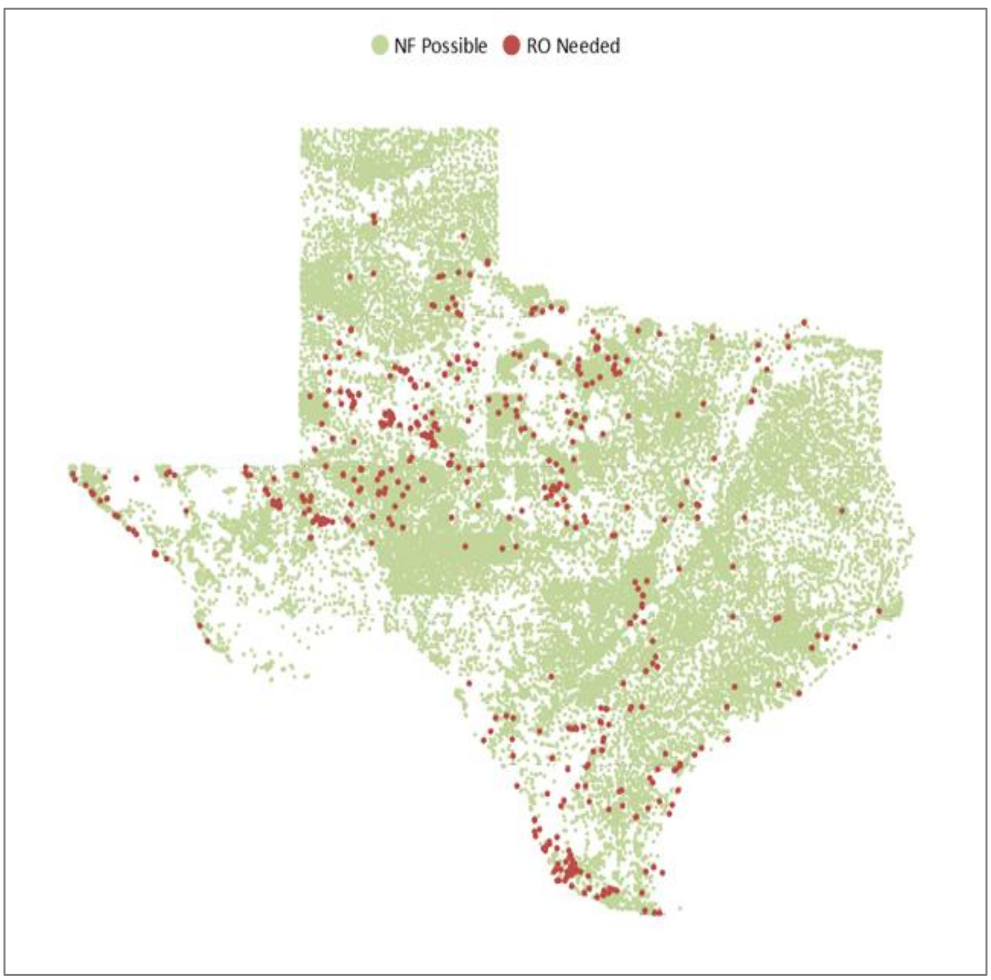
RECLAMATION

Managing Water in the West

Treating Brackish Groundwater in Texas: A Comparison of Reverse Osmosis and Nanofiltration

Final Report Submitted to the Texas Water Development Board



U.S. Department of the Interior
Bureau of Reclamation

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Treating Brackish Groundwater in Texas: A Comparison of Reverse Osmosis and Nanofiltration

Final Report Submitted to the Texas Water Development Board

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Executive Summary

Desalination of brackish groundwater using membrane treatment processes is an opportunity to develop new water resources in arid regions. Currently, there are 34 municipal brackish groundwater desalination facilities in Texas with a total design capacity of 73 million gallons per day [1]. The majority of desalination plants in Texas use reverse osmosis membranes. Although reverse osmosis is an effective treatment technology, the energy required for treatment is one of the factors limiting broader application of brackish groundwater desalination throughout the state. Nanofiltration membranes have the benefit of operating at a lower applied pressure than reverse osmosis membranes; however, the salt rejection capability of nanofiltration membranes is lower. Therefore, if the desired finished water quality targets can be met with nanofiltration membranes, costs and energy savings may realized by utilizing nanofiltration rather than reverse osmosis for desalination.

In coordination with the Texas Water Development Board, the Bureau of Reclamation (Reclamation) conducted a preliminary study to identify groundwater wells in Texas that are candidates for treatment with nanofiltration rather than reverse osmosis. The cost and operational impacts of using different types of desalination membranes were quantified. This assessment was conducted for general planning purposes and is intended to provide qualitative guidance regarding the treatability of groundwater in Texas.

Several wells representing a broad range of groundwater quality were selected from the Texas Groundwater Database. The water quality parameters from the database were used as inputs into membrane manufacturer software programs to predict the permeate water quality from seven commercially available reverse osmosis and nanofiltration membranes with varying salt rejection capability.

A linear correlation was observed between the salt concentration in the feed water and the resulting salt concentration in the permeate. Using this correlation, the Texas Groundwater Database was analyzed to identify wells that could be treated to less than 500 milligrams per liter total dissolved solids concentration using nanofiltration membranes.

The results of the database analysis were also used to estimate some of the key cost differences associated with membrane material selection for water types in which either membrane is capable of meeting the permeate salt concentration target of 500 milligrams per liter. Nanofiltration membranes produce permeate with higher total dissolved solids and less blending of the feed water with the permeate is allowable. Therefore, the amount of water that must be treated by a nanofiltration process is greater than that for a reverse osmosis process. The membrane plant size can be up to 12 percent (%) larger for nanofiltration compared to reverse osmosis for the feed water sources analyzed in this study.

Therefore, because membrane system capital costs are calculated based on the feed capacity [33] it is assumed that the maximum capital cost increase of using nanofiltration rather than reverse osmosis would be equivalent to the difference in the plant size.

Compared to nanofiltration membranes, reverse osmosis membranes require higher operating pressure to produce the same volume of water due to differences in feed and permeate osmotic pressure and membrane permeability. The reduction in pressure observed for nanofiltration membranes compared to reverse osmosis can reduce the energy consumption by approximately 40% for the feed water sources considered in this study. This reduction in feed pressure translates to a reduction in power consumption, kW/gal, for nanofiltration compared to reverse osmosis.

Although not quantified as part of this study, several other factors must be considered when assessing the practicality and costs associated with using nanofiltration versus reverse osmosis. These include scaling and inorganic fouling potential and associated cleaning costs/operational logistics, the type and amount of concentrate generated, post treatment considerations, regulatory requirements, and degree of tolerated risk.

Acronyms

ft^2	square feet
gpd	gallons per day
gpm	gallons per minute
kg/m^3	kilogram per cubic meter
kW	kilowatt
kW/kgal	kilowater per thousand gallons
MCL	maximum contaminant level
MGD	million gallons per day
m/s	meter per second
mg/L	milligrams per liter
NF	nanofiltration
Pa	Pascal
%	percent
psi	pounds per square inch
RO	reverse osmosis
TWDB	Texas Water Development Board
TDS	total dissolved solids

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1. Introduction

In many areas of world, there are rising concerns over the availability of fresh water supplies as the demand for water continues to grow due to increasing municipal, agricultural, and industrial water needs. While conventional water supply and management strategies continue to provide the majority of local and regional water supplies, the amount of fresh water supplied by desalination will continue to increase. Drought, combined with an increasing demand for water, has led water managers to further emphasize the importance of desalination.

In Texas, there is an abundance of brackish groundwater. Brackish groundwater is generally considered to be water with salinity greater than 1,000 milligrams per liter (mg/L) and less than 10,000 mg/L total dissolved solids (TDS). The estimated volume of brackish groundwater in the state of Texas is greater than 2.7 billion acre-ft [1]. Currently, there are more than 46 municipal water desalination facilities in Texas; 34 use brackish groundwater as the source supply with a total design capacity of 73 million gallons per day [1]. Figure 1 summarizes the desalination capacity in Texas, including plant size, feed water source, and feed water salinity. The major drawback to more wide-spread implementation of desalination is the high capital and operational costs. The cost of membrane desalination increases as the salinity of the source water increases because the operational pressure of the membrane system needs to exceed the osmotic pressure of the feed solution.

The majority of desalination plants in Texas use reverse osmosis (RO) membranes. Although RO is an effective treatment method, the high energy requirement for RO is one factor that contributes to the high cost of desalination which limits the utilization of brackish groundwater in the state of Texas. Nanofiltration membranes require a lower operating pressure than RO; however, they also have a lower salt rejection capability. The objective of the study is to identify whether nanofiltration (NF) membranes can be used rather than RO membranes for treatment of brackish groundwater to meet municipal drinking water standards.

RO is a pressure driven process in which fresh water (solvent) is separated from saline water (solution) by applying a pressure in excess of the osmotic pressure of the solution. Water is transferred through a dense membrane tailored to retain both monovalent and divalent salts and low molecular weight solutes. NF membranes are similar to RO membranes; however, they have a lower selectivity for monovalent salts than RO membranes. NF membranes are best suited for removal of divalent ions, such as calcium, magnesium, and sulfate. Monovalent ions, such as sodium and chloride, are poorly rejected by NF membranes.

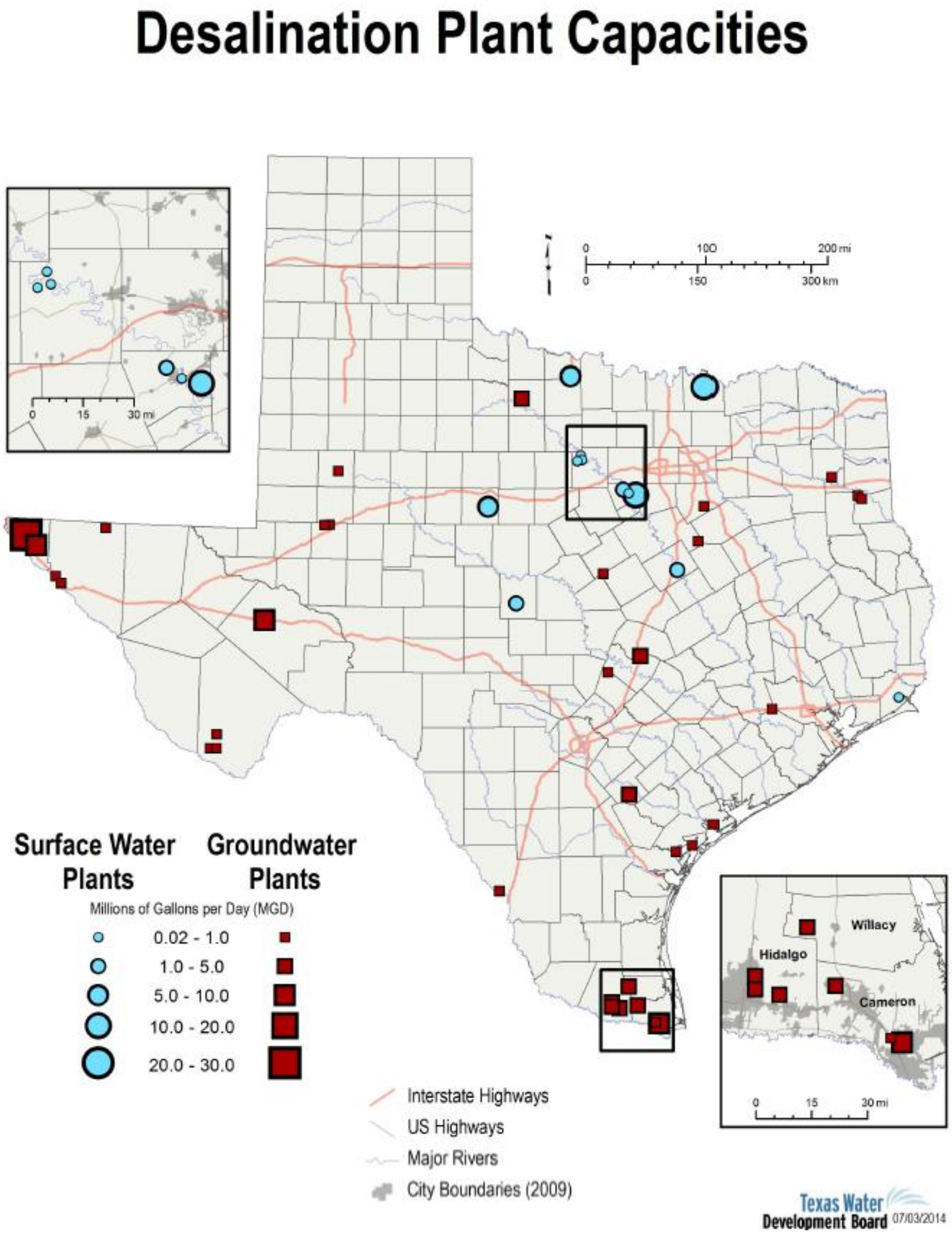

Figure 1. Existing desalination capacity in Texas (TWDB Desalination Database 2010).

The majority of membrane related research focuses on reducing the cost of membrane processes by one of the following approaches: improving material properties by developing new membranes or surface modifications [2-17], improving operational strategies [3, 5, 18-21], reducing fouling rates and increasing the effectiveness of membrane cleaning [22-32]. One often overlooked aspect of reducing membrane desalination cost is membrane material selection to provide the level of desalination needed to meet product water goals at the lowest applied pressure. Pairing of commercially available membrane material properties to specific feed water qualities and target water quality goals can reduce the energy requirement to produce desalinated water and the need for product water post treatment and stabilization. Little guidance exists for water planners to select the optimal membrane that will result in the lowest process cost.

In this work, we use the groundwater quality database developed by the TWDB to identify the groundwater resources in the state of Texas that are treatable to less than 500 mg/L TDS using nanofiltration membranes. Using membrane manufacturer modeling software, we developed correlations for permeate water TDS and feed pressure as a function of the source water quality. These correlations were used to identify brackish water sources suitable for treatment with NF rather than RO and to estimate capital and energy cost differences associated with membrane selection.

The outcomes of this effort can be used at the planning level to identify whether RO or NF can be used for desalination of different water types. This study identifies the economic benefits and practical limitations to using NF rather than RO for brackish groundwater desalination in Texas. A mass balance and simplified cost model were used to estimate the cost savings by implementing NF rather than RO for the wells in which suitable water quality is produced using NF.

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2. Analysis of Texas Groundwater Database

The State of Texas has compiled a Groundwater Quality Database. The database contains over 100,000 entries. The major ion analysis is provided for each entry in the database. This section describes how the database was used to determine which groundwater sources in Texas are treatable using NF. In order to select wells representing the range of brackish groundwater quality in the state of Texas, an analysis was conducted on the Texas Groundwater Database.

Database culling is the process of systematically removing entries that are incomplete or inaccurate to improve the integrity of the resulting analyses. A set of culling criteria, described in Table 1, were applied to the database. The first culling criterion is that samples must contain a complete analysis and samples were removed if they contained negative or missing constituent concentrations. The second criterion is an ionic balance is within 15% meaning that the concentration of negative ions and positive ions is similar. The third condition is a pH in a reasonable range (5 to 10) for groundwater; a significant deviation from neutral pH is indicative of a sample preservation error or contamination. The final culling criterion applied requires samples to have calcium concentration greater than the magnesium concentration. Magnesium salts have lower solubility than calcium salts; therefore, a magnesium concentration greater than calcium concentration indicates an error in the analysis.

Database entries that did not meet the culling criteria were removed from consideration. Additionally, for wells with multiple entries, the concentrations were averaged so that the database contained one entry for each well. Table 1 indicates the order in which the criteria were applied and the number of entries removed for each criterion.

The culling process removed 30,088 well samples, reducing the database from 110,005 to 79,917 samples. Several wells also contained multiple entries and the values were averaged, reducing the final database to 42,414 well samples.

Table 1. The criteria followed for the culling of the Texas Groundwater Quality Database.

Category	Criteria	Number of entries eliminated
Incomplete analysis of collected sample	Na ≤ 0 Ca, Mg, Cl, or SO_4, reported with HCO_3 or alkalinity = zero or not reported	1,045
Overall sample analysis quality	Ionic balance exceeds limits (15%)	17,946
Contamination	pH < 5.0 or > 10.0	8,149
Analysis integrity	Mg ≥ Ca	3,993

Figure 2 shows the TDS distribution of wells within the culled database. The vast majority of the wells have a TDS less than 3,000 mg/L. This may be indicative of the fact that wells were not drilled intentionally in areas known to have very high TDS. However, for the purpose of this study, the large number of wells with relatively low TDS indicate the potential for treating the water from these brackish wells using NF membranes.

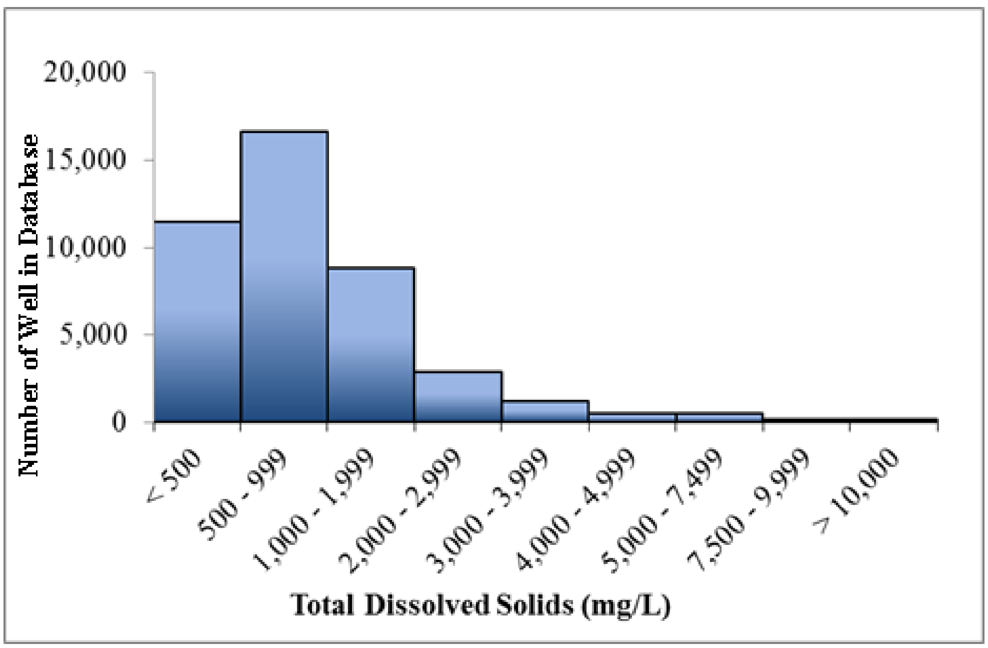

Figure 2. Histogram of total dissolved solids in the culled database.

The range of constituent concentrations observed in well data varies considerably. A box and whisker plot, Figure 3, shows the maximum, minimum, and the 25th, 50th, and 75th percentile values for constituent concentrations within the culled database.

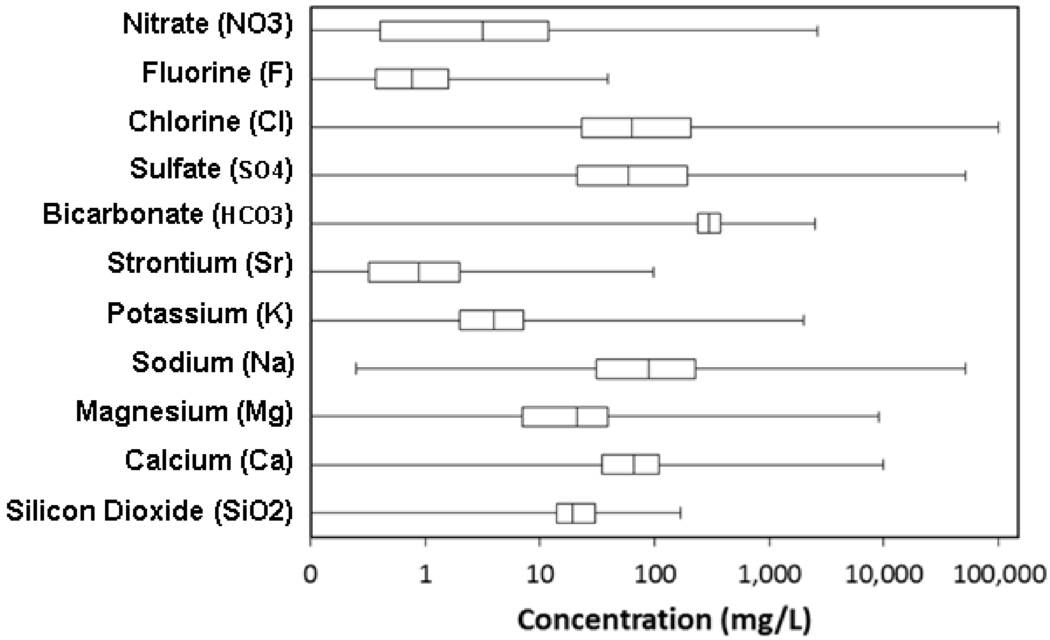

Figure 3. The box plot shows the maximum, minimum, and the 25, 50, and 75th percentile values for constituent concentrations from the culled database.

The ionic composition of a feed water and the rejection capability of the membrane determines the permeate TDS concentration. Generally, waters with higher TDS concentrations contain relatively more monovalent ions, primarily sodium and chloride, than divalent ions. Lower TDS waters were found to be dominated by a divalent cation and a monovalent anion.

Stiff diagrams are commonly used to illustrate the major ion composition of a feed water. Stiff diagrams allow for a rapid assessment of different water sources by visually comparing the shapes of graphs of different water sources. While water quality analyses typically report ion concentrations in units of mass per volume, such as mg/L, the concentration in terms of equivalent charge is used to represent ion concentration in Stiff diagrams. Figure 4 shows the stiff diagram made by taking the average of each constituent concentration for each entry in the culled database.

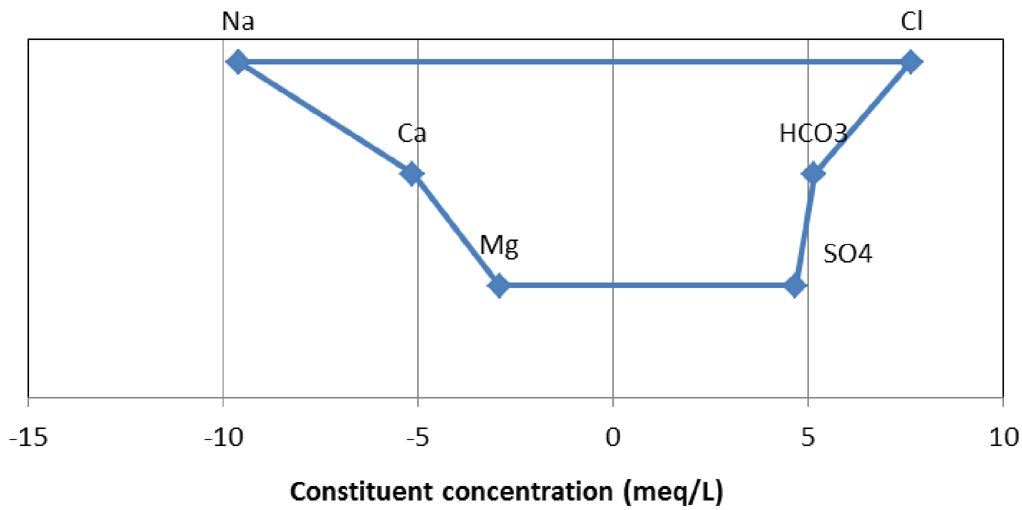

Figure 4. This stiff diagram compares the average constituent concentrations for each entry in the culled database.

The wells from the culled data were mapped using their geographic location and TDS value.
Figure 5 depicts the geographic variability of TDS and Figure 6 shows the graphical locations of Texas' major aquifers. When comparing the two figures side by side, it can be seen that the water quality varies based on geologic formation. Some key observations are that Ogallala Aquifer has reasonably better water quality than the Gulf Coast or Pecos Valley Aquifer.

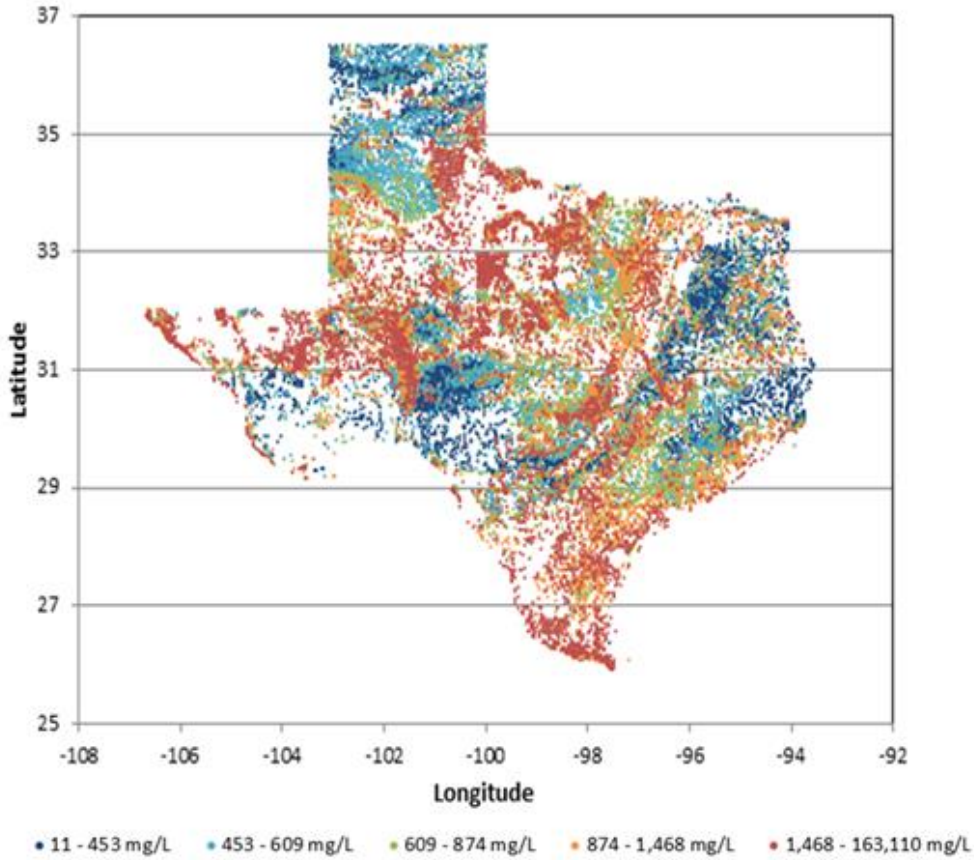

Figure 5. Geographic variability of total dissolved solids.

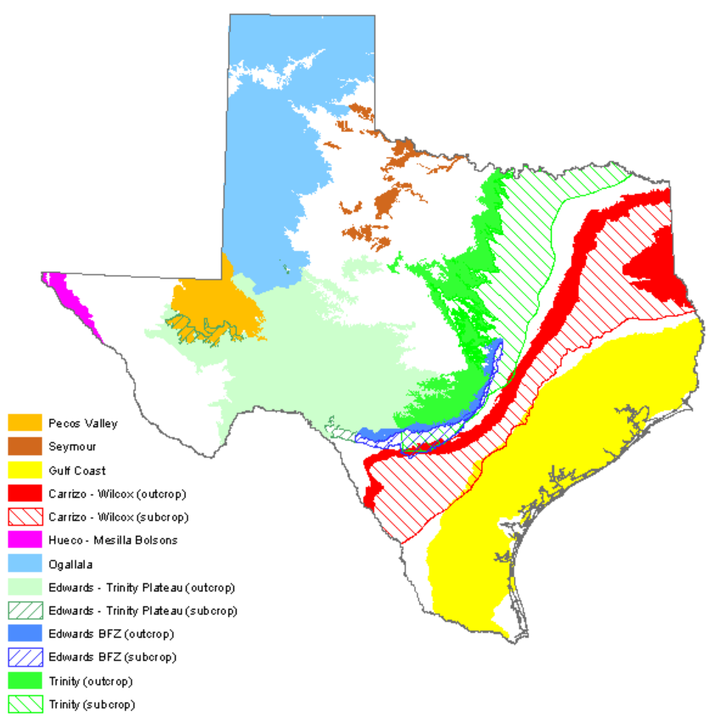

Figure 6. Geographic location of major aquifers in Texas
(http://www.twdb.state.tx.us/groundwater/aquifer/major.asp)

The database analysis was used to identify a representative set of well entries to include in the modeling portion of this study. The water quality data from twelve database entries were chosen to represent a geographical distribution and a wide range of TDS concentrations. Section 3 describes the water composition for these twelve samples.

Twelve wells were chosen geographically by splitting Texas into different regions and picking wells with TDS values in the low (500 to 1,000 mg/L), medium (1,000 to 5,000 mg/L), and high (5,000-10,000 mg/L) ranges. Based on preliminary results that indicated a correlation between the feed sodium concentration and permeate TDS (see Section 4), additional wells were chosen to ensure that a wide range of feed sodium concentrations were represented in the data set. Figure 7 shows the location of the wells that were used in the analysis.

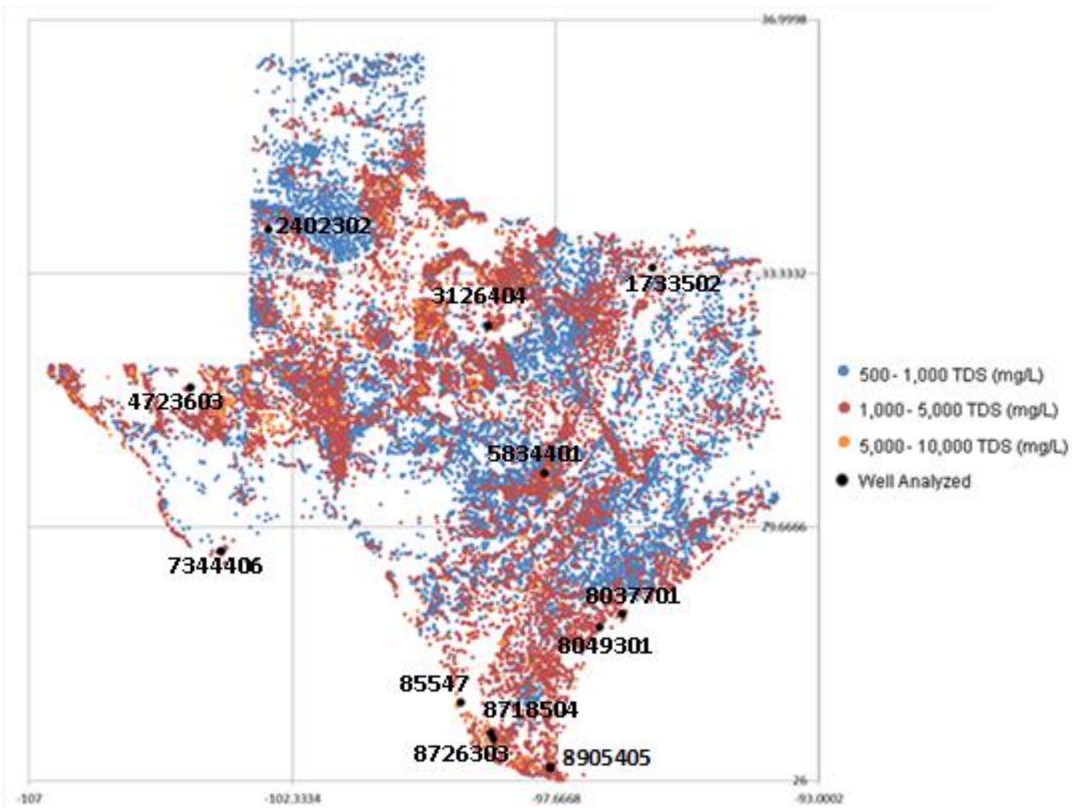

Figure 7. Location of wells with varying low, medium, and high TDS values and location of wells used for membrane analysis.

3. Water Quality Matrix

Twelve representative wells were selected to represent the range of brackish groundwater in Texas. The wells were selected based on geographical location and feed water constituents.

In addition to the data sets from the Texas Groundwater Quality database, feed water quality data from seven RO water treatment plants in Texas were considered.

Feed water quality was obtained for the following plants:

- Holiday Beach Water Supply Corporation – Fulton
- City of Ballinger Water Treatment Plant Reverse Osmosis Addition – Ballinger
- Southmost Regional Water Authority (Southmost) – Brownsville
- City of Fort Stockton Osmosis/Desalination Facility – Fort Stockton
- Horizon Regional Municipal Utilities District RO Plant – Horizon City
- North Cameron/Hidalgo Water Authority - Cameron
- Kay Bailey Hutchinson Desalination Plant - El Paso

Tables 2 and 3 contain the major ion analysis for the seven RO treatment plants and the twelve brackish water wells.

Table 2. Example feed water quality for selected reverse osmosis treatment plants in Texas.

Parameters	Fulton	Ballinger	Brownsville	Ft. Stockton	Cameron	Horizon City	El Paso
pH	7.59	-	-	-	-	-	-
TDS (mg/L)	2,217	1,167	3,434	2,711	4,017	1,764	2,463
Calcium, Ca^{2+} (mg/L)	31.5	100	128	372	201	100	139
Magnesium, Mg^{2+}, (mg/L)	27.3	50	54	32	71.4	23.8	37.5
Potassium, K^{+} (mg/L)	16.1	10	12	0	16	17.6	16.7
Sodium, Na^{+} (mg/L)	630	180	980	459	1,110	445	714
Bicarbonate, HCO_3^{-} (mg/L)	540	110	357	415	150	88	97.6
Chloride, Cl^{-} (mg/L)	615	350	763	696	1,150	449	1,213
Fluoride, F^{-} (mg/L)	1.4	0.4	0.9	1.5	1	0.8	0
Nitrate, NO_3^{-} (mg/L)	0.02	0.3	0	6.1	2.5	0.51	0
Sulfate, SO_4^{2-} (mg/L)	285	350	1,100	703	1,300	605	246
Silica, SiO^{2}	22.7	12	30	21.6	9.2	30.5	0

Table 3. Water quality characteristics for selected brackish groundwater wells.

Parameter	St. Well 2402302	St. Well 1733502	St. Well 4723603	St. Well 5834401	St. Well 7344406	St. Well 8554701	St. Well 8049301	St. Well 8037701	St. Well 8905405	St. Well 8718504	St. Well 8726303	St. Well 3126404
pH	7.28	7.85	6.8	7.6	7.6	8.55	6.9	7.8	7.81	8.25	7.9	7.75
TDS (mg/L)	6,917	6,948	6,636	5,026	5,400	6,901	5,386	3,605	5,463	5,702	6,914	6,096
Calcium, Ca^{2+} (mg/L)	400	42.5	789	60.0	632	4.4	296	39	141	51	292	74
Magnesium, Mg^{2+}, (mg/L)	167	16.5	250	92	365	1.7	157	24	135	0.8	49	28
Potassium, K^{+} (mg/L)	19.3	13	-	-	20	-	20	-	5	15.1	-	-
Sodium, Na^{+} (mg/L)	1,853	2,535	1,354	1,700	420	2,358	1400	1,260	1,552	1,960	2,080	2,188.
Bicarbonate, HCO_3^{-} (mg/L)	305	691	201	342	538	2,159	592	433	456	59	236	455
Chloride, Cl^{-} (mg/L)	1,553	3,613	2,050	2,700	150	2,353	2,620	1,820	1,703	2,807	2,520	3,263
Fluoride, F^{-} (mg/L)	0.05	2.1	-	-	1.2	2.05	-	-	1.6	2.55	-	-
Nitrate, NO_3^{-} (mg/L)	1.83	0.95	42	-	100	0.4	-	0.5	2.8	0.04	0.8	-
Sulfate, SO_4^{2-} (mg/L)	2,596	35	1,950	132	3,156	9.5	272	13	1,452	786	1,640	85
Silica, SiO^{2}	14	12	-	-	17	14	29	15	19.7	19.2	96	10

4. Predictive Modeling of Membrane Process

The Dow ROSA™ and Hydranautics IMS Design™ programs were used to estimate the permeate water quality and feed pressure for a hypothetical membrane plant using seven different types of desalination membranes and twelve different feed water qualities.

4.1 Hypothetical Membrane Treatment Process

In order to model the membrane performance for the feed water matrix, a hypothetical membrane plant was used. The delivered water (membrane permeate plus blending, when applicable) was assumed to be 200 gallons per minute (gpm). The system recovery was set at 85% and it was assumed that antiscalant and pH adjustment would be used. A two stage membrane system with a 2:1 array configuration with six elements per vessel was used. Blending of feed water with permeate was simulated if the permeate TDS was less than 500 mg/L. The schematic diagram representing the model case is shown in Figure 8.

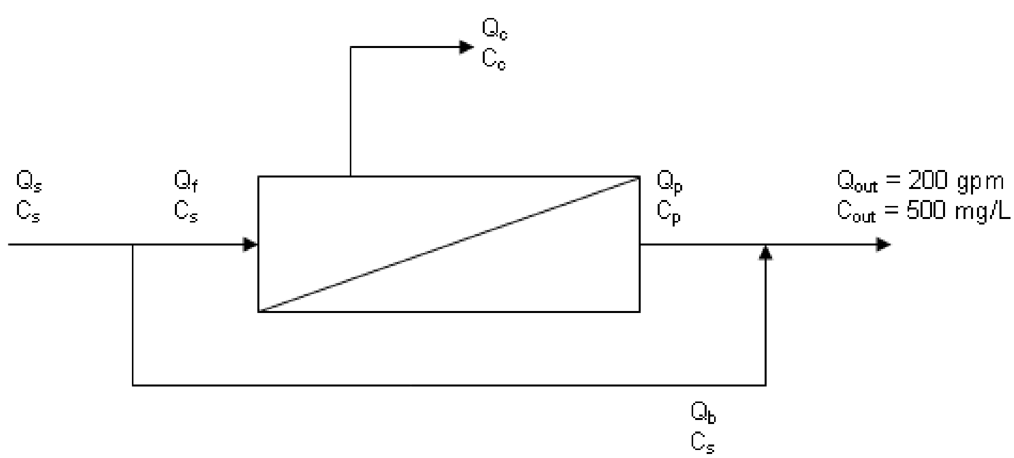

Figure 8. Schematic diagram of membrane process.

The following are variable definitions for the process streams labeled in Figure 8:

- Qs - Incoming feed stream flow rate (gpm)
- C_s - TDS concentration (mg/L) of incoming feed stream (Q_s, Q_f, and Q_b have the same concentration)
- Q_f - Membrane process feed flow rate (gpm)
- Q_c - TDS concentration (mg/L) of the concentrate stream
- Q_p – membrane permeate flow rate (gpm)
- C_p – TDS concentration of membrane permeate (mg/L)
- Q_b – flow rate of blend water (gpm)

- Q_{out} – Delivered water flow rate which also equals the sum of membrane permeate flow rate and blend water flow rate, (gpm)
- C_{out} – TDS concentration of the delivered water (mg/L)

The following parameters were defined for the hypothetical treatment process, Table 4.

Table 4. Design parameters for the hypothetical treatment process.

Parameter	Value
Delivered water flow rate (gpm)	200
Desalination process recovery (%)	85
Membrane array configuration	2 stages, 2:1 array
Number of membrane elements per vessel	6

4.2 Reverse Osmosis and Nanofiltration Membrane Specifications

Table lists the membranes used and the specifications for each membrane (supplied by the membrane manufacturer), including active area, salt rejection, and productivity. Specifications provided by membrane manufacturers represent data collected by the manufacturer using a feed source containing 2,000 mg/L salt (NaCl unless otherwise noted in the table) at 77 degrees Fahrenheit and 15% membrane recovery.

Table 5. Membrane specifications.

Membrane	Type	Active Area (ft^2)	Salt rejection (%)			Pressure normalized productivity (gpd)/(psi)
			NaCl	$MgSO_4$	$CaCl_2$	
NF90	NF	400	85-95	> 97	NA	107
ESNA1-LF2	NF	320	77	NP	NP	111
ESNA1-LF-LD	NF	320	NP	NP	89	109
XLE	RO	440	99	NP	NP	112
BW30	RO	365	99.5	NP	NP	42
ESPA1	RO	320	99.3	NP	NP	80
XFR LE	RO	400	99.4	NP	NP	77

*NP = data not provided by membrane manufacturer in specification sheet.

4.3 Membrane Performance Modeling

Membrane manufacturer simulations were conducted for each feed water source and membrane type. The software programs issue design warnings if any of the simulation conditions are outside the acceptable range. Two design warnings were commonly encountered during the simulations: maximum permeate flow exceeded and recovery per element exceeded.

When the above design resulted in design warnings for a given feed water quality, the backpressure on stage 1 was increased to balance the flows between the two stages. When changing the back pressure was not sufficient to satisfy the design warnings, the recovery was lowered incrementally. A recovery of 75 % was used as the lower limit for a two stage system. If design warning persisted at 75% recovery, the stage configuration was changed to 3:1 array. The 3:1 array configuration was only necessary for simulations using NF membranes for feed water sources with sodium concentration greater than 1,200 mg/L. The recovery, feed pressure, and product TDS were tabulated for each feed water and membrane type modeled.

The permeate TDS values obtained using each of the different membranes from modeling effort were plotted against the feed TDS and the feed sodium concentration. Figure 9 illustrates the relationship between the feed TDS concentration and the permeate TDS. Similarly, Figure 10 illustrates the relationship between the feed sodium concentration and the permeate TDS. The thick line in both figures shows the 500 mg/L secondary maximum contaminant level (MCL) for TDS. Therefore, all points which fall below the line meet the target permeate TDS level.

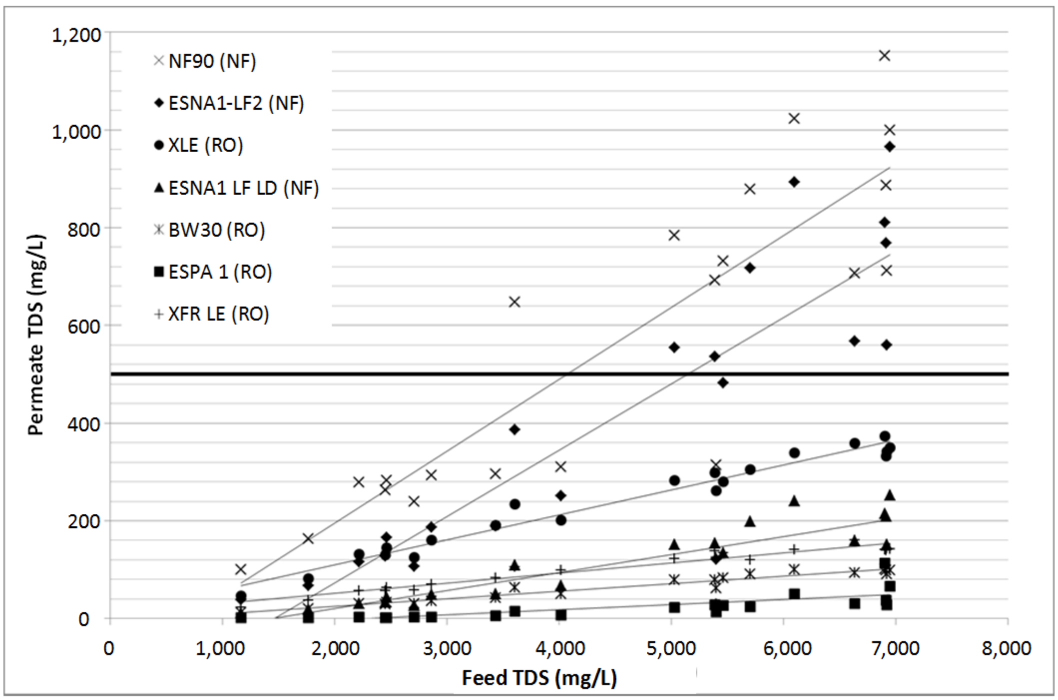

Figure 9. Linear correlation between feed TDS and permeate TDS for NF and RO membranes. Bold line shows the secondary MCL of 500 for TDS.

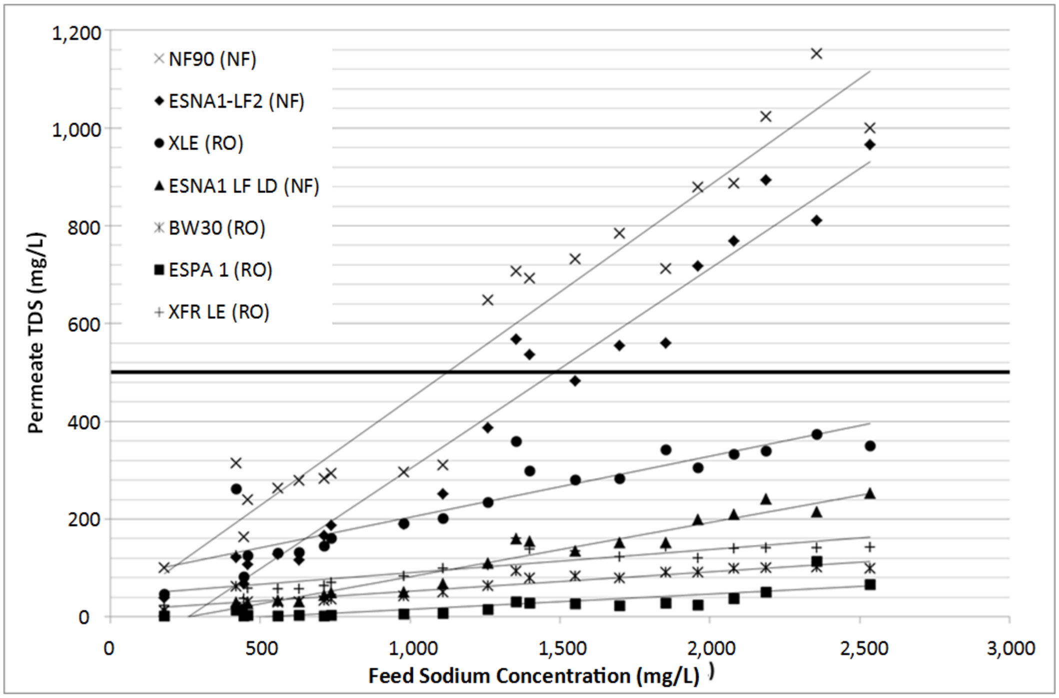

Figure 10. Linear correlation between feed sodium concentration and permeate TDS for NF and RO membranes. Bold line shows the secondary MCL of 500 for TDS.

One NF membrane and all four RO membranes were able to treat the feed waters to a permeate TDS concentration less than the 500 mg/L target value for all water types we considered (feed TDS less than 7,000 mg/L and feed sodium concentration less than 2,500 mg/L). Table 6 provides a summary of the percent of variance, R-squared, for each range of membrane permeate TDS output. R-squared is the fraction by which the variance of the errors is less than the variance of the dependent variable. The feed TDS concentration shows a stronger correlation for predicting permeate TDS for three of the four RO membranes than NF membranes. Similarly, the feed sodium concentration shows a stronger correlation for predicting permeate TDS for the NF membranes than RO membranes. Because RO membranes show high rejection of all ions, it is to be expected that the ionic composition has less of an impact on the permeate TDS for RO.

Table 6. R-squared Coefficients for each NF and RO membrane shown in Figure 9 and 10.

Membrane	Type	R-squared Coefficients for Figure 9 (dependent on feed TDS)	R-squared Coefficients for Figure 10 (dependent on feed Sodium)
NF90	NF	77.5%	93.1%
ESNA 1 LF2	NF	77.1%	95.7%
ESNA1 LF LD	NF	77.0%	95.1%
XLE	RO	96.8%	78.7%
BW30	RO	95.2%	85.2%
ESPA 1	RO	56.6%	66.9%
XFR LE	RO	94.1%	67.2%

Using the trendline function in Excel, equations were obtained to describe the permeate TDS as a function of the feed sodium concentration for the NF membranes. These equations were solved using the target permeate TDS of 500 mg/L to find the maximum feed sodium concentration treatable to the target TDS using the membranes. This results in a maximum feed sodium concentration of 1,120 mg/L and 1,510 mg/L for the NF90 and ESNA1-LF2 respectively. The more conservative value of 1,120 mg/L was applied to the Texas Groundwater database to determine which wells could be effectively treated with a NF membrane. Figure 11. 1 shows the geographical locations of all the wells and indicates wells that can be treated to less than 500 mg/L using NF. Based on this analysis, the majority of wells represented in the database can be treated to less than 500 mg/L TDS using NF.

It should be noted that in some cases, the concentration of other constituents in the permeate may exceed the Safe Drinking Water Act Maximum Contaminant level even if the TDS concentration is less than 500 mg/L. This level of analysis was outside of the scope of this study; however, this should be considered when making the final determination of the suitability of NF for a specific application.

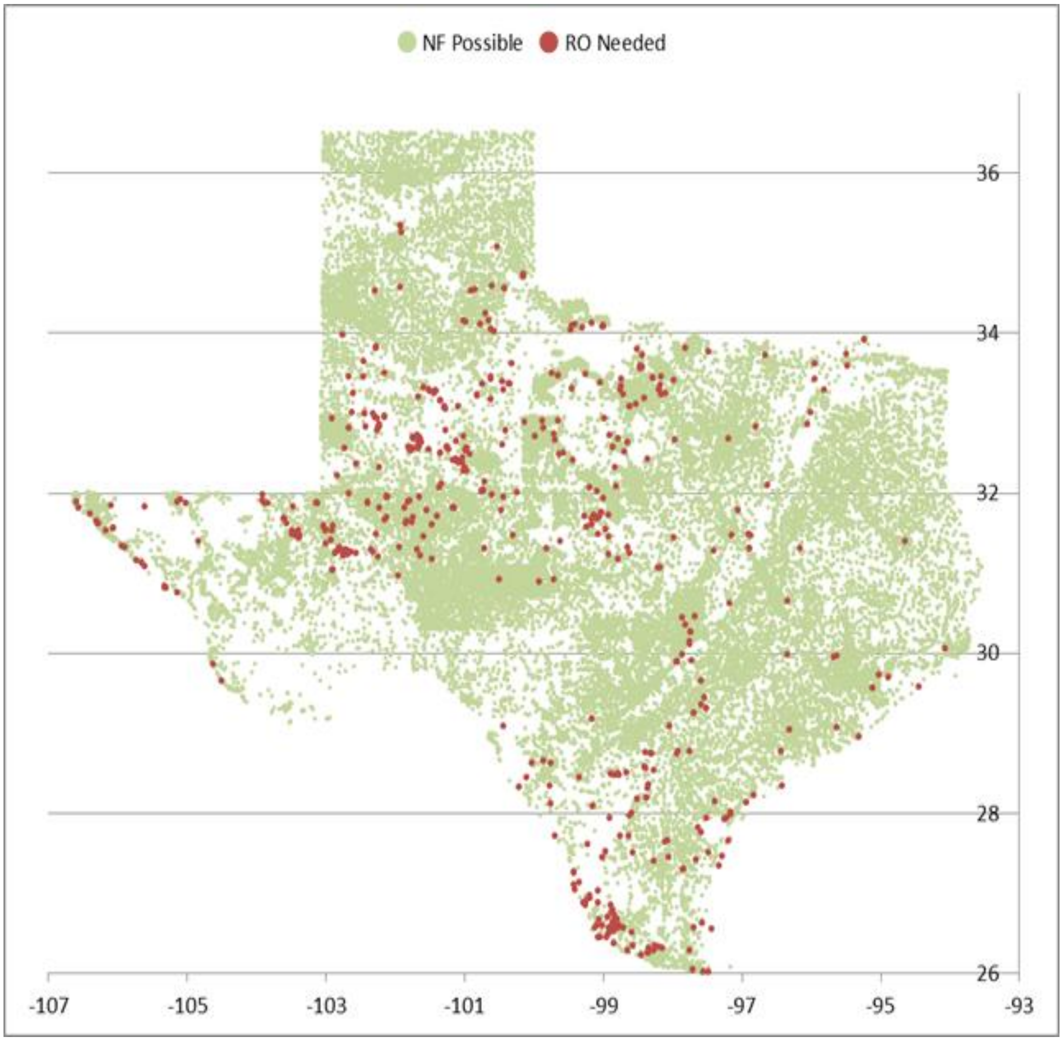

Figure 11. Geographical locations of wells with sodium concentrations under 1,120 mg/L that can be effectively reduce TDS concentrations to below 500 mg/L using a NF membrane (based on performance modeling of three NF membranes).

5. Membrane process design and cost comparison

NF membranes operate at a lower applied pressure since they do not have a high salt rejection capability compared to RO. However, RO has the capability of treating high TDS water to high permeate water quality. Additionally, because of the very low TDS in the water produced by RO, there is a possibility of blending feed water with RO permeate while still delivering water less than the target TDS of 500 mg/L. It should be noted that in order to utilize blending, the concentration of other constituents in the blended water must not exceed any Safe Drinking Water Act Maximum Contaminant Levels. This section looks at the resulting economic impact of the trade-offs between RO and NF for feed water types that may be treated to less than 500 mg/L TDS using both types of membranes.

The following two sections compare process design and energy requirements using the RO and NF membranes described earlier.

5.1 Process design

Based on the permeate TDS, feed TDS, and target delivered flow rate a mass balance was conducted to determine the membrane feed flow rate, the raw water flow rate, and the blend flow rate. A salt balance around the membrane system was used to solve for the blending flow rate and the permeate flow rate. The recovery was then used to find the membrane feed flow rate for each membrane.

Feed water sources with lower TDS allow for more blending without exceeding the target delivered water TDS of 500 mg/L regardless of the type of membrane used. RO membranes are capable of higher salt rejection and produce permeate with a lower TDS than NF. This allows more blending water to be used with the RO permeate to achieve the targeted product water's TDS and flow rate. More blending water also enables the use of less feed water into the membrane. Because membrane plant size is proportional the amount of feed water to be treated, ultimately the size of the plant may be decreased when using RO versus NF. Figure 12 illustrates the difference in feed water flow rate for each of the membranes considered in this study.

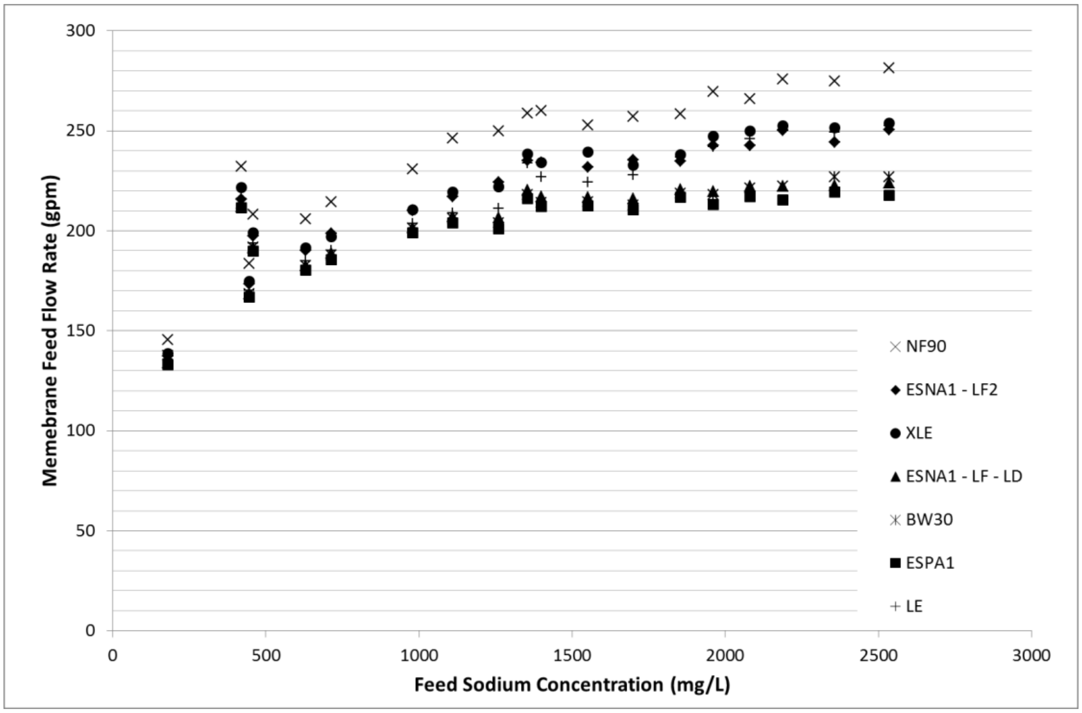

Figure 12. Membrane system feed flow rate for NF and RO.

The membrane process feed water flow rate determines the amount of membrane area required for the treatment system. Using a high rejection RO membrane with blending can reduce the required membrane area. For feed water qualities with a high sodium concentration, this effect is more significant. For the feed water qualities evaluated in this study, the maximum reduction in required membrane area achieved by using RO rather than NF was 12%. Because membrane system capital costs are calculated based on the feed capacity [33], it is assumed that the maximum capital cost decrease of using RO rather than NF is less tan 12%.

5.2 Energy requirements

NF requires as a lower pressure than RO because the membranes have different ion rejection rates. Operating at lower pressures for NF results in saving on energy costs compared to RO operation. Figure 133 shows the required feed pressure for each of the simulations conducted.

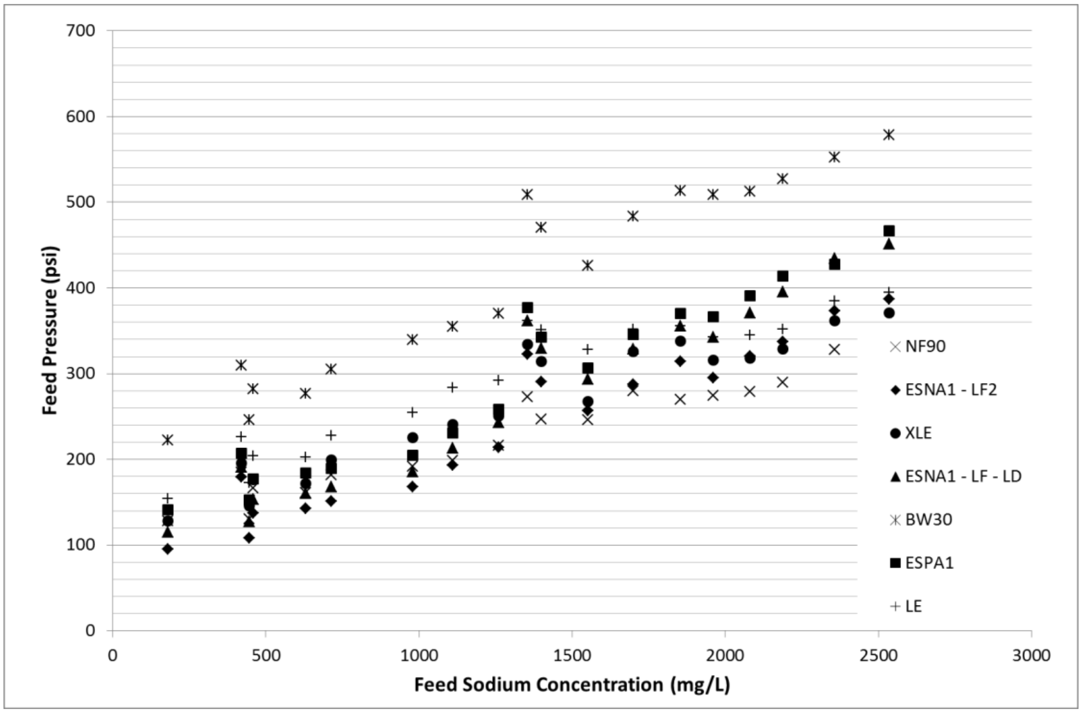

Figure 13. Feed pressure requirements for RO and NF simulations.

Pump power requirements were calculated using Equations 1 and 2 that show the relationships between the input flow rate and required pressure.

$$P = \frac{\rho * g * H * Q_{in}}{\eta} \qquad \text{(Equation 1)}$$

$$H = \frac{P_2 - P_1}{\rho * g} + \frac{v_2^2}{2g} \qquad \text{(Equation 2)}$$

Where P is power in Watts, Q_{in} is the total water fed to the desalination system, P_2 is the pressure leaving the pump (Pascals, Pa), P_1 is the pressure entering the pump (Pa), ρ is the water density (kg/m^3), v is the fluid velocity (m/s), and η is the pump efficiency.

Equations 1 and 2 were then combined into Equation 3.

$$P = \frac{Q_{in} * \left((P_2 - P_1) + \frac{\rho * v^2}{2} \right)}{\eta} \qquad \text{(Equation 3)}$$

The difference in the energy required (kW per gallon permeate produced) to achieve the desired operating pressure for the NF and RO membranes was calculated. Figure 144 shows the increase in the energy requirement for RO compared to NF.

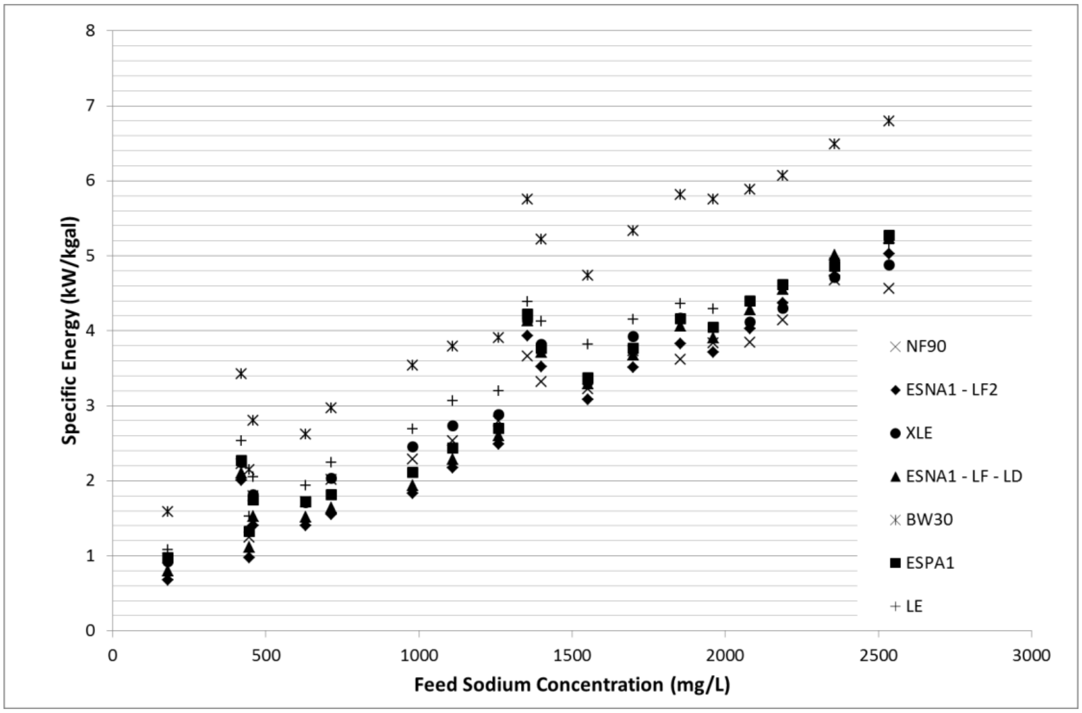

Figure 14. Reduction in specific energy consumption for NF compared to RO

Figure 14 shows that using NF rather than RO, when possible, can reduce the energy consumption by approximately 40%. Energy is equal to roughly 1/3 of the operating and maintenance costs associated with membrane processes.

5.3 Other factors influencing cost

While the pumping energy requirement and blending are key factors in comparing the cost of NF and RO treatment, there are a number of factors that are also impacted. Some of these factors are discussed qualitatively in this section.

Because the salt rejection of NF membranes is lower than for RO membranes, NF membranes experience less concentration polarization which lessens the probability of inorganic fouling. As a result, there is a decrease in energy requirements and less frequent need for chemical cleaning. The cleaning process consumes chemicals and requires plant downtime, both of which affect the economics of the membrane process.

As well, considering the fact that RO permeate contains less than 100 mg/L TDS in brackish groundwater desalination plants (where feed TDS is usually less than 3,000 mg/L), alkalinity and hardness are often added to RO permeate to make the finished water less corrosive.

Furthermore, it is anticipated that the concentrate generated from NF will be less saline than that generated from RO. This has the potential to reduce the cost of concentrate disposal or enable a less expensive method of concentrate disposal.

While many of the cost factors may support the selection of NF rather than RO, other factors may support selection of RO. Because RO produces a higher quality permeate, RO is often seen as a more conservative treatment option and may slightly reduce the risk of exceeding constituent concentrations of concern.

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6. Conclusions

In Texas, brackish groundwater is primarily treated with RO. However, little guidance exists for water planners to select the optimal membrane that will result in the lowest process cost. Although RO is an effective treatment method, the energy requirements for RO can impede more widespread use of brackish groundwater as a viable application throughout the state.

This study examines the salt rejection capability of NF and RO membranes to provide a planning-level understanding of potential benefits of using NF rather than RO where appropriate. The analysis of the Texas Groundwater database and the use of ROSA and IMSdesign created projections for different water qualities and estimated the permeate TDS that would result from using each of the seven membranes included in the study.

From the calculations made, it was determined that the majority of groundwater wells in Texas could be treated with NF membranes producing a permeate TDS lower than 500 mg/L. Furthermore, it was shown that the feed sodium concentration was a suitable indicator of whether NF could produce the targeted TDS level in the permeate.

RO permeate is very low in TDS and blending of feed water with permeate can be used to increase the delivered water volume without exceeding the targeted TDS. Therefore, in order to produce the same volume of delivered water, RO membranes enable the use of more blending water and consequently the amount of water that needs to be treated by the membranes is reduced. Therefore, a plant utilizing RO membranes will require less membrane area than if NF membranes were used. Based on the analysis conducted in this study, we estimate that a plant using NF membranes would require at most 12% more membrane area than one using RO membranes. Because membrane system capital costs are calculated based on the feed capacity [33], it is assumed that the maximum capital cost increase of using NF rather than RO is 12%.

NF membranes have lower salt rejection and higher water permeability; therefore, the energy requirement to produce the same volume of water is lower for NF membranes than for RO membranes. We found that the energy savings resulting from using NF rather than RO could be as high as 40%. A lifecycle cost analysis would need to be completed in order to quantify the cost savings that could be realized by using NF rather than RO.

Other factors to consider when selecting between NF and RO membranes include concentrate disposal, regulatory requirements, and degree of tolerated risk associated with exceeding targeted constituent concentrations.

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