5.40	5.16	4.89
Feed pressure (bar)		13.58	13.34	9.19	10.68	13.10
Pressure drop (bar)		0.16	0.16	0.17	0.16	0.16
Permeate pressure (bar)		0.09	0.17	0.06	0.07	0.08
Conductivity Feed (µS/cm)		1479.35	1441.89	1421.22	1414.64	1406.38
Conductivity concentrate (µS/cm)		1630.36	2108.60	2331.66	2350.97	2481.99
Conductivity Permeate (µS/cm)		6.94	7.43	10.19	9.19	8.64
Feed Temperature (oC)		11.48	11.51	11.59	11.62	11.41
Feed Analysis						
		15%	**40%**	**47%**	**50%**	**53%**
NH4+	(mg/l)	8.43	11.91	14.09	13.97	14.04
HCO3-	(mg/l)	91.317	119.01	137.25	149.63	155.85
Cl-	(mg/l)	400.38	521.30	611.27	668.42	676.10
Ca2+	(mg/l)	154.43	241.2	257.67	277.77	296.87
Na+	(mg/l)	85.12	120.60	126.83	137.20	145.60
EC	(mS/m)	131.1	170.5	196.5	212	212
pH		7.32	7.47	7.55	7.54	7.55

Ionic Balance (feed analysis)	-0.91	1.29	-0.34	-0.70	0.30

Feed Analysis						
		15%	40%	47%	50%	53%
NH4+	(mmol/l)	0.47	0.66	0.78	0.77	0.78
HCO3-	(mmol/l)	1.50	1.95	2.25	2.45	2.55
Cl-	(mmol/l)	11.29	14.71	17.24	18.86	19.07
Ca2+	(mmol/l)	3.85	6.02	6.43	6.93	7.41
Na+	(mmol/l)	3.70	5.25	5.52	5.97	6.33
EC	(mS/m)	225.00	225.00	225.00	225.00	225.00
pH		7.32	7.47	7.55	7.54	7.55

Permeate Analysis						
		15%	40%	47%	50%	53%
NH4+	(mg/l)	0.12	0.17	0.29	0.25	0.23
HCO3-	(mg/l)	4.27	4.94	5.49	4.941	4.697
Cl-	(mg/l)	0.91	1.49	1.81	1.42	1.33
Ca2+	(mg/l)	0.16	0.18	0.213	0.182	0.19
Na+	(mg/l)	0.57	0.73	1.28	1.03	0.93
EC	(mS/m)	0.53	0.63	0.93	0.75	0.7
pH		5.59	5.6	5.83	5.71	5.68

Permeate Analysis						
		15%	40%	47%	50%	53%
NH4+	(mmol/l)	0.01	0.01	0.02	0.01	0.01
HCO3-	(mmol/l)	0.07	0.08	0.09	0.08	0.08
Cl-	(mmol/l)	0.03	0.04	0.05	0.04	0.04
Ca2+	(mmol/l)	0.00	0.00	0.01	0.00	0.00
Na+	(mmol/l)	0.02	0.03	0.06	0.04	0.04
EC	(mS/m)	0.53	0.63	0.93	0.75	0.70
pH		5.59	5.60	5.83	5.71	5.68

Ratio					Initial ratio
15%	**40%**	**53%**	**62%**	**68%**	
3.07	2.82	3.10	3.16	3.04	3;1

Ionic strength					Initial Ionic strength
15%	**40%**	**53%**	**62%**	**68%**	
16.19	23.32	25.75	27.89	29.18	20

Results of the permeability and rejection					
Recoveries	**15%**	**40%**	**47%**	**50%**	**53%**
Jw (l/m2h)	24.95	25.20	16.73	20.30	24.95
B_value (ammonium) (l/m2h)	0.3603	0.3648	0.3516	0.3700	0.4156
Rejection (ammonium)	0.9858	0.9857	0.9794	0.9821	0.9836
B_value (sodium) (l/m2h)	0.1682	0.1534	0.1706	0.1536	0.1604
Rejection (sodium)	0.9933	0.9939	0.9899	0.9925	0.9936

4:1 molar ratio

Input			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	46.17	58.4397	0.79
HCl		36.458	0.31
CaCl2	604.83	110.978	5.45
pH	7.202		

Total Concentration (mmol/l)Input	
NH4+	0.56
HCO3-	2.00
Cl-	12.56

Ca2+	5.45
Na+	2.79

Sensors EU					
Recovery	**15%**	**40%**	**47%**	**50%**	**53%**
Feed flow rate (m3/h)	6.81	2.56	2.19	2.04	1.93
Concentrate flowrate (m3/h)	5.79	1.53	1.17	1.00	0.91
Circulation flowrate (m3/h)	0.00	4.26	4.62	4.77	4.89
Feed pressure (bar)	13.49	13.38	13.11	13.25	13.10
Pressure drop (bar)	0.16	0.16	0.16	0.16	0.16
Permeate pressure (bar)	0.14	0.24	0.08	0.08	0.08
Conductivity Feed (µS/cm)	1440.05	1402.61	1392.24	1378.53	1371.48
Conductivity concentrate (µS/cm)	1583.67	2069.67	2258.02	2389.13	2445.37
Conductivity Permeate (µS/cm)	7.08	7.92	8.20	8.39	8.88
Feed Temperature (oC)	11.52	11.53	11.47	11.44	11.49

Feed Analysis						
		15%	**40%**	**47%**	**50%**	**53%**
NH4+	(mg/l)	8.70	12.21	13.26	14.26	14.69
HCO3-	(mg/l)	85.10	111.08	133.22	147.56	144.45
Cl-	(mg/l)	381.22	507.41	595.71	653.44	660.03
Ca2+	(mg/l)	180.93	265.33	211.57	307.70	317.27
Na+	(mg/l)	60.02	85.29	72.32	98.55	101.93
EC	(mS/m)	122.90	164.50	186.16	205.00	215.00
pH		7.10	7.24	7.34	7.53	7.56

Ionic Balance (feed analysis)	-0.03	1.49	-4.55	-0.42	0.09

Feed Analysis						
		15%	**40%**	**47%**	**50%**	**53%**
NH4+	(mmol/l)	0.48	0.68	0.74	0.79	0.81
HCO3-	(mmol/l)	1.39	1.82	2.18	2.42	2.37

Cl-	(mmol/l)	10.75	14.31	16.80	18.43	18.62
Ca2+	(mmol/l)	4.51	6.62	5.28	7.68	7.92
Na+	(mmol/l)	2.61	3.71	3.15	4.29	4.43
EC	(mS/m)	122.90	164.50	186.16	205.00	215.00
pH		7.10	7.24	7.34	7.53	7.56

Permeate Analysis						
		15%	**40%**	**47%**	**50%**	**53%**
NH4+	(mg/l)	0.17	0.21	0.26	0.30	0.35
HCO3-	(mg/l)	4.09	4.94	4.82	4.82	4.82
Cl-	(mg/l)	1.07	1.43	1.47	1.72	2.35
Ca2+	(mg/l)	0.21	0.22	0.24	0.25	0.24
Na+	(mg/l)	0.44	0.59	0.69	0.73	0.75
EC	(mS/m)	0.57	0.66	0.71	0.75	1.09
pH		5.44	5.41	5.44	5.66	5.75

Permeate Analysis						
		15%	**40%**	**47%**	**50%**	**53%**
NH4+	(mmol/l)	0.01	0.01	0.01	0.02	0.02
HCO3-	(mmol/l)	1.39	0.08	0.08	0.08	0.08
Cl-	(mmol/l)	10.75	0.04	0.04	0.05	0.07
Ca2+	(mmol/l)	0.01	0.01	0.01	0.01	0.01
Na+	(mmol/l)	2.61	0.03	0.03	0.03	0.03
EC	(mS/m)	0.57	0.66	0.71	0.75	1.09
pH		5.44	5.41	5.44	5.66	5.75

Ratio					Initial ratio
15%	**40%**	**47%**	**50%**	**53%**	
3,93	3,68	4,89	4,11	4,00	4;1

Ionic strength	Initial Ionic strength

15%	40%	47%	50%	53%	
16,65	23,50	21,99	28,32	28,95	20

Results of the permeability and rejection					
Recoveries	**15%**	**40%**	**47%**	**50%**	**53%**
Jw (l/m2h)	24.95	25.20	25.02	25.45	24.95
B_value (ammonium) (l/m2h)	0.4877	0.4363	0.5002	0.5505	0.6092
Rejection (ammonium)	0.9808	0.9830	0.9804	0.9788	0.9762
B_value (sodium) (l/m2h)	0.1846	0.1753	0.2403	0.1896	0.1841
Rejection (sodium)	0.9927	0.9931	0.9905	0.9926	0.9927

5:1 molar ratio

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	6.43	58.4397	0.11
HCl	0.6	36.458	0.01
CaCl2	633.68	110.978	5.71
pH	7.2		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	12.10
Ca2+	5.71
Na+	2.11

Sensors EU					
Recovery	**15%**	**42%**	**46%**	**50%**	**53%**

Feed flow rate (m3/h)	6.81	2.59	2.22	2.04	1.93
Concentrate flowrate (m3/h)	5.79	1.50	1.20	1.02	0.91
Circulation flowrate (m3/h)	0.00	4.30	4.59	4.75	4.89
Feed pressure (bar)	13.42	14.10	13.17	13.15	13.10
Pressure drop (bar)	0.16	0.16	0.16	0.16	0.16
Permeate pressure (bar)	0.15	0.09	0.08	0.08	0.08
Conductivity Feed (µS/cm)	1420.88	1379.27	1369.83	1357.25	1348.52
Conductivity concentrate (µS/cm)	1543.69	2045.63	2077.62	2196.68	2322.05
Conductivity Permeate (µS/cm)	7.17	7.05	7.31	7.64	8.26
Feed Temperature (oC)	11.48	11.53	11.52	11.56	11.50

Feed Analysis						
		15%	**42%**	**46%**	**50%**	**53%**
NH4+	(mg/l)	8.53	11.56	13.01	13.66	14.07
HCO3-	(mg/l)	95.22	126.94	137.86	140.61	151.46
Cl-	(mg/l)	413.87	537.01	603.47	603.77	660.82
Ca2+	(mg/l)	194.00	283.30	306.87	325.57	333.63
Na+	(mg/l)	47.25	68.69	74.03	77.40	79.31
EC	(mS/m)	134.00	170.90	193.70	201.00	216.00
pH		7.35	7.64	7.63	7.65	7.67

Ionic Balance (feed analysis)	-1.03	0.54	-0.03	1.03	-0.24

Feed Analysis						
		15%	**42%**	**46%**	**50%**	**53%**
NH4+	(mmol/l)	0.47	0.64	0.72	0.76	0.78
HCO3-	(mmol/l)	1.56	2.08	2.26	2.30	2.48
Cl-	(mmol/l)	11.67	15.15	17.02	17.03	18.64
Ca2+	(mmol/l)	4.84	7.07	7.66	8.12	8.32
Na+	(mmol/l)	2.06	2.99	3.22	3.37	3.45
EC	(mS/m)	134.00	170.90	193.70	201.00	216.00
pH		7.35	7.64	7.63	7.65	7.67

Permeate Analysis						
		15%	42%	46%	50%	53%
NH4+	(mg/l)	0.198	0.267	0.311	0.334	0.344
HCO3-	(mg/l)	4.697	4.575	4.575	4.697	4.880
Cl-	(mg/l)	1.542	1.362	1.258	1.373	2.001
Ca2+	(mg/l)	0.247	0.260	0.249	0.244	0.279
Na+	(mg/l)	0.404	0.519	0.559	0.598	0.648
EC	(mS/m)	0.670	0.590	0.600	0.630	0.690
pH		5.700	5.780	5.840	5.860	5.870

Permeate Analysis						
		15%	42%	46%	50%	53%
NH4+	(mmol/l)	0.01	0.01	0.02	0.02	0.02
HCO3-	(mmol/l)	1.56	0.07	0.07	0.08	0.08
Cl-	(mmol/l)	11.67	0.04	0.04	0.04	0.06
Ca2+	(mmol/l)	0.01	0.01	0.01	0.01	0.01
Na+	(mmol/l)	2.06	0.02	0.02	0.03	0.03
EC	(mS/m)	134.00	0.59	0.60	0.63	0.69
pH		7.35	5.78	5.84	5.86	5.87

Ratio					Initial ratio
15%	42%	46%	50%	53%	
5,24	4,75	4,89	4,69	4,99	5;1

Ionic strength					Initial Ionic strength
15%	42%	46%	50%	53%	
17,56	24,57	26,93	27,98	29,33	20

Results of the permeability and rejection					
Recoveries	**15%**	**42%**	**46%**	**50%**	**53%**
Jw (l/m2h)	24.95	26.66	24.95	24.90	24.95
B_value (ammonium) (l/m2h)	0.5937	0.6302	0.6105	0.6246	0.6257
Rejection (ammonium)	0.9768	0.9769	0.9761	0.9755	0.9755
B_value (sodium) (l/m2h)	0.2152	0.2029	0.1899	0.1939	0.2055
Rejection (sodium)	0.9914	0.9924	0.9924	0.9923	0.9918

Appendix F: Calculations regarding the different pH and 3:1 molar ratio

I. XLE

pH=5

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	88.8	58.4397	1.52
CaCl2	554.92	110.984	5.00
HCl		36.458	0.95
pH	4.9		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.03
Ca2+	5.00
Na+	3.52

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.81	1.93
Concentrate flowrate (m3/h)	5.79	0.91
Circulation flowrate (m3/h)	0.00	4.88
Feed pressure (bar)	4.92	5.37
Pressure drop (bar)	0.20	0.20
Permeate pressure (bar)	0.11	0.22
Conductivity Feed (µS/cm)	1396.72	1290.07
Conductivity concentrate (µS/cm)	1527.19	2327.22

Conductivity Permeate (μS/cm)		64.34	87.44
Feed Temperature (oC)		11.55	11.65
Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	8.07	12.06
HCO3-	(mg/l)	6.00	6.84
Cl-	(mg/l)	398.91	636.39
Ca2+	(mg/l)	145.77	246.40
Na+	(mg/l)	82.45	131.70
EC	(mS/m)	136.98	175.89
pH		5.58	5.65

Ionic Balance (feed analysis)	-0.04	9.77

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.45	0.67
HCO3-	(mmol/l)	0.10	0.11
Cl-	(mmol/l)	11.25	17.95
Ca2+	(mmol/l)	3.64	10.71784
Na+	(mmol/l)	3.59	5.73
EC	(mS/m)	136.98	175.89
pH		5.58	5.65

Permeate Analysis			
		15%	**53%**
NH4+	(mg/l)	1.47	1.91
HCO3-	(mg/l)	3.12	2.94
Cl-	(mg/l)	15.44	21.39
Ca2+	(mg/l)	1.00	1.17

Na+	(mg/l)	8.38	11.73
EC	(mS/m)	5.16	7.15
pH		5.25	5.24

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.08	0.11
HCO3-	(mmol/l)	0.05	0.05
Cl-	(mmol/l)	0.44	0.60
Ca2+	(mmol/l)	0.02	0.03
Na+	(mmol/l)	0.36	0.51
EC	(mS/m)	5.16	7.15
pH		5.25	5.24

Ratio		Initial Ratio
15%	**53%**	
2.8	2.8	3;1

Ionic strength		Initial ionic strength
15%	**53%**	
15	33.7	20

Results of the permeability and rejection		
Recoveries	**15%**	**53%**
Jw (l/m2h)	24.95	24.88
B_value (ammonium) (l/m2h)	5.5575	4.6811
Rejection (ammonium)	0.8178	0.8416
B_value (sodium) (l/m2h)	1.6259	1.7778

Rejection (sodium)	0.9388	0.9333

pH=6

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	98.8	58.4397	1.69
CaCl2	554.92	110.984	5.00
HCl		36.458	0.95
pH	6.09		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.20
Ca2+	5.00
Na+	3.69

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.82	1.91
Concentrate flowrate (m3/h)	5.79	0.91
Circulation flowrate (m3/h)	0.00	4.87
Feed pressure (bar)	4.60	5.31
Pressure drop (bar)	0.21	0.20
Permeate pressure (bar)	0.06	0.24
Conductivity Feed (µS/cm)	1344.98	1242.68
Conductivity concentrate (µS/cm)	1468.30	2259.96
Conductivity Permeate (µS/cm)	37.68	53.51
Feed Temperature (oC)	11.74	11.72

Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	9.10	11.30
HCO3-	(mg/l)	55.29	89.78
Cl-	(mg/l)	432.73	542.53
Ca2+	(mg/l)	154.30	260.23
Na+	(mg/l)	70.20	111.77
EC	(mS/m)	115.90	185.83
pH		6.69	6.90

Ionic Balance (feed analysis)	-1.86	1.70

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.50	0.63
HCO3-	(mmol/l)	0.91	1.47
Cl-	(mmol/l)	12.21	15.30
Ca2+	(mmol/l)	3.85	6.49
Na+	(mmol/l)	3.05	4.86
EC	(mS/m)	115.90	185.83
pH		6.69	6.90

Permeate Analysis			
		15%	**53%**
NH4+	(mg/l)	0.63	0.87
HCO3-	(mg/l)	4.44	4.38
Cl-	(mg/l)	7.74	11.18
Ca2+	(mg/l)	0.61	0.76
Na+	(mg/l)	5.01	6.97
EC	(mS/m)	3.31	4.54
pH		5.35	5.36

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.03	0.05
HCO3-	(mmol/l)	0.07	0.07
Cl-	(mmol/l)	0.22	0.32
Ca2+	(mmol/l)	0.02	0.02
Na+	(mmol/l)	0.22	0.30
EC	(mS/m)	3.31	4.54
pH		5.35	5.36

Ratio		Initial Ratio
15%	**53%**	
3.7	3	3;1

Ionic strength		Initial ionic strength
15%	**53%**	
16	24.1	20

Results of the permeability and rejection		
Recoveries	**15%**	**53%**
Jw (l/m2h)	25.20	24.67
B_value (ammonium) (l/m2h)	1.8741	2.0659
Rejection (ammonium)	0.9308	0.9227
B_value (sodium) (l/m2h)	1.1393	0.9616
Rejection (sodium)	0.9567	0.9625

pH=8

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	143.18	58.4397	2.45
CaCl2	554.92	110.984	5.00
HCl		36.458	
pH	8.04		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.01
Ca2+	5.00
Na+	4.45

Sensors EU		
Recovery		**15%**
Feed flow rate (m3/h)		6.83
Concentrate flowrate (m3/h)		5.78
Circulation flowrate (m3/h)		0.00
Feed pressure (bar)		6.40
Pressure drop (bar)		0.20
Permeate pressure (bar)		1.50
Conductivity Feed (µS/cm)		1537.61
Conductivity concentrate (µS/cm)		1683.83
Conductivity Permeate (µS/cm)		31.29
Feed Temperature (oC)		11.55
Feed Analysis		
		15%

NH4+	(mg/l)	8.55
HCO3-	(mg/l)	112.00
Cl-	(mg/l)	390.08
Ca2+	(mg/l)	161.90
Na+	(mg/l)	98.81
EC	(mS/m)	136.70
pH		7.86

Ionic Balance (feed analysis)	0.01

Feed Analysis		
		15%
NH4+	(mmol/l)	0.47
HCO3-	(mmol/l)	1.84
Cl-	(mmol/l)	11.00
Ca2+	(mmol/l)	4.04
Na+	(mmol/l)	4.30
EC	(mS/m)	136.70
pH		7.86

Ratio	Initial Ratio
15%	
2.7	3;1

Ionic strength	Initial ionic strength
15%	
16.9	20

Results of the permeability and rejection

Recoveries	**15%**
Jw (l/m2h)	25.75
B_value (ammonium) (l/m2h)	1.4977
Rejection (ammonium)	0.9450
B_value (sodium) (l/m2h)	1.3492
Rejection (sodium)	0.9502

II. LG

pH=5

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	88.8	58.4397	1.52
CaCl2	554.92	110.984	5.00
HCl		36.458	1
pH	4.9		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.08
Ca2+	5.00
Na+	3.52

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.81	1.93
Concentrate flowrate (m3/h)	5.79	0.91

Circulation flowrate (m3/h)	0.00	4.89
Feed pressure (bar)	13.42	12.73
Pressure drop (bar)	0.16	0.16
Permeate pressure (bar)	0.05	0.05
Conductivity Feed (µS/cm)	1378.77	1262.46
Conductivity concentrate (µS/cm)	1528.33	2349.89
Conductivity Permeate (µS/cm)	17.37	16.77
Feed Temperature (oC)	11.45	11.61

Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	8.13	12.03
HCO3-	(mg/l)	9.30	6.54
Cl-	(mg/l)	393.49	596.97
Ca2+	(mg/l)	153.10	260.43
Na+	(mg/l)	74.89	118.93
EC	(mS/m)	128.06	189.27
pH		5.77	5.56

	Ionic Balance (feed analysis)	0.10	11.55
Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.45	0.67
HCO3-	(mmol/l)	0.15	0.11
Cl-	(mmol/l)	11.10	16.84
Ca2+	(mmol/l)	3.82	11.33
Na+	(mmol/l)	3.26	5.17
EC	(mS/m)	128.06	189.27
pH		5.77	5.56

Permeate Analysis

		15%	53%
NH4+	(mg/l)	0.21	0.44
HCO3-	(mg/l)	1.44	2.28
Cl-	(mg/l)	1.72	2.57
Ca2+	(mg/l)	0.38	0.47
Na+	(mg/l)	0.32	0.61
EC	(mS/m)	1.23	1.34
pH		4.84	4.93

Permeate Analysis			
		15%	53%
NH4+	(mmol/l)	0.01	0.02
HCO3-	(mmol/l)	0.02	0.04
Cl-	(mmol/l)	0.05	0.07
Ca2+	(mmol/l)	0.01	0.02
Na+	(mmol/l)	0.01	0.03
EC	(mS/m)	1.23	1.34
pH		4.84	4.93

Ratio		Initial Ratio
15%	53%	
3.0	2.9	3;1

Ionic strength		Initial ionic strength
15%	53%	
15.1	34.0	20

Results of the permeability and rejection

Recoveries	**15%**	**53%**
Jw (l/m2h)	24.95	25.04
B_value (ammonium) (l/m2h)	0.6616	0.9509
Rejection (ammonium)	0.9742	0.9634
B_value (sodium) (l/m2h)	0.105728	0.081355148
Rejection (sodium)	0.99578	0.996761241

pH=6

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	98.8	58.4397	1.69
CaCl2	554.92	110.984	5.00
HCl		36.458	0.85
pH	6.09		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.10
Ca2+	5.00
Na+	3.69

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.84	1.90
Concentrate flowrate (m3/h)	5.79	0.90

Circulation flowrate (m3/h)	0.00	4.90
Feed pressure (bar)	12.56	12.42
Pressure drop (bar)	0.16	0.16
Permeate pressure (bar)	0.11	0.10
Conductivity Feed (μS/cm)	1345.59	1238.09
Conductivity concentrate (μS/cm)	1471.12	2270.81
Conductivity Permeate (μS/cm)	8.01	10.43
Feed Temperature (oC)	11.49	11.63

Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	7.79	12.66
HCO3-	(mg/l)	63.15	89.30
Cl-	(mg/l)	358.18	614.83
Ca2+	(mg/l)	154.73	257.70
Na+	(mg/l)	70.13	115.20
EC	(mS/m)	129.60	190.20
pH		6.93	6.93

Ionic Balance (feed analysis)	0.06	-0.23

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.43	0.70
HCO3-	(mmol/l)	1.03	1.46
Cl-	(mmol/l)	10.10	17.34
Ca2+	(mmol/l)	3.86	6.43
Na+	(mmol/l)	3.05	5.01
EC	(mS/m)	129.60	190.20
pH		6.93	6.93

Permeate Analysis			
		15%	**53%**
NH4+	(mg/l)	0.22	0.30
HCO3-	(mg/l)	4.26	4.44
Cl-	(mg/l)	1.22	1.86
Ca2+	(mg/l)	0.19	0.23
Na+	(mg/l)	0.54	0.86
EC	(mS/m)	0.83	0.84
pH		5.36	5.35

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.012	0.017
HCO3-	(mmol/l)	0.070	0.073
Cl-	(mmol/l)	0.034	0.052
Ca2+	(mmol/l)	0.005	0.006
Na+	(mmol/l)	0.023	0.037
EC	(mS/m)	0.830	0.840
pH		5.360	5.350

Ratio		Initial Ratio
15%	**53%**	
3.2	3.3	3;1

Ionic strength		Initial ionic strength
15%	**53%**	
15.0	25.1	20

Results of the permeability and rejection		
Recoveries	**15%**	**53%**
Jw (l/m2h)	25.72	24.46
B_value (ammonium) (l/m2h)	0.7476	0.5937
Rejection (ammonium)	0.9718	0.9763
B_value (sodium) (l/m2h)	0.1076	0.1111
Rejection (sodium)	0.9958	0.9955

pH=8

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	143.18	58.4397	2.45
CaCl2	554.92	110.984	5.00
HCl		36.458	
pH	8.04		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.01
Ca2+	5.00
Na+	4.45

Sensors EU	
Recovery	**15%**
Feed flow rate (m3/h)	6.78
Concentrate flowrate (m3/h)	5.79

Circulation flowrate (m3/h)	0.00
Feed pressure (bar)	12.92
Pressure drop (bar)	0.16
Permeate pressure (bar)	0.24
Conductivity Feed (µS/cm)	1563.64
Conductivity concentrate (µS/cm)	1717.10
Conductivity Permeate (µS/cm)	6.15
Feed Temperature (oC)	11.49

Feed Analysis		
		15%
NH4+	(mg/l)	8.57
HCO3-	(mg/l)	113.58
Cl-	(mg/l)	402.50
Ca2+	(mg/l)	165.23
Na+	(mg/l)	98.90
EC	(mS/m)	136.20
pH		7.82

Ionic Balance (feed analysis)	-0,19

Feed Analysis		
		15%
NH4+	(mmol/l)	0,48
HCO3-	(mmol/l)	1,86
Cl-	(mmol/l)	11,35
Ca2+	(mmol/l)	4,12
Na+	(mmol/l)	4,30
EC	(mS/m)	136,20
pH		7,82

Permeate Analysis		
		15%
NH4+	(mg/l)	0.18
HCO3-	(mg/l)	5.61
Cl-	(mg/l)	0.82
Ca2+	(mg/l)	0.15
Na+	(mg/l)	0.83
EC	(mS/m)	0.63
pH		6.47

Permeate Analysis		
		15%
NH4+	(mmol/l)	0.01
HCO3-	(mmol/l)	0.09
Cl-	(mmol/l)	0.02
Ca2+	(mmol/l)	0.00
Na+	(mmol/l)	0.04
EC	(mS/m)	0.63
pH		6.47

Ratio	Initial Ratio
15%	
2.8	3;1

Ionic strength	Initial ionic strength
15%	
26.2	20

Results of the permeability and rejection	
Recoveries	**15%**
Jw (l/m2h)	24.32
B_value (ammonium) (l/m2h)	0.5218
Rejection (ammonium)	0.9790
B_value (sodium) (l/m2h)	0.2069
Rejection (sodium)	0.9916

III. Espa2max

pH=5

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	98.8	58.4397	1.69
CaCl2	554.92	110.984	5.00
HCl		36.458	1.5
pH	4.89		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.75
Ca2+	5.00
Na+	3.69

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.81	1.93
Concentrate flowrate (m3/h)	5.80	0.91

Circulation flowrate (m3/h)	0.00	4.87
Feed pressure (bar)	8.61	8.98
Pressure drop (bar)	0.16	0.16
Permeate pressure (bar)	0.37	0.56
Conductivity Feed (μS/cm)	1372.06	1262.61
Conductivity concentrate (μS/cm)	1525.64	2352.95
Conductivity Permeate (μS/cm)	23.03	32.47
Feed Temperature (oC)	11.56	11.71

Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	7.94	11.42
HCO3-	(mg/l)	4.82	4.82
Cl-	(mg/l)	386.92	613.35
Ca2+	(mg/l)	150.87	264.88
Na+	(mg/l)	69.11	105.23
EC	(mS/m)	117.20	170.36
pH		5.23	5.23

Ionic Balance (feed analysis)	-0.02	1.05

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.44	0.63
HCO3-	(mmol/l)	0.08	0.08
Cl-	(mmol/l)	10.91	17.30
Ca2+	(mmol/l)	3.764	6.609
Na+	(mmol/l)	3.01	4.58
EC	(mS/m)	117.20	170.36
pH		5.23	5.23

Permeate Analysis			
		15%	**53%**
NH4+	(mg/l)	0.30	0.50
HCO3-	(mg/l)	4.58	4.45
Cl-	(mg/l)	4.18	6.36
Ca2+	(mg/l)	0.07	0.07
Na+	(mg/l)	3.00	4.68
EC	(mS/m)	1.83	2.69
pH		5.24	5.3

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.02	0.03
HCO3-	(mmol/l)	0.07	0.07
Cl-	(mmol/l)	0.12	0.18
Ca2+	(mmol/l)	0.002	0.002
Na+	(mmol/l)	0.13	0.20
EC	(mS/m)	1.83	2.69
pH		5.24	5.3

Ratio		Initial Ratio
15%	**53%**	
3.189808	3.335651	3;1

Ionic strength		Initial ionic strength
15%	**53%**	
14.74861	24.5137	20

Results of the permeability and rejection

Recoveries	**15%**	**53%**
Jw (l/m2h)	24.71	25.09
B_value (ammonium) (l/m2h)	0.9701	1.1487
Rejection (ammonium)	0.9622	0.9562
B_value (sodium) (l/m2h)	0.6490	0.7088
Rejection (sodium)	0.9744	0.9725

pH=6

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	98.8	58.4397	1.69
CaCl2	554.92	110.984	5.00
HCl		36.458	1.3
pH	6.03		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.55
Ca2+	5.00
Na+	3.69

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.8	1.94
Concentrate flowrate (m3/h)	5.8	0.91
Circulation flowrate (m3/h)	0	4.89
Feed pressure (bar)	8.87	9.36
Pressure drop (bar)	0.15931	0.16

Permeate pressure (bar)	0.72	0.43
Conductivity Feed (μS/cm)	1446.96	1367.92
Conductivity concentrate (μS/cm)	1596.33	2547.42
Conductivity Permeate (μS/cm)	19.53	27.43
Feed Temperature (oC)	11.53	11.49

Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	8.89	14.53
HCO3-	(mg/l)	47.28	66.92
Cl-	(mg/l)	353.57	619.42
Ca2+	(mg/l)	170.70	290.20
Na+	(mg/l)	70.57	118.17
EC	(mS/m)	118.70	195.50
pH		6.34	6.40

Ionic Balance (feed analysis)	1.33	1.86

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.49	0.81
HCO3-	(mmol/l)	0.77	1.10
Cl-	(mmol/l)	9.97	17.47
Ca2+	(mmol/l)	4.26	7.24
Na+	(mmol/l)	3.07	5.14
EC	(mS/m)	118.70	195.50
pH		6.34	6.40

Permeate Analysis			
		15%	**53%**

NH4+	(mg/l)	0.28	0.43
HCO3-	(mg/l)	5.80	5.80
Cl-	(mg/l)	3.09	4.67
Ca2+	(mg/l)	0.08	0.10
Na+	(mg/l)	2.53	3.95
EC	(mS/m)	1.67	2.20
pH		5.12	5.15

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.02	0.02
HCO3-	(mmol/l)	0.09	0.09
Cl-	(mmol/l)	0.09	0.13
Ca2+	(mmol/l)	0.002	0.002
Na+	(mmol/l)	0.11	0.17
EC	(mS/m)	1.67	2.20
pH		5.12	5.15

Ratio		Initial Ratio
15%	**53%**	
3.02	3.12	3;1

Ionic strength		Initial ionic strength
15%	**53%**	
15.67	26.74	20

Results of the permeability and rejection		
Recoveries	**15%**	**53%**

Jw (l/m2h)	24.46	25.34
B_value (ammonium) (l/m2h)	0.7955	0.7729
Rejection (ammonium)	0.9685	0.9704
B_value (sodium) (l/m2h)	0.5327	0.5226
Rejection (sodium)	0.9787	0.9798

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	143.18	58.4397	2.45
CaCl2	554.92	110.984	5.00
HCl		36.458	
pH	8.27		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	13.01
Ca2+	5.00
Na+	4.45

Sensors EU	
Recovery	**15%**
Feed flow rate (m3/h)	6.81
Concentrate flowrate (m3/h)	5.80
Circulation flowrate (m3/h)	0.00
Feed pressure (bar)	9.99
Pressure drop (bar)	0.16
Permeate pressure (bar)	0.92
Conductivity Feed (µS/cm)	1380.99

Conductivity concentrate (μS/cm)	1540.48
Conductivity Permeate (μS/cm)	10.30
Feed Temperature (oC)	11.54

Feed Analysis		
		15%
NH4+	(mg/l)	7.56
HCO3-	(mg/l)	101.69
Cl-	(mg/l)	488.22
Ca2+	(mg/l)	3.14
Na+	(mg/l)	359.53
EC	(mS/m)	154.80
pH		8.02

Ionic Balance (feed analysis)	0.62

Feed Analysis		
		15%
NH4+	(mmol/l)	0.42
HCO3-	(mmol/l)	1.67
Cl-	(mmol/l)	13.77
Ca2+	(mmol/l)	0.08
Na+	(mmol/l)	15.64
EC	(mS/m)	154.80
pH		8.02

Permeate Analysis		
		15%
NH4+	(mg/l)	0.08
HCO3-	(mg/l)	5.55
Cl-	(mg/l)	1.38
Ca2+	(mg/l)	0.00

Na+	(mg/l)	1.75
EC	(mS/m)	0.72
pH		6.7

Permeate Analysis		
		15%
NH4+	(mmol/l)	0.00
HCO3-	(mmol/l)	0.09
Cl-	(mmol/l)	0.04
Ca2+	(mmol/l)	6.04E-06
Na+	(mmol/l)	0.08
EC	(mS/m)	0.72
pH		6.7

Ratio	Initial Ratio
15%	
0.96	3;1

Ionic strength	Initial ionic strength
15%	
31.65	20

Results of the permeability and rejection	
Recoveries	**15%**
Jw (l/m2h)	24.66
B_value (ammonium) (l/m2h)	0.2637
Rejection (ammonium)	0.9894
B_value (sodium) (l/m2h)	0.1204
Rejection (sodium)	0.9951

Appendix G: Calculations regarding different pH and molar ratios of 1:1 and 5:1

I. XLE

1:1 molar ratio and pH=5

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	970.15	58.4397	16.60
HCl		36.458	0.95
pH	5.09		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	18.11
Ca2+	
Na+	18.60

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.81	1.91
Concentrate flowrate (m3/h)	5.79	0.91
Circulation flowrate (m3/h)	0.00	4.85
Feed pressure (bar)	5.37	5.84
Pressure drop (bar)	0.20	0.20
Permeate pressure (bar)	0.10	0.16
Conductivity Feed (µS/cm)	1809.79	1667.62
Conductivity concentrate (µS/cm)	2041.62	3175.38

Conductivity Permeate (µS/cm)		72.54	97.87
Feed Temperature (oC)		11.56	11.68

Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	7.98	13.21
HCO3-	(mg/l)	17.51	22.51
Cl-	(mg/l)	618.89	883.67
Ca2+	(mg/l)		
Na+	(mg/l)	346.00	583.00
EC	(mS/m)	154.74	247.00
pH		5.92	6.11

Ionic Balance (feed analysis)	-2.25	0.80

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.44	0.73
HCO3-	(mmol/l)	0.29	0.37
Cl-	(mmol/l)	17.46	24.93
Ca2+	(mmol/l)		
Na+	(mmol/l)	15.05	25.36
EC	(mS/m)	154.74	247.00
pH		5.92	6.11

Permeate Analysis			
		15%	**53%**
NH4+	(mg/l)	0.29	0.41
HCO3-	(mg/l)	5.19	5.06
Cl-	(mg/l)	16.82	24.58
Ca2+	(mg/l)		
Na+	(mg/l)	11.68	19.41

EC	(mS/m)	5.90	8.41
pH		5.32	5.29

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.02	0.02
HCO3-	(mmol/l)	0.08	0.08
Cl-	(mmol/l)	0.47	0.69
Ca2+	(mmol/l)		
Na+	(mmol/l)	0.51	0.84
EC	(mS/m)	5.90	8.41
pH		5.32	5.29

Ratio		Initial Ratio
15%	**53%**	
1.15	0.97	1;1

Ionic strength		Initial ionic strength
15%	**53%**	
16.6	25.7	20

Results of the permeability and rejection		
Recoveries	**15%**	**53%**
Jw (l/m2h)	24.95	24.51
B_value (ammonium) (l/m2h)	0.9550	0.7927
Rejection (ammonium)	0.9631	0.9687
B_value (sodium) (l/m2h)	2.037107	2.09065
Rejection (sodium)	0.924519	0.921404

1:1 molar ratio and pH=8

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	1019.83	58.4397	17.45
CaCl2			
HCl		36.458	
pH	8.02		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	18.01
Ca2+	0.00
Na+	19.45

Sensors EU	
Recovery	**15%**
Feed flow rate (m3/h)	6.80
Concentrate flowrate (m3/h)	5.80
Circulation flowrate (m3/h)	0.00
Feed pressure (bar)	5.32
Pressure drop (bar)	0.20
Permeate pressure (bar)	0.29
Conductivity Feed (μS/cm)	2017.55
Conductivity concentrate (μS/cm)	2266.30
Conductivity Permeate (μS/cm)	27.39
Feed Temperature (oC)	11.56
Feed Analysis	

		15%
NH4+	(mg/l)	8.19
HCO3-	(mg/l)	106.99
Cl-	(mg/l)	535.29
Ca2+	(mg/l)	
Na+	(mg/l)	382.50
EC	(mS/m)	174.08
pH		7.64

Ionic Balance (feed analysis)	0.24

Feed Analysis		
		15%
NH4+	(mmol/l)	0.45
HCO3-	(mmol/l)	1.75
Cl-	(mmol/l)	15.10
Ca2+	(mmol/l)	
Na+	(mmol/l)	16.64
EC	(mS/m)	174.08
pH		7.64

Permeate Analysis		
		15%
NH4+	(mg/l)	0.13
HCO3-	(mg/l)	5.12
Cl-	(mg/l)	5.84
Ca2+	(mg/l)	
Na+	(mg/l)	4.74
EC	(mS/m)	2.40
pH		6.18

Permeate Analysis		
		15%
NH4+	(mmol/l)	0.01
HCO3-	(mmol/l)	0.08
Cl-	(mmol/l)	0.16
Ca2+	(mmol/l)	
Na+	(mmol/l)	0.21
EC	(mS/m)	2.40
pH		6.18

Ratio	Initial Ratio
15%	
1	1;1

Ionic strength	Initial ionic strength
15%	
17.0	20

Results of the permeability and rejection	
Recoveries	**15%**
Jw (l/m2h)	24.55
B_value (ammonium) (l/m2h)	0.3898
Rejection (ammonium)	0.9844
B_value (sodium) (l/m2h)	0.3077
Rejection (sodium)	0.9876

5:1 molar ratio and pH=8

Input Data

Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	18.12	58.4397	0.31
CaCl2	663.72	110.984	5.98
HCl		36.458	
pH	8.13		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	12.83
Ca2+	5.98
Na+	2.31

Sensors EU		
Recovery		**15%**
Feed flow rate (m3/h)		6.83
Concentrate flowrate (m3/h)		5.78
Circulation flowrate (m3/h)		0.00
Feed pressure (bar)		6.40
Pressure drop (bar)		0.20
Permeate pressure (bar)		1.50
Conductivity Feed (µS/cm)		1537.61
Conductivity concentrate (µS/cm)		1683.83
Conductivity Permeate (µS/cm)		31.29
Feed Temperature (oC)		11.55
Feed Analysis		
		15%
NH4+	(mg/l)	7.50
HCO3-	(mg/l)	97.17

Cl-	(mg/l)	336.54
Ca2+	(mg/l)	179.27
Na+	(mg/l)	49.52
EC	(mS/m)	116.70
pH		7.50

Ionic Balance (feed analysis)	0.43

Feed Analysis		
		15%
NH4+	(mmol/l)	0.42
HCO3-	(mmol/l)	1.59
Cl-	(mmol/l)	9.49
Ca2+	(mmol/l)	4.47
Na+	(mmol/l)	2.15
EC	(mS/m)	116.70
pH		7.50

Permeate Analysis		
		15%
NH4+	(mg/l)	0.59
HCO3-	(mg/l)	4.70
Cl-	(mg/l)	6.18
Ca2+	(mg/l)	0.71
Na+	(mg/l)	3.48
EC	(mS/m)	2.45
pH		5.67

Permeate Analysis		
		15%

NH4+	(mmol/l)	0.03
HCO3-	(mmol/l)	0.08
Cl-	(mmol/l)	0.17
Ca2+	(mmol/l)	0.02
Na+	(mmol/l)	0.15
EC	(mS/m)	2.45
pH		5.67

Ratio	Initial Ratio
15%	
4.31	5;1

Ionic strength	Initial ionic strength
15%	
22.60	20

Results of the permeability and rejection	
Recoveries	**15%**
Jw (l/m2h)	25.75
B_value (ammonium) (l/m2h)	2.1984
Rejection (ammonium)	0.9213
B_value (sodium) (l/m2h)	1.9450
Rejection (sodium)	0.9298

II. Espa2max

1:1 molar ratio and pH=5

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)

NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	98.8	58.4397	1.69
CaCl2			
HCl	500	36.458	1.3
pH	6.03		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	3.55
Ca2+	0.00
Na+	3.69

Sensors EU			
Recovery		**15%**	**53%**
Feed flow rate (m3/h)		6.80	1.928788
Concentrate flowrate (m3/h)		5.80	0.90697
Circulation flowrate (m3/h)		0.00	4.887576
Feed pressure (bar)		9.87	10.37
Pressure drop (bar)		0.16	0.15
Permeate pressure (bar)		1.50	1.54
Conductivity Feed (µS/cm)		1806.18	1660.045
Conductivity concentrate (µS/cm)		2051.90	3220.71
Conductivity Permeate (µS/cm)		22.85	32.76061
Feed Temperature (oC)		11.51	11.67788
Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	8.17	13.27
HCO3-	(mg/l)	21.84	16.35
Cl-	(mg/l)	543.50	850.90

Ca2+	(mg/l)		
Na+	(mg/l)	365.23	573.90
EC	(mS/m)	163.30	242.00
pH		5.92	5.78

Ionic Balance (feed analysis)	0.65	1.43

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.45	0.74
HCO3-	(mmol/l)	0.36	0.27
Cl-	(mmol/l)	15.33	24.00
Ca2+	(mmol/l)		
Na+	(mmol/l)	15.89	24.96
EC	(mS/m)	163.30	242.00
pH		5.92	5.78

Permeate Analysis			
		15%	**53%**
NH4+	(mg/l)	0.07	0.11
HCO3-	(mg/l)	6.04	5.49
Cl-	(mg/l)	3.36	6.11
Ca2+	(mg/l)		
Na+	(mg/l)	3.50	5.59
EC	(mS/m)	1.82	2.74
pH		5.24	5.15

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.00	0.01
HCO3-	(mmol/l)	0.10	0.09

Cl-	(mmol/l)	0.09	0.17
Ca2+	(mmol/l)		
Na+	(mmol/l)	0.15	0.24
EC	(mS/m)	1.82	2.74
pH		5.24	5.15

Ratio		Initial Ratio
15%	**53%**	
1.0	0.9	1;1

Ionic strength		Initial ionic strength
15%	**53%**	
16.01	24.98	20

Results of the permeability and rejection		
Recoveries	**15%**	**53%**
Jw (l/m2h)	24.46	25.00
B_value (ammonium) (l/m2h)	0.1991	0.2089
Rejection (ammonium)	0.9919	0.9917
B_value (sodium) (l/m2h)	0.5351	0.5910
Rejection (sodium)	0.9786	0.9769

1:1 molar ratio and pH=8

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	1019.83	58.4397	17.45

CaCl2			
pH	8.47		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	18.01
Ca2+	0.00
Na+	19.45

Sensors EU		
Recovery		**15%**
Feed flow rate (m3/h)		6.80
Concentrate flowrate (m3/h)		5.80
Circulation flowrate (m3/h)		0.00
Feed pressure (bar)		11.41
Pressure drop (bar)		0.16
Permeate pressure (bar)		2.30
Conductivity Feed (µS/cm)		1814.84
Conductivity concentrate (µS/cm)		2070.83
Conductivity Permeate (µS/cm)		9.82
Feed Temperature (oC)		11.52
Feed Analysis		
		15%
NH4+	(mg/l)	7.43
HCO3-	(mg/l)	102.05
Cl-	(mg/l)	353.24
Ca2+	(mg/l)	152.27
Na+	(mg/l)	90.78
EC	(mS/m)	120.50
pH		8.01

Ionic Balance (feed analysis)	0.32

Feed Analysis		
		15%
NH4+	(mmol/l)	0.41
HCO3-	(mmol/l)	1.67
Cl-	(mmol/l)	9.96
Ca2+	(mmol/l)	3.80
Na+	(mmol/l)	3.95
EC	(mS/m)	120.50
pH		8.01

Permeate Analysis		
		15%
NH4+	(mg/l)	0.20
HCO3-	(mg/l)	5.25
Cl-	(mg/l)	2.09
Ca2+	(mg/l)	0.02
Na+	(mg/l)	1.68
EC	(mS/m)	0.88
pH		6.57

Permeate Analysis		
		15%
NH4+	(mmol/l)	0.01
HCO3-	(mmol/l)	0.09
Cl-	(mmol/l)	0.06
Ca2+	(mmol/l)	0.000198
Na+	(mmol/l)	0.07
EC	(mS/m)	0.88

pH		6.57

Permeate Analysis		
		15%
NH4+	(mg/l)	0.20
HCO3-	(mg/l)	5.25
Cl-	(mg/l)	2.09
Ca2+	(mg/l)	0.02
Na+	(mg/l)	1.68
EC	(mS/m)	0.88
pH		6.57

Permeate Analysis		
		15%
NH4+	(mmol/l)	0.01
HCO3-	(mmol/l)	0.09
Cl-	(mmol/l)	0.06
Ca2+	(mmol/l)	0.000198
Na+	(mmol/l)	0.07
EC	(mS/m)	0.88
pH		6.57

Ratio	Initial Ratio
15%	
1.43	1;1

Ionic strength	Initial ionic strength
15%	

23.6	20

Results of the permeability and rejection	
Recoveries	**15%**
Jw (l/m2h)	24.50
B_value (ammonium) (l/m2h)	0.6777
Rejection (ammonium)	0.9731
B_value (sodium) (l/m2h)	0.4619
Rejection (sodium)	0.9815

5:1 molar ratio and pH=8

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	18.12	58.4397	0.31
CaCl2	633.72	110.984	5.71
HCl		36.458	
pH	8.41		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	12.29
Ca2+	5.71
Na+	2.31

Sensors EU	
Recovery	**15%**
Feed flow rate (m3/h)	6.80
Concentrate flowrate (m3/h)	5.80

Circulation flowrate (m3/h)		0.00
Feed pressure (bar)		10.76
Pressure drop (bar)		0.16
Permeate pressure (bar)		1.86
Conductivity Feed (µS/cm)		1294.14
Conductivity concentrate (µS/cm)		1436.03
Conductivity Permeate (µS/cm)		10.35
Feed Temperature (oC)		11.60
Feed Analysis		
		15%
NH4+	(mg/l)	7.61
HCO3-	(mg/l)	102.48
Cl-	(mg/l)	327.76
Ca2+	(mg/l)	178.07
Na+	(mg/l)	47.67
EC	(mS/m)	117.00
pH		8.12

Ionic Balance (feed analysis)	0.46

Feed Analysis		
		15%
NH4+	(mmol/l)	0.42
HCO3-	(mmol/l)	1.68
Cl-	(mmol/l)	9.25
Ca2+	(mmol/l)	4.44
Na+	(mmol/l)	2.07
EC	(mS/m)	117.00
pH		8.12

Permeate Analysis		
		15%
NH4+	(mg/l)	0.34
HCO3-	(mg/l)	5.25
Cl-	(mg/l)	1.95
Ca2+	(mg/l)	0.04
Na+	(mg/l)	1.50
EC	(mS/m)	0.88
pH		7.69

Permeate Analysis		
		15%
NH4+	(mmol/l)	0.02
HCO3-	(mmol/l)	0.09
Cl-	(mmol/l)	0.05
Ca2+	(mmol/l)	0.00
Na+	(mmol/l)	0.07
EC	(mS/m)	0.88
pH		7.69

Ratio	Initial Ratio
15%	
4.38	5;1

Ionic strength	Initial ionic strength
15%	
22.31	20

Results of the permeability and rejection

Recoveries	**15%**
Jw (l/m2h)	24.52
B_value (ammonium) (l/m2h)	1.1469
Rejection (ammonium)	0.9553
B_value (sodium) (l/m2h)	0.7967
Rejection (sodium)	0.9685

III. LG

1:1 molar ratio and pH=5

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	970.15	58.4397	16.60
HCl	565	36.458	0.95
pH	5.09		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	18.11
Ca2+	
Na+	18.60

Sensors EU		
Recovery	**15%**	**53%**
Feed flow rate (m3/h)	6.81	1.93
Concentrate flowrate (m3/h)	5.79	0.92
Circulation flowrate (m3/h)	0.00	4.90
Feed pressure (bar)	13.52	13.25
Pressure drop (bar)	0.16	0.16

Permeate pressure (bar)	0.10	0.04
Conductivity Feed (µS/cm)	1815.72	1664.69
Conductivity concentrate (µS/cm)	2051.65	3204.38
Conductivity Permeate (µS/cm)	21.94	22.46
Feed Temperature (oC)	11.44	11.63

Feed Analysis			
		15%	**53%**
NH4+	(mg/l)	7.96	11.90
HCO3-	(mg/l)	31.96	17.81
Cl-	(mg/l)	538.00	809.14
Ca2+	(mg/l)		
Na+	(mg/l)	352.00	575.00
EC	(mS/m)	160.70	250.00
pH		6.13	5.83

Ionic Balance (feed analysis)	0.05	2.55

Feed Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.44	0.66
HCO3-	(mmol/l)	0.52	0.29
Cl-	(mmol/l)	15.18	22.82
Ca2+	(mmol/l)		
Na+	(mmol/l)	15.31	25.01
EC	(mS/m)	160.70	250.00
pH		6.13	5.83

Permeate Analysis			
		15%	**53%**
NH4+	(mg/l)	0.18	0.38
HCO3-	(mg/l)	2.93	4.33

Cl-	(mg/l)	3.08	4.00
Ca2+	(mg/l)		
Na+	(mg/l)	1.62	2.72
EC	(mS/m)	1.59	1.87
pH		4.83	4.96

Permeate Analysis			
		15%	**53%**
NH4+	(mmol/l)	0.01	0.02
HCO3-	(mmol/l)	0.05	0.07
Cl-	(mmol/l)	0.09	0.11
Ca2+	(mmol/l)		
Na+	(mmol/l)	0.07	0.12
EC	(mS/m)	1.59	1.87
pH		4.83	4.96

Ratio		Initial Ratio
15%	**53%**	
1.0	0.9	1;1

Ionic strength		Initial ionic strength
15%	**53%**	
15.73	24.39	20

Results of the permeability and rejection		
Recoveries	**15%**	**53%**
Jw (l/m2h)	24.95	24.83
B_value (ammonium) (l/m2h)	0.5906	0.8112
Rejection (ammonium)	0.9769	0.9684

B_value (sodium) (l/m2h)	0.254566	0.273108406
Rejection (sodium)	0.9899	0.98912

1:1 molar ratio and pH=8

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	1019.83	58.4397	17.45
CaCl2			
HCl		36.458	
pH	8.02		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	18.01
Ca2+	0.00
Na+	19.45

Sensors EU	
Recovery	**15%**
Feed flow rate (m3/h)	6.80
Concentrate flowrate (m3/h)	5.80
Circulation flowrate (m3/h)	0.00
Feed pressure (bar)	12.44
Pressure drop (bar)	0.16
Permeate pressure (bar)	0.09

Conductivity Feed (µS/cm)	2027.72
Conductivity concentrate (µS/cm)	2282.12
Conductivity Permeate (µS/cm)	7.01
Feed Temperature (oC)	11.49

Feed Analysis		
		15%
NH4+	(mg/l)	8.20
HCO3-	(mg/l)	93.57
Cl-	(mg/l)	475.48
Ca2+	(mg/l)	
Na+	(mg/l)	393.53
EC	(mS/m)	151.80
pH		7.50

Ionic Balance (feed analysis)	2.63

Feed Analysis		
		15%
NH4+	(mmol/l)	0.45
HCO3-	(mmol/l)	1.53
Cl-	(mmol/l)	13.41
Ca2+	(mmol/l)	
Na+	(mmol/l)	17.12
EC	(mS/m)	151.80
pH		7.50

Permeate Analysis		
		15%
NH4+	(mg/l)	0.06
HCO3-	(mg/l)	5.80

Cl-	(mg/l)	0.72
Ca2+	(mg/l)	
Na+	(mg/l)	1.48
EC	(mS/m)	0.59
pH		6.47

Permeate Analysis		
		15%
NH4+	(mmol/l)	0.00
HCO3-	(mmol/l)	0.09
Cl-	(mmol/l)	0.02
Ca2+	(mmol/l)	
Na+	(mmol/l)	0.06
EC	(mS/m)	0.59
pH		6.47

Ratio	Initial Ratio
15%	
0.85	1;1

Ionic strength	Initial ionic strength
15%	
16.26	20

Results of the permeability and rejection	
Recoveries	**15%**
Jw (l/m2h)	24.36
B_value (ammonium) (l/m2h)	0.1795
Rejection (ammonium)	0.9927

B_value (sodium) (l/m2h)	0.0919
Rejection (sodium)	0.9962

5:1 molar ratio and pH=8

Input Data			
Chemicals	Conc. (g/m3)	Mr (g/mol)	Conc. (mmol/l)
NH4Cl	30	53.489	0.56
NaHCO3-	168	84.0057	2.00
NaCl	18.12	58.4397	0.31
CaCl2	663.72	110.984	5.98
HCl		36.458	
pH	8.13		

Total Concentration (mmol/l)_Input	
NH4+	0.56
HCO3-	2.00
Cl-	12.83
Ca2+	5.98
Na+	2.31

Sensors EU	
Recovery	**15%**
Feed flow rate (m3/h)	6.83
Concentrate flowrate (m3/h)	5.78
Circulation flowrate (m3/h)	0.00
Feed pressure (bar)	6.40
Pressure drop (bar)	0.20
Permeate pressure (bar)	1.50
Conductivity Feed (µS/cm)	1537.61
Conductivity concentrate (µS/cm)	1683.83
Conductivity Permeate (µS/cm)	31.29

Feed Temperature (oC)		11.55
Feed Analysis		
		15%
NH4+	(mg/l)	9.05
HCO3-	(mg/l)	100.00
Cl-	(mg/l)	350.00
Ca2+	(mg/l)	183.00
Na+	(mg/l)	49.70
EC	(mS/m)	133.00
pH		7.45

Ionic Balance (feed analysis)	0.28

Feed Analysis		
		15%
NH4+	(mmol/l)	0.50
HCO3-	(mmol/l)	1.64
Cl-	(mmol/l)	9.87
Ca2+	(mmol/l)	4.57
Na+	(mmol/l)	2.16
EC	(mS/m)	133.00
pH		7.45

Permeate Analysis		
		15%
NH4+	(mg/l)	0.25
HCO3-	(mg/l)	4.70
Cl-	(mg/l)	0.91
Ca2+	(mg/l)	0.23
Na+	(mg/l)	0.51
EC	(mS/m)	0.52

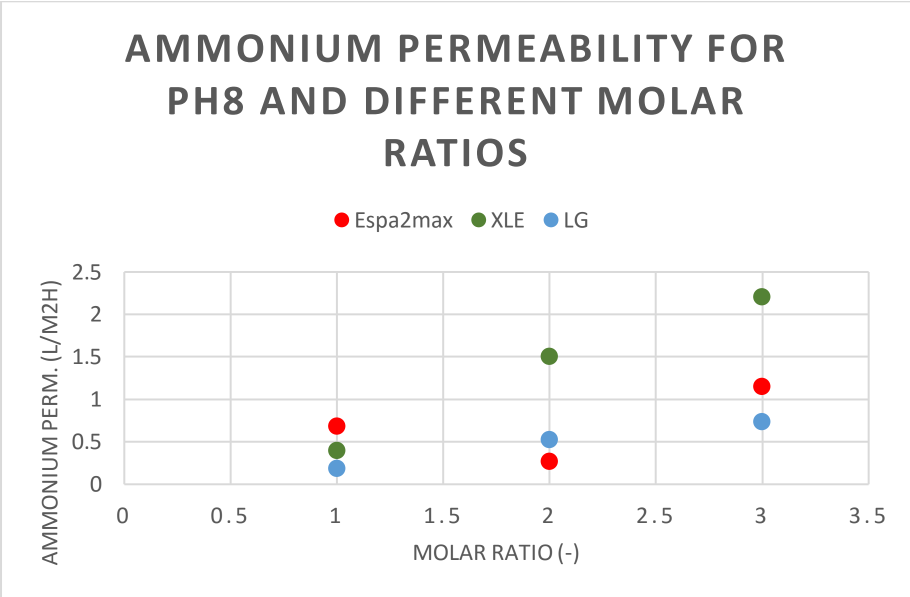
pH		5.84

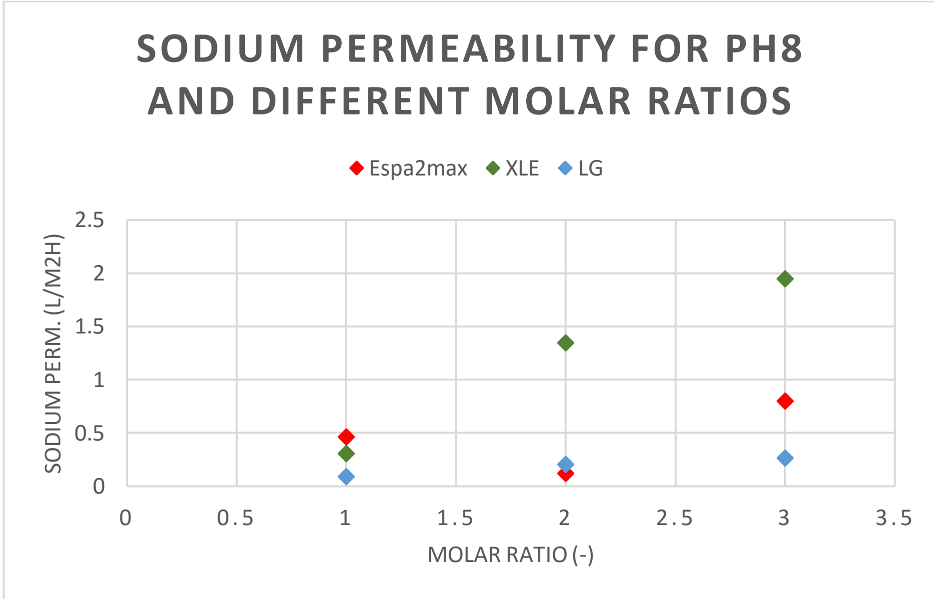
Permeate Analysis		
		15%
NH4+	(mmol/l)	0.01
HCO3-	(mmol/l)	0.08
Cl-	(mmol/l)	0.03
Ca2+	(mmol/l)	0.005706
Na+	(mmol/l)	0.02
EC	(mS/m)	0.52
pH		5.84

Ratio	Initial Ratio
15%	
4.3	5;1

Ionic strength	Initial ionic strength
15%	
23.3	20

Results of the permeability and rejection	
Recoveries	**15%**
Jw (l/m2h)	25.75
B_value (ammonium) (l/m2h)	0.7315
Rejection (ammonium)	0.9724
B_value (sodium) (l/m2h)	0.2680
Rejection (sodium)	0.9897


AMMONIUM PERMEABILITY FOR PH8 AND DIFFERENT MOLAR RATIOS
Espa2max
XLE
LG
AMMONIUM PERM. (L/M2H)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
MOLAR RATIO (-)


SODIUM PERMEABILITY FOR PH8 AND DIFFERENT MOLAR RATIOS
Espa2max
XLE
LG
SODIUM PERM. (L/M2H)
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
MOLAR RATIO (-)

Appendix H: Calculations for ionic strengths based on recoveries

Recovery	**15%**	**40%**	**42%**	**47%**	**50%**	**53%**	**56%**	**59%**	**60%**	**62%**	**68%**	**70%**
Concentration factor	1.176471	1.666667	1.724138	1.886792	2	2.12766	2.272727	2.439024	2.5	2.631579	3.125	3.333333
Ionic strength	0.023529	0.033333	0.034483	0.037736	0.04	0.042553	0.045455	0.04878	0.05	0.052632	0.0625	0.066667

Appendix I: Calculations for supersaturation of $CaCO_3$

Artificial water					
CO3 (mg/l)	0.025	0.025	0.026	0.022	0.035
CO3 (mmol/l)	0.000	0.000	0.000	0.000	0.001
CO3 (mol/l)	4.16667E-07	4.1667E-07	4.3333E-07	3.6667E-07	5.8333E-07
Ca2+ (mg/l)	166	186	194	269	336
Ca2+ (mmol/l)	4.13965	4.63840	4.83791	6.70823	8.37905
Ca2+ (mol/l)	0.0041	0.0046	0.0048	0.0067	0.0084
ksp'	1.72485E-09	1.9327E-09	2.0964E-09	2.4597E-09	4.8878E-09
difference	0.5133	0.5752	0.6239	0.7320	1.4547

Raw water			
CO3 (mg/l)	0.447	0.985	1.4
CO3 (mmol/l)	0.0075	0.0164	0.0233
CO3 (mol/l)	0.00000745	1.64167E-05	2.3333E-05
Ca2+ (mg/l)	113.2	203.3	277.5
Ca2+ (mmol/l)	2.8229	5.0698	6.9202
Ca2+ (mol/l)	0.0028	0.0051	0.0069
ksp'	2.10309E-08	8.32296E-08	1.6147E-07
difference	6.2592	24.7707	48.0569