Texas Water Development Board

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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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Part II. Performance Evaluation of Reverse Osmosis Membrane Computer Models

Final Report

by
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1 Executive summary

Under the current Texas Administrative Code, membranes (both low-pressure and desalting) are considered “innovative technologies.” To implement membrane treatment for drinking water, pilot testing is required for approval by the Texas Commission on Environmental Quality. In many cases, demonstration-scale pilot testing is a costly and time-consuming approach to achieve regulatory approval of reverse osmosis/nanofiltration membrane systems particularly for smaller water treatment systems.

The use of software-based computer models is an alternative method for predicting membrane performance. Semi-empirical calibrated computer models are available at no cost and are used frequently by engineers and manufactures to assist in the design of membrane water treatment plants.

This study investigated the accuracy and precision of computer models provided by six different reverse osmosis membrane manufacturers. The accuracy analysis compared the computer model performance projections with the observed performance of seven full-scale membrane facilities. The accuracy of each computer model was the degree to which the computer model performance projections matched the observed membrane system performance at facility start-up. The precision analysis compared the performance projections from computer models provided by multiple membrane manufacturers for similar membranes and operating conditions. The precision analysis was based on observed operating conditions at two full-scale facilities, and water quality data from one undeveloped brackish groundwater aquifer located in Texas.

The error associated with the accuracy of computer models in predicting membrane feed pressures ranged from an under-prediction of 7.4 percent to an over-prediction of 31.3 percent. Salt rejections were generally over-predicted by the computer models. The degree of error varied from 0.1 to 5.9 percent. Accuracy of the model is likely influenced by manufacturer specific safety factors and the feed water quality data provided by the model user. Over prediction of membrane feed pressure provides for greater reliability, particularly where it affects the hydraulic design of pumps used to supply pressure and flow to the system.

The precision of the computer models was greatest for first stage feed pressure (-11.8 to 16.8 percent relative difference) and salt rejection (-1.5 to 2.7 percent relative difference), and lowest for membrane system concentrate pressures (-23 to 21.5 percent relative difference). The precision for rejections of calcium (-0.6 to 1.3 percent relative difference) and sulfate (-0.6 to 0.6 percent relative difference) was the greatest among the individual ions, while the precision for bicarbonate (-25.3 to 13.6 percent relative difference) was the lowest. The low degree of precision in predicting bicarbonate rejection was likely due to the different methods used by each computer model to calculate the speciation of the carbonate system.

The statistical analysis performed using conductivity measurements from permeate samples taken from parallel pressure vessels at several full-scale plants demonstrated that the error associated with the computer models is not expected to be exceeded by the variability in performance observed in the field due to membrane manufacturing processes.

In summary, the overall accuracy and precision demonstrated by the computer models evaluated as part of this study were within a reasonable level of expectation considering the limited amount of the start-up data available. The level of accuracy for first stage feed pressures was sufficient to facilitate a conservative selection of a first stage feed pump. The level of accuracy for rejection of most ion constituents and total dissolved solids was within the expected range considering the limited amount of start-up feed and permeate water quality data. Computer model accuracy was comparable to the accuracy provided by the results of a pilot study for the one full-scale facility for which pilot test data was available. Another pilot study evaluation demonstrated the similarity of performance provided by pilot testing and computer models in predicting the performance of a full-scale reverse osmosis membrane system. Computer models created to predict the performance of two different membranes used during single-element pilot tests demonstrated a sufficient degree of accuracy to validate the use of computer models in predicting the performance of a full-scale membrane system.

The precision demonstrated by the computer models was, in most cases, sufficient to facilitate the design of a membrane system to accommodate similar membranes from multiple membrane manufacturers.

This study also demonstrated the need for a manual of practice for the use of computer models in predicting the performance of reverse osmosis membrane systems. The computer models used in this evaluation incorporated different methods of accounting for factors such as anion-cation balancing of feed water, affects of membrane aging on salt passage and feed pressure, and interstage pressure losses. When these factors are fully understood and accounted for by the user, computer models are capable of providing accurate predictions of membrane performance, and convergence among the predictions generated by different computer models using similar membranes and feed water quality can be achieved.

Even though differences between models exist, this study demonstrated that they can predict the performance of a membrane system with an acceptable degree of accuracy precision when they are used properly. A standard manual of practice would help to ensure a consistent level of input data quality, an understanding by the user of the similarities and differences between the different models available, and the appropriate interpretation of the output generated by these models.

2 Introduction

2.1 Background

Development of alternative and new water resources is critical to sustainable growth of the State of Texas, and the use of reliable membrane water treatment systems will likely play an important role in developing these sustainable sources. Unfortunately, misconceptions about membrane technologies exist in part by regulators, decision makers, and the general public, which have affected the industry by limiting the growth of application of membranes for water treatment (Mickley, 2001). Under the current Texas Administrative Code, membranes (both low-pressure and desalting) are considered "innovative technologies" and to implement membrane treatment for drinking water, at the time this study was commissioned, pilot testing was required for approval by the Texas Commission on Environmental Quality. In many cases, the use of demonstration-scale pilot testing is a costly and time-consuming approach to achieve regulatory approval of reverse osmosis/nanofiltration membrane systems, particularly for smaller water treatment systems. To help facilitate a more rapid and less costly approach to approval of reverse osmosis/nanofiltration membrane systems, alternative regulatory and testing approaches were evaluated in *Part I. Alternatives to Pilot Plant Studies for Membrane Technologies*.

The least costly alternative method for predicting membrane performance is the use of software-based computer models. Semi-empirical calibrated computer models are available at no cost and are used frequently by engineers and manufactures to assist in the design of membrane water treatment plants. The model algorithms are proprietary and as a result are not disclosed to the public; however, the theoretical concepts and equations used as the basis of the model are detailed in water treatment texts (Howe *et al*., 2012). To understand the predictive value of these computer models, the model projections will be compared to full-scale performance.

2.2 Project goals

The purpose of this project is to develop a guidance document with a more efficient pathway to safely achieve regulatory approval for membrane systems used to treat brackish groundwater in the State of Texas. The goals are to (1) perform a review of evaluation methods for predicting full-scale membrane and operating performance, (2) analyze model, pilot, and full-scale data to validate and establish accuracy values for predicting actual performance using computer models, and (3) prepare a manual of practice for the appropriate use of computer models for predicting the performance of reverse osmosis membrane systems.

2.3 Pilot testing alternatives evaluation objectives

The second phase of this project is to assess a pilot-testing alternative for desalting membranes treating brackish groundwater. Several methods of predicting membrane performance were identified in the literature review. These methods include computer models, bench-scale membrane testing, single-element pilot testing, and demonstration-scale pilot testing. Based on the literature review and engineering practice, the recommended method is the use of computer models as a predictive tool for system performance when designing a membrane desalination plant. To achieve the objective of this project – to assess pilot testing alternatives – these computer models were evaluated to determine their usefulness at predicting the hydraulic and water quality performance of a full-scale membrane system when compared to the conventional, demonstration-scale pilot testing methodology currently required by Texas Commission on Environmental Quality. This analysis includes the following steps:

1. Acquire computer model output, pilot test data, and full-scale plant data from various membrane manufactures for several reverse osmosis facilities treating brackish groundwater.
2. Analyze and compare the output of membrane system computer models to pilot and actual plant data with respect to water quality and operating parameters. The goal of this analysis is to characterize the accuracy of available computer models.
3. Analyze and compare the output of the six membrane system computer models using comparable membranes. The goal of this analysis is to characterize the precision of available computer models.

The methodology of analyzing the differences between computer models and pilot or full-scale data (Chapter 3) begins with a justification of computer model selection and analytical design. Then key model parameters such as feed water quality and pressure losses that have an impact on feed pressure determination and ion rejections are addressed. The data matrix is summarized in terms of recovery, membrane type, vessel array, and total dissolved solids concentration. The chapter concludes with a description of how the accuracy and precision analysis of model, pilot, and full-scale data was performed.

The results and discussion (Chapter 4) presents an analysis of the accuracy and precision of the computer models used to predict the performance of various membrane types included in the data collection effort (such as, general brackish, fouling resistant, and low energy). Each accuracy analysis discusses the membrane system, assumptions made to complete the analysis, and the membrane performance comparison between the model and full-scale system. The precision analysis presents the precision of the six models to simulate the membrane performance at a single data point. The results of an evaluation that compared the performance of pilot testing to computer model projections is presented for one brackish water facility where pilot test and full-scale data was available, and one brackish groundwater aquifer where only pilot test data was available.

The conclusions (Chapter 5) present the data spread on operating pressures and salt rejections identified as part of the accuracy and precision analysis, and include a summary discussion of the findings of the study.

3 Methodology

3.1 Analytical design

The intent of the analytical design was to compare predicted membrane performance to full-scale performance in desalination plants using computer models. Resulting comparisons are divided into two sections: accuracy and precision. The accuracy analysis compares model or pilot data to actual full-scale performance. The outcome of the analysis was an accuracy measurement of operating pressure and ion rejections for each case study. The analysis was completed for several case studies to achieve the primary outcome, which was to demonstrate the capacity of computer models to predict full-scale performance. The precision analysis compares membrane performance among the various membrane manufactures. Input data representing full-scale plant operation was entered to the corresponding manufacture's computer model and compared to the computer models of similar membrane elements treating identical source water. The output of the models provided a method of measuring the precision that may be achieved among computer models offered by the different membrane manufacturers using comparable membrane elements.

3.2 Selection of reverse osmosis membrane computer models

Commercial membrane system computer models were selected from six membrane manufacturers that represent the majority of installed reverse osmosis membrane systems nationwide. Prior to 2013, Dow Water & Process Solutions, Toray, and Hydranautics encompassed about 95 percent of all municipal installations within the United States. These three major industry players plus an additional three manufacturers account for more than 98 percent of the domestic municipal desalination membrane market. Table 3-1 lists the computer models selected according to membrane manufacturer, with website links to download each model.

Table 3-1. List of reverse osmosis membrane computer models.

Computer model	Manufacture name	Website link
ROSA 8.0.3	Dow	http://www.dowwaterandprocess.com/support_training/design_tools/rosa.htm
Winflows 3.1.2	GE	http://www.gewater.com/winflows.jsp
Toray Design System 2 2.0.1.26	Toray	https://ap8.toray.co.jp/toraywater/
KMS ROPRO 8.05	KOCH	http://www.kochmembrane.com/Resources/ROPRO-Software.aspx
CSMPRO 4.1	CSM	http://www.csmfilter.com/
IMSdesign 2011.19	Hydranautics	http://www.membranes.com/index.php?pagename=imsdesign

3.3 Model Input Parameters

Operating parameters used with the computer models were selected to facilitate the comparison of known pilot-scale and full-scale performance (such as, operating pressures and water quality) to the output of the computer models. The following is a summary of the types of parameters that can affect model calculations that predict the performance of a membrane desalination system:

- *Feed water quality*. For constant permeate flows, higher raw water total dissolved solids concentrations and lower temperatures both result in higher feed pressures. At constant permeate flows and feed water recoveries, the permeate quality is influenced by both raw water mineral content and temperature.
- *Pressure losses*. Pressure losses associated with flow through valves, pipefittings and piping in general all affect the pressure available to push water through an reverse osmosis membrane. Elevation changes from the feed pump to the membrane train also affect the discharge pressure required by the membrane feed pumps. Each of the available computer models has a different method for accounting for these types of losses.
- *Permeate backpressure*. The friction losses through the permeate piping system and elevation change from the membrane train to any downstream processes (that is, degasification tower) needs to be accounted for in the membrane model because the feed pump must also work against this permeate backpressure to produce the desired permeate flow rate.
- *Membrane characteristics*. Membrane manufacturers offer general brackish water, fouling resistant, and low energy membrane elements. The membrane element selection will vary based upon the design engineer's objectives. Typically, salt rejection goals and energy consumption are key factors that must be considered. Computer models can also predict differences in operating conditions based upon membrane age and fouling.
- *Hydraulic operating conditions*. Permeate flow (that is, flux) and recovery rates can affect the feed pressure and permeate quality of a membrane system. Similarly, some membrane system designers choose to implement flux balancing techniques that help distribute the permeate production between stages of a multi-stage membrane system. Computer modeling of a membrane system should be performed to closely simulate the installed conditions. Permeate flow rate (flux), recovery, interstage booster pump pressure, and permeate back pressure are all tools that should be used by the design engineer to simulate the full-scale production.

It is important to consider that the model output can only be as accurate as the information provided to it. Table 3-2 summarizes these key model input parameters that are subsequently discussed in greater detail.

3.3.1 *Feed Water Quality Data*

The various computer models have similar user interfaces for inputting feed water quality data. There are two steps to establish the feed water quality:

1. *Input source water classification.* For the purposes of this study, the water source or water type is limited to brackish water; however, brackish water is also identified in the models as well water, brackish well water, and well water with a silt density index less than 3. In the computer models, the source water classification is linked with guidelines and warnings that include limits for salt saturation, flux, and concentrate flow rate.
2. *Input the source water quality data*. Table 3-3 lists ions common among the six software models. The element iron is an input in all the programs except in the ROSA model. Winflows and KMS ROPRO also allow the user to specify manganese concentrations. Other ions such as bromide and phosphate can also be entered in feed water quality for the Winflows and TorayDS programs. In addition, hydrogen sulfide can be entered for Winflows and IMSdesign models.

The mineral data required by the computer models constitute the major cations and anions found in natural waters. The validity of the analytical data entered into the software model and the subsequent mineral scaling (solubility) calculations used to determine the maximum recovery that can be achieved, both depend on the accuracy of these inputs.

Because of the importance of carbonate chemistry in determining appropriate pretreatment and recovery limits, computer models require the user to define the concentration of the various carbonate species, which is both pH and temperature dependent. However, the entry and methods used to determine of the concentration of carbonate species (such as, $CO_2/HCO_3^-/CO_3^{2-}$) vary based upon the computer model used:

- ROSA, Toray DS2, CSMPRO, and IMSdesign require the user to input pH, temperature, and concentration of bicarbonate. Using this information, the model calculates the concentrations of carbonate and carbon dioxide.
- Winflows requires the user to enter pH, temperature, and the total alkalinity as calcium carbonate. The concentrations of bicarbonate, carbonate, and carbon dioxide are subsequently determined by calculation.
- KMS ROPRO allows the user to enter pH, temperature, bicarbonate, and carbonate concentrations, but the user can also enter the P-alkalinity or M-alkalinity, where P-alkalinity is the amount of carbonate and hydroxyl alkalinity present and M-alkalinity (also known as total alkalinity) is the amount of bicarbonate, carbonate, and hydroxide present in the water. When the user enters the bicarbonate and carbonate value, the pH value is recalculated, and the model provides the user with a warning stating the pH will be adjusted.

Table 3-2. Summary of model inputs for key parameters.

Parameter	Carbonate system				Ion balance	Pressure losses			Pressure control		Membrane characteristics				
Software	**Alkalinity**	**HCO3**	**CO3**	**CO2**	**Sodium /chloride**	**Pre - stage[a]**	**Inter- stage 1[b]**	**Inter- stage 2[b]**	**Permeate back- pressure[c]**	**Interstage boost**	**Type (element model)**	**Age**	**Flow factor**	**Flux decline**	**Salt passage increase**
ROSA	_	U	E	E	U4	U	E	_	U	U	U	_	U[h]	_	_
Winflows	U	E	E	E	U	_	U	U	U	U	U	U	_	U	U
Toray DS2	_	U	E	E	U[e]	U	U	U	U	U	U	U	U[h]	_	U
KMS ROPRO	U	U	U	_	_	_	U	U	U	U	U	U	_	U	_
CSMPRO	_	U	E	E	U[f]	_	E	_	U	U	U	U	_	U	U
IMSdesign	_	U	E	E	U	_	E	_	U	U	U	U	U[h]	U	U

U=User specified E=Embedded

[a]Pressure losses associated with flow of water through check valves, open butterfly valves, pipe fittings and pipe friction from the pump discharge to the reverse osmosis train. It may also include elevation changes between the pump discharge and the reverse osmosis train in some cases.
[b]Pressure losses associated with flow of water through valves, piping fittings and friction losses between stages of the reverse osmosis train.
[c]Pressure within the permeate piping at the reverse osmosis train. This may include losses associated with flow through check valves, open butterfly valves, pipe fittings and pipe friction. It may also include positive elevation changes such as degasification towers as well as any pressure losses resulting from spray nozzles within the degasification tower.
[d]Adjust by Cations, Anions, all Ions
[e]Adust by $MgS0_4$
[f]User can add Na, Cl, NaCl (adjust both ion concentrations)
[g]Auto Balance but program completes with Na or Cl
[h]Fouling allowance as a decimal factor less than 1.00

Table 3-3. List of water quality parameters required by computer models.

Cations	Anions	General
• Ca^{+2}	• Cl^{-}	• pH
• Mg^{+2}	• SO_4^{-2}	• Temperature
• Na^{+}	• $CO_2/HCO_3^{-}/CO_3^{-2}$	
• K^{+}	• NO_3^{-}	
• Ba^{+2}	• F^{-}	
• Sr^{+2}	• B^{+3} (see note a)	
• NH_4^{+}	• SiO_2	

[a] Boron is present in groundwater as boric acid, H_3BO_3. While boron, as an element, is a cation with a valence of +3, it appears in groundwater combined with the anionic functional group (BO_3^{-3}) of boric acid. It is therefore listed among the anions by the membrane computer models.

The computer models can also be used to determine if the field data collected was analyzed and reported appropriately. Because the various computer models require the user to input the major cations and anions commonly found in natural waters, the sum of the equivalent concentrations of cations and anions should be equal (that is, Σ cations (milliequivalent per liter) = Σ anions (milliequivalent per liter)). If the sum of the cations and anions are not approximately equal, the data should be reviewed and possibly reanalyzed. Generally, a difference in equivalent concentrations of cations compared to anions greater than 5 percent is considered significant. Adjustments to the user-supplied feed water chemistry can be made if determined appropriate by the computer model user. These adjustments can be seen in the output reports where the raw or feed water quality is different from the input feed water quality. Most available computer models allow the user to balance ions through the addition of sodium and/or chloride although options do vary:

- In the project information input tab within the ROSA model, the user can select the preferred salt for balancing from sodium chloride, calcium chloride, and calcium sulfate. Then in the feed water data input tab ROSA allows the user to specify how to perform the balance by adding individual ions, adjusting cations, adjusting anions, or adjusting all ions as shown in Figure 3-1.
- Winflows allows the user either to add sodium, or chloride, or to automatically balance. If the user selects automatic balance, the program balances by adding either sodium or chloride.
- Toray DS2 provides the user two options to balance with sodium chloride or magnesium sulfate. For example, when the user selects sodium chloride the program adds either sodium or chloride depending on if the water is deficient in cations or anions.
- KMS ROPRO does not have a feature to automatically balance cations and anions, but it shows a charge balance chart that can assist the user while the user manually balances the feed water.
- CSMPRO allows the user to balance by adding sodium, chloride, and sodium chloride. If the user balances with sodium chloride, the software adjusts both ions concentrations by reducing one and increasing the other.
- IMSdesign allows the user to balance automatically, but not to choose the ions that are added.

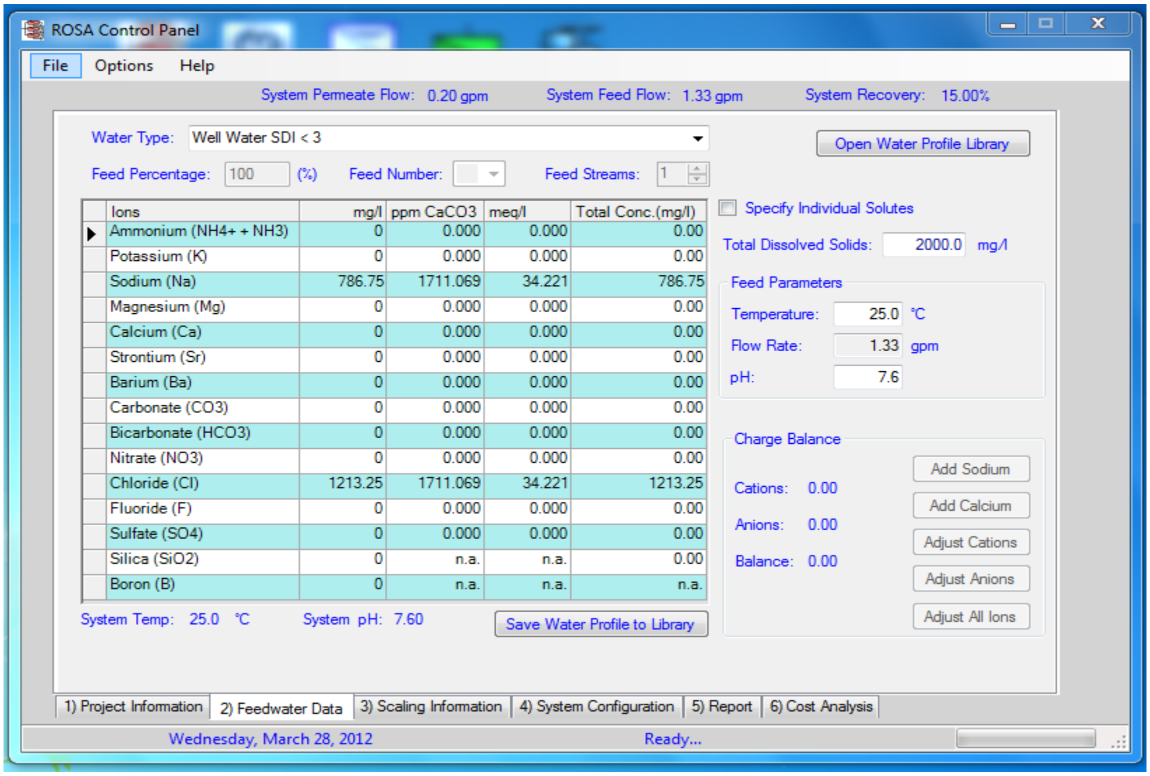

Figure 3-1. **ROSA model feed water data interface.**

3.3.2 *Pressure losses*

Pressure losses within system piping must be considered to accurately compare computer model output with pilot scale and full-scale operating data. These pressure losses may be the result of water flow through check valves, open butterfly valves, pipefittings and piping sections. Most of the models allow the user to input the magnitude of pressure loss based upon (separately) calculated conditions. However, a few models do not allow the user to specify the amount of pressure losses, but, rather, the pressure losses are embedded in the model. Nomenclature for pressure loss input may vary from one software model to another. The following is a summary of options available for each model:

- The ROSA model allows the user to change the amount of pressure loss from the default of 5 pounds per square inch in the project information interface. The pressure loss is called "Pre-stage ΔP" and must be greater than zero. The input value for "Pre-stage ΔP" is used in two locations: 1) between the feed pump discharge and first stage element, and 2) between the subsequent stages of the membrane array. The limitation of this software is that the "Pre-stage ΔP" is considered by the model to be the same for these two locations and cannot be separated to more accurately represent the losses that may be different. The output reports generated by ROSA do not indicate or display the input value for pressure losses, but the values are represented in the system pressures (that is, feed and concentrate) shown.
- The Winflows model refers to pressure losses as "inter-stage pressure loss." The software allows the user to input a value for pressure loss in each stage of the membrane system's

array in the "Reverse Osmosis Element Data" interface as shown in Figure 3-2. No losses can be entered by the user to account for losses between the membrane feed pump and the first stage. Therefore, if the user enters a pressure loss in stage 1, the loss occurs between stages 1 and 2. The output report refers to the pressure loss differently with a name of "Pre-stage Pressure Change Drop."

- The KMS ROPRO model refers to pressure loss as "inter-bank pressure loss" and the output reports the loss as manifold loss.
- The Toray DS2 model refers to the pressure losses as "inter-banking piping loss" in the computer model data input tabs, and as "piping loss" in the report. Pressure losses for KMS ROPRO and Toray DS2 occur in same two locations in similar manner as Winflows.
- CSMPRO and IMSdesign do not allow the user to specify the amount or location of the pressure loss but rather embeds the loss in the programs. The pressure loss is a fixed inter-stage loss between stages 1 and 2. The assumed value of this interstage pressure loss is 5 pounds per square inch for both models. The output reports of both models do not reference the pressure losses.

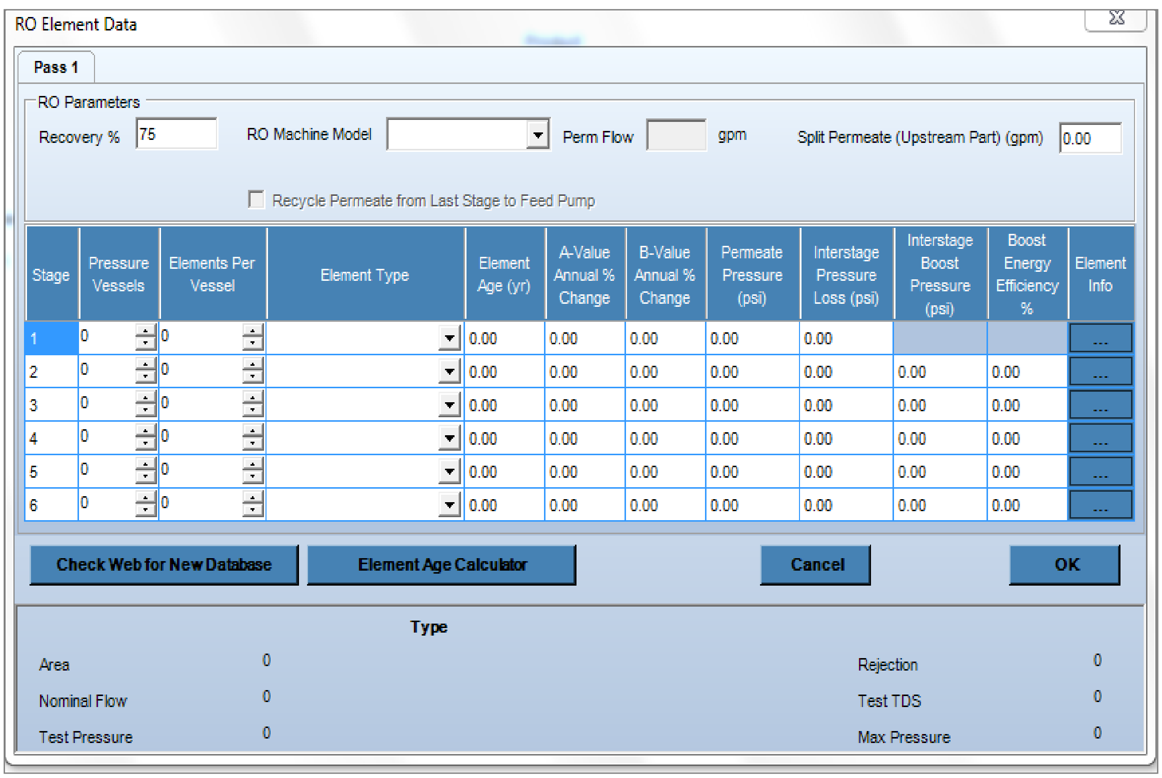

Figure 3-2. Winflows system configuration program interface.

3.3.3 *Permeate backpressure*

It is important to consider that the output generated by a membrane system computer model needs to account for pressure losses in the permeate stream. To produce the required permeate flow rate from the membrane system, the feed pump that supplies raw water to the membrane train must supply enough pressure to overcome friction losses in the raw water piping and membrane system, the friction losses through the membrane itself, the osmotic pressure associated with the salinity of the feed water, and the friction losses and elevation changes associated with moving the permeate water from the membrane train to the downstream treatment processes (that is, degasification towers).

To compare computer model output to pilot scale and full-scale data, it is important to account for the permeate backpressure that is representative of the installed condition. The various computer models each allow the user to enter a permeate backpressure for the entire train or to enter a backpressure specific to an individual stage. If data is available (such as, existing membrane treatment facility), actual permeate backpressure values should be input for the expected range of operating conditions. If real data is not available, (such as, membrane facility design), permeate backpressure should be calculated to a reasonable degree of accuracy using accepted hydraulic modeling (such as, calculation) methods.

3.3.4 *Membrane characteristics*

There are a variety of membrane element characteristics that may influence the results of a comparison between computer modeling output and full-scale, installed conditions. These include:

- Membrane material
- Feed spacer thickness – 26, 28 and 34 mil spacers are common. New low differential pressure elements use 34 mil feed spacers.
- Effective membrane area – for 8-inch diameter elements, 400 and 440 square feet elements are most common.
- Rated salt rejection
- Membrane age or fouling condition – fouling may increase or decrease salt rejection, and increase the pressure required to produce a given permeate flow rate from the membrane element.

With the exception of membrane age or fouling condition, each of these parameters is specific to the membrane element used. To facilitate comparisons with pilot and full-scale systems the same membrane element should be selected by the user in the computer model. It should be noted that membrane elements are a commodity product and manufacturers offer comparable membranes with similar characteristics. Therefore, it is possible to design a system to use more than one membrane manufacturer’s product. Comparisons may also be made by comparing computer model performance projections from one manufacturer to performance data available for a different manufacturer’s installed membrane system.

As a membrane system is operated, over time certain operating conditions may result in a deterioration of membrane performance. Examples of such deterioration are:

- Fouling will decrease water permeability, and may increase or decrease salt passage, depending on the nature of the fouling
- Exposure to cleaning chemicals and abrasive particles may decrease the salt rejection (such as, increase salt passage)
- Increased pressure loss through the membrane itself (such as, decreased membrane permeability)
- Increased pressure loss as water flows through the feed channels of the membrane elements

It is important to note here that time by itself has no impact on membrane performance. It is the combination of time and the exposure of the membrane elements to fouling conditions, cleaning chemicals, hydraulic forces, and abrasive particles that results in a deterioration in the performance of a membrane system that is often observed as the membranes age. Each membrane system is unique and as such, the design engineer should use sound engineering judgment when determining appropriate factors to use in the computer model(s) to simulate the affects of aging.

For some groundwater reverse osmosis plants, it is also possible that the membrane system may operate for years with no fouling or change in the original membrane properties. Each case is unique and the design engineer should evaluate a range of conditions to ensure that the required quantity and quality of water produced over the plant's membrane life can be met on a reliable basis.

Membrane system computer models simulate the effects of membrane aging by:

- Adjusting the water permeability, and
- Adjusting the salt passage.

All six computer models are able to simulate aging effects on the membrane water permeability and only four models (Winflows, Toray DS2, CSMPRO, IMSdesign) simulate changes to salt passage. Nomenclature varies with each computer model, but in general, the following terms are used by the models:

- Membrane age, flow factor, fouling allowance, and annual flux decline [1]are used to describe water permeability through the membrane.
- Salt passage increase (expressed as a percent increase per year) is used to describe the increase in membrane salt passage.

New membranes are indicated by a flow factor of one (or an age of zero), and where available, a salt passage increase of zero percent. As membranes age, the flow factor is decreased (or age increased) and the salt passage may be increased. The following is a summary of how each computer model differs in its handling of membrane aging:

---

[1] Annual flux decline, as used by the computer models, represents a decline in specific flux (also referred to as water permeability). That is, membrane flux normalized for temperature and pressure, expressed as gallons per square foot per day per pound per square inch.

- The KMS ROPRO model requires the user to input an annual fouling allowance and the membrane age in years. When the membrane age value increases, the model calculates the decrease in permeability (such as, increase in pressure to maintain the same flow) or salt passage increase by multiplying the membrane age by the annual fouling allowance and percent salt passage increase to obtain feed pressure and permeate quality for the aged membrane system.
- In the ROSA software, a membrane age parameter is not available. The user can; however, change the “flow factor” to simulate aging effects on water permeability. Selection of the flow factor is subjective, but Dow recommends a flow factor from 0.75 to 0.85 for three-year-old membranes. Dow’s fouling allowance does not affect the salt passage calculation. It only affects the determination of pressure required to maintain the desired flow rate.
- In the Winflows model, the user can specify the element age and the “A” and “B” annual percent change values, where A-value is flux decline and B-value is scale increase. The user also has the option to enter the A- and B-values as a factor value and not a percent, which then does not require the membrane age. Additional to the age and A-value percent indicated by the user, an internal exponential factor changes the A-value by maximum of 10 percent. Under the help menu, the user can click design guidelines and find recommended A- and B-values for different source waters. For brackish well water, the suggested A- and B-values are three and five percent, respectively.
- For CSMPRO, the user can enter the membrane age, annual flux decline (percent per year), and annual salt passage increase (percent per year). The model calculates the total percent change in flux and salt passage and simulates the effects. Similarly, the Toray DS2 model requires the user to enter the element age, salt passage increase (percent per year), and fouling allowance (as a decimal, similar to Dow’s “flow factor”).
- IMSdesign model allows the user to input the membrane age, fouling factor (similar to Dow’s “flow factor”), annual flux decline (percent change per year), and annual salt passage increase (percent change per year). Once the user specifies a membrane age greater than zero the model calculates the flux and rejection decline, which is reflected by an increase in pressure and salt passage. Additionally, the user has the option to model water permeability effects without having to input a membrane age greater than zero by inputting only a fouling factor.

3.3.5 *Hydrodynamics and permeate flux*

When comparing the results of computer models to pilot and full-scale data, from a standpoint of both accuracy and precision, all conditions were evaluated at the same flux (that is, permeate flow) and recovery. The overall, stage 1 and stage 2 flux rates of the actual plant were matched in the models.

In the precision analyses, an equivalent membrane was selected from each manufacture to match the membrane in the system of the plant being assessed. The designated equivalent membrane may not have had the same surface area, but for the majority the areas were the same. When a selected equivalent membrane from another manufacture had a different surface area, the permeate flows were scaled by the ratio of areas in the elements of comparison (example, 400 square feet and 440 square feet). While permeate flux was matched, cross flow velocity differed between two membranes where larger surface area membrane elements had higher cross flow velocities.

3.4 Analytical matrix for accuracy and precision

A total of ten model and full-scale data sets were collected, including one pilot test, as shown in Table 3-4. The water treatment plants are located in Texas, Florida, Arizona, Maryland, Kentucky and Kansas. Water quality (mineral) analyses are available for four of the data sets. The total dissolved solids concentrations for all feed water data sets ranges from 450 to 2,860 milligrams per liters. All water treatment plants have a reverse osmosis design of two stages with 75 to 85 percent recovery.

The data sets can be categorized by membrane type, recovery, and total dissolved solids concentration. All membrane designs evaluated in this research used brackish water reverse osmosis membranes, which were further classified as fouling-resistant, low-energy (or low-pressure), or general brackish water membranes.

3.5 Analysis

The objective of this research was to characterize the accuracy of commercial reverse osmosis computer model projections compared to full-scale performance, as well to characterize the precision of computer models for similar membranes from different manufacturers. All tasks consisted of creating models and comparing the output data to full-scale data (accuracy) and the output data of other models (precision). The following subsections detail the procedure for each analysis.

3.5.1 *Accuracy procedure*

Prior to beginning the modeling procedure, the computer model used to design the existing full-scale water treatment plant (referred to as the projection model or design projection model in this report) was duplicated using the current computer model (which, generally, is a newer version than the original model). Output reports of both models, old and new, were reviewed and compared. Start-up data was actual plant data at startup (membrane age zero), collected in the initial days of operation. The data generally included the total permeate flow, first and second stage permeate flows, pressures, and conductivities or total dissolved solids concentrations. Start-up data for the water treatment plants was either a time-series or a single point. The data was also differentiated between measured and calculated parameters (example, total dissolved solids calculated from conductivity).

When start-up time series data was available, the data was reviewed for variation over the testing period by plotting total permeate flow versus time and identifying and removing any outliers. The 50th percentile flow as well as the high-point and low-point were selected to replicate using the models. The maximum and minimum flow rates were also identified and modeled in an attempt to characterize accuracy over the entire envelope of operating conditions. However, the high and low points may represent unsteady state conditions during reverse osmosis operation transition (example, adjusting a pump or valve). Computer models simulate steady state events with steady state conditions; thus, simulation of extreme flow events may or may not be an appropriate comparison. Once the modeling points were chosen, the design inputs of start-up such as feed water quality, flows, recovery, and pressures were entered into the model.

Table 3-4. Full-scale reverse osmosis plants.

Membrane characteristic	Project name	State	Feed total dissolved solids (milligram per liter)	Recovery (percent)	Stage 1 (PVxE)	Stage 2 (PVxE)	Water quality data	Full scale data	Pilot data	Computer model	Membrane
General brackish	Eastern Correctional Institute Reverse Osmosis	MD	1,250	80	10x6	5x6	-	Yes	-	Toray	TM720-400
General brackish	Goldsworthy WRD	CA	1,774	80	42x7	24x7	-	Yes	-	CSM	RE8040-BE
Fouling resistant	Scottsdale	AZ	1,287	85	13x7	7x7	Yes	Yes	-	CSM	RE16040-Fen
Low energy	Clay Center	KS	1,426	75	12x6	6x6	-	Yes	-	Rosa	XLE-440
Low energy	Hardinsburg	KY	453	80	14x7	7x7	Yes	Yes	-	Hydranautics	ESPA1/2
Low energy	Kay Bailey Hutchison Start-Up	TX	1,458	83	48x7	24x7	Yes	Yes	-	Hydranautics	ESPA1
Low energy	Kay Bailey Hutchison 5-Year	TX	2,646	83	48x7	24x7	Yes	Yes	-	Hydranautics	ESPA1
Low energy	North Lee County	FL	2,861	80	38x7	18x7	Yes	Yes	Yes	Rosa	LE-440i

[a] PVxE = Number of pressure vessels and number of elements per vessel.

Feed water data

Entering data from the feed water analysis was the first step in creating each condition that was modeled. The feed water quality information used to create the original design computer models did not exactly represent actual startup conditions. Additionally, a full set of feed water quality was typically not available as part of a start-up data set. If comprehensive startup water quality data was not available, the ion concentrations from the original design model of each project were used and proportionally adjusted to represent known startup conditions. Total dissolved solids concentration (a characterization of salinity) was a common water quality parameter provided in the form of (1) concentration measurements or (2) conductivity. Depending on whether startup total dissolved solids or conductivity data was provided, two different approaches were used:

1. When startup data provided analytically determined total dissolved solids concentrations, then the following steps were performed:
    a. A salinity ratio was calculated by dividing the analytically determined total dissolved solids of the startup by the original model total dissolved solids.
    b. The ion concentrations for the original model were proportionally adjusted by multiplying each ion concentration by the salinity ratio.
2. When startup data provided only conductivity data, the following steps were completed:
    a. Water quality data used as a basis of design was entered into the appropriate computer model, and raw water, permeate water total dissolved solids, and conductivity values were calculated by the model.
    b. A "total dissolved solids/conductivity factor" was then calculated by dividing the model total dissolved solids by the model conductivity (example, (1,500 milligrams per liter) / (2,727 microsiemens per centimeter) = 0.55 milligrams per liter per microsiemens per centimeter.
    c. Next, the startup data raw water and permeate conductivity was multiplied by the total dissolved solids /conductivity factor to estimate start-up total dissolved solids concentrations based on conductivity.
    d. A "salinity ratio" was calculated by dividing the total dissolved solids of the startup by the original model total dissolved solids.
    e. Original design model ion concentrations were adjusted proportionally by multiplying each ion concentration by the salinity ratio.

It is important to note that, even though the best available data representing full-scale start-up conditions was used, the conversion of feed water conductivity to total dissolved solids represents an introduction of systematic error into the accuracy and precision analysis. Total dissolved solids values derived from conductivity measurements are subject to the following sources of error:

- While most dissolved anions and cations show a strong capacity to carry electrical current, this capacity is diminished at higher concentrations
- Some ionic constituents, such as ammonia, show a relatively low current carrying capacity relative to their concentrations.

- The relationship between conductivity and concentration varies with temperature and concentration

For both approaches, temperature and pH were matched for each start-up modeling point as the temperature in a given day/hour maybe different for each point. If the original design model projections indicated the addition of acid to adjust the pH, the adjustment was also performed in the startup model simulation. Adjustment of the feed water pH can be performed in all membrane system computer models by indicating the target pH. The model automatically calculates the chemical dose required to achieve the target pH.

System configuration

To determinate the accuracy of the computer models when compared to the full-scale installations, data representing full-scale operating conditions was entered into each model. These conditions (parameters) included:

- Permeate flow
- Recovery
- Membrane element model
- Number of pressure vessels and elements per pressure vessel
- Number of pressure vessel stages within the membrane array
- Pressure losses through feed water and interstage piping
- Total permeate backpressure
- Any permeate throttling or interstage booster pump pressures used to balance permeate flux within the membrane array

After the system configuration data shown above was entered into each computer model, an output report from each model was generated and reviewed.

Each computer model was iteratively revised (calibrated) by adjusting throttling and/or boost pressures to exactly match the permeate flux in stages 1 and 2 of the full-scale plant. If permeate flux balance between stages at the full-scale plant was managed by permeate throttling, the second stage permeate backpressure was fixed and the first stage permeate backpressure was adjusted. In cases where flux balance at the full-scale plant was managed by an interstage boost pump, permeate backpressure for both stages was fixed and the interstage pressure boost was adjusted.

An example of a report produced by the IMSdesign computer model is shown in Figure 3-3.

Hydranautics Membrane Solutions Design Software, v. 2011 10/15/2012

Permeate THROTTLING(VARIABLE)

RO program licensed to:	EEM		
Calculation created by:	EEM		
Project name:	KHB Plant - Train 1-7/28/07-3:00 PM	Permeate flow:	1002.00 gpm
HP Pump flow:	1419.3 gpm	Raw water flow:	1419.3 gpm
Feed pressure:	101.8 psi	Permeate recovery:	70.6 %
Feedwater Temperature:	25.0 C(77F)		
Feed water pH:	7.30	Element age:	0.0 years
Chem dose, ppm (100%):	0.0 H2SO4	Flux decline % per year:	7.0
		Fouling Factor	1.00
		Salt passage increase, %/yr:	10.0
Average flux rate:	7.2 gfd	Feed type:	Well Water

Stage	Perm. Flow gpm	Flow/Vessel Feed gpm	Flow/Vessel Conc gpm	Flux gfd	Beta	Conc.&Throt. Pressures psi	Conc.&Throt. Pressures psi	Element Type	Elem. No.	Array
1-1	773.0	29.6	13.5	8.3	1.09	88.9	28.6	ESPA1	336	48x7
1-2	229.0	26.9	17.4	4.9	1.03	72.5	4.0	ESPA1	168	24x7

	Raw water		Feed water		Permeate		Concentrate	
Ion	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3
Ca	111.9	279.1	111.9	279.1	2.859	7.1	373.7	932.0
Mg	30.3	124.7	30.3	124.7	0.774	3.2	101.2	416.5
Na	558.0	1213.0	558.0	1213.0	66.621	144.8	1738.0	3778.2
K	10.4	13.3	10.4	13.3	1.517	1.9	31.7	40.7
NH4	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
Ba	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
Sr	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
CO3	0.2	0.3	0.2	0.3	0.000	0.0	0.6	1.1
HCO3	101.9	83.5	101.9	83.5	34.550	28.3	263.6	216.1
SO4	102.5	106.8	102.5	106.8	3.179	3.3	341.0	355.2
Cl	1019.5	1437.9	1019.5	1437.9	88.581	124.9	3255.0	4590.9
F	0.5	1.3	0.5	1.3	0.115	0.3	1.4	3.7
NO3	0.3	0.2	0.3	0.2	0.265	0.2	0.4	0.3
B	0.00		0.00		0.000		0.00	
SiO2	0.0		0.0		0.00		0.0	
CO2	7.43		7.43		7.43		7.43	
TDS	1935.5		1935.5		198.5		6106.7	
pH	7.30		7.30		6.85		7.74	

	Raw water	Feed water	Concentrate
CaSO4 / Ksp * 100:	2%	2%	9%
SrSO4 / Ksp * 100:	0%	0%	0%
BaSO4 / Ksp * 100:	0%	0%	0%
SiO2 saturation:	0%	0%	0%
Langelier Saturation Index	-0.27	-0.27	1.07
Stiff & Davis Saturation Index	-0.29	-0.29	0.79
Ionic strength	0.04	0.04	0.12
Osmotic pressure	20.2 psi	20.2 psi	63.6 psi

(a)

Hydranautics Membrane Solutions Design Software, v. 2011 10/15/2012

Permeate THROTTLING(VARIABLE)

RO program licensed to:	EEM		
Calculation created by:	EEM		
Project name:	KHB Plant - Train 1-7/28/07-3:00 PM	Permeate flow:	1002.00 gpm
HP Pump flow:	1419.3 gpm	Raw water flow:	1419.3 gpm
Feed pressure:	101.8 psi	Permeate recovery:	70.6 %
Feedwater Temperature:	25.0 C(77F)		
Feed water pH:	7.30	Element age:	0.0 years
Chem dose, ppm (100%):	0.0 H2SO4	Flux decline % per year:	7.0
		Fouling Factor	1.00
		Salt passage increase, %/yr:	10.0
Average flux rate:	7.2 gfd	Feed type:	Well Water

Stage	Perm. Flow gpm	Flow/Vessel Feed gpm	Flow/Vessel Conc gpm	Flux gfd	Beta	Conc.&Throt. Pressures psi	Conc.&Throt. Pressures psi	Perm. TDS	Element Type	Elem. No.	Array
1-1	773.0	29.6	13.5	8.3	1.09	88.9	28.6	112.4	ESPA1	336	48x7
1-2	229.0	26.9	17.4	4.9	1.03	72.5	4.0	465.3	ESPA1	168	24x7

Stg	Elem no.	Feed pres psi	Pres drop psi	Perm flow gpm	Perm Flux gfd	Beta	Perm sal TDS	Conc osm pres	Concentrate saturation levels CaSO4	SrSO4	BaSO4	SiO2	Lang.
1-1	1	101.8	2.9	3.2	11.6	1.11	45.6	22.6	2	0	0	0	-0.1
1-1	2	98.9	2.4	2.9	10.5	1.10	52.8	25.4	3	0	0	0	0.0
1-1	3	96.5	2.0	2.6	9.3	1.10	61.1	28.4	3	0	0	0	0.1
1-1	4	94.4	1.7	2.3	8.2	1.10	71.1	31.8	3	0	0	0	0.3
1-1	5	92.7	1.5	2.0	7.1	1.11	83.0	35.3	4	0	0	0	0.4
1-1	6	91.2	1.3	1.7	5.9	1.10	97.3	39.0	5	0	0	0	0.5
1-1	7	89.9	1.1	1.4	4.9	1.09	114.3	42.6	5	0	0	0	0.6
1-2	1	85.8	2.6	2.4	8.6	1.09	120.2	48.0	6	0	0	0	0.8
1-2	2	83.2	2.3	1.9	6.8	1.07	129.6	51.7	6	0	0	0	0.9
1-2	3	81.0	2.1	1.5	5.5	1.06	141.2	55.1	7	0	0	0	0.9
1-2	4	78.9	1.9	1.2	4.4	1.05	154.9	58.1	7	0	0	0	1.0
1-2	5	77.0	1.7	0.9	3.4	1.04	169.8	60.5	8	0	0	0	1.0
1-2	6	75.3	1.6	0.7	2.6	1.03	185.7	62.4	8	0	0	0	1.1
1-2	7	73.6	1.6	0.5	1.9	1.03	202.4	63.8	9	0	0	0	1.1

Stage	NDP psi
1-1	37.4
1-2	26.9

(b)

Figure 3-3. Output report produced by the IMSdesign computer model.

3.5.2 *Precision procedure*

The purpose of the precision analysis was to compare the output of various computer models using comparable membrane products offered by different manufacturers. Therefore, membrane selection was an important factor for the precision analysis. A list of 8-inch diameter reverse osmosis and nanofiltration membranes was compiled from the six manufacturers' membrane specifications. The table inputs included the following:

- Membrane type (that is, general brackish water, fouling resistant, and low energy)
- Surface area
- Permeate flow
- Nominal stabilized salt rejection

Similarly, the standard testing conditions for the membranes were collected and the following values were listed:

- Solution composition and concentration
- Feed pressure
- pH
- Temperature
- Recovery

Equivalent membranes for each of the other five manufactures were selected for the precision evaluation in three steps.

1. The compiled membrane property data table was used to characterize the installed membrane based on flux, area, and testing standard conditions.
2. An industry cross-reference guide was used to identify industry-recognized equivalent membranes offered by the five other manufacturers. Various cross-reference guides are available on the internet. These guides are offered by industry vendors and manufactures such as Siemens and Dow (Siemens, 2012 and Dow, 2012). Dow's reverse osmosis cross reference tool allows the user to select the manufacturer, size, type, and product name of a membrane and in return, the tool provides membrane equivalents offered by Dow.
3. Finally, membrane manufacturers were contacted to verify if the equivalent membrane selection was correct, and if not, to ask for their suggestion regarding an equivalent membrane.

At times, the membrane selected as "nearest equivalent" had a smaller surface area since a direct equivalent was not offered. Instead of removing that membrane from the comparison, the flow was adjusted by the ratio of the membrane areas to maintain equivalent flux, which is proportional to permeate quality.

Once the membranes were selected and permeate flows adjusted as required, the feed water quality was entered into the computer model and ion concentrations were balanced to achieve electro-neutrality. Pressure losses associated with the membrane system piping were closely matched among the six membrane manufacturers. Similar to the accuracy analysis, the interstage boost pressure or first stage permeate backpressure was iteratively adjusted until the model flux matched the full-scale plant flux for stage 1 and stage 2. The median permeate flow rate for each case study was used for the model projections.

3.5.3 *Pilot Test Data Comparison*

Pilot test data was provided for one facility (North Lee County, Florida) represented in the computer model accuracy evaluation. This pilot test data facilitated comparisons between:

- Demonstration-scale pilot testing and full-scale plant operation
- Pilot testing and reverse osmosis computer model projections

Additionally, data from a pilot study (San Antonio Water System) using a brackish groundwater supply was evaluated to facilitate comparisons between:

- Demonstration-scale pilot testing and reverse osmosis computer model projections
- Single-element pilot testing and reverse osmosis computer model projections

Results from this evaluation are presented in Chapter 4.

4 Results and discussion

4.1 Accuracy

Accuracy is the degree to which the model predicts the full-scale plant performance. Quantification of this accuracy was presented as percent error between the model and full-scale data (hydraulics and water quality). Percent error was calculated by taking the difference between the model and actual data and dividing by the actual data. A positive percent error indicated an over-prediction by the model, while a negative value indicated under-prediction.

4.1.1 *Membrane characteristic: general brackish water*

Eastern Correctional Institute, Westover, Maryland

The Eastern Correction Institute is a reverse osmosis treatment plant located in Westover, Maryland. This facility was constructed in 2010 to treat brackish groundwater. The facility is equipped with three reverse osmosis trains that are constructed in a two-stage array consisting of ten pressure vessels in the first stage, and five vessels in the second stage. Each pressure vessel contains six membrane elements. Each train is operated to produce a permeate flow rate of 308 gallons per minute at a recovery of 80 percent. The installed membrane is the Toray TM720-400, which has a nominal membrane area of 400 square feet, and a rated permeate flow and nominal salt rejection of 10,200 gallons per day and 99.7 percent, respectively.

For this accuracy analysis, the following data was used:

- Water quality data taken from the original computer model projections. This data was collected during the design of this facility.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected during the start-up of Trains A and B. This data was provided by the reverse osmosis system supplier. Data for Train C was not

available. Because this data represented start-up conditions, a fouling factor value of 1.0 (no fouling) was assumed.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- A complete set of analytically determined feed water quality data representing start-up conditions was not available for the project. A pH of 8.5 was assumed, based on output data from the original (design) computer model. Feed water total dissolved solids was estimated based on a conductivity-to- total dissolved solids conversion factor derived from the original computer model's output data.
- The basis for the feed water quality data used in the original computer model is unknown. This data may not be fully representative of the feed water that was delivered to the system during start-up.
- Feed water quality data required adjustment in the computer models using sodium chloride to achieve an electrical balance between cations and anions.
- Information regarding permeate backpressure for individual stages was not provided.
- Data for total permeate conductivity representing start-up conditions was not provided. First and second stage permeate conductivities were provided and used to calculate the total permeate conductivity which was used to determine permeate total dissolved solids based on a total dissolved solids -to-conductivity conversion factor.

A comparison between computer model output and operating data from the start-up of the full-scale plant is presented in Table 4-1. This table shows the percent error between the operating data and the computer model projections. Positive error values represent an over-estimation, while negative values represent under-estimation.

Table 4-1. Summary of computer model errors for pressures and rejection at the Eastern Correctional Facility.

		Computer model error (percent)				
		Pressure			Rejection	
Train	**Flow condition**	**Feed Stage 1**	**Feed Stage 2**	**Concentrate Stage 2**	**Overall**	**Stage 1**
A	Min	5.7	5.1	6.5	1.2	1.1
	Median	6.1	5.5	7.9	1.2	1.2
	Max	5.0	4.3	5.8	1.1	1.1
B	Min	11.3	10.5	12.7	1.4	1.3
	Median	12.1	10.8	13.3	1.4	1.3
	Max	11.1	9.1	12.3	1.6	1.5

Actual start-up data such as permeate flow, feed pressure, and conductivity for Trains A and B are illustrated in Figure 4-1 and Figure 4-2. In addition, the median operating data point used in the computer model was overlaid onto the actual performance data to provide a comparison between model performance and actual plant performance. The computer model over-predicted the feed pressures at the median operating points by 6.1 percent for Train A and 12.1 percent for Train B. The computer model over-predicted rejection by 1.2 to 1.4 percent. The average rejection for both Train A and B, as predicted by the computer model, is 98.4 percent. The actual rejection observed at the full-scale plant during start-up was 97.2 percent.

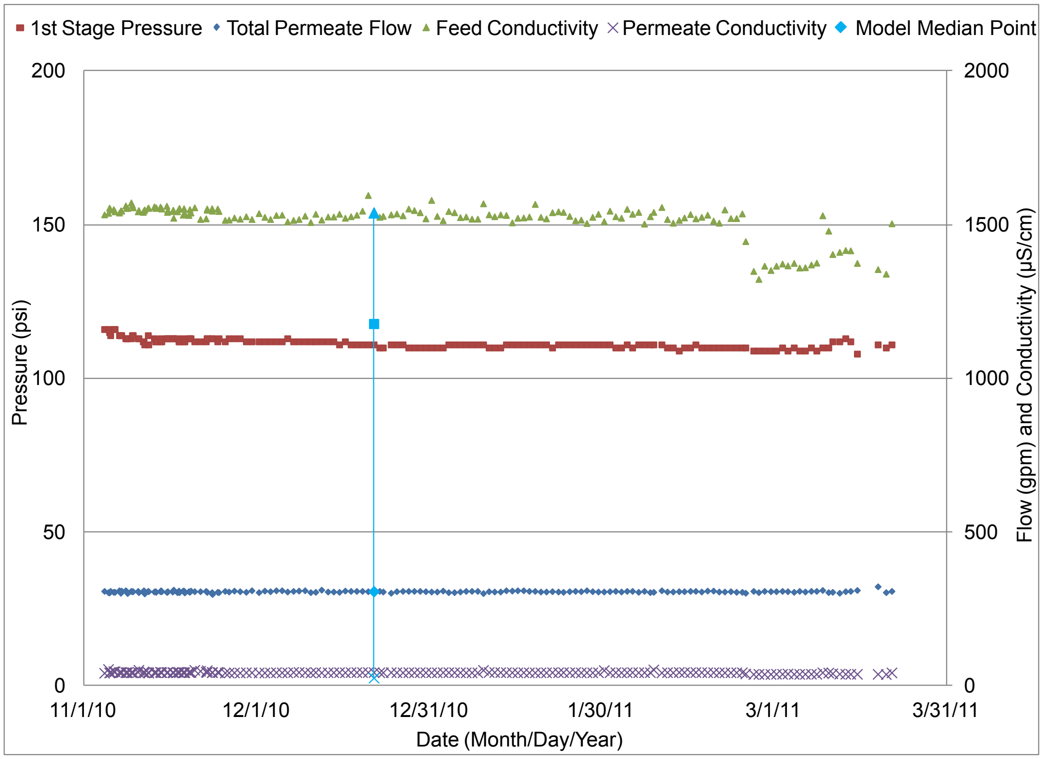

Figure 4-1. **Actual start-up (time-series) vs. model data (median points emphasized with vertical line) comparison for Eastern Correctional Train A.**

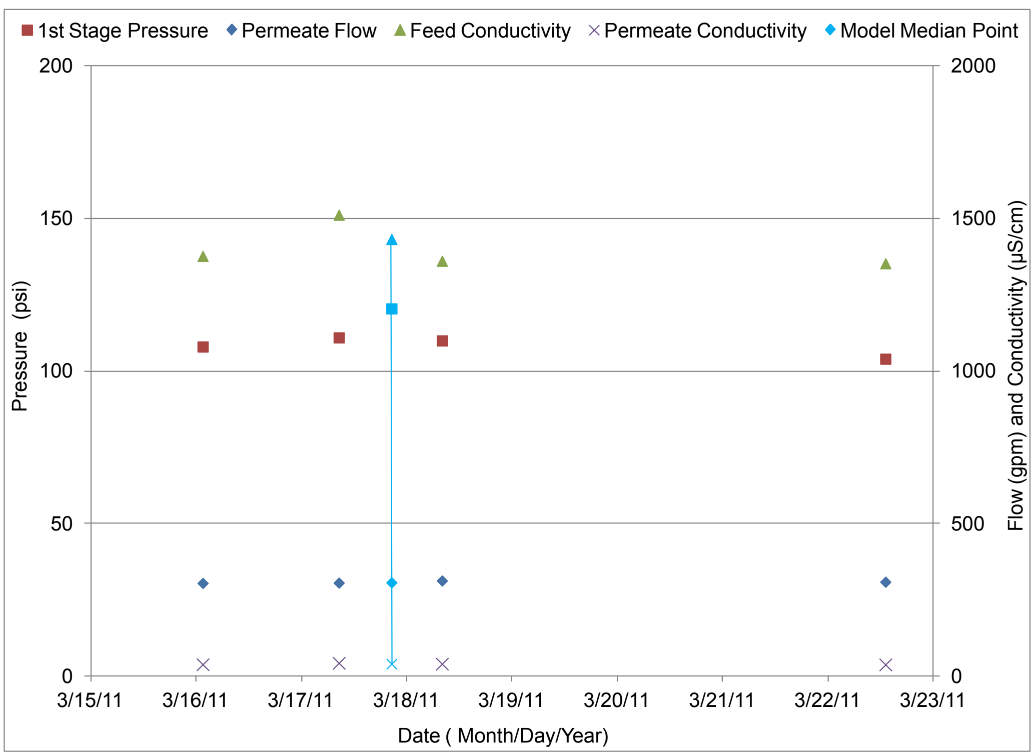

Figure 4-2. **Actual start-up (time-series) vs. model data (median points emphasized with vertical line) comparison for Eastern Correctional Train B.**

The over-prediction of feed pressures by the computer model can likely be attributed to the limited available data representing start-up conditions. The differences between rejection values observed during startup and predicted by the computer model are within the expected range of accuracy considering the limited nature of the start-up feed water quality data provided.

Goldsworthy, City of Torrance, California

The Robert W. Goldsworthy Desalter is a 2.75 million gallon per day reverse osmosis treatment plant located in City of Torrance, California. This facility was constructed in 2001 to treat a saline groundwater plume in the West Coast Basin. The facility is equipped with one reverse osmosis train that is configured in a two-stage array consisting of 42 pressure vessels in the first stage, and 24 vessels in the second stage. Each pressure vessel contains seven membrane elements. The trains are operated to produce a permeate flow rate of 1,400 gallons per minute at a recovery of 79.7 percent. The installed membrane is the CSM RE8040-BE with a membrane area of 400 square feet, a permeate flow rate of 10,500 gallons per day, and a nominal salt rejection of 99.4 percent.

For this accuracy analysis, the following data was used:

- Water quality data taken from the original computer model projections. This data was collected during the design of this facility.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected during start-up, which include two points each observed on a different day. This data is provided by the reverse osmosis system supplier involved in the project. Because start-up data was used, a fouling factor of 1.0 (no fouling) was assumed.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- A complete set of analytically determined feed water quality data representing start-up conditions was not available for the project. Startup total dissolved solids was estimated based on known conductivity using a conversion factor.
- Feed water quality data obtained from the original computer model required adjustment using sodium chloride to achieve an electrical balance between cations and anions.
- Information regarding permeate backpressure was not provided.
- Individual stage one and stage two permeate flux values representing startup conditions were not provided.
- Location representing startup feed pressure measurement was unavailable. For the purposes of this analysis, it was assumed that feed pressure was measured at a location immediately downstream of the first stage feed pumps. A pressure loss of 5 pounds per square inch in the first stage feed piping was assumed in the computer model.

A comparison between computer model output and operating data from the start-up of the full-scale plant is presented in Table 4-2. This table shows the percent error between the operating data and the computer model projections. Positive error values represent an over-estimation, while negative values represent under-estimation.

Table 4-2 Summary of computer model errors for pressures and rejection at Goldsworthy.

	Model error (percent)			
Date	**Feed pressure Stage 1**	**Concentrate pressure Stage 1**	**Concentrate pressure Stage 2**	**Rejection**
3/2/12	-5.3	-8.8	-14.5	0.61
3/3/12	-7.0	-11.8	-17.3	0.66
Median	-3.7	-7.7	-13.2	0.64

Actual start-up pressures and total dissolved solids concentrations are shown in Figure 4-3. The median operating data point used in the computer model was overlaid onto the actual performance data to provide a comparison between model performance and actual plant performance. At this operating condition, the computer model under-predicted feed pressures by 3.7 percent, and over-predicted rejection by approximately 0.6 percent.

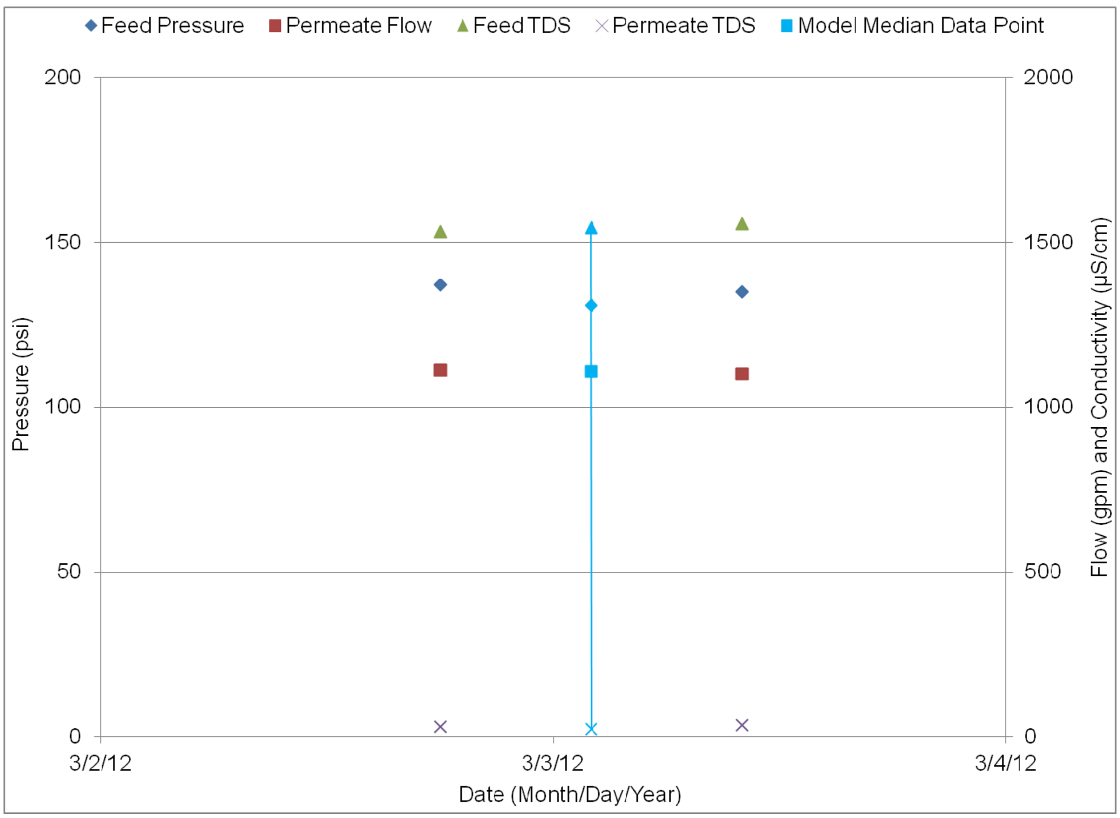

Figure 4-3. Actual start-up (time-series) vs. model data (median points emphasized with vertical line) comparison for Goldsworthy.

Permeate conductivity measurements for all pressure vessels in both membrane stages are presented in Figure 4-4. This figure demonstrates the variability among the 66 pressure vessels. Ideally, the feed water quality, flow, and pressure within the vessels of an individual stage should be the same since the vessels are operating in parallel. The conductivity removal of each pressure vessel was computed, ranked, and assigned a statistical population percentile. By plotting the conductivity reduction versus standardized z-value (in standard deviations), as shown in Figure 4-5, the statistical distribution of the pressure vessels can be characterized.

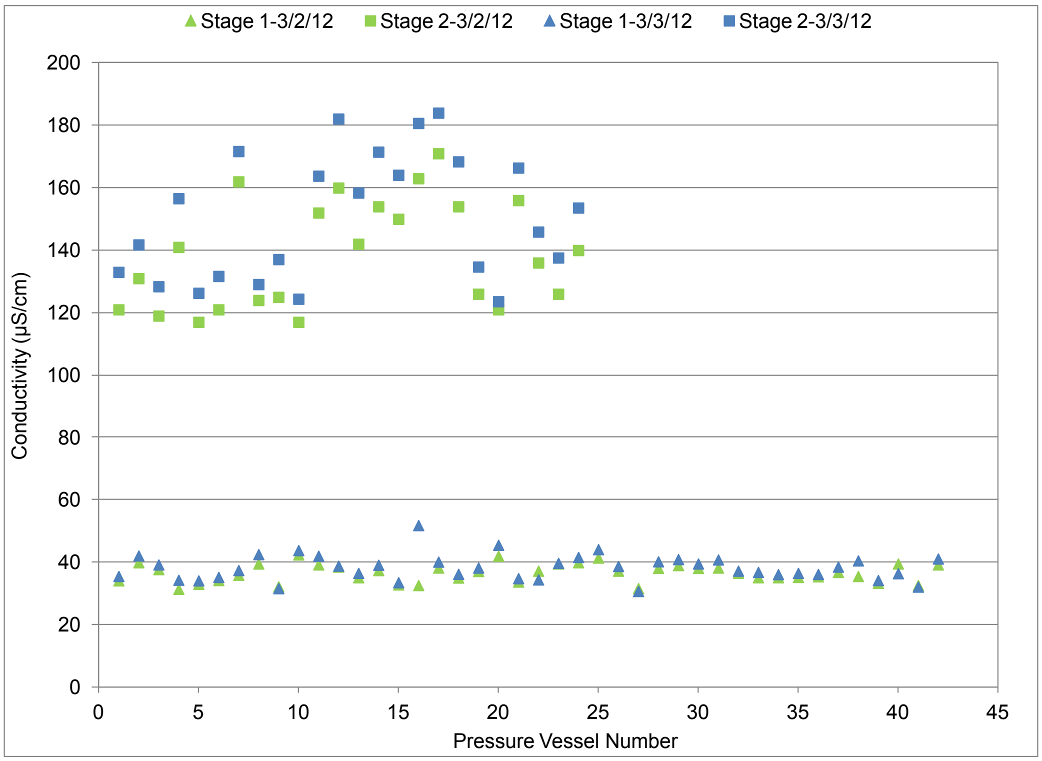

Figure 4-4. Stage 1 and 2 pressure vessel conductivities at Goldsworthy.

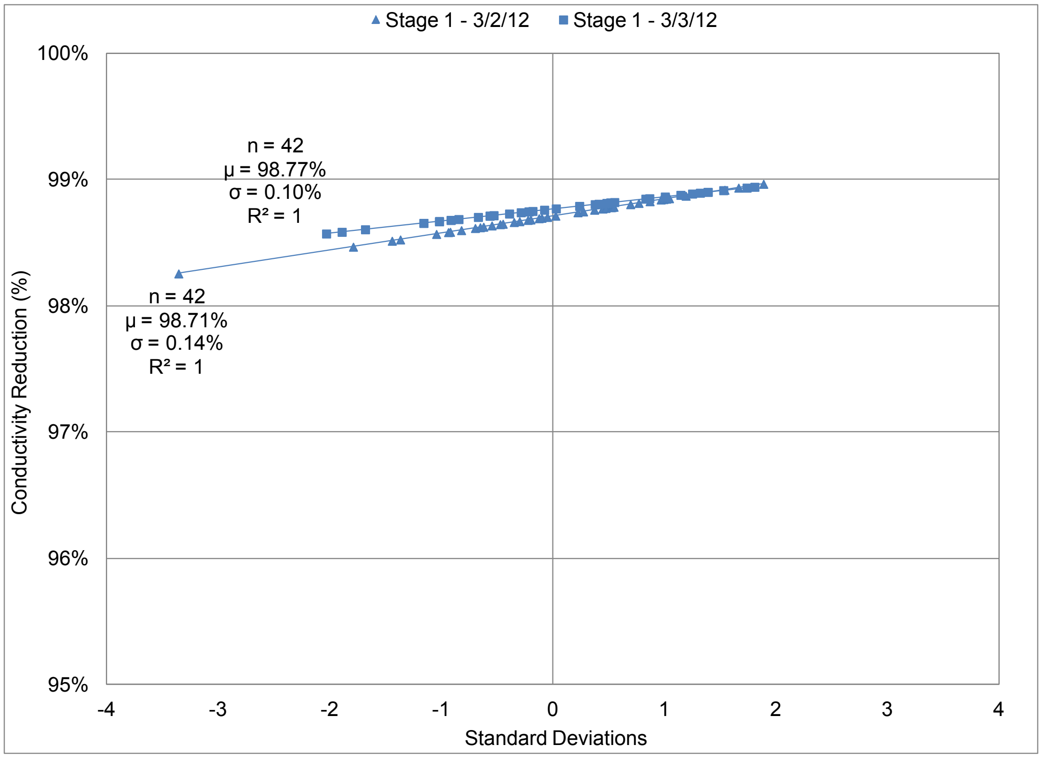

Figure 4-5. Standardized Z-values of conductivity removal within individual pressure vessels at Goldsworthy.

For both sampling days, a linear regression of the stage one conductivity removal shows a near-perfect fit (R-squared value equal to unity), which indicates that the data variation of conductivity reduction follows the normal distribution. Furthermore, the standard deviation of conductivity reduction was determined to be 0.1 percent and 0.14 percent for the two days, which corresponds to a coefficient of variation of 0.0010 to 0.0014. In statistics, the coefficient of variation is a measure used to characterize the variability between data sets. Such a low coefficient of variation indicates that there is a high degree of confidence that the each full-scale pressure vessels will produce consistent permeate salinity compared to the other pressure vessels. Therefore, the permeate salinity from the full-scale system can be approximated by a mean value without the need to account for significant variability due to the membrane manufacturing process. Moreover, the variability in permeate salinity is significantly smaller than the error in accuracy of the model, which is also relatively small based on the above analysis for predicting salt rejection. The significance of this statistical analysis is that the error associated with the computer models is not expected to be exceeded by the variability in performance observed in the field due to manufacturing processes.

The limited accuracy of the total dissolved solids data used to represent start-up conditions may have contributed to the under-prediction of feed pressures by the computer model. The start-up total dissolved solids value (and resulting projected feed pressure requirement) is directly related to the conductivity-to- total dissolved solids conversion factor that was used. For example, by increasing the conductivity-to- total dissolved solids factor from 0.51 to 0.55, the relative difference between the model-predicted and actual start-up feed pressure is reduced from 3.7 to 1.6 percent.

The differences between rejection values observed during start-up and predicted by the computer model are within the expected range of accuracy considering the limited nature of the start-up feed water quality data provided.

4.1.2 *Membrane characteristic: fouling resistant*

Scottsdale, Scottsdale, Arizona

The City of Scottsdale's Water Campus Advanced Water Treatment Facility is located in Scottsdale, Arizona. This facility was constructed in 1999 to treat wastewater effluent. The recent facility expansion includes the addition of three reverse osmosis trains that are constructed in a two-stage array consisting of 13 pressure vessels in the first stage, and seven vessels in the second stage. Each pressure vessel contains seven membrane elements. The trains are operated to produce a permeate flow rate of 1,668 gallons per minute at a recovery of 85 percent. The membrane installed is the 16-inch CSM RE16040-FEn with active area of 1,600 square feet, a permeate flow of 41,000 gallons per day, and a nominal salt rejection of 99.7 percent.

For this accuracy analysis, the following data was used:

- Water quality data taken from the original computer model projections. This data was collected during the design of this facility. Feed water quality data is representative of a location downstream of acid addition.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected during start-up, which included one point. This data was provided by the reverse osmosis system supplier involved in the project. Because start-up data was used, a fouling factor of 1.0 (no fouling) was assumed.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- A complete set of analytically determined feed and permeate water quality data representing start-up conditions was not available for the project. Feed water and permeate total dissolved solids was estimated based on conductivity-to- total dissolved solids conversion factors derived from the original computer model.
- The basis for the feed water quality data used in the original computer model is unknown. This data may not be fully representative of the feed water that was delivered to the system during start-up.
- Feed water quality data obtained from the original computer model required adjustment using sodium chloride to achieve an electrical balance between cations and anions.
- Information regarding permeate backpressure for individual stages was not provided.
- Total permeate conductivity was not provided; However, the first and second stage conductivities were provided and used to back calculate the total permeate.

- Location representing startup feed pressure measurement was unavailable. For the purposes of this analysis, it was assumed that feed pressure data was measured at a location immediately downstream of the first stage feed pumps. A pressure loss of 5 pounds per square inch in the first stage feed piping was assumed in the computer model.

Actual pressures and total dissolved solids concentrations are shown in Figure 4-6. The computer model results were overlaid onto the actual performance data to provide a comparison between model performance and actual plant performance. The feed pressure predicted by the computer model closely matched the actual startup feed pressure. The computer model over-predicted rejection by approximately 0.3 percent.

Conductivities of all pressure vessels in the reverse osmosis system are shown in Figure 4-7. Similar to the Goldsworthy analysis, a normal distribution and relatively low coefficient of variation (0.0023) were observed in conductivity reduction for first-stage pressure vessels, as shown in Figure 4-8.

While the analysis demonstrated good agreement between the model-predicted and actual start-up feed pressures, conclusions related to this information must consider the limited amount of, and omissions in, the available start-up data.

The differences between rejection values observed during startup and predicted by the computer model are within the expected range of accuracy considering the limited nature of the start-up feed water quality data provided.

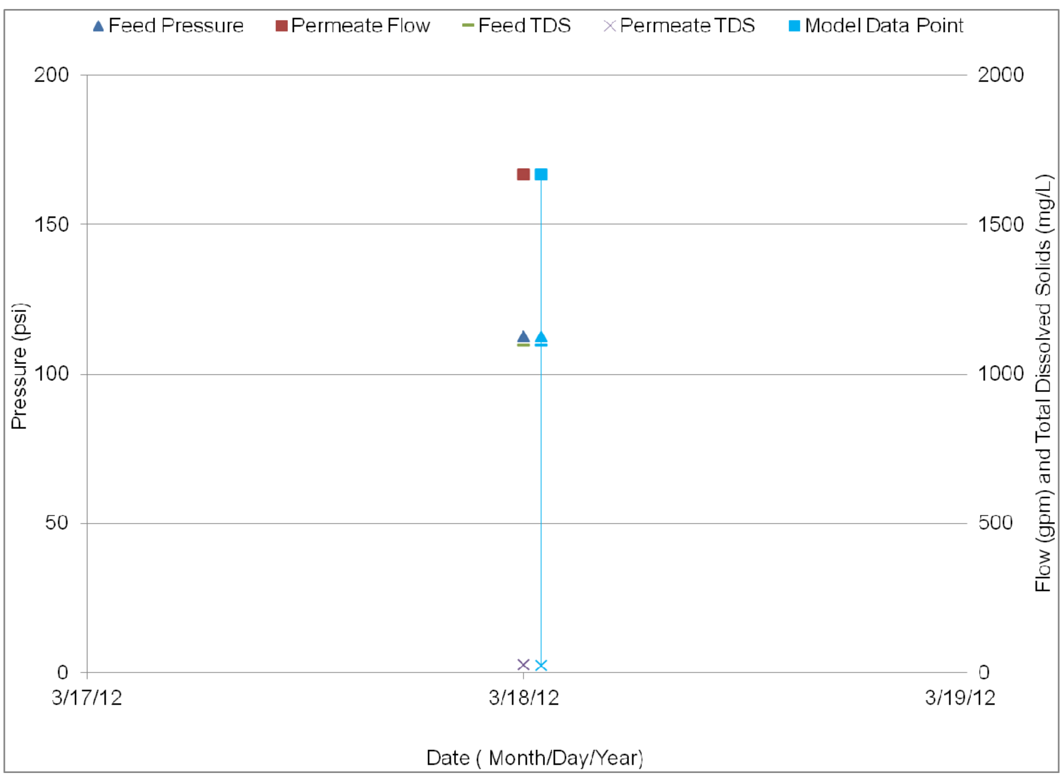

Figure 4-6. Actual start-up (single points only) vs. model data (single points emphasized with vertical line) comparison for Scottsdale.

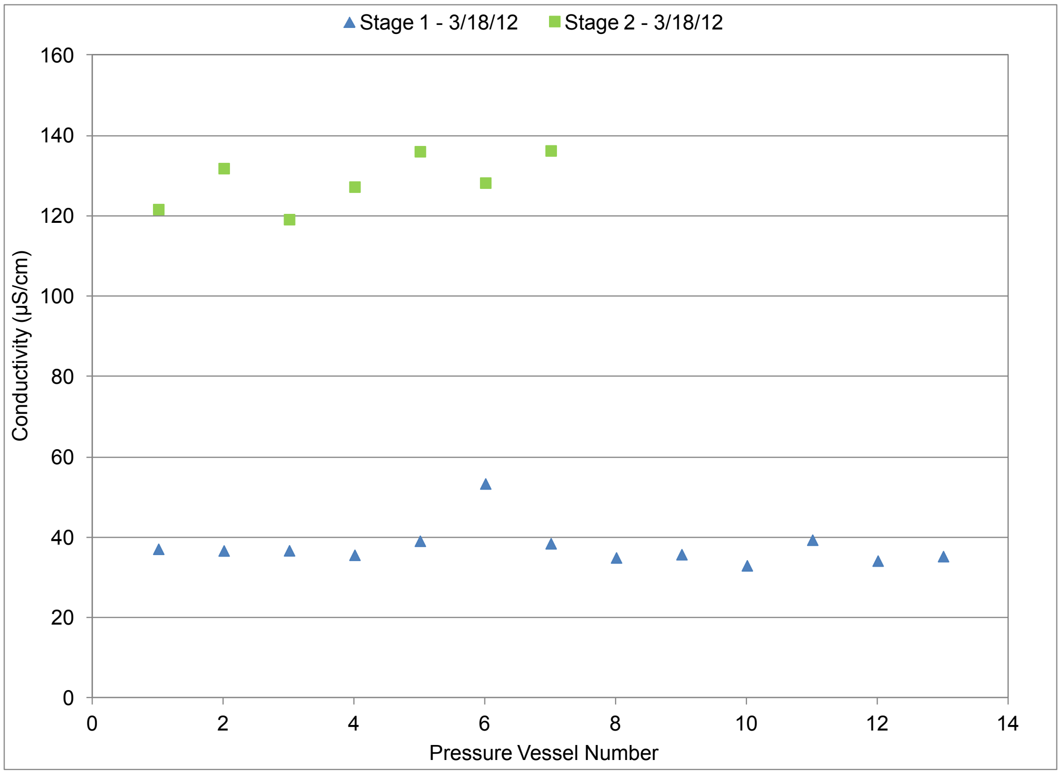

Figure 4-7. **Stage 1 and 2 pressure vessel conductivities at Scottsdale.**

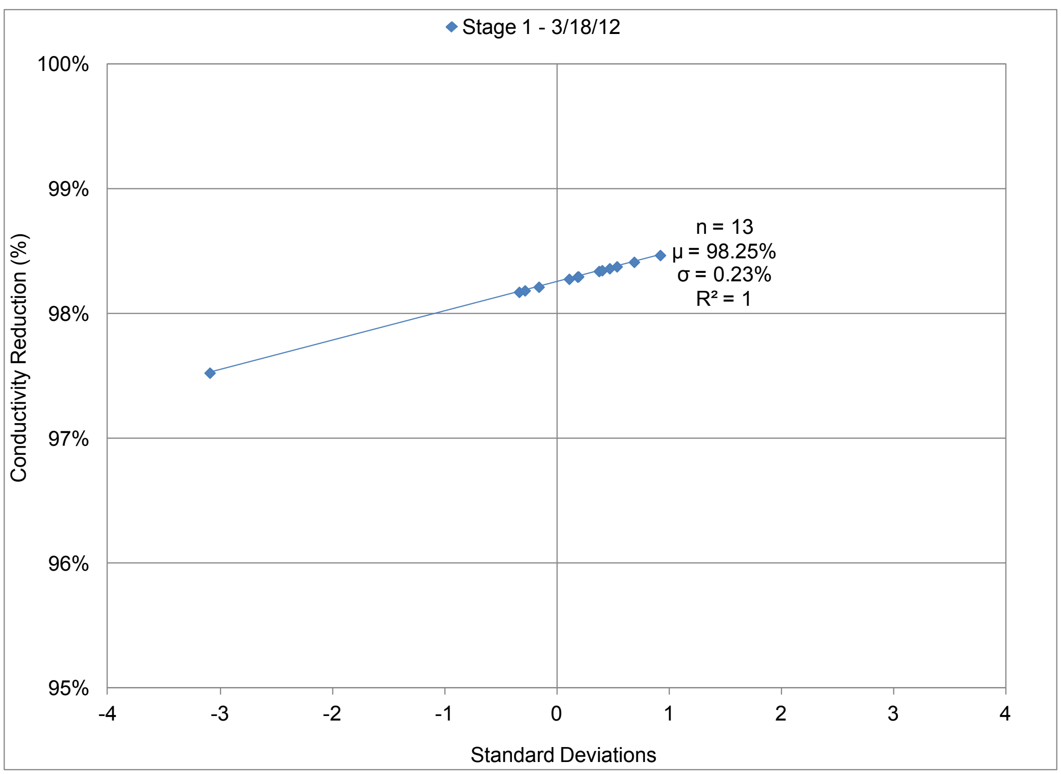

Figure 4-8. **Normal distribution of conductivity reduction for Scottsdale Stage 1 pressure vessels.**

4.1.3 *Membrane characteristic: low energy*

Clay Center Public Utilities Commission Water Treatment Reverse Osmosis Plant, Clay Center, Kansas

The Clay Center Public Utilities Commission Water Treatment reverse osmosis plant is located in Clay Center, Kansas. This facility was constructed in 2010 to treat brackish (such as, hard) groundwater. The facility consists of two reverse osmosis trains configured in a two-stage array consisting of 12 pressure vessels in the first stage, and 6 pressure vessels in the second stage. Each pressure vessel contains 6 membrane elements. The trains are operated to produce a permeate flow rate of 525 gpm at a recovery of 75 percent. The membrane installed is the Dow Filmtec XLE-440 with an active area of 440 square feet, a permeate flow of 12,700 gallons per day, and a nominal rejection of 99.0 percent.

For this accuracy analysis, the following data was used:

- Water quality data taken from the original computer model projections. This data was collected during the design of this facility.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected during start-up. This data was provided by the reverse osmosis system supplier involved in the project. Because start-up data was used, a fouling factor of 1.0 (no fouling) was assumed.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- A complete set of analytically determined feed and permeate water quality data representing start-up conditions was not available for the project. Feed water and permeate total dissolved solids was estimated based on conductivity-to- total dissolved solids conversion factors derived from the original computer model. Start-up feed water pH was assumed to be equal to the value used in the original computer model.
- The basis for the feed water quality data used in the original computer model is unknown. This data may not be fully representative of the feed water that was delivered to the system during start-up.
- Feed water quality data obtained from the original computer model required adjustment using sodium chloride to achieve an electrical balance between cations and anions.

A comparison between computer model output and operating data from the start-up of the full-scale plant is presented in Table 4-3. This table shows the percent error between the operating data and the computer model projections. Positive error values represent an over-estimation, while negative values represent under-estimation.

Table 4-3. Summary of computer model errors for pressures and rejection at the Clay Center Facility

		Computer model error (percent)					
		Pressure			Rejection		
Train	Flow condition	Feed Stage 1	Feed Stage 2	Interstage boost	Overall	Stage 1	Stage 2
A	Min	11.7	1.3	-8.8	-0.5	-0.11	-0.7
	Median	11.0	1.3	-10.8	0.2	0.57	-0.3
	Max	10.8	5.1	0.9	-0.3	0.12	-0.5
B	Min	7.7	0.2	-4.8	-0.4	-0.10	-0.6
	Median	6.4	-1.4	-4.2	0.1	0.43	-0.3
	Max	8.9	2.7	4.0	-0.2	0.16	-0.5

In general, the first and second stage feed pressures were over-predicted by the model, except for the boost pressure which the model generally under-predicted. For most data points, the computer model slightly under-predicted total dissolved solids rejection.

Actual start-up pressures and total dissolved solids concentrations for Trains A and B are shown in Figure 4-9 and Figure 4-10, respectively. The computer model results were overlaid onto the actual performance data to provide a comparison between model performance and actual plant performance.

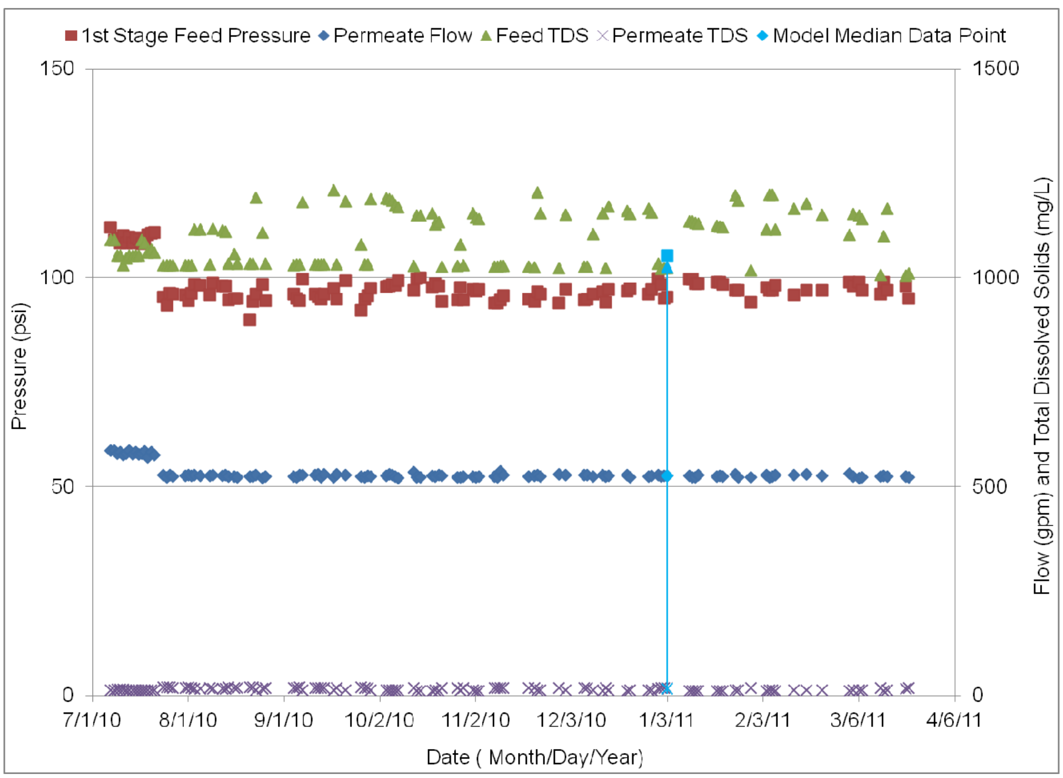

Figure 4-9. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Clay Center, Train A.

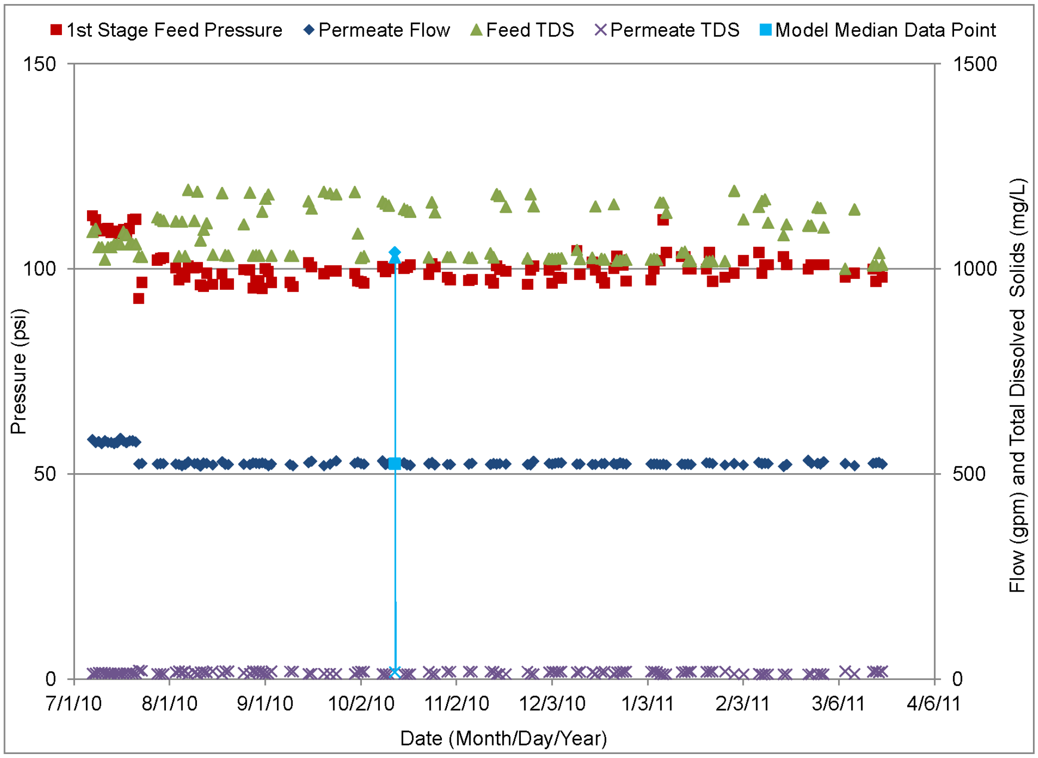

Figure 4-10. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Clay Center, Train B.

The over-prediction of feed pressures by the computer model can likely be attributed to the lack of accurate total dissolved solids data representing start-up conditions. The differences between rejection values observed during startup and predicted by the computer model are within the expected range of accuracy considering the limited nature of the start-up feed water quality data provided.

Hardinsburg, Hardinsburg, Kentucky

The Hardinsburg reverse osmosis treatment plant was constructed in 2007 to treat brackish groundwater. The facility is located in Hardinsburg, Kentucky, and consists of two reverse osmosis trains configured in a hybrid two-stage array consisting of 14 pressure vessels in the first stage, and 7 pressure vessels in the second stage. Each pressure vessel contains seven membrane elements. Installed first stage membranes are the Hydranautics ESPA 2 with an active area of 400 square feet, a rated permeate flow of 9,000 gallons per day, and a nominal salt rejection of 99.6 percent. Installed second stage membranes are the Hydranautics ESPA 1 with an active area of 400 square feet, a rated permeate flow of 12,000 gallons per day, and a nominal salt rejection of 99.3 percent. The trains are operated to produce a permeate flow rate of 556 gallons per minute at a recovery of 80 percent.

For this accuracy analysis, the following data was used:

- Analytically determined feed and permeate water quality data was collected at start-up.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected during start-up. This data was provided by the reverse osmosis system supplier involved in the project. Because start-up data was used, a fouling factor of 1.0 (no fouling) was assumed.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- Water quality data was not adjusted to achieve an electrical balance between cations and anions. As discussed later, this may have affected the computer model predictions of sodium rejection.

A comparison between computer model and observed start-up pressures and rejections is presented in Table 4-4 and Table 4-5, respectively. Positive error values represent an over-estimation, while negative values represent under-estimation.

Table 4-4. Summary of computer model errors for pressures at Hardinsburg

		Computer model error (percent)		
Train	**Flow condition**	**Feed Stage 1**	**Concentrate Stage 1**	**Concentrate Stage 2**
A	Min	3.2	0.2	-4.2
	Median	7.1	1.6	-3.5
	Max	3.5	-0.8	-4.4
B	Min	7.7	5.6	0.9
	Median	6.9	3.9	0.1
	Max	7.0	3.9	0.2

Table 4-5. Summary of computer model errors for rejection at Hardinsburg.

		Computer model error (percent)							
Train	**Flow condition**	**Sodium**	**Calcium**	**Chloride**	**Sulfate**	**Nitrate**	**Silica**	**Bicarbonate**	**TDS**
A	Min	33.0	-0.4	2.7	3.3	-3.2	-1.3	4.5	3.3
	Median	38.6	-0.4	2.9	3.1	-3.1	-1.2	4.7	3.4
	Max	30.7	-0.4	2.5	2.9	-3.9	-1.1	4.5	3.3
B	Min	39.3	-0.4	3.4	3.2	-2.5	-1.1	3.9	2.9
	Median	33.6	-0.4	3.2	3.3	-2.6	-1.1	3.5	2.9
	Max	33.5	-0.4	3.2	3.5	-2.3	-1.1	3.7	2.9

To achieve the flux balance observed during start-up conditions, the average first stage permeate backpressure estimated by the computer model was 38.8 pounds per square inch. This was in contrast to the actual permeate backpressure of 9 to 18 pounds per square inch. The computer model over predicts first stage feed pressures by an average of 5.9 percent for both Trains A and B. Concentrate pressure is over estimated by an average of 2.4 percent in the first stage and under estimated in the second stage by an average of 1.8 percent.

Figure 4-11 and Figure 4-12 illustrate the four days of full-scale operational data available for Trains A and B, respectively. The average error of the model for total dissolved solids rejection was 3.1 percent. In general, the computer model under predicted rejection of calcium, silica, and nitrate and over predicted rejection of sodium, chloride, sulfate, and bicarbonate.

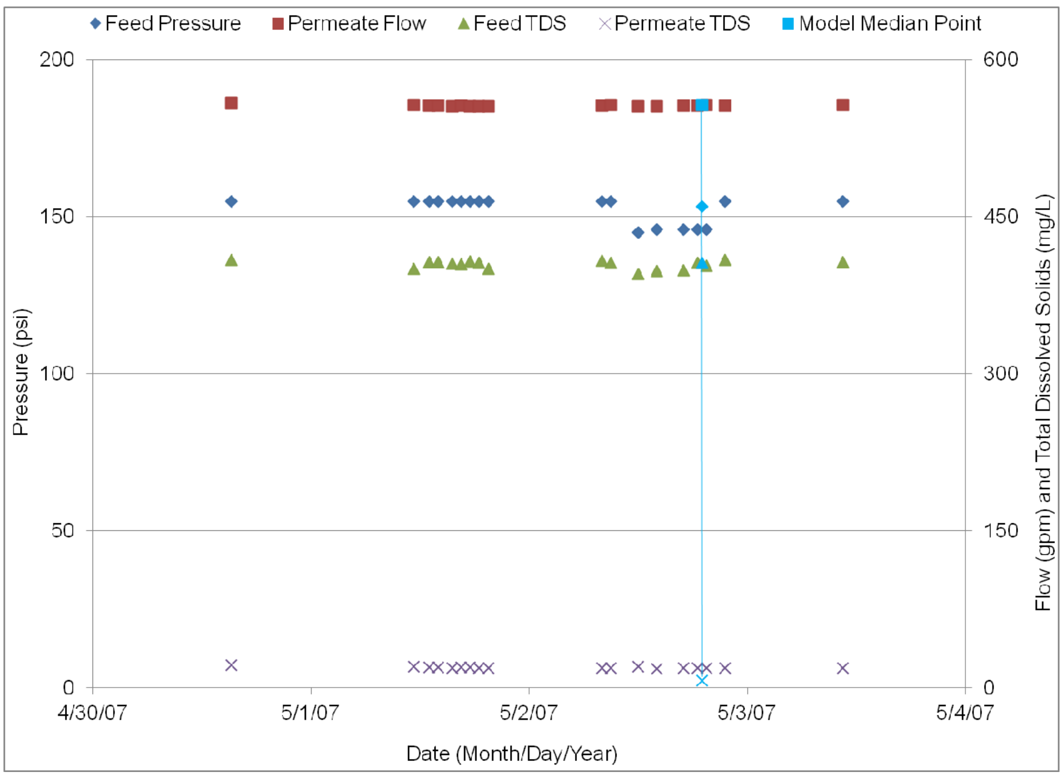

Figure 4-11. **Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Hardinsburg Train A.**

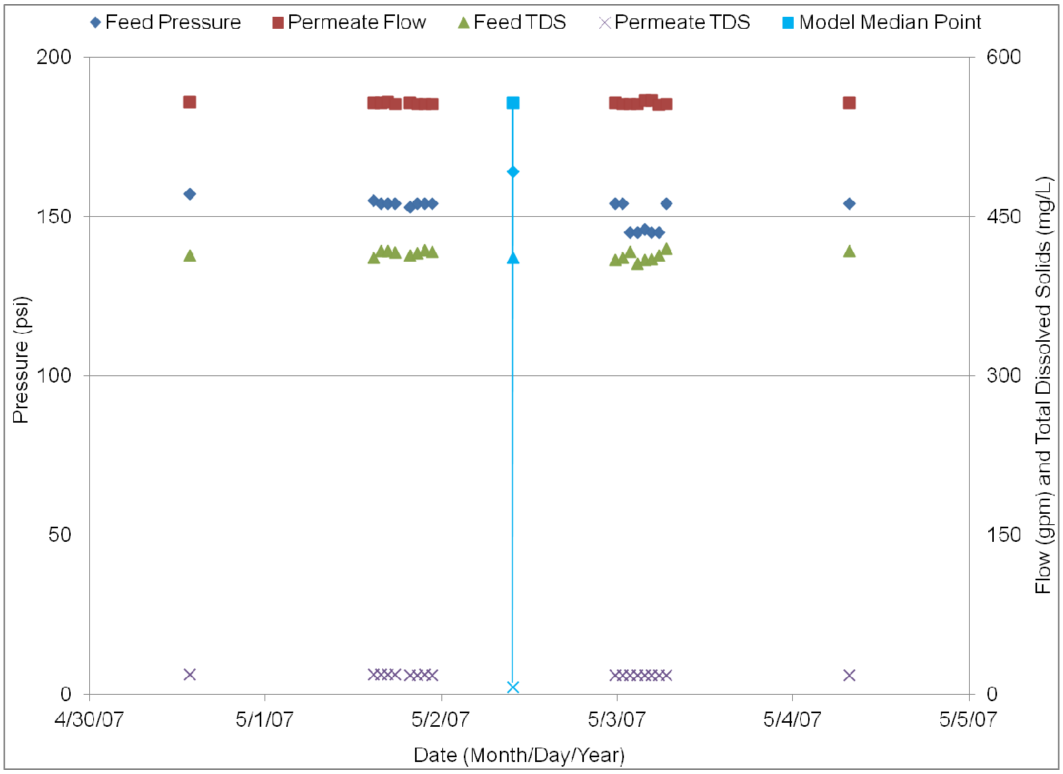

Figure 4-12. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Hardinsburg Train B.

The 7 percent over-prediction of feed pressures by the computer model is conservative but is not extreme. This level of conservatism is generally desirable in membrane system computer model output because it ensures adequate sizing of the first stage feed pump. Compared to the accuracy analyses for other facilities where analytically determined start-up feed water quality was not available, this analysis represents a more descriptive characterization of the conservatism "built into" a membrane system computer model with respect predicting to system feed pressure determination.

The differences between rejection values observed during startup and predicted by the computer model are within the expected range of accuracy for most constituents, except for sodium. The large degree of error (approximately 35 percent) associated with the computer model's prediction of sodium rejection may have been influenced by the analytical methods used to determine actual sodium concentrations in the feed water and permeate during start-up. For example, considering the Train 1 median operating condition, if feed water sodium concentrations are adjusted to provide electrical neutrality between cations and anions, the difference between the sodium rejection observed in the field and predicted by the computer model is only 6 percent.

Kay Bailey Hutchison Desalination Plant, El Paso, Texas – 2007 Startup

The Kay Bailey Hutchison Desalination Plant is a reverse osmosis treatment plant located in El Paso, Texas. This facility was constructed in 2007 to treat brackish groundwater, and consists of five reverse osmosis trains that are configured in a two-stage array consisting of 48 first stage pressure vessels, and 24 second stage vessels. Each pressure vessel contains seven membrane elements. In 2007, the trains were operated to produce a permeate flow rate of 954 gallons per minute at a recovery of 70 percent. The membrane installed was the Hydranautics ESPA1 with a membrane area of 400 square feet, a rated permeate flow rate of 12,000 gallons per day, and a nominal salt rejection of 99.3 percent.

For this accuracy analysis, the following data was used:

- Water quality data taken from the original computer model projections. This data was collected during the design of this facility.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected during start-up. This data was provided by the reverse osmosis system supplier involved in the project. Because start-up data was used, a fouling factor of 1.0 (no fouling) was assumed.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- A complete set of analytically determined feed and permeate water quality data representing start-up conditions was not available for the project. Feed water and permeate total dissolved solids was estimated based on conductivity-to- total dissolved solids conversion factors derived from the original computer model.
- The basis for the feed water quality data used in the original computer model is unknown. This data may not be fully representative of the feed water that was delivered to the system during start-up.
- Feed water quality data obtained from the original computer model required adjustment using sodium chloride to achieve an electrical balance between cations and anions.

A comparison between computer model and observed start-up pressures and rejections is presented in Table 4-6. Positive error values represent an over-estimation, while negative values represent under-estimation.

Actual start-up pressures and conductivities for each train are shown in Figure 4-13 through Figure 4-17. The computer model results were overlaid onto the actual performance data to provide a comparison between model performance and actual plant performance.

Actual permeate backpressures for first and second stages were on average 21 pounds per square inch and 4 pounds per square inch, respectively. In general, the model over predicts pressures and salt rejections for the system, as shown in Table 4-16. First stage feed pressures are over estimated by 16.0 percent, which is the average percent error of all five trains. The model estimates a first stage permeate backpressure of 30 pounds per square inch, compared to the actual permeate pressure of 21 pounds per square inch.

Table 4-6. Summary of computer model errors for pressures and rejection at Kay Bailey Hutchison Start-up.

		Computer model error (percent)				
		Pressures			Rejection	
Train	**Flow condition**	**Feed Stage 1**	**Concentrate Stage 1**	**Concentrate Stage 2**	**Overall**	**Stage 1**
A	Min	11.3	10.5	4.3	7.1	4.3
	Median	14.3	13.2	8.1	3.4	2.3
	Max	14.4	14.1	9.8	3.3	2.4
B	Min	0.1	28.5	6.8	3.5	1.8
	Median	23.7	22.2	17.6	5.9	2.3
	Max	11.9	8.6	3.6	6.7	4.3
C	Min	4.4	5.4	8.5	-0.5	-0.4
	Median	6.2	5.4	8.9	0.2	-0.2
	Max	6.7	6.4	10.3	0.2	0.1
D	Min	22.7	19.3	18.9	3.4	3.0
	Median	21.9	21.9	17.8	3.6	3.3
	Max	20.9	17.3	15.7	3.7	3.1
E	Min	23.8	19.2	18.2	3.5	3.0
	Median	23.3	20.0	18.8	5.0	4.3
	Max	34.9	27.7	28.0	5.0	3.6

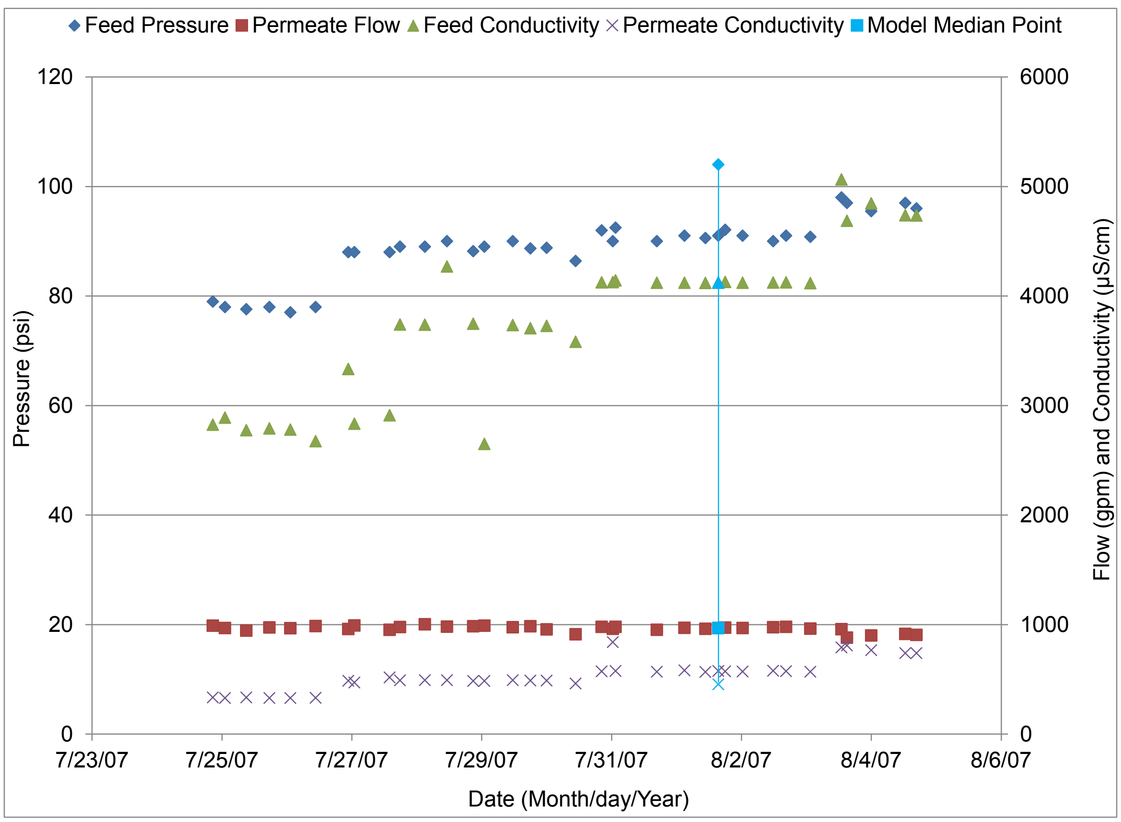

Figure 4-13. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Kay Bailey Hutchison Train A.

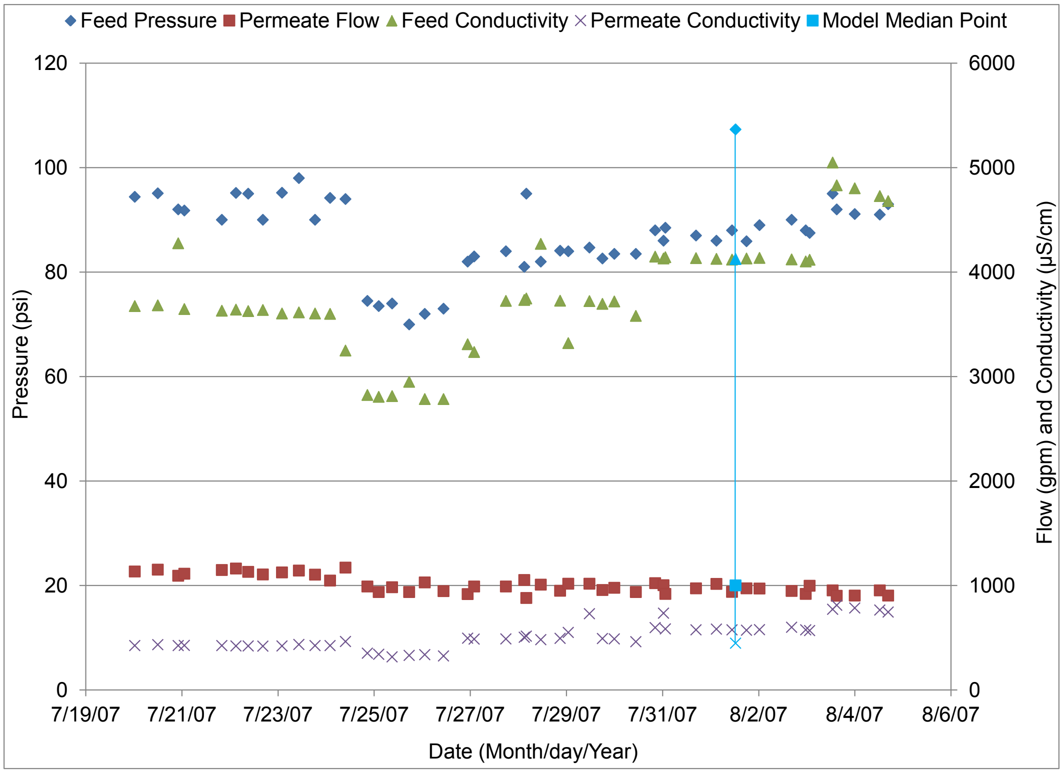

Figure 4-14. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Kay Bailey Hutchison Train B.

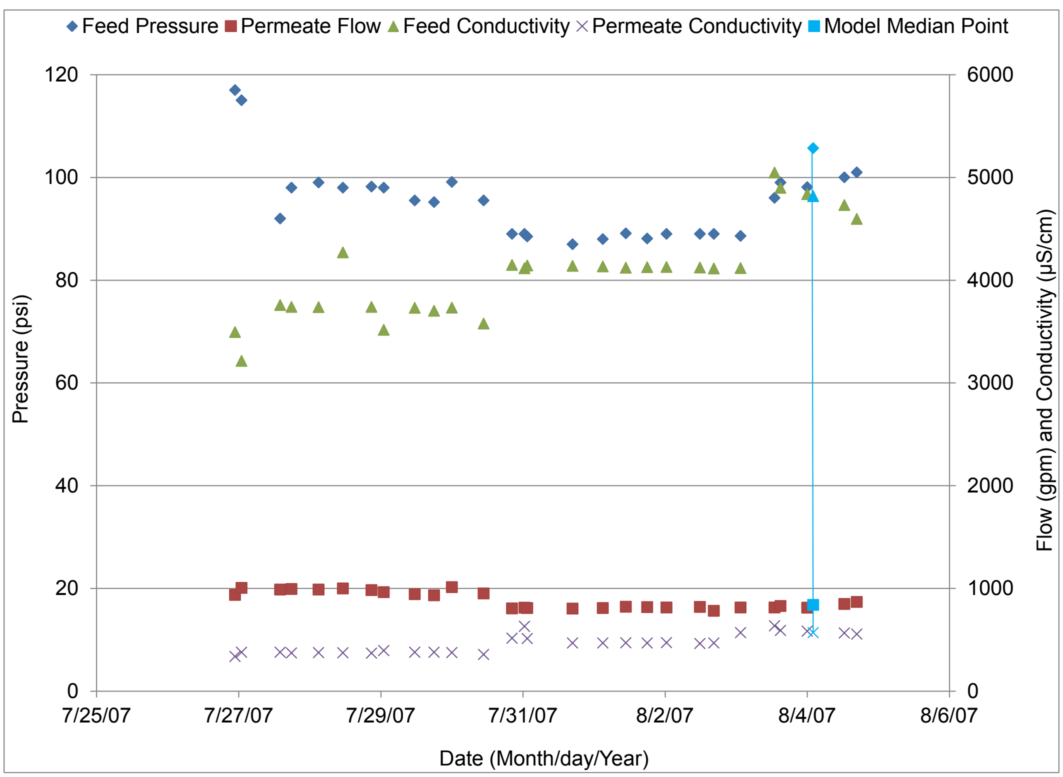

Figure 4-15. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Kay Bailey Hutchison Train C.

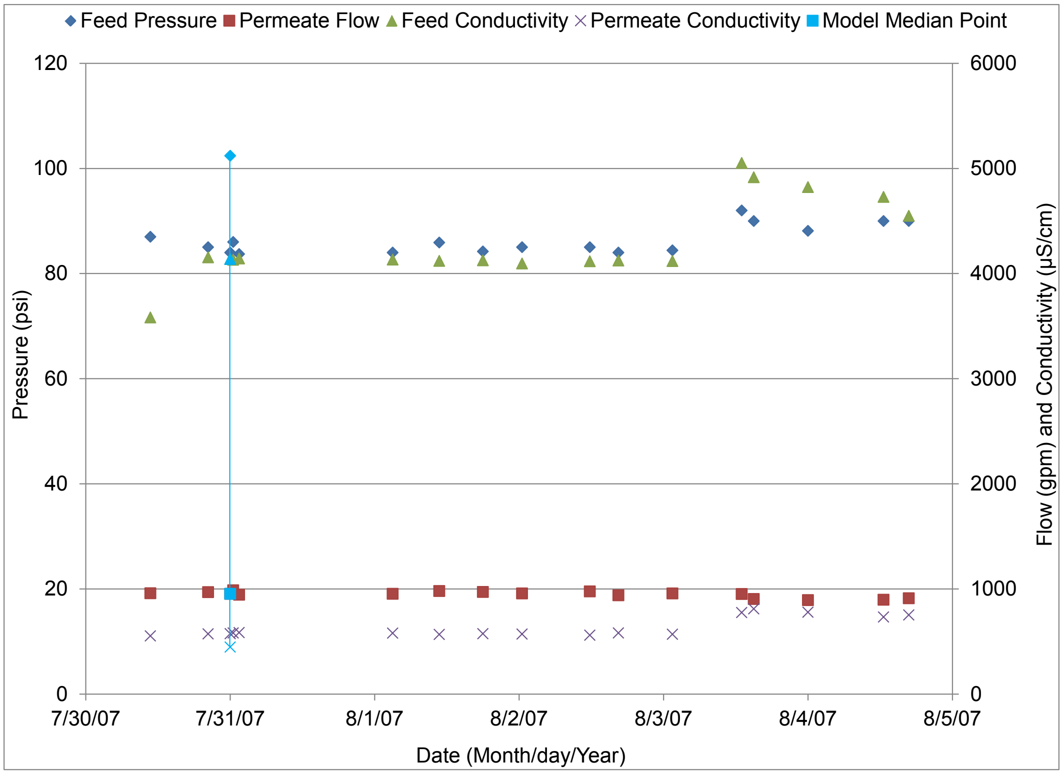

Figure 4-16. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Kay Bailey Hutchison Train D.

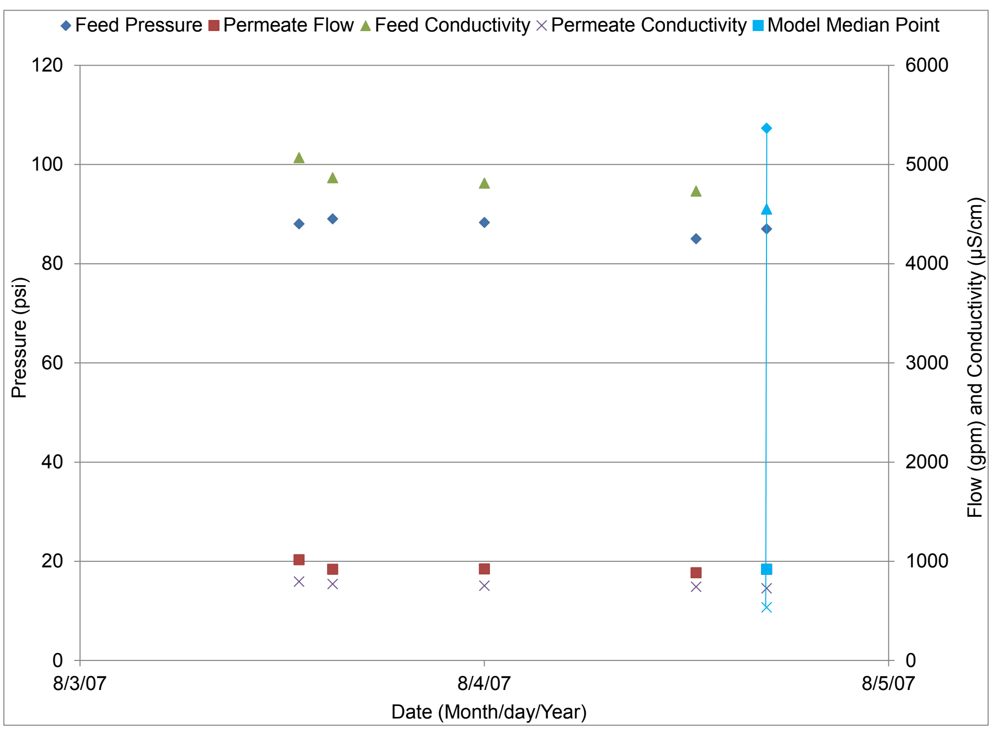

Figure 4-17. Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for Kay Bailey Hutchison Train E.

Salt rejection is also over predicted by the model. The model's average overall rejection for all five trains is 88.9 percent with a standard deviation of 1.4 percent, compared to the plant's rejection of 85.9 percent. Average percent error of all trains for overall salt rejection is 3.6 percent, while the error for first stage rejection is 2.5 percent.

The relatively large over prediction (16 percent) of first stage feed pressures by the computer model is not typical of computer models where accurate analytically-determined feed water data is available. In this analysis, the computer model feed pressure predictions may have been influenced by the methods used to estimate concentrations of individual ion constituents in the feed water at start-up based on data obtained from the original computer model. Additionally, the computer model generally over predicts the feed-side differential pressures across each membrane stage. An over-prediction of feed-side differential pressure directly contributes to an over-prediction of first stage feed pressure. While the prediction errors on the side of conservatism (such as, the first stage feed pump selected based on the computer model will be oversized, not undersized) this degree of conservatism is unnecessary and is likely the result of several contributing factors – (1) the limited nature of the feed water quality data provided, and (2) the computer model's conservative approach to estimating feed-side differential pressures, and (3) uncertainty related to the exact location of the pressure instruments used to determine first stage feed and permeate pressures.

The differences between rejection values observed during startup and predicted by the computer model are within the expected range of accuracy.

Kay Bailey Hutchison Desalination Plant, El Paso, Texas – five-year operation

This analysis was based on actual plant performance data collected approximately 5 years after the plant startup. At this time, the trains were operated to produce a permeate flow rate of 2,097 gallons per minute at a recovery of 83.5 percent. The original reverse osmosis membranes remained in operation.

For this accuracy analysis, the following data was used:

- Water samples were collected on June 7, 2012 from Trains A, C, D, and E. (Train B was offline.) Water quality analyses were performed at the Center for Inland Desalination Systems laboratory at The University of Texas at El Paso.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected approximately five years after facility start-up. This data was provided by the El Paso Water Utilities. Because the membranes had been in operation for five years, the computer model assumed a conservative fouling factor of 0.70, and an annual salt passage increase of 10 percent.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- The feed water quality data used in the computer models was based on one instant in time and may not be fully representative of the feed water that is typically delivered to the system.

- Information related to actual membrane condition (degree of fouling or scaling, frequency of membrane cleanings, etc) was not provided.

A comparison between computer model and observed five-year pressures and rejections is presented in Table 4-7 and Table 4-8, respectively. Positive error values represent an over-estimation, while negative values represent under-estimation.

Table 4-7. Summary of computer model errors for pressures at Kay Bailey Hutchison at five-year operation.

		Computer model error (percent)		
Train	**Flow condition**	**Feed Stage 1**	**Concentrate Stage 1**	**Concentrate Stage 2**
A	Median	19.4	26.6	25.8
C	Median	31.3	40.0	47.7
D	Median	13.3	18.6	16.5
E	Median	23.5	28.2	28.1

Table 4-8. Summary of computer model errors for rejection at Kay Bailey Hutchison at five-year operation.

		Computer model error (percent)					
Train	**Flow condition**	**Sodium**	**Calcium**	**Chloride**	**Sulfate**	**Magnesium**	**Total dissolved solids**
A	Median	8.3	-1.9	10.0	-3.6	-2.2	4.8
C	Median	2.4	-2.3	4.6	-3.4	-2.4	1.0
D	Median	3.4	-2.5	5.7	-3.7	-2.7	0.8
E	Median	4.2	-2.1	6.2	-3.4	-2.4	1.8

The average full-scale first stage permeate backpressure was 37.4 psi compared to the computer model prediction of 48.5 pounds per square inch, which represents an average difference of 11.1 pounds per square inch (equivalent to a 30.2 percent error). First stage feed, first stage concentrate, and second stage concentrate pressures are over estimated by averages of 21.9, 28.3, and 30.2 percent, respectively. For all four trains, the computer model predicted a salt rejection of 88.4 percent, compared to the actual salt rejection of 86.6 percent. Rejection of sodium and chloride was over predicted by the model, while rejection of calcium, sulfate, and magnesium was under predicted. Figure 4-18 presents actual performance data for pressure, flow, and total dissolved solids concentrations compared with computer model projections for each train.

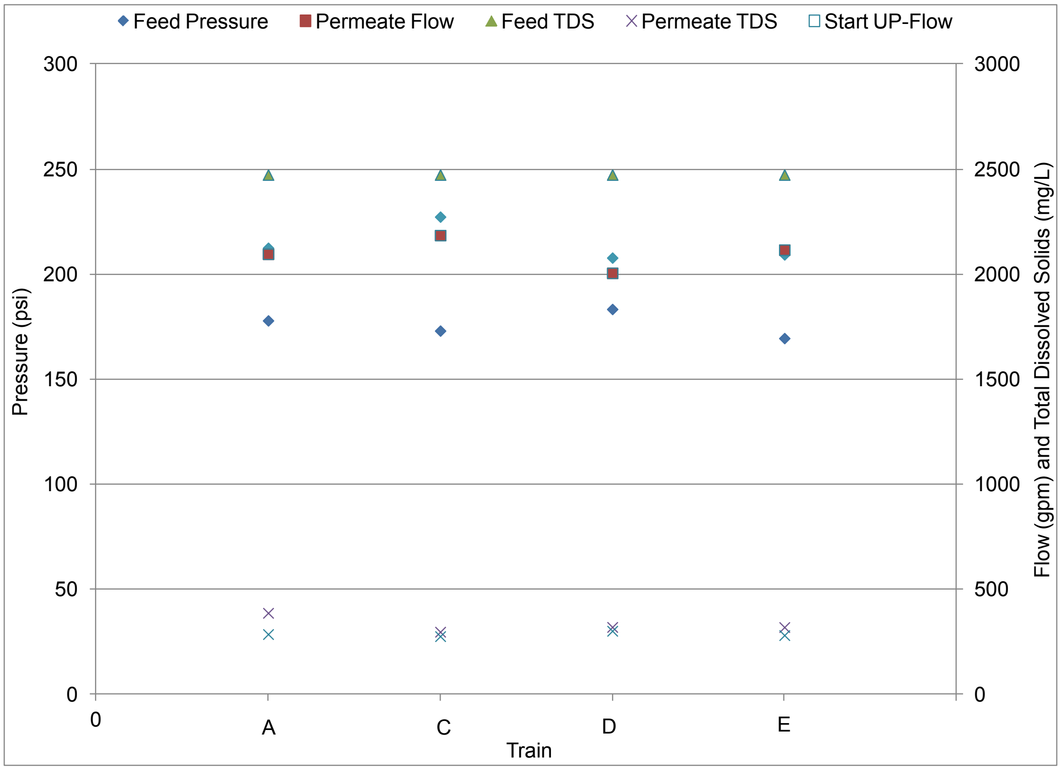

Figure 4-18. Actual year five vs. model data comparison for Kay Bailey Hutchison Trains A,C,D, and E.

The computer model over predicts first stage feed pressures by a significant margin (22 percent on average). There may be several explanations for why this occurs:

- There may have been inaccuracies in the analytical determinations of feed water ion constituents.
- The selected fouling factor (0.70) may not accurately represent the actual membrane conditions at a membrane age of five years. The reverse osmosis trains at this facility have not operated continuously over this period. Each train is operated intermittently, with one train operating at a given time, rotating among the trains. This operational scheme may correlate to a higher fouling factor than was used in the computer model. For example, increasing the fouling factor to 0.90 (this value represents a lower degree of membrane fouling) results in a predicted feed pressure that is within 11 percent of the actual feed pressure observed.
- The exact location of the pressure instruments used to determine first stage feed and permeate pressures was not provided.
- The computer model generally over predicted feed-side differential pressure across the membranes.

The computer model prediction of feed pressure errors on the side of conservatism (such as, the first stage feed pump selected based on the computer model will be oversized, not undersized) but this degree of conservatism is unnecessary. This highlights an important issue that the designer should bear in mind when using a computer model to predict the performance of a membrane system, that is computer *model predictions are only as accurate as the input data provided* (feed water quality, hydraulic parameters, membrane conditions, etc).

The differences between rejection values observed during startup and predicted by the computer model are within an acceptable range of accuracy (0.8 to 4.8 percent) for the design of reverse osmosis membrane systems for drinking water applications

North Lee County, Lee County, Florida

The North Lee County reverse osmosis treatment plant is located in Lee County, Florida. This facility was originally constructed in 2006 to treat brackish groundwater. A recent expansion in 2011 doubled the plant's permeate production capacity. The facility consists of four reverse osmosis trains that are configured in a two-stage array consisting of 38 pressure vessels in the first stage, and 17 vessels in the second stage. Each pressure vessel contains seven membrane elements. The trains are operated to produce a permeate flow rate of 1,740 gallons per minute at a recovery of 80 percent. The membrane installed is the Dow Filmtec LE-440i, which has an active area of 440 square feet, a rated permeate flow of 12,650 gallons per day, and nominal salt rejection of 99.3 percent.

For this accuracy analysis, the following data was used:

- Water quality data taken from the original computer model projections. This data was collected during the design of this facility.
- Computer model projections furnished by the reverse osmosis system supplier involved in the design of this facility.
- Computer model projections completed by the authors.
- Pressure, flow, and conductivity data collected during start-up. This data was provided by the reverse osmosis system supplier involved in the project. Because start-up data was used, a fouling factor of 1.0 (no fouling) was assumed.

The following limitations associated with the data set may have affected the results of this accuracy analysis:

- A complete set of analytically determined feed and permeate water quality data representing start-up conditions was not available for the project. Feed water and permeate total dissolved solids was estimated based on conductivity-to- total dissolved solids conversion factors derived from the original computer model.
- Feed water quality data obtained from the original computer model required adjustment using sodium chloride to achieve an electrical balance between cations and anions.
- At the time this data was collected, sulfuric acid was added to the feed water prior to entering the membrane system to reduce the pH of the feed water from 7.1 to 5.5. The computer model estimated the dose; the actual chemical dose may have differed from the modeled chemical dosing.
- Interstage boost pressure was not explicitly stated in the start-up data, but was calculated by subtracting the second stage feed pressure from first stage concentrate pressure and adding a 5 pounds per square inch allowance for interstage piping pressure losses.

A comparison between computer model and observed start-up pressures and rejections is presented in Table 4-9. Positive error values represent an over-estimation, while negative values represent under-estimation. Start-up data for only two of the operating trains was available.

Table 4-9. Summary of computer model errors for pressures and rejection at North Lee County.

		Computer model error (percent)							
		Pressures					Salt rejection		
Train	**Flow condition**	**Feed Stage 1**	**Concentrate Stage 1**	**Feed Stage 2**	**Concentrate Stage 2**	**Boost**	**Overall**	**Stage 1**	**Stage 2**
C	Min	-1.2	-10.3	-4.9	-8.3	9.2	2.5	2.2	1.9
	Median	-0.2	-9.6	-3.7	-7.4	12.2	2.7	2.3	1.9
	Max	-8.5	-19.3	-17.0	-22.7	-6.4	1.7	1.6	1.5
D	Min	0.3	-8.9	-4.9	-8.6	7.6	1.9	1.9	1.7
	Median	-0.1	-8.4	-5.9	-8.9	4.4	2.3	1.9	1.7
	Max	-1.3	-9.3	-6.3	-14.2	6.6	2.8	2.2	2.4

Overall, the model under predicted feed and concentrate pressures. First stage feed pressures were under predicted by an average of 1.4 percent and concentrate by 10.7 percent. Interstage boost pressure was over predicted by 5.4 percent. In general, salt rejection was over predicted by the model. Train C and Train D provided an actual average salt rejection of 93.3 and 94.2 percent compared to model predictions of 95.3 and 95.4, respectively. Actual start-up pressures and conductivity values for each train are shown in Figure 4-19 and Figure 4-20. The computer model results were overlaid onto the actual performance data to provide a comparison between model performance and actual plant performance.

The actual first stage feed pressures and the computer model predictions demonstrated good agreement, well within the level of accuracy required to properly select a first stage feed pump. The differences between actual salt rejection and the model predictions are within the expected range of accuracy considering the limited nature of the start-up feed water quality data provided.

The observed conductivity removal within the fist and second stage vessels of each train were plotted against their standardized z-values in Figure 4-21 and Figure 4-22. The linearity of this data indicates that the salt rejection within individual pressure vessels follows a standard normal distribution, with a coefficient of variation less than 0.05 percent. This indicates that there is a high degree of confidence that the each full-scale pressure vessels will produce consistent permeate salinity compared to the other pressure vessels. Therefore, the permeate salinity from the full-scale system can be approximated by a mean value without the need to account for significant variability due to the membrane manufacturing process. Moreover, the variability in permeate salinity is significantly smaller than the error in accuracy of the model, which is also relatively small based on the above analysis for predicting salt rejection. The significance of this statistical analysis is that the error associated with the computer models is not expected to be exceeded by the variability in performance observed in the field due to manufacturing processes.

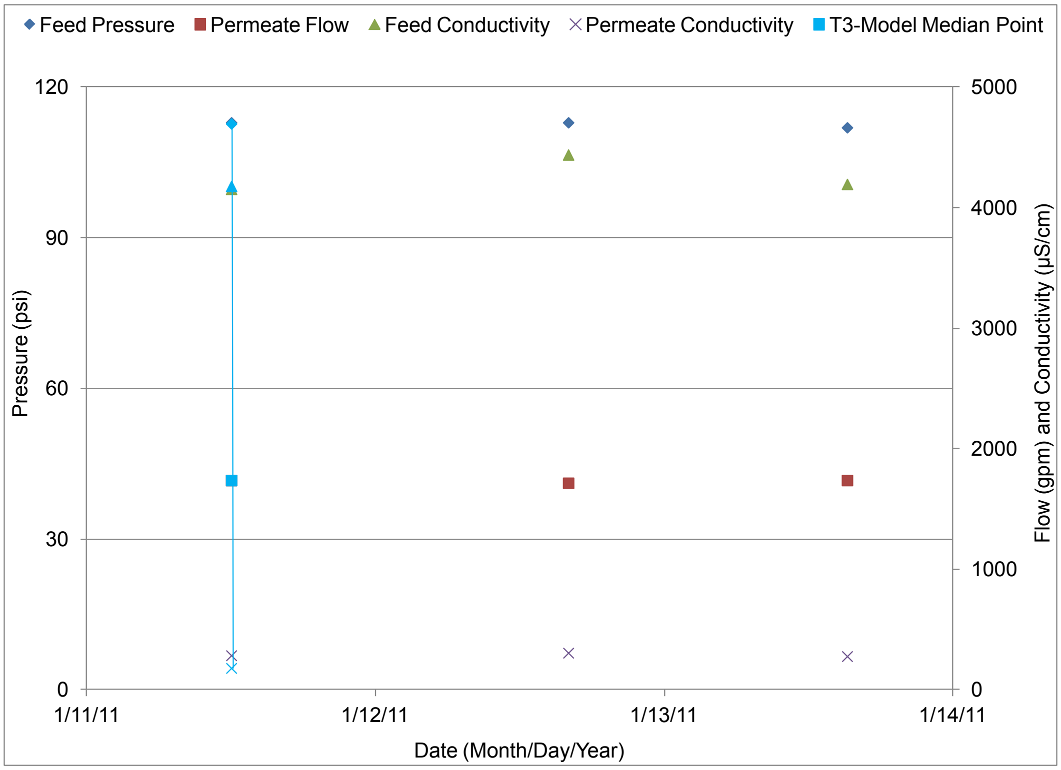

Figure 4-19. **Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for North Lee County Train C.**

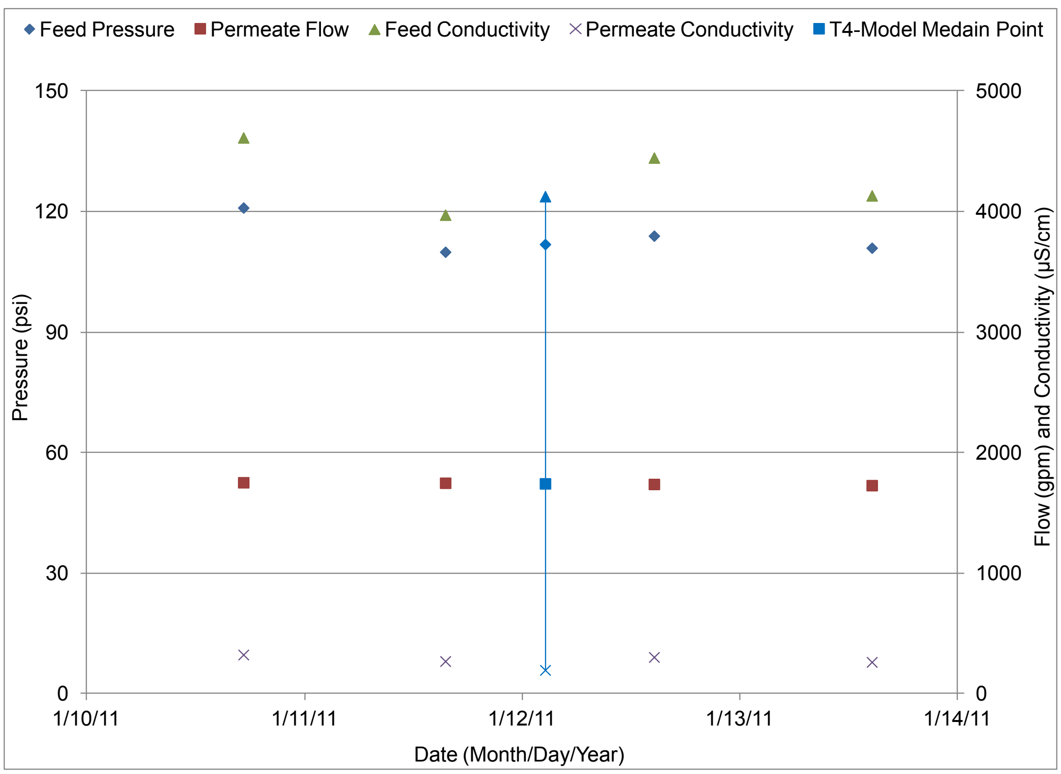

Figure 4-20. **Actual start-up (time series) vs. model data (median points emphasized with vertical line) comparison for North Lee County Train D.**

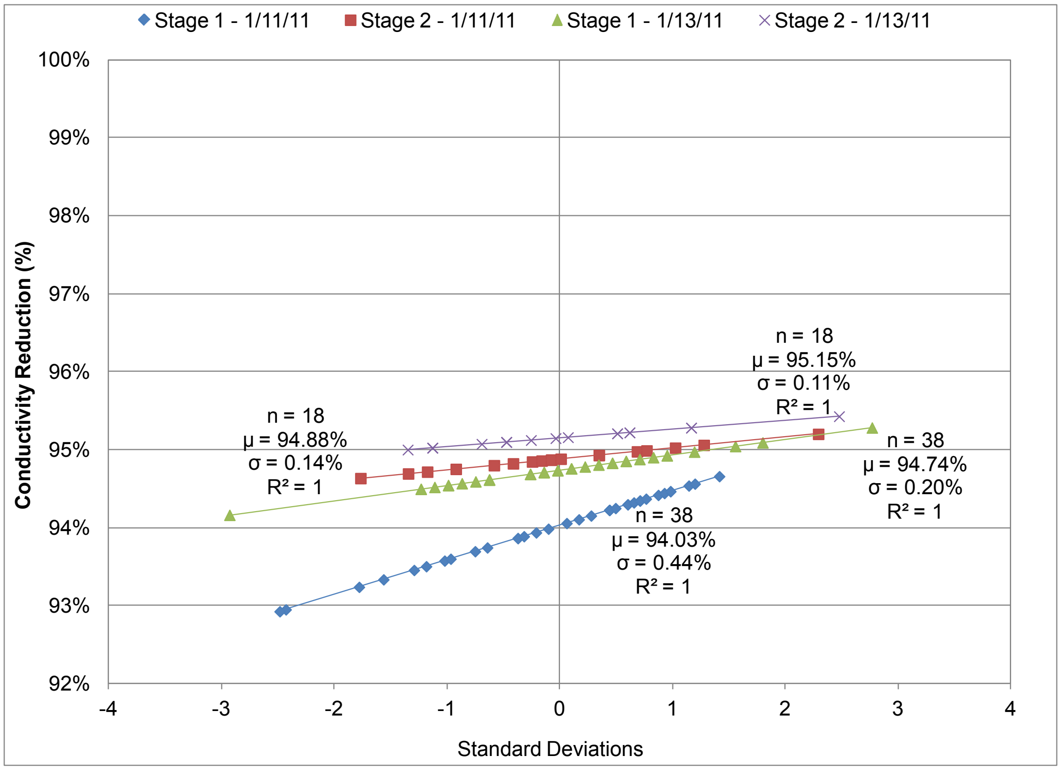

Figure 4-21. **Standardized Z-values of conductivity removal within individual pressure vessels for North Lee County Train C.**

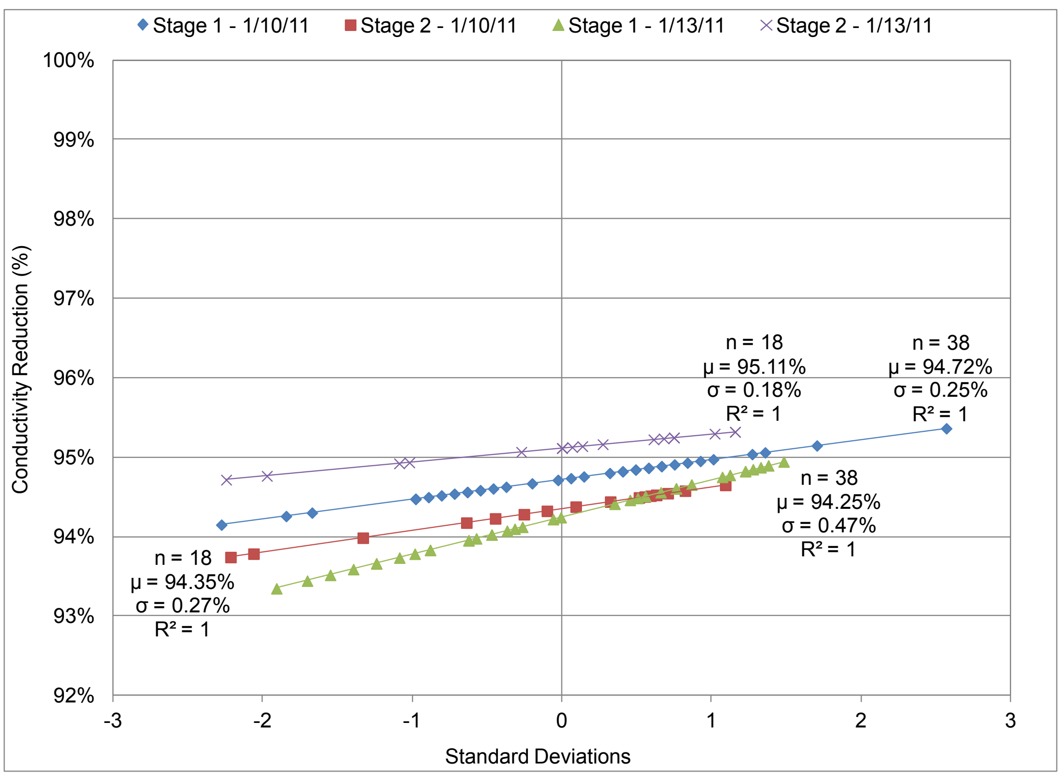

Figure 4-22. **Standardized Z-values of conductivity removal within individual pressure vessels for North Lee County Train D.**

4.2 Precision

The precision analysis compared the similarity of six different membrane manufacturers using similar membranes. Precision results were presented in relative percent differences. Relative percent difference is the difference between the performance of a single manufacturer's model and the average performance of all models, divided by the average performance of all models. Five data sets were evaluated for precision based on three operating conditions: (1) new membranes, (2) five-year-old membranes, and (3) a combination of five-year-old membranes and high feed water salinity.

Another method that was used to compare variability within a set of data was the coefficient of variation. The coefficient of variation was discussed previously in the accuracy analysis. It is equal to the standard deviation divided by the average. The coefficient of variation facilitates a comparison between data sets with different testing conditions, units, and means. A greater coefficient of variation indicates greater variability within a data set.

4.2.1 *Clay Center*

For the precision analysis of the Clay Center data set, the selected point for assessment was the median flow value for Train A, which occurred on January 3, 2011. A low energy reverse osmosis membrane, DOW XLE-440, was installed in the reverse osmosis system. Each membrane has an area of 440 square feet, a rated permeate flow of 12,700 gallons per day, and a nominal salt rejection of 98.0 percent. Equivalent membranes were selected based on flux, rejection, and standard testing conditions. Membrane specifications and testing conditions for all six membranes are listed in Table 4-10. Testing for all membranes was performed at a temperature of 25 degrees Celsius, a recovery of 15 percent, and a pH range of 6.5 to 7.5.

Table 4-10. Selected membranes for clay center precision analysis.

Computer model	Membrane	Area (square feet)	Rated permeate flow (gallons per day)	Nominal salt rejection (percent)	Test solution	Test solution concentration (milligrams per liter)	Test feed pressure (pounds per square inch)
ROSA 8.0.3	XLE-440	440	12,700	99.0	NaCl	500	100
Winflows 3.1.2	AK-440 LE	440	12,300	99.3	NaCl	500	115
Toray DS2 2.01.43	TMH20A-440	440	12,100	99.3	NaCl	500	100
ROPRO 8.05	8040-ULP-400	400	8,900	98.65	NaCl	2,000	125
CSMPRO 4.1	RE8040-BLF	400	11,500	99.2	NaCl	500	100
IMSdesign 2011.19	ESPA2 Max	440	13,200	99.2	NaCl	500	100

At the time that this study was performed, Koch and CSM did not offer a direct equivalent membrane model with 440 square feet area. As a result, a membrane with a smaller area of 400 square feet was chosen and total permeate flows were reduced by a factor of 0.909 (that is, 400/440). Identical system configuration and feed quality data was entered into the computer models provided by the six membrane manufacturers. Interstage pressure boosting was incorporated into the Clay Center reverse osmosis membrane array design. Similar to the accuracy analysis, the interstage boost pressure was iteratively changed in the computer models to match the observed first and second stage permeate flux values. By matching first and second stage flux values at the median flow condition, flows and recovery were also matched. This facilitated a meaningful comparison of pressures and rejections predicted by each computer model.

The average first stage feed pressure predicted by all of the computer models was 104.1 pound-force per square inch gauge with a standard deviation of 7.8 pounds per square inch. The resulting coefficient of variation was 7.5 percent. Figure 4-2 shows a side-by-side comparison of computer model pressure results for the Clay Center median flow point. In general, Figure 4-25 indicates that variation in first and second stage concentrate pressure predictions (standard deviations of 14.5 pounds per square inch for Stage 1 concentrate pressure, and 11.5 pounds per square inch for Stage 2 concentrate pressure) was greater than the variation in first stage feed pressures (standard deviation of 7.8 pounds per square inch). Table 4-11 presents the relative percent differences for first stage feed, second stage feed, concentrate, and interstage boost pressures. The average interstage boost pressure was 36.6 pound-force per square inch gauge with a standard deviation of 5.4 pounds per square inch.

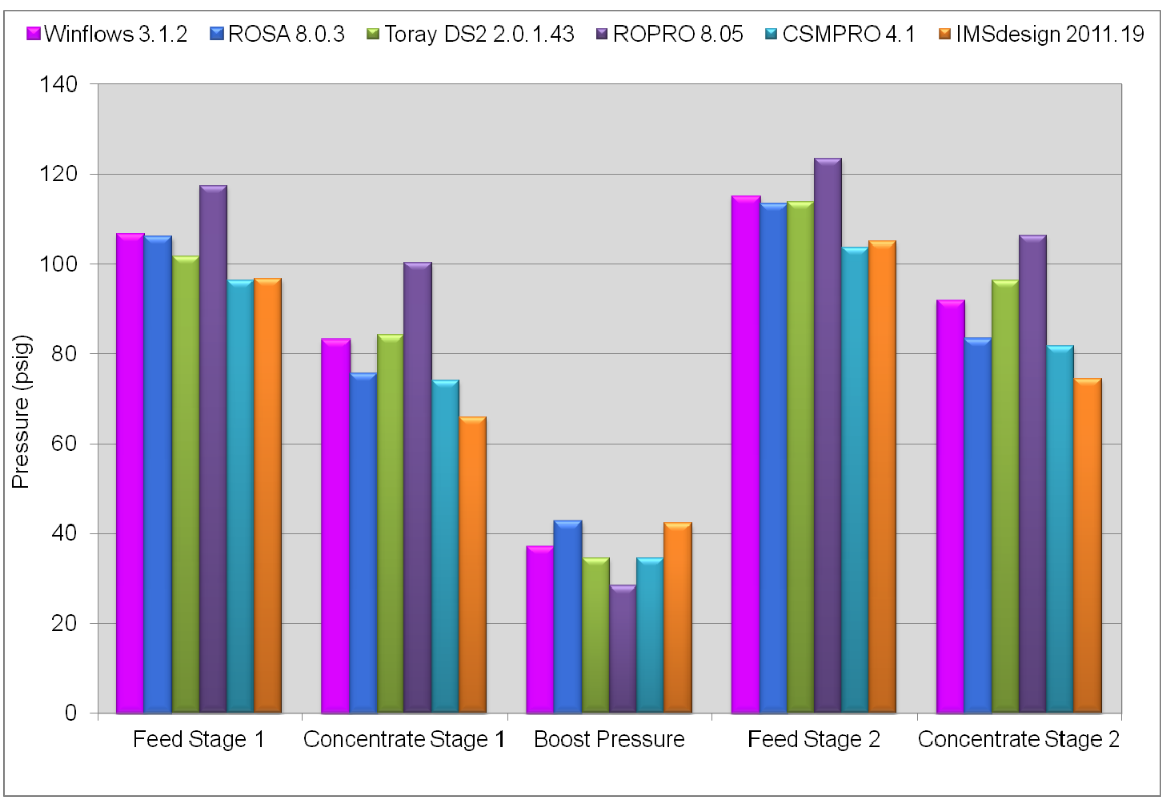

Figure 4-23. Comparison of pressures predicted by computer models simulating Clay Center Operation.

Table 4-11. Summary of relative differences in membrane system pressures for Clay Center Simulation.

	Relative difference (percent from mean)				
Computer model	**Feed Stage 1**	**Concentrate Stage 1**	**Boost**	**Feed Stage 2**	**Concentrate Stage 2**
ROSA 8.0.3	1.7	-11.6	16.6	0.7	-6.5
Winflows 3.1.2	2.3	-2.9	1.0	2.3	3.0
Toray DS2 2.01.43	-2.3	-1.4	-5.4	1.3	8.4
ROPRO 8.05	12.7	17.4	-22.6	9.9	19.6
CSMPRO 4.1	-7.4	-7.9	-5.4	-7.7	-8.2
IMSdesign 2011.19	-7.1	-23.0	15.7	-6.5	-16.3
Average (pounds per square inch)	104.1	80.5	36.6	85.5	89.0
Standard deviation (pounds per square inch)	7.8	11.8	5.4	14.5	11.5
Coef. of Variation (percent)	7.5	14.6	14.8	6.4	12.9

The average salt rejection was 98.1 percent with a standard deviation of 0.8 percent. When comparing computer model rejections side-by-side as in Figure 4-21, overall salt rejections are similar, but noticeable deviations include sodium for ROPRO and bicarbonate for IMSdesign. A summary of relative differences between predicted rejections for individual ions is presented in Table 4-12.

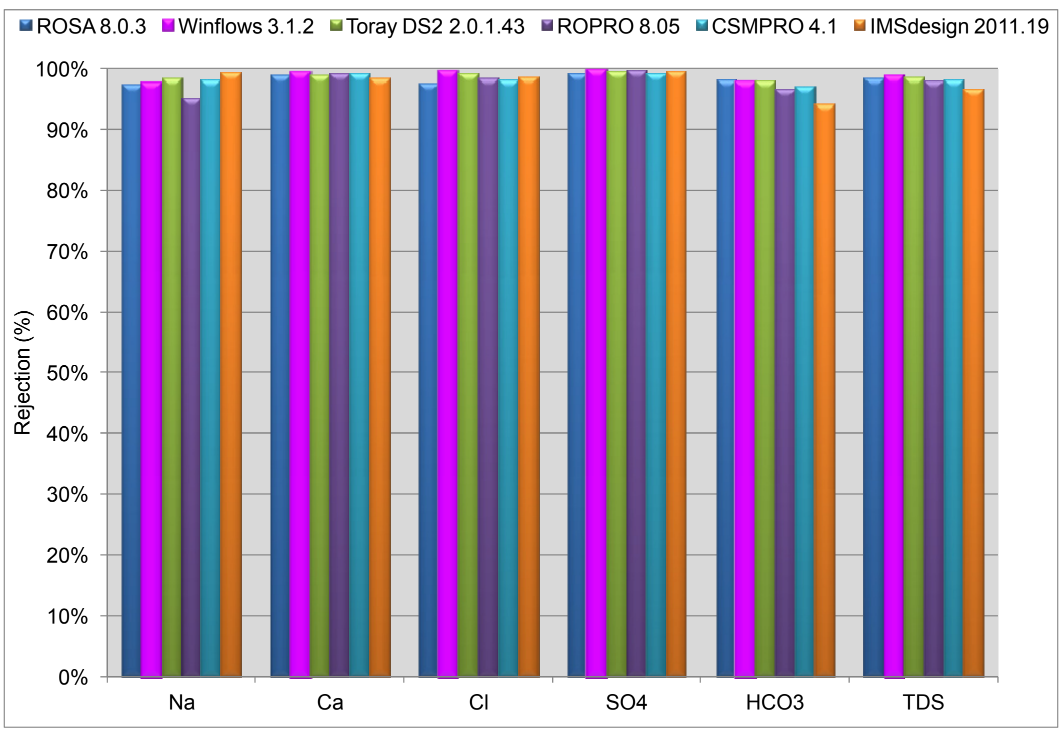

Figure 4-24. Comparison of individual ion and overall salt rejections predicted by computer models simulating clay center operation.

Table 4-12. Summary of relative differences in salt rejections for Clay Center Simulation.

	Relative Difference (percent from mean)					
Computer Model	**Na^+**	**Ca^{2+}**	**Cl^-**	**SO_4^{2-}**	**HCO_3^-**	**Total dissolved solids**
ROSA 8.0.3	-0.9	0.0	-1.4	-0.3	1.4	0.4
Winflows 3.1.2	-0.8	0.3	0.7	0.3	1.1	0.7
Toray DS2 2.01.43	0.0	0.1	0.2	0.0	1.3	0.5
ROPRO 8.05	-3.2	0.2	-0.6	0.2	-0.1	0.0
CSMPRO 4.1	-0.1	0.2	-0.6	-0.4	0.3	0.2
IMSdesign 2011.19	0.9	-0.6	-0.3	0.0	-2.7	-1.5
Average (percent)	97.7	99.0	98.6	99.5	97.0	98.1
Standard deviation (percent)	1.4	0.3	0.7	0.3	1.5	0.8
Coefficient of Variation (percent)	1.4	0.3	0.7	0.3	1.6	0.8

Design warnings were not generated by any of the six models. The ROSA model generated solubility warnings stating that the Langelier Saturation Index and Stiff-Davis Stability Index were greater than zero, and that the barium sulfate and silica percent saturations were greater than 100 percent. The ROPRO, Winflows, and CSM computer models also generated similar solubility warnings.

4.2.2 *Kay Bailey Hutchinson Desalination Plant – five-year operation*

The data point selected for the computer model precision analysis was Train 4 observed on June 7, 2012 at 11:20 am. This data point represents the average day data. The Kay Bailey Hutchinson analysis facilitated a comparison of methods used by different computer models to predict membrane system performance as membrane aging occurs. Over time, both the water permeability and salt rejection of a membrane system may deteriorate. Each of the six computer models evaluated in this study facilitated the simulation of membrane aging, but only four of the models simulated the time variation of both water permeability and salt passage. These four computer models were selected for this evaluation. A detailed discussion of the affects of aging on membrane system performance was provided in Section 3.3. A membrane age of five years, an annual flux decline of 7 percent, and an annual salt passage increase of 10 percent was input into each model. In the TorayDS2 model, flux decline was entered as a fouling allowance factor of 0.65. Table 4-13 lists membrane specifications and testing conditions for each membrane selected for this analysis. For each membrane listed, testing was performed at a temperature of 25 °C, a recovery of 15 percent, and a pH range of 6.5 to 7.5.

Table 4-13 indicates that the AG-400 membrane manufactured by GE has a higher nominal salt rejection than the other three membranes evaluated. As will be discussed later in this section, the AG-400 membrane required a higher feed pressure and produced a higher quality permeate at the same flux and recovery values as the three other membranes selected.

Table 4-13. Selected membranes for Kay Bailey Hutchison five-year precision analysis.

Computer model	Membrane	Area (square feet)	Permeate flow (gallons per day)	Nominal salt rejection (percent)	Test solution	Test solution concentration (milligrams per liter)	Test feed pressure (pounds per square inch)
Winflows 3.1.2	AG-400	400	10,500	99.8	NaCl	2,000	225
Toray DS2 2.01.43	TM720C-400	400	8,200	99.2	NaCl	2,000	150
CSMPRO 4.1	RE8040-BLN	400	12,000	99.2	NaCl	1,500	150
IMSdesign 2011.19	ESPA1	400	12,000	99.3	NaCl	1,500	150

Permeate throttling is incorporated at the Kay Bailey Hutchison facility to manage permeate flux of the stage 1 and stage 2 membranes. Similar to the accuracy analysis, the observed second stage backpressure of 8 pounds per square inch was matched and the first stage permeate throttling pressure was iteratively changed to match the observed first and second stage permeate flux values. A pressure loss of 5 pounds per square inch was applied for interstage manifold losses in Toray and CSM models. IMSdesign assumed a 3 pounds per square inch interstage pressure loss, which is embedded in the model programming. By matching first and second stage flux values, flows and recovery were also matched. This facilitated a meaningful comparison of pressures and rejections predicted by each computer model.

Among the four computer models evaluated, an average feed pressure of 222 pound-force per square inch gauge was predicted with a standard deviation of 25.2 pounds per square inch. The corresponding coefficient of variation was 11.4 percent. The average predicted first stage permeate pressure was 29.7 pounds per square inch with a standard deviation of 16.9 pounds per square inch. Figure 4-25 displays first and second stage feed pressure, concentrate pressure, and permeate backpressures predicted by each computer model.

Table 4-14 presents a summary of the relative percent differences of the pressures.

Table 4-14. Summary of relative differences in reverse osmosis system pressures for Kay Bailey Hutchison simulation.

	Relative differences (percent from mean)				
Computer model	**Feed Stage 1**	**Concentrate Stage 1**	**Throttling Stage 1**	**Feed Stage 2**	**Concentrate Stage 2**
Winflows 3.1.2	16.8	19.3	-100	19.5	21.0
Toray DS2 2.01.43	2.5	-0.2	-31.9	-0.4	1.5
CSMPRO 4.1	-1.7	-8.6	73.4	-9.0	-9.6
IMSdesign 2011.19	-0.8	-10.4	58.5	-10.0	-13.0
Average (pounds per square inch)	222.0	205.2	29.7	200.7	190.4
Standard deviation (pounds per square inch)	25.2	11.2	16.9	10.6	14.4
Coefficient of Variation (percent)	11.4	13.6	81.3	13.7	15.3

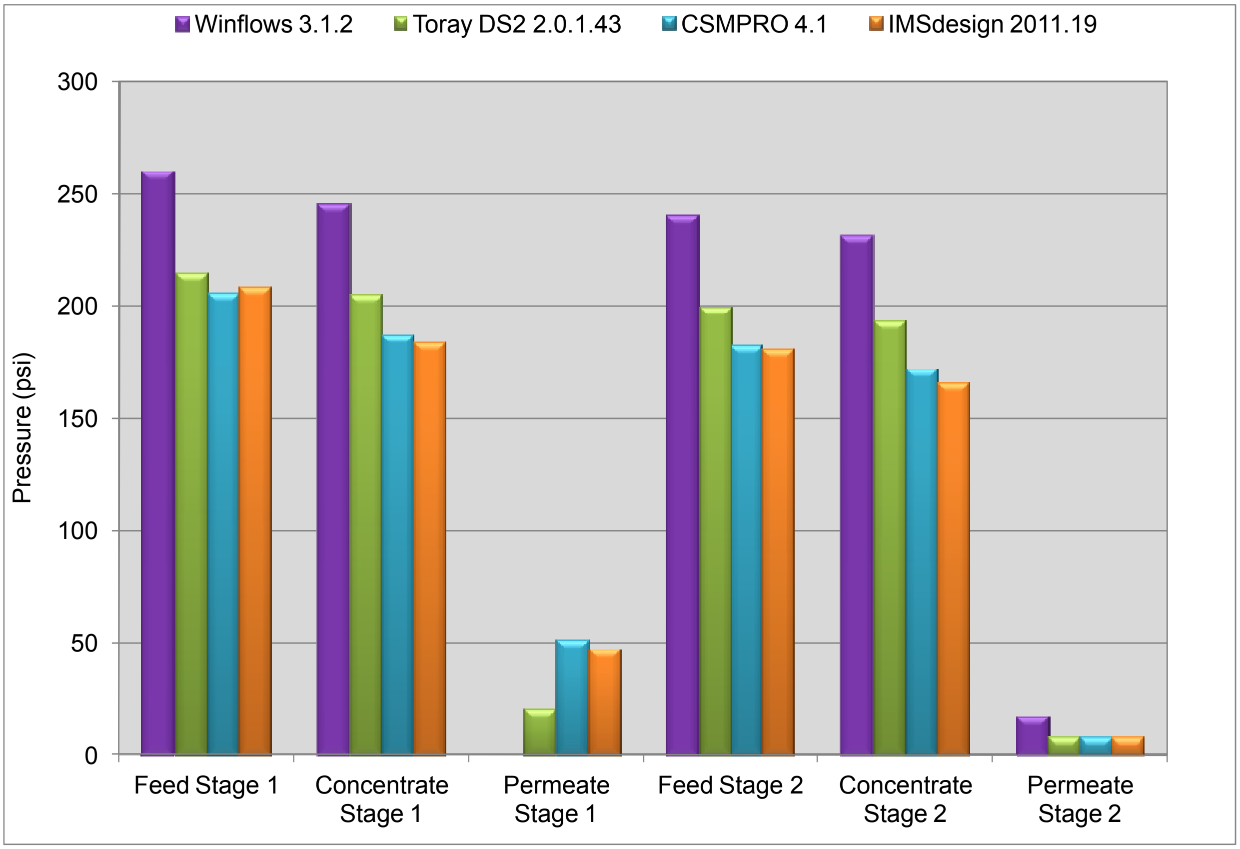

Figure 4-25. Comparison of pressures predicted by computer models simulating Kay Bailey Hutchison year-5 operation.

Bicarbonate and total dissolved solids varied in a small amount from model to model (presumably because of slightly different equilibrium constants used in each model to calculate speciation of the carbonate system). The average model total dissolved solids rejection was 93.8 percent with a standard deviation of 4.4 percent. The ion with greatest deviation among the ions was bicarbonate with average rejection of 85.7 percent and standard deviation of 16.5 percent. Figure 4-26 displays the rejections, and Table 4-15.

Table 4-15 lists the relative percent differences of the rejections for all four models.

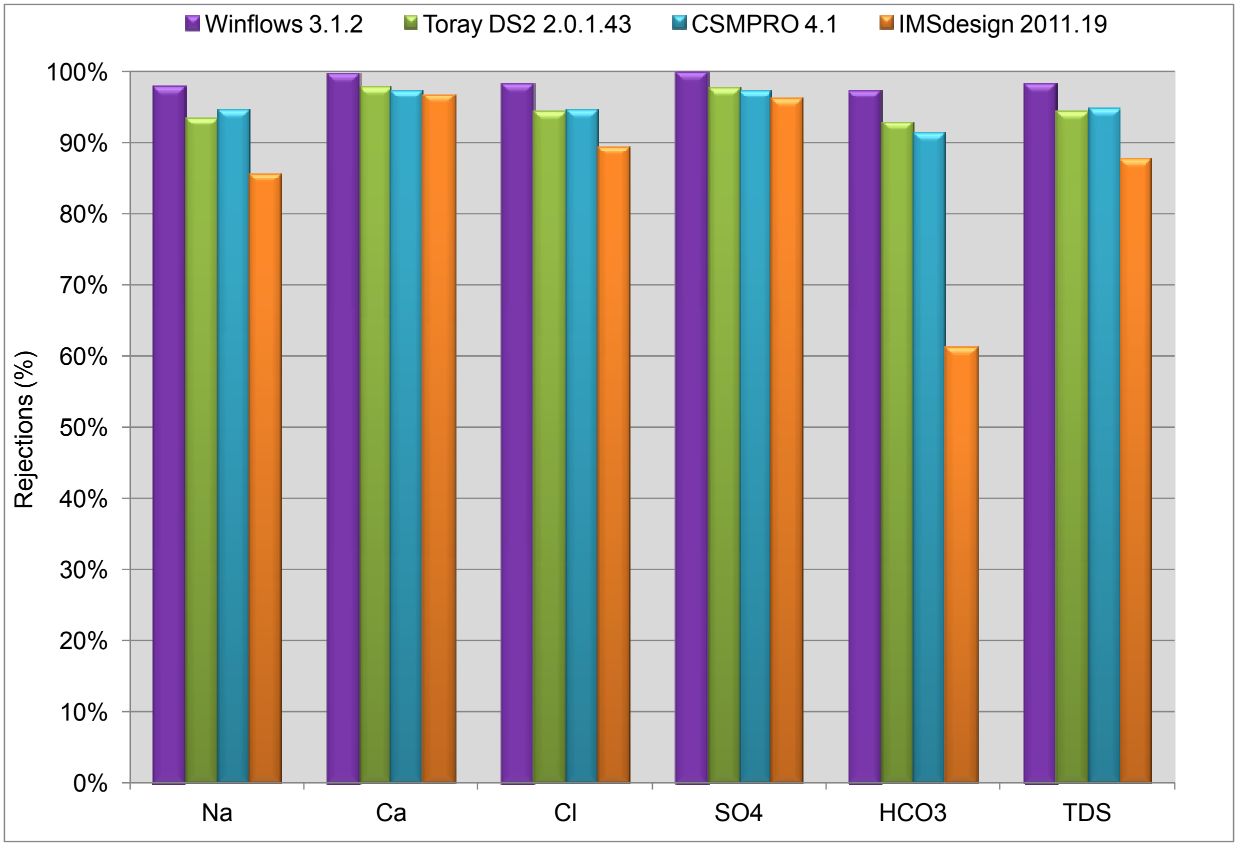

Figure 4-26. **Comparison of Individual ion and overall salt rejections predicted by computer models simulating Kay Bailey Hutchison year-5 operation.**

Table 4-15. **Summary of relative differences in salt rejections for Kay Bailey Hutchison year-five simulation.**

	Relative difference (percent from mean)					
Reverse osmosis model	**Na^+**	**$Ca2^+$**	**Cl^-**	**$S0_4^{2-}$**	**HCO_3^-**	**Total dissolved solids**
Winflows 3.1.2	5.3	1.6	4.2	2.0	13.4	4.7
Toray DS2 2.01.43	0.6	0.1	0.2	-0.1	8.6	0.7
CSMPRO 4.1	1.9	-0.6	0.6	-0.4	6.7	1.1
IMSdesign 2011.19	-7.8	-1.1	-5.0	-1.6	-28.6	-6.5
Average (percent)	93.0	97.9	94.2	97.7	85.7	93.8
Standard deviation (percent)	5.2	1.1	3.6	1.5	16.5	4.4
Coefficient of variation (percent)	5.5	1.2	3.8	1.5	19.3	4.7

The results of this analysis indicate good agreement among three of the computer models (Toray DS2, CSMPRO, and IMSdesign) for predictions of pressure and rejection. The Winflows computer model varies significantly from the average predicted value of first stage feed pressure (16.8 percent relative variation), and consistently predicts greater ion rejections than the other three computer models. This may be attributed to the GE membrane (model AG-400) selected for the Winflows model. This membrane has a higher nominal rejection (99.8 percent) than the other three membranes (99.2 to 99.3 percent). Additionally, higher rejection membranes tend to require higher feed pressure to produce a given permeate flux. This likely contributed to the higher feed pressures predicted by the Winflows model. It is also possible that the Winflows model was programmed to provide a larger degree of conservatism in its pressure predictions than the other three models.

4.2.3 *Capitan Reef aquifer model*

The Capitan Reef is a brackish aquifer in Texas that is being considered for use as a water source. This analysis facilitated a study of the effects of aging and high total dissolved solids concentration (6,000 milligrams per liter) on computer model precision. The membrane selected for the modeling was the Hydranautics ESPA2-LD operating at a recovery of 70 percent. Membrane specifications and testing conditions for the ESPA2-LD, as well as manufacturer equivalents are listed in Table 4-16.

Table 4-16. Selected membranes for the Capitan Reef Precision Analysis.

Computer model	Membrane	Area (square feet)	Permeate flow (gallons per day)	Nominal salt rejection (percent)	Test solution	Test solution concentration (milligrams per liter)	Test feed pressure (pounds per square inch)
Winflows 3.1.2	AG8040F-400	400	10,500	99.5	NaCl	2,000	225
Toray DS2 2.01.43	TM720C-400	400	8,200	99.2	NaCl	2,000	150
CSMPRO 4.1	RE8040-FLR	400	9,000	99.6	NaCl	1,500	150
IMSdesign 2011.19	ESPA2-LD	400	10,000	99.6	NaCl	1,500	150

A permeate backpressure of 15 pounds per square inch was assumed for both stages. An interstage boost pump was used to control first and second stage permeate flux. The four computer models predicted an average first stage feed pressure of 188.6 pound-force per square inch gauge, with a standard deviation of 19.9 pounds per square inch, corresponding to a coefficient of variation of 10.6 percent. The average interstage boost pressure was predicted to be 79.6 pound-force per square inch gauge, with a standard deviation of 5.6 pounds per square inch. Figure 4-27 displays pressure predictions from each model. Table 4-17 shows the relative difference in pressure predictions provided by the computer models.

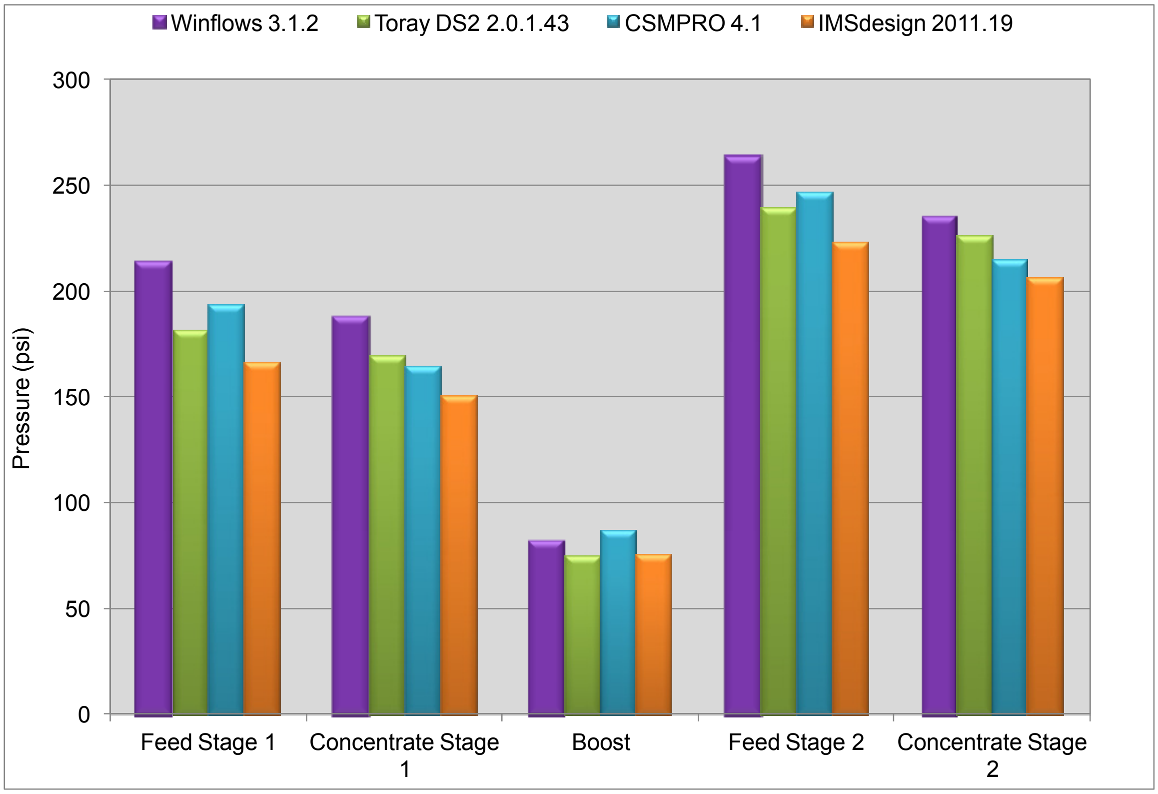

Figure 4-27. Comparison of pressures predicted by computer models simulating Capitan Reef Operation.

Table 4-17. Summary of relative differences in membrane system pressures for Capital Reef Simulation.

	Relative differences (percent from mean)				
Computer model	**Feed Stage 1**	**Concentrate Stage 1**	**Boost**	**Feed Stage 2**	**Concentrate Stage 2**
Winflows 3.1.2	13.2	11.5	2.2	8.4	6.4
Toray DS2 2.01.43	-4.0	0.8	-6.0	-1.6	2.7
CSMPRO 4.1	2.5	-2.0	9.1	1.4	-2.6
IMSdesign 2011.19	-11.8	-10.3	-5.3	-8.2	-6.5
Average (pounds per square inch)	188.6	168.0	79.6	243.1	220.2
Standard deviation (pounds per square inch)	19.9	15.1	5.6	16.8	12.5
Coefficient of variation (percent)	10.6	9.0	7.1	6.9	5.7

Similar to the precision analysis for the Kay Bailey Hutchison Year-5 operation, the Winflows computer model predicted higher system pressures than the other three models. It should be noted that the Hydranautics ESPA2-LD membrane selected for this evaluation has larger 34-mil feed channel spacers than conventional brackish water reverse osmosis membranes. These larger feed channel spacers facilitate a lower pressure drop along the membrane feed channel, which results in a lower feed pressure requirement for a given permeate flux. This lower pressure requirement is evident from Figure 4-29.

A comparison of individual ion rejections predicted by each computer model is shown in Figure 4-28. The average overall salt rejection was 97.7 percent, with a standard deviation of 0.9 percent. Rejection of bicarbonate demonstrated a greater variation with an average of 94.8 percent and a standard deviation of 2.8 percent. The larger variation in bicarbonate rejection may be due to the different methods used by the computer models to determine equilibrium concentrations of the carbonate system species and pH adjustment. Sulfate rejection demonstrated the least variation with an average rejection of 98.9 percent and a standard deviation of 0.6 percent. Table 4-18 lists the relative percent differences for various ion rejections.

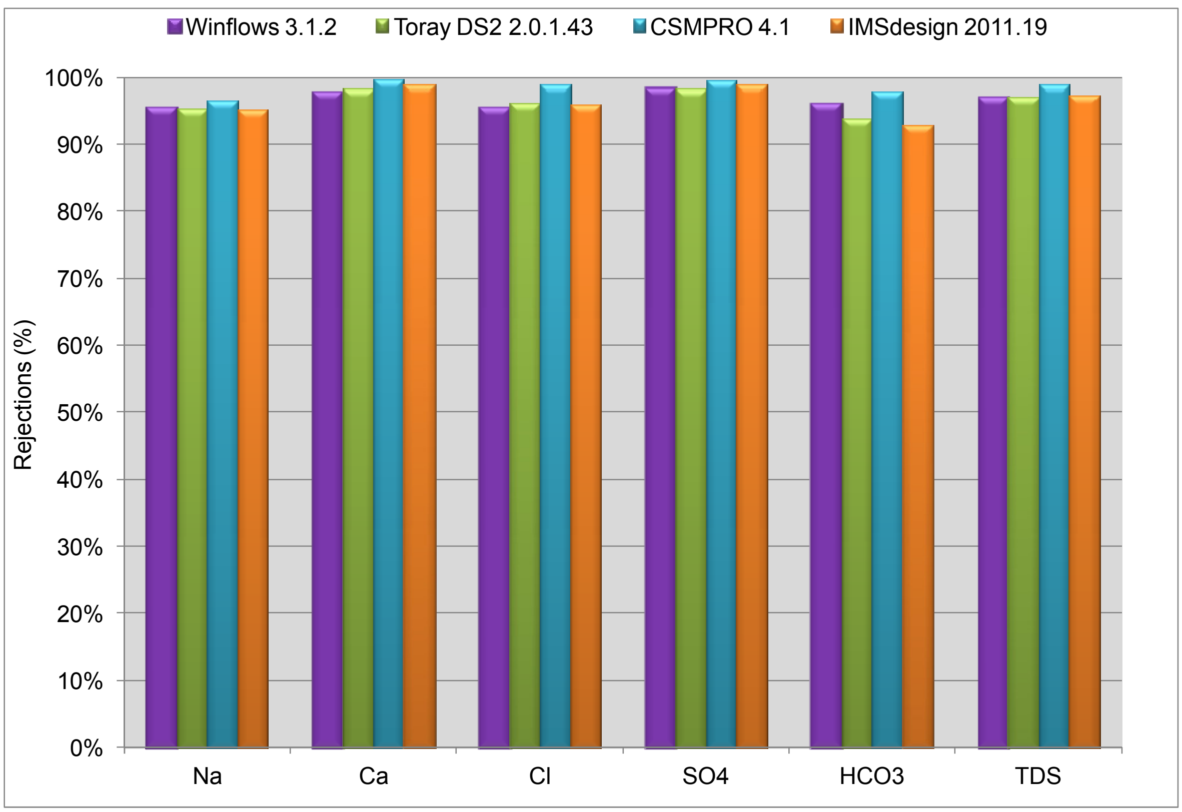

Figure 4-28. Comparison of Individual ion and overall salt rejections predicted by computer models simulating Capitan Reef Operation.

Table 4-18. Summary of relative differences in salt rejections for Capitan Reef Simulation.

	Relative difference (percent from mean)					
Reverse osmosis model	**Na^+**	**Ca^{2+}**	**Cl^-**	**SO_4^{2-}**	**HCO_3^-**	**Total dissolved solids**
Winflows 3.1.2	-0.3	-1.3	-1.7	-0.6	1.2	-0.8
Toray DS2 2.01.43	-0.4	-0.6	-0.8	-0.6	-1.1	-0.7
CSMPRO 4.1	1.0	0.7	1.9	0.5	3.2	1.1
IMSdesign 2011.19	-0.6	0.0	-1.1	0.1	-2.1	-0.4
Average	95.7	99.0	97.0	98.9	94.8	97.7
Standard deviation	0.8	0.7	1.6	0.6	2.7	0.9
Coefficient of variation	0.8	0.7	1.7	0.6	2.8	1.0

Scale warnings were generated in all models stating that saturation limits were exceeded for calcium sulfate, barium sulfate, and strontium sulfate. Additionally, the Langelier Saturation Index and Stiff-Davis Stability Index exceeded the recommended limits, and a warning recommended the use of a scale inhibitor or pH adjustment of the feed water. Winflows generates design warnings indicating that the elements limits were exceeded for permeate flux, recovery, and flow rate.

4.3 Pilot test vs. computer model evaluations

4.3.1 North Lee County

In addition to data related to the performance of the full-scale membrane system at start-up, the data set provided for the North Lee County reverse osmosis facility contained performance data from a demonstration-scale pilot study that was performed for sixteen months between October 2009 and January 2011. An evaluation of the pilot test data was conducted to quantify the differences between the pilot test performance, computer model predictions, and the actual performance of the full-scale membrane system.

The net applied pressure is the driving force that causes water to permeate through a reverse osmosis membrane. Net applied pressure is given by the equation:

$$NAP = \Delta P - \Delta \pi \qquad \text{Equation 4-1}$$

Where:

NAP = Net applied pressure
ΔP = Transmembrane pressure differential, pounds per square inch
$\Delta \Pi$ = Differential osmotic pressure across the membrane, pounds per square inch

Transmembrane pressure differential is the average feed-concentrate side pressure minus the permeate side pressure. Differential osmotic pressure is a function of the salinity of the feed-concentrate and permeate streams.

First and second stage net applied pressure for the membrane system pilot, computer model, and full-scale start-up are presented in Figure 4-26. Net applied pressure values for the full-scale start-up were calculated from average daily pressures.

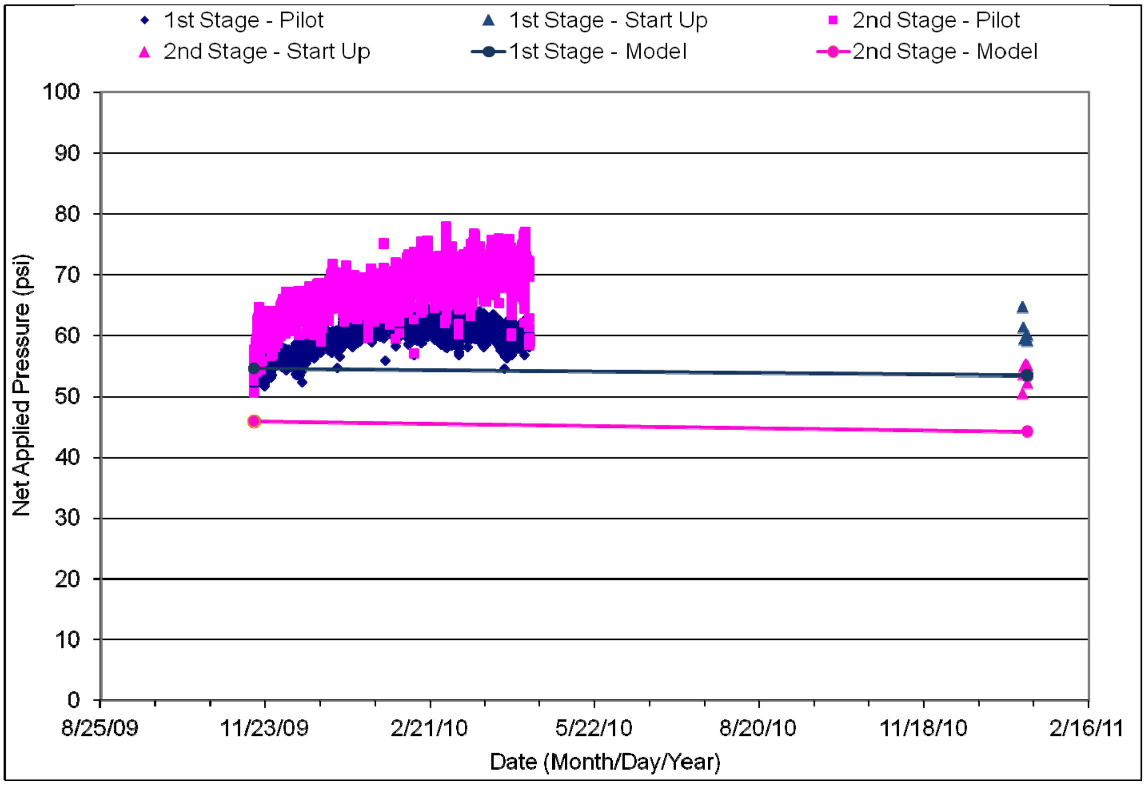

Figure 4-29. North Lee County net applied pressure comparison.

The computer model provided a reasonable approximation of first stage net applied pressure for both the pilot study and full-scale start-up with an under prediction of 11.8 percent relative to the start-up condition. The computer model under predicted second stage net applied pressure at the start-up condition by a similar margin. Figure 4-30 indicates that the computer more accurately predicted second stage net applied pressure than the pilot study projected for the startup condition.

Overall salt rejection predicted by the computer model, and observed during the pilot study and full-scale startup is presented in Figure 4-30.

The initial rejection of the pilot is similar to the full-scale startup rejection. The model rejection is less than the long-term pilot rejection. It should be noted that the available data representing full-scale start-up conditions might not be representative of stabilized membrane system performance. Data gathered a week or two after start-up may have reflected a higher overall salt rejection (more closely matching the computer model prediction) than the values presented in Figure 4-30.

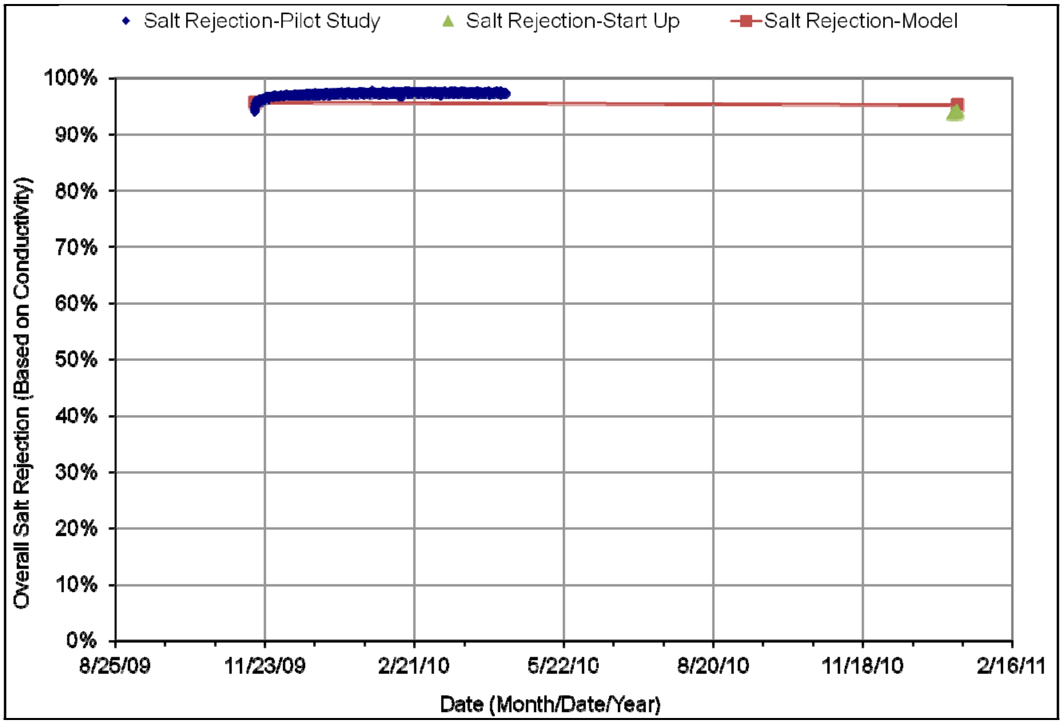

Figure 4-30. North Lee County overall salt rejection.

4.3.2 San Antonio Water System

A reverse osmosis pilot study was performed for the San Antonio Water System. The purpose of the pilot study was to obtain data to be used as a basis for the final design, permitting, and construction of a full-scale reverse osmosis system to treat brackish groundwater from the Wilcox Formation near San Antonio, Texas. A demonstration-scale pilot test of a three stage reverse osmosis membrane system achieved 55 days of total operation between April and June 2009.

The purpose of the following evaluation was to compare the results of the demonstration-scale pilot test with computer performance projections. The membranes used in the pilot test were manufactured by Toray. Because the computer model provided by Toray did not facilitate the modeling of the 2.5-inch membranes used in the third stage of the demonstration-scale pilot plant, in consultation with Toray, a full-scale reverse osmosis train was simulated by scaling up the pilot test unit from 18 gallons per minute to 1,491 gallons per minute (2.15 million gallons per day). To facilitate a meaningful comparison between pilot test results and the computer model projections, permeate flux and recovery of the simulated full-scale reverse osmosis train were constrained to match the pilot test values for each membrane stage.

Design parameters for the demonstration-scale pilot unit and the simulated full-scale reverse osmosis train are presented in Table 4-19.

Table 4-19. San Antonio Water System demonstration-scale pilot design parameters.

Parameter	Unit	Pilot	Full-scale
Membrane stages	Number	3	3
Overall recovery	Percent	90	90
Feed flow rate	Gallons per minute	20	1,655
Permeate flow rate	Gallons per minute	18	1,491
Average system permeate flux	Gallons per square feet per day	14.9	14.9
Feed water total dissolved solids	Milligrams per liter	1,581	1,581
Feed water temperature	Degree Celsius	32.6	32.6
Stage 1			
Membrane elements	Model	Toray TM-710	TM720D-400
Area	Square feet	87	400
Stabilized salt rejection	Percent	99.7	99.8
Rated permeate flow	Gallons per minute	1.67	7.64
Elements per Vessel	Number	6	6
Vessels per Stage	Number	2	36
Average permeate flux	Gallons per square feet per day	14.9	14.9
Recovery	Percent	54	54
Stage 2			
membrane elements	Model	Toray TM-710	TM720D-400
area	Square feet	87	400
stabilized salt rejection	Percent	99.7	99.8
Rated permeate flow	Gallons per minute	1.67	7.64
Elements per vessel	Number	6	6
Vessels per stage	Number	1	18
Average permeate flux	Gallons per square feet per day	16.0	16.0
Recovery	Percent	63	63
Stage 3			
membrane elements	Model	Toray TM7-2540	TM720D-400
area	Square feet	29	400
stabilized salt rejection	Percent	99.7	99.8
rated permeate flow	Gallons per minute	0.56	7.64
elements per vessel	Number	6	6
vessels per stage	Number	1	6
average permeate flux	Gallons per square feet per day	11.8	11.8
Recovery	Percent	42	42

The pilot unit incorporated second and third stage permeate throttling as well as interstage pressure boosting between the first and second stages. Interstage boost pressure and permeate pressure were iteratively adjusted in the computer model to match the recovery and flux values of the pilot test for each stage.

Analytically determined feed water data was available for the pilot study and was used in the computer model.

A summary comparison of average pilot testing results and computer model performance projections are provided in Table 4-20.

Table 4-20. San Antonio Water System demonstration-scale pilot vs computer model comparison.

Parameter	Unit	Computer model	Pilot average	Percent relative difference
Feed pressure				
Stage 1	Pound-force per square inch gauge	109.2	116.6	-6.55
Stage 2	Pound-force per square inch gauge	206.7	199.6	4.39
Stage 3	Pound-force per square inch gauge	196.0	192.9	1.59
Second stage boost	Pound-force per square inch gauge	110	91.3	18.6
Permeate pressure				
Stage 1	Pound-force per square inch gauge	4	4.5	-11.8
Stage 2	Pound-force per square inch gauge	62	50	21.4
Stage 3	Pound-force per square inch gauge	12	8	40
Concentrate pressure				
Stage 1	Pound-force per square inch gauge	101.7	113.3	-10.8
Stage 2	Pound-force per square inch gauge	201	192.9	4.11
Stage 3	Pound-force per square inch gauge	187.6	170.8	9.37
Overall salt rejection	Percent	99.0	97.9	1.1
Individual ion rejection				
Sodium	Percent	99.0	98.0	1.0
Calcium	Percent	99.6	99.5	0.1
Chloride	Percent	98.6	98.5	0.1
Sulfate	Percent	99.5	99.7	-0.2

Table 4-20 indicates that feed pressures were similar between the pilot study and the computer model, with a maximum relative difference of -6.55 percent associated with the first stage feed pressure. Permeate backpressure and second stage boost pressure were adjusted in the computer model to match the permeate flux values observed during the pilot test. As such, they demonstrated the greatest relative difference among operating pressures.

The computer model over predicts overall salt rejection by 1.1 percent. Rejections for individual ions are very close, with the sodium demonstrating the greatest relative difference at 1 percent.

A graphical comparison of first stage feed pressures and overall salt rejections is provided in Figure 4-31.

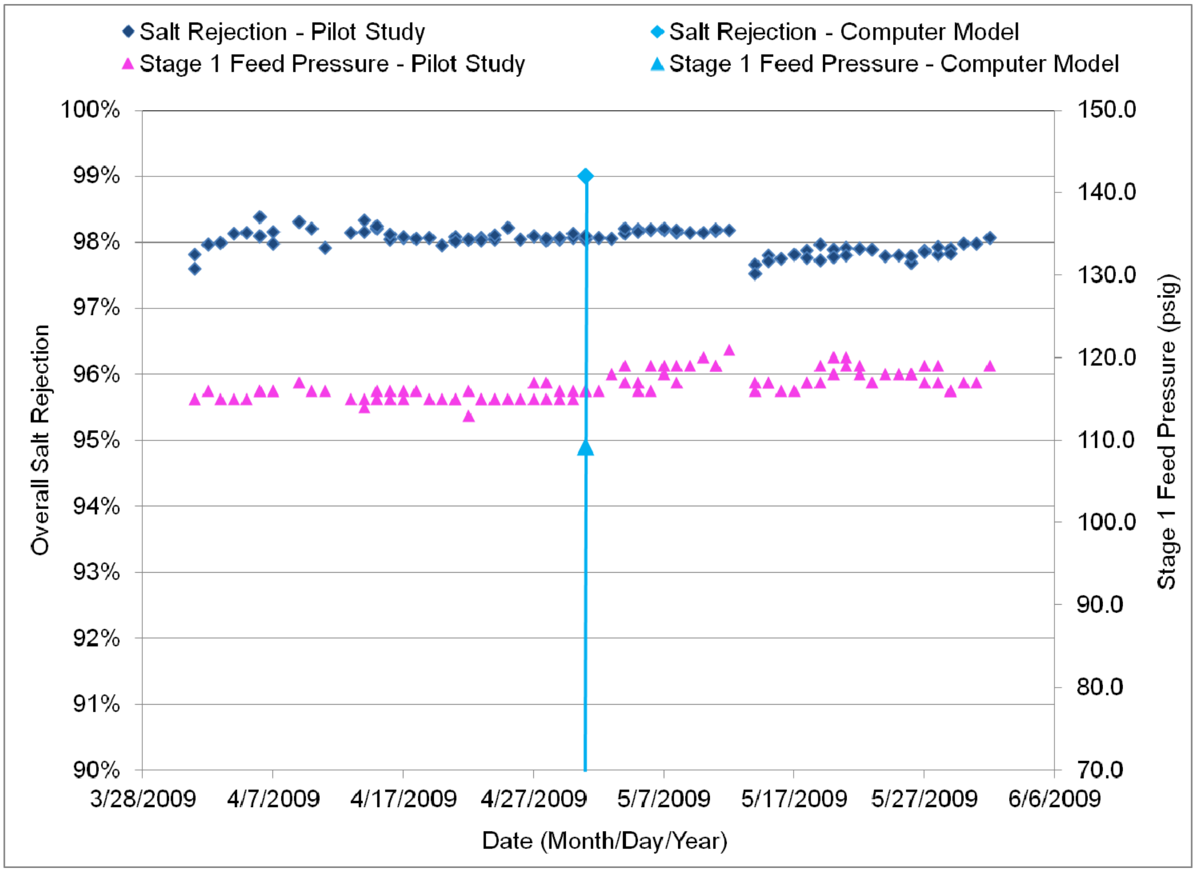

Figure 4-31. SAWS Evaluation – Comparison of Stage 1 feed pressure and overall salt rejection for pilot data (time series) and model data (median points emphasized with vertical line).

The value of this evaluation is that it demonstrates the similar performance provided by pilot testing and computer models in predicting the performance of a full-scale reverse osmosis membrane system.

In addition to the demonstration-scale pilot test that was performed using the Toray membranes, two (2) single element pilot tests were performed in parallel with the demonstration scale pilot using membranes manufactured by Dow Filmtec and Hydranautics. The purpose of using single-element pilot plants instead of demonstration-scale pilot plants is primarily to reduce the amount of water required both for supply and disposal. The data obtained from a single-element pilot test can be used to determine if special considerations are necessary regarding lead element fouling or tail element scaling. Although the hydraulic performance and permeate quality associated with a single membrane element is not similar to that of a high recovery, multi-stage reverse osmosis array, data from the single-element testing can be compared to the membrane manufacturer's computer model at the conditions tested. Adherence of the single element test data to the projected performance will validate the model and allow for performance comparisons of a full-scale system using the manufacturer's computer model.

Design parameters for the two single-element pilot test units are provided in Table 4-21.

Table 4-21. San Antonio Water System single-element pilot design parameters.

Parameter	Unit	Dow filmtec pilot	Hydranautics pilot
Elements	Number	1	1
Overall recovery	Percent	10.8	12.6
Feed flow rate	Gallons per minute	8.74	8.72
Permeate flow rate	Gallons per minute	0.94	1.10
Element permeate flux	Gallons per square feet per day	17.35	18.6
Feed water total dissolved solids	Milligrams per liter	1,581	1,581
Feed water temperature	Degrees Celsius	32.6	32.6
Membrane element	Model	BW30-4040	ESPA2-4040
Area	Square feet	78	85
Stabilized salt rejection	Percent	99.7	99.6
Rated permeate flow	Gallons per minute	1.67	1.32

The single element pilot test units were supplied the same feed water as the Toray demonstration-scale unit. Computer models of similar full-scale multi-stage reverse osmosis trains were created for each membrane manufacturer. Flux and recovery values for the single-element pilot tests were selected to represent the operating conditions of the lead elements in the simulated full-scale, multi-stage reverse osmosis trains.

Summaries of the single-element pilot testing results that include comparisons to the computer model projections at the testing conditions are provided in Table 4-22.

Table 4-22. San Antonio Water System single-element pilot vs computer model comparison.

Parameter	Unit	Computer model	Pilot average	Percent relative difference
Dow Filmtec Pilot				
Feed Pressure	Pound-force per square inch gauge	124.0	132.3	-6.5
Permeate Pressure	Pound-force per square inch gauge	17	17	0
Concentrate Pressure	Pound-force per square inch gauge	121.8	129.3	-6.0
Overall Salt Rejection	Percent	98.8	97.6	1.3
Individual Ion Rejection				
Sodium	Percent	98.8	97.4	1.4
Calcium	Percent	99.5	99.2	0.3
Chloride	Percent	98.5	98.2	0.4
Sulfate	Percent	99.2	99.0	-0.2
Hydranautics Pilot				
Feed Pressure	pound-force per square inch gauge	135.3	119.2	12.7
Permeate Pressure	pound-force per square inch gauge	33.8	33.8	0
Concentrate Pressure	pound-force per square inch gauge	130.8	114.9	12.9
Overall Salt Rejection	Percent	99.5	98.25	1.3
Individual Ion Rejection				
Sodium	Percent	99.4	98.6	1.0
Calcium	Percent	99.9	99.9	0.0
Chloride	Percent	99.2	98.9	0.3
Sulfate	Percent	99.8	99.8	0.0

The results presented in Table 4-22 indicate that the Hydranautics computer model over predicted membrane feed pressure by 12.7 percent, while the Filmtec model under predicted feed pressure by 6.5 percent. Both models over predicted overall salt rejection by 1.3 percent. The degree of accuracy to which the computer models predicted the performance of the single membrane elements was comparable to the accuracy demonstrated by the models simulating the full-scale membrane facilities discussed earlier in this Chapter.

5 Conclusions

A key finding of this research is the acknowledgement of the predictive value of available computer models for reverse osmosis membrane systems. Computer models are not perfectly accurate or precise, but these models demonstrate sufficient accuracy and precision to warrant reliance by design engineers, researchers, and regulators for the prediction of the stabilized performance of reverse osmosis membrane systems treating brackish groundwater. General trends observed from the accuracy and precision analyses of these models are summarized here.

5.1 Limitations of the Evaluation

Acknowledgement of the cumulative error introduced to the accuracy and precision evaluations, from data collection and throughout the analysis, is important. Sources of error for this study can be assigned to one of the two following categories:

1. Inaccurate or incomplete data
2. Systematic errors

A discussion of the general sources of error in each category listed above follows.

5.1.1 Inaccurate or Incomplete Data

It is possible that the data used in these evaluations included error from multiple sources, such as human error commonly associated with manual data entry, machine error from data acquisition system malfunctions, or error associated with unsteady operation of the membrane system. Furthermore, some of the data sets used in this study were limited to a small number of data points, which may or may not be representative of stabilized full-scale operation. Start-up data based on the first few days of system operation does not account for changes in salt rejection and permeability (also known as, specific flux) commonly observed during the conditioning period of a membrane system's lifecycle. As such, the start-up data provided may not represent stabilized system performance. A systematic procedure was implemented for the accuracy and precision analyses, but even the best systematic procedure cannot eliminate error introduced by inaccurate or incomplete data.

Likely, the most significant source of error in the accuracy analysis was the limited availability of analytically derived feed water quality data representing start-up conditions. The limited nature of the available feed water quality data necessitated the use of two analytical methods, which may have introduced systematic error into the evaluations: (1) The use of a derived conductivity-to-total dissolved solids conversion factor, and (2) The adjustment of individual ions proportional to feed water conductivity.

Additionally, several of the data sets provided did not include information regarding permeate backpressures for individual membrane stages, and none of the available data sets contained information that specified the exact locations representing recorded membrane feed pressures.

Systematic Errors

In every case, the best available data representing start-up conditions was used in the computer modeling effort. In many cases, due to incomplete data representing feed water quality at start-up conditions, conductivity data was used to approximate feed water total dissolved solids based on a derived conductivity-to- total dissolved solids conversion factor. The limitations of this method were discussed earlier in this report. The conversion of conductivity to total dissolved solids is common practice in the brackish water desalination industry, particularly when determinations must be made in the field where analytical methods are cumbersome or impossible. It is not however, the most accurate method for determining total dissolved solids. Small changes in the derived conversion factor can influence total dissolved solids values and subsequent system performance projections generated by computer models. As demonstrated earlier in this report, increasing the conductivity-to- total dissolved solids factor used in the Goldsworthy accuracy evaluation from 0.51 to 0.55 reduced the relative error (between the computer model prediction and the values observed during full-scale start-up) in first stage feed pressure from 3.7 to 1.6 percent. This highlights the importance of obtaining the best feed water quality data when designing an reverse osmosis membrane system with computer models. In most cases, analytically-determined feed water quality data that provides information regarding the concentration of individual ion constituents should be obtained by the design engineer.

In several cases, analytically determined feed water quality data representing conditions observed during the original facility design was available, but such data representing start-up conditions was unavailable. In these cases, the ratio of original design and start-up conductivities was used to proportionally adjust the concentration of individual ions recorded during the original design to represent start-up concentrations. This method is often used in industry to adjust feed water quality due to small variations in conductivity. The advantage of this method is that it eliminates the repetition of expensive and time-consuming analytical tests. The disadvantage of this method is that it may not accurately represent the changes in concentrations of individual ion constituents. In many cases, a change in feed water conductivity is due to an increase or decrease in a small number of individual ions (e.g., sodium and chloride). Individual ionic species contribute differently to the osmotic pressure of a solution. As such, osmotic pressure is not only related to the total dissolved concentration, but also the concentration of individual species in the feed water. The error introduced by this method is expected to be less than the error caused by the estimation of total dissolved solids from conductivity.

Finally, the use of a computer model introduces an inherent source of systematic error into the accuracy and precision evaluations. As discussed earlier, different computer models address issues such as interstage piping pressure losses, and membrane aging affects in different ways. Users of these models must be aware of the differences and limitations associated with the methods incorporated by each of the models. These models, if used properly, serve as reasonably accurate tools for predicting membrane system performance. To facilitate and ensure the proper use of these models by design engineers, researchers, and regulators, there is a need for a standardized manual of practice for the use of computer models for the design of reverse osmosis membrane systems (see the Texas Water Development Board *Manual of Practice for the Use of Computer Models for the Design of Reverse Osmosis/Nanofiltration Membrane Processes*).

5.2 Trends of Major Parameters

A general trend observed in the accuracy analyses is that operating pressures and salt rejections tend to be over-predicted by the model. The over-prediction was greater for operating pressures (as high as 31 percent) compared to salt rejections (as high as 5 percent). The greatest percent error was that observed in the analyses of interstage boost pressures and permeate backpressures. In the precision analysis, the spread of the relative differences in operating pressures was greater than salt rejections (overall and individual ions).

5.3 Computer Model Accuracy and Precision

5.3.1 *Accuracy*

The error associated with the accuracy of computer models in predicting membrane feed pressures ranged from an under-prediction of 7.4 percent to an over-prediction of 31.3 percent. The computer models prediction of second stage concentrate pressure had a percent error ranging from -13.2 percent to + 47.7 percent. It is possible that some computer models incorporate a "safety factor" in the prediction of required feed pressures, as these are used to size feed pumps. Such embedded safety factors make the models less accurate, but are more conservative from a design perspective. Conservative models may increase the reliability of water production, but at the expense of less efficient operation.

Salt rejections were generally over-predicted by the computer models. The degree of error varied from 0.1 to 5.9 percent. Table 5-1 presents the percent error associated with the operating pressures and salt rejections predicted by the computer models for each accuracy evaluation. Figure 5-1 presents a box plot of the percent error data for computer model predictions of operating pressures and salt rejection. A box plot is a convenient tool for visualizing the variability within a data set. The top of each box represents the third quartile of the percent error data set. Twenty-five percent of percent error values were determined to be above this value. The bottom of each box represents the first quartile of the percent error data set. Twenty-five percent of percent error values were determined to be below this value. The line through each box represents the second quartile, or median, of the percent error data set. The single data point within the box represents the mean, or average, of the data set. The small horizontal hash mark at the top of the "whisker" above the third quartile represents the maximum data point. The hash mark at the bottom of the "whisker" below the first quartile represents the minimum data point.

Figure 5-1 indicates that variability in percent error was considerably greater for operating pressures than for salt rejection. Figure 5-1 also indicates that most predictions for first stage feed pressure were conservative. Predicted values of first stage feed pressure were generally higher than the actual values observed during the start-up of the full-scale facilities.

The statistical analysis performed using conductivity measurements from permeate samples taken from parallel pressure vessels at several full-scale plants demonstrated that the error associated with the computer models is not expected to be exceeded by the variability in performance observed in the field due to membrane manufacturing processes.

Table 5-1. Accuracy Analysis - Summary of computer model errors for pressures and rejection.

		Pressure					Salt rejection		
Facility	**Train**	**Stage 1 Feed pressure**	**Stage 1 concentrate pressure**	**Interstage Boost Pressure**	**Stage 2 concentrate pressure**	**Stage 1 permeate pressure**	**Overall**	**Stage 1**	**Stage 2**
Eastern Correctional Institute	A	6.1	-	-	7.9	-	1.2	1.2	-
	B	12.1	-	-	13.3	-	1.4	1.3	-
Goldsworthy	A	-7.4	-7.7	-	-13.2	17.0	0.64	-	-
Scottsdale	A	-0.1	-	-	-	25	0.3	0.5	-
Clay Center	A	11.0	18.1	-10.8	3.9	-	0.2	0.6	-0.3
	B	6.4	7.8	-4.2	-0.1	-	0.1	0.4	-0.3
Hardinsburg	A	7.1	1.6	-	-3.5	209.4	3.4	-	-
	B	6.9	3.9	-	0.1	145.6	2.9	-	-
Kay Bailey Hutchison Start-up	A	14.3	13.2	-	8.1	52.1	3.4	2.3	-
	B	23.7	22.2	-	17.6	64.8	5.9	2.3	-
	C	6.2	5.4	-	8.9	57.9	0.2	-0.2	-
	D	21.9	21.9	-	17.8	41.1	3.6	3.3	-
	E	23.3	20.0	-	18.8	32.2	5.0	4.3	-
Kay Bailey Hutchison 5-Year	A	19.4	26.6	-	25.8	27.8	4.8	-	-
	B	31.3	40.0	-	47.7	54.7	1.0	-	-
	C	13.3	18.6	-	16.5	8.8	0.8	-	-
	D	23.5	28.2		28.1	29.3	1.8	-	-
North Lee County	A	-0.2	-9.6	12.2	-7.4	-	2.7	2.3	1.9
	B	-0.1	-8.4	4.4	-9.0	-	2.3	1.9	1.7

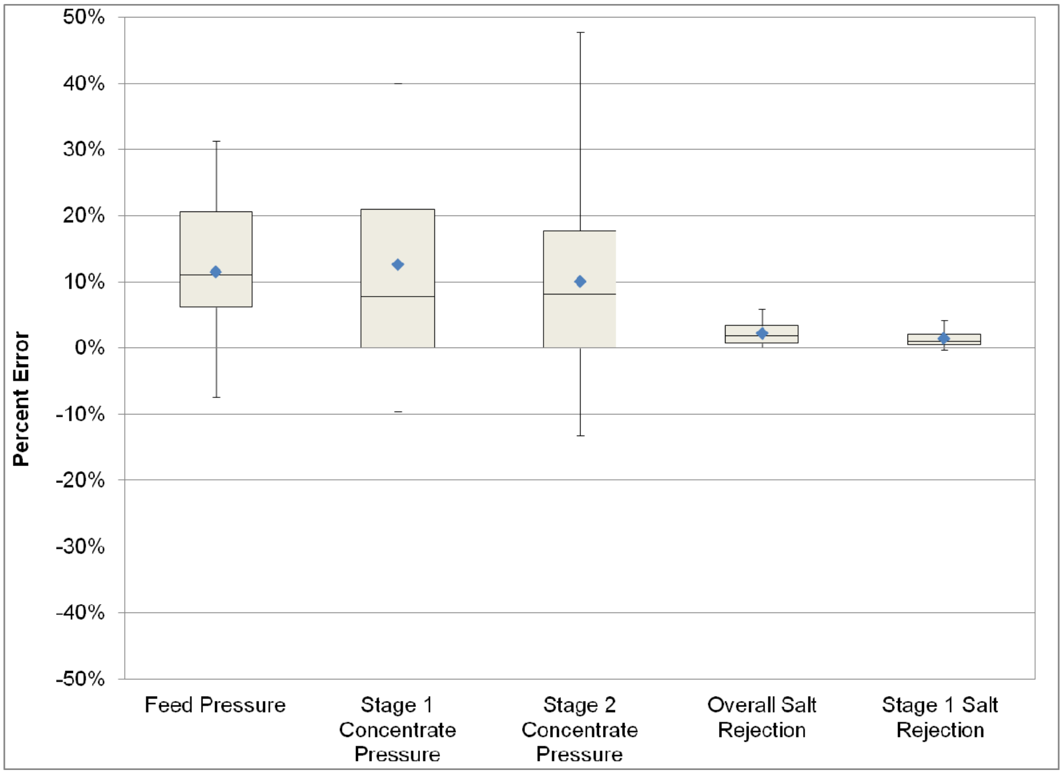

Figure 5-1. Accuracy Analysis - Distribution of pressure and rejection errors.

5.3.2 Precision

Table 5-2 and Table 5-3 present the relative differences for operating pressures and salt rejections, respectively. Figure 5-2 indicates that the relative differences for first and second stage concentrate pressure are the greatest, while the relative difference for first stage feed pressure and interstage pressure boost is the smallest. Figure 5-3 presents the relative differences for the rejection of individual ion constituents, and total dissolved solids. The spread of relative differences for calcium and sulfate is the smallest among the various ions. The greater relative difference for sodium and chloride was a direct result of these salts being used in the computer models to balance the electro neutrality of the membrane feed water at several membrane facilities. This adjustment of the sodium and chloride concentrations also resulted in a change in the total dissolved solids concentrations. Bicarbonate demonstrates the largest variability among the computer models evaluated. This is likely due to the different methods used by each computer model to calculate the speciation of the carbonate system.

Table 5-2. Precision Analysis - Summary of relative differences in reverse osmosis system pressures.

Facility	Membrane manufacture	Stage 1 Feed pressure	Stage 1 concentrate pressure	Interstage boost Pressure	Stage 2 Feed pressure	Stage 2 concentrate pressure
Clay Center	Dow	1.7	-11.6	16.6	0.7	-6.5
	GE	2.3	-2.9	1	2.3	
	Toray	-2.3	-1.4	-5.4	1.3	8.4
	Koch	12.7	17.4	-22.6	9.9	19.6
	CSM	-7.4	21.5	-5.4	-7.7	-8.2
	Hydranautics	-7.1	-23	15.7	-6.5	-16.3
Kay Bailey Hutchison 5-Year	GE			-	19.5	21.0
	Toray	2.5	6.6	-	-0.4	1.5
	CSM	-1.7	-2.3	-	-9.0	-9.6
	Hydranautics	-0.8	-4.3	-	-10.0	-13.0
Capitan Reef Aquifer	GE	13.2	11.5	2.2	8.4	6.4
	Toray	-4	0.8	-6	-1.6	2.7
	CSM	2.5	-2	9.1	1.4	-2.6
	Hydranautics	-11.8	-10.3	-5.3	-8.2	-6.5

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Table 5-3. Precision Analysis - Summary of relative differences in reverse osmosis system salt rejections.

Facility	Manufacture	Na^{+}	Ca^{2+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	TDS
Clay Center	Dow	-0.9	0	-1.4	-0.3	1.4	0.4
	GE	-0.8	0.3	0.7	0.3	1.1	0.7
	Toray	0	0.1	0.2	0	1.3	0.5
	Koch	-3.2	0.2	-0.6	0.2	-0.1	0
	CSM	-0.1	0.2	-0.6	-0.4	0.3	0.2
	Hydranautics	0.9	-0.6	-0.3	0	-2.7	-1.5
Kay Bailey Hutchison 5-Year	GE						
	Toray	2.4	0.6	1.7	0.6	13.6	2.3
	CSM	3.8	-0.1	2	0.3	11.7	2.7
	Hydranautics	-6.1	-0.5	-3.7	-0.9	-25.3	-5
Capitan Reef	GE	-0.3	-1.3	-1.7	-0.6	1.2	-0.8
	Toray	-0.4	-0.6	-0.8	-0.6	-1.1	-0.7
	CSM	1	0.7	1.9	0.5	3.2	1.1
	Hydranautics	-0.6	0	-1.1	0.1	-2.1	-0.4

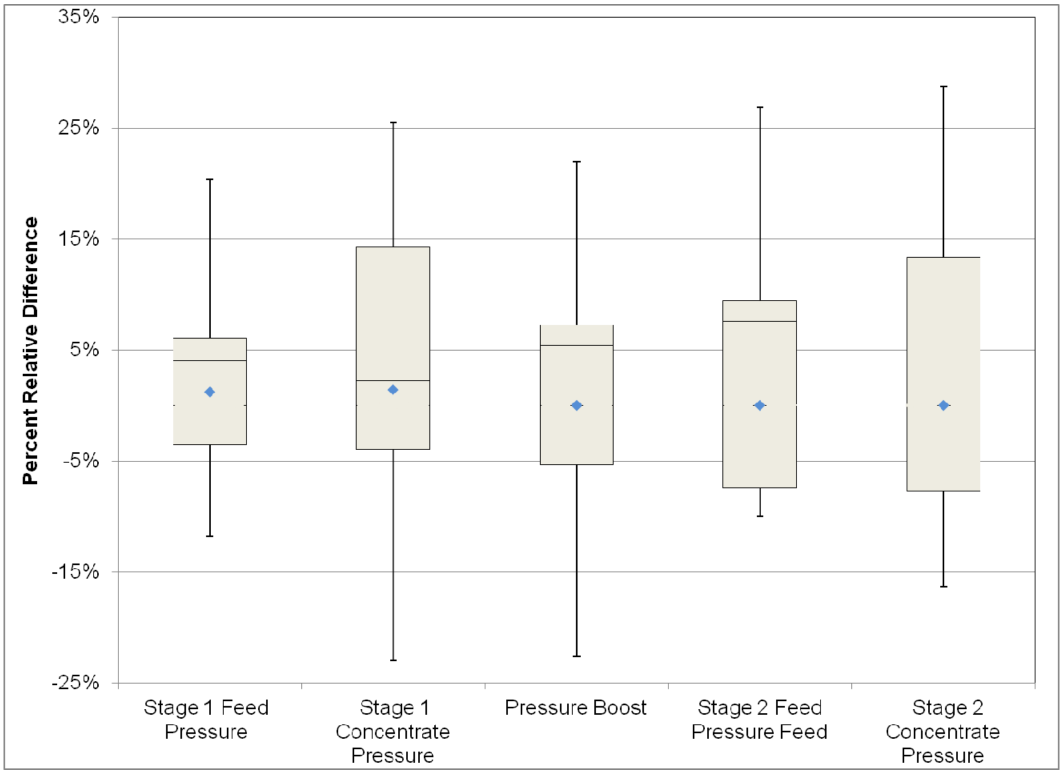

Figure 5-2. Precision Analysis - Distribution of percent relative differences in operating pressures.

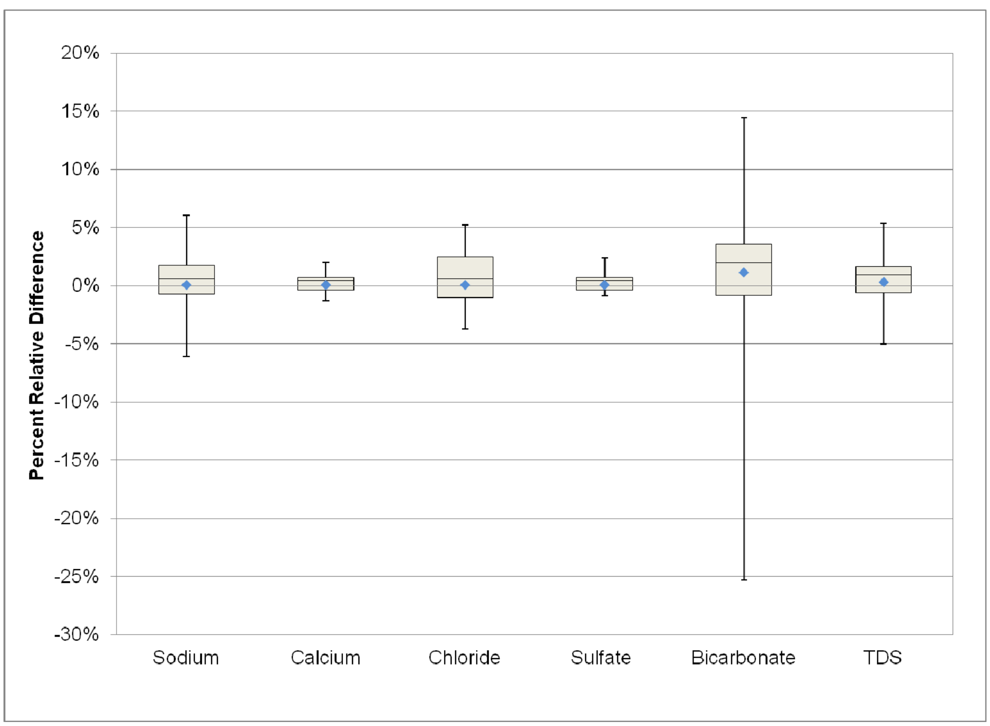

Figure 5-3. Precision Analysis - Distribution of percent relative differences in rejections.

5.4 Discussion

In summary, the overall accuracy and precision demonstrated by the computer models evaluated as part of this study were within a reasonable level of expectation despite potential errors associated with the quality of the start-up data available. The level of accuracy for first stage feed pressures was sufficient to facilitate a conservative selection of a first stage feed pump. The level of accuracy for rejection of most ion constituents and total dissolved solids was within the expected range considering limited nature of start-up feed and permeate water quality data provided. Computer model accuracy was comparable to the accuracy provided by the results of the pilot study for the one full-scale facility (North Lee County) for which pilot test data was available. Another pilot study (San Antonio Water System) evaluation demonstrated the similarity of performance provided by pilot testing and computer models in predicting the performance of a full-scale reverse osmosis membrane system. The computer models created to predict the performance of the membranes used during the San Antonio Water System single-element pilot tests demonstrated a sufficient degree of accuracy to validate the use of computer models in predicting the performance of a full-scale membrane system.

The precision demonstrated by the computer models were, in most cases, sufficient to facilitate the design of a membrane system to accommodate similar membranes from multiple membrane manufacturers. One exception was the Winflows 3.1.2 computer model provided by GE. For two of the cases evaluated in the precision analysis, this computer model predicted significantly higher operating pressures than the other models used in the analysis.

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7 Appendix A - Pumping Energy Requirements

Overall pumping energy usage is one factor that a design engineer must consider when selecting feed pumps for a reverse osmosis membrane system. Pumping energy usage may be determined by relating the projected pump operating conditions of flow and total developed head to the pump operating and efficiency curves. A multitude of pump manufacturers and pump designs exist, representing a range of achievable pumping efficiencies. One tool that is available to assist design engineers with pump selection is the online program Pump-Flo™ (http://pump-flo.com/). In this program, engineers can enter operating conditions (such as, flow rate, and suction and discharge pressures) and constraints (such as, material specifications). The program then queries a database of pump curves and returns an output of a variety of pumps applicable to the desired operation. Pump-Flo™ can also optimize the pump speed and size to obtain the highest efficiency.

The Pump-Flo™ program contains catalogs of 81 different pump companies of which three were selected: Afton Pumps, Pentair, and Flowserve. Afton Pumps was chosen since they are currently in use at the Kay Bailey Hutchinson desalination plant in El Paso, TX. Flowserve pumps have also been used in reverse osmosis systems. Pentair was selected because of the wide selection of affiliates appearing in Pump-Flo™: Aurora, Fairbanks-Morse, Hydromatic, Layne/Verti-line, and Myers. All of these companies have links on their websites for a design program, which link back to Pump-Flo™.

Given the reverse osmosis models, pumps were selected using the online program Pump-Flo™; operating pressures and flow rates for each of the eight accuracy cases were entered, and the highest efficiency pumps from each of the three pump companies were selected for analysis. Pump models and efficiencies for each of the eight cases are listed in Table A-1.

The minimum permeate specific energy consumption was calculated by dividing the overall pumping power requirement by the total permeate flow rate. The mathematical expression for specific energy consumption is shown below:

$$SEC_{perm,min} = \frac{\dot{W}_{net,feed}}{Q_{net\ perm}}$$

In the expression above, Q and $\acute{W}$ represent the total permeate flow rate, and overall pumping power requirement, respectively. In the case that a booster pump was present, the total power calculated was taken as the summation of the power consumption of the first stage feed pump and the second stage booster pump.

The calculated specific energy consumption for various pump-motor combinations accounted for the rated feed pump and motor efficiencies. A motor efficiency of 93 percent was assumed for all cases.

The permeate specific energy consumption for each pump manufacturer was plotted against feed water total dissolved solids in Figure A-1. The data in Figure A-1 demonstrates a consistently decreasing trend in SEC for theoretical feed water total dissolved solids concentrations less than 1,500 milligrams per liter, followed by an increasing trend for theoretical feed water concentrations greater than 1,500 milligrams per liter.

The use of energy recovery technology was not assumed in this evaluation. Previous studies have shown that the use of energy recovery technology (that is, pressure exchangers, turbo-chargers, turbine-assisted boost pumps, etc.) can reduce overall pumping energy requirements by 10 to 20 percent, depending on the application and the technology selected. Another factor determining the overall pumping energy use at a membrane facility is the use of variable frequency drives that adjust pump speed to satisfy operating flow and pressure requirements.

It should also be noted that the pumps selected for this evaluation represent the maximum achievable efficiency at the design conditions of flow and pressure. Energy efficiency is only one factor to be considered when selecting a membrane feed pump. The selected pump must also be able to satisfy all expected combinations of flow and total developed head that will be encountered during the lifecycle of a membrane facility. Pump material selection must consider the corrosive nature of the fluid to be pumped. Geometric constraints, such as total available footprint, will also influence the selection of a membrane system feed pump.

Table A-1. Summary of design parameters and pump selection.

Parameter		Clay Center	ECI	Goldsworthy	Hardinsburg	KBH Start-Up	KBH 5Yr	N Lee County	Scottsdale
Q-feed Stg 1	gpm	724.59	385.17	1389.00	695.97	1360.34	2512.95	2173.85	1963.87
Q-feed Stg 2	gpm	359.77	-	-	-	-	-	981.06	-
Q-perm net	gpm	543.82	307.25	1107.00	556.75	945.95	2101.53	1739.57	1668.50
TDS-feed	mg/L	1071.76	1188.28	1544.25	366.82	2202.00	2474.20	2074.75	1098.44
TDS-perm net	mg/L	16.53	18.75	23.35	6.88	248.11	287.30	97.41	23.96
r	%	0.75	0.80	0.80	0.80	0.70	0.84	0.80	0.85
P feed	psi	116.75	119.78	122.64	159.80	104.76	214.33	113.09	107.74
	ft	269.31	276.30	282.89	368.60	241.65	494.37	260.86	248.52
P boost	psi	38.84	-	-	-	-	-	68.10	-
	ft	89.59	-	-	-	-	-	157.08	-
Afton Pumps	Feed Model	4x6 - 9H	3x4 - 10	6x8 - 18L	3X4 - 11H	12x16 - 14L*	12x16 - 14L*	8x12 - 18L	6x8 - 18L
	η-feed	74.0%	67.6%	70.0%	69.3%	46.0%	80.0%	70.5%	70.5%
	Boost Model	3x4 - 7L	-	-	-	-	-	4x6 - 9L	-
	η-boost	67.3%	-	-	-	-	-	73.2%	-
	SEC	1.94	1.73	1.71	2.25	2.55	2.50	1.97	1.40
Pentair	Feed Model	12M-SS	7B-SS	12FHL-SS	11EM-SS	12NSS	14D-SS	14F-SS	14F-SS
	η-feed	81.4%	69.4%	82.4%	80.6%	82.3%	81.5%	82.0%	81.9%
	Boost Model	12EM-SS	-	-	-	-	-	12N-SS*	-
	η-boost	77.3%	-	-	-	-	-	82.1%	-
	SEC	1.75	1.69	1.46	1.93	1.43	2.45	1.71	1.21
Flowserve	Feed Model	3LR-9A	2-1/2LR-10C	6LR-18A	4LR-11A	6LR-16B	8LR-23S	8LR-16B	6LR-18A
	η-feed	75.6%	69.8%	79.7%	73.1%	79.2%	76.2%	81.2%	80.8%
	Boost Model	4LR-11A	-	-	-	-	-	6LR-16B	-
	η-boost	73.0%	-	-	-	-	-	76.1%	-
	SEC	1.88	1.68	1.51	2.13	1.48	2.62	1.75	1.22

*Pump model known to be currently in service

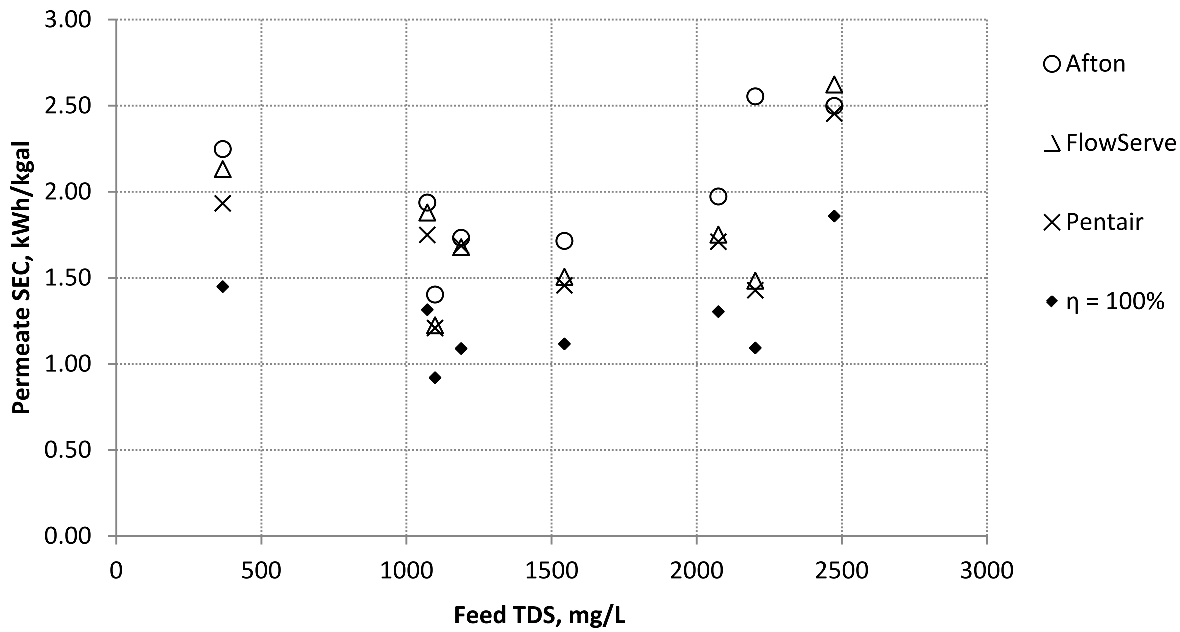

Figure A-1. Permeate specific energy consumption vs. feed total dissolved solids.

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8 Appendix B – Review Comments and Responses

Component B – Summary of the Reverse Osmosis Membrane Model Performance Data Evaluation	
Comment	**Response**
Comments from TWDB	
Appendix B relating to pumping energy requirements appears not to have been as thoroughly evaluated as proposed in the scope of work for the project. Please address.	The original scope for the cost analysis was amended. The appendix reflects the amended scope.
The charts that show actual start-up vs. model data comparison are difficult to understand. Please provide charts that show the comparison clearly.	Text in figure captions revised to clarify data sets.
Page 59, Table 4-19: SAWS' pilot had three stages. The table shows Stage 2 twice.	Table revised.
Figure 4-31: It is difficult to compare the model data vs. actual study data from this graph. Please provide a graph that shows this comparison clearly.	Text in figure caption revised to clarify data sets.
Comments from TCEQ	
Page 1, Para. 4 – Are you over-predicting the size of the pump or over-predicting the performance (permeability) of the membrane? From your statement that the assessment is conservative, I assume you mean that the required size of the pump is over-predicted?	Text revised.
Page 2, Para. 5 – The TCEQ process has already changed to allow the new review process. Technical guidance can be found on the TCEQ website at the following link: http://www.tceq.texas.gov/drinkingwater/techinical_guidance/staff_guidance/exceptions/reverse-osmosis-ro-treatment-for-secondary-contaminants-in-brackish-groundwater-at-a-public-water-system-pws	Text revised.
Page 19, Para. 3, Item 2 – Provide the name of the industry cross-reference document used for the membrane selection.	An internet path was provided in Section 6: References.
Page 63, Para. 4 – Missing a word in the 2nd sentence of section 5.1.1 between 'were limited' and 'a small number'.	Text revised.

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