Texas Water Development Board

Final Report

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Developing Practical Alternatives to Pilot Plant Studies for Innovative Water Technologies

- Part I. Alternatives to Pilot Plant Studies for Membrane Technologies
- Part II. Performance Evaluation of Reverse Osmosis Membrane Computer Models
- Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes

January 2014

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Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/ Nanofiltration Membrane Processes

Final Report

by
Don DeMichele
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January 2014

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1 Introduction

1.1 Background

The Texas Commission on Environmental Quality currently considers reverse osmosis as an "innovative" treatment method for the removal of drinking water contaminants from a groundwater source. This definition is the result of an absence of specific requirements in the Texas Commission on Environmental Quality rules that provides design, operation, maintenance, and reporting criteria for a treatment process. Due to the status of brackish groundwater reverse osmosis as an innovative treatment method, any proposed new treatment facility requires the approval of an exception request by the Texas Commission on Environmental Quality prior to review of facility plans and specifications. The exception request approval letter establishes the treatment criteria.

Title 30 Texas Administrative Code Chapter 290.42(g) of the Texas Commission on Environmental Quality rules requires that a licensed professional engineer submit an exception request for a proposed brackish groundwater reverse osmosis treatment facility. In the past, an exception request included the requirement of pilot test data, or data collected at similar full-scale operations, to substantiate that the produced water will meet the requirements of Title 30 Texas Administrative Code Chapter 290, Subchapter F: *Drinking Water Standards Governing Water Quality and Reporting Requirements for Public Water Systems*. Due to current drought and water scarcity, the prompt commissioning of a new water source is critical. As a response to the need for timely process reviews during a drought period, the Texas Commission on Environmental Quality, based on stakeholder input, will allow the use of output data from computer modeling software programs in lieu of data obtained from on-site pilot testing to approve a reverse osmosis membrane systems. Please contact the Texas Commission on Environmental Quality or visit their website for current guidance on the approval process and requirements for reverse osmosis membrane systems.

1.2 Purpose

The purpose of this document is to establish a standard of care for the use of computer models to develop design criteria for reverse osmosis and nanofiltration processes that treat groundwater. The purpose of this document is not to replace sound engineering judgment on the part of the responsible design engineer. The intent is to provide the basic framework from which the design engineer, incorporating sound engineering judgment, may design a reverse osmosis or nanofiltration membrane treatment process using computer models offered by a number of membrane manufacturers. Used properly, computer models have demonstrated that they are an effective tool for the design of membrane treatment processes that provide reliable product water flows and quality. For more detailed information regarding the accuracy and precision of membrane system computer models, refer to the Texas Water Development Board report *Part II. Performance Evaluation of Reverse Osmosis Membrane Computer Models*.

2 Materials

2.1 Design software

2.1.1 Introduction

A number of reverse osmosis and nanofiltration membrane manufacturers have created and made available membrane system computer models. These models are available either through download from the manufacturers' websites, or through contact with the manufacturers or their representatives. A sample list of available computer models is provided in Table 2-1.

Table 2-1. Reverse osmosis and nanofiltration design computer models.

Manufacturer	Model Name	Website
CSM	CSMPro V.5.0	www.csmfilter.com
Dow Water & Process Solutions	ROSA V.8.0.3	www.dowwaterandprocess.com
Hydranautics	IMSDesign V.2012.8	www.membranes.com
Koch Membrane Systems	KMSROPRO V.8.06	www.kochmembrane.com
NanoH2O	Q+ V.2.0	www.nanoh2o.com
Toray	TorayDS2 V2.0.1.58	www.toraywater.com
Trisep	TROI	www.trisep.com
General Electric	Winflows 3.1.2	www.gewater.com/winflows.jsp

The computer models listed in Table 2-1 are periodically updated. The latest version of any modeling software should be obtained prior to developing design criteria for a new reverse osmosis or nanofiltration process. Each of these models uses a graphical user interface that allows the user to visualize the physical configuration of the subject membrane array. The computer models typically include separate tabs/screens for different design components. The tabs/screens are arranged in a logical sequence such that the user can "step" through the design process one tab or screen at a time. Specific instructions regarding the proper use of each model are available through the respective membrane manufacturer.

2.1.2 Background

Software limitations

The membrane system computer models listed in Table 2-1 have proven to be effective tools when used in accordance with the guidelines provided by the respective membrane manufacturers. They are, however, subject to several limitations. It is important for the design engineer to have an understanding of these limitations to ensure that data output from these models is interpreted and used properly in the design of a reverse osmosis or nanofiltration membrane facility.

Variability due to manufacturing

Computer models are tools that may be used to predict the stabilized performance for a specific reverse osmosis or nanofiltration system at a given set of operating conditions. Performance projections are based on the membrane manufacturer's performance specifications for a particular membrane element. Individual element performance specifications often allow for a deviation of ±15 percent of the nominal flow value. Salt rejection for a given membrane may also vary from the specified nominal rejection. For these reasons, the measured field performance of a membrane system is unlikely to match exactly the performance predicted by the modeling software. In general, the more membrane elements a system has, the closer the computer model predictions will be to measured field performance. This is due to the canceling effects of positive and negative deviations from the nominal performance values. A membrane system with many membrane elements is more likely to demonstrate these canceling effects of performance deviations than a membrane system with only a few membrane elements.

Membrane fouling and/or scaling

Over time, the accumulation of contaminants on a membrane surface (fouling), or the precipitation of inorganic salts (scaling) will require a corresponding increase in membrane feed pressures in order to maintain constant membrane flux (that is, constant product water flow produced by the system), and a consistent produced water quality. Computer models account for membrane fouling or scaling by incorporating a user-selectable "fouling factor" that is used to predict the performance of fouled/aging membranes. In general, a fouling factor of 1.00 represents the performance of a new, clean membrane system. Fouling factors less than 1.00 are used to represent a loss in membrane permeability due to fouling or scaling. When treating brackish groundwater with a silt density index of less than three, it is common practice to adjust the fouling factor by 7 to 8 percent per year, such that a fouling factor of approximately 0.75 represents membrane performance after three years of operation. Membrane manufactures provide specific guidance regarding the selection of an appropriate fouling factor based on considerations such as water source type, degree of pretreatment and feed water quality.

Some membrane manufacturers refer to the fouling factor as a "flow factor," as it also takes into consideration the impacts to membrane performance due to age, operating temperature, and pressure, and a safety margin. In addition to a fouling factor, some membrane manufacturers also allow the user to assume an annual percent flux decline and salt passage increase. If operated within the manufacturer's recommended operating parameters, age alone will have a negligible affect on membrane salt passage. Factors that may cause an increase in salt passage over time include exposure to oxidants, inappropriate pretreatment, and frequent and aggressive chemical cleanings.

When used in accordance with a membrane manufacturer's instructions, fouling factors can be effective tools to predict the performance of a membrane system as fouling or scaling occurs. Fouling factors can be used by the design engineer to select feed pumps and select system piping pressure ratings to facilitate an increase in membrane feed pressure over time caused by fouling or scaling.

Fouling factors will not predict if a particular membrane system will experience fouling or scaling. Source water quality is generally the best indicator of membrane system performance. As such, membrane manufacturers have published guidelines that set limits for membrane system operational parameters for multiple categories of water sources based on water quality.

The operation of a membrane system outside of these limits will often result in problems due to fouling or scaling.

Ultimately, it is the responsibility of the design engineer to specify membrane system operating criteria that will minimize the potential for fouling and scaling, and limit the impacts to produced water capacity and water quality should fouling or scaling occur.

Variations in source water quality

When designing a reverse osmosis or nanofiltration membrane process using computer models, the design engineer must account for variations in source water quality. These variations may be short term, such as seasonal fluctuations in surface water temperature and salinity, or long term, such as the gradual increase of groundwater total dissolved solids due to intrusion from seawater or a higher salinity aquifer. At a minimum, reverse osmosis or nanofiltration membrane projections should be performed using best and worst-case water quality based on the best water quality data available. For groundwater sources, historical water quality data may be limited to one or two sets of data representing recent conditions. For surface water sources, a minimum of several years of historical data is desired to demonstrate seasonal variations in water quality. When significant variations in groundwater quality are expected (such as, suspected seawater intrusion, known aquifer fissures, other historical problems with subject aquifer), predictions of future water quality should be determined by a licensed hydro geologist.

For both small and large membrane systems, source water quality data should generally be less than 5 years old, and include data on primary and secondary contaminants, as well as water quality inputs required by the membrane computer model.

Special cases of source water quality

For the membrane treatment of waters with a defined origin and composition, computer models can predict system performance to a reasonable degree of accuracy. There are some cases; however, where pilot testing is required to ensure proper membrane system design. Several examples are listed below:

- Special or new applications of a membrane technology (such as, process or waste water effluents)
- Restrictive permeate quality requirements associated with industrial applications. An example would be ultrapure water for the semiconductor industry.
- Removal of water quality constituents that are not output by the computer models and for which reverse osmosis or nanofiltration is not listed as a best available technology by the U.S. Environmental Protection Agency.
- Systems with recoveries at the limit of, or in excess of manufacturer recommendations

For these cases, pilot testing can be performed to determine the appropriate design and operating characteristics for a membrane system. These characteristics include feed pressures required for the desired flux and permeate water quality, maximum recovery rates, and membrane fouling/scaling characteristics.

Engineering judgment

Computer models are not a substitute for sound engineering judgment. Computer models will often provide a basis for the development of membrane system design criteria, but there are many aspects of reverse osmosis and nanofiltration membrane system design that are not addressed by computer modeling alone. Decisions regarding equipment and materials selection, redundancy requirements, physical equipment layouts, accessibility, and other critical issues must be made by the design engineer through the use of sound engineering judgment. It is also important for the design engineer to consider applying factors of safety. It is left to the design engineers' judgment to define where safety factors are applied (and their magnitude) based on specific circumstances.

Design for multiple membrane manufacturers

Computer models provide a large membrane element selection from within a particular manufacturer’s product offering. For most reverse osmosis and nanofiltration applications, multiple manufacturers offer membranes providing comparable performance. To ensure flexibility for future membrane replacement, the treatment process and equipment should be designed to accommodate membrane elements from multiple suppliers. The output of multiple computer model software programs (such as, representing different vendors) should therefore be used to make design decisions.

Membrane (type) selection

The design engineer must be responsible for the selection of an appropriate type of membrane product to meet the project goals. For example, in many cases, computer model output will show that both nanofiltration and reverse osmosis membrane elements can meet the treatment goals for a particular facility. Both nanofiltration and reverse osmosis membranes will reject nitrate and hardness to varying degrees. Due to economic considerations, nanofiltration is almost always used to remove hardness, and reverse osmosis is typically used to treat for nitrate at full-scale membrane facilities. While the previous example is rather straightforward, there are real-world cases where other parameters of concern may complicate the selection of nanofiltration or reverse osmosis technologies. A brief list of such parameters is provided below:

- Disinfection and disinfection byproducts precursor material
- Taste and odor
- Iron
- Manganese
- Sulfate
- Sodium
- Chloride
- Fluoride
- Total dissolved solids
- Concentrate disposal
- Combinations of the above

In these cases, the most cost effective membrane technology must be analyzed given site-specific water quality, treatment goals, and ability to dispose of concentrate flows. The decision to select either nanofiltration or reverse osmosis membrane technology often results from a detailed economic evaluation of each technology.

Within families of membranes (reverse osmosis or nanofiltration) manufactures have published single-element performance test results for their products. These tests are based on similar testing conditions (that is, pressure, flows, temperature, and salinity) for comparable membranes. The published test results can be used by the design engineer to select an appropriate membrane for the feed water quality and treatment goals.

2.1.3 Basics of software data input and output

Data input

Data input using membrane system computer models is typically divided into several categories (or tabs) including the following:

- Project Information
- Feed Water Information
- Scaling Information
- System Configuration

The information provided below is typical of most reverse osmosis and nanofiltration computer software models. Data input methods and formats vary slightly for each membrane manufacturer listed in Table 2-1, but the type and amount of data input are similar for each.

<u>Project information</u>

Project name, case description, date, and similar data are entered in this category/tab.

<u>Feed water information</u>

Data such as classification of source water (that is, groundwater, surface water, seawater, wastewater, etc.), feed water pH, temperature, turbidity, silt density index, and feed water chemistry (such as, specific mineral concentrations, conductivity, and/or total dissolved solids concentrations) are entered in this category/tab.

<u>Scaling information</u>

Membrane computer models require the design engineer to enter information regarding the selected scale control method. User inputs may include:

- Design recovery and temperature
- Chemical and dose used for pH adjustment
- Leakage of calcium and magnesium from upstream ion exchange processes

As will be discussed in the Data Output section to follow, computer models provide warnings if the solubility limit of a particular salt is exceeded at a user specified recovery. Additional information about the scientific principles related to solubility, scaling, and recovery are presented in Section 2.1.4. The user should consult with an antiscalant manufacturer to determine an appropriate antiscalant, dose, and recovery for the particular application.

<u>System configuration</u>

Information related to the configuration of the membrane system is entered under this category/tab. An example list of system configuration information includes the following:

- Flow configuration (such as, is concentrate recirculation used?)
- Permeate staging (selection of multiple passes)
- Permeate flow/flux
- Recovery rate
- Feed flow rate
- Recirculation flows (if concentrate recirculation flow configuration is selected)
- Number of feed stages in each pass
- Number of pressure vessels per stage
- Membrane element selection
- Number of membrane elements per pressure vessel
- Factors to adjust for fouling (user selectable – may include flow loss and/or salt passage variation)
- Permeate backpressure
- Interstage booster pump pressure
- Blending flow rate (such as, bypass of raw water around the reverse osmosis process)
- Pump efficiencies

Some of the parameters listed above can be calculated from others. An example would be the calculation of feed flow based on an input of recovery and permeate flow. Average membrane flux is calculated based on the specified permeate flow and the total membrane area. If necessary system design information is lacking, or if the system design information provided by the user is outside the limits recommended by the membrane manufacturer, the computer model will provide on-screen warnings that will direct the user to enter or modify the required information before proceeding with a system analysis.

Most computer models offered by membrane manufacturers provide a schematic display of the membrane system configuration, so that the impacts of adjusting system configuration inputs can be visualized immediately.

Data output

Output from computer models generally includes the following information:

- Total system feed, concentrate, and permeate flows
- Differential pressure drop across each stage
- Required feed pressure to each stage
- Pressure of concentrate streams leaving each stage
- Average system permeate flux
- Average net driving pressure across membrane elements
- Average osmotic pressure of feed and concentrate streams
- total dissolved solids concentrations of system permeate and concentrate streams
- total dissolved solids, flow, flux, and pressure information for each membrane element

- Saturation levels of sparingly soluble salts in the concentrate stream of each membrane element
- Warnings (if applicable) related to flow, pressure, flux, and solubility limits, and other critical process parameters
- Values of scaling indices (such as, Langelier Saturation Index, and Stiff and Davis Index)
- Required system pumping power (kilowatt) and specific energy (kilowatt hour per 1000 gallons)

Output generated by computer models is provided in printable reports that can be customized (to varying degrees) to meet the formatting requirements of a particular project.

2.1.4 Scientific principles of modeling software

Water quality

The characteristics of the membrane feed water determine, to a large degree, the performance of the membrane system. Based on feed water quality data provided by the user, membrane system computer models incorporate principles of diffusive mass transfer and equilibrium water chemistry to estimate permeate water quality and the tendency of the membrane system to experience scaling. The following serves as an introductory discussion of these concepts. For a more detailed discussion, the reader should refer to American Water Works Association (AWWA), *Manual of Water Supply Practices M46, Reverse Osmosis and Nanofiltration*, and the U.S. Environmental Protection Agency (EPA), *Membrane Filtration Guidance Manual* (AWWA, 2007 and USEPA, 2005).

<u>Diffusion & permeate quality prediction</u>

Because salt removal by non-porous reverse osmosis and nanofiltration membranes is controlled by diffusion, it is helpful to have an understanding of what diffusion is and how it influences the concentration of dissolved salts in the membrane permeate water produced.

Diffusion is the passage of dissolved salts through a membrane due to a difference in salt concentrations on either side of the membrane. Diffusion of dissolved salts is in the direction of decreasing concentration, that is salts diffuse from the feed to the permeate side of the membrane. The rate of diffusion is influenced by several factors including:

- Mass transfer characteristics of a particular membrane. The mass transfer characteristics of a membrane are accounted for in the available computer models.
- Concentration of dissolved salt species at the membrane surface.
- Temperature.

The diffusion rate of dissolved salts through a non-porous reverse osmosis or nanofiltration membrane is generally unaffected by changes in membrane feed pressure. In contrast to salt passage, the passage of water through a semi permeable membrane is a pressure-driven process. That is, as the feed pressure increases, the flux of water through the membrane also increases. Therefore, for a given feed water quality, the concentration of dissolved salts in the reverse osmosis or nanofiltration membrane permeate water can be controlled by making adjustments to the membrane feed pressure. An increase in membrane feed pressure will result in lower membrane permeate concentrations.

While diffusion rates are generally unaffected by changes in pressure, changes in temperature have a strong influence on diffusion. If temperature increases, and other parameters are held constant, permeate flux and salt passage through a reverse osmosis or nanofiltration membrane will increase. If the water (permeate) flux rate were held constant, as the temperature of the feed water is increased, the concentration of dissolved salts in the permeate will increase (and the feed pressure required to produce that flux rate will decrease).

These principles of diffusion are incorporated into the algorithms of computer models to predict the quality of permeate produced by a reverse osmosis or nanofiltration membrane system for a specified chemistry, temperature, and permeate water flux rate.

<u>Solubility, scaling, & recovery determination</u>

<u>Solubility</u>. The solubility of a salt represents the degree to which it may be dissolved in water at a specific temperature. The solubility of a salt at a specific temperature is given by its solubility product at that temperature, defined as:

$$K_{sp} = [A^{b^+}]^a [B^{a^-}]^b \qquad \text{Equation 2-1}$$

Where;

K_{sp} = Solubility product of the salt
A = Cation constituent of salt
B = Anion constituent of salt
a = Stoichiometric coefficient of cation in the salt's equilibrium equation, charge of anion
b = Stoichiometric coefficient of anion in the salt's equilibrium equation, charge of cation

The solubility product varies with temperature. In general, salts become more soluble at higher temperatures. There are important exceptions to this rule. One exception is calcium carbonate, which becomes less soluble and may precipitate at higher temperatures.

Because dissolved salts are rejected by reverse osmosis and (to a lesser degree) nanofiltration membranes as water passes through the membrane as permeate, the concentration of these salts in the feed stream rises along the membrane feed path. If a salt's concentration exceeds its solubility product at the system operating temperature, the salt will begin to precipitate out of solution. Precipitation of dissolved salts in a membrane system can lead to membrane scaling and reduced membrane performance.

Control of mineral scaling is an essential component of the design of a reverse osmosis or nanofiltration system treating brackish surface or groundwaters. Computer models can predict with reasonable accuracy the occurrence of scaling based on feed water chemistry and target recovery values.

<u>Recovery</u>. The recovery of a membrane system is the fraction (stated as percent) of feed water volume that passes through the membrane(s) as permeate. System recovery for brackish water reverse osmosis and nanofiltration applications generally ranges between 70 and 85 percent. Due to the greater osmotic pressures associated with seawater's higher salinity, seawater reverse osmosis applications are usually limited to recoveries of approximately 50 percent. For 8-inch membrane elements used in large-scale systems, maximum recovery for individual membrane elements is generally limited to approximately 15 percent for brackish water applications, and

between 13 and 15 percent for seawater applications. Recoveries for similar elements configured in series tend to be higher for the lead elements, and lower for the tail elements. The design engineer should consult the membrane manufacture's recommendations regarding maximum recovery for specific membrane elements.

In brackish water applications, recovery is typically limited by the solubility of a "limiting salt." Since a greater fraction of feed water is converted to permeate at higher recoveries, the concentration of dissolved salts in the feed stream also increases. The higher salt concentration in the feed stream results in the following:

- Higher rate of salt diffusion across the membrane with corresponding increase in permeate salinity at a given flux rate
- Greater feed stream osmotic pressure with corresponding reduction in permeate flux at a given pressure
- Increased potential for precipitation of dissolved salts

For a constant permeate flux, the net effects of operating a reverse osmosis or nanofiltration membrane system at higher recoveries are (1) an increase in required feed water pressure, (2) an increase in permeate salinity, and (3) an increased potential for membrane scaling.

Besides membrane scaling, energy consumption, and permeate water quality, there are other considerations that the design engineer must take into account when determining the design recovery for a reverse osmosis or nanofiltration membrane system. These include the value of the raw water, and capital costs for equipment related to membrane system pretreatment.

Computer models provide warnings when the maximum allowable recovery is exceeded for an individual membrane. These programs also provide information regarding the saturation levels of individual species of dissolved salts that may limit recovery for a particular system configuration and feed water quality.

<u>Controlling scale formation</u>. Scaling occurs on the surface of a membrane when the concentration of a salt in the feed water exceeds its solubility limit. Computer models incorporate the principles of equilibrium chemistry to predict the occurrence of scaling due to several common limiting salts such as:

- Calcium Carbonate
- Calcium Sulfate
- Barium Sulfate
- Strontium Sulfate
- Silica
- Calcium Fluoride
- Calcium phosphate

Depending on the feed water quality and system recovery, acid, scale inhibitors (sometimes referred to as antiscalants), softening, or appropriate combinations thereof may be used to control scale formation. The computer model will provide a solubility warning for common limiting salts and may recommend a target feed water pH and the use of a scale inhibitor.

Acid addition to adjust feed water pH is very effective and often used to prevent the precipitation of calcium carbonate and calcium phosphate, but it is generally ineffective in preventing other types of scale such as that caused by sulfate salts. In fact, the use of sulfuric acid may actually contribute to sulfate scaling due to the contribution of additional sulfate ions.

Scale inhibitors work by several different mechanisms:

- Inhibiting the formation of crystalline precipitates at supersaturation
- Chelation of metal ions to keep them in suspension
- Dispersion to maintain colloids in suspension

The selection of an appropriate scale inhibitor is facilitated by computer models created and used by the scale inhibitor vendors. Several of these models are available for public use. A sample list of scale inhibitor manufacturers is provided in Table 2-2.

Table 2-2. Scale inhibitor computer models.

Manufacturer	Model Name	Website
American Water Chemicals	Note a	www.membranechemicals.com
Avista	Avista Advisor V3.0	www.avista.com
PWT	Note a	www.pwtchemicals.com
BWA Water Additives	ProDose	www.wateradditives.com
King Lee Technologies	Note a	www.kingleetech.com
Nalco	Note a	www.nalco.com

[a]These vendors do not furnish their projection software for public use. Contact the vendor directly and provide them your water quality. Ask for a copy of the projection software output for your engineering records.

In addition to models provided by scale inhibitor vendors, several water chemistry software packages are available with the capability to simulate the affects of scaling based on specific water chemistry. These models allow the user to select a commercially available scale inhibitor product from a number of vendors, and optimize a scale inhibitor dose based on membrane system operating parameters. One example would be Hyd-RO-Dose^{TM}, offered by French Creek Software, Inc.

Scale inhibitor computer models require input similar to that required for membrane system computer models. Information related to feed water quality, membrane selection, membrane system configuration, flows, and pressures are provided by the user. The subsequent output from the software model provides a recommendation for an appropriate scale inhibitor selection. This output, along with the output from the membrane system computer model, should be saved with the design engineer's project records. *The design engineer should apply any appropriate factors of safety that they see fit or maximum recovery for a reverse osmosis or nanofiltration membrane system based upon the output of the scale inhibitor manufacturer models.*

A number of the scale inhibitor vendors listed in Table 2-2 do not provide their computer models to the public. In these cases, the design engineer may contact the vendor directly and provide the required information for the subject reverse osmosis or nanofiltration system. The vendor can provide a copy of the projection software output for the project records. An example demonstrating the use of scale inhibitor computer models is provided in Chapter 4.

Less common methods of scale control include lime softening, and aeration/chemical oxidation followed by filtration to remove iron and manganese. Softening, using a lime softening process or strong acid cation ion exchange resin, is effective in removing calcium, magnesium, and barium from membrane system feed waters. When compared to acid addition or antiscalant use, the primary disadvantage of softening is cost.

Hydraulics

Because reverse osmosis and nanofiltration are pressure-driven processes, the required membrane feed pressure is a critical hydraulic design parameter. As discussed previously, membrane feed pressure directly influences membrane flux and permeate water quality. Membrane system computer models account for the five components of membrane feed pressure listed below:

1. Osmotic pressure
2. Pressure loss through the membrane
3. Permeate backpressure
4. Pressure loss along the feed channel of multiple membrane elements configured in series within a pressure vessel
5. Friction losses in the feed piping between membrane feed stages

Osmotic pressure corresponds to the difference in chemical potential between two solutions. Osmotic pressure is directly proportional to the concentration of a solute within a solution. In reverse osmosis and nanofiltration processes, the osmotic pressure between two solutions must be overcome before water will pass through a semipermeable membrane from the concentrated solution to the dilute solution.

For fresh and brackish waters (total dissolved solids < 12,000 milligrams per liter), average osmotic pressure within a membrane stage is closely approximated by the following equation:

$$\Delta\Pi = 0.01 \times \left(\frac{TDS_F + TDS_C}{2} - TDS_P \right) \quad \text{Equation 2-2}$$

Where:

$\Delta\Pi$ = Osmotic pressure, pounds per square inch
TDS_F = Total dissolved solids concentration in the feed water, milligrams per liter
TDS_C = Total dissolved solids concentration in the concentrate water, milligrams per liter
TDS_P = Total dissolved solids concentration in the reverse osmosis permeate water, milligrams per liter

Pressure loss generated as water passes through a membrane as permeate is dependent on the water mass transfer characteristics of the membrane. This pressure loss is also referred to as net applied pressure. Net applied pressure is given by the equation:

$$NAP = \frac{F_W}{K_W} = \Delta P - \Delta\pi$$ Equation 2-3

Where:

NAP = Net applied pressure
F_W = Permeate flux, gallons per day per square feet
K_W = Water mass transfer coefficient of the membrane, gallons per day per square feet per pounds per square inch
ΔP = Transmembrane pressure differential, pounds per square inch
$\Delta\Pi$ = Osmotic pressure, pounds per square inch

This equation shows that the pressure loss generated as water passes through a membrane (net applied pressure) is directly proportional to permeate flux, and inversely proportional to the membrane's water mass transfer coefficient. Much of the recent progress in lowering the operating (energy costs) for reverse osmosis and nanofiltration membrane technology has resulted in improved water mass transfer characteristics, with a resulting reduction in net applied pressure requirement.

Permeate backpressure is the result of pressure losses (friction) within the membrane permeate channels and collection tubes, membrane array permeate header losses, and pressure resulting from friction losses and elevation changes within a treatment facility's permeate piping network. Permeate backpressure should be calculated to a reasonable degree of accuracy and used as an input in membrane modeling programs. It is recommended that the design engineer perform hydraulic calculations and/or collect actual hydraulic data (if facility is existing) to determine the expected permeate backpressure at the membrane array.

Feed channel pressure losses are generated as a result of friction that occurs when feed water flows through the feed channel of each membrane element configured in series within a pressure vessel. Low differential membranes minimize these losses by providing a larger feed channel cross-sectional area to reduce flow velocities. A recent study showed that membranes incorporating new 34-mil feed channel spacers reduce feed channel pressure losses by approximately 50 percent when compared to conventional 28-mil feed spacers (DeMichele, 2013).

Some computer models of reverse osmosis and nanofiltration membrane systems provide user adjustable inputs to characterize the pressure losses in the feed piping between membrane stages (if multiple membrane stages are used). The feed pressure to the second stage membrane array in a two-stage system is equal to the concentrate pressure of the first stage minus the pressure losses within the interstage piping plus any pressure contributed by an interstage boost pump (if interstage boost pumping is incorporated).

When sizing the first stage feed pump for a reverse osmosis or nanofiltration membrane system, it is important that the design engineer account for the pressure losses in the piping between the discharge of the feed pump and the first stage of the membrane system. Some computer models use an adjustable input to assume these piping pressure losses. In most cases, a model of the piping system should be created, using accepted principles of hydraulics, to provide the data required to accurately size the first stage feed pump.

It is important that the first stage feed pump be sized to accommodate the full range of membrane system flows and pressures. The design engineer should consider the expected range of the following parameters over the life of the membrane system:

- Source water quality and temperature
- Membrane system recovery
- Membrane condition (clean vs. fouled/scaled)

Another important consideration is the elevation used in the piping system hydraulic model for the location of the membrane feed pressure output from the membrane system computer model. The standard of care is to assume that feed pressure required by the membrane system model is located at the midpoint of the membrane system's vertical dimension.

Further detail regarding the sizing of a first stage feed pump, as well as considerations related to the sizing of an interstage boost pump, are provided in Chapter 3 of this document.

2.1.5 Design limits and warnings

In order to minimize fouling and scaling, and to prevent mechanical damage, the design of a membrane system should ensure that each membrane element operates within a recommended range of operating parameters. Computer models provide warnings to the user when the limits for any of these parameters are exceeded. Several of the more important membrane system design limits are discussed below.

Feed water parameters

Reverse osmosis and nanofiltration membrane elements are subject to fouling from dissolved organics, bacteria, suspended particles, and colloid material. Information related to the potential of membrane fouling caused by these constituents must be available when predicting the performance of a reverse osmosis or nanofiltration system using a computer model.

The turbidity and silt density index values of the membrane feed water are typically used to characterize the water's fouling potential. Silt density index is described in ASTM method D4189, and is based on the plugging rate of a standard 0.45-micrometer membrane filter. Turbidity can be measured using an in-line continuous monitor. Most membrane manufacturers limit the maximum silt density index value of the feed water to between 1 and 5, depending on the water source. The turbidity of the feed water is typically limited to no greater than 0.1 Nephelometric turbidity units.

Other feed water parameters that may be limited include total organic carbon, biochemical oxygen demand, chemical oxygen demand, and particle count. An example of a membrane manufacture restricting these parameters in the membrane feed water is Hydranautics, which limits these parameters to the following values:

- Total organic carbon – No greater than 2 milligrams per liter for ground and surface water sources. No greater than 5 milligrams per liter for tertiary waste.
- Biochemical oxygen demand - No greater than 4 milligrams per liter as oxygen for ground and surface water sources. No greater than 10 milligrams per liter as oxygen for tertiary waste.

- Chemical oxygen demand - No greater than 6 milligrams per liter as oxygen for ground and surface water sources. No greater than 15 milligrams per liter as oxygen for tertiary waste.

Not all membrane manufacturers publish limits for biochemical oxygen demand and chemical oxygen demand, and limits for silt density index, turbidity, and total organic carbon may vary between manufacturers. The design engineer should select design values based on the most limiting condition for the membranes specified.

The Langelier Saturation Index, and the Stiff and Davis Stability Index are used by engineers to characterize the scaling potential of water with respect to calcium carbonate. Langelier Saturation Index is typically used when evaluating groundwater, while Stiff and Davis Stability Index is used to characterize seawater. If an appropriate scale inhibitor is used, membrane manufacturers limit these scaling indices to the following values at the membrane concentrate stream:

- Langelier Saturation Index and Stiff and Davis Stability Index – No greater than 1.8 for typical designs. No greater than 2.5 for aggressive designs. Aggressive designs may require more frequent cleanings with harsher chemical solutions.

If a scale inhibitor is not used, or scale control is to be provided by acid addition alone, the Langelier Saturation Index or Stiff and Davis Stability Index in the membrane concentrate stream is limited to negative values. Note also that some scale inhibitor manufacturers may have products that exceed the saturation limits recommended by the membrane manufacturer's computer software. The design engineer should use engineering judgment when determining the upper limits for recovery based upon the output warnings and recommendations of both the membrane manufacturer's and the scale inhibitor supplier's computer models.

<u>Maximum element feed pressure</u>

Maximum acceptable reverse osmosis and nanofiltration membrane feed pressures are governed by membrane element construction. Brackish water reverse osmosis and nanofiltration membranes are generally limited to feed pressures below 600 pounds-force per square inch gauge, while seawater reverse osmosis membranes can typically withstand feed pressures up to 1,200 pounds-force per square inch gauge. Failure modes of membrane elements exposed to excessive feed pressures include (but are not limited to) membrane intrusion into the permeate collection channels, compaction of the membrane scroll within an element resulting in mechanical damage and/or loss of effective membrane surface area, and bursting of the membrane element's outer wrapping. An example scenario where feed pressure limits could be exceeded is an application where brackish water reverse osmosis membranes are used to treat high total dissolved solids groundwater (greater than 10,000 milligrams per liter) at a high (>80 percent) feed water recovery rate. From the perspective of membrane element feed pressure limits, seawater reverse osmosis membranes would be a more appropriate membrane selection for this application.

<u>Maximum element pressure drop</u>

The maximum pressure drop across the feed channel of a reverse osmosis or nanofiltration membrane is governed by mechanical failure considerations. The maximum pressure drop for a single element is generally limited to 10 pounds-force per square inch gauge. The pressure drop across a multi-element vessel is limited to between 40 and 50 pounds-force per square inch gauge.

Mechanical damage resulting from exceeding pressure drop limits can include bursting of the membrane element's outer wrapping, telescoping of the membrane scroll, and possible compaction at the ends of a telescoped scroll against element anti-telescoping devices.

Membrane feed and concentrate flow limits

As water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration exceeds the concentration in the bulk solution. This increase of salt concentration is called concentration polarization, and is characterized by a concentration polarization factor, commonly referred to as Beta. The concentration polarization factor can be defined by the following equation (Hydranautics, 2001):

$$CPF(Beta) = \frac{C_W}{C_B}$$

Equation 2-4

Where:

CPF = Concentration Polarization Factor (Beta)
C_W = Solute concentration at the membrane wall
C_B = Solute concentration within the bulk feed stream

Figure 2-1 presents a graphical representation of concentration polarization along the surface of a membrane.

The impact of concentration polarization is the reduction of actual product water flow rate and salt rejection versus theoretical estimates. The effects of concentration polarization are as follows:

- Greater osmotic pressure at the membrane surface than in the bulk feed solution and higher feed pressure requirement for a given permeate flux rate
- Reduced water flow across membrane
- Increased salt diffusion across membrane
- Increased probability of exceeding solubility of sparingly soluble salts at the membrane surface, and the distinct possibility of precipitation causing membrane scaling.

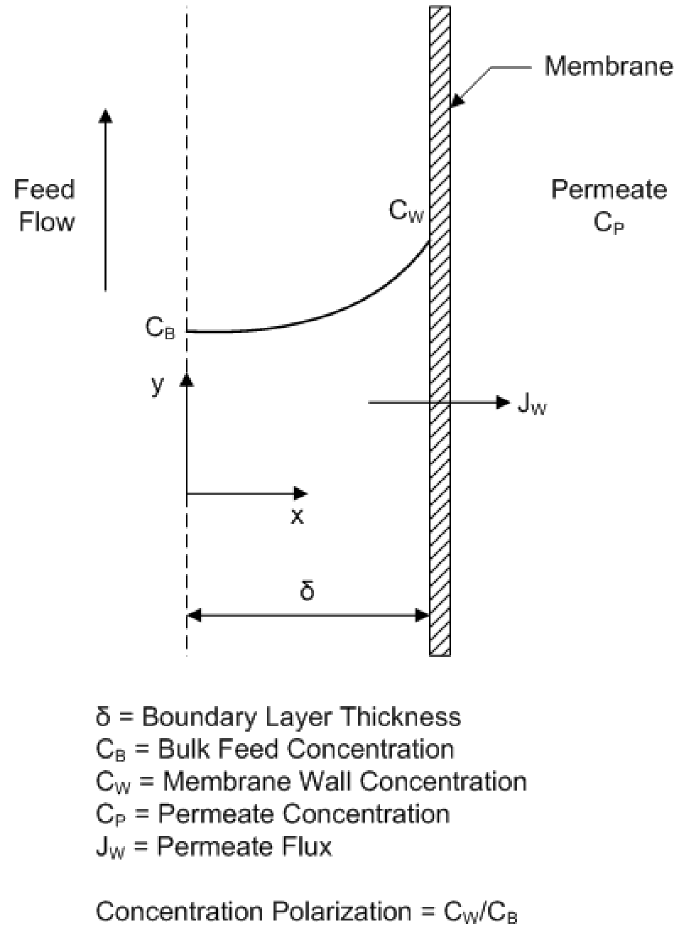

Figure 2-1. Concentration Polarization

An increase in permeate flux will increase the delivery rate of ions to the membrane surface and increase the concentration at the membrane surface. An increase of feed flow increases turbulence and reduces the thickness of the high concentration layer near the membrane surface. Therefore, the Beta factor is directly proportional to permeate flow, and inversely proportional to average feed flow.

Since Beta is inversely proportional to average feed flow,, membrane manufacturers typically require a minimum feed flow of 35 to 40 gallons per minute for an 8-inch reverse osmosis vessel to maintain the design value for Beta of less than 1.18 to 1.20 (depending on the manufacturer) for brackish groundwater.. Additionally, a minimum concentrate flow of 12 to 13 gallons per minute is typically required for individual 8-inch pressure vessels.

Maximum element flow rates are also important to consider. When element flow rates are too high, the maximum allowable feed channel differential pressure may be exceeded. To prevent mechanical damage resulting from excessive feed channel pressure drop, membrane manufacturers typically limit maximum feed flows through individual 8-inch pressure vessels to between 65 and 75 gallons per minute.

Reverse osmosis and nanofiltration system design software provides warnings to assist the user in determining if flow rates are too low or too high. The design engineer varies the number of parallel pressure vessels in a stage or elements in a pressure vessel to maintain the system design within the required minimum and maximum flow limits.

Membrane element recovery

The maximum recovery that an individual membrane element may provide is determined by minimum and maximum element flow rates. If the maximum recovery limit for a membrane is exceeded, one or more of the following corrective measures may be taken:

- Add more membranes within each pressure vessel.
- Incorporate concentrate recycling.
- Use a booster pump between stages to compensate for osmotic pressure increases in the second stage.
- Use declining permeate backpressure from the first to last stage of the membrane system.
- Use a hybrid system design with lower permeability membranes in the first stage and higher permeability membranes in the second stage.

The design engineer should refer to the references in Section 5 for detailed discussions regarding the appropriate use of each of these corrective measures.

Maximum system flux

It has been demonstrated that membrane fouling (both particle and organic) increases exponentially at flux rates above a certain “critical” flux value (International Desalination Association, 1999). The system flux is defined as the total permeate flow (in gallons per day) divided by the total membrane surface area (square feet) in the membrane system. Ranges for system flux values standard to the reverse osmosis and nanofiltration membrane industry are provided below:

- Brackish groundwater – 14 to 18 gallons per square foot per day, depending on feed water quality
- Brackish surface water – 10 to 14 gallons per square foot per day, depending on level of pretreatment
- Seawater – 7 to 10 gallons per square foot per day, depending on level of pretreatment

The design system flux is usually selected by the design engineer based on the type of pretreatment used, the reverse osmosis Feed water quality, and a balance between capital, and operation and maintenance costs. For a given permeate production rate, a membrane system with lower system flux will require lower feed pressures (with lower associated pumping energy), and generally require less frequent chemical cleanings, but will require greater capital investment due to the need for more membrane elements and pressure vessels than a system with a higher system flux.

Computer models determine the system flux based upon the user input flow information, and the total membrane area of the system. Warnings are provided to the user if the calculated system flux exceeds the maximum recommended value for a particular membrane treating a given source water.

Maximum element flux

The flux rate across a single membrane element is limited to control fouling potential, and to ensure that individual membrane performance may be predicted accurately by membrane modeling software. Typical ranges of flux limits for individual membrane elements, depending on source water category, are provided below:

- Brackish groundwater – 20 to 30 gallons per square foot per day, depending on feed water quality
- Brackish surface water – 15 to 25 gallons per square foot per day, depending on level of pretreatment
- Seawater – 17 to 30 gallons per square foot per day, depending on level of pretreatment

Because of the way that reverse osmosis and nanofiltration membranes are arranged in a full-scale system, flux rates are highest at the first (lead) element within an individual pressure vessel. Excessive flux values at the lead membrane element contribute to high fouling rates and an increase in concentration polarization that can result in scaling due to precipitation of sparingly soluble salts.

It should be noted that, in certain cases, flux limits for individual membrane elements might be violated (with associated software generated warnings) even though the limits for system flux are satisfied. Several of the methods used to limit the recovery of an individual membrane element can also be used to limit the flux across individual membrane elements, and more evenly distribute flux across the membrane system. These methods include permeate throttling, interstage boost pumping, and the use of a hybrid membrane system arrangement.

3 Methods

3.1 Preliminary data requirements

3.1.1 Water quality

An example list of water quality data that should be made available to the design engineer prior to the design of a reverse osmosis or nanofiltration membrane system is presented in Table 3-1. This list is not exhaustive. For surface water, other parameters such as total suspended solids, color, and algae, may be required to determine the appropriate type of pretreatment (before the reverse osmosis or nanofiltration membranes) or other, additional treatment processes that may be required. The list presented in Table 3-1; however, will provide the design engineer sufficient information pertaining to salt removal and recovery determination by commercially available membrane system computer models.

Groundwater quality can change over time. In order to account for the expected changes to groundwater quality over time, the design engineer should request the services of a licensed hydro geologist. A hydro geologist report should include water quality projections based on factors such as well placement and utilization schemes, characteristics of the producing and adjacent aquifer(s), and characteristics of the geological formations unique to the well field.

Some well fields experience a deterioration of water quality due to the effects of upconing and lateral migration. Upconing may occur when a more saline aquifer is present below the source aquifer. If overexploitation of the source aquifer occurs, the hydraulic head within the source aquifer may fall to levels that allow water from the more saline aquifer below to flow into the source aquifer. Upconing is generally a local phenomenon, and usually occurs near the site of pumping from the source water aquifer (International Water Management Institute, 2013).

The water quality projections in the hydro geologist report should account for the effects of upconing and lateral migration if they are present.

Table 3-1. Required water quality data.

Parameter	Unit	Test[a]	Detection limit
Temperature	Degrees Celsius	Field	-
pH	Standard unit	Field	2 to 12
Turbidity	Nephelometric turbidity units	Field	0.01
Silt density index	Standard unit	Field	1
Hydrogen sulfide	milligrams per liter	Field	0.5
Alkalinity[b]	milligrams per liter as $CaCO_3$	Lab	1.0
Total dissolved solids[c]	milligrams per liter	Lab	10
Calcium	milligrams per liter	Lab	1.0
Magnesium	milligrams per liter	Lab	1.0
Sodium	milligrams per liter	Lab	1.0
Potassium	milligrams per liter	Lab	1.0
Ammonia	milligrams per liter	Lab	0.050
Barium	milligrams per liter	Lab	0.002
Strontium	milligrams per liter	Lab	0.010
Sulfate	milligrams per liter	Lab	10
Chloride	milligrams per liter	Lab	5
Fluoride	milligrams per liter	Lab	0.050
Phosphate	milligrams per liter	Lab	1.0
Silica	milligrams per liter	Lab	1.0
Boron	milligrams per liter	Lab	0.050
Iron[d]	milligrams per liter	Lab	0.1
Manganese	milligrams per liter	Lab	0.002
Aluminum	milligrams per liter	Lab	0.025

[a]Analytes shall be measured using an Environmental Protection Agency-approved analytical method, or a method published in the most recent edition of *Standard Methods for the Examination of Water and Wastewater*, published jointly by the American Public Health Association, the American Water Works Association, and the Water Environment Federation.

[b]Errors will result in the determination of alkalinity if temperature, and pH effects are not accounted for. This can also affect the results of the evaporation test for total dissolved solids (total dissolved solids).

[c]Total dissolved solids should be measured using evaporation test methods, and a summation of ions. A cation-anion balance should be performed. For the ion summation method, a 2-5 percent balance between cations and anions should be achieved. If pH and temperature is properly accounted for in the calculation of alkalinity using the evaporation test, and a good cation-anion balance is achieved using the ion summation method, the results of the ion summation method and the evaporation tests should show similar total dissolved solids values.

[d]If the groundwater is anaerobic, speciation between ferrous and ferric iron is required.

Figure 3-1 presents graphs of projected dissolved chloride concentrations for a well field at a reverse osmosis membrane facility located where the source water quality is expected to deteriorate over time. This figure shows that, based on the specific well field utilization plan, the concentration of dissolved chlorides at each well is expected to increase over a 20-year period.

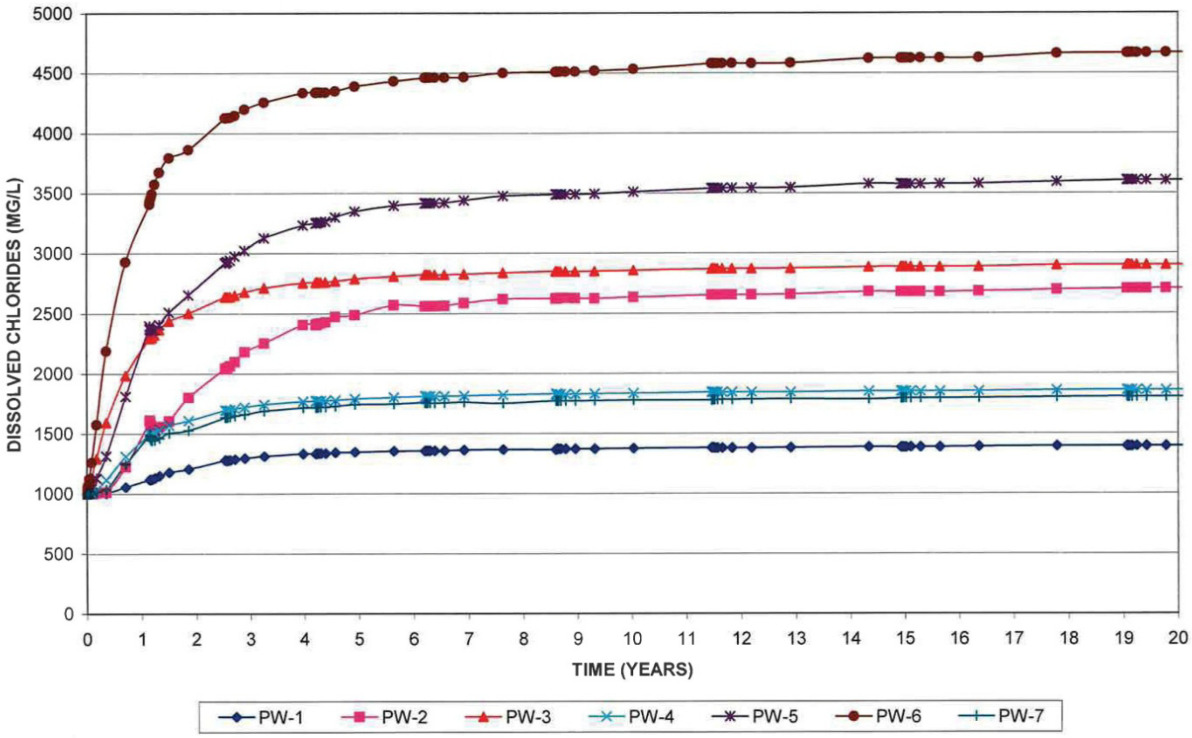

Figure 3-1. Projected dissolved chloride variations at brackish well field.

Surface water quality can also vary with time. Variations in surface water quality may be due to seasonal fluctuations in temperature and rainfall. Figure 3-2 presents a graph of historical water quality at a brackish water reservoir in Texas. The salinity at this reservoir has been steadily increasing over the 2 year period for which data is available.

Fluctuations in turbidity from silt and colloidal material are commonly associated with a surface water source. A comprehensive discussion of pretreatment technologies used to address these particulate materials is beyond the scope of this manual. The selected pretreatment technology must be capable of providing a reverse osmosis or nanofiltration feed water that consistently satisfies the membrane manufacturer's criteria for turbidity and silt density index.

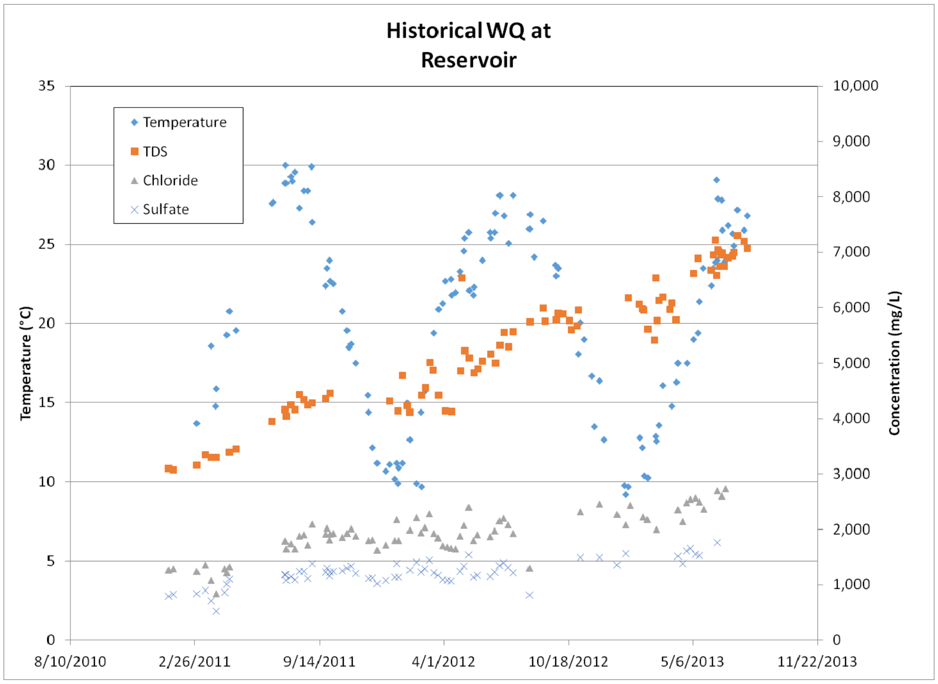

Figure 3-2. **Variations in surface water quality over time.**

Quality control

Because of the importance that water quality plays in the design of a reverse osmosis and nanofiltration treatment system, quality control of water quality data needs to occur at both the analytical and end-user stages of the modeling process. At the analytical stage, water quality samples should be analyzed by a National Environmental Laboratory Accreditation Program (NELAP) accredited laboratory. Analytical equipment used for field sampling of water quality parameters such as pH and temperature should be appropriately calibrated based on their respective methods. In providing the analytical results to the end-user, the laboratory or person sampling has the primary responsibility for quality control. At this point, the end-user is responsible for checking the quality of the data they are using for computer modeling.

Common errors encountered in the use of water quality data, most of which are associated with laboratory analysis methodologies, are briefly discussed below:

- Under-reporting concentrations due to the use of dilution water in laboratory samples. Laboratories sometime under-report data from these tests by as much as one or two orders of magnitude, depending upon the volume of dilution water used.
- Under-reporting total dissolved solids concentrations when measured by gravimetric methods. Gravimetric analysis involving evaporation and drying of a measured sample in a tared container is the most common method for determining total dissolved solids in the laboratory. When using gravimetric methods to determine total dissolved solids, samples containing high concentrations of bicarbonate require special care to minimize the conversion of bicarbonate to carbonic acid, and the subsequent loss of carbonic acid as carbon dioxide to the atmosphere. Even the most carefully conducted evaporative total

dissolved solids analysis will result in a loss of approximately 50 percent of bicarbonate due to these effects.

In both cases, laboratory data can be reviewed for accuracy by:

- Demonstrating electrical equilibrium by summing the milliequivalents per liter concentrations of dissolved cations and anions. The sum of the cations should be equal to the sum of the anions for the water to be electrically neutral. When reviewing laboratory data for accuracy, the electrical balance should be within 2 to 5 percent.
- The results of the gravimetric (evaporative) total dissolved solids analysis should be compared against the sum of individual ions expressed as milligrams per liter. When comparing the summation of ions to the total dissolved solids value obtained by evaporation, only 50 percent of the bicarbonate value used in the summation should be included. The comparison should show agreement (to within 10 percent) between the gravimetric analysis and ion summation (AWWA, Standard Methods, 1998). If the total dissolved solids, value determined by gravimetric analysis is more than 10 percent higher than the sum of individual ions, it is likely that one or more significant contributor ions have been excluded from the summation. If the sum of individual ions is greater than the total dissolved solids, as determined by evaporation, both values are suspect, and the sample should be reanalyzed.

3.1.2 Plant flow capacity

It is the responsibility of the treatment facility owner and their design engineer to protect the safety and health of the public. To this end, certain minimum pressures and flow capacities within the water distribution system must be reliably maintained. Minimum pressure requirements are enforced to ensure that adequate pressure is available for fire fighting and peak hourly flow operations, and to prevent contaminants from entering the distribution pipes. Texas Commission on Environmental Quality regulations require a minimum pressure of 35 pounds-force per square inch gauge at all points within the distribution network at flow rates of at least 1.5 gallons per minute per connection when a system relies on pumps and emergency generators. The minimum flow requirement does not apply to systems using elevated storage. When the system is intended to provide fire-fighting capacity, a minimum pressure of 20 pounds per square inch during combined fire and drinking water flow conditions is typically required. To achieve this minimum pressure at peak hourly and fire flows, a normal working pressure between 60 to 80 pounds-force per square inch gauge is usually required in the distribution system. This normal working pressure should be verified by a professional engineer through hydraulic modeling of the distribution system.

In order to properly establish the flow capacity of a reverse osmosis or nanofiltration membrane treatment facility, information regarding current and future system demands including maximum day, peak hourly flow and fire flow must be available. Water supply master plans are often developed by public water treatment works owners and their consulting engineers. These master plans characterize water system demands based on historic water use data and projections of future population growth. The timeframe considered in master plans may vary, but the purpose is consistently the same: To characterize the ability of a public water system (including water source, treatment works, and storage and distribution system) to meet the flow and pressure demands placed on the system. The master plan will identify projected shortfalls in system capacities, and may identify measures that can be taken to ensure that future system demands are satisfied. These measures may include source water development, construction of a new treatment facility (or expansion of an existing one), development of additional storage capacity, or improvements to the water distribution system.

The overall size of a reverse osmosis or nanofiltration treatment plant is usually established by the water supply master plan based upon maximum day flow rates. Peak flow rates including peak hour and fire flows are typically satisfied using storage. When determining the size of treatment trains within a reverse osmosis or nanofiltration treatment plant, it is important for the design engineer to understand how the treatment facility will be operated. That is, the facility may function to provide a consistent flow of water throughout the day (base loading plant), or may be used to satisfy peak system demands (peaking plant). The intended operation of the plant will influence how the membrane system is designed. A base loading plant may be designed with fewer, larger capacity membrane trains, while the design for a peaking plant may include more trains of smaller capacity to minimize stopping and starting of trains as flow demands vary. Reverse osmosis and nanofiltration trains are typically designed to operate at a constant flow rate. Adjustment of permeate flows from individual trains should be avoided due to the following reasons:

- Recovery will vary – industry standard of care is to decrease recovery as permeate flow decreases. This results in a higher percentage of wasted water and higher operating costs. Recovery should vary to maintain the minimum membrane element concentrate flow rates (discussed in Chapter 2) specified by the membrane manufacturers. If the minimum flow rate is not maintained, mineral scaling will occur. For a given system design, concentrate flow may be adjustable within a narrow range without violating minimum membrane element concentrate flow rates. This may facilitate - without decreasing recovery - small reductions to be made to concentrate flows in response to small permeate flow reductions. This practice is not recommended as it introduces the possibility of operator error and the risk of subsequent membrane scaling.
- Permeate quality will vary – permeate concentrations of dissolved salts, total dissolved solids and other minerals will increase as permeate flow decreases due to the affects of diffusion (discussed in Chapter 2).

For these reasons, permeate flow rate and concentrate flow rate from a reverse osmosis or nanofiltration train are typically held constant by design engineers.

Provided that the resulting finished water satisfies, all of the regulated maximum contaminant limits, blending of raw water with membrane permeate may be incorporated to accomplish the following:

- Reduce membrane train capacity requirements while meeting production (flow) goals at a lower capital cost.
- Help achieve finished water alkalinity goals. Sufficient alkalinity is required to minimize corrosion, and prevent pH variations within the distribution system.
- Help achieve finished water hardness goals. Sufficient hardness is required to minimize corrosion in the distribution system.

The design engineer should understand the impacts to raw water blending capacity created by the following factors :

- Projected source water quality changes.
- Adjustments to feed water recovery rate.
- Variations in permeate water quality due to variations in feed water quality, and membrane selection and age (or condition – such as clean or fouled).

The portion of the total plant capacity that may be satisfied using raw water blending is provided by the following equation:

$$Q_B = Q_T\left(\frac{C_T - C_P}{C_R - C_P}\right) \qquad \text{Equation 3-1}$$

Where:
Q_B = Raw water blending flow (gallons per minute)
Q_T = Required blended water capacity (gallons per minute)
C_R = Concentration of limiting water quality constituent in raw water (milligrams per liter)
C_T = Target concentration of limiting water quality constituent in blended water (milligrams per liter)
C_P = Concentration of limiting water quality constituent in permeate (milligrams per liter)

An example calculation of blending flow is provided in Chapter 4.

The required raw water flow to a membrane facility is a function of the design blended water capacity, the membrane feed water recovery rate, and the blending water flow. The relationship between these parameters is characterized by the following equation:

$$Q_R = \frac{Q_T - Q_B}{R} + Q_B \qquad \text{Equation 3-2}$$

Where:
Q_R = Total required raw water flow (gallons per minute)
Q_B = Raw water blending flow (gallons per minute)
Q_T = Total required finished (blended) water capacity of the treatment plant (gallons per minute)
R = Membrane feed water recovery rate

This equation shows that total raw water flows are decreased as the membrane recovery rate and blend flows are increased.

Once the required capacity of a membrane treatment facility is established, the design engineer should verify that the source is capable of supplying adequate raw water flows to meet the capacity. If the raw water flow is available, the reverse osmosis or nanofiltration treatment plant design can proceed and the membrane treatment equipment flow rate (Q_P) is established by subtracting Q_T from Q_B.

3.1.3 Hydraulic profiles

Early in the design phase, the design engineer should conduct a hydraulic analysis of the proposed treatment facility. The hydraulic analysis plays a critical role in assuring the plant can meet its production goal and the performance of treatment processes – both of which relate to the health and safety of the public receiving this water. The results of the hydraulic analysis form the basis for piping and equipment sizing and selection. A proper hydraulic analysis will account for limiting operating conditions of flow and pressure at a membrane treatment facility. At a minimum, the hydraulic analysis should consider two limiting scenarios as follows:

Scenario 1 – Minimum process flow and system pressure drop

This scenario incorporates best case membrane feed water (raw water) quality, new membrane condition, minimum process flow rates, and lowest expected pressure drop across membrane prefilters and membrane arrays.

Scenario 2 – Maximum process flow and system pressure drop

This scenario incorporates worst case membrane feed water (raw water) quality, fouled membrane condition, maximum process flow rates, and highest expected pressure drop across membrane prefilters and membrane arrays.

The scenarios listed above should be performed at the design feed water recovery. If the recovery rate is expected to vary over the life of the facility, the hydraulic analysis should consider the associated impacts to pressures and flows at all points within the system.

As part of the hydraulic analysis, the design engineer should generate a hydraulic profile for the treatment facility. A hydraulic profile is a visual representation of the hydraulic grade line at various points within the facility. The hydraulic grade line at a selected location is computed as:

$$HGL = \frac{p}{\rho g} g_c + z \qquad \text{Equation 3-3}$$

Where:

HGL = Hydraulic grade line (feet).
p = Measured static pressure (pound-force per square foot). Equal to pound-force per square inch x 144 square inch per square foot
ρ = Density of water. Taken to be approximately 62.4 (pound-mass per cubic foot) at temperatures between 32 and 70 degrees Fahrenheit.
g = Gravitational constant. Approximately equal to 32.2 (feet per seconds squared).
g_c= Constant of proportionality. Approximately equal to 32.2 (pound-mass x feet) / (pound-force x seconds squared).
z = Elevation at selected location relative to a baseline value (feet).

Computer programs are available that can be used to assist the design engineer in modeling the hydraulics within a membrane facility. Some of these programs provide hydraulic grade line information as user-selectable output for selected locations within the piping network. The hydraulic profiles presented in this manual were generated using AFT Fathom V.8.0, developed by Applied Flow Technology.

Sample hydraulic profiles for a typical reverse osmosis membrane process treating brackish groundwater are provided in Figures 3-3 and 3-4.

Figure 3-3 presents a sample hydraulic profile for the membrane feed and permeate streams at a typical reverse osmosis facility. Besides friction losses within piping, the major pressure components associated with this system are (1) pressure drop across the cartridge filters, (2) pressure boost provided by first stage membrane feed pumps, (3) pressure losses associated with the reverse osmosis membranes, and (4) the permeate backpressure created by the blended permeate degasifiers. Smaller or less complex membrane systems will also require a hydraulic profile, but may not require all of the elements shown in Figure 3-3 (i.e., cartridge filters, second stage membrane array, degasification, etc.).

Figure 3-4 presents a sample hydraulic profile for the membrane concentrate stream at a reverse osmosis facility. Besides friction losses within piping, the major pressure components associated with this system are (1) pressure losses associated with the reverse osmosis membranes, (2) pressure boost at the interstage boost pump, (3) pressure drop across the energy recovery turbines and concentrate flow control valves, (4) pressure drop across a backflow preventer, and (5) the concentrate backpressure at a deep injection well.

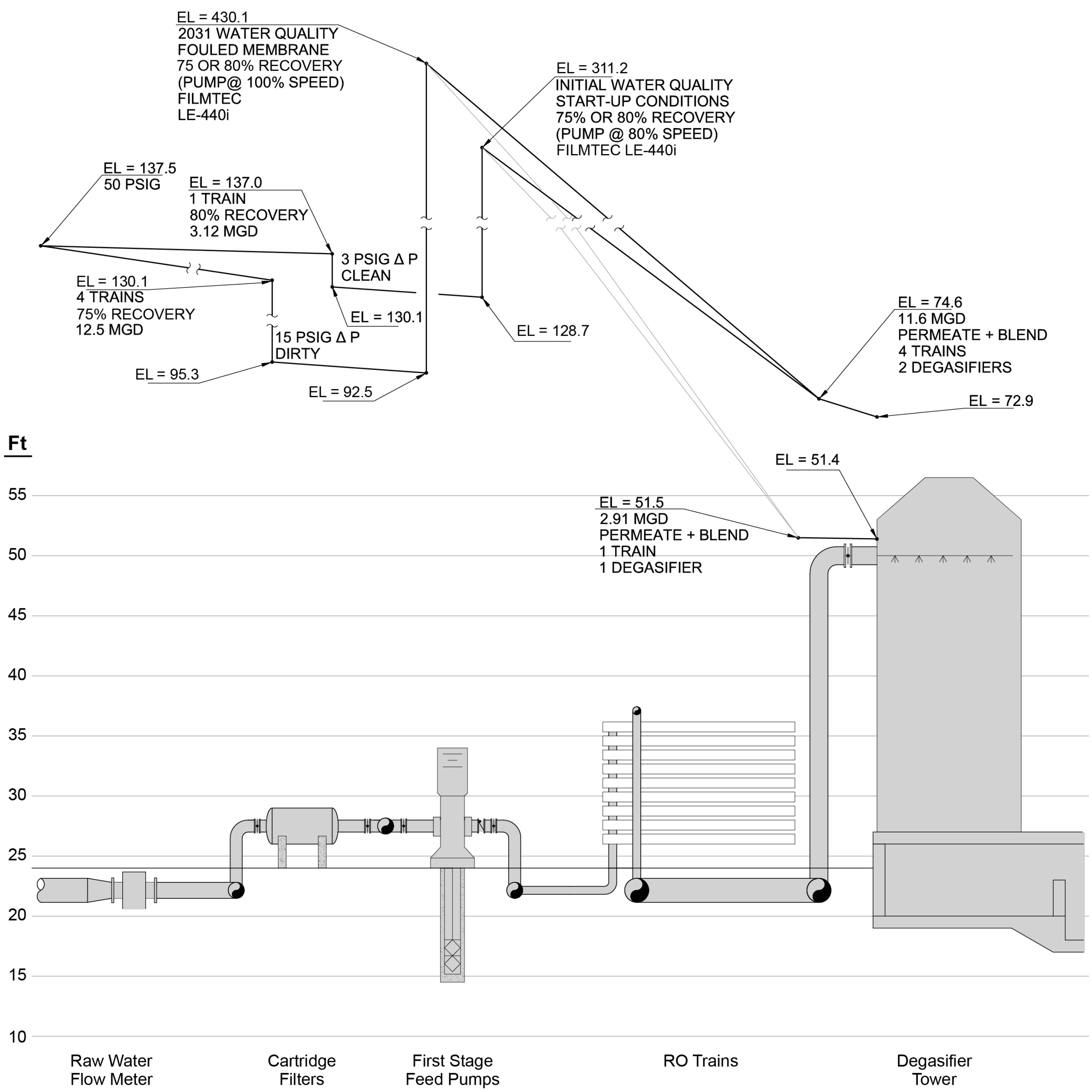

Figure 3-3. Sample hydraulic profile – membrane feed and permeate.

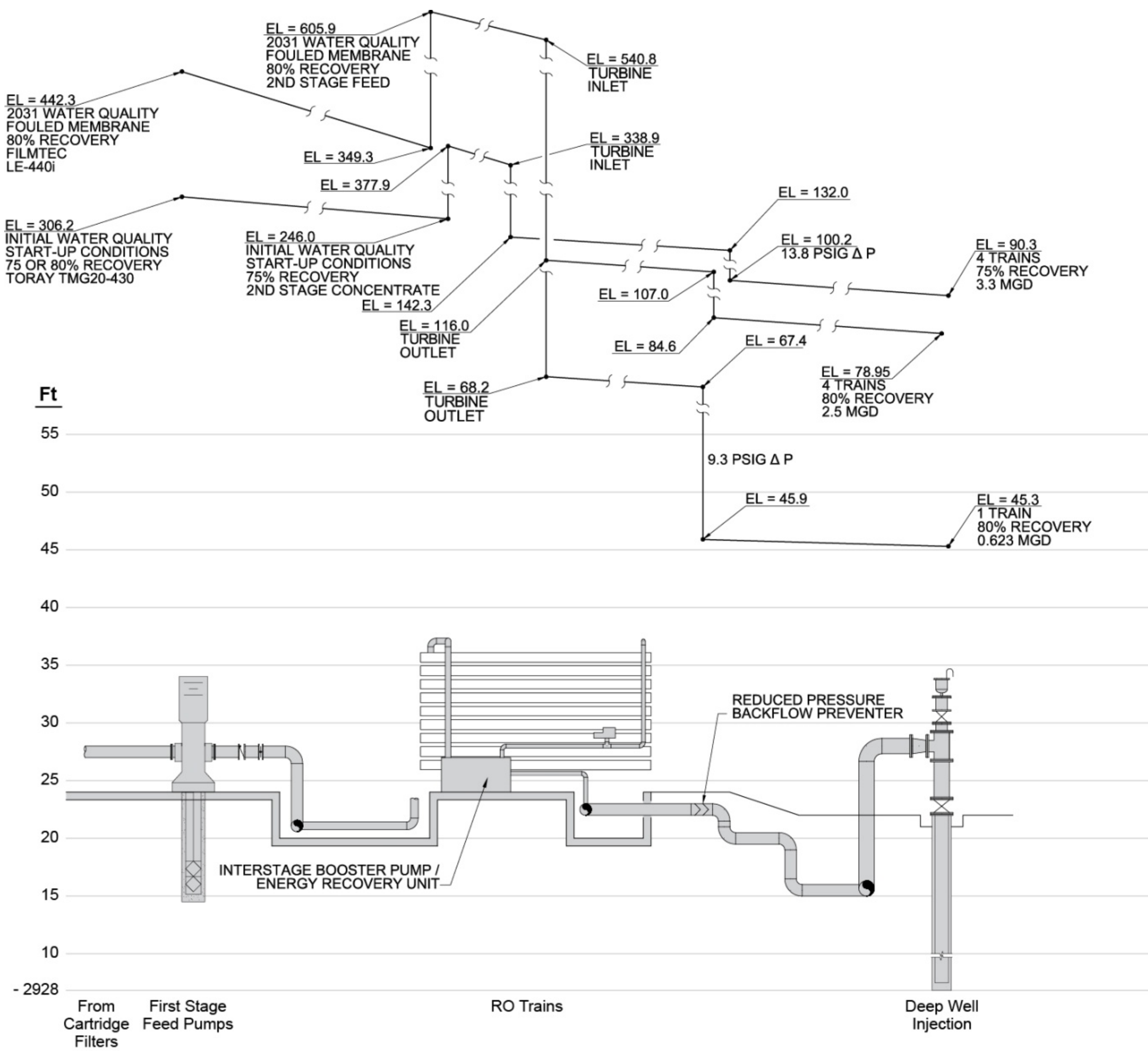

Figure 3-4. **Sample hydraulic profile – membrane concentrate.**

Reverse osmosis pump suction pressure

The pressure at the suction of the first stage reverse osmosis feed pump is influenced by several factors, as shown by Figure 3-3. For the piping system described by this figure, the static pressure near the raw water flow meter was maintained at 50 pound-force per square inch gauge by the well field pumps. The minimum HGL at the suction of the feed pump resulted from a maximum pressure drop across the cartridge filters (dirty filters) of 15 pound-force per square inch gauge, and greater piping friction losses at maximum raw water flows. The design engineer should verify that the pressure calculated at the suction of the reverse osmosis feed pump is sufficient to supply the net positive suction head requirement of the particular pump specified. Most pump manufacturers provide net positive suction head requirement curves for their pumps.

Net positive suction head requirement curves are determined in laboratories using standardized methodologies (Hydraulic Institute, 2012). Net positive suction head requirement curves are generated by throttling the pump's inlet pressure with a valve until a three percent loss in rated head at a given flow is observed across the first stage of the pump. The net positive suction head available should always be greater that the net positive suction head requirement at every operating condition to avoid loss of pump performance and potential damage to the pump caused by cavitation.

Net positive suction head available is calculated as follows (Hydraulic Institute, 2012):

$$NPSHA = H_{bar} + h_s - H_{vap} - h_{fs} - \sum h_m - h_{vol} - FS \qquad \text{Equation 3-4}$$

Where:

NPSHA = Net Positive Suction Head Available (feet)
H_{bar}=Barometric Pressure Head (feet – corrected for elevation above sea level)
h_s=Static head of intake water surface above pump impeller eye (feet)
H_{vap}=Liquid Vapor Pressure Head (feet), corresponding to the highest sustained operating temperature
h_{fs} = Pipe friction between suction intake/source and pump inlet (feet)
Σh_m = Sum of minor piping friction losses between suction intake/source and pump inlet (feet)
h_{vol} = Partial pressure of dissolved gases (such as air) in water (feet) – this is customarily ignored
FS = Safety factor used to account for uncertainty in hydraulic calculations and possible swirling and/or uneven velocity distribution at the pump intake (feet). Consult the pump manufacturer for recommended value for a specific pump.

The design engineer should ensure that the specified pump operates with a minimum margin of net positive suction head available above the listed net positive suction head requirement for every operating condition. A detailed discussion of appropriate net positive suction head available margins is provided in the Hydraulic Institute Standards.

Reverse osmosis pump discharge pressure

When sizing the first stage feed pump, the design engineer should account for the pressure losses in the piping system between the pump discharge and the first stage of the reverse osmosis membrane array. As previously discussed, the elevation assigned to the location associated with the required membrane feed pressure calculated by the membrane system computer model should be accounted for when sizing the first stage feed pump. The standard of care is to assume that the required feed pressure calculated by the computer model is located at the midpoint of the membrane system's vertical dimension. By accounting for minimum and maximum total developed head requirements resulting from minimum and maximum suction and discharge pressures and any flow variations resulting from adjustments to system feed water recovery, an "envelope of operation" may be characterized for the feed pump. This operation envelope should be used by the design engineer to facilitate proper pump selection.

Permeate backpressure

The static pressure at the permeate side of the reverse osmosis membranes directly impacts required membrane feed pressure. For a given net applied pressure, the membrane feed pressure increases proportionally to the permeate backpressure. Permeate backpressure can be created by the downstream piping and post-treatment processes. In addition, permeate backpressure can be generated intentionally by valves in order to balance the permeate flux between membrane stages. Most membrane system computer models incorporate a user-selectable permeate backpressure input. To properly determine the discharge pressure required by a reverse osmosis or nanofiltration train feed pump, it is important for the design engineer to determine the expected permeate backpressure from the hydraulic model of the membrane facility. This value should be used as the basis for the permeate backpressure in the membrane system computer model.

Concentrate backpressure

The concentrate stream leaving the membrane array contains residual high pressure. A concentrate flow control valve is typically used to control the concentrate flow and throttle this pressure prior to concentrate disposal. The recovery for useful purposes of this residual concentrate pressure using energy recovery technologies is discussed later in this chapter. It is important for the design engineer to understand the impact of concentrate backpressure on issues such as concentrate control valve sizing and selection, and the implementation of energy recovery. It is especially important to characterize concentrate backpressure at facilities incorporating deep well injection for concentrate disposal. The backpressure present at the head of a deep injection well is often highly dependent on flow rate. The design engineer should consult field test data to determine the relationship of wellhead pressure to flow rate for a particular well installation.

3.1.4 Post-treatment considerations

A detailed discussion of post-treatment considerations and methods is beyond the scope of this manual. The intent of this discussion is to make the design engineer aware of the unique post-treatment issues that must be addressed when designing a reverse osmosis or nanofiltration membrane system. These issues are especially important when designing a reverse osmosis system, due primarily to the aggressive chemical nature of reverse osmosis permeate.

Permeate from reverse osmosis membranes typically contains high concentrations of carbonic acid, few minerals, and very little alkalinity. As such, it is aggressive from a corrosion standpoint, and is prone to large variations in pH, which can further complicate corrosion problems.

While most bicarbonate alkalinity is rejected by a reverse osmosis membrane, carbonic acid (dissolved carbon dioxide) is not. Also, if acid is added to the membrane feed water to control calcium carbonate scaling, the associated reduction in pH will result in the conversion of bicarbonate to carbonic acid in the membrane feed stream. Decarbonation using an aeration process is often incorporated to remove excess carbonic acid from membrane permeate, and thereby increase the pH of the finished water. Decarbonation is often used in combination with chemical pH adjustment to convert some of the carbonic acid to bicarbonate alkalinity.

Alkalinity may also be supplemented using chemical treatment such as the addition of sodium carbonate or sodium bicarbonate, and the use of limestone contactors (AWWA, 2007).

Another important post-treatment consideration is the addition of hardness to control corrosion. This may be accomplished through raw water blending, lime addition, and the use of limestone contactors.

Corrosion inhibitors may also be added to the membrane permeate to reduce its corrosivity. Corrosion inhibitors work by forming protective films on pipe walls (phosphate and silicate inhibitors), or reacting with metal ions to form a passivating layer (orthophosphates).

Several corrosion control computer models are available to asses the full impact of all proposed post-treatment processes on the corrosivity of the finished water. The Rothberg, Tamburini, and Winsor model, available through the American Water Works Association is one example of useful post treatment chemistry and corrosion control models available to design engineers.

3.2 Design basis for system to be modeled

3.2.1 Design recovery

The maximum feed water recovery attainable using reverse osmosis or nanofiltration treatment is limited by concerns related primarily to mineral scaling of the reverse osmosis or nanofiltration membranes. A discussion of recovery limits is provided in Chapter 2. For a two-stage reverse osmosis membrane system treating brackish groundwater, feed water recovery generally ranges between 65 to 85 percent. For the purposes of membrane system computer modeling, a recovery value within the range recommended by the membrane (or scale inhibitor) manufacturer for the given water quality and source category should be selected as a starting point. The design engineer should then exercise discretion and apply any safety factors they determine appropriate based on site-specific conditions.

While mineral scaling may typically determine the design recovery rate, other factors such as concentrate disposal permit requirements, and cost may determine the actual recovery. Surface water discharge of reverse osmosis and nanofiltration concentrate is becoming increasingly difficult to permit. As such, dissolved concentrations of salts and other contaminants in the concentrate stream may determine what recovery rate is permissible for this type of discharge. Additionally, similar to membrane flux determination, a lifecycle cost evaluation may provide useful information for the selection of a design recovery. The cost evaluation should consider factors such as (1) the value of the raw water and the cost of alternative supply development, (2) raw water pumping and pretreatment costs, (3) cost of concentrate disposal, (4) expected membrane system operation and maintenance costs, and (5) impacts of recovery selection to permeate quality and acceptable raw water blending flows (if raw water blending is to be incorporated).

3.2.2 Flux rate

A design flux rate should be selected based on system performance and economic considerations. Membrane manufactures provide guidelines (discussed previously in Chapter 2) regarding recommended flux ranges based on categories of source water type and quality. A design flux rate should be selected that prevents excessive fouling rates while limiting capital investment. A lifecycle cost evaluation can often provide useful information for the selection of design flux.

3.2.3 Train size and number

Once the required permeate flow capacity for the facility has been established, using methods discussed previously, the design engineer should determine the number and permeate capacity of individual membrane trains. General criteria are provided in the list below:

- The number and size of trains should correspond with the intended operation of the facility. Compared to a base loading plant, which may require fewer trains with higher permeate capacity, a peaking facility may require a larger number of smaller capacity trains. The number and size of individual trains should minimize the starting and stopping of trains to meet system demand.
- If applicable, the size of an individual train should correspond to the minimum daily system demand.
- Redundancy requirements of state and local regulatory agencies should be satisfied. If required, a redundant train should be provided to ensure that the maximum system demand is satisfied with one train out of service. An additional train may be desired to provide permeate for clean-in-place activities. At the time this Manual of Practice was written, the Texas Commission on Environmental Quality did not require redundant membrane train(s).
- If trains are equipped with dedicated first stage feed pumps, consideration should be given to maximum allowable flows based on any electrical constraints (such as, motor voltage and sizing), particularly for projects with existing electrical infrastructure such as plant rehabilitations or expansions
- It is common practice, though not a requirement, to size individual trains equally.

3.2.4 Train configuration

Membrane area per train

The total membrane surface area for an individual train may be determined from the design permeate capacity, and flux values. The calculation is as follows:

$$A_m = \frac{Q_p}{J} \qquad \text{Equation 3-5}$$

Where:

A_m = Total membrane surface area required for an individual train (square foot)
Q_p= Required permeate capacity for an individual train (gallons per day)
J = Design permeate flux (gallons per day per square foot), also stated as (gallons per square foot per day)

Elements per train

The minimum required number of elements per train may be determined from the total required surface area and the area of the individual elements selected. The calculation is shown below:

$$E_T = \frac{A_m}{A_E} \qquad \text{Equation 3-6}$$

Where:

E_T = Total number of membrane elements for an individual train
A_m = Total membrane surface area for an individual train (square foot)
A_E = Membrane surface area provided by the selected membrane element (square foot)

Pressure vessel staging, quantity, and element capacity

The determination of pressure vessel staging, the number of pressure vessels, and number of elements per pressure vessel is typically an iterative process governed by economics, and feed and concentrate flow limits.

The number of elements in a pressure vessel is determined based upon the need to maintain a membrane manufacturer's specified minimum concentrate flow rate leaving the last element in each vessel. The concentrate flow rate leaving this last element is a function of recovery and the number of vessels in parallel.

An economic evaluation of membrane array alternatives should consider capital costs of more vessels vs. the operating costs of higher feed pressures associated with more elements in an individual vessel.

There are several factors that determine how membrane systems are arranged into stages. Staging of pressure vessels involves determining the appropriate number of vessels in parallel and the number of stages to achieve the desired recovery rate.

The following are typical rules of thumb; however each case should be evaluated individually by a design engineer:

- For systems with up to 75 percent recovery, two stages of 6-element vessels are common.
- For systems with recoveries between 76 to 87 percent, two stages of 7-element vessels are common.
- For systems with recoveries > 88 percent, three stages of 6-element vessels are common

If the number of elements per pressure vessel is known, the minimum required number of pressure vessels may be calculated using the equation below:

$$N_{PV} = \frac{E_T}{E_{PV}} \qquad \text{Equation 3-7}$$

Where:

N_{PV}=Minimum number of pressure vessels required per train (rounded up to the nearest integer)
E_T = Total number of membrane elements for an individual train
E_{PV} = Number of elements per pressure vessel

References are available to assist the design engineer with the configuration of the membrane trains. One such reference is the *Manual of Water Supply Practices M46 Reverse Osmosis and Nanofiltration*, published by the American Water Works Association.

3.2.5 Start-up & end of project life conditions

The design engineer should account for start-up and end-of-project life conditions in the membrane system computer model projections. These conditions are characterized by changes in feed water quality, permeate quality, and membrane conditions (that is, irreversible fouling) that typically require additional feed pressure to maintain production flow rates.

Fouling factor

A detailed discussion of fouling factors and their appropriate use is provided in Chapter 2. A fouling factor that represents clean, unfouled membrane conditions should be selected to represent start-up conditions. For end-of-project-life conditions, impacts to membrane system performance resulting from the anticipated level of membrane fouling can be estimated by selecting a fouling factor (or flow factor) less than 1.00. Values between 0.65 and 0.75 are most commonly used; however, the design engineer should use their judgment when selecting this condition.

Water quality

When the quality of the feed water is expected to vary over the life of membrane facility, computer model projections should account for these variations. A discussion of different feed water variations and their causes is provided earlier in this chapter. Deterioration of feed water quality will result in higher membrane feed pressures necessary to achieve the design permeate flow rate (flux), and a decrease in permeate water quality which may require less bypass (blending) flows over time.

3.2.6 System optimization

Flux balancing

The rate of fouling within a membrane system depends strongly on permeate flux at each membrane element. The first several elements in series within a pressure vessel commonly produce the highest permeate flows. This is a result of the combination of two factors; (1) These membrane elements are exposed to the lowest total dissolved solids feed water, and (2) the highest membrane feed pressure occurs at the location of these elements. This is shown graphically in Figure 3-5.

The effect of pressure drop and an increase in feed water total dissolved solids across a membrane system can significantly affect the productivity of membranes located in the second and third stages. The potential for flux imbalance is most pronounced in systems that incorporate low-pressure reverse osmosis or nanofiltration membranes.

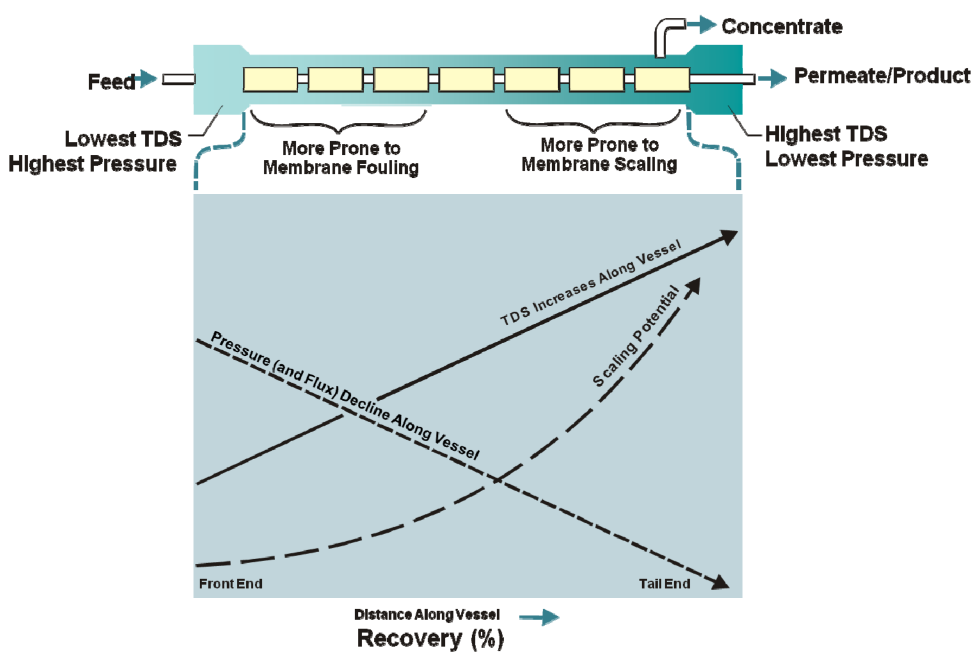

Figure 3-5. Flux decline within a pressure vessel.

Flux imbalance leads to an increased potential for fouling in the lead membrane elements, and can also result in a reduction in overall permeate quality. Flux balancing, across the entire array of membranes, is often used to limit the flux in the first stage, and increase the flux in later stages. Flux balance is commonly achieved by incorporating one of three methods discussed below and presented in Figure 3-6 Membrane system computer models can provide performance data for systems incorporating any of these common methods.

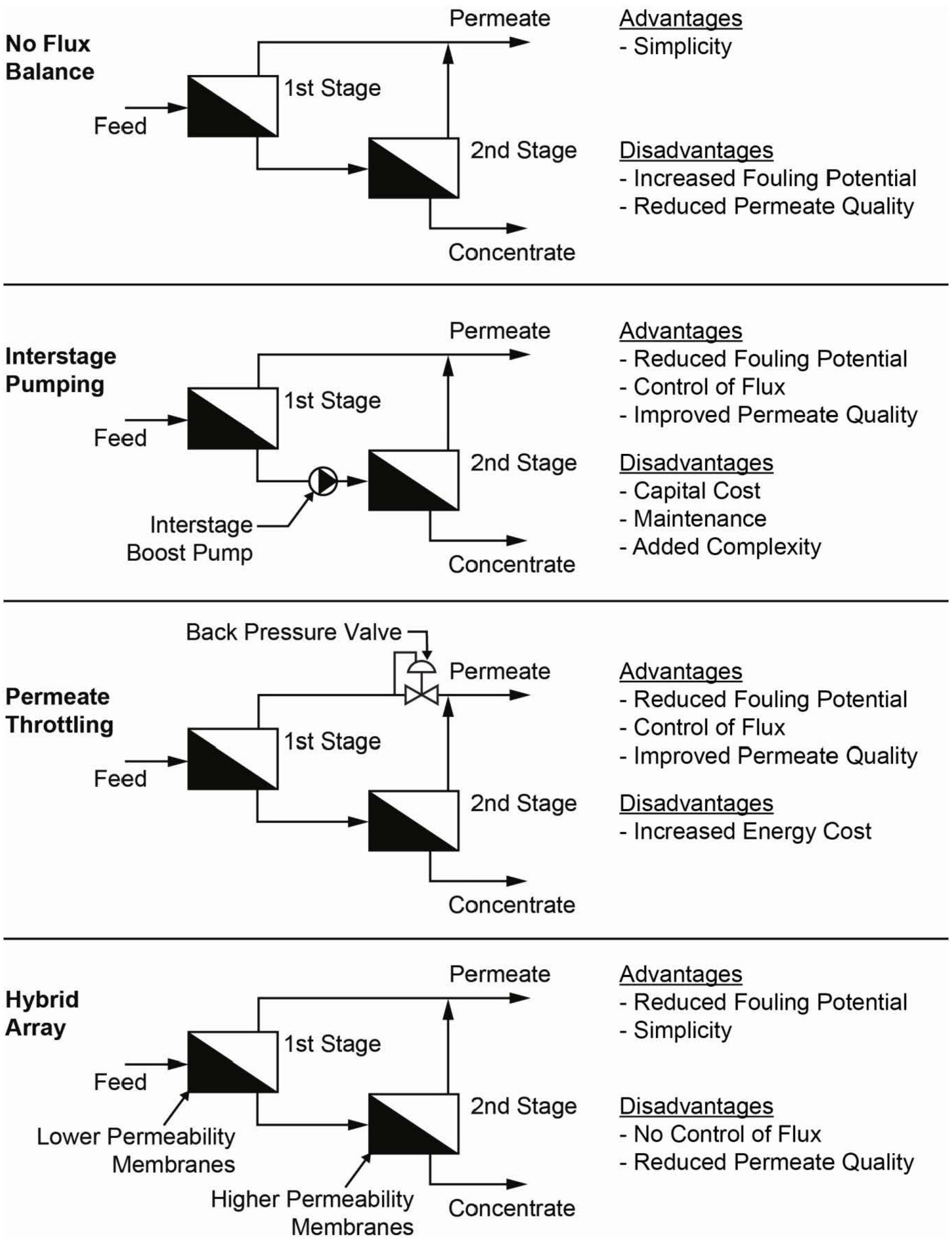

Figure 3-6. Flux balancing alternatives.

Interstage booster pumps

By placing an interstage boost pump upstream of the second and/or third stage membranes, individual stage permeate flow rate can be controlled, lower overall permeate total dissolved solids can be achieved, and pumping energy can be optimized across stages. Interstage boost pumping is the most common method used to achieve balance of flux between membrane stages.

Permeate throttling

This method incorporates a backpressure valve in the permeate pipe leaving the first membrane stage. This backpressure reduces the net applied pressure across the first stage elements, which results in a reduction of first stage flux. When compared to an unthrottled system, the productivity of the later stages is increased due to the resulting increase in residual first stage concentrate pressure (second stage feed pressure), and reduction in second stage feed water total dissolved solids. A primary disadvantage of permeate throttling is the additional energy consumption caused by throttling the first stage permeate (due to higher first stage membrane feed pressures).

Hybrid arrays

Hybrid arrays improve flux balance by incorporating membrane elements with lower water permeability in the first stage and elements with higher permeability in the later stages. A key challenge to this type of design is maintaining permeate quality goals because the high permeability membranes in the second stage typically have poorer salt rejection and result in poorer overall total dissolved solids than the other options. Additionally, when fouling occurs in either the first, second or subsequent stages, there is no mechanical means (that is, valve or pump) to continue to control flux balance.

Each design situation is unique and it is incumbent upon the design engineer to evaluate a particular membrane system to achieve a reliable flow and performance.

Energy recovery

Several technologies are available to recover the residual hydraulic energy typically lost across the concentrate control valve of a brackish water reverse osmosis membrane train. Energy recovery devices most suited for the concentrate flows and pressures typically associated with brackish water reverse osmosis technology include the following:

- Turbocharger technology: A turbine extracts the hydraulic energy from the concentrate stream, converting it to mechanical energy. A pump impeller on a common shaft with the turbine converts this mechanical energy to pressure energy in the membrane feed or interstage stream.
- Isobaric energy recovery: Incorporates direct hydraulic to hydraulic energy transfer in which the concentrate stream, through direct contact, transfers hydraulic energy to the feed stream.
- Turbine-assisted interstage boost pumping: Similar to turbocharger technology, but incorporates a motor to augment pressure boosting.
- Concentrate turbine equipped with induction generator and regenerative variable frequency drive: Converts hydraulic energy from the concentrate stream to electrical energy, which is then fed back to the facility’s power distribution system.

Output from membrane system computer models can be used to assist in the selection and optimization of an energy recovery technology for a given application.

It should be noted that the use of isobaric energy recovery devices may result in a small increase in first stage membrane feed stream salinity (Sessions, 2011). This occurs because of the direct contact between concentrate and feed streams that is associated with these devices. If isobaric energy recovery devices are specified for a membrane facility, the design engineer should account for any expected impacts to feed stream salinity in the membrane system computer model. The energy recovery device manufacturer should be consulted in order to determine these impacts to feed stream salinity for a given application.

4 Modeling examples

4.1 Introduction

The material discussed in Chapters 1 through 3 presents practical and theoretical considerations related to computer modeling of reverse osmosis and nanofiltration membrane systems in general terms. This chapter provides detailed information on the steps required to perform computer modeling of two real reverse osmosis membrane systems treating brackish water. The first example is based on the expansion of a reverse osmosis membrane facility that treats brackish groundwater from an aquifer influenced by a lower aquifer of higher salinity. The membrane system modeling for this example was performed using ROSA V.8.0.3 provided by DOW Water and Process Solutions, TorayDS2 V2.0.1.58 provided by Toray, and IMSDesign V.2012.8 provided by Hydranautics.

The second example is based on a reverse osmosis facility that treats brackish surface water. The water source is subject to seasonal variations in temperature with a steady increase in salinity resulting from recent drought conditions in Texas. A microfiltration pretreatment process provides consistent removal of turbidity upstream of the reverse osmosis membranes. The membrane system modeling for this example was performed using ROSA V.8.0.3 provided by DOW Water and Process Solutions.

4.2 Example 1 – Groundwater influenced by high salinity lower aquifer

4.2.1 Model input

The raw water quality data presented in Table 4-1 was input into the computer modeling software. Current raw water total dissolved solids was determined using the ion summation method. A detailed discussion of the ion summation method was provided in Chapter 3. The results of this method demonstrated a good balance (to within 1 percent) between cations and anions. The source aquifer for this facility is primarily composed of limestone and dolomite formations, and is one of the most productive aquifers in the world. Raw water at this facility is provided by 17 supply wells. Water from each well is blended within a common feed line upstream of the treatment facility. Based on a report completed by the owner’s geologic consultant, the quality of the raw water is expected to deteriorate over the next 20 years. This is due primarily to intrusion of higher salinity water from a lower aquifer. The hydro geologic consultant determined that the intrusion was due to (1) inadequate spacing between existing wells with resulting excessive draw-down levels, and (2) fractures and porosity in the formation between aquifers. The excessive draw-down levels that resulted from the inadequate spacing between wells resulted in a pressure gradient between the higher salinity lower aquifer and the source aquifer above. The porosity and fractures in the formation between the aquifers provided a path for higher salinity water below to migrate upward into the source aquifer above.

Table 4-1. Example 1 - design water quality.

Parameter	Units	Raw water: Current	Raw water: 20-year projected	Reverse osmosis permeate[1]	Blended water[2]	Post-treatment goals
Temperature	Degrees Celsius (degrees Fahrenheit)	29 (84)	29 (84)	29 (84)	29 (84)	29 (84)
pH	Standard unit	7.66	7.68	6.3 to 6.8	6.5 to 6.8	7.8 to 8.5
Alkalinity	milligrams per liter as $CaCO_3$	115	115	4 to 12	15 to 20	> 30
Total hardness	milligrams per liter as $CaCO_3$	755	994	13 to 29	56 to 124	< 110 avg
CCPP[3]	milligrams per liter as $CaCO_3$			-14 to -12	-12 to -8	4 to 10
Total dissolved solids	milligrams per liter	2,239	3,646	40 to 170	345 to 378	< 400
Turbidity	Nephelometric turbidity units	<0.2	<0.2	< 0.1	< 0.2	< 0.3
Silt density index	Standard unit	0.1 to 0.69	0.1 to 0.69	ND	ND	-
Hydrogen sulfide	milligrams per liter	3.0	3.0	3.0	3.0	0
Iron	milligrams per liter	ND	ND	ND	ND	-
Manganese	milligrams per liter	ND	0.009	0	0	-
Calcium	milligrams per liter	134	146	2.2 to 4.1	8 to 21	6 to 19
Magnesium	milligrams per liter	102	153	1.7 to 4.3	8 to 16	8 to 16
Sodium	milligrams per liter	508	946	17 to 85	< 100	< 100
Potassium	milligrams per liter	ND	16.3	0 to 0.65	-	-
Ammonium	milligrams per liter	0.5	0.5	0.03 to 0.04	-	-
Barium	milligrams per liter	0.053	0.059	0	-	-
Strontium	milligrams per liter	25.8	25.8	0.41 to 0.48	-	-
Carbon dioxide	milligrams per liter	4.3	4.2	3.7 to 4.0	3.8 to 3.9	0
Carbonate	milligrams per liter	0.98	0.96	0	0 to 0.1	1 to 2
Bicarbonate	milligrams per liter	141	141	5 to 14	18 to 25	32 to 35
Sulfate	milligrams per liter	269	373	3 to 14	< 200	< 200
Chloride	milligrams per liter	1,057	1,840	30 to 135	< 200	< 200
Fluoride	milligrams per liter	1.0	1.0	0.04 to 0.16	0.18	0.8
Nitrate	milligrams per liter	0.1	0.1	0.03 to 0.05	-	-
Silica	milligrams per liter as SiO_2	15.4	15.4	0.28 to 0.32	-	-

Notes: ND - Non-Detect or No Data

[a] reverse osmosis permeate quality is based upon membrane performance models. Actual quality is expected to vary within the range presented depending on membrane selection, feed water quality, and membrane condition.

[b] Blended water consists of reverse osmosis permeate and bypassed raw water. Blended water quality depends on raw water bypass and permeate quality and flow rates.

[c] Calcium Carbonate Precipitation Potential. A positive value indicates the level of calcium carbonate supersaturation. A negative value indicates the level below saturation.

The recommendations in the geologic consultant's report included changes to the well field operating scheme to minimize intrusion of higher salinity water and extend well life. Even with the implementation of these recommendations, the salinity of the groundwater source is expected to increase significantly (from 2,240 to approximately 3,650 milligrams per liter as total dissolved solids) over the next 20 years. The constituents that are expected to increase most dramatically over time are chloride, sulfate, sodium, and magnesium. This is presented graphically in Figure 4-1.

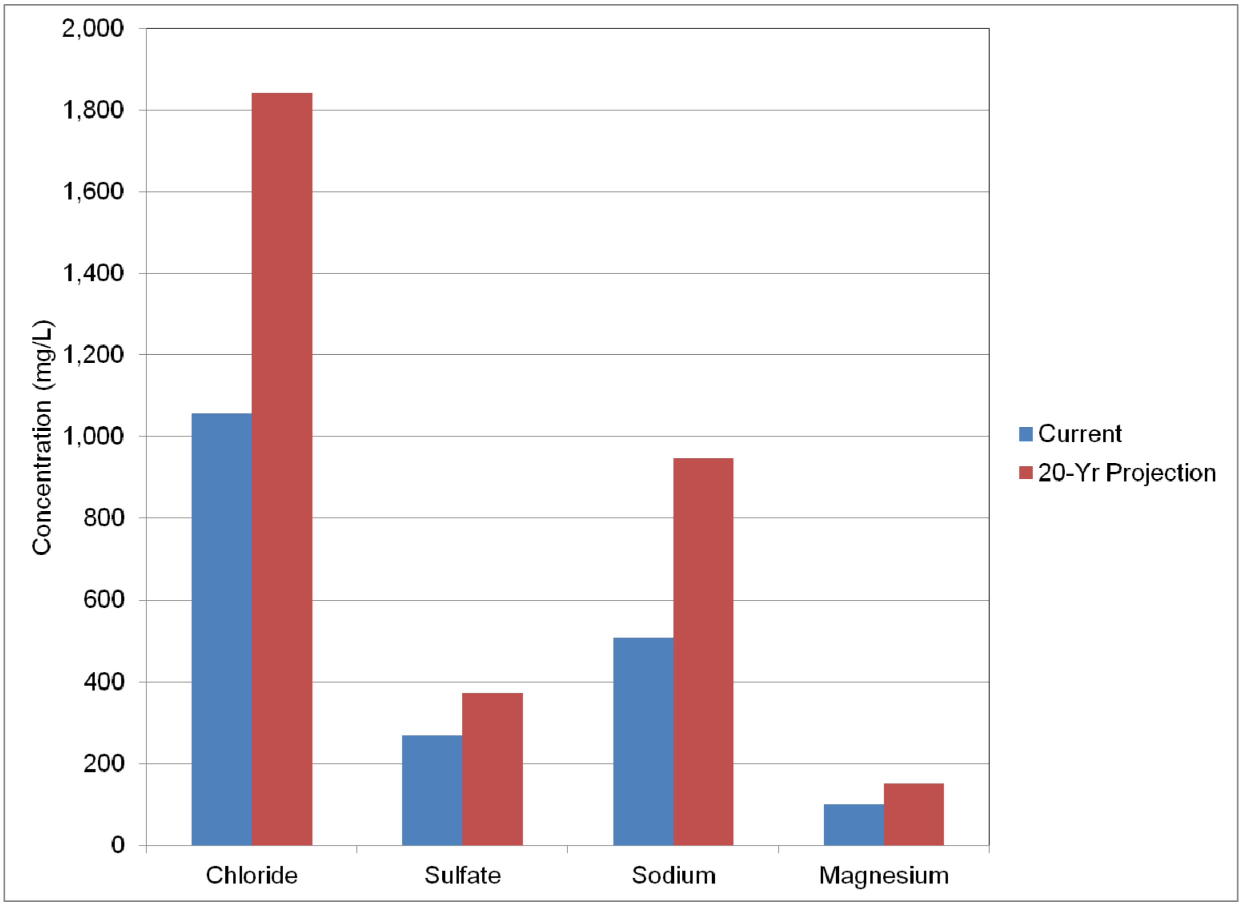

Figure 4-1. Expected raw water salinity increase.

Four operating scenarios were modeled for this membrane system in order to determine (1) the operating envelope of the first stage reverse osmosis feed pumps, (2) expected permeate water quality variations with resulting variations in acceptable raw water blending flows, and (3) concentrate pressures and flows which were used to size the energy recovery device selected for this application. Descriptions of the operating scenarios modeled for this facility are provided in Table 4-2.

Table 4-2. Example 1 – reverse osmosis membrane system operating scenarios.

Scenario	Recovery	Feed water quality	Membrane condition
1	75 percent	Year – 0	Clean
2	80 percent	Year – 0	Clean
3	75 percent	Year - 20	Fouled
4	80 percent	Year - 20	Fouled

In addition to the raw water quality data presented in Table 4-1, the data presented in Table 4-3 was incorporated as input in the reverse osmosis membrane system computer model.

Table 4-3. Example 1 - modeling input data.

Parameter	Unit	Value
Feed water classification	Not applicable	Brackish Well, silt density index < 3
Permeate flow per train	Gallons per minute	1,733
Recovery rate	percent	75 to 80
Membrane fouling/flow factor	Not applicable	0.75 to 1.00
Stages	Number	2
Pressure vessels – first stage	Number	38
Pressure vessels – second stage	Number	18
Elements per vessel	Number	7
Membrane element selection	Not applicable	See note a
Area per element	Square feet	430 to 440
Feed Stream pH adjustment	Not applicable	None
Permeate backpressure (each stage) [(a)]	Pound-force per square inch gauge	10 to 20
Interstage pressure boost	Pound-force per square inch gauge	70 to 111

[a] Refer to Table 4-4 for description of membranes modeled for this facility.

[b] Permeate backpressure was determined through hydraulic modeling considering high and low plant production, elevation of the downstream discharge and friction losses in process piping.

A screenshot from the "System Configuration" tab of the membrane system computer model is provided in Figure 4-2.

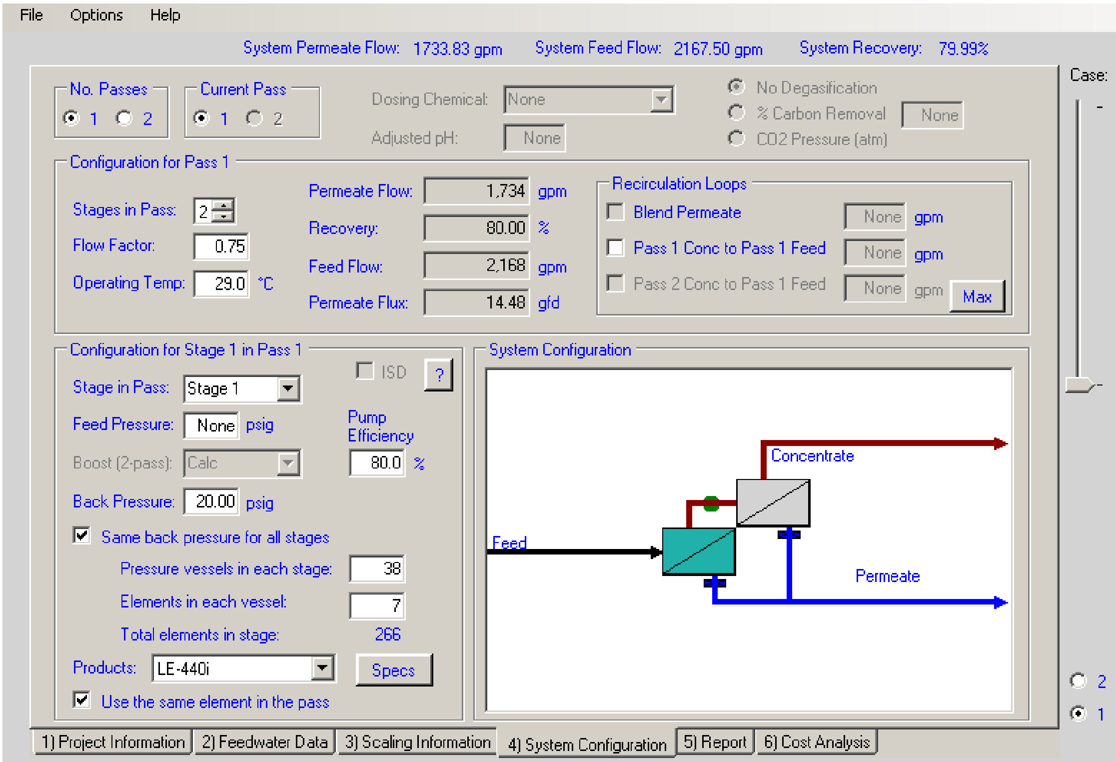

Figure 4-2. Example 1 – membrane modeling software screenshot.

In addition to providing an interface for user input of system configuration data, the configuration tab shown in Figure 4-2 provides a graphic representation of the membrane train configuration, including membrane stages, interstage boost pump, and feed, concentrate, and permeate flow streams. The screenshot presented in Figure 4-2 was taken from ROSA V.8.0.3 provided by DOW Water and Process Solutions. Software models provided by other membrane manufacturers include similar user input tabs.

Three different reverse osmosis membranes were modeled for this facility. Table 4-4 provides a description of each membrane. As shown in Table 4-4, each membrane element modeled provides a surface area between 430 and 440 square feet. Modeled membrane elements represent comparable low pressure, high productivity offerings from each listed membrane manufacturer.

Table 4-4. Example 1 – reverse osmosis membranes modeled.

Manufacturer	Model No.[(1)]	Surface area (square feet)
DOW/Filmtec	LE-440i	440
Hydranautics	ESPA 2 MAX	440
Toray	TMG20-430	430

[a] Membranes evaluated represent comparable product offerings by each manufacturer for brackish water reverse osmosis applications

4.2.2 Model output

A summary of the output data provided by each membrane system model performed for this example is presented in Table 4-5.

Table 4-5. Example 1 – model output.

Membrane	**Value**			
Feed water quality	Initial year-0		Projected year-20	
Membrane condition	Clean (flow factor = 1.00)		Fouled (flow factor = 0.75)	
Feed water recovery	75 percent	80 percent	75 percent	80 percent
Average Flux (gallons per square foot per day)				
Dow/Filmtec LE-440i	14.5	14.5	14.5	14.5
Hydranautics ESPA 2 Max	14.5	14.5	14.5	14.5
Toray TMG20-430	14.7	14.7	14.7	14.7
First Stage Feed Pressure (pound-force per square inch gauge)				
Dow/Filmtec LE-440i	113	113	165	166
Hydranautics ESPA 2 Max	114	115	158	158
Toray TMG20-430	115	116	162	164
Interstage Pressure Boost (pound-force per square inch gauge)[(a)]				
Dow/Filmtec LE-440i	70	76	97	112
Hydranautics ESPA 2 Max	75	76	101	114
Toray TMG20-430	62	70	85	100
Concentrate Pressure (pound-force per square inch gauge)				
Dow/Filmtec LE-440i	118	135	196	223
Hydranautics ESPA 2 Max	112	127	180	207
Toray TMG20-430	129	145	200	224
Permeate total dissolved solids (milligrams per liter)				
Dow/Filmtec LE-440i	60	66	103	115
Hydranautics ESPA 2 Max	48	57	97	113
Toray TMG20-430	64	76	144	169
Permeate pH				
Dow/Filmtec LE-440i	6.3	6.3	6.3	6.3
Hydranautics ESPA 2 Max	6.3	6.4	6.4	6.5
Toray TMG20-430	6.2	6.2	6.3	6.3

[a] Interstage pressure boost required to balance flux between first and second stage membranes.

Several observations can be made from a review of the data presented in Table 4-5.

1. The average flux for the Toray membranes is the highest at 14.7 gallons per square foot per day. This is a direct result of the required train permeate flow rate of 1,733 gallons per minute and the smaller membrane area (430 square feet) for the selected Toray elements.

First stage feed and interstage boost pressures for each operating scenario and membrane manufacturer are comparable.

Concentrate pressures for the Toray membranes are generally higher than for the DOW/Filmtec and Hydranautics membranes.

Permeate total dissolved solids is similar for each membrane at the initial, Year-0 water quality condition. At the Year-20 water quality condition, the Toray membranes demonstrate a significantly higher permeate total dissolved solids value than the other membranes evaluated.

Permeate pH is similar for each membrane evaluated.

The data presented in Table 4-5 represents the range of operating conditions that can be expected using each of the membranes evaluated. The design engineer may use this information to size and select first stage feed and interstage boost pumps, and energy recovery equipment that will satisfy the operating requirements of multiple membrane manufacturers. Raw water bypass (blending) flow rates may also be estimated over the range of conditions

Raw water blending calculation

The reverse osmosis facility in this example incorporates raw water blending to supplement permeate capacity and increase finished water production. The permeate flow capacity of each reverse osmosis train has been fixed at 1,733 gallons per minute (2.5 million gallons per day) each. The acceptable raw water bypass flow at this facility can be calculated using Equation 3-1 and the following relationship:

$$Q_T = Q_B + Q_P \qquad \text{Equation 4-1}$$

Where:

Q_B = Raw water blending flow (gallons per minute)
Q_T = Blended water capacity (gallons per minute)
Q_P = Permeate flow (gallons per minute)

Equation 4-1 can be used to rearrange Equation 3-1 as follows:

$$Q_B = Q_P\left(\frac{C_T - C_P}{C_R - C_T}\right) \qquad \text{Equation 4-2}$$

Where:

C_R = Concentration of limiting water quality constituent in raw water (milligrams per liter)
C_T = Target concentration of limiting water quality constituent in blended water (milligrams per liter)
C_P = Concentration of limiting water quality constituent in permeate (milligrams per liter)

Equation 4-2 can be used to calculate acceptable blending flows when permeate flow and water quality goals are known. The total plant capacity can then be determined using Equation 4-1.

Table 4-6 presents a summary of acceptable raw water bypass flows for each operating condition and membrane evaluated based upon a maximum blended water total dissolved solids goal of 400 milligrams per liter. This goal of 400 milligrams per liter for total dissolved solids was set by the owner in order to provide a generous margin respective to the secondary maximum contaminant level of 500 milligrams per liter (based on EPA secondary standards).

Table 4-6. Example 1 – raw water bypass flows (per reverse osmosis train).

Membrane	Value			
Feed water quality	Initial year-0		Projected year-20	
Membrane condition	Clean (flow factor = 1.00)		Fouled (flow factor = 0.75)	
Feed water recovery	75 percent	80 percent	75 percent	80 percent
Dow/Filmtec LE-440i (gallons per minute)	285	338	197	172
Hydranautics ESPA 2 Max (gallons per minute)	307	289	208	176
Toray TMG20-430 (gallons per minute)	275	251	113	63

The data presented in Table 4-6 indicates that the maximum raw water bypass flow may be achieved when using Dow/Filmtec LE-440i membranes at the Year-0 feed water quality and 80 percent recovery condition. This is to be expected, as permeate total dissolved solids is projected to be lowest at this condition using this membrane. Acceptable bypass flows are the lowest when using the Toray TMG20-430 membranes at the Year-20 feed water quality and 80 percent recovery condition. As presented in Table 4-5, permeate total dissolved solids is significantly higher at the Year 20 feed water quality condition when using the Toray membrane.

Hydraulic profiles

General considerations regarding hydraulic profiles were discussed in Chapter 3.1.3. This topic is briefly discussed here to emphasize the importance of properly incorporating data from the hydraulic model of the facility into the membrane system computer model and vice versa.

Before computer modeling of the membrane system is performed, a hydraulic evaluation of the permeate piping downstream of the membrane trains should be performed to determine the expected permeate backpressure at the minimum and maximum permeate flows. The permeate backpressures determined from the hydraulic evaluation should be incorporated into the membrane system computer model. Changes in permeate backpressure will directly affect calculated membrane feed pressure requirements.

Figure 4-3 presents the hydraulic profile for the membrane feed and permeate streams for the facility in Example 1.

For hydraulic model of this facility, the important data that must be provided from the membrane system computer model includes (1) membrane feed pressure, and (2) membrane concentrate pressure. The hydraulic grade line at the discharge of the first stage feed pumps accounts for not only the membrane feed pressure as projected by the membrane system computer model, but also the pressure losses that occur in the piping between the first stage feed pumps and the first stage reverse osmosis membranes. This additional information can only be obtained from a hydraulic evaluation of the first stage feed piping.

If desired, the hydraulic profile may include information specific to individual membrane stages. This information would include hydraulic grade line data corresponding to (1) first stage membrane concentrate pressure, (2) interstage boost pump suction and discharge pressures, and (3) second stage membrane feed pressure.

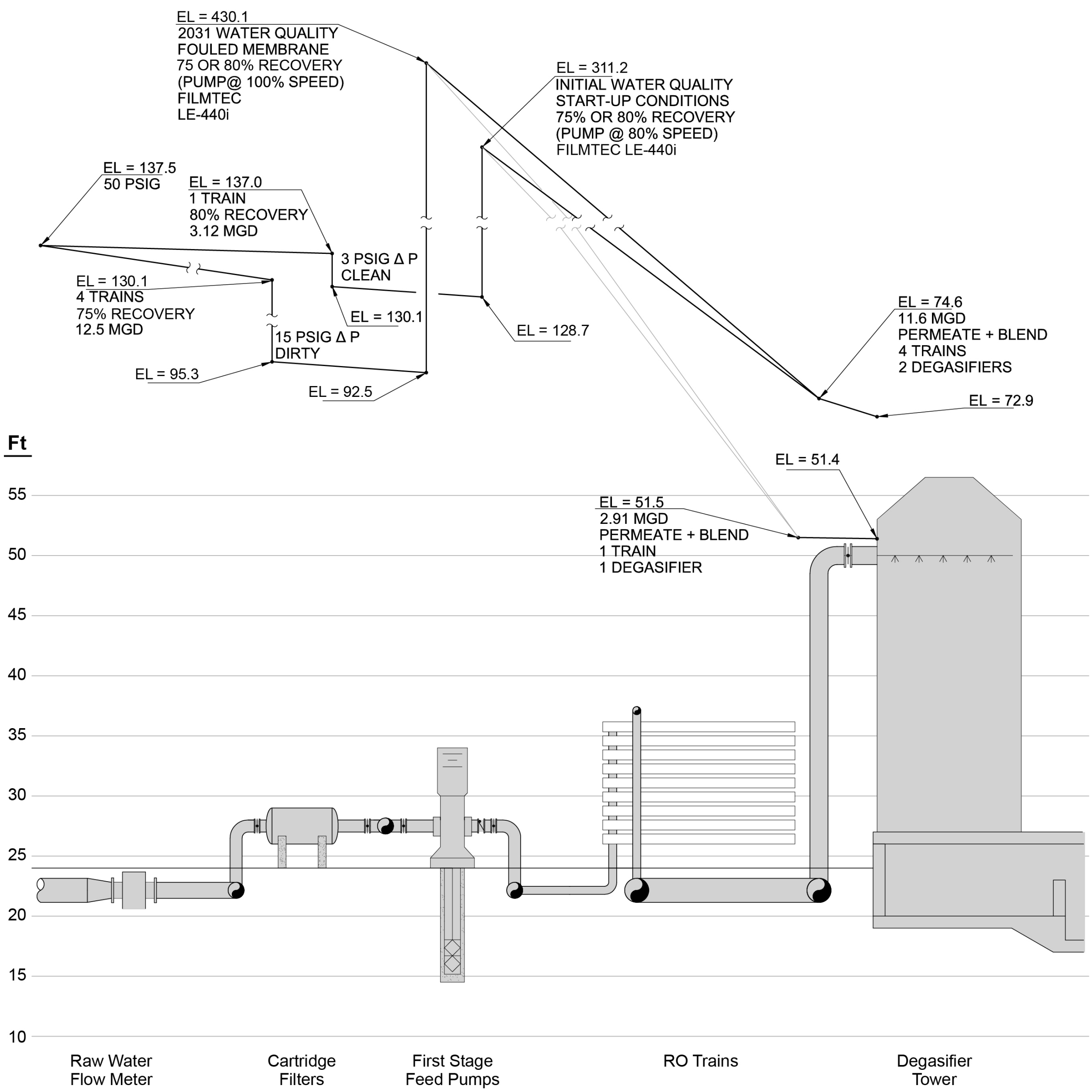

Figure 4-3. Example 1 hydraulic profile – membrane feed and permeate.

The hydraulic grade line values at the suction and discharge of the first stage feed pump shown in Figure 4-3 can be used to characterize the operating envelope of the pump. This operating envelope represents the expected range of operating conditions for the pump during all anticipated combinations of feed water quality, installed membrane selection, and membrane fouling. The operating envelope for the first stage feed pumps for the facility in Example 1 is presented in Figure 4-4.

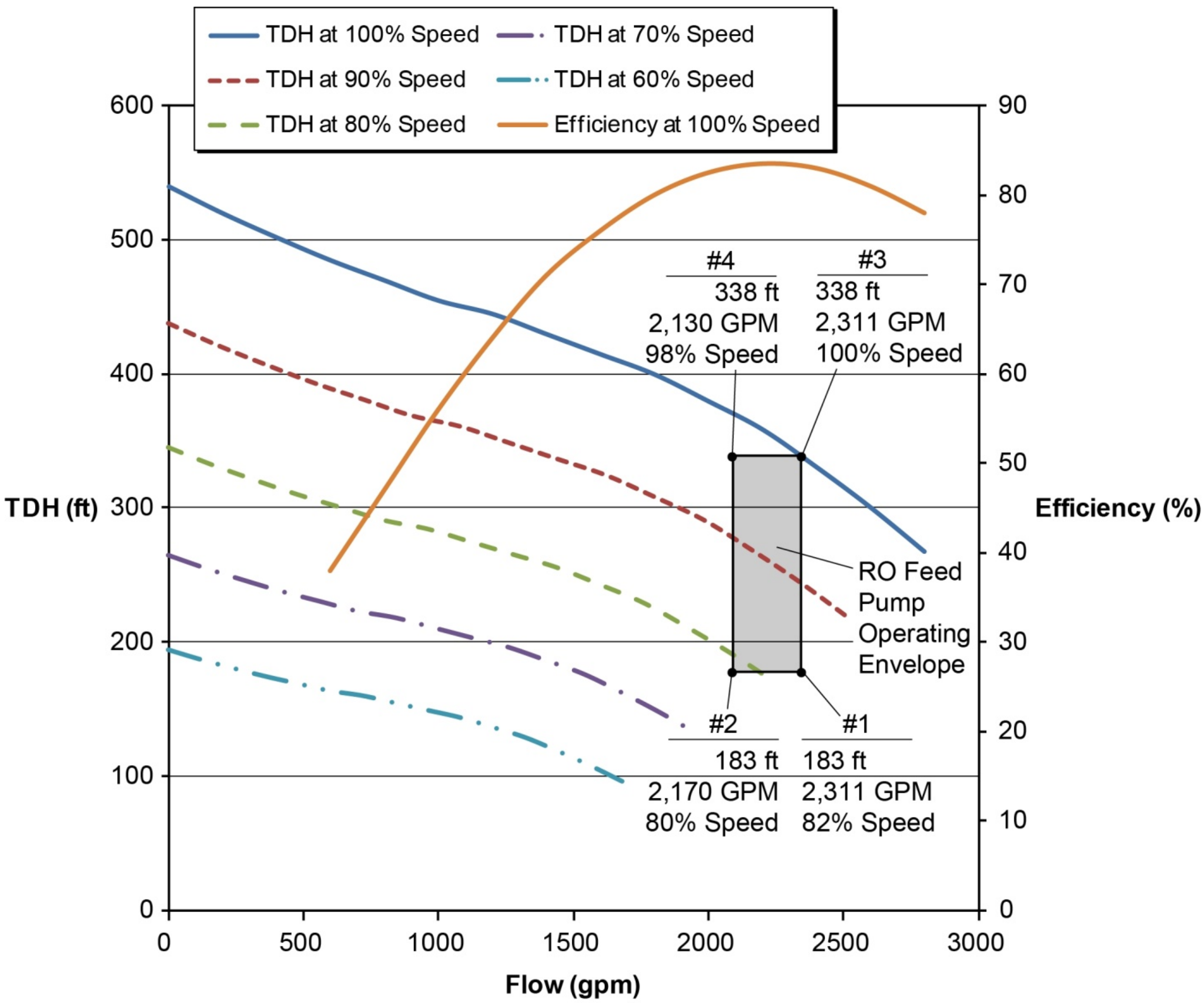

Figure 4-4. **Example 1 - reverse osmosis feed pump operating envelope.**

Figure 4-4 presents Pump Efficiency (%) vs Flow curve (at 100 percent pump speed), and the Total Developed Head vs. Flow curves for the specified first stage membrane feed pumps at several pump speeds. These pumps are equipped with variable frequency drives. These drives allow the pump speed to be automatically adjusted by the facility's programmable logic controller to maintain a setpoint for a constant reverse osmosis permeate flow from each train regardless of the downstream membrane selection, membrane fouling, or feed water quality.

Figure 4-4 indicates that the first stage reverse osmosis feed pumps will operate at speeds between 80 and 100 percent of maximum at all anticipated conditions of facility operation. A review of the efficiency vs. flow curve presented in Figure 4-4 shows that, when operated at speed close to 100 percent of maximum at the flow rates indicated, these pumps will operate close to their rated best efficiency point.

Figure 4-5 presents the hydraulic profile for the membrane concentrate stream for the facility in Example 1.

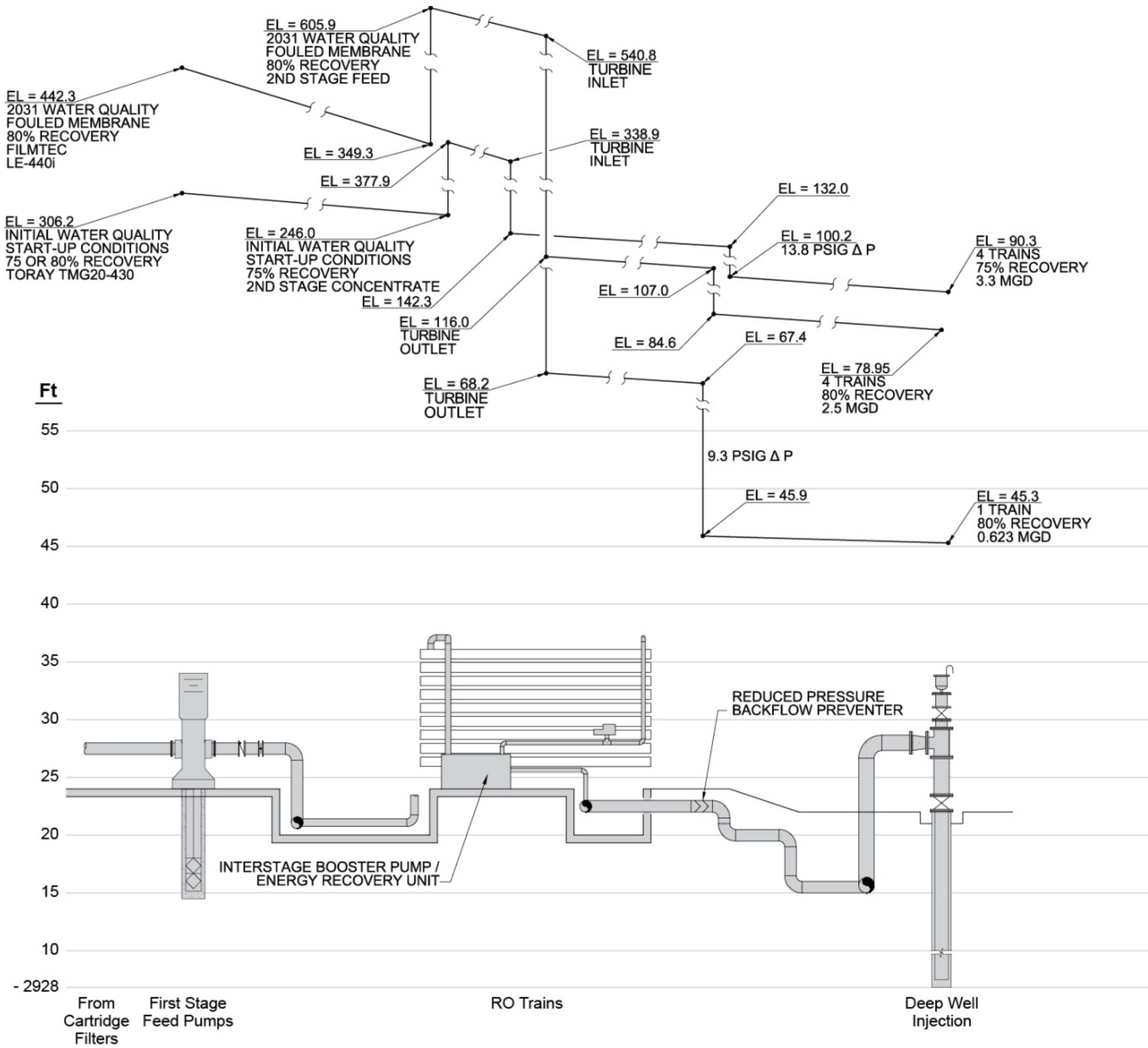

Figure 4-5. Example 1 hydraulic profile - membrane concentrate.

For hydraulic model of this facility, the important data that must be provided from the membrane system computer model includes (1) first stage membrane feed pressure, and (2) second stage membrane concentrate pressure. This facility incorporated energy recovery turbines mounted on a common shaft with the interstage boost pumps. Together with the concentrate backpressure data provided by the facility hydraulic model, the second stage concentrate pressure provides the basis for sizing the energy recovery turbines.

data provided by the facility hydraulic model, the second stage concentrate pressure provides the basis for sizing the energy recovery turbines.

Antiscalant selection and dosing

The output from the membrane system computer models provided warnings that the concentration of barium sulfate, strontium sulfate, and calcium fluoride had exceeded their respective solubility limits in the reverse osmosis concentrate stream. For this application, an antiscalant is required to prevent precipitation of these constituents in the feed/concentrate stream, and subsequent membrane scaling.

A computer model developed by Avista Technologies was used to determine the performance of an antiscalant (Avista Vitec 3000) supplied by the same antiscalant manufacturer. The results of the computer model indicate that an antiscalant dose of 2.0 milligrams per liter would effectively control membrane scaling based on the input feed water chemistry and a design recovery of 80 percent. Avista's software estimates that, at the specified design recovery, the saturation of these salts is at most 15 percent of the maximum recommended concentration when using their inhibitor at this dose. A dose of 2.0 milligrams per liter represents the minimum recommended dose for the Avista product. In this case, the minimum dose was governed by the requirement to achieve a 10 milligram per liter concentration of scale inhibitor in the concentrate stream.

The user of these programs should refer to the manufacturer's instructions regarding input and output water quality parameters. For example, the user should understand if nitrate concentration is defined as milligrams per liter as nitrogen or as nitrate, as these differ by a factor of 4.43.

Table 4-.7 presents the concentration of each constituent of concern as a percentage relative to saturation in the reverse osmosis concentrate stream. Also listed in Table 4-7 are the allowable concentrations of each constituent when the selected antiscalant is used at the recommended dose in the reverse osmosis feed water.

Table 4-7. Example 1 – antiscalant performance summary.

Constituent	Concentration in reverse osmosis concentrate stream[a]	Concentration w/antiscalant[a,b]
Barium sulfate	1,240 percent	12 percent
Strontium sulfate	356 percent	15 percent
Calcium fluoride	624 percent	1 percent

[a] Relative to saturation.
[b] Results are based on performance projections for selected antiscalant (Avista Vitec 3000). Results may vary based upon selected antiscalant and dosage.

Appendix B presents the output reports from the antiscalant computer model used for this example. The design engineer should always consult with the antiscalant manufacturer (or their representative) when selecting an antiscalant and dose for a given application.

4.3 Example 2 – Surface water with seasonal temperature and salinity variation

4.3.1 Model input

The raw water source for this facility is a reservoir that has been experiencing a steady increase in salinity due to prolonged drought conditions. The graph in Figure 4-5 presents the historical variation in temperature and increase in salinity within the reservoir, representing a 31-month period between January 2011 and August 2013. Raw water temperatures vary seasonally between a winter low temperature of 9 °C, and a summer high temperature of 30 °C.

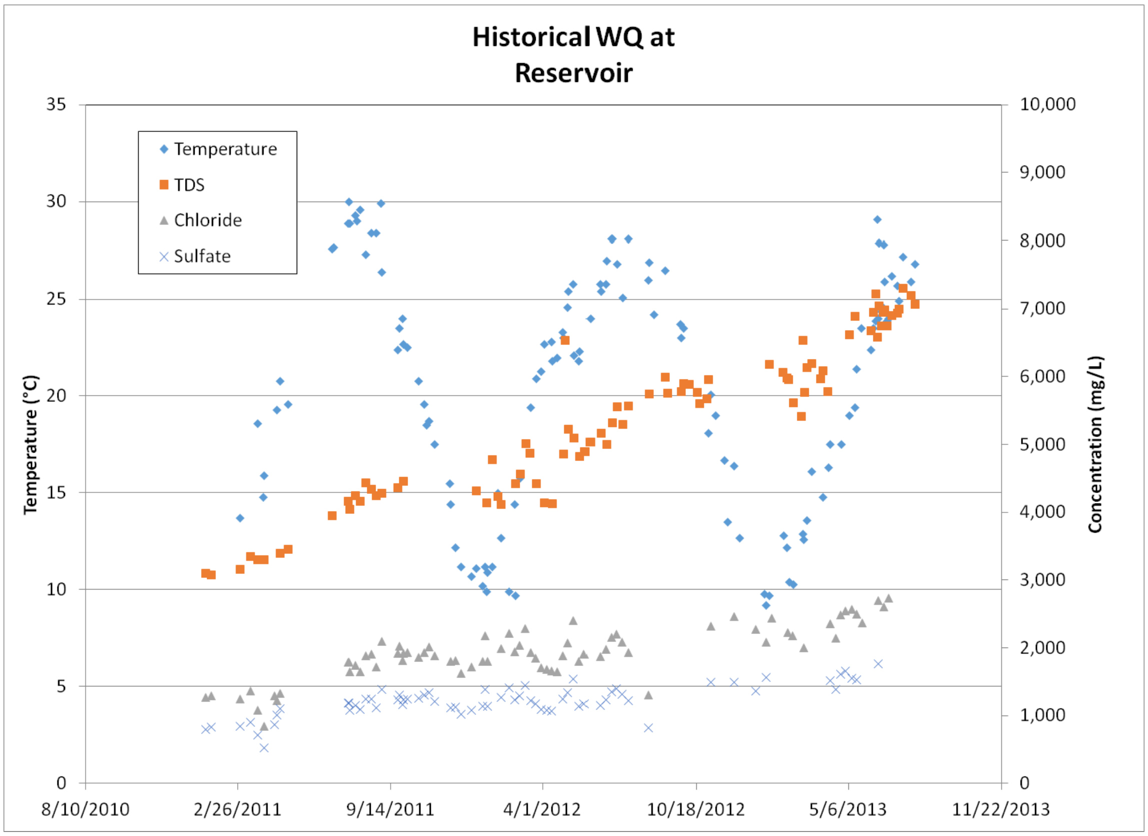

Figure 4-6. Seasonal surface water quality variation.

The graph presented in Figure 4-6 indicates that concentrations of both chloride and sulfate have been increasing over time, reflecting the trend of increasing total dissolved concentration over the same time period.

Table 4-8 presents design water quality data for this facility. The raw water quality presented in this table was input into the selected membrane manufactures computer models, while the permeate water quality represents information output by the computer models.

Table 4-8. Example 2 - design water quality.

Parameter	Units	Raw water: Best Case	Raw water: Worst Case	Reverse osmosis permeate[(a)]
Temperature	Degrees Celsius (degrees Fahrenheit)	30 (86)	9 (48)	Approx. same as raw water
pH	Standard unit	8.7	8.7	5.1 to 5.4
Alkalinity	milligrams per liter as $CaCO_3$	90	90	1.6 to 4.3
Total hardness	milligrams per liter as $CaCO_3$	791	1,241	3.1 to 10.3
CCPP[(b)]	milligrams per liter as $CaCO_3$			-81 to -61
Total dissolved solids	milligrams per liter	2,266	7,983	44 to 135
Turbidity	Nephelometric turbidity units	<0.2	<0.2	< 0.1
Silt density index	Standard unit	0.1 to 0.69	0.1 to 0.69	ND
Iron	milligrams per liter	1.0	1.0	ND
Manganese	milligrams per liter	0	0	0
Calcium	milligrams per liter	160	340	0.8 to 2.1
Magnesium	milligrams per liter	95	95	0.6 to 1.2
Sodium	milligrams per liter	483	2,379	14 to 49
Potassium	milligrams per liter	16	16	0.4 to 0.8
Ammonium	milligrams per liter	0	0	0
Barium	milligrams per liter	0.153	0.153	0
Strontium	milligrams per liter	7.0	7.0	0.02 to 0.09
Carbonate	milligrams per liter	1.92	1.92	0
Bicarbonate	milligrams per liter	110	110	1.6 to 4.3
Sulfate	milligrams per liter	504	2,016	3 to 12
Chloride	milligrams per liter	886	3,013	21 to 69
Fluoride	milligrams per liter	0.7	0.7	0.01 to 0.04
Nitrate	milligrams per liter	1.2	1.2	0.06 to 0.21
Silica	milligrams per liter as SiO_2	15.0	15.0	0.05 to 0.21

Notes: ND - Non-Detect or No Data
[a] Reverse osmosis permeate quality is based upon membrane performance models. Actual quality is expected to vary within the range presented depending on membrane selection, feed water quality, and membrane condition.
[b] Calcium Carbonate Precipitation Potential. A positive value indicates the level of calcium carbonate supersaturation. A negative value indicates the level below saturation.

Raw water blending is not incorporated at this facility. Instead, RO permeate is blended with treated water from a conventional water treatment facility and then pumped to the distribution system.

Four (4) scenarios were selected for computer modeling. These scenarios represent the expected variations in feed water quality, membrane conditions, and permeate flows.

Scenario 1 – Best case water quality, maximum permeate flow per train. A feed water TDS concentration was selected to represent a design margin of 1,000 milligrams per liter below the lowest recorded measurement. A design margin below the lowest recorded TDS measurement was used to represent feed water quality associated with the minimum total developed head requirements of the RO feed pump. The value of 1,000 milligrams per liter is based on the water quality at the project site. This value should be selected based on site-specific water quality.Feed water temperature was selected to match the maximum-recorded temperature of 30 °C. Since both TDS and temperature impact the membrane feed pressure requirements, it is not necessary to provide a design margin for both parameters. The design margin was applied to the feed water TDS, as this is the least predictable of the two parameters due to the recent drought conditions. Drought cycles are inherently less predictable than summer and winter temperatures. This scenario incorporates the design permeate flow rate of 1,389 gpm per train at a maximum system recovery of 75 percent. This scenario assumes clean RO membranes.

Scenario 2 – Best case water quality, minimum permeate flow per train. This scenario assumes the same feed water quality as Scenario 1. A minimum permeate flow rate of 1,250 gpm per train was established based on the minimum concentrate flows for individual membrane elements recommended by the membrane manufacturers. This scenario assumes clean RO membranes.

Scenario 3 – Worst case water quality, maximum permeate flow per train. A feed water TDS concentration was selected to represent a design margin of 1,000 milligrams per liter above the highest recorded measurement. A design margin above the highest recorded TDS measurement was used to represent feed water quality associated with maximum total developed head requirements of the RO feed pump. The value of 1,000 milligrams per liter is based on the water quality at the project site. This value should be selected based on site-specific water quality. Feed water temperature was selected to match the minimum-recorded temperature of 9 °C. This scenario incorporates the design permeate flow rate of 1,389 gpm per train at a maximum system recovery of 75 percent. This scenario assumes fouled RO membranes, and incorporates a fouling factor of 0.75 in the membrane system computer models.

Scenario 4 – Worst case water quality, minimum permeate flow per train. This scenario assumes the same feed water quality as Scenario 3. A minimum permeate flow rate of 1,250 gpm per train was established based on the minimum concentrate flows for individual membrane elements recommended by the membrane manufacturers. This scenario assumes fouled RO membranes, and incorporates a fouling factor of 0.75 in the membrane system computer models.

These four operating scenarios are summarized in Table 4-9.

Table 4-9. Example 2 – reverse osmosis membrane system operating scenarios.

Scenario	Recovery	Feed water quality	Permeate flow per train	Membrane condition
1	75 percent	Best Case	Maximum	Clean
2	73 percent	Best Case	Minimum	Clean
3	75 percent	Worst Case	Maximum	Fouled
4	73 percent	Worst Case	Minimum	Fouled

From an observation of Table 4-9, it is important to note that as permeate flow is reduced, the system recovery decreases. As discussed earlier, membrane manufacturers place limits on the minimum allowable concentrate flow for individual membrane elements. As such, the concentrate flow associated with an individual train should be controlled based on a setpoint that does not result in violating the membrane manufacture's minimum concentrate flow limits for individual elements. A violation of this limit can occur when the concentrate flow from an individual train is controlled to maintain a setpoint system recovery. In this case, as the train's permeate flow setpoint is decreased, the concentrate flow also decreases. If the concentrate flow decreases enough, the minimum concentrate flow limits can be violated, resulting in a greater tendency for membrane scaling, particularly at the tail elements in a train. A superior method for controlling concentrate flow is to base concentrate flow on a flow setpoint. In this case, as the permeate flow setpoint is reduced, the concentrate flow remains constant. The disadvantage to this method is a reduction in system recovery at lower permeate flows. The advantage is a reduced risk of membrane scaling caused by improper membrane system operation.

In addition to the raw water quality data presented in Table 4-8, the data presented in Table 4-10 was incorporated as input in the reverse osmosis membrane system computer models.

Table 4-10. Example 2 - modeling input data.

Parameter	Unit	Value
Feed water classification	Not applicable	Surface Water, Membrane Pretreatment, silt density index < 3
Permeate flow per train	Gallons per minute	1,250 to 1,389
Recovery rate	percent	73 to 75
Membrane fouling/flow factor	Not applicable	0.75 to 1.00
Stages	Number	2
Pressure vessels – first stage	Number	36
Pressure vessels – second stage	Number	18
Elements per vessel	Number	7
Membrane element selection	Not applicable	See note a
Area per element	Square feet	400
Feed Stream pH adjustment	Not applicable	Sulfuric Acid[c]
Permeate backpressure (each stage) [b]	Pound-force per square inch gauge	2 to 5
Interstage pressure boost	Pound-force per square inch gauge	44 to 133

[a] Refer to Table 4-11 for description of membranes modeled for this facility.

[b] Permeate backpressure was determined through hydraulic modeling considering high and low plant production, elevation of the downstream discharge and friction losses in process piping.

[c] Sulfuric acid dose ranges from 36 to 52 milligrams per liter

A screenshot from the "RO Design" tab of the Hydranautics IMSDesign V.2012.8 membrane system computer model is provided in Figure 4-7.

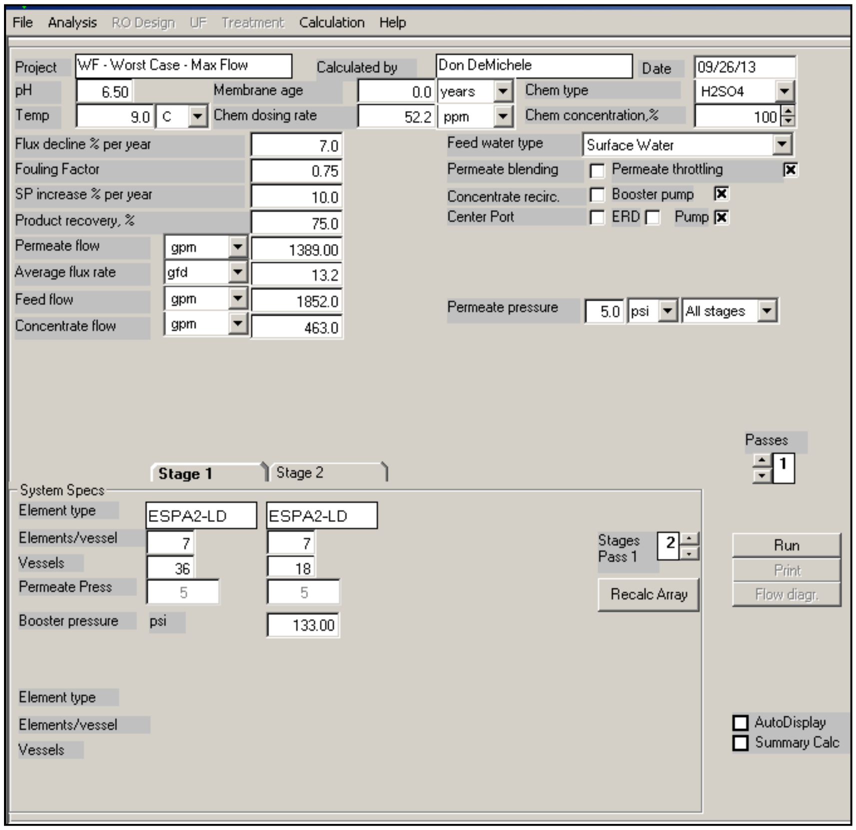

Figure 4-7. Example 2 – membrane modeling software screenshot.

Two different reverse osmosis membranes were modeled for this facility. Table 4-11 provides a description of each membrane. As shown in Table 4-11, both membrane elements modeled provide a surface area of 400 square feet. Modeled membrane elements represent comparable low pressure, high productivity offerings from each listed membrane manufacturer. For this facility, low-differential membranes with large 34-millimeter feed channel spacers were selected.

Table 4-11. Example 2 – reverse osmosis membranes modeled.

Manufacturer	Model No.[1]	Surface area (square feet)
DOW/Filmtec	XFRLE-400/34i	400
Hydranautics	ESPA 2 LD	440

[a] Membranes evaluated represent comparable product offerings by each manufacturer for brackish water reverse osmosis applications

Low-differential membranes with 34-millimeter feed channel spacers reduce differential pressure across membrane stages by approximately 50 percent (as compared to conventional 28-millimeter feed spacers) by reducing flow velocities within the membrane feed channels. Depending on feed water quality, RO system recovery, and membrane flux rates, the total feed water pumping power requirement is reduced by approximately 10 percent

4.3.2 Model output

A summary of the output data provided by each membrane system model performed for this example is presented in Table 4-12.

Table 4-12. Example 2 –model output.

Membrane	Value			
Feed water quality	Best Case		Worst Case	
Membrane condition	Clean (flow factor = 1.00)		Fouled (flow factor = 0.75)	
Permeate Flow Rate	Max	Min	Max	Min
Average Flux (gallons per square foot per day)				
Dow/Filmtec XFRLE-400/34i	13.2	11.9	13.2	11.9
Hydranautics ESPA 2 LD	13.2	11.9	13.2	11.9
First Stage Feed Pressure (pound-force per square inch gauge)				
Dow/Filmtec XFRLE-400/34i	89	83	284	263
Hydranautics ESPA 2 LD	98	91	235	221
Interstage Pressure Boost (pound-force per square inch gauge)[a]				
Dow/Filmtec XFRLE-400/34i	49	44	152	135
Hydranautics ESPA 2 LD	48	44	133	120
Concentrate Pressure (pound-force per square inch gauge)				
Dow/Filmtec XFRLE-400/34i	106	97	395	359
Hydranautics ESPA 2 LD	116	107	339	313
Permeate total dissolved solids (milligrams per liter)				
Dow/Filmtec XFRLE-400/34i	57	60	56	60
Hydranautics ESPA 2 LD	44	46	127	135
Permeate pH				
Dow/Filmtec XFRLE-400/34i	5.4	5.4	5.1	5.1
Hydranautics ESPA 2 LD	5.2	5.2	5.1	5.1

[a] Interstage pressure boost required to balance flux between first and second stage membranes.

Several observations can be made from a review of the data presented in Table 4-12.

1. First stage feed, interstage boost, and concentrate pressures for each operating scenario and membrane manufacturer are comparable. The largest variations occur during the worst-case water quality scenarios.
2. Permeate total dissolved solids is similar for each membrane at best-case water quality condition. At the worst-case water quality condition, the Hydranautics membranes demonstrate a significantly higher permeate total dissolved solids value than the other membrane evaluated.
3. Permeate pH is similar for each membrane evaluated. The low pH is a result of the dosing of sulfuric acid upstream of the RO membranes to reduce scaling potential. The sulfuric acid dose predicted by the membrane system computer models ranged between 36 and 52 milligrams per liter.

The data presented in Table 4-12 represent the range of operating conditions that can be expected using each of the membranes evaluated. The design engineer may use this information to size and select first stage feed and interstage boost pumps, and energy recovery equipment that will satisfy the operating requirements of multiple membrane manufacturers.

Hydraulic profiles

General considerations regarding hydraulic profiles were discussed in Chapter 3.1.3, and illustrated further as part of Example 1. Hydraulic profiles present a graphical summary of the hydraulic grade line along the process flow path. Important information provided by hydraulic profiles include raw water pressure, RO feed pump suction and discharge pressure, RO membrane feed, permeate, and concentrate pressure, and pressure losses within piping and across devices such as valves and filters.

Figure 4-8 presents the hydraulic profile for the membrane feed and permeate streams for the facility in Example 2.

While not provided as part of this example (provided in Example 1), a hydraulic profile for the concentrate stream may provide important information that may be used to select and size energy recovery equipment.

As demonstrated previously in Example 1, the hydraulic grade line values at the suction and discharge of the first stage feed pump determined during hydraulic modeling can be used to characterize the operating envelope of the pump. The operating envelope represents the expected range of operating conditions for the pump during all anticipated combinations of flow, feed water quality, installed membrane selection, and membrane fouling. The operating envelope for the first stage feed pumps for the facility modeled in Example 2 is presented in Figure 4-9.

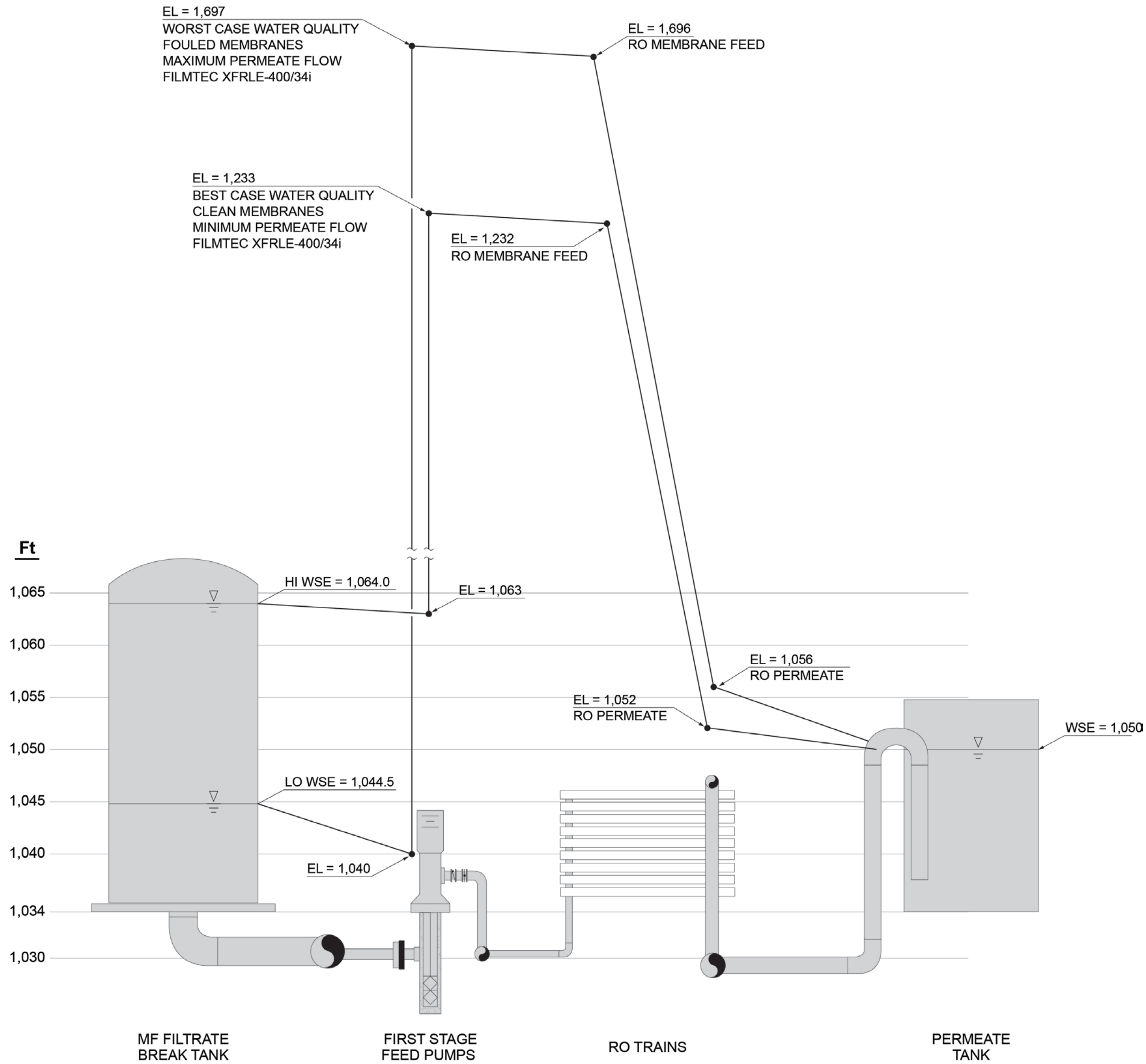

Figure 4-8. Example 2 hydraulic profile.

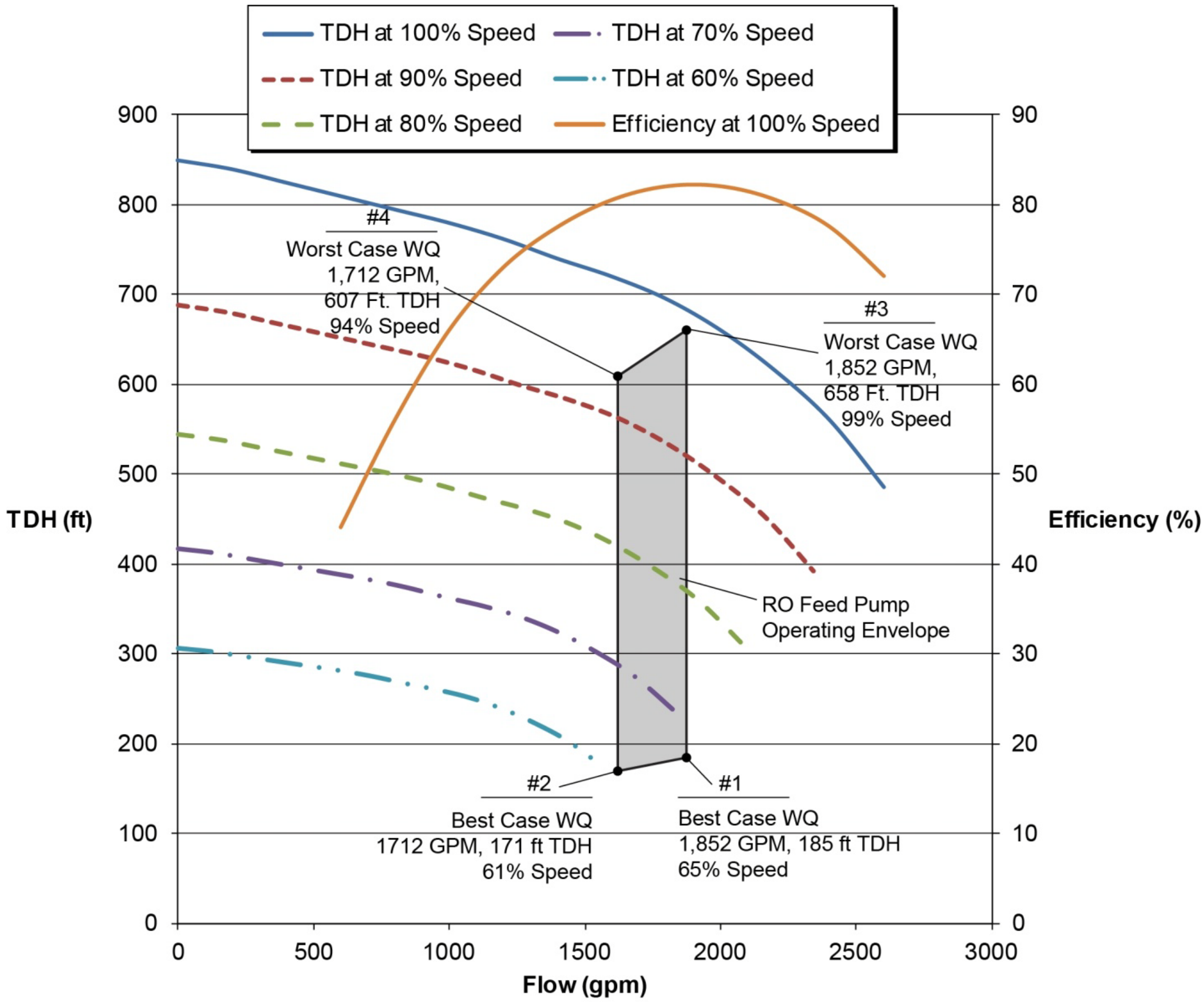

Figure 4-9. Reverse osmosis feed pump operating envelope.

Figure 4-9 presents the Pump Efficiency (%) vs Flow curve (at 100 percent pump speed), and Total Developed Head (TDH) vs. Flow curves for the specified first stage membrane feed pumps at several pump speeds. These pumps are equipped with variable frequency drives. These drives allow the pump speed to be automatically adjusted by the facility's programmable logic controller (PLC) to maintain a setpoint for a constant RO permeate flow from each train regardless of downstream conditions such as membrane selection, membrane fouling, or feed water quality.

Figure 4-9 indicates that the first stage RO feed pumps will operate at speed between 61 and 99 percent of maximum at all anticipated conditions of facility operation. A review of the efficiency vs. flow curve presented in Figure 4-9 shows that, when operated under the worst-case water quality and maximum permeate flow scenario, these pumps will provide maximum efficiency.

Similar to Example 1, the important data that must be provided from the membrane system computer model for the hydraulic profile of the facility includes (1) first stage membrane feed pressure, and (2) second stage membrane concentrate pressure.

Antiscalant selection and dosing

Similar to Example 1, the output from the membrane system computer models provided warnings that the concentration of barium sulfate, strontium sulfate, and calcium fluoride had exceeded their respective solubility limits in the reverse osmosis concentrate stream. An antiscalant is required to prevent precipitation of these constituents in the feed/concentrate stream, and subsequent membrane scaling.

A computer model developed by Avista Technologies was used to determine the performance of the selected antiscalant (Avista Vitec 3000). The results of the computer model indicate that an antiscalant dose of 2.0 milligrams per liter would be required to control membrane scaling based on the expected worst-case feed water chemistry at a recovery of 75 percent. Avista's software estimates that the saturation of these salts is at most 71 percent of the maximum recommended concentration when using their inhibitor at this dose. As such, a dose of 2.0 milligrams per liter with this antiscalant would be adequate to minimize scaling of the RO membranes.

Table 4-13 presents the concentration of each constituent of concern as a percentage relative to saturation in the reverse osmosis concentrate stream. Also listed in Table 4-13 are the allowable concentrations of each constituent when the selected antiscalant is used at the recommended dose in the reverse osmosis feed water.

Table 4-13. Example 2 – antiscalant performance summary.

Constituent	Concentration in reverse osmosis concentrate stream[a]	Concentration w/antiscalant[a,b]
Barium sulfate	6,450 percent	1 percent
Strontium sulfate	168 percent	8 percent
Calcium fluoride	210 percent	71 percent

[a] Relative to saturation.
[b] Results are based on performance projections for selected antiscalant (Avista Vitec 3000). Results may vary based upon selected antiscalant and dosage.

The design engineer should always consult with the antiscalant manufacturer (or their representative) when selecting an antiscalant and dose for a given application.

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6 Appendix A – Glossary

Anion: A negatively charged atom or molecule that forms when an atom acquires one or more extra electrons. Anions may be present in solids and in solution in water or other solvents.

Antiscalant: A chemical that inhibits or delays precipitation and subsequent scale formation of sparingly soluble inorganic salts and silica.

Brackish Water: Water having a mineral content in the range between fresh water and seawater. In water-desalting practice, brackish water is generally considered to be water containing 1,000 to 10,000 milligrams per liter of total dissolved solids.

Calcium Carbonate Precipitation Potential Index: An index that predicts the milligrams per liter of calcium carbonate (CaCO3) that should dissolve or precipitate with a particular water. The equation used to determine this index is:

$$CCPP = 50{,}000([Alk]_i - [Alk]_{eq})$$

Where:

CCPP = calcium carbonate precipitation potential, in milligrams per liter as $CaCO_3$

50,000 = a unit conversion factor

$[Alk]_i$ = measured total alkalinity of a given water, in milligrams per liter as $CaCO_3$

$[Alk]_{eq}$ = total alkalinity that the water would have in equilibrium, measured as milligrams per liter as CaCO3

A positive value indicates the degree of supersaturation. A negative value indicates the level below saturation.

Cation: A positively charged ion (e.g., H^+ or Zn^{2+}) or radical (as NH^{4+}) that migrates toward the cathode.

Concentrate: The concentrated solution containing constituents removed or separated from the feedwater by a membrane water treatment system. It is commonly in the form of a continuous flow stream. Concentrate is also called reject, brine, retentate, or blowdown, depending on the specific membrane process.

Concentration Polarization: In a membrane treatment process, the phenomenon in which retained solutes accumulate at the membrane surface in concentrations greater than the bulk stream.

Diffusion: A process whereby molecules or particles move and intermix because of a concentration gradient driving force; the movement of a compound within a medium or from one medium to another. For example, longitudinal diffusion refers to the movement of a compound in a conduit at a speed either faster or slower than the mean velocity of the solution, whereas boundary layer diffusion refers to the movement of a compound to or from a solution through a boundary layer surrounding a particulate medium. Molecular diffusion is quantified by Fick's law.

Feedwater: The water to be treated that is fed into a given water treatment system.

Flow Factor: Analogous to Fouling Factor.

Flux Rate: For a membrane separation process, the volume or mass of permeate passing through the membrane per unit area per unit time. Solvent (water) flux rate is commonly expressed in gallons per square foot per day, or cubic meters per square meter per second, or meters per second.

Fouling: In a membrane water treatment process, the deposition of material such as colloidal matter, microorganisms, and metal oxides on the membrane surface or in its pores, causing a change in membrane performance (e.g., flux decline).

Fouling Factor: Factor used by membrane system computer models to characterize the affects of membrane fouling and/or scaling.

Hydraulic Grade Line: A line (hydraulic profile) indicating the piezometric level of water at all points along a conduit, open channel, or stream. In a closed conduit under pressure, artesian aquifer, or groundwater basin, the line would join the elevations to which water would rise in pipes freely vented and under atmospheric pressure. In pipes under pressure, each point on the hydraulic profile is an elevation expressed as the sum of the height associated with the pipe elevation, the pipe pressure, and the velocity of the water in the pipe. In an open channel, the hydraulic grade line is the free water surface. Hydraulic profiles are commonly used to establish elevations through the processes that make up a treatment.

Hydraulic Profile: A visual representation of the hydraulic grade line at various points within a membrane treatment facility.

Ion: An atom that is electrically unstable because it has more or fewer electrons than protons. thus, it is an electrically charged particle. A positive ion is called a cation, and a negative ion is called an anion. In aqueous solution, ions may not actually exist as isolated charged atoms but tend to form a variety of hydrated complexes.

Langelier Saturation Index (LSI): A calculated value based on total dissolved solids, calcium concentration, total alkalinity, pH, and solution temperature. Indicates the tendency of a water solution to precipitate or dissolve calcium carbonate. Typically used for brackish waters having a total dissolved solids concentration below 10,000 milligrams per liter.

Mass Transfer Coefficient: A constant of proportionality that is specific to an individual compound and is used in a mass transfer expression to determine equilibrium conditions between two phases. Mass transfer coefficients are determined experimentally; the units will depend on the nature of the mathematical expression and the phase transfer. For membrane treatment processes, this coefficient quantifies the passage of dissolved salts (solutes) through a membrane.

Membrane: A natural or synthetic permselective material. Membranes used for water treatment are commonly synthetic organic polymers. In the case of pressure-driven membranes, the polymers are permeable to water (solvent) but reject solutes; for electrodialysis membranes, the polymers are permeable to ions but not to water.

Membrane Element: Flat sheet membranes and spacers formed into a spiral wound shape around a central permeate tube and wrapped in fiberglass or tape. One or more such membrane elements are placed inside pressure vessels for operation.

Membrane System Computer Model: A computer program, developed by a manufacturer of nanofiltration and/or reverse osmosis membranes, that is used to characterize the performance of a membrane system under a given set of operating conditions.

Nanofiltration: A pressure-driven membrane separation process that generally removes substances in the nanometer size range. Its separation capability is controlled by the diffusion rate of solutes through a membrane barrier and by sieving and is dependent on the membrane type. In potable water treatment, nanofiltration is typically used to remove nonvolatile organics larger than the 200–500-dalton molecular weight cutoff (e.g., natural and synthetic organics, color, disinfection by-product precursors) and multivalent inorganics (for softening).

Nephelometric Turbidity Units: A unit for expressing the cloudiness (turbidity) of a sample as measured by a nephelometric turbidimeter. A turbidity of 1 ntu is equivalent to the turbidity created by a 1:4,000 dilution of a stock solution of 5.0 milliliters of a 1.000-gram hydrazine sulfate ($(NH_2)_2 \cdot H_2SO_4$) in 100 milliliters of distilled water solution plus 5.0 milliliters of a 10.00-gram hexamethylenetetramine ($(CH_2)_6N_4$) in 100 milliliters of distilled water solution that has stood for 24 hours at 25 ± 3° Celsius.

Net Applied Pressure: In a pressure-driven membrane treatment system, the hydraulic pressure differential across the membrane minus the osmotic pressure differential across the membrane.

Net Positive Suction Head: A measure of the pressure at the suction side of the pump, including atmospheric pressure and vapor pressure of the liquid being pumped.

Net Positive Suction Head Available: Net positive suction head that is available at a given flow rate and for a given set of operating conditions. Should always be greater than the net positive suction head required to avoid pump cavitation.

Net Positive Suction Head Required: Minimum net positive suction head that must be available at the suction of a pump to avoid pump cavitation. Determined by pump manufacturer for a range of flows.

Osmosis: A natural phenomenon whereby water (or some other solvent) diffuses from the lower-concentration side to the higher-concentration side of a permselective (semipermeable) membrane barrier in a process of equalizing concentrations on both sides.

Osmotic Pressure: The pressure exerted on a solution as a result of osmosis. It is dependent on the molar concentration of the solutes and the temperature of the solution. An approximation of osmotic pressure for a natural water is 1 pound per square inch (6.9 kilopascals) per 100 milligrams per liter total dissolved solids. See also osmosis.

Permeability: A measure of the relative ease with which water flows through a porous material. A sponge is very permeable; concrete is much less permeable. Permeability is sometimes called perviousness.

Permeate: For a pressure-driven membrane treatment process, the portion of the feed solution that passes through the membrane. For potable water membrane treatment systems, the permeate is often referred to as the product flow stream.

Post-treatment: An additional treatment step following a primary treatment process, such as permeate post-treatment for corrosion control or disinfection following membrane desalting.

Precipitation: The process of particle formation during a chemical reaction.

Pressure Vessel: A device designed to contain pressure, such as a housing used for pressure filters or membranes.

Recovery: In a membrane water treatment system, the fraction of the feedwater that is converted to permeate, filtrate, or product.

Reverse Osmosis: A pressure-driven membrane separation process that removes ions, salts, and other dissolved solids and nonvolatile organics. The separation capability of the process is controlled by the diffusion rate of solutes through a membrane barrier and by sieving; it is dependent on the membrane type. In potable water treatment, reverse osmosis is typically used for desalting, specific ion removal, and natural and synthetic organics removal. It is no longer commonly called hyperfiltration.

Salt Passage: The ratio of concentration of a dissolved salt in the permeate divided by the concentration of the same dissolved salt in the feedwater. Generally expressed as a percentage.

Salt Rejection: In a pressure-driven membrane process, a measure of the membrane’s ability to retard or prevent passage of solutes and other contaminants through the membrane barrier.

Scale Inhibitor: See antiscalant.

Scaling: The deposition of scale on a surface. In the context of membrane treatment processes, the precipitation of inorganic salts on the feed-concentrate side of a membrane.

Semipermeable Membrane: A membrane used for separation of constituents in a fluid based on differences in one or more constituent properties, such as diffusion rate, solubility, electrical charge, or size and shape.

Silt Density Index (SDI): An empirical measure of the plugging characteristics of membrane feed water based on passing the water through a membrane filter test apparatus containing a 0.45-micrometer pore diameter filter (commonly a cellulosic type) in a dead-end filtration mode at a constant feed pressure (typically 30 pounds per square inch [207 kilopascals]) for a specified duration (15 minutes most common) and observing the flow rate decline. The silt density index is calculated based on the measured time required for collection of a 500-milliliter filtrate sample at the beginning of the test filtration period (t_i) and the time for collection of a 500-milliliter filtrate sample at a later time (t_f). For a test period T, the SDI value (which is dimensionless) is calculated as follows:

$$SDI_T = \frac{1 - \frac{t_i}{t_f}}{T} \; x \; 100$$

Where:

ti = initial time to collect 500-milliliter sample, in seconds
tf = final time to collect 500-milliliter sample, in seconds
T = filtration test period, in minutes

Stage: One of many steps in the operation of an evaporator, filter, compressor, or pump, each of which is operated at different conditions of pressure. Such a stage is also called an effect. For membrane treatment processes, a stage refers to a set of pressure vessels installed in parallel.

Stiff and Davis Stability Index (S&DSI): An index, generally applicable to waters with total **dissolved** solids greater than 10,000 milligrams per liter, that indicates whether a water is in equilibrium with calcium carbonate ($CaCO_3$).

S&DSI = $pH_a - pH_s$

Where:

pHa = the actual pH of the water
pHs = the pH of saturation, the pH of the water if it were saturated and at equilibrium with calcium carbonate
The pHs value is calculated based on the concentrations of calcium and alkalinity, as well as a specified constant that is dependent on ionic strength and temperature. Stiff-and-Davis stability index values greater than, less than, or equal to zero indicate the tendency of a water to deposit calcium carbonate, dissolve it, or be at equilibrium with it, respectively. They are used for scale-control calculations, such as for reverse osmosis membrane concentrate streams.

Telescoping: The movement of the membrane leaves of a spiral-wound membrane element in the direction of feedwater flow. Caused by excessive pressure drop across an element.

Total Dissolved Solids: The weight per unit volume of solids remaining after a sample has been filtered to remove suspended and colloidal solids. The solids passing the filter are evaporated to dryness. The filter pore diameter and evaporation temperature are frequently specified. Typically reported as milligrams per liter.

Train: An independent treatment process or group of processes in series. Commonly, multiple trains are placed in parallel in a treatment facility to subdivide the overall treatment capacity or for some other purpose. For nanofiltration and reverse osmosis applications, one of multiple individually controlled and operated membrane elements and pressure vessels. Multiple trains are arranged in parallel and subdivide the overall membrane treatment capacity into more than one segment.

Turbidity: (1) A condition in water caused by the presence of suspended matter, resulting in the scattering and absorption of light. (2) Any suspended solids that impart a visible haze or cloudiness to water and can be removed by treatment. (3) An analytical quantity, usually reported in nephelometric turbidity units, determined by measurements of light scattering. The turbidity in finished water is regulated by the US Environmental Protection Agency.

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7 Appendix B – Example 1 - Antiscalant Performance Projections

Avista Advisor

Project Details

Project:	Example 1 - Yr-20, 80 Percent Recovery
Permeate Flowrate:	6934.4USGPM This is split into 4 trains of 1733.6USGPM
System Recovery:	80%

Antiscalant Projection

The projection is based on the following feed water analysis. The adjusted feed is the analysis after pH correction, and any ions have been added to balance the analysis. The concentrate analysis has been manually input.

Ion	Feed Water	Adjusted Feed	Concentrate	
Sodium	946.60	946.60	2521.24	mg/l
Potassium	16.30	16.30	0.00	mg/l
Calcium	146.00	146.00	669.03	mg/l
Magnesium	153.00	153.00	509.10	mg/l
Iron	0.00	0.00	0.00	mg/l
Manganese	0.00	0.00	0.00	mg/l
Barium	0.06	0.06	0.25	mg/l
Strontium	25.80	25.80	128.81	mg/l
Aluminium	0.00	0.00	0.00	mg/l
Chloride	1840.00	1841.03	5246.24	mg/l
Sulfate	373.00	373.00	1343.05	mg/l
Bicarbonate	141.00	141.00	692.97	mg/l
Nitrate	0.10	0.10	0.48	mg/l
Fluoride	1.00	1.00	4.96	mg/l
Phosphate	0.00	0.00	0.00	mg/l
Silica	15.40	15.40	76.33	mg/l
CO2	4.41	4.41	4.56	mg/l
TDS		3659.29	11192.47	
pH	7.66	7.66	8.31	

Water Source: Well Water

Water Temperature: 29º C

Product Choice

Vitec Choice:	Vitec 3000
Dosage:	2.00mg/l
Usage:	207.78 lb per day.

There is one dosing pump and chemical tank per membrane train.
With 4 trains, each pump will deliver 4.99USGPD

Application

Dosed Solution Strength: 100%
Pump Rate: 19.95USGPD
52.47ml/m

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Avista Advisor

Project Details

Project: Example 1 - Yr-20, 80 Percent Recovery
Permeate Flowrate: 6934.4USGPM This is split into 4 trains of 1733.6USGPM
System Recovery: 80%

Scaling Potential.

Stiff and Davies Index (S&DI)

The reject stream has a S&DI of 1.85.
Vitec 3000 has a limit of 3.00

Calcium Carbonate Precipitation Potential (CCPP)

The concentrate has a CCPP of 237mg/l.
This is within the limits of Vitec 3000.

Calcium Sulfate

The concentrate has a calcium sulphate saturation of 39.10%.
This is within the limits of Vitec 3000.

Barium Sulfate

The concentrate has a barium sulphate saturation of 1239.82%.
This is within the limits of Vitec 3000.

Strontium Sulfate

The concentrate has a strontium sulphate saturation of 355.57%.
This is within the limits of Vitec 3000.

Calcium Fluoride

The concentrate has a calcium fluoride saturation of 623.99%.
This is within the limits of Vitec 3000.

Silica

The concentrate has a silica level of 76.33mg/l.
Silica has a solubility of 179.9mg/l at this temperature and brine pH.

Magnesium Hydroxide

The concentrate has a magnesium hydroxide saturation of 0.19%.

Calcium Phosphate

No phosphate was included in the feed water analysis.

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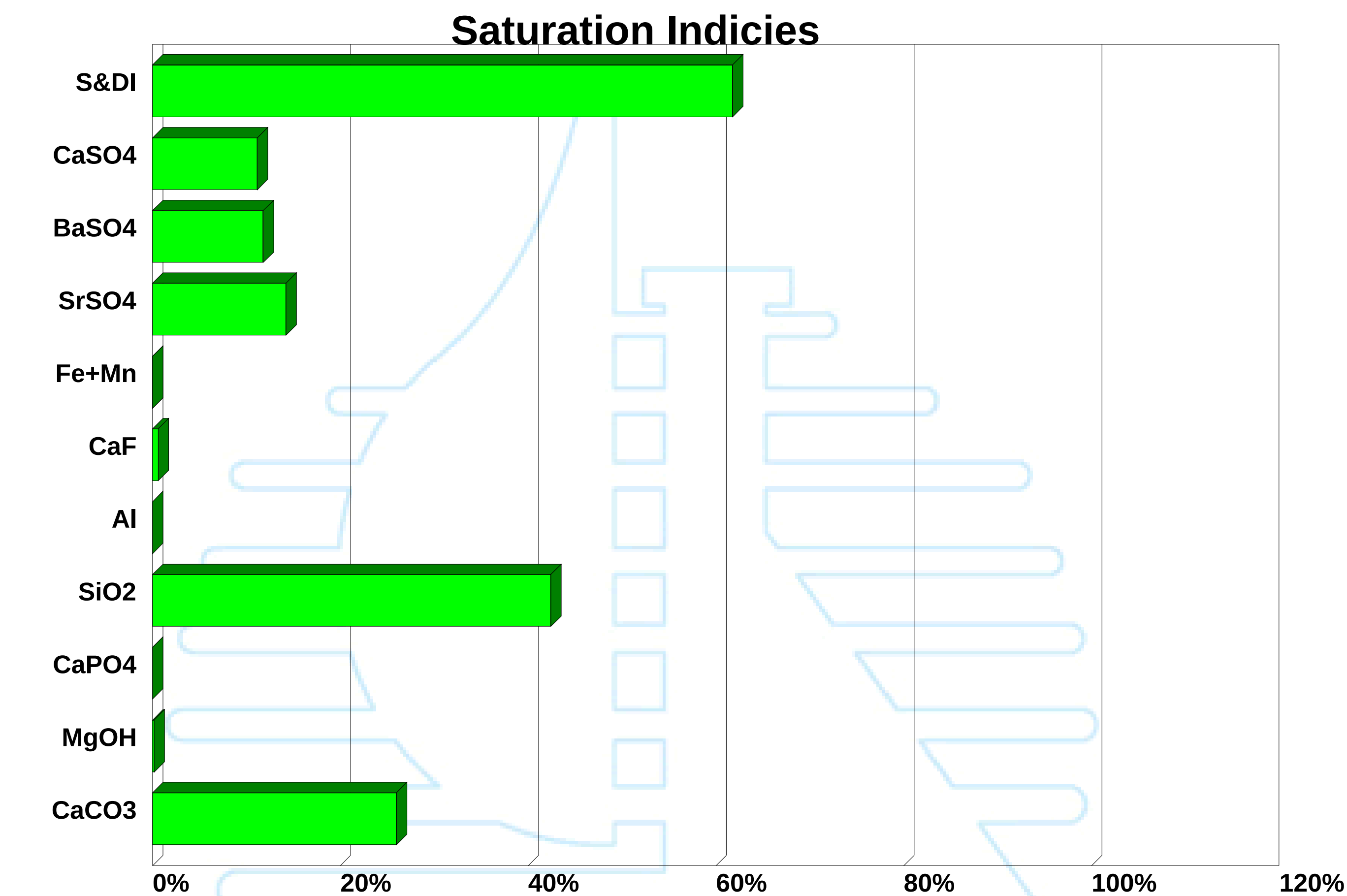
Avista Advisor

Project Details

Project: Example 1 - Yr-20, 80 Percent Recovery
Permeate Flowrate: 6934.4USGPM This is split into 4 trains of 1733.6USGPM
System Recovery: 80%



Product Choice

Vitec Choice: Vitec 3000
Dosage: 2.00mg/l
Usage: 207.78 lb per day.
There is one dosing pump and chemical tank per membrane train.
With 4 trains, each pump will deliver 4.99USGPD

Application

Dosed Solution Strength: 100%
Pump Rate: 19.95USGPD
52.47ml/m

8 Appendix C – Review Comments and Responses

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
Comments from TWDB	
Please include the contract number in the report.	Contract number included.
Please consider including snap shots of the computer models when referring to a specific component in the discussions.	Screen shots from two different computer models are provide in Figure 4.2 and Figure 4.7. The intent is provide examples of the general configuration used by computer models. Formats used by computer models are often updated by membrane manufacturers.
Please include the surface water desalination example in the final report.	The surface water example has been added as Example 2 in the Manual of Practice.
The manual is discusses the overall design process especially the hydraulics in greater detail in Component C. Please ensure to refer the reader to component A or B.	Reference to Component B (Case Studies Report) has been added at the end of Section 1.2 Purpose.
The component does not have an executive summary. As required for TWDB contract reports, please include an executive summary.	Discussed comment with TWDB. To provide consistency with other industry Manuals of Practice, TWDB has waived the requirement for an executive summary.
The component does not have sections on conclusions or recommendations. If appropriate, please consider including these sections.	Discussed comment with TWDB. To provide consistency with other industry Manuals of Practice, TWDB has waived the requirement for a recommendations/conclusions section.
Paragraph 2.1.1 – Introduction	
Page 4, second paragraph, third sentence: Please consider broadening the sentence to “Each of these models uses a friendly interface that walks the user step by step through the design process.” The sentence addresses only the graphic representation of the membrane train provided in the model.	Text revised accordingly.

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
Page 9, last paragraph: Please consider breaking up the Solubility and Recovery Determination subsection into two and making the beginning of the Recovery Determination subsection the last paragraph.	The solubility of sparingly soluble salts will limit the maximum recovery achievable using reverse osmosis to treat brackish groundwater. As such, these topics are closely related, and should be discussed together in the context of modeling principles.
Page 10, last paragraph: Please consider starting new subsection called Scale Inhibitors or name as seemed appropriate.	Scale inhibitors are not a scientific modeling principle. Their use may be recommended based on computer model analysis using the principles of solubility. As such, the placement of the scale inhibitor discussion is appropriate.
Page 12, last paragraph: Please consider moving or expanding on the paragraph which discusses how the computer models relate to all the detail on pressure. Potentially can move the Data Output section in 2.1.3. Similarly, on page 10, second to last paragraph, please consider expanding or moving to the above section.	There is an important interplay between RO treatment plant hydraulics and the membrane computer model pressure inputs/outputs. Refer to Examples 1 and 2 in the MOP for detailed discussions of these relationships.
Page 13, first paragraph, second sentence: Please consider specifying the computer models that use an adjustable input.	Such a list would be subject to change in the future as membrane manufacturers update and revise their modeling software. The intent is to direct the engineer to account for the pressure losses in the piping between the feed pump(s) and the membrane array.
Paragraph 2.1.5 – Design Limits and Warnings	
Page 13, last paragraph, second sentence: Please consider specifying the computer model.	Text has been revised to reference Hydranautics as an example of a membrane manufacturer that places limits on membrane feed water TOC, BOD, and COD.
Page 14, second paragraph, first sentence: Please consider removing the sentence and starting with "The Langlier Saturation Index…"	Text revised accordingly.
Page 14, second paragraph, second and third sentence: Please spell Langelier correctly.	Text revised accordingly.

<table>
<tr><th colspan="2">Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes</th></tr>
<tr><th>Comment</th><th>Response</th></tr>
<tr><td>Page 15, third paragraph: Please consider adding a graphic illustrating concentration polarization.</td><td>New figure created and added to report .</td></tr>
<tr><td colspan="2">Paragraph 3.1.1 – Water Quality</td></tr>
<tr><td>Page 17, section 3.1.1, last paragraph. Please change “affects” to “effects” in this paragraph.</td><td>Text revised accordingly.</td></tr>
<tr><td>Page 19, Figure 3.2: Please include the seasonal surface water quality graph in the final report.</td><td>Figure has been added.</td></tr>
<tr><td colspan="2">Comments from TCEQ</td></tr>
<tr><td>In general, we don’t see anything about how models are not perfect and that the professional engineer will need to provide a bit of a “safety factor” or “wiggle room” to allow for variability in the model. We know it’s a no brainer, but not every PE is familiar and we suggest a statement to plan for a safety factor would be a good idea.</td><td>Several pages of discussion are provided in Section 2.1.2 regarding the limitations of computer models, and the proper use of these models within the context of these limitations.

General discussions of safety factors are provided on pages 29, 47, and 50 (much of 1st paragraph). The MOP places emphasis on engineering judgment. Defining what the value of a safety factor should be for a particular situation is not the purpose of the MOP. Engineers use their judgment to apply factors of safety. It is left to the engineer to define where safety factors are applied - and their magnitude - based on specific circumstances.</td></tr>
</table>

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
Page 1, Section 1.1 – Revise to read as follows: The Texas Commission on Environmental Quality currently considers reverse osmosis as an “innovative” treatment method for the removal of drinking water contaminants from a groundwater source. This definition is the result of an absence of specific requirements in the Texas Commission on Environmental Quality rules that provides design, operation, maintenance, and reporting criteria for all treatment processes. Due to the status of brackish groundwater reverse osmosis as an innovative treatment method, any proposed new treatment facility requires the approval of an exception request by the Texas Commission on Environmental Quality prior to review of facility plans and specifications. The exception request approval letter establishes the treatment criteria. Title 30 Texas Administrative Code (30 TAC) Chapter 290.42(g) of the Texas Commission on Environmental Quality rules requires that a licensed professional engineer submit an exception request for a proposed brackish groundwater reverse osmosis treatment facility. In the past, an exception request included the requirement of pilot test data, or “data collected at similar full scale operations”, to substantiate that the produced water will meet the requirements of Title 30 Texas Administrative Code Chapter 290, Subchapter F: *Drinking Water Quality and Reporting Requirements for Public Water Systems*. Due to the current drought and water scarcity, the prompt commissioning of a new water source is critical. As a response to the need for timely process reviews during a drought period, the Texas Commission on Environmental Quality , based on stakeholder input, will allow the use of output data from computer modeling software programs in lieu of data obtained from on-site pilot testing to substantiate that the treatment process meets the drinking water rules and to grant an exception to use reverse osmosis.	The text in Section 1.1 was revised with the exception of the suggested third paragraph. The suggested third paragraph appeared to contain policy statements related to the revisions of TCEQ guidance documents. This information did not seem appropriate for the final MOP.

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
The revised TCEQ process allows approval of reverse osmosis for brackish water treatment under the current rules for innovative/alternate treatment in 30 TAC §290.42(g). The TCEQ determined that the computer models (with adequate supporting documentation) met the requirement for demonstrating that the reverse osmosis treatment will produce water that meets the drinking water quality standards specified in Subchapter F of Chapter 290. As an alternative to time consuming and complicated revision to the Chapter 290 Subchapter D rules, the new TCEQ guidance document (available on the TCEQ website at www.tceq.texas.gov/goto/desal) allows a streamlined path to demonstrate the effectiveness of reverse osmosis treatment for brackish groundwater treatment. The computer models investigated either did not model or did not model accurately the primary contaminants or pathogens, thus the computer models, at this time, can only be used for brackish groundwater.	
Page 3, Para.2 (and Page 31, Para. 3) – Can we give any guidance in regards to the engineering judgment is required to select appropriate fouling factor?	Text revised accordingly.
Page 3, last Para. – Can you provide more discussion on what makes “good” water quality data? You have a great discussion about using hydrogeology, which large systems will use, but we can see small systems needing guidance on what to use. How to know if the information they may already have (from other wells, or old data) is good enough and what to do if all they have is data that they aren’t quite sure of.	A discussion of minimum requirements for source water quality data for both large and small systems has been included at the end of this paragraph.
Page 4, Para. 2 (2nd bullet) – What do you mean by restrictive permeate quality? Is this permeate water quality that is better than can be demonstrated by modeling?	Text has been revised to clarify the meaning of “restrictive” permeate quality for industrial applications (such as ultrapure water for the semiconductor industry).

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
Page 4, last Para – It would be a good to include in the examples brackish water with no MCL issues.	The intent of this list is to present “parameters of concern” that may complicate selection between NF and RO membrane technology. TDS is listed.
Page 7, Para. 1 – Is leakage the right way to say this? Isn’t this just a byproduct of the ion exchange process?	The term “leakage” is an Ion Exchange industry-accepted term that refers to the passage of target ions (such as calcium and magnesium cations) through an ion exchange bed. Leakage directly affects the ion exchange effluent water quality. A high degree of leakage is often the result of inefficient resin bed regeneration.
Page 9, Para. 3 – How does the selection of a fouling factor affect the diffusion rate made in the model?	The fouling/flow factor is an adjustment to membrane water permeability only. This factor does not make adjustments to salt passage/diffusion.
Page 9, Para. 4 – Temperature is not in the solubility product equation (Eq. 2.1) yet it is specific for a given temperature. Please explain.	A discussion of the solubility product’s dependence on temperature is not suited for the material presented in the Manual of Practice. The temperature dependence of the solubility product is related to the changes in free energy and enthalpy associated with equilibrium. A number of references are available that discuss this topic. One such reference is *Chemistry for Environmental Engineering and Science (Fifth Ed.)* by Sawyer, McCarty, and Parkin.

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
Page 9, last Para. – It says that single elements can only get 15% for brackish water. We have seen small water systems use a single element (or 2 elements) and achieve 70 to 85% recovery. The source water was over 1500 TDS. Are you saying that single element systems can only achieve 15% recovery?	Statement has been revised to include the qualification for 8-inch membranes. Statement included to state that the design engineer "should consult the membrane manufacture's recommendations regarding maximum recovery for specific membrane elements." Also, please note the difference between element and system recoveries. A single element may only achieve 15% recovery, but single-element system may be designed with recycle loops (for example) to achieve higher recoveries.
Page 10, Table 2.2 – What about the French Creek Software?	A brief discussion of third-party water chemistry software packages has been added to the text.
Page 11, Para. 3 (No 5) – We recommend clarifying that the losses in item 5 are frictional losses.	Text revised to read "Friction losses in the feed piping…"
Page 11, Para. 5 (Eq 2.2) – Specify the units of conversion. Left side of the equation is in psi, and the right side is in mg/L.	Equation 2.2 is a "rule of thumb" approximation accepted by the desalination industry in estimating the osmotic pressure of brackish water (TDS < 12,000 ppm). Performing dimensional analysis on the mathematical approximation presented in Equation 2.2 would be inappropriate, as the units are unequal.
Page 14, last paragraph (Para. 5) – This seems like a vague description of a scenario that may, or may not, be a system that is under designed.	This scenario was presented only as an example of a situation where sea water membrane may be a better selection than brackish water membranes based on the feed pressure limits associated with the membrane type. A clarification was added to define high TDS feed water as exceeding 10,000 ppm.

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
Page 15, Para. 5 – So, a minimum feed flow of 35 to 40 gpm equates to a Beta less than 1.20 for an 8-inch module? The logic is not clear with respect to why a minimum feed flow of 35 to 40 gpm is inversely proportional to a Beta of 1.18 to 1.2. Where does the 35 to 40 gpm come from?	Additional information explaining the concept of concentration polarization, along with a graphic depicting the process, has been added to the text. The recommended minimum feed flow values for 8-inch elements are manufacturer's standard recommendations to keep Beta below 1.18 to 1.20. These values will vary based on specific project conditions.
Page 16, Para. 2 (Membrane Element Recovery) – How does concentrate recycling increase recovery? Perhaps, additional explanations of these five options can be provided in Section 3 – Methods.	The design engineer should refer to the references for detailed explanations regarding how each of the five methods listed affect membrane element recovery. A statement to this regard has been added to the text.
Page 17, last Para. – Please define or explain "upconing".	Explanation of upconing (with reference) has been added to text.
Page 20, Para. 2 (Quality Control) – We would substitute 'analysis' for 'reporting' in the description of the lab errors. These are mistakes in lab methodology.	Text revised accordingly.
Page 20, Para. 2 (Quality Control) – We would suggest including a NELAP accredited laboratory for drinking water parameters.	TCEQ website link: http://www.tceq.texas.gov/field/qa/env_lab_accreditation.html
Page 21, Para. 1 – Though true that TCEQ requires 35 psi at 1.5 gpm/con when a system wants to apply to use pumps and emergency generators instead of elevated storage, we do not have a similar requirement for systems designed with elevated storage. The rules simply state that the system must maintain 35 psi normally and 20 psi during emergency events and no flows are mentioned.	Text revised accordingly.
Page 25, Figure 3.3 – Could you consider adding an example from a simpler system, like a one-pass RO for a small BGW system?	Smaller/simpler systems (i.e., single stage, no cartridge filters, no degasification, etc.) will still require a hydraulic profile, only with fewer components. The intent of the examples selected was to show the most likely scenarios for large-scale membrane facilities.

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
Page 29, Para 3 – You suggest using a specific software model. We know at TCEQ we can never recommend a specific brand or company, we are not sure if the TWDB has the same requirements.	A disclaimer page with language provided by TWDB was added to the beginning of the report.
Page 30, Para 2 – (Train Size and Number, Bullet 3) – Since this is a guide for Texas, you may want to include that Texas does not require redundant trains (at this time).	Text revised accordingly.
Page 30, Para. 2 (Train Size and Number, bullet 4) – Where do the electrical constraints come from in sizing the first stage feed pumps?	Electrical constraints on pump size/voltage are more relevant for plant rehabilitation/expansion projects where there is existing electrical infrastructure. Text revised accordingly.
Page 30, Equation 3.6 – We would recommend using the equations out of the US EPA Membrane Guidance Document.	Equation 2.1 does not have a counterpart in the references, but is based on accepted principals of inorganic chemistry. Equation 2.2 does not have a counterpart in the references, but is based on industry accepted “rules of thumb” for feed water TDS within the stated range. Equation 2.3 is from EPA Membrane Guidance Document Equation 2.18, and AWWA Manual of Water Supply Practices M46 Equation 2-5 (note). Equation presentation has been modified to suit discussion in text. Equation 2.4 was taken from Hydranautics publication *Terms and Equations of Reverse Osmosis*, January 23, 2001. Equation 3.3 has been adapted from standard texts on fluid mechanics – simplified to facilitate understanding and utility by reader.

Component C – Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes	
Comment	**Response**
	Equation 3.4 is the same as Equation 10-23 from Hydraulic Institute Standard ANSI/HI 9.6.1, 2012 Equation 3.5 was derived from Equation 2.1 of the EPA Membrane Guidance Document – rearranged to solve for membrane area. Equations 3.6, 3.7, 4.1, and 4.2 do not have counterparts in the references. They are provided here as a convenience to the reader. Equations 3.1, 3.2, 4.1 and 4.2 are based on simple mass balance principles.
Page 32, Fouling factor – We would suggest more discussion of the fouling factor.	A detailed discussion of fouling factors and their appropriate use is provided in Chapter 2. Reference to this Chapter is provided.
Page 32, Flux Balancing – We think this whole section is excellent.	Acknowledged. Thank-you.
Page 35, Para 2 (Energy Recovery) – Provide a better explanation for the isobarice energy recovery? The direct contact between the concentrate and feed streams requires more explanation.	An excellent, detailed discussion of isobaric energy recovery technology, and the associated feed/concentrate stream mixing phenomenon can be found in the AMTA conference proceedings reference. Reference added to this section.
Page 36, 4.2.1 Model Input – It might be useful to reference that the ion summation method is discussed on page 20, Quality Control.	Reference to discussion of ion summation method in Chapter 3 has been added.
Page 43, Para. 1 – We recommend you discuss why the system picked 400 mg/L TDS as its goal.	This goal of 400 milligrams per liter for total dissolved solids was set by the owner in order to provide a generous margin respective to the secondary maximum contaminant level of 500 milligrams per liter. Text revised accordingly.

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Comment	**Response**
Page 47, Antiscalant Selection and Dosing – The software selected 2.0 mg/L as the appropriate dosage. Based on the estimated 15% of the allowable manufacturer's maximum recommended concentration, this seems like a very conservative choice. Is this selection based on a safety factor, or just to reduce the frequency of cleaning intervals, or something else?	A dose of 2.00 milligrams per liter represents the minimum recommended dose for the Avista product. In this case, the minimum dose was governed by the requirement to achieve a 10 milligram per liter concentration of scale inhibitor in the concentrate stream. Text revised accordingly.
Page 48 – If you need help locating a SW RO plant, please let us know.	Acknowledged. The City of Wichita Falls has generously provided water quality data for their surface water RO facility. This data serves as the basis for Example 2 in Chapter 4.
Appendix A – Glossary – Where available, it would be great if you could use the US EPA definitions for these terms (40 CFR 141.2) or TCEQ definitions (30 TAC 290.38)	Definitions in glossary have been revised to include definitions from 30 TAC 290.38, and the AWWA Drinking Water Dictionary where appropriate.
Avista Advisor – If possible please include Nitrate is as N or as Nitrate. We have seen this cause confusion with other models that have been submitted.	Text revised accordingly.

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