2012-01-01

Alternatives to Piloting in Bracksih Waters: Accuracy and Precision of Commerical Reverse Osmosis Membrane Design Model Projections

Erika Mancha
University of Texas at El Paso, erika.mancha@hotmail.com

ALTERNATIVES TO PILOTING IN BRACKISH WATERS: ACCURACY AND PRECISION OF COMMERICAL REVERSE OSMOSIS MEMBRANE DESIGN MODEL PROJECTIONS

ERIKA MANCHA

Department of Civil Engineering

APPROVED:

W. Shane Walker, Ph.D., Chair

Thomas Davis, Ph.D.

Irasema Coronado, Ph.D.

Benjamin C. Flores, Ph.D.
Dean of the Graduate School

Dedication

Dedicated to all the individuals that supported and encouraged me throughout the process.

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by

ERIKA MANCHA, Bachelor of Science

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Civil Engineering
THE UNIVERSITY OF TEXAS AT EL PASO
December 2012

Acknowledgements

I would like to express my sincere gratitude to my graduate advisor and committee chair, Dr. W. Shane Walker, whose guidance and countless effort helped make this thesis possible. I would like to thank my committee members, Dr. Thomas A. Davis and Dr. Irasema Coronado, for accepting to be part of the committee and taking the time to read and provide feedback on this thesis. In addition, a special thanks to the Center for Inland Desalination System group at The University of Texas at El Paso for their support.

In addition, I would like to express my gratitude to Dr. Justin Sutherland for providing industry knowledge and guidance. I would also like to thank Tom Seacord from Carollo Engineers, Jorge Arroyo and Saquib Shirazi from Texas Water Development Board, as well as David Williams and Marlo Berg from the Texas Commission on Environmental Quality. A special thanks to all the membrane manufactures (Dow Chemical, GE, Toray, Koch, CSM, and Hydranautics), specifically these individuals who provided assistance with their reverse osmosis models: Steven Coker, Peter Eriksson, Henia Yacubowicz, Roy Daly, and Wayne Bates.

Finally, I would like to thank my family and friends for their encouragement and support and God for guiding me on my path.

Abstract

In a time of economic recession and drought, the Texas Water Development Board is reviewing alternatives to the current Texas Commission on Environmental Quality requirement of demonstration-scale pilot testing membrane desalination to decrease permitting costs and project construction delays. One alternative is to use engineering judgment with membrane manufacturer's software models to predict membrane performance and ensure that product water quality requirements will be met. To comply with state permitting requirements, the first few months of successful full-scale operation can be submitted in lieu of pilot demonstration.

The goal of this research is to characterize the accuracy and precision of commercial membrane design software models. The objective of this research is to compare actual membrane performance with computer software model predictions and evaluate the accuracy and precision of these models with respect to hydrodynamic and water quality parameters.

The accuracy of membrane desalination models was analyzed by adjusting modeling parameters such as feed, boost, and throttling pressures to match full-scale membrane system flux and then comparing real and simulated operating pressures, bulk salt (total dissolved solids) rejections, and specific contaminant rejections (e.g., sodium, calcium, chloride, sulfate, carbonate, silica, etc.).

The precision of membrane desalination models was analyzed by comparing the model output results from a set of membrane manufactures' models for "equivalent" membrane systems. Membrane manufactures included in this comparison are Dow Chemical, GE, Toray, Koch, CSM, and Hydranautics with their respective software models: ROSA8.0.3, Winflows 3.1.2, Toray DS2 2.0.1.26, ROPRO 8.05, CSMPRO 4.1, and IMSdesign 2011.19. A list of specifications of brackish water, fouling resistant, and low energy reverse osmosis was compiled from the six manufacturers that detailed surface area, permeate flow rate, and testing conditions. Equivalent membranes among the six manufactures were selected based on flux and rejection

performance, as well as testing conditions. Manufactures were also consulted to verify the selection of “equivalent” membranes.

These commercial software models are compared for several full-scale desalination systems (including the Kay Bailey Hutchison Desalination Plant in El Paso, TX), demonstrating variation in brackish groundwater quality/composition (1500-5000 mg/L TDS) and overall system recovery (75%-85%).

Conclusions indicate that membrane desalination manufactures’ software models are relatively accurate with respect to the prediction of operating pressures and salt/contaminant rejection. Based on this research, the models tend to conservatively over-estimate the required feed pressures, and they tend to slightly over-estimate the salinity removal of the membranes. Furthermore, the simulation of “equivalent” membrane systems among different manufacturers reveals differences in predicted operating pressures and contaminant rejections, but self-categorized membrane types generally perform relatively similarly.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

By 2060, the Texas population is projected to be 46.3 million people compared to the 2010 population of approximately 25.4 million people (TWDB, 2012a). The Texas Water Development Board (TWDB) estimates that an additional 8.3 million acre-feet of water will be needed in Texas by 2060 if new water supplies are not developed to offset population growth and a reduction in existing water supplies due to drought (TWDB, 2012a). 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 water resources.

Desalinated water is expected to be an increasingly important water supply to fill this water demand, with an estimated 310,000 acre-feet per year by 2060. Seawater and brackish water contain dissolved solids (salts) that need to be removed (a process called "desalination") to produce potable water. Desalting membrane systems such as nanofiltration, reverse osmosis, and electrodialysis are typically used for this purpose. Seawater desalination is available along the Gulf Coast, and there is an estimated 2.7 billion acre-feet of brackish water available statewide (TWDB, 2007). The majority of the new desalination capacity is expected to come from 60 percent brackish desalination and the rest from seawater desalination (TWDB, 2011). Currently in Texas, there is no seawater desalination, and the brackish desalination capacity installed is 134,500 acre-feet per year (Shirazi and Arroyo, 2011). The two brackish desalination water sources are approximately 60 percent groundwater and 40 percent surface water (Arroyo, 2011). Reverse osmosis is the primary desalination technology utilized in Texas to generate drinking water.

Low-pressure membrane treatment processes (such as microfiltration and ultrafiltration) are alternatives to conventional granular media filtration for turbidity and pathogen removal, and

may require a smaller land area footprint. Low-pressure membrane systems are quite robust with respect to variations in source water quality (such as seasonal effects on rivers and lakes).

Unfortunately, misconceptions about membrane technologies exist in part among regulators, decision makers, and the general public, which have impacted the industry by limiting the growth of application of membranes for water treatment (Mickley, 1999). Under the current Texas Administrative Code, membranes (both low-pressure and desalting) are considered “innovative technologies” for water treatment. To implement membrane treatment for drinking water, municipalities and water districts are required to perform demonstration-scale pilot testing for permitting approval by the Texas Commission on Environmental Quality (TCEQ).

Demonstration-scale pilot testing is costly for water systems and can be a significant fraction of the total cost of the full-scale treatment system. As a result, the requirement for pilot testing can be a deterrent for the use of membrane technologies. In certain situations, such as brackish water desalination, pilot testing may not be necessary for full-scale technical design. Therefore, review of the current TCEQ membrane permitting procedure is imperative for potential revision, in light of Texas future water demands, the current state of membrane technologies, and membrane performance evaluation methods. A revised permitting process that reduces or avoids pilot testing requirements could facilitate more rapid and less costly implementation of membrane technologies for meeting current and future water demands.

1.2 Goals and Objectives

1.1.1 Project Goals

The goal of this project is to develop a guidance document for more efficient pathways to safely approve desalting membrane systems in the State of Texas. The objectives of this project are (1) to perform a review of membrane performance evaluation methods (especially alternatives to demonstration-scale pilot testing) for predicting full-scale performance and (2) analyze model, pilot, and full-scale data to validate and establish accuracy values for predicting

actual performance and (3) To prepare a guidance document on alternatives to membrane pilot studies for TCEQ acceptance and outreach.

1.1.2 Literature Review Objectives

The first phase of this project is a literature review of membrane technology, methods for predicting performance of full-scale systems, and state permitting approaches of membrane technologies. The objectives of the literature review are as follows:

1. Evaluate the current state of low-pressure and desalting membrane technologies;
2. Summarize the alternative approaches to demonstration-scale pilot testing; and
3. Evaluate other states' approaches for approving membrane technologies for drinking water treatment.

The assessment of membrane technology (Chapter 2) begins with a background on membrane development in Texas. Methods for predicting full-scale treatment operation (Chapter 3) identifies the type of predictive methods, such as computer model, bench-scale, and pilot-scale tests and overviews the primary function of the methods in general. More specifically, the low-pressure membrane methods examined are filtration models, bench-scale hollow-fiber and flat-sheet testing, single-element testing, and demonstration-scale testing. Similarly, the same four categories of tests are discussed for application to desalting membranes.

In Chapter 4, the federal regulatory requirements for pilot testing for membrane treatment with groundwater and surface water sources are examined. Next, Texas's approach on regulations, permitting, and piloting requirements is detailed. Then a comparison of federal and state membrane treatment regulations is provided for the following eight states: Arizona, California, Florida, Illinois, New Mexico, South Carolina, Virginia, and Wisconsin.

1.1.3 Analyses objectives

The second phase of this project is to assess alternatives to pilot testing for desalting membranes, which are commercial software models, bench-scale membrane testing, single-element testing, and pilot testing. Based on the literature review and engineering design practice,

the alternative selected for a detailed analysis is commercial software models. The tasks for the data evaluation of commercial reverse osmosis models are the following:

1. Acquire model, pilot, and full-scale data from various membrane manufactures.
2. Analyze and compare commercial reverse osmosis membrane design models to model, pilot, and actual plant data with respect to water quality and operating parameters.
3. Identify trends among major parameters of the data sets and assign accuracy percentages to membrane performance prediction.

The methodology of the data analysis (Chapter 5) begins with a justification of computer software model selection and analytical design. Then key model parameters such as feed water quality and pressure losses that have an impact on ion rejections and operating accuracies are addressed. The data matrix is summarized in terms of recovery, membrane type, 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 is performed.

Results discussion (Chapter 6) examines eight full-scale performance data sets and compares them with model predictions in the accuracy analysis which measures the degree to which the model and full-scale plant are equal. Then four data sets are analyzed for precision to demonstrate the confidence of reproducing the same data point for six different membrane manufacturer models. The chapter on conclusions (Chapter 7) identifies trend of major parameters and discusses reliability of models predicting pressures and rejections.

Chapter 2: Membrane Technology Development

2.1 OVERVIEW

The membrane industry has advanced dramatically over the past century, as shown in 0. Membrane technology was developed in the mid-1800s; the first "reverse osmosis" nitrocellulose synthetic membrane was created by Adolph Fick in 1855. The first desalination plant was installed in 1888 in Tas-Miela, Malta, a small island located in Mediterranean Sea. In 1937, Sartorius GmbH commercially manufactured nitrocellulose membranes, and subsequent researchers developed cellulose acetate membranes in the mid-1950s (Binnie, 2002). The first spiral wound module was created by General Atomics in 1967, and the development of the composite membrane was one of the greatest achievements in reducing energy consumption in membrane treatment systems. With the development of automated membrane synthesis, the membrane market has become quite competitive, and the cost of consistent and reliable membranes has decreased dramatically in recent years.

A significant part of the state of membrane technology is the number and capacity of membrane plants currently being used in the world. Low pressure membrane plants in 2007 had global installed capacity of about 3,600 million gallons per day (MGD) (NWRI, 2008). The world production of desalinated water is approximately 0.6 percent of world water production which equates to 17,225 MGD (IEA-ETSAP, 2012). Globally approximately 15,000 desalination plants exist with 18,915 MGD design capacity (IEA-ETSAP, 2012). The main technology utilized for global production of desalinated water is reverse osmosis and accounts for 60 percent (IEA-ESTAP, 2012).

Nationwide surveys were conducted by Mickley and Associates to identify municipal water treatment plants with membrane filtration for the periods prior to 1992, 1999 to 2002, and 2002 to 2010 (Mickely, 1993, Mickely, 2006, Mickely, 2011). The last survey from 2002 to 2010 only updated the data for desalting membrane plants. These surveys examined treatment plants by size, type, and location. The most recent study identifies a total of 422 low pressure and

desalting membrane water and wastewater treatment plants with a capacity of 25,000 gallons per day (0.025 million gallons per day) or greater (Mickley, 2006).

Low-pressure membrane plants (microfiltration and ultrafiltration) multiplied from 1 to 188 in the period from 1992 to 2002 (Mickley, 2006). The first microfiltration and ultrafiltration plants were installed in the United States in 1980 and 1993, respectively. Of the 188 low-pressure plants in 2002, 155 (82 percent) were microfiltration and 33 (18 percent) were ultrafiltration. Microfiltration plants are predominately located in California (22 percent), Colorado (12 percent), and Virginia (10 percent) (Mickley, 2006). For ultrafiltration plants, there is not a predominant location since the number of plants is small and spread out throughout the United States. (The state with the largest number of ultrafiltration plants is California with four plants.) Memcor, now a subsidiary of Siemens, is the predominant provider for microfiltration plants, followed by Pall. The primary providers for ultrafiltrtion systems are AquaSource, Koch, and Zenon.

From 2002 to 2010, 324 plants apply reverse osmosis, nanofiltration, and electrodialysis, which are referred to as desalting plants. These surveys revealed that desalting plants increased from 133 to 324 in 1992 and 2010, respectively, and these desalting plants are located primarily in Florida (45 percent), California (14 percent), and Texas (9 percent) (Mickley, 2011). The first reverse osmosis plant identified in the study was installed in 1966, and by 2010, the total number of reverse osmosis plants had grown to 260. The first nanofiltration plant was installed in 1999, and by 2010, a total of 43 nanofiltration plants exist. As of 2010, the distribution of desalting plants by type was 73 percent brackish reverse osmosis, 3 percent Seawater reverse osmosis, 13 percent nanofiltration, 6 percent electrodialysis/electrodialysis reversal, 3 percent microfiltration with reverse osmosis, and 1 percent microfiltration with nanofiltration.

Texas membrane plants represent only a small portion of the total world and nationwide capacity. Texas has a total of 69 low pressure and desalting membrane plants and 302 million gallons per day capacity. Water production and water treatment plants for low pressure and desalting membranes is approximately 181 million gallons per day for 25 plants and 121 million

gallons per day for 44 plants, respectively. In 1993, the first low pressure membrane plant in Texas is constructed in Sherman with a 10 million gallons per day capacity. The Upper Trinity River Authority Harpool water treatment plant with a capacity of 20 million gallons per day becomes the largest low pressure membrane plant in 2006. Several small desalting membrane plants originate back in 1990. In 2007, the largest desalination plant in Texas and the nation, Kay Bailey Hutchison, was constructed with a design capacity of 27.5 million gallons per day in El Paso, Texas.

The use of membranes for water and wastewater treatment has grown significantly in recent years. Drivers for this growth include increasingly stringent water quality regulations, decreasing water supply, decreasing available land for conventional treatment systems, ability to remove multiple pathogens and contaminants, and decreasing membrane capital costs.

2.2 Low-pressure filtration membrane technologies

Microfiltration and ultrafiltration membranes are frequently used for particle and pathogen filtration and typically operate with relatively low differential pressures. Membrane equipment is quite durable with a design life of several decades, but the membrane replacement frequency is typically five to ten years. A chronological summary of large low-pressure membrane filtration plants in Texas is provided in Figure 2.2

2.3 Desalting membrane technologies

Membrane technologies for potable desalination of brackish, saline, and sea waters include nanofiltration, reverse osmosis, and electrodialysis. The salinity of “brackish” water is loosely defined as having a concentration of 1,000 to 10,000 milligrams per liter of total dissolved solids. For example the Secondary Standard for total dissolved solids is 500 milligrams per liter nationally and 1,000 milligrams per liter regionally, and the average salinity of seawater is nearly 35,000 milligrams per liter. Nanofiltration and reverse osmosis are pressure-driven processes where the transmembrane pressure must overcome the natural osmotic pressure of the feed water to force water through semi-permeable membranes. Electrodialysis represents a

family of electrically-driven separation processes where an electric voltage is used to draw ions through ion-exchange membranes. Over the past two decades, desalting membrane systems have increased in number and grown in plant capacity in the State of Texas, as shown in Figure 2.3. TWDB has created a desalination plant database that includes information for 44 desalination plants (TWDB, 2012b). The data base provides a desalination plant report with information on the location, water production, and membrane system of the plant.

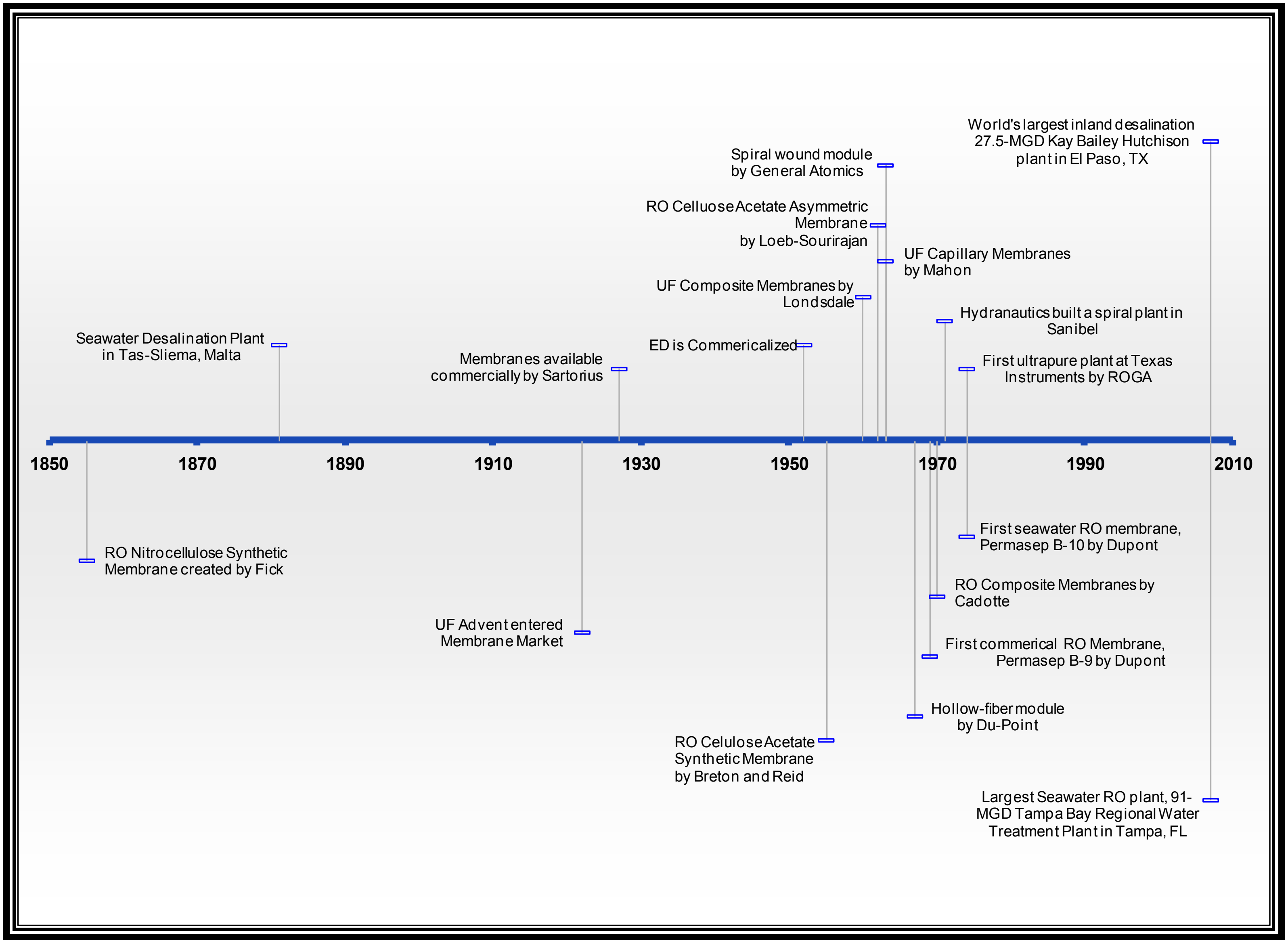


Figure 2.1: Membrane technology developments (1850-2010).

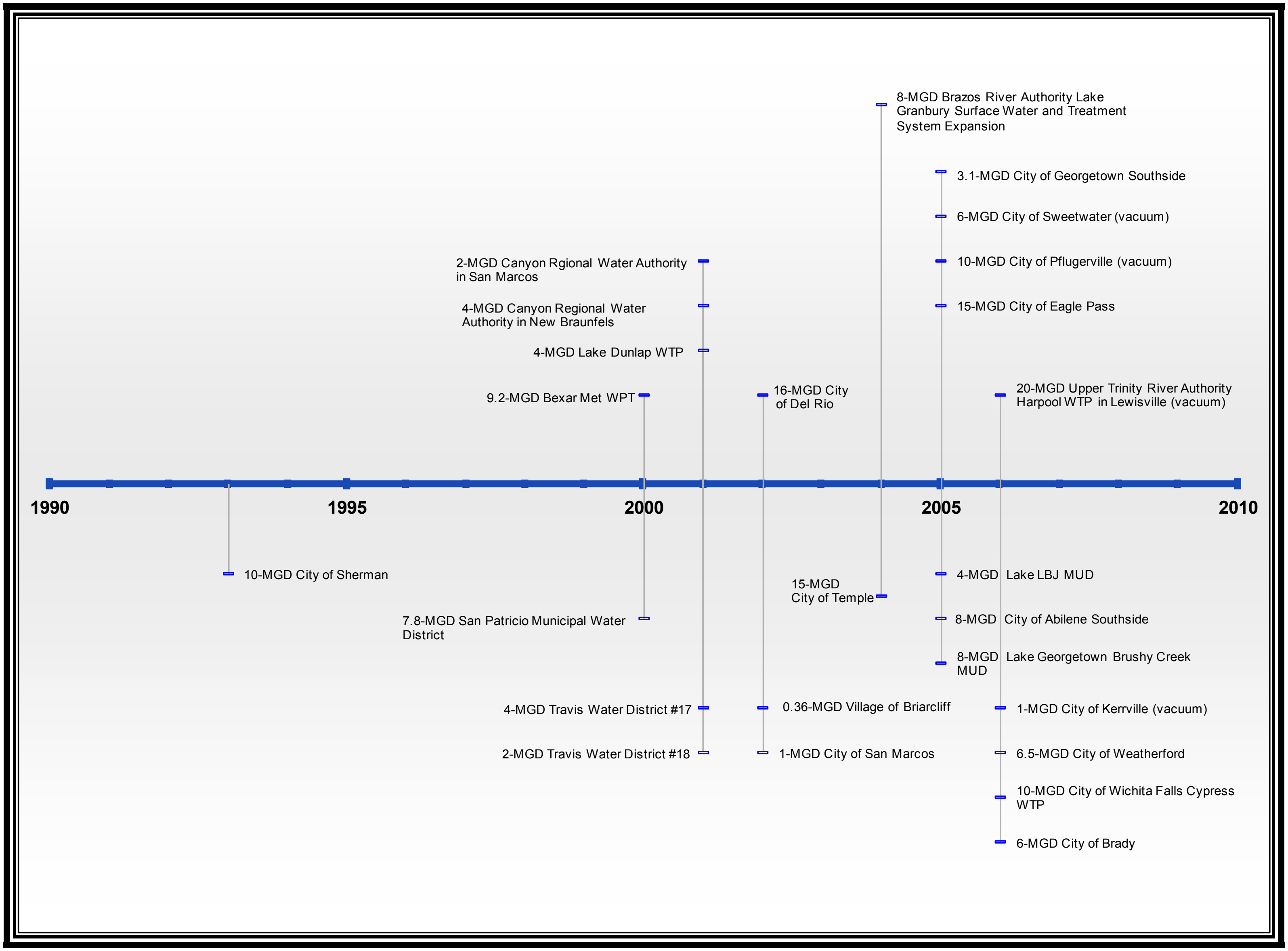
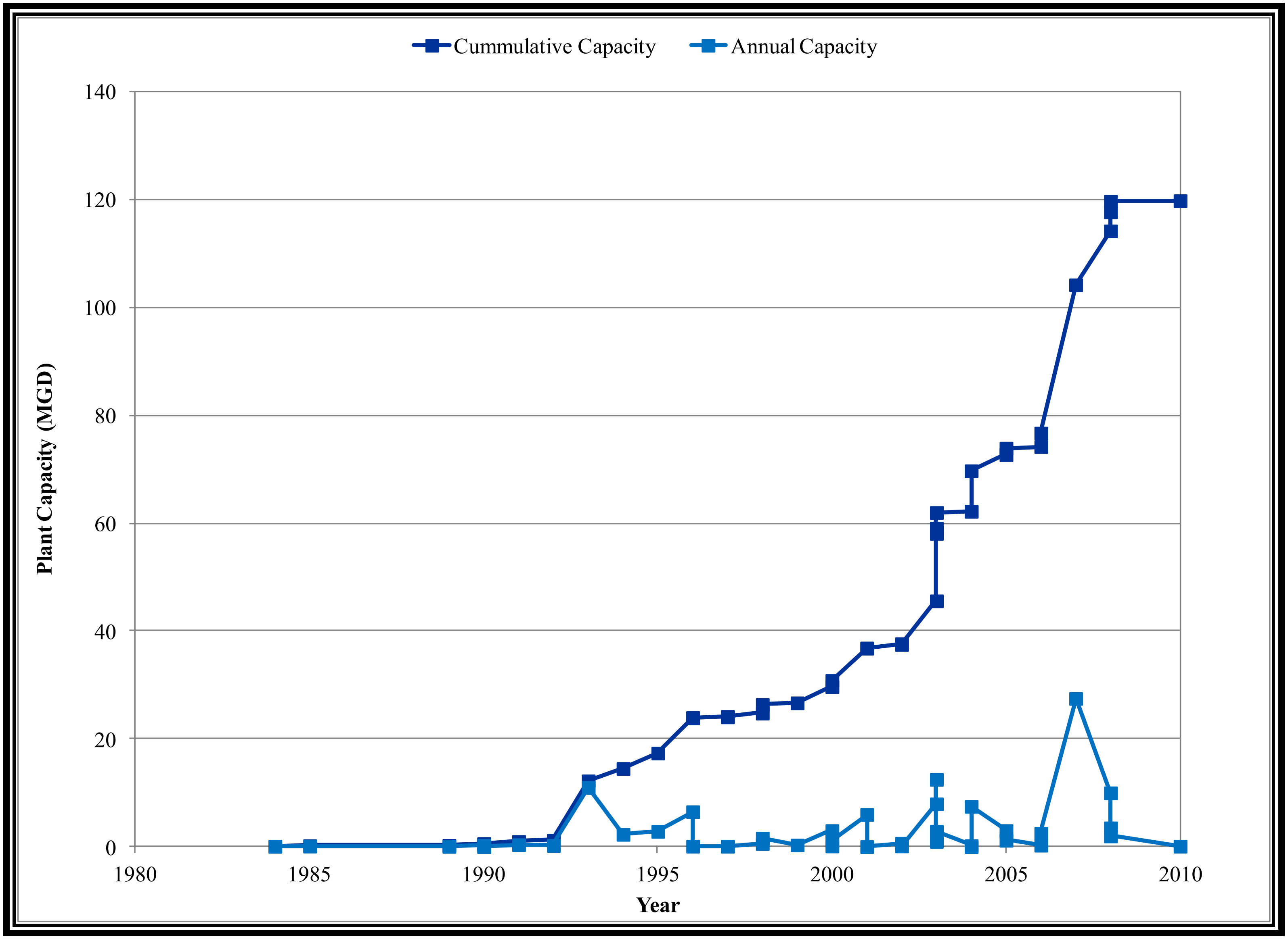
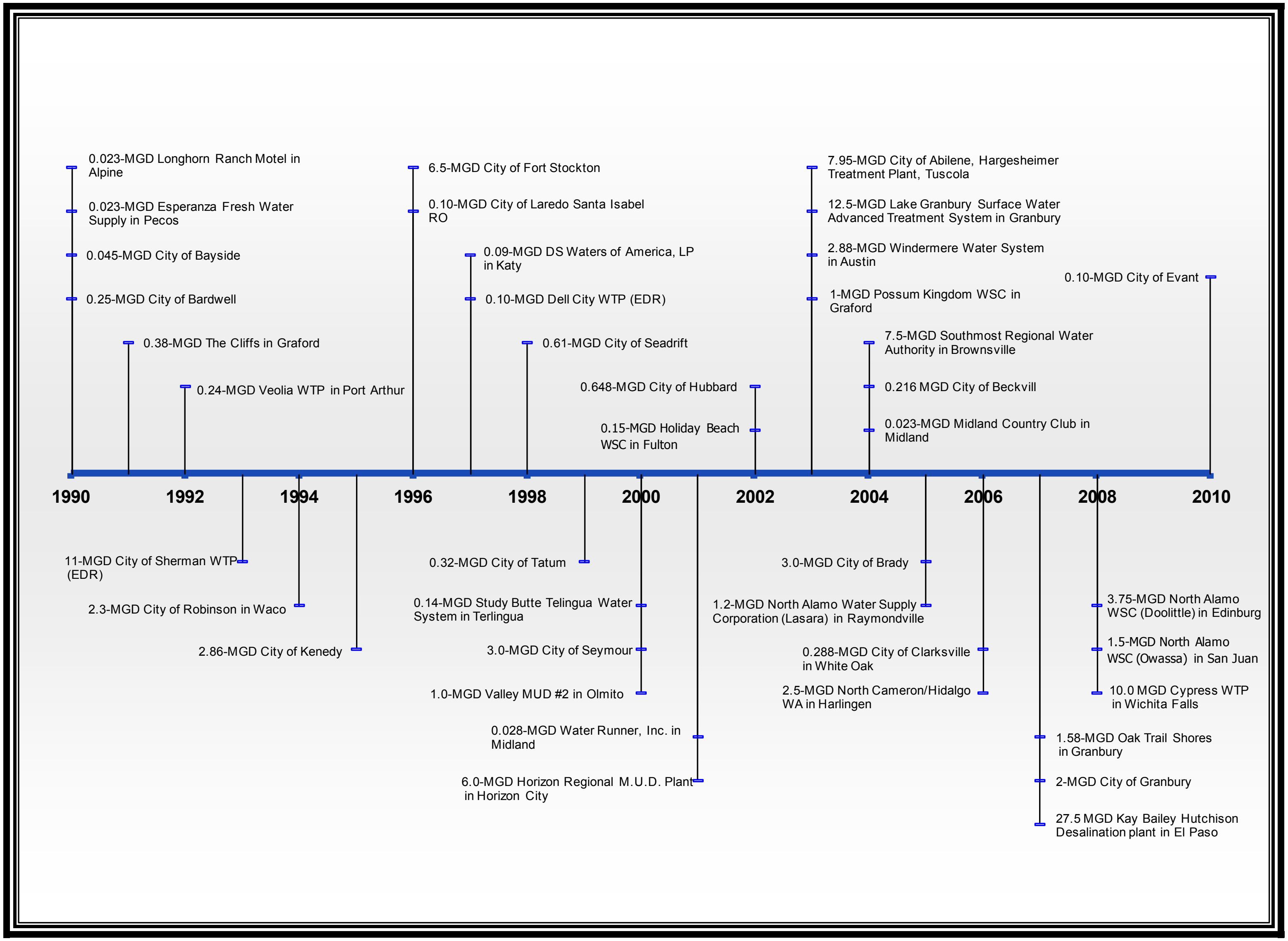


Figure 2.2: Low pressure membrane installations in Texas (1990-2010).



Cummulative Capacity
Annual Capacity
Plant Capacity (MGD)
0
20
40
60
80
100
120
140
1980
1985
1990
1995
2000
2005
2010
Year

(a)



(b)

Figure 2.3: Desalting membrane applications in Texas (1990-2010).

Chapter 3: Methods for Predicting Full-Scale Treatment System Operation

3.1 Overview

The performance of membranes in full-scale water treatment plants may be evaluated and predicted by several methods. Described here are four categories of performance prediction and testing: (1) computer modeling, (2) hollow-fiber testing (for low-pressure) or flat-sheet testing (for low-pressure or desalting), (3) single-element testing, and (4) demonstration-scale pilot testing. These methods are used individually or in combination to aid in design and operation of full-scale membrane water treatment plants. Each method is uniquely valuable for predicting aspects of full-scale performance, with tradeoffs in the investment of design time and financial cost, as shown in Table 3.1.

Computer models for desalting processes have been developed to predict full-scale water treatment performance based on engineering design criteria and empirical operation. Most computer models for predicting the performance of commercial membranes have been calibrated by empirical data from the other three methods listed here and full-scale operation data. The models are similar, but not identical. Unfortunately, the technical details of commercial models are proprietary and not typically available for review. However, computer models are not entirely "black boxes", because output parameters such as recovery, flux, rejections are based on basic permeability and solubility equations that can be verified and approximated by hand calculations. A benefit of computer models is their ability to perform iterations for multiple discrete units within a membrane element for permeate flux and concentrations within a matter of seconds. Calculating by hand the quantity and quality of water produced in a membrane element is a long process. The process begins with an element being sectioned into ten discrete units along the flowpath and 20 calculations are performed to calculate water and salt fluxes for each discrete section of the element, for a total of 200 calculations per element. This process is illustrated in Example 17-5 in Water Treatment Principles and Design (MWH, 2012). The importance of desalting models is to provide a conceptual and predictive understanding of the

transfer of water and solutes through reverse osmosis (MWH, 2012). Computer models are frequently used in the design of desalting membrane systems to predict bulk operation parameters, and they are generally useful for predicting the rejection of common contaminants.

Hollow-fiber or flat-sheet testing is a relatively simple laboratory method of analyzing a small sample of membranes for basic contaminant rejection. Hollow-fiber and flat-sheet tests of low-pressure membranes are frequently operated in a dead-end filtration mode, whereas flat sheet tests of desalting membranes are frequently operated with cross-flow in a system called Rapid Bench-Scale Membrane Testing. These flat sheet tests are relatively brief and inexpensive compared to the other membrane testing methods, and they are frequently used to determine the rejection of individual contaminants specific to the project source water. However, the sensitivity of performance prediction to hydraulic conditions is typically only qualitative. That is, Rapid Bench-Scale Membrane Testing operation is intended to simulate typical hydraulic conditions such as flux and cross-flow velocity, but the flat sheet geometry is significantly different than the full-scale spiral-wound geometry and representative full-scale operating conditions cannot be reproduced. When bench-scale data are allowed in lieu of a demonstration pilot, TCEQ will specify the limiting conditions for the use of the data. For example, the restriction can state that bench-scale data cannot be used to support the hydraulics of an array or project recovery after a clean in place.

Single-element testing is quite valuable for demonstrating water quality and hydraulic performance of actual commercial membrane elements. Single-element pilot units are typically very mobile, and at relatively low flow rates compared to demonstration-scale piloting, single-element piloting can usually be performed on actual project source water at significantly lower cost than demonstration scale piloting. However, for desalting membranes, predicting the variations of water quality and hydraulic performance within a multiple-element vessel and multiple vessel/stage are not necessarily available through single-element testing. The data from a desalting membrane single-element pilot test may be used to calibrate the respective computer

model for a membrane to evaluate multiple-element vessel and/or to determine particulate removal pretreatment needs.

Demonstration-scale piloting is the largest-scale and most expensive of the methods discussed here, but it is able to provide design engineers valuable performance data with respect to multiple element and multiple stage operation. System water quality data can be demonstrated for steady-state blending of product from multiple stages as a function of operational parameters such as flux and overall system recovery.

Table 3.1: Membrane performance prediction methods, sensitivities, and design costs for low-pressure and desalting membranes.

Parameters	Computer Modeling	Bench-scale Testing	Single Element Testing	Pilot Testing
Primary Use	Assist engineers to design treatment	To calibrate models and economically screen membranes and pretreatment alternatives	To assesses single element	To simulate the operation of a full-scale system
Objective	To predict the performance of a membrane system Low Pressure: Predict fouling potential by NOM Desalting: Predict full-scale membrane performance	To obtain log-removal and fouling potential of selected water and operating conditions Low Pressure: Evaluate fouling potential and log-removal based on selected pressure and flux Desalting: Evaluate membrane performance based on material and pretreatments.	To examine operating parameters and product quality Low Pressure: Evaluate recovery, flux, pressures, cleaning frequencies Desalting: Demonstrate water quality and hydraulic performance of membrane elements	To gather data on water quality and operation parameters and evaluate membrane performance and stage relationships Low Pressure: Above Desalting: Evaluate pretreatment effectiveness and pressure effects.
Membrane Size	4-, 8-, 16-inch diameter	19 cm x 14 cm	2.5-inch diameter	4- or 8-inch diameter
Product Water Quality Characteristics	Desalting: Quantitative Total Dissolved Solids (TDS) and ion rejections	Low Pressure: Quantitative turbidity, TDS, and virus rejection Desalting: Qualitative ion rejection at single points in membrane element	Low Pressure: Quantitative turbidity, TDS, and virus rejection Desalting: Quantitative ion rejection at single points	Low Pressure: Quantitative for quality parameters Desalting: Quantitative for systems with multiple stages
Hydraulic Characteristics	Desalting: Quantitative Pressures and fluxes	Qualitative for hydraulic	Low Pressure: Quantitative for simulating element performance Desalting: Quantitative for simulating lead-element performance	Quantitative for hydraulic parameters
Time	Hours	Hours to days	Days to week	Week to months
Financial	Minimal	Small	High	High

3.2 Low-pressure membrane

3.2.1 Filtration models

Filtration models have been proposed and used by various researchers to model the cumulative effects of cake formation and pore size on low-pressure membranes. The objective of a filtration model is to predict the fouling potential of a membrane by natural organic matter. Flux models for clean low-pressure membrane are based on the Poiseuille Equation of flow of through a small tube, while also accounting for the surface density (ρ, number of pores per unit area of membrane surface) and tortuosity (τ, a dimensionless value between zero and unity) of membrane pores, as shown in the following equation (Davis, 2010):

$$J = \rho_{pores}\, \tau \frac{\pi r^4}{8\mu t_{mem}} \Delta P = \frac{\Delta P}{\mu\, R_m} \qquad \text{Eq. (3-1)}$$

where r is the radius of the pores, μ is the viscosity of the fluid, t_{mem} is the thickness of the membrane, and ΔP is the transmembrane pressure. Alternatively, the flux can be modeled similarly to Darcy's law, which consolidates the geometric parameters into a single parameter indicating the "resistance" (Rm) of the membrane. Tortuosity is a porous-media transport parameter that quantifies the nonlinearity of the pathway through the membrane pores; that is, tortuosity is the total tortuous path length traveled by a water molecule through a membrane divided by the thickness of the membrane. Aside from membranes containing non-interconnected pores of uniform size and length, tortuosity is a random variable that is a function of the probability distributions of pore size, length, and interconnectivity. Turbidity can be characterized through three-dimensional scanning/imagery techniques.

Time dependent flux model equations for low pressure membranes consist of the following phenomena: pore sealing, internal pore constriction, pore sealing with superposition, cake filtration. Corresponding flux equations, major features, and assumptions for these models can be found in water treatment references (e.g., Davis, 2010 and MWH, 2012).

Filtration models require fairly detailed calibration by empirical testing with site-specific water quality. Input parameters for models are obtained from bench-scale tests. Testing of individual waters is required because organic fouling is highly dependent on the specific types and concentrations of organic material present in the raw water. Low-pressure filtration systems are typically operated in a dynamic (non-steady state) batch mode which requires cyclic backwashing/cleaning. As a result, a generic and universally applicable, mechanistic and time-dependent, low-pressure flux model has not been adopted for low-pressure filtration performance.

Nonetheless, filtration models have not been able to adequately explain fouling behavior of membranes, because fouling can be attributed to various fouling mechanisms. Fouling and flux are impacted by the membrane pore sizes, the fouling cake layer on the surface of the membrane, and the adsorption of fouling particles within the membrane pores. As a result, fouling of membranes may be explained by one, two, or a combination of filtration models. In addition microfiltration and ultrafiltration membrane systems are proprietary and vary among manufactures, thus making it difficult to create and apply a standardize computer model.

3.2.2 Bench-scale hollow-fiber and flat-sheet testing

Bench-scale tests for low-pressure membranes may be used by manufacturers for quality management of their product and by researchers and engineers to economically screen several membranes or pretreatment alternatives in a short period of time (hours to days). The objective of performing bench tests for low-pressure membranes is to obtain log-removal and fouling potential of the membranes for raw water based on selected operating conditions (pressure and flux).

Bench-scale tests have historically included testing with a single hollow fiber, a bundle of hollow fibers, and flat sheets to evaluate the removal of microorganisms and particulate matter under various operating conditions (Nguyen, 2010, Marwah et al 2006, Chiu et al 2006). In hollow-fiber testing, a 0.5 to 1-inch diameter module with fiber(s) approximately one foot in

length has been used in dead-end or cross-filtration modes. For flat sheet testing, two types of cells have been used in dead-end mode for testing: small unstirred cells that use a 55 millimeter diameter membrane sheet and the Sepa CF Membrane Element Cell that use a 19 centimeter by 14 centimeter membrane sheet (Figure 3.1).

Despite the variety of approaches to bench-scale testing of low-pressure membranes, the results of some of these studies are for relative comparison of operating conditions and do not adequately characterize full-scale operation. For example, Marwah et al. (2006) used flat sheet and hollow fiber membranes operated at constant pressure (declining flux) in their bench tests to evaluate the impact of source water quality and pretreatment on microfiltration and ultrafiltration membranes. The results of the testing provided some guidance for membrane selection and pretreatment, but were not directly comparable to a full-scale system that use hollow fibers operated at constant flux.

In contrast, Nguyen (2010) evaluated the fouling characteristics of organic nitrogen compounds on two hollow-fiber poly(vinylidene-fluoroethylene) (polyvinylidene fluoride) membranes using 0.5-inch diameter by one-foot long module operated at a constant flux in dead-end mode. The testing was done to validate the development of three new fouling indices for low-pressure membranes (total fouling index, hydraulic irreversible fouling index, and chemical irreversible fouling index). The fouling indices calculated from the bench-scale results were compared to data from full-scale plants operated under similar raw water, flux, and pressure conditions. The researcher found that bench-scale fouling indices were representative of the full-scale as long as the test was done for 3 to 4 days. Future use of these indices is meant to provide a standard, non-proprietary, assessment for comparing the fouling potential of various low-pressure membranes.

In general, the use of bench-testing of low pressure membranes has declined in recent years as state regulations have required pilot test data for their implementation at full-scale. Nevertheless, it has been and continues to be an important tool in the development of low-pressure membranes.

Source: GE Energy, 2012 and Adapted from EPA, 1996b

Figure 3.1: The GE SepaTM CF II flat sheet membrane testing apparatus.

3.2.3 Single-element testing

A Single-Element Bench Scale Test assesses a single-membrane pressure vessel. The purpose of single-element testing is to examine the impact of recovery, flux, and operating pressures on the quality of filtrate and determine the required cleaning frequencies of the membrane. Certain functions in a single-element testing allow examining additional parameters such as biofouling and scaling effects on the membrane because of the longer testing periods and recycle loop control.

The single-element bench-scale unit is operated with a continuous feed water source and a concentrate recycle loop for a period of days or weeks. For spiral wound elements, a minimum 2.5-inch diameter pressure vessel may be used for Single-Element Bench Scale Test, but larger diameter, such as 4-inch and 8-inch, an also be used. Many low-pressure systems are operated with hollow-fibers, so a single module may be tested for evaluating performance. Since the geometry and operation of low-pressure hollow-fiber membrane filtration systems are not standardized across the industry, side-by-side comparison of particular membrane systems may be performed with single-elements for narrowing the selection of systems for demonstration- and full-scale.

3.2.4 Demonstration-scale pilot testing

A demonstration-scale pilot test is generally considered to be the most representative of a full-scale water treatment process because it incorporates essentially all of the operational details of a full-scale system, only at a smaller scale. The objective of pilot testing is for an engineer to gather data on water quality and operation parameters to assist in the design of a water treatment facility. Furthermore, pilot testing helps establish, maximize, and validate performance parameters, which in return provide insight on element and stage relationships and membrane area requirements. In contrast, challenge testing (as defined by the Long Term 2 Enhanced State Water Treatment Rule) is not the same as pilot testing. For challenge testing, the objective is to determine the log-removal credit for a specific membrane product.

The Environmental Protection Agency created a Membrane Filtration Guidance Manual to assist state agencies, engineers, and utilities with the use of membrane filtration in water treatment plants to meet the Long Term 2 Enhanced State Water Treatment Rule (United States Environmental Protection Agency, 2005b). States are allowed to place their own regulations whether the regulations follow Environmental Protection Agency manuals or industry practice as long as minimum national requirements are met. However, as the manual notes in the piloting chapter, "the Long Term 2 Enhanced State Water Treatment Rule does not contain any requirements for pilot testing membrane filtration systems; thus, this chapter is simply intended to provide general guidance in terms of widely recognized industry practices" (United States Environmental Protection Agency, 2005b).

Similar to bench-scale testing, source water quality parameters are necessary inputs for the selection and evaluation of water treatment systems. Prior to conducting a demonstration-scale pilot test, a selection must be made of low-pressure membrane filtration systems for evaluation as they vary from manufacturer to manufacturer. The engineer has to select the membrane material, driving force (pressure or vacuum), and filtration direction (inside-out or outside-in). Engineers may use bench-scale and single-element tests to determine pretreatment and membrane system needs. They can also approximate the optimal membrane flux and

backwash frequency with water quality parameters (United States Environmental Protection Agency, 2005b).

Pilot study protocols are required by some states agencies to be submitted prior to conducting pilot tests. Submitting a protocol allows the states to provide input that can be integrated into the pilot study before beginning testing rather than after testing and having to repeat the tests. Pilot studies are typically conducted on-site near the water source. The Membrane Filtration Guidance Manual recommends, at a minimum, conducting three 30-day operational cycles to establish, optimize, and validate the system (United States Environmental Protection Agency, 2005b). Furthermore, four to seven months of pilot operation is recommended in the guidance manual. Other industry guidance suggests that pilot test periods can be significantly shorter if conducted in periods of worst-case water quality (American Water Works Association, 2005).

3.3 Desalting membrane

3.3.1 Models

Desalting membrane software models are theoretically-based, empirically-calibrated membrane models created by manufactures, which are frequently used by engineers for the design of water treatment plant. When accurate water quality data are available, an engineer can design a treatment process solely based on the computer model. Engineers are also able to use the membrane system design software to compare the performance of different membranes and manufacturers and select several membranes for design or further evaluation. In general, the objective of a software model is to predict full-scale membrane performance.

In industry practice, the flux of water through the membrane is typically calculated by projection software as a function of the mass transfer coefficient of the membrane (kw), the transmembrane pressure (ΔP), the difference in osmotic pressure between the feed and permeate ($\Delta\pi$), as shown in the following equation:

$$J=k\_w (\Delta P-\Delta\pi) \qquad \text{Eq. (4-2)}$$

Thus, applying a greater feed pressure results in a greater flux of water through the membrane, but requires more electrical power to supply the higher pressure and flow. Solute rejection and transport is modeled in commercial membrane software as a mathematic function of solute diffusivity in the membrane, and the difference in concentration of the solute between the feed and permeate.

Membrane manufacturers perform in-house flat-sheet testing and single-element testing and use these water quality and flux data (in combination with pilot study data) to calibrate their models for membrane performance on various water qualities. Several membrane manufacturers have produced commercial design software that models the performance of pilot and full-scale systems of their nanofiltration and reverse osmosis membranes (DOW, 2012c; General Electric, 2012b; Hydranautics, 2012b; KOCH, 2012b; Toray, 2012b). These commercial software models are very similar and have similar input and output components.

Initial input data required for the use of computer models are water quality characteristics, pretreatment options, and membrane system configuration. More specifically the commercial software requires the user to input parameters for:

- Influent water quality (e.g., temperature; pH; total dissolved solids; concentrations of individual ions such as sodium, magnesium, calcium, chloride, nitrate, sulfate, carbonate, boron, and silica; etc.).
- Scaling control options such as acid or antiscalant dosing.
- Operating parameters such as flux, flow, feed pressure, backpressure, system recovery.
- Membrane selection.
- Process configuration such as number of passes, number of stages per pass, number of pressure vessels per stage, and number of elements per vessel (DOW, 2012d).

Typically, manufactures specify allowable feedwater quality with respect to Silt Density Index (SDI). However, some manufactures provide examples of brackish water composition for

wells (DOW, 2012e), and others provide design guidelines. The software model then calculates permeate and concentrate water qualities and checks the process configuration for infeasibilities. The computer models outcome notifies the user whether water quality standards are met and identifies potential problems such as low pressure, high flux, scaling potential, and low/high flow rates. Notifications in model are typically given as design and saturation limitation warnings. A predominate limitation of computer models is that they only predict precipitation scaling potential by equilibrium (saturation) comparisons. Another model constraint is the use of waters with extreme high and low temperatures and total dissolved solids. Further research is required to specify quantitative limitations of the models.

Computer models for electrically-driven desalting membrane systems such as electrodialysis reversal are very similar with respect to input and output water quality parameters, except that electrically-driven computer models simulate the transport of ions through membranes (compared to the transport of water through membranes in pressure-driven membrane systems). These models are used to calculate the number of stacks and the electrical power requirements. Currently, commercial electrodialysis design model programs are not available to the public.

3.3.2 Bench-scale membrane testing

Desalting membrane bench-scale tests are conducted using a small sheet of membrane and small volume of water for a period of hours or days. Manufactures use bench-scale membrane tests, along with other types of testing and operating data, to calibrate their computer models. Similar to low pressure bench-scale membrane tests, engineers use desalting membrane bench-scale tests to inexpensively compare performance of various membranes. The primary value of bench-scale tests is to evaluate membrane performance with respect to rejection of solutes not typically considered by commercial software models. Even with the relatively successful characterization, bench-scale testing results of desalting membranes do not characterize the hydraulics and long-term performance of full-scale operations.

The Information Collection Rule required public water systems serving more than 100,000 people to submit water quality data for 18 months (Environmental Protection Agency, 1996a). The Information Collection Rule Manual for Bench and Pilot Studies (Environmental Protection Agency, 1996b) is a guidance document created by the Environmental Protection Agency to assist engineers and utilities required to complete studies and submit data reports. The manual provides guidance for bench- and pilot-scale studies for membrane filtration primarily applicable to desalting membranes within the Information Collection Rule context.

Desalting membrane bench-scale tests utilize flat-sheet testing membranes. Similar to low pressure flat-sheet-membrane testing, two types of cells have been used in the dead-end mode for testing: small unstirred cells that use a 55-millimeter diameter membrane sheet and the Sepa CF Membrane Element Cell that use a 19-cm by 14-cm membrane sheet. Figure 4 2 illustrates a cross-flow membrane cell typically used in bench-scale tests. The Information Collection Rule guidance manual suggests performing Rapid Bench-Scale Membrane Tests on two membranes with the following four recoveries: final stage average (90 percent), conservative average (70 percent), average (50 percent), and first stage average (30 percent).

The output parameters obtained from bench-scale tests are general impacts of flux, pressure, and recovery on permeate quality and membrane performance. Bench-scale tests are used to aid in the process of narrowing or selecting the best membrane for rejecting solutes that cannot be predicted using computer models. The Information Collection Rule manual reports that Rapid Bench-Scale Membrane Tests can predict full-scale performance with the following accuracies:

1. Initial membrane productivity within 10% of the initial productivity observed in pilot studies.
2. Solute rejections within 2% to 20% of rejections observed in pilot studies.
3. Cleaning frequencies within 40% of those observed on the pilot-scale.
4. The potential for severe and rapid membrane fouling.
5. Concentrate water quality

Grooters (2006) conducted a four hour membrane screening test (MST) and five day Rapid Bench-Scale Membrane Tests using Sepa CF Membrane Cell and then compared to pilot tests to evaluate the performance of nanofiltration membranes on Colorado River water. A membrane screening test is a shorter-duration rapid bench-scale test. Similar performance resulted for all three scales of test. More specifically the observed percent difference between membrane screening tests and rapid bench-scale membrane tests for rejection and bulk rejection in this study were 4 percent and 2 percent, respectively. The conductivity and hardness data for feed and bulk rejection differed by no more than 4 percent and 2 percent. In comparison of the rapid bench-scale membrane tests and pilot test, the bulk rejection differed by approximately 10 percent. The team concluded that membrane screening tests can be used to predict membrane rejection at pilot scale and to select a membrane based on constituent rejection (Grooters et al, 2006).

Allgeier and Summers (1995) investigated flux and rejection of thin composite nanofiltration membranes for surface water (pretreated) and groundwater (untreated) using rapid bench-scale membrane tests. The results of the study indicated that the pressure, flux, and rejection values obtained for the nanofiltration membrane are similar to the values reported by manufacturer and indicative of short-term performance.

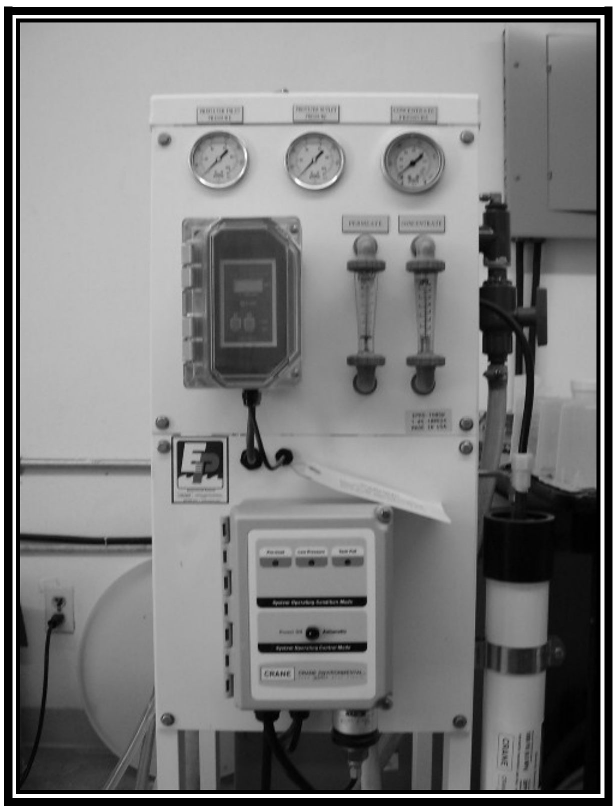
3.3.3 Single-element pilot testing

A Single-Element Bench-Scale Test is a test conducted on-site in continuous-flow mode using a single-element pressure vessel of a minimum size of 2.5-inch diameter and 40-inch length (Environmental Protection Agency, 1996b). A photograph of an actual single-element test unit is provided in Figure 3.2.

A single-element test can be operated as if the membrane were a lead element in a pressure vessel for the first stage of a full-scale system. The flux data from test may be used to validate the modeling software for total dissolved solids reduction. The test data can also be used to determine particle removal needs for pretreatment. Lead elements in the first stage are the

most informative because they are the most challenged by particle fouling. The next most informative element is the last element in the last stage, because scaling is first noticed at that location. The salt concentration increases as water passes through the feed or reject channel, and the outlet is the last element.

Manufacturers routinely use single-element testing with 4-inch diameter membranes to develop permeate flow and membrane rejection data for their product specifications. This testing is conducted using standard conditions (for example, 2,000 mg/L sodium chloride solution, 225 psi, 25oC, pH 8, and 15 percent recovery) by many manufacturers, allowing comparison of nanofiltration and reverse osmosis membrane products.

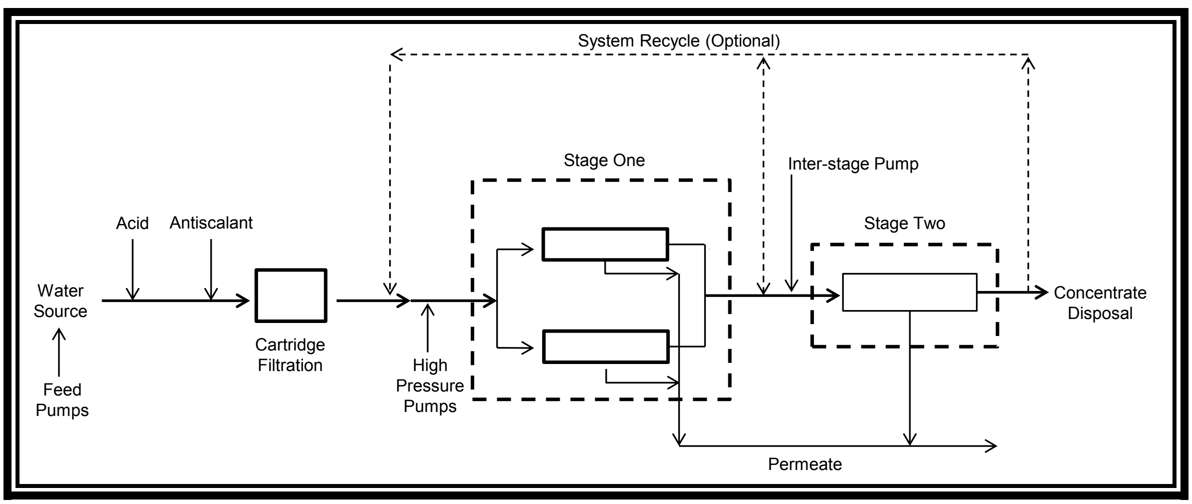


Source: Anthony Tarquin, UTEP

Figure 3.2: Example of a single element test unit.

3.3.4 Demonstration-scale pilot testing

A demonstration-scale pilot test is designed to more accurately simulate the hydraulics and operation of a full-scale system compared to rapid bench-scale membrane testing and single-element testing. A true demonstration-scale pilot plant requires at least two stages, with element, vessel, and array staging similar to full-scale design as shown in Figure 3.3. The system is operated at the same pressure, flux, and recovery as the proposed full-scale system, which provides the best indicator of overall full-scale performance in terms of pretreatment needs, fouling, and permeate water quality. Raw water flow rates for demonstration-scale pilot testing may range from 15 to 240 gallons per minute, depending on the size of the membranes used and the number of treatment trains tested in parallel.



Source: Adapted from EPA, 1996b.

Figure 3.3: Schematic of a two-stage pilot system.

Pilot testing may include membrane elements with 8-, 4-, and 2.5-inch diameters to develop membrane flux criteria. Typically, 8- and 4-inch diameter elements are used in the first two stages of an array and 2.5-inch diameter elements may be used if a third stage is needed. Membrane and pretreatment compatibility with the proposed raw water, flux, and recovery may be screened using computer modeling and flat-sheet testing.

The duration of a pilot study may be two to several months of operational time, depending on the project objectives, regulatory requirements, and variability of raw water quality. The additional time needed for site preparation before the pilot will depend on its complexity. Site preparation will require considerations for raw water supply and pumping, effluent discharge, power supply, equipment shelter, process piping and tanks, and availability of labor. If no infrastructure previously exists (as with some new groundwater treatment plants) site preparation may be costly and require several months to complete.

McCurday (2006) performed a five month pilot study on a reverse osmosis membrane for a groundwater source to evaluate pretreatment, particle fouling, and mineral scaling and compare performance from the pilot study to computer model projections. Groundwater quality for Beebe Draw aquifer consisted of sodium, chloride, magnesium, silica, calcium, and other major ions. All three membranes had salt rejections of roughly 99 percent, which were within 0.2 percent of the manufacturer's specifications. The computer model calculations were very similar to the data collected during the pilot study (concentrate, permeate, and salt rejections).

Chapter 4: Federal and State Regulations for pilot testing

4.1 Unites States federal regulations for membrane treatment

4.1.1 Background

Since 1986, the United States Environmental Protection Agency (USEPA) has promulgated increasingly higher standards for the filtration of surface waters. Additionally, in 2006, the USEPA required increased protection to groundwater sources against microbial pathogen contamination. A summary of the key provisions of these rules is presented in Table 4.1.

Table 4.1: Summary of United States Federal Water Treatment Rules

Rule	Code of Federal Regulations	Key filtration provisions
Surface Water Treatment Rule	Subpart H 40 CFR §141.70-76	Surface water systems must provide treatment equivalent of 3-log *Giardia* and 4-log virus
Interim Enhanced Surface Water Treatment Rule	Subpart P 40 CFR §141.170-175	Combined filter effluent turbidity limit of 0.3 Nephelometric Turbidity Unit Requires individual filter monitoring Requires 2-log *Cryptosporidium* removal
Long Term 1 Enhanced Surface Water Treatment Rule	Subpart T 40 CFR §141.500-571	Systems serving less than 10,000 must meet same standards as IESWTR
Long Term 2 Enhanced Surface Water Treatment Rule	Subpart W 40 CFR §141.700-723	Requires additional removal of *Cryptosporidium* in system with elevated influent concentrations Identified several “toolbox” technologies to achieve additional *Cryptosporidium* removal
Ground Water Rule	Subpart S 40 CFR §141.400-405	Requires monitoring for fecal indicators in groundwater sources May require 4-log virus removal and/or inactivation depending on risk

Until promulgation of the Long Term 2 Enhanced Surface Water Treatment Rule, membrane technology was not specifically addressed by the surface water treatment rules. It was

considered an alternative filtration technology by federal and state regulators. In the Long Term 2 Enhanced Surface Water Treatment Rule, membrane technology is presented as a distinct technology for compliance with the rule. The Membrane Filtration Guidance Manual (USEPA, 2005b) was developed to aid state regulators with the use of membrane technology for compliance, including requirements for challenge testing, direct integrity testing, continuous indirect integrity monitoring and recommended practices for pilot testing and implementation considerations. Nevertheless, the regulatory framework of the Long Term 2 Enhanced Surface Water Treatment Rule and Guidance Manual only apply to membrane systems used to achieve Cryptosporidium removal (predominantly low-pressure membrane filtration systems). The use of membrane technology for Giardia and virus removal may be regulated under the other surface water treatment rules at the states' discretion.

The Ground Water Rule may require 4-log virus removal and/or inactivation in a groundwater source depending on a state's trigger level for fecal indicators. A groundwater source that requires corrective action under this rule will typically use chemical disinfection but may use membrane filtration to comply with the rule. Membranes used for this purpose are required to be characterized by a molecular weight cutoff or an equivalent parameter. Similar to requirements for surface water, membranes may be subject to challenge or demonstration studies to receive log-removal credit for viruses and direct integrity monitoring (USEPA, 2008). Other than the need to remove viruses in some groundwater sources, the federal regulations do not have specific requirements for treatment and technology testing to meet drinking water standards. Rather, they provide lists of best available technologies, which may include membrane technologies, to meet the maximum contaminant level for specific contaminants.

Based on the federal regulations, states have some flexibility in how they implement the testing and approval of membrane technologies. The following sections include a detailed description of the current requirements for membrane technology testing and approval in Texas and a comparison of membrane technology testing and approval in other states for surface- and ground waters.

4.2 Texas Approach

4.2.1 Membrane technologies in Texas Administrative Code

Texas Commission on Environmental Quality (TCEQ) has been delegated authority by the United States Environmental Protection Agency to administer the state's drinking water program and enforces Rules and Regulations for Public Waters Systems found in the Texas Administrative Code. In the Texas Administrative Code, an "innovative/alternate treatment" is defined as any treatment process that does not have design requirements specified in other sections of the Texas Administrative Code, which includes both membrane filtration and demineralization (30 Texas Administrative Code § 290.38). Unlike many other states, TCEQ does not differentiate between the use of innovative technologies on groundwaters and surface waters. In this regard, TCEQ exceeds the federal requirements.

The implementation of innovative/alternate treatment systems requires pilot test data (30 Texas Administrative Code §290.42(g)). The Texas Administrative Code language is similar to the language in 40 Code of Federal Regulations §141.73 (d). In the Code of Federal Regulations, pilot studies or other means are indicated to be used to demonstrate performance. In contrast, the Texas Administrative Code allows the use of pilot test data or data collected at similar full-scale operations. The Texas Administrative Code specifies that pilot test data must be representative of actual operating conditions, a pilot study protocol may be required, and a one-year manufacturer's performance warranty may also be required (Appendix 8.1.1).

Membrane filtration systems are specifically addressed in 30 Texas Administrative Code §290.42(g)(3), and a copy of the code is included in Appendix 8.1.1 of this report. The membrane requirements for challenge testing, direct integrity testing, and indirect integrity monitoring are the same as in federal regulations.

4.2.2 TCEQ Permitting Process

New water systems and major improvements to existing systems are subject to a plan approval process prior to construction and operational monitoring after construction (30 Texas

Administrative Code §290.39). The agency has 60 days to complete the review of the plans and specifications of the project, but typically their review time is less. All materials submitted for review must be signed and sealed by a registered Texas Professional Engineer. Materials required for submittal include, but are not limited to, a plan review form, engineering reports, technical plans, specifications, legal documents, and business plans.

The engineering report, in general, includes a project description, calculations, and figures. The following is a list of items the engineering report should incorporate based on Rule 30 Texas Administrative Code §290.39(e) (1):

- Project description of proposed site and surroundings
- Population data of present and future areas to be served
- Quantity and quality of water source
- Maximum and minimum water demands of present and future
- Design data; pumping, water storage, delivery, and pressure capacities
- Type of treatment and equipment

All items submitted for review such as reports, plans, specifications, and business plan must be approved prior to starting construction. If changes are made to approved design, plans, and specifications of the water system, TCEQ needs to be notified in writing and they will determine if a resubmission is required. The changes to the water system cannot be applied in the field until approved. A list of changes that are considered significant appears in 30 TAC §290.39(j) (1). The agency has the authority to stop the construction and operation of a water system if it is a danger to the public. Once the water treatment plant is operating, plant and membrane performance is tracked in monthly operation reports.

4.2.3 Demonstration piloting requirements for membrane performance verification

The use of innovative technologies to treat groundwater or surface water is considered upon submittal of pilot data. To generate new data, there is a need for a pilot study to demonstrate the performance of the proposed membrane system. The pilot requirements, such as

duration of study and objectives, are very similar to the recommendations in the piloting section of the Membrane Filtration Guidance Manual for surface water treatment. However, here TCEQ exceeds the federal mandate and has applied similar requirements to groundwater and surface water. Otherwise, the piloting requirements found in the TCEQ staff guidance documents provides additional detail not found in the national regulations or guidance manuals, including provisions for the removal of dissolved solids using nanofiltration and reverse osmosis.

The specific requirements, such as the duration of the study and parameters to be measured during the pilot study, are not addressed in the state regulations. However, staff guidance documents exist, which TCEQ reviewers use and are available to the public on their website (TCEQ, 2004a-d). TCEQ regulations state that a protocol may be required to be reviewed and approved prior to commencing the pilot study (30 Texas Administrative Code §290.42(g)). Even though a protocol is not mandated in state code, in practice, a protocol is always required. The review of the protocol is beneficial to both parties as the agency may identify items lacking in the study prior to conduct of study, which may expedite the approval process. The staff guidance documents also imply the non-official requirement of a pilot study protocol.

The piloting process consists of submitting a protocol of the pilot study, conducting the pilot study, and presenting the results of the study and recommendations for the full-scale design in a report. The pilot study is expected to be representative of full-scale plant operation conditions. This includes water characteristics such as salinity, turbidity, and temperature, in addition to using a membrane of the same material and construction as the full-scale system. The water treatment process of the full-scale plant will be simulated in the pilot study, and the study should include disinfection, pretreatment, and other processes. In addition, a one-year manufacturer's performance warranty for the membrane may be required. Modifications made to the pilot study during Stage 2 or 3 may require repeating the study. Modifications are allowed in Stage 1 where the treatment process is being optimized.

The pilot study is performed for a minimum period of 90 days in three stages. Stage 2 and 3 must have a testing period of at least 30 and 10 days, respectively. The study should be performed during the season with the most difficult water quality and operation conditions. The first stage is to determine and establish performance parameters such as backwash, flux, recovery, and clean-in-place rates. The second stage is to improve or optimize the efficiency of the parameters established in the first stage and to demonstrate continuous consistent performance. The final stage is to validate the performance of the prior stages and note any decline in effectiveness. Particularly, the third stage is to demonstrate specific flux recovery following a clean-in-place procedure and the effectiveness of the cleaning procedure. After each stage and prior to beginning the next stage, a clean-in-place and direct integrity test must be performed. Direct integrity testing must be conducted at least once every seven days, or daily for systems in Bins 1, 2, 3 or 4. The parameters to be monitored and the frequency of data records vary among stages. Greater details of what is anticipated to be in the protocol can be found in TCEQ's guidance document titled, "Review of Pilot Study Protocols for Membrane Filtration" (TCEQ, 2004c).

Results of the study are compiled in a report and presented to TCEQ. A separate TCEQ guidance document titled, "Review of Pilot Study Reports for Membrane Filtration" (TCEQ, 2004d), details the items that are expected to be in the pilot study report. In general, the report should include the methods and equipment utilized, equipment calibrations performed, rainfall data collected, and test values gathered.

Membrane filtration without pretreatment can receive a 2.0-log removal credit for Cryptosporidium and 3.0-log removal credit for Giardia (regardless of the actual pathogen removal efficiencies). For membrane filtration with coagulation and flocculation, the log removal credit is the same for Cryptosporidium and Giardia with addition of receiving1.0-log removal for viruses (TCEQ, Weddell). With coagulation, flocculation, and clarification, and membrane filtration, the log removal credit for virus increases to 2.0 and the other credits are the same.

A disadvantage of the current TCEQ approval process for membrane treatment systems is that the requirement for demonstration piloting may encumber significant financial costs for the design of a membrane water treatment plant. Pilot testing costs vary from project to project. Parameters that affect pilot costs include availability of appropriate facilities, laboratory analysis costs, size and number of processes in the treatment train, and testing schedule. Including the setup, labor, supplies, and water quality testing, the total cost of piloting a membrane system ranges from $50,000 to $100,000 (Vickers, 2005). Based on recent projects in Texas that are ongoing with TWDB, the cost of pilot testing ranges from $75,000 to $2,690,945 (as shown in Table 4.2).

Table 4.2: Pilot cost and membrane filtration method for projects in Texas.

Project name	**Source[1]**	**Feed total dissolved solids (mg/L)**	**Pilot cost (US $)**	**Membrane system process train**	**Design capacity (MGD)**	**Project cost (US $M)**
Brazos River WTP	SW	1800	75,000	microfiltration/ultrafiltration	1.0	$5.0 M
Colorado River Metro Water District Big Spring Water Reclamation Plant	RW	2700-2800	750,000	microfiltration/ultrafiltration and reverse osmosis	2.5	$13.5 M
Fort Hancock	GW	1600-2400	-	reverse osmosis	0.4	$3.9 M
Hickory Aquifer Well Field	GW	<1000	750,000	reverse osmosis		$122 M
Kay Bailey Hutchison	GW	4300-4400	-	reverse osmosis	27.5 (15)	$87 M
Parker County SUD	-	-	-	microfiltration and reverse osmosis		
Roscoe Reverse Osmosis WTP	-	800-1000	75,000	reverse osmosis	0.43	$1.77 M
San Antonio Water Systems	-	-	2,690,945			$341 M
Southernmost Regional Water Authority	-	3500	0			$23 M
Walden Conjunctive Use WTP	RW & GW		760,000	microfiltration, nanofiltration, and reverse osmosis		>$5.45 M

Note: [1] SW: Surface Water; RW: Reclaimed Wastewater; GW: Groundwater

Note: Data provided by Texas Water Development Board

4.3 Comparison of regulations with other states

A comparison of the Texas approach with eight key states was conducted to evaluate how membrane filtration is addressed in state code and practice and to identify national trends. States were chosen for comparison based on historical and recent development of membrane treatment. Information regarding regulations and practices for the eight states was collected by searching each state's administrative code, guidance documents, and enforcement agency website. Plan reviewers of public water systems for various states were contacted via email and telephone to verify and expand on the information from the initial search and gain responses to any unanswered questions. Each state's section includes an analysis of state regulations, permitting requirements, and pilot requirements for water treatment facilities with groundwater and surface water sources.

Normally, membrane technologies are approved if the proposed treatment system meets national and state drinking water regulations. However, the flexibility and strictness of the approval process typically depends on practices internal to each state regulatory agency. The internal agency practices are an accumulation of engineering experience, the state's project experience, and the philosophy towards either the engineer's or the state drinking water program's responsibility to protect the public. A summary of certain aspects of regulatory requirements and practices in eight select states (in comparison with Texas) is provided in Table 4.3. Permitting codes are listed in the first column, and aspects of these codes are summarized with respect to the level of performance demonstration required, design and performance data approval, and manufacturing and engineering responsibilities.

When submitting a permit to construct a membrane treatment plant, the states surveyed require the engineer to submit a report detailing the technical basis of the treatment plant's design. The design parameters of the full-scale design and components of the engineer's report are typically rule-based requirements. This type of report is an industry standard and generally follows the criteria presented in Recommended Standards for Water Works (Great Lakes, 2007).

At times, a state may also issue guidance documents that may include instructions, a checklist, and an application, created by the regulatory department to assist the applicant in the permitting process. These guidance documents may also include instructions on the technical report.

For the states examined, pilot testing requirements were commonly included in internal staff guidance documents created to aide employees in permit reviews. These guidance documents consequently serve as supplements to state regulations because of the lack of detail in the state code. Permit submittal requirements are defined by state code. However, once an initial permit application and attachments are submitted, the department may request additional information that is not identified in the state code. The basis for the requests of additional information may be due to internal office practices or guidance documents.

Table 4.3: State regulations for membrane permitting and performance demonstration.

State	Permitting Regulations	Full-Scale Plant Design Parameters and Performance Data Required by State Regulatory Code[1]	Level of Performance Demonstration Required by State Regulatory Code Before Full-Scale Design	Manufacturer's Performance Warranty As Required By State	Submittal Requirements from State Guidance Documents or Practice For Construction Plan Approval
Texas	Texas Administrative Code (TAC) Chapter 30, Subchapter D, Section 290, Section 290.42(g)	• Flux, recovery, pretreatment, blending & post-treatment (corrosion control) strategy • NSF 60/61 certification for chemicals & materials of construction • "may be required"	Ground- and Surface-Water: Demonstration-scale pilot test by professional engineer, or data from other utility with similar water quality.	• One-year manufacturer's performance warranty • Bond guarantee may be required from the manufacturer for technologies subject to probationary acceptance	Ground- and Surface-Water: • Demonstration test report must be prepared by a Professional Engineer • Engineering Report submitted with construction permit application • Design/Construction contract documents
Arizona	Arizona Administrative Code (AAC), R-18-4 (Department of Environmental Quality Safe Drinking Water) and R-18-5 (Department of Environmental Quality Environmental Reviews and Certifications)	• Design Standards based on Engineering Bulletin No. 10, Guidelines for the Construction of Water Systems (ADEQ, 1978) • Construction Plans • Construction Specifications • Project description • Calculations • System capacity • Fire flow analysis • Pressure analysis	Ground- and Surface-Water: Not Required, Engineer's Discretion	Informal Requirement, Manufacture's performance warranty	• Engineer Report • Design documents and application forms
Florida	Florida Administrative Code (FAC) 62-555.320(2) & FAC 62-555.330(3) which references *Recommended Standards for Water Works*	• Hydraulic profile and various design flow rates • Sizes, capacity, loading rates, and other design parameters • Chemical application points and doses • Residuals disposal • Backflow prevention	Groundwater: Not Required, Engineer's Discretion Surface water: • Manufacture technical information • Data and report from Pilot-scale study or Full-scale plant • Operation and maintenance requirements	No requirement	Groundwater: • Preliminary Design Report with construction permit application • Design/Construction contract documents Surface water: • Preliminary Design Report with construction permit application • Manufacture technical information • Data and report from Pilot-scale study or Full-scale plant • Operation and maintenance requirements • Design/Construction contract documents
Illinois	Illinois Administrative Code, Title 35, Subtitle F, Chapter I, Part 611, Section 743(b)	• Design basis • Operation requirements • General layout • Detailed plans • Specifications • Recommended Standards for Water Works	Groundwater: 3 - 6 months of pilot testing Surface Water: 12 month Pilot test	No requirements	Surface water and groundwater: • Protocol • Completed study • Report with results of study • Design/construction contract documents

State	Permitting Regulations	Full-Scale Plant Design Parameters and Performance Data Required by State Regulatory Code[1]	Level of Performance Demonstration Required by State Regulatory Code Before Full-Scale Design	Manufacturer's Performance Warranty As Required By State	Submittal Requirements from State Guidance Documents or Practice For Construction Plan Approval
		• Interim Standard on Membrane Technologies			
New Mexico	New Mexico Administrative Code (NMAC), Title 20, Chapter 7, Part 10 Recommended Standards for Water Supply Systems, Section 4.3 Filtration	• Pretreatment design • Cleaning system design • Plans • Specifications • Flux rates	Groundwater: Not Required, Engineer's Discretion Surface water: Pilot plant studies or other means	No requirements	• Application • Engineering report • Plans • Specifications
South Carolina	Primary Drinking Water Regulation R.61-58.D(10)	• Flux, recovery, pretreatment, blending & post-treatment (corrosion control) strategy • Concentrate and cleaning waste disposal plan • Flow meter, pressure instrument, and sample tap positions • Valves for membrane cleaning • Monitoring equipment for pH, conductivity, temperature, turbidity and any other parameters required by MCL • NSF 60/61 certification for chemicals & materials of construction • Disinfection required	Groundwater: Not Required, Engineer's Discretion Surface water: Pilot plant studies or other means	No requirements	Groundwater: • Engineer's Report with construction permit application • Design/Construction contract documents Surface water: • Engineer's Report with construction permit application • Plans, Specifications, and design data
Virginia	Virginia Administrative Code(VAC), 12VAC5-590-420 (B) (2) (d) 12VAC5-590-880	• Schematic flow diagrams • Hydraulic profiles • Points of chemical application • Capacities • Filtration rates • Backwash rate • Retention times	Groundwater: Not Required, Engineer's Discretion Surface Water: Pilot plant studies or other means	No requirements	Ground water and surface water: • Application • Preliminary Meeting • Engineer Report • Plans • Specifications • Business plan
Wisconsin	Wisconsin Administrative Code, Natural Resources (NR), NR811.50 NR 108 Requirements for Plans and Specifications Submittal for Reviewable Projects and Operations of Community Water systems, NR 809 Safe Drinking Water NR 811 Requirements for the Operator and Design of Community Water Systems	• Recommended Standards for Water Works • Interim Standard on Membrane Technologies • Chemicals NSF/ANSI Standard 60 certified • Schematic flow diagram • Pipe layout • Hydraulic profile • Points of chemical application	Groundwater: Not Required, Engineer's Discretion Surface Water: Pilot Testing for 9-12 months for ultrafiltration/microfiltration	No requirements	Groundwater and surface water: • Engineering Report • Plans • Specifications • Results report of pilot study

4.3.1 Arizona

The Arizona Department of Environmental Quality (ADEQ) enforces environmental regulations of the Arizona Administrative Code, and drinking water regulations are included in 18 Arizona Administrative Code 4. Arizona's drinking water regulations are undergoing major revision, but the current regulations are brief and direct the reader to the Code of Federal Regulations (ADEQ, 2008a). A draft of the revised drinking water regulations is available from the Arizona Department of Environmental Quality that shows the actual incorporation of the Code of Federal Regulations, but it is not final (ADEQ, 2008b).

Early in a water treatment project (including the use of membrane technology), the project team is required to meet with Arizona Department of Environmental Quality to present preliminary drawings and data (for example, model projections for reverse osmosis systems) and discuss the need for testing of the proposed treatment system. Pilot studies are not required by rule for regulatory approval of membrane systems treating either surface- or ground-waters. Arizona Department of Environmental Quality may require pilot studies on a case-by-case basis, but this is rare. Pilot testing for surface waters is not required because the two main surface waters in Arizona are the Colorado River and Gila Salt River Basins, which are well-characterized water sources. Arizona residents receive drinking water from municipal distribution systems which receive water from surface waters such as rivers, lakes, and reservoirs (ADEQ, 2012). Water quality parameters that have been more problematic are aesthetic issues such as color, taste, odor, and algal blooms.

The design of the membrane treatment system is left to the judgment of the professional engineer based on the design standards for water treatment and distribution systems as summarized in Engineering Bulletin No. 10, Guidelines for the Construction of Water Systems, issued by Arizona Department of Environmental Quality (1978). Approval of membrane systems by Arizona Department of Environmental Quality is based on internal practices established through accrual of state project experience. For cases in which a water source does not meet a

specific maximum contaminant level, the state may recommend that the treatment system achieve 80 percent of the respective maximum contaminant level as a safety factor in the design.

Design and construction of drinking water systems are reviewed and approved by the Drinking Water Facilities Review Unit in the Safe Drinking Water Section, which is part of the Engineering Review Program in the Water Quality Division Program of Arizona Department of Environmental Quality. The permit review process consists of two stages. The first stage is a submittal for "approval to construct," in which an application, engineer's report, plans, and specifications are included. A manufacturer's warranty for the membrane utilized in the system is informally required. Most submissions for water treatment designs include product specifications and a membrane performance warranty. It is in the interest of the project's operating cost and reliability to use a membrane with a good life span. When reviewing the manufacturer information, the regulatory reviewer seeks for the manufacturer to have NSF International certification and a good reputation. This review period is 53 to 83 days, depending on the complexity of the project.

Once the water treatment plant is built, the second stage of the process includes an application for the "approval to operate" permit. The plant design must be built in accordance with the approved permit, otherwise the engineer is required to indicate any changes, and Arizona Department of Environmental Quality will decide whether a new permit or more information is required.

In addition, a new permit is required for a water treatment plant changing from conventional treatment to membrane filtration. In general any changes from the approved permit, requires a resubmittal. If a membrane is being replaced with the same membrane, it is not considered a deviation from the approved permit, but only maintenance. When changing manufacture and membrane material, it is left to the engineer's discretion to submit a letter of notification of this change.

The performance of water treatment plants is tracked by the compliance and analytical results from turbidity and chlorine residual measurements. Performance is also evaluated during review inspections as part of sanitary surveys.

4.3.2 California

The California Department of Public Health enforces environmental regulations of the California Code of Regulations, and drinking water regulations are included in California Code of Regulations 17 and California Code of Regulations 22. In July 2007, California Department of Health Services was restructured into the California Department of Public Health and the Department of Health Care Services. The California Regulation Related to Drinking Water manual was compiled to assist California Department of Public Health personnel when reviewing permits and needing a quick reference to regulations (California Department of Public Health, 2011). Treatment and pilot testing requirements for water treatment facilities are different if the source is groundwater or surface water. This is consistent with federal requirements.

Membrane systems are categorized as “alternative filtration technologies” for surface water treatment, requiring performance demonstration to meet the requirements of the surface water treatment rules (22 California Code of Regulations § 64653(f)).

Typically, the first step in evaluating the use of membrane treatment for a surface water source is to check the California Surface Water Treatment Alternative Filtration Technology Demonstration Report. This report summarizes a list of accepted membrane technologies, their corresponding log-removal credits, and reasoning behind the appointed removal credit for a surface water source (California Department of Health Services, 2001). The removal efficiency of alternative technologies is based on studies that follow the California Surface Water Treatment Rule. For each membrane approved, the report provides the following: manufacture information; name of the study and who conducted it; water source; log-removal credits for Cryptosporidium, Giardia, and virus; performance standards; and operation criteria. Additional

topics discussed for each membrane are membrane integrity, filter backwash, and membrane cleaners. First-year operational reports that summarize the membrane performance and any deviations are included at end of the report. Since the "alternative to filtration" rule focuses on pathogen removal, the membranes approved in the Demonstration Report are predominantly low-pressure membranes. For membranes and/or water sources that are not listed in the Demonstration Report, a California Department of Public Health -approved challenge test will need to be conducted to receive log-removal credit for the membrane/source water combination.

Even with the log removal credit, California Department of Public Health strongly recommends pilot testing using the proposed treatment scheme and surface water for one year. The purpose of this testing is to evaluate the impact of seasonal water quality on membrane performance. This includes fouling characteristics and disinfection by-product formation that may occur from recycling maintenance backwashes, enhanced cleaning backwashes, and/or clean-in-place streams. Seawater reverse osmosis plants will require pilot testing, but are typically limited to 2-log removal credit for Cryptosporidium and Giardia because a tracer that can be "discretely quantified" (as required by the Membrane Filtration Guidance Manual) to the log-removal value being sought is currently unavailable for reverse osmosis membranes.

For groundwater sources, no pilot testing is required as long as the proposed treatment technology is a best available technology (BAT) capable of meeting the respective maximum contaminant levels for the treated water. Primary constituents such as arsenic and radium have specified best available technologies in the regulations (USEPA, 2007b). The removal technologies listed for arsenic removal are the following: activated alumina, anion exchange, mixed bed ion exchange, green sand filtration, oxidation/coagulation/filtration, lime softening, and reverse osmosis (USEPA, 2007b). These groundwater systems are not subject to the same piloting requirements as surface waters, because the membranes (typically nanofiltration and reverse osmosis) are not being used for pathogen removal. The design of these treatment systems is, therefore, left to the judgment of the professional engineer.

For technologies proposed for treating groundwater that are not designated as a best available technology, a pilot study will be required to demonstrate technology performance including removal efficiency. Non-BAT approvals are not site specific and the California Department of Public Health can use the pilot study data when reviewing another application using the same technology for similar water sources elsewhere in California.

District engineers in the California Department of Public Health, with the consultation of the California Department of Public Health's Water Treatment Committee, grant or deny permits. The permitting process begins with the manufacturer or the public water system interested in using the technology (for surface water or non- best available technology groundwaters) submitting a written request. Then a demonstration study protocol is developed with and approved by the district engineer and WTC. Finally, the study is conducted and the results are compiled in a report and submitted for review. If approved, a report is due after a year of operation summarizing the performance of the technology.

Regardless of the water source, a public water system is required to submit a domestic water supply permit for a new source or modification in treatment of an existing source. An application guidance document is available for this permit (California Department of Public Health, 2007). A major focus is on the preparation of the technical report. The following elements of the technical report addressed in the guidance document are general water system information, source water information, treatment and design information, operational plans, and environmental documentation. Permit requirements for domestic public water system are listed in 22 California Code of Regulations § 64552.

4.3.3 Florida

Florida Department of Environmental Protection enforces environmental regulations (Chapter 62-555 and 62-550) in the Florida Administrative Code. Treatment requirements for water treatment facilities are different for sources from groundwater and surface water. In

general, the treatment requirements are not explicit in the state code, but the state regulations provide reference to the Code of Federal Regulations, 40 CFR141.

Treatment techniques for surface water sources are detailed in Florida Administrative Code Rule 62-550.817 and are similar to United States Environmental Protection Agency requirements for the surface water treatment rules. Although membrane filtration is not listed as a filtration method, the code states “systems providing reverse osmosis, ultrafiltration, or nanofiltration shall provide sufficient disinfection to achieve a minimum of 0.5-log Giardia lamblia cyst and 2-log virus inactivation to supplement membrane filtration treatment” (Florida Administrative Code Rule 62-550.817(2) (b) (4)(d)). Pilot testing is required for membrane treatment systems using a surface water source. Nevertheless, ”well-operated” membrane filtration systems (including reverse osmosis, nanofiltration, and ultrafiltration) are granted 2.0 log-removal credit for Cryptosporidium, 2.0 log-removal credit for viruses, and a 2.5 log-removal credit for Giardia lamblia based on effluent turbidity standards. (Rule 62-550.817(9) (b), Florida Administrative Code). Disinfection is expected to be used to achieve the remaining log-removal credit that may be required.

Groundwater classifications and standards are addressed in Florida Administrative Code Chapter 62-520. Pilot testing is not required for water treatment plants using these sources. In general, water quality issues that are address by groundwater treatment are elevated total dissolved solids, sulfate, and other secondary contaminants. The design of a groundwater treatment system is left to the judgment of the professional engineer. If conducted, design reports for groundwater systems to Florida Department of Environmental Protection may include data and analysis from a manufacturer and bench-scale tests.

In Florida, water treatment plants are classified into categories based on the treatment process, which is used to determine the permit fee. A water treatment plant that uses a membrane process such as electrodialysis, electrodialysis reversal, microfiltration, ultrafiltration, nanofiltration, or reverse osmosis is classified as Category II (FAC Section 62-699.310 (e)) (Florida Department of Environmental Protection, 2007). A “Specific Permit to Construct PWS

Components" is required when constructing a water treatment facility (Florida Department of Environmental Protection, 2003). Together with the application, a design report is also submitted describing the following existing and post development conditions: location, costs, water source, impacts to public water system, design, and operating capacities, and the treatment process to be used. Projects that involve a new water source or new treatment facility require the following additional information: water quality data, chemical doses, residual quantities, schematic/flow diagram, hydraulic profile, and a discussion on techniques used to meet primary and secondary standards (Section 62-555.520, Florida Administrative Code). Membrane plant performance is tracked using monthly compliance reports and sanitary survey inspections every 3 years.

4.3.4 Illinois

The Illinois Environmental Protection Agency enforces Primary Drinking Water Standards (Title 35, Part 611) in the Illinois Administrative Code. Treatment requirements and pilot testing differ for public water systems with groundwater or surface water sources.

Public water systems with sources from surface water or groundwater under the influence of surface water have to meet requirements similar to the United States Environmental Protection Agency surface water treatment rules. Membrane technologies are categorized under "other filtration technologies" and also referred to as an "alternative filtration technology" (35 Illinois Administrative Code 611.250 (d)). Pilot testing of Membranes Filtration for Treating Surface Waters is an internal document that is used by staff in the permit section of the Division of Public Water Supplies, which details the requirements for pilot testing for water facilities with surface water sources (Illinois Environmental Protection Agency, 2001). Pilot testing is required for one year using operating conditions representative of full-scale. Illinois Environmental Protection Agency requires a protocol of the pilot study to be submitted prior to beginning pilot testing. Additional requirements include conducting continuous monitoring for particle counts and turbidity. Chemicals and equipment used for the study must be NSF International Standard 61 certified and five years of raw water data should be reviewed (Illinois Environmental

Protection Agency, 2001). Once the pilot study is complete, a report detailing the results is submitted along with a construction permit application.

For groundwater sources, six months of pilot testing is required, but the testing period can be shortened based on the water quality of the project. The time frame may be shorted to a minimum of three months, provided that consistent general raw water quality data is available (for example pH and hardness) for the source.

The permitting requirements for public water systems are detailed in Part 602 and 652. To construct a water treatment plant, a construction permit followed by operation permit upon completion of the facility can be obtained from the Division of Public Water Supplies Permit Section. In conjunction with a Division of Public Water Supplies Application for Construction form, a design report, general layout, detailed plans, and specifications are submitted for review (Illinois Environmental Protection Agency, 2000). Performance of membrane systems is tracked using monthly reports and periodic inspections.

4.3.5 New Mexico

New Mexico Environmental Department enforces State and Federal Drinking Water Regulations in the New Mexico Administrative Code. General requirements for drinking water facilities are addressed in the 20.7.10 New Mexico Administrative Code (New Mexico Administrative Code, 2002). The requirements are not explicit but rather provide reference to adoptions of the Code of Federal Regulations and standard manuals. Several guidance documents used by the department are listed in 20.7.10.102 New Mexico Administrative Code. The manuals include, but are not limited to, American Water Works Association manuals, New Mexico Environmental Department manuals, and Recommended Standards for Water Works (Great Lake, 2007).

The Recommended Standards for Water Supply Systems, Policies for the design, review, and approval of plans and specifications for water supply systems and treatment works manual contains design standards for water facilities used by state employees as guidelines. For source

development of surface waters (Section 3.1), minimum treatment requirements are determined by New Mexico Environmental Department, and filtration should be provided to all surface water and groundwater under the direct influence of surface water. Membrane filtration is defined by New Mexico Environmental Department to include microfiltration, ultrafiltration, nanofiltration, reverse osmosis, electrodialysis, and electrodialysis reversal. Microfiltration and ultrafiltration membranes are granted log-removal credits for Giardia, Cryptosporidium, and viruses for a proposed full-scale system based on pilot- or full-scale removal data. In many cases, these data are well-established for the surface waters of New Mexico and pilot testing may not be required. Electrodialysis and electrodialysis reversal receive no log removal credit because the treated water is not passed through a membrane barrier with these technologies. No reference was made to the mechanism for granting nanofiltration and reverse osmosis log removal credit for surface waters.

New Mexico Environmental Department has indicated in Section 4.3.3 that a pilot study should investigate operational parameters such as, but not limited to, flux rates, pretreatments of source water, and membrane cleanings (New Mexico Environmental Department, 2006). Prior to commencing a pilot study or the design of a water treatment system, the interested party should contact and schedule a meeting with New Mexico Environmental Department to discuss the proposed project and review available water quality data. Consent must be received from New Mexico Environmental Department before beginning the pilot study.

Under source development of groundwater (Section 3.2) in the Recommended Standards for Water Supply Systems, filtration requirements are not addressed. In practice, pilot testing is not required for groundwaters, and treatment system design is left to the judgment of the professional engineer. This is consistent with federal requirements.

A review of the permitting process is found in 20.7.10.201 New Mexico Administrative Code. An Application for Construction or Modification of a Public Water Supply System must be submitted 30 days prior to advertising a project for bid or entering a construction contract (New Mexico Environmental Department, 2011). Along with the application, the following items

need to be submitted: an engineering design summary, plans, specifications, disinfection system plan, and an inventory of existing or potential contamination within a 1,000-foot radius. Plans should include the layout of the water treatment facility with details such as elevations, sections, and diagrams. The disinfection plan should indicate sampling frequency, sampling location, and an emergency plan in case of contamination. If the water source is new, a nitrate sample must be collected. In addition, "documents demonstrating that the public water system has sufficient technical, managerial, and financial capacity" are required to be submitted (20.7.10.201(D) (1)). The documentation and information required to prove the applicant's capacities are detailed in Appendix A of the application. Performance of membrane treatment systems are tracked by sanitary surveys every three years for community systems and five years for non-community systems and operation reports that detail turbidity and chlorine residual measurements are required.

4.3.6 South Carolina

South Carolina Department of Health and Environmental Control enforces State Primary Drinking Water Regulations (R.61-58) found in the South Carolina Administrative Code of Regulations. Treatment and filtration requirements are addressed separately for surface water (R.61-58.3) and groundwater sources (R.61-58.2).

Membrane technologies are considered an "innovative treatment technique" by South Carolina Department of Health and Environmental Control. Design requirements for surface water sources are in R.61-58.3. Pilot testing may be required to demonstrate performance of the filtration method for surface water sources. Typically, pilot testing is performed for one-year to evaluate seasonal variations in fouling characteristics of a membrane. Also, South Carolina Department of Health and Environmental Control may require a pilot test if an existing membrane is replace with one by a different manufacturer and/or material. To date, South Carolina Department of Health and Environmental Control has not had to review an application for membrane replacement.

Treatment requirements for groundwater sources are in R.61-58.2(D). Pilot testing is not required for approval of membrane treatment systems using these sources. This is consistent with federal requirements.

To permit a water facility, a Construction Permit Application is submitted to the Water Facilities Permitting Division of Bureau of Water (South Carolina Department of Health and Environmental Control, 2008). The agency has a maximum of 45 days to complete the technical review, but the average review period is 25 days. The review process is separated into two phases (South Carolina Department of Health and Environmental Control, 2004).

In the first phase a preliminary engineering report is submitted and reviewed before starting final design. The preliminary engineering report is prepared in accordance with Regulations 61-58.1(C) which include a description of the following: project area, water source, water treatment plant, waste disposal handling, and an alternative water source economic and engineering assessment. The water treatment plant description should include capacities, treatment method, and flow diagram.

In the second phase, final plans, specifications, and design calculations are presented for the construction of the water treatment plant. The submittal package consists of the following items: plans, specifications, design calculations, a location map, construction easements, a letter from the entity supplying the water, a letter from the entity accepting operation and maintenance responsibility, and a letter from the local government of that potable water planning authority. Plans should include a flow diagram, hydraulic profiles, as well as points of chemical application and sampling (R.61-58.1 (E)). Specifications should encompass construction and material (R.61-58.1(F)). Design data for the water treatment plan indicate retention times, velocities, filtration rates, overflow rates, and backwash rates (R.61-58(G)). Membrane plant performance is tracked by South Carolina Department of Health and Environmental Control with monthly operating reports that include turbidity and other measurements.

4.3.7 Virginia

The Virginia Department of Health enforces Water Works Regulations (Chapter 590) in the Virginia Administrative Code. The Water Works Regulations is separated further into three parts: General Framework for Waterworks Regulations (Part I), Operation Regulations for Waterworks (Part II), and Manual of Practice for Waterworks Design (Part III).

Treatment technique requirements for waterworks with sources from surface water or groundwater under the direct influence of surface water are found in Part II in 12VAC5-590-420. Membrane filtration is categorized under "other filtration technologies" (12VAC5-590-420 (B) (2) (d)). Pilot testing is required to establish that, in combination with disinfection, a membrane system can achieve 3-log inactivation of Giardia lamblia, 4-log inactivation of viruses, and 2-log inactivation of Cryptosporidium. Virginia Department of Health allows the use of a single membrane module (identical to the one proposed for the full-scale system) and a "smaller-scale" membrane module (identical in material and similar in construction to the proposed full-scale module).

For groundwater sources, Virginia Department of Health does not require pilot testing unless the water source(s) have "poor" quality where the state regulator and engineer define "poor" quality. In general, the design of these treatment systems is left to the judgment of the professional engineer.

The Division of Water Supply Engineering in Virginia Department of Health reviews the requests to construct water treatment plants. The permit process consists of five steps to obtain an operation and construction permit, which include the following: (1) submitting Water Works Application Form, (2) participating in a preliminary meeting, (3) developing a business plan, (4) submitting an engineering report, and (5) submitting plans and specification (Virginia Department of Health, 2007a-b). A preliminary meeting is held to discuss the proposed project and identify additional permits required from other agencies such as a permit from the Virginia Department of Environmental Quality for the withdrawal or discharge to a water system. A

business plan is also required only for first time owners of a water treatment facility. The specifics of submittal items for obtaining a construction permit are located in 12VAC5-590-200.

Performance of all water treatment plants is tracked by monthly operating reports that provide the highest turbidity measurements and integrity testing results with log removals. Onsite inspections are also completed every six months.

4.3.8 Wisconsin

The Wisconsin Department of Natural Resources enforces drinking water regulations found in the Wisconsin Administrative Code. Wisconsin is part of the ten states that use the Recommended Standards for Water Works (Great Lakes, 2007). The Wisconsin administrative code was updated in December 2011, and all rules are effective January 2012. The applicable chapters related to drinking water are the following: Requirements for Plans and Specifications for Reviewable Projects and Operations of Community Water Systems, Sewerage Systems, and Industrial Wastewater Facilities (Chapter NR 108), Safe Drinking Water (Chapter NR 809), Requirements for the Operation and Maintenance of the Public Water Systems (Chapter NR 810), and Requirements for the Operation and Design of Community Water Systems (Chapter NR 811).

Water treatments requirements are different when public water systems use groundwater versus surface water and groundwater under the direct influence of surface water. However, Wisconsin Department of Natural Resources incorporates the requirements for testing membrane systems using surface- and ground-waters in one section (NR 811.50). The membrane filtration section covers water quality considerations, pilot testing, challenge testing, pretreatment, membrane materials, backwashing, membrane cleaning, membrane integrity testing, monitoring, and post treatment. This section is provided in Appendix 8.2 of this report.

Pilot testing membrane systems is required for surface water sources to establish the performance of the technology, but may be waived if the technology is being used in another facility and operating successfully. The plans, specifications, and engineering report should be

submitted for review prior to beginning the testing. A pilot study protocol is an informal requirement, and manufacture performance warranty is not required. Testing should last the time necessary to be able to establish the treatment efficiency and operation parameters. For microfiltration and ultrafiltration with a surface water source, pilot testing should be conducted for nine to twelve months. In general, requirements should follow the Environmental Protection Agency Membrane Filtration Guidance Manual.

For groundwater sources, pilot testing is not required unless the water quality is "poor" where "poor" water quality is not defined in the Wisconsin regulations. When pilot testing is required, testing should be conducted for two to seven months for groundwater sources that use nanofiltration and reverse osmosis membranes.

Wisconsin Department of Natural Resources has a maximum of 90 days to review a permit, but they usually take 60 days for projects that are not water main extensions. New community water systems also have to acquire a capacity certification before initiating operation. For a permit submittal, an engineering report, plans, and specifications are required to submit for review and comment. The details of engineering report, plan, and specifications are addressed in NR108 and NR811.09 (Wisconsin Department of Natural Resources, 2011a and 2011b). Performance of the treatment facilities are compiled thru the monthly reports and direct integrity testing (pressure decay) performed every eight hours for surface water systems.

Chapter 5: Methodology

5.1 Analytical Design

The general concept of the design is to compare predicted membrane performance to full-scale performance in desalination plants. The design analysis is divided into two sections: accuracy and precision. The accuracy analysis compares model or pilot data to actual membrane performance. The immediate outcome of the analysis is an accuracy measurement of rejections and operating pressure for each data set. The analysis is completed for several data sets to achieve the overarching outcome which is the ability to demonstrate the capacity of a model to predict full-scale performance. Precision analysis assesses membrane performance among the various membrane manufactures. The full-scale performance is entered to the corresponding manufacture's model and compared to models of similar membrane systems treating identical source water. The output of the models provides a way to measure how precise models are with respect to each other.

5.2 Selection of Reverse Osmosis Membrane Models

Selection of the six commercial membrane software models was based on selecting manufactures' models that represent the majority of installed reverse osmosis membranes systems nationwide. Dow chemical, Toray, and Hydranautics encompasses about 95 percent of the installations and by including the other three models the project accounts for about 98 percent.

A RO/NF Computer Modeling workshop offered at the 2012 AMTA/AWWA Membrane Technology Conference was also attended to familiarize the user with the programs. The workshop provided attendees an overview of five manufacture models and breakout sessions to two software models of their choice, led by the manufacture's technical expert. Table 5.1 lists the computer software model versions, membrane manufacturer, and website link to download the software model.

Table 5.1: List of Reverse Osmosis Design Software Models

Software Model	Manufacture	Website Link
ROSA 8.0.3	Dow Chemical	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

5.3 Parameters

To compare models on an equivalent basis, specific parameters of the models and full-scale design were selected to characterize the water quality and hydraulic performance of the desalination system. Water quality parameters include concentrations of individual elements/ions/compounds, as well as total dissolved solids (TDS), operating pressures, and product water fluxes. Balancing feed water, pressure losses, and membrane aging are important topics because how the user inputs these parameters into the model impacts the results outputted by the model. Table 5.2 summarizes key parameters which are detailed in the latter sections.

Table 5.2: Summary of model inputs for key parameters

Parameter	Bicarbonate				Ion Balance	Pressure Losses			Membrane Aging			
Software	Alkalinity	HCO_3	CO_3	CO_2	Sodium/Chloride	Pre - Stage	Inter-stage 1	Inter-stage 2	Age	Flow Factor	Flux	Scale
ROSA	_	U	E	E	U[1]	U	E	_	_	U	_	_
Winflows	U	E	E	E	U	_	U	U	U	_	U	U
Toray DS2	_	U	E	E	U[2]	U	U	U	U	U[5]	_	U
KMS ROPRO	U	U	U	_	_	_	U	U	U	_	U[6]	_
CSMPRO	_	U	E	E	U[3]	_	E	_	U	_	U	U
IMSdesign	_	U	E	E	U[4]	U	E	_	U	U	U	U

U=User specified E=Embedded

[1]Adjust by Cations, Anions, all Ions

[2]Adust by $MgS0_4$

[3]User can add Na, Cl, NaCl (adjust both ion concentrations)

[4]Auto Balance but program completes with Na or CL

[5]Fouling allowance in factor

[6]Fouling allowance in percent

5.3.1 Water Quality Inputs

The various software models have similar user interfaces for inputting ion concentrations of the feed water quality. 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 the following: well water, brackish well water, and well water with a Silt Density Index (SDI) less than 3. In the software models, the user specifies the water classification which is interlinked with saturation limitation, flux, and concentrate flow rate warnings produced by the software.

Table 5.3 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.

Table 5.3: List of Cations and Anions in the Commercial Models

Cations	Anions
• Ca^{2+}	• Cl^{-}
• Mg^{2+}	• SO_4^{2-}
• Na^{+}	• $CO_2/HCO_3^{-}/CO_3^{2-}$
• K^{+}	• NO_3^{-}
• Ba^{2+}	• F^{-}
• Sr^{2+}	• B^{3+}
• NH_4^{+}	• SiO_2

ROSA, TorayDS2, CSMPRO, and IMSdesign allow the user to input concentration of bicarbonate, and the software calculates the amount of carbonate and carbon dioxide (based on the pH input by the user). Winflows requires the user to enter the total alkalinity as calcium carbonate. KMS ROPRO allows the user to enter the 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 program provides the user with a warning stating the pH will be adjusted.

An important consideration about feed water data is that some models take water quality as the user specified, whether balanced or not, and other models take the user specified ion concentrations and automatically charge balance (electroneutrality) before entering the system. Adjustments to the user-supplied feedwater chemistry can be seen in the output reports where the raw or feed water is different from the feed or adjusted feed water. Most programs allow the user to balance ions through the addition of sodium and/or chloride.

In the project information interface of ROSA, the user can identify the preferred salt for balancing from sodium chloride, calcium chloride, and calcium sulfate. Then in the feedwater data interface ROSA allows the user to specify how to perform the balance by adding chloride, adding sodium, or to balance by adjusting cations, anions, or all ions as shown in Figure 5.1. 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. The Toray DS2 model provides the user two options to balance with sodium chloride or magnesium sulfate. When the user uses sodium chloride the program adds either sodium or chloride depending if the water is deficient in cations or anions. KMS ROPRO does not have a button a user can press to balance, 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. The IMSdesign software model allows the user to balance automatically, but not to choose the ions that are added.

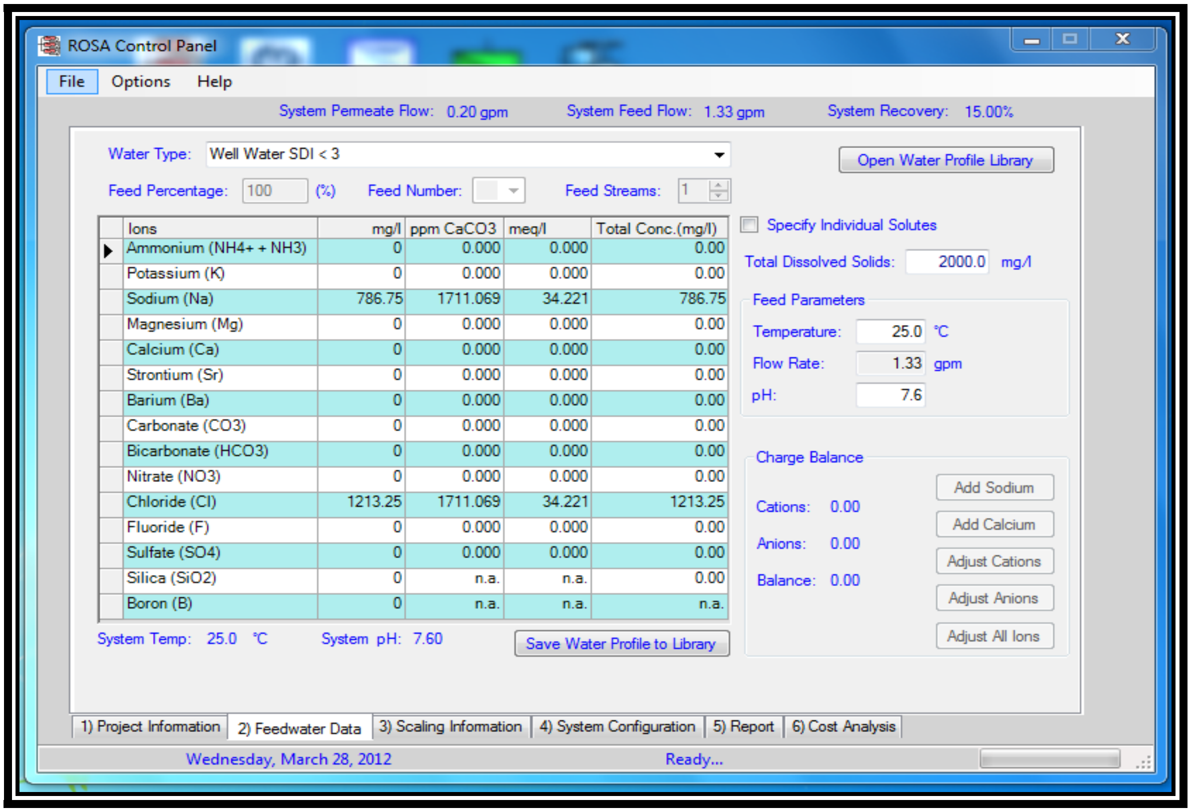


Figure 5.1: ROSA model feed water data interface.

5.3.2 Operating Pressures and Pressure losses

Reverse osmosis models include functions for predicting operating pressures: inlet and outlet pressures of feed, concentrate, and permeate streams in each stage. Some reverse osmosis systems are designed and operated with a feed pump and an inter-stage boost pump or permeate throttling or combination of both boost and throttling. Permeate throttling (i.e., permeate back pressures) consists of placing a valve at the permeate end in earlier stages of the first stage of the system to force water to the following stages. Inter-stage boost provides extra pressure to increase water flux in the second stage. All models are able to simulate inter-stage boost pressure and permeate back pressure.

Piping and manifold pressure losses are a key factor when comparing operating pressures, because the losses can occur at various locations and by different amounts. Furthermore, piping and manifold losses can have two reference names in the same model, one

in the user interface and another in output report. Most of the models allow the user to input the quantity of pressure loss. 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.

The ROSA model allows the user to change the amount of pressure loss from the default of 5 pounds per square inch (psi) at the beginning of the design in the project input interface. The pressure loss is called “pre-stage” and has to be greater than zero. The user can approximate pressure negligible losses by entering an amount that is close to zero (e.g., 0.0001 psi). The pressure losses are accounted for at two locations: between the feed and first stage element, and between the first and second stage. The limitation of this software is that the “pre-stage pressure loss” occurs automatically at these two locations and cannot be separated. The user has to change the “pre-stage loss” amount to tailor their design, if required, since the pressure loss is set to a default value. The output reports do not indicate or refer to the pressure losses.

The Winflows model refers to pressure losses as “inter-stage pressure loss.” The software allows the user to input a loss in first stage and second stage of the system in the “RO Element Data” interface as shown in Figure 5.2. If the user enters a pressure loss in first stage, the loss occurs between first and second stages. If the user enters a loss in second stage, the loss is removed from the interstage boost pressure. The output report refers to the pressure loss differently with a name of “Pre-stage Pressure Change Drop”.

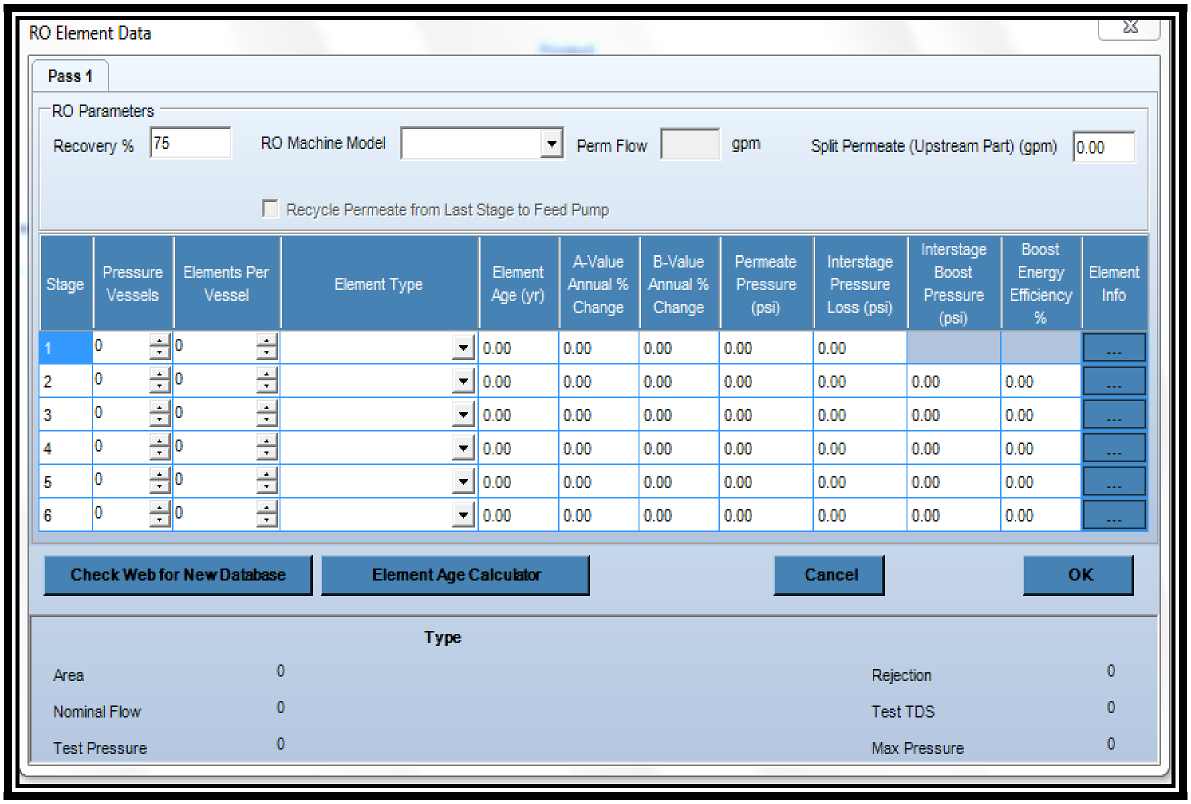


Figure 5.2: Winflows system configuration program interface.

The KMS ROPRO model refers to pressure loss as "inter-bank pressure loss" and the output reports the loss as manifold loss. The user is allowed to input permeate back pressure loss in first and second stages and inlet pressure boost in the second stage in the membrane array configuration interface.

The Toray DS2 model refers to the pressure losses as "inter-banking piping loss" in the software model and as "piping loss" in the report. The user can input in the permeate back pressure interface a pressure loss in first and second stages and boost pressure in the interbank boost interface. 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 first and second stages, and is, of 5 psi for IMSdesign and 3 psi for CSMPRO. The output reports of both models do not reference the pressure losses.

5.3.3 Hydrodynamics and Fluxes

For both accuracy and precision comparisons, all reverse osmosis membrane filtration designs are normalized by flux. The overall pass, first stage, and second stage fluxes of the actual plant are matched in the models.

In precision analyses, an equivalent membrane is selected from each manufacture to match the membrane in the system of the plant being assessed. The designated equivalent membrane may not have the same surface area, but for the majority the areas are the same. When a selected equivalent membrane from another manufacture has a different surface area, the permeate flows are scaled by the ratio of areas in the elements of comparison (e.g., 400 ft2 and 440 ft2). While fluxes are matched, cross flow velocity may differ between two membranes where larger surface area membranes have higher cross flow velocities.

5.3.4 Membrane Aging

Effects of membrane aging are simulated in the computer models in two ways: water permeability and salt permeability. Over time, the flow thru a membrane is affected by membrane fouling which results in a decline in flux if operated at a constant pressure or an increase in pressure if operated at a constant flux.. Scaling reduces the membrane salt rejection or increases salt passage with age, depending if membrane performance is viewed as rejection or salt passage. The general impacts to the system from fouling and scaling include an increase in the pressure required to produce the same amount of water and a decline in the quality of the water. All six computer models are able to simulate aging effects on the membrane water permeability and only four models (Winflows, Toray Design System, CSMPRO, IMSdesign) simulate changes to salt passage. In all computer models, new membranes are indicated by an age of zero, a flow factor of one, and salt increase of zero percent. The KMS ROPRO model differs and a fouling allowance of zero percent indicates a new membrane. When the membrane

is aged the model calculates the total flux decline or salt passage increase by multiplying the membrane age by the percent change to obtain the total percent change.

In the ROSA software, a membrane age parameter is not available. The user can, however, change the “flow factor” to simulate aging effects of 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 prefers not to show scaling effects because scaling is affected by the type and dose of antiscalant applied and by the operation, which can vary from project to project. KMS ROPRO allows the user to enter a membrane age and fouling allowance percent. Even if the user enters an age greater than zero without a fouling allowance, the model will not be affected; the user has to input a fouling allowance to simulate aging effects on flow and pressure.

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 of inputting 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-value and B-value for different source waters. For brackish well water, the suggested A- and B-values are three and five percent, respectively.

For CSMPRO4, the user can enter the membrane age, flux decline in percent per year, and salt passage increase in percent per year. The model calculates the total percent change in flux and salt passage and simulates the effects. Similarly, in Toray Design System the element age, salt passage in percent per year, and fouling allowance as a factor can be entered by the user.

IMSdesign model allows the user to input the membrane age, fouling factor, flux decline, and salt passage increase in 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.

5.4 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 5.1. The water treatment plants are located in Texas, Florida, Arizona, Maryland, Kentucky, and Kansas. Water quality analyses are available for four of the data sets. The total dissolved solids concentrations for all 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 use brackish water reverse osmosis membranes, which can be further classified as fouling-resistant, low-energy (or low-pressure), or general brackish water membranes.

Table 5.4: Full-scale Reverse Osmosis Plants

Membrane Type	Project Name	State	Feed TDS (mg/L)	Recovery (%)	Stage 1 (PVxE)	Stage 2 (PVxE)	Water Quality Data	Full Scale Data	Pilot Data	Computer Model	Membrane
Brackish Water	Aransas MUD	TX	2,217	75	2x6	1x6	-	Yes	-	Toray	TM720N-400
Brackish Water	Eastern Correctional Institute RO	MD	1,379	80	10x6	5x6	-	Yes	-	Toray	TM720-400
Brackish Water	Goldsworthy WRD	-	1,774	80	42x7	24x7	-	Yes	-	CSM	RE8040-BE
Brackish Water	Horizon MUD	TX	1,764	83	24x6	12x6	-	Yes	-	Toray	TM720N-400
Brackish Water	Pinewoods	FL	2,452	85	13x7	6x7	-	Yes	-	Rosa	BW30LE-440
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	Fort Stockton	TX	2,712	78	10x6	5x6	-	Yes	-	Toray	TM720L-400
Low Energy	Hardinsburg	KY	453	80	14x7	7x7	Yes	Yes	-	Hydranautics	ESPA1/2
Low Energy	KBH- start-up	TX	1,458	83	48x7	24x7	Yes	Yes	-	Hydranautics	ESPA1
Low Energy	KBH-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

5.5 Analytical Matrix for Accuracy and Precision

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

5.5.1 Accuracy

Prior to beginning the modeling procedure, the model used to design the existing full-scale water treatment plant (referred to as the projection model or design projection model in this report) is duplicated using the current software 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 is actual plant data at startup (membrane age zero), collected in the initial days of operation. The data generally includes 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 (e.g., TDS calculated from conductivity).

When start-up time series data is available, the data are 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 median point is preferred over the arithmetic mean for characterizing the centrality of a statistical distribution because the median is less sensitive to bias from extreme highs or lows. The maximum and minimum flow rates were also identified and modeled in an attempt to characterize the accuracy over the entire envelope of operating conditions. However, the high and low points may represent unsteady state conditions during RO operation transition (e.g. adjusting a pump or valve). Computer software 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 quality, flows, recovery, and pressures are entered into the model.

Feed Water Data. Entering the feed analysis is the first step in creating a model. A full set of feed water quality is typically not available as part of a start-up data set. If water quality data are not available, the ion concentrations from the original design model of each project are used and proportionally adjusted. Total dissolved solids (TDS) concentration (a characterization of salinity) was a common water quality parameter provided in the form of (1) concentration measurements or (2) conductivity. Depending on the TDS form provided, two different approaches are used.

First approach is when startup data provided total dissolved solids concentration measurements then the following steps are performed:

- Calculate "ion ratio" by dividing the startup and model TDS values for each data point.
- Adjust original design model ion concentrations proportionally by multiplying ion ratio by the ion concentration.

Second approach is when startup data provided conductivity the following steps are completed:

- Water quality of feed is first entered into the corresponding model and a TDS and conductivity values estimated by the model are obtained.
- "TDS factor" is then computed by dividing the model TDS and model conductivity value.
- Next, the startup data conductivity is multiplied by the TDS factor to compute a TDS concentration for each point.
- Lastly, the "ion ratio" is calculated by dividing the calculated TDS and the model TDS.

For both approaches, temperature and pH are matched for each start-up modeling point as the temperature in a given day/hour maybe different for each point. If the design model

projection indicates the addition of acid to adjust the pH, the adjustment is also performed in the model simulation. Adjustment of the pH can be performed in all computer software programs by indicating the new pH and the model automatically calculates the chemical dose required.

System Configuration. Initiated by entering the exact permeate flow and recovery from the actual design. Similarly, the same type of membrane, number of pressure vessels and elements, and stages are entered. Finally, the back pressures and/or boost pressures are inputted, and the report is created and reviewed.

The new model is iteratively revised by adjusting throttling and/or boost pressures to exactly match the permeate flux in first and stages of the full-scale plant. If the system design was managed by throttling (i.e., permeate back pressures) the second stage back pressure was matched and the first stage back pressure was iteratively changed. When the membrane system is designed with boost pressure, the back pressures are matched and the boost pressure is iteratively changed. An example of a report produced by the IMSdesign models is shown in Figure 5.3.

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 5.3: An example of a report for IMSdesign software model.

5.5.2 Precision

Membrane selection is 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 (i.e. brackish water, fouling resistant, and low energy), surface area, permeate flow, and salt rejections (i.e. minimized and stabilized). Similarly, the testing conditions for the membranes were collected and the following values were listed: solution composition and concentration, feed pressure, pH, temperature, and recovery.

In precision analysis, membrane selection is an essential step. Equivalent membranes for each of the other five manufactures are picked in three steps. The first step is to use the compiled membrane table and select a membrane based on flux, area, and testing standard conditions. The second step is to use an industry cross-reference guide to review the membrane that the industry

refers to as equivalent. Various cross-reference guides are available on the internet, and which are compiled 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 manufacture, size, type, and product name of the other membrane and in return the tool provides membrane equivalents from Dow. Finally, an email was sent to the manufacturer to verify if the selected membrane was correct and to ask for their suggestion of an equivalent membrane.

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

Once the membranes are selected and permeate flows reduced, if required, the feed water quality is entered and balanced to ensure the adjusted feed water entering the reverse osmosis membrane system is the same. Pressure losses of the system configuration also have to be simulated the same across the six membrane manufacturers. Similar to the accuracy analysis, the boost or first stage permeate pressure is iteratively adjusted until the model flux is matched to the actual data flux for first stage and second stage. The median point for the data set was used for the model projections.

5.5.3 Pilot versus Full-Scale

The North Lee County data set included pilot testing results for the membrane filtration system. The pilot test results consist of time series data for a year and four months and the full scale data for a period of three days. Pilot test data are reviewed to understand how key parameters are computed. To follow the pilot computations and format, the start-up parameters are entered into an Excel sheet and then calculated in a similar manner. Two comparisons result from the analysis: pilot testing versus full-scale plant performance and model prediction versus full-scale plant performance.

Chapter 6: Results and Discussion

6.1 Accuracy

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

6.1.1 Brackish Water Reverse Osmosis Membrane Type

6.1.1.1 Eastern Correctional Institute

Located in Westover, Maryland, the Easter Correction Institute reverse osmosis system consists of three trains, Train A, B, and C, each producing 308 gallons per minute (gpm) of permeate flow. Train A began operating in November 2010, and the other two trains began operating in Spring 2012. Startup data for Train A are available from November 4, 2010 to March 21, 2011 and contain a total of 166 data points. Train B has four data points in 2011 from March 16 to 21. The reverse osmosis system operates at 80% recovery and consists of at two stage array configuration of 60 by 30 with seven elements in each pressure vessel. The installed membrane is the Toray TM720-400 with a membrane area of 400 square feet, a permeate flow rate of 10,200 gpm, and salt rejection 99.7%. Minimum, median, and maximum point are assigned for Trains A and B (where data for Train C was not provided) and were modeled using the manufacturer's respective computer software.

Because water quality is not available for the project, the ion concentrations were obtained from the design model. Conductivity is the measurement provided to approximate total dissolved solids. A TDS factor is estimated using the approximated TDS and conductivity values from the model. Then, the TDS factor is used to calculate the TDS concentration for each data

point. Lastly, an ion factor is computed and the ion concentrations are proportionally adjusted. The pH for each data point is not included in the data as a result for all six data points a pH of 8.5 as shown in the projection model is assumed.

The design model does not indicate the use of permeate throttling or boost in the reverse osmosis system, but it does include an inter-stage pressure loss of 3 psi. Total permeate pressures are given in startup data, but the individual first and second stage permeate back pressures are not specified. When modeling the data points, the second stage permeate back pressure is assumed to be equal the total permeate pressure provided in the data set, the inter-stage pressure loss is included, and permeate throttling is used to match the fluxes. A scale warning is created by the software when the Silt Destiny Index is greater than zero, the model predicts a SDI of 1.25 for Train A and 1.10 for Train B. (Please note that SDI is referred as the Stiff Davis Index (S&DSI) in the output report). The warning notifies the user that they will need to contact an antiscalant vendor to find the appropriate antiscalant for the project's specific feed water since the SDI is a measure of fouling capacity. As a third party reviewer the data from the RO system is used assuming the appropriate action whether adding antiscalant or acid or both is executed by the design engineer.

Operational data such as permeate flow, feed pressure, and conductivity for Train A and Train B are illustrated in Figure 6.1 and Figure 6.2, respectively. In addition, the modeled median data point is overlapped on the existing performance data to provide a comparison of model performance to the actual plant performance.

The model over predicts the feed pressures for the median points by 6.1% for Train A and 12.1% for Train B. Model predictions for system and first stage TDS rejections of median points are over predicted by 1.3 % and 1.2%, respectively. The average model system TDS rejection for both Train A and B is 98.4% compared to 97.2 % for full-scale. A summary of the percent errors for various system pressures and rejections are shown in Table 6.1.

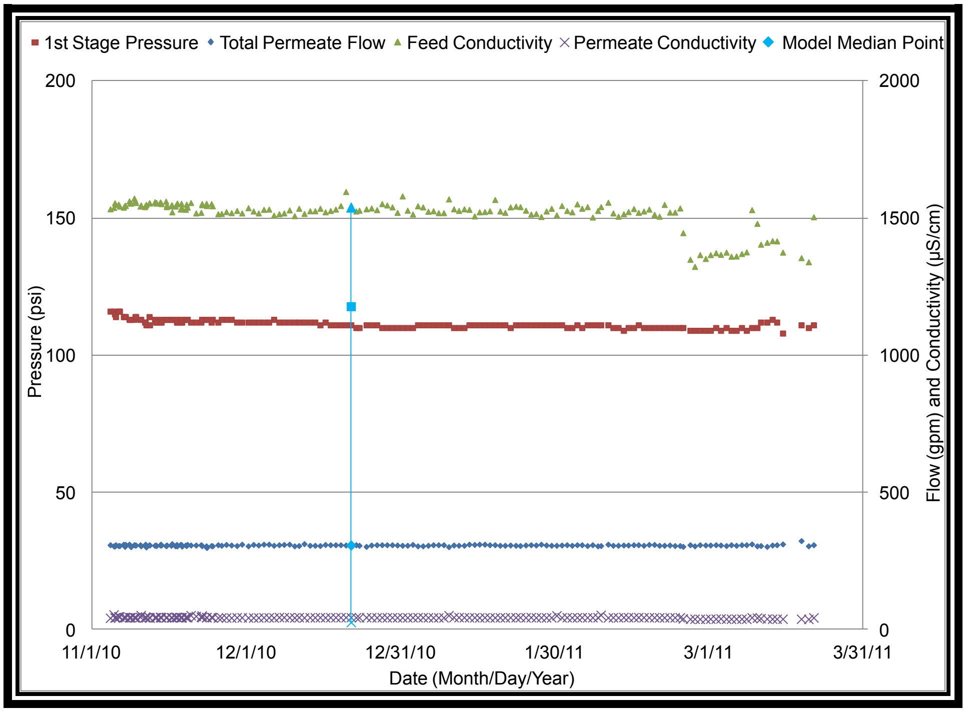


Figure 6.1: Full-scale operational data with model median point for Eastern Correctional Train A.

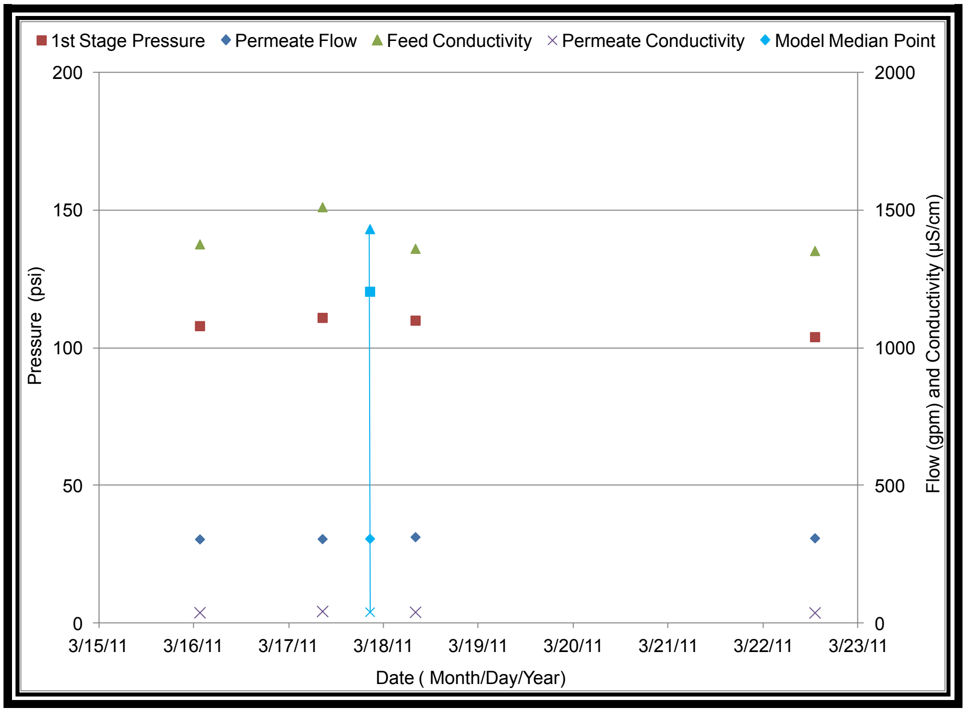


Figure 6.2: Full-scale operational data with model median point for Eastern Correctional Train B.

Table 6.1: Relative error summary of pressures and total dissolved solids for Eastern Correctional.

		Percent Error (%)				
		Pressures			Rejections	
Train	Point	Feed Stage 1	Feed Stage 2	Concentrate Stage 2	TDS Pass	TDS 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

6.1.1.2 Goldsworthy

The Robert W. Goldsworthy Desalter is a 2.75 million gallons per day (MGD) membrane filtration plant located near the City of Torrance, California. The plant treats a saline plume in the West Coast Basin that resulted from preventing seawater intrusion. In 2001 the plant went into operation and is under the jurisdiction of the Water Replenishment District of Southern California.

The Goldsworthy data set contains two startup points each observed on a different day. The reverse osmosis system operates at 80% recovery and consists of a two stage array configuration of 42 by 24 with seven elements in each pressure vessel. Feed water quality from the given projection model is utilized for modeling. Conductivity is provided in startup data as TDS. To proportionally adjust ion concentrations for each data point, a TDS factor and ion ratio is calculated. Since permeate flows for stage one and two are not specified, the flux is proportioned based on the models first and second stage flux ratios. The membrane installed in the RO system is the CSM RE8040-BE with a membrane area of 400 square feet, a permeate flow rate of 10,500 gpm, and a salt rejection of 99.4%. A 10 psi permeate throttling is used in the model to manage the system's fluxes.

Actual pressures and TDS concentrations are shown in Figure 6.3. Conductivity measurements for all pressure vessel in both first and second stages are shown Figure 6.4 which shows that variability exists among the 66 pressure vessels. Ideally the quality, flow, and pressure of feed water entering each pressure vessel should be the same since the vessels are

operating in parallel. The conductivity reduction 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 6.5, the statistical distribution of the pressure vessels can be characterized. For both sampling days, a linear regression of the first stage conductivity reduction shows a perfect fit (R-squared value equal to unity), which indicates that the data variation of conductivity reduction follows the normal distribution.

Multiple design and scale warnings were produced by the model based on the water quality and reverse osmosis design. Two design warnings are produced stating that the element recovery of 15.0% is being exceeded and the element concentrate flow rate of 16.0 gpm is not reached. The model yields a scale warning that indicated the barium sulfate concentration is 2,940 % and has exceeded the concentrate limit. Additionally, the Langelier Saturation Index (LSI) is greater than the limit of 0.20 and the Stiff & Davis Index is greater than zero which requires the use of a scale inhibitor or pH adjustment or both.

Feed pressures are under predicted by the model by an average of 9.0%. Model average TDS rejection is 98.5% and the plant average rejection is 97.9%, which results in a model over prediction. Table 6.2 summarizes the percent error for feed pressure, concentrate pressure, and TDS rejection.

Table 6.2: Summary of pressures and total dissolved solids relative error for Goldsworthy.

	Percent Error (%)			
Date	Feed Pressure Stage 1	Concentrate Pressure Stage 1	Concentrate Pressure Stage 2	TDS Rejection Pass
3/2/12	-8.9	-8.8	-14.5	0.61
3/3/12	-10.7	-11.8	-17.3	0.66
Median	-7.4	-7.7	-13.2	0.64

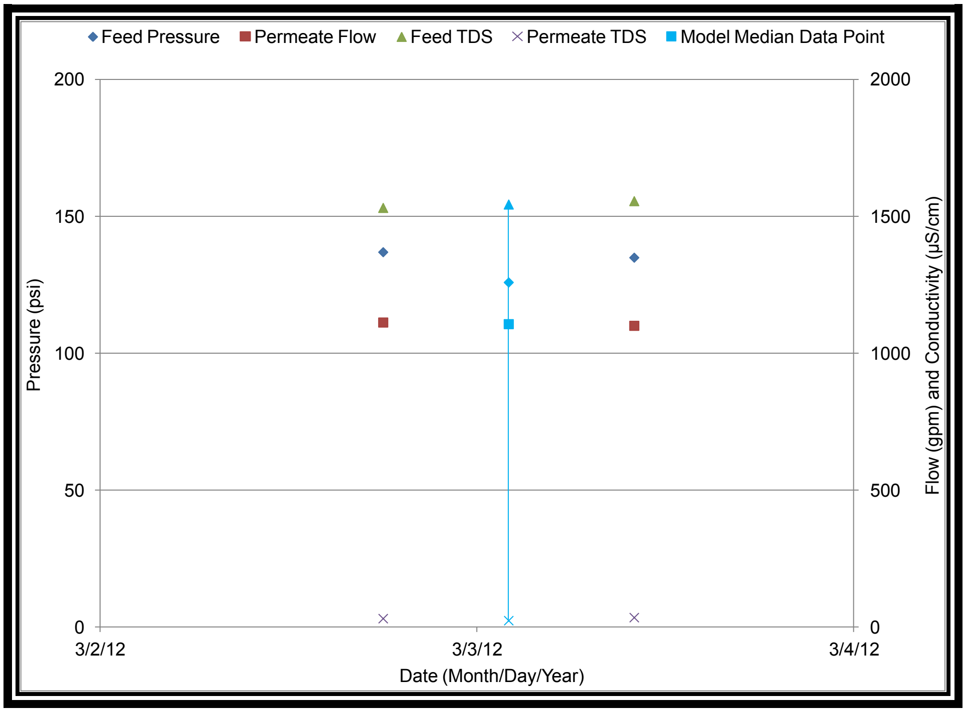


Figure 6.3: Full-scale operation data with the model median data point of Goldsworthy.

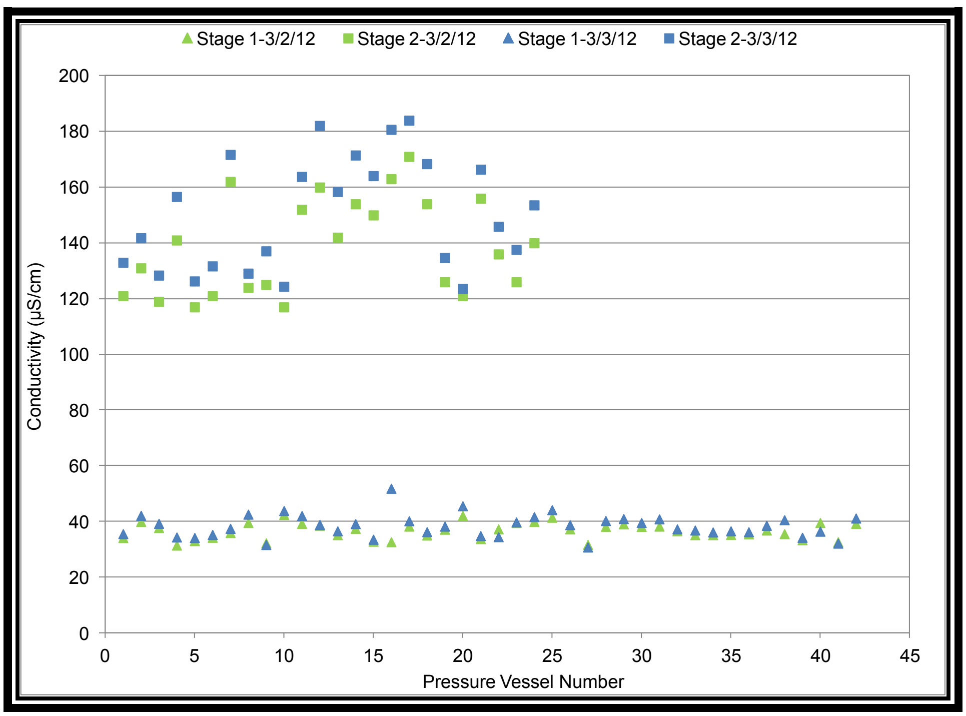


Figure 6.4: Pressure vessel water conductivities for Stage 1 and 2 of Goldsworthy.

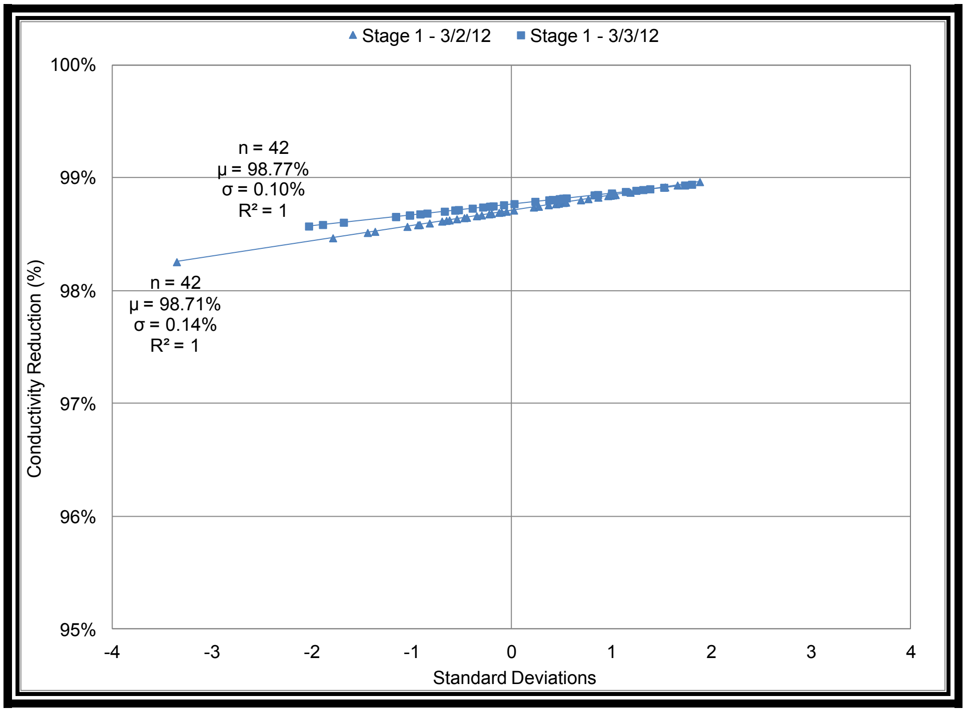


Figure 6.5: Normal distribution of water conductivity reduction for Goldsworthy Stage 1 pressure vessels.

6.1.2 Fouling Resistance Reverse Osmosis Membrane Type

6.1.2.1 Scottsdale

Scottsdale data are from the City of Scottsdale's Water Campus Advanced Water Treatment Facility recently expanded in July 2012. The expansion included the addition of three 2.4 million gallons per day trains with 16-inch diameter membranes. The project is the largest reclamation facility in the nation to use large diameter membranes.

Feed quality is approximated from the design model and the calculated TDS factor and ion ratio using the given conductivity measurement. The project data set consists of one conductivity profile from Train 22. Feed water parameters supplied in the profile are measurements after the addition of acid.

The reverse osmosis membrane system operates at 85% recovery and consists of a two stage array configuration of 13 by 7 with seven elements in each pressure vessel. The membrane installed is the CSM RE16040-Fen with active area of 1,600 square feet, a permeate flow of

41,000 gallons per day, and a salt rejection of 99.7%. Stage one and two permeate flows were estimated by multiplying manufacturer provided vessel flows and the number pressure vessels for each stage. Permeate throttling is not used in the projection model, but throttling is employed when modeling to be able tune into the first and second stage flows. Permeate pressure given in the profile is assumed to equal the second stage pressure and is entered as that.

Figure 6.6 illustrates the operational data of the plant and model. Findings indicate a negative 4.6 percent error in the model and actual feed pressures. The model permeate throttling pressure is approximately 4.25 psi compared to 3.40 psi of the plant. Percent error of TDS rejection for system and first stage are 0.3% and 0.5%, respectively. The model TDS rejection is 97.8 % and first stage rejection is 98.8 %. In contrast to the plant pass rejection of 97.5 % and first stage rejection of 98.3 %. Conductivities of all pressure vessels in the reverse osmosis system are shown in Figure 6.7. Variability has no impact on the membrane performance as demonstrated in Figure 6.8.

Two design warnings are generated for the data point stated that the element recovery of 14.0% is exceeded and the permeate flux of 16.0 gallons per square foot per day is also surpassed. Scale warnings indicate that a scale inhibitor or pH adjustment or both actions is required because the Langelier Stiff Index is greater than negative 0.20 and Stiff & Davis Index is greater than zero.

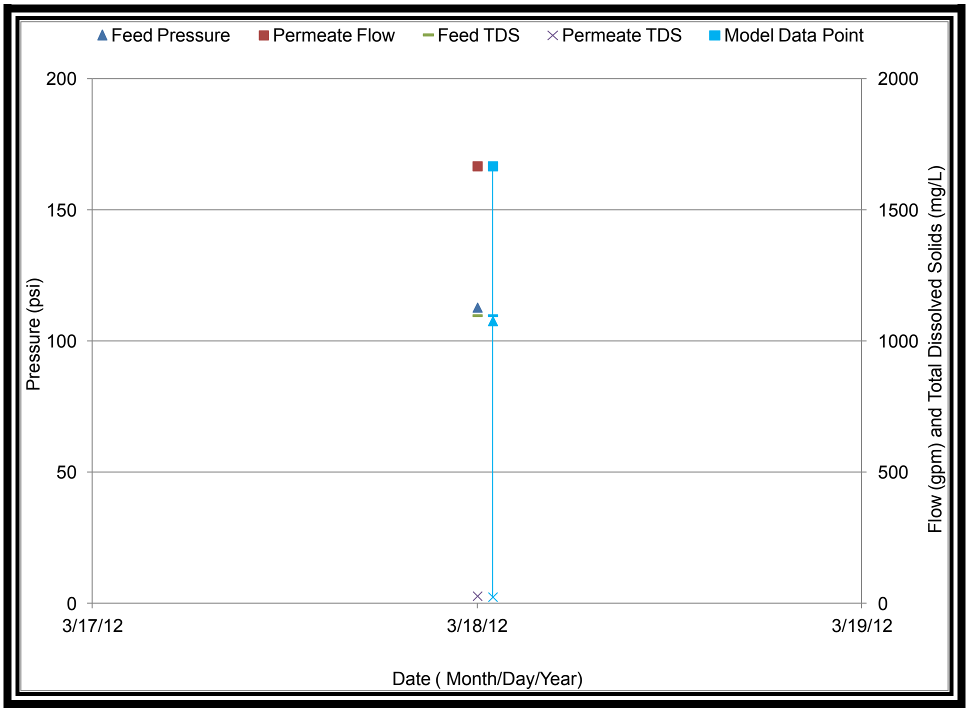


Figure 6.6: Full-scale operation data with the model data point of Scottsdale.

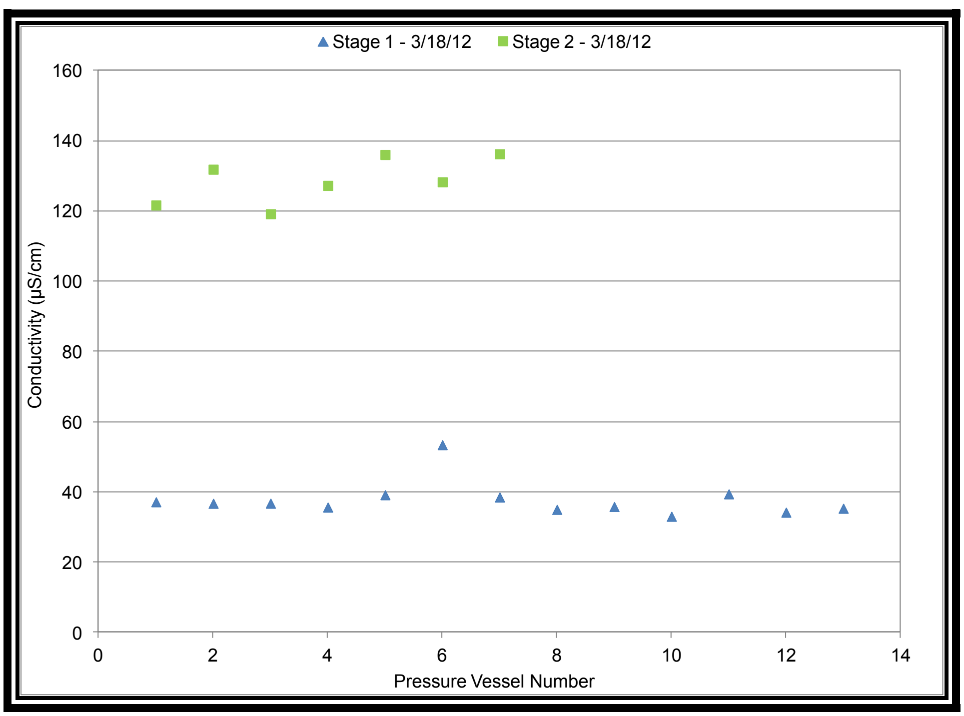


Figure 6.7: Pressure vessel water conductivities for Stage 1 and 2 of Scottsdale.

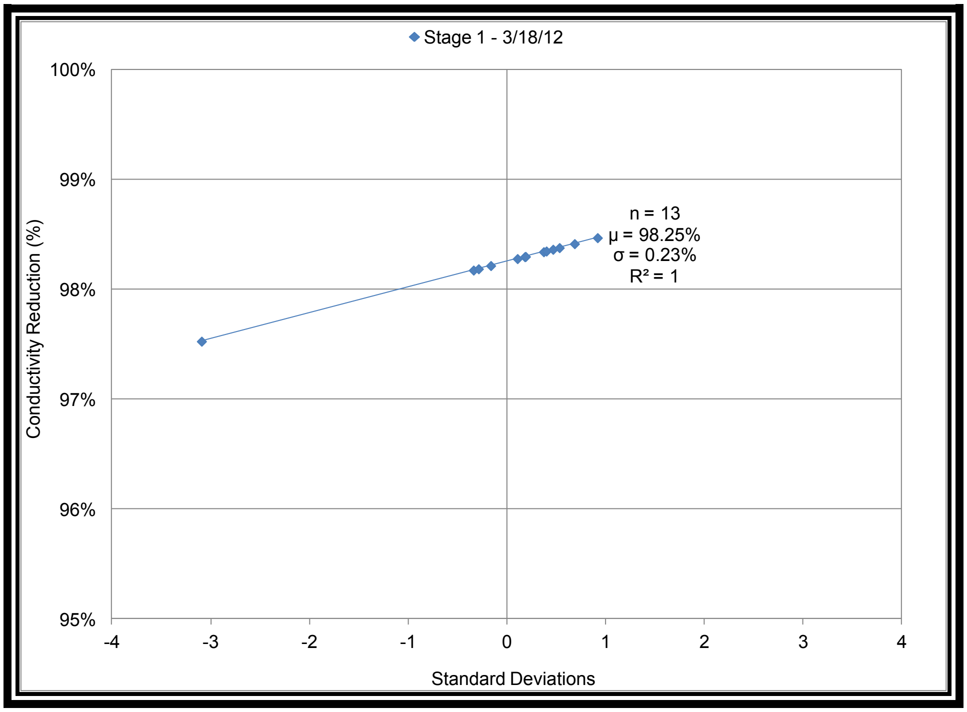


Figure 6.8: Standardized z-value of water conductivity for pressure vessels in Stage 1 of Scottsdale.

6.1.3 Low Energy Reverse Osmosis Membrane Type

6.1.3.1 Clay Center

The Clay Center Public Utilities Commission Reverse Osmosis plant is located in Clay Center, Kansas and has been in operation since July 2010. The reverse osmosis membrane system operates at 75% recovery and consists of a two stage array configuration of 12 by 6 with six elements in each pressure vessel. The RO system produces 580 gallons per minute of permeate. 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 rejection of 99.0%.

Full-scale feed water quality is estimated using the design projection model. In the data sheet, conductivity is converted to a TDS concentration by multiplying by a TDS factor of 0.752. The same TDS factor is applied along with the calculated ion ratio to proportion the feed water quality of each data point. A pH of 7 obtained from the design model is assumed for all points since the data does not provide that information.

To optimize permeate flows between the stages an inter-stage boost is applied to the first stage concentrate in addition to permeate throttling. The boost pressure is calculated by subtracting the given first stage concentrate pressure from the second stage feed pressure. First and second stage permeate throttling pressures are kept the same from the plant to the model and the boost pressure is iteratively changed to match second stage permeate flow.

Table 6.3 presents the percent error of various pressures and TDS rejections of Train A and Train B. In general the first and second stage feed and concentrate pressures are over-predicted by the model, except for the boost pressure which the model under-predicts. Average first stage and second stage TDS rejections of Train A in the plant are 98.7% and 98.3%, respectively, and differ slightly from Train B first and second stage rejections of 98.9%, and 98.8%, respectively. The model's first stage rejection for Train A is 98.9% and Train B is 98.9% where the second stage rejections is 98.80% for both trains. The average pass rejection for the plant's Train A and Train B is 98.6% compared to the model's 98.5%. For most data points the model under predicts TDS rejections which is supported with a negative percent error. Figure 6.9 and Figure 6.10 illustrate the operational data of Train A and Train B, respectively, as well as the model median data point.

Design warnings are not generated for any of the modeled data points. Various solubility warnings are produced for the system. Warnings specify that the Langelier Saturation Index and Stiff & Davis Stability Index are greater than zero. Additionally, the barium sulfate and silica saturation limits are greater than 100%. The barium sulfate saturation percent's for raw and adjusted feed is 375 % and for concentrate is 1610 %. Silica saturation limit is only exceeded in the concentrate with a 124 %.

Table 6.3: Relative error difference summary of pressures and total dissolved solids for Clay Center

	Percent Error (%)							
	Pressure					Rejection		
Train/ Point	Feed Stage 1	Concentrate Stage 1	Feed Stage 2	Concentrate Stage 2	Boost Interstage	TDS Pass	TDS Stage 1	TDS Stage 2
A Min	11.7	15.0	1.3	4.4	-8.8	-0.5	-0.11	-0.7
A Median	11.0	18.1	1.3	3.9	-10.8	0.2	0.57	-0.3
A Max	10.8	14.2	5.1	9.3	0.9	-0.3	0.12	-0.5
B Min	7.7	10.1	0.2	2.0	-4.8	-0.4	-0.10	-0.6
B Median	6.4	7.7	-1.4	-0.1	-4.2	0.1	0.43	-0.3
B Max	8.9	8.4	2.7	5.9	4.0	-0.2	0.16	-0.5

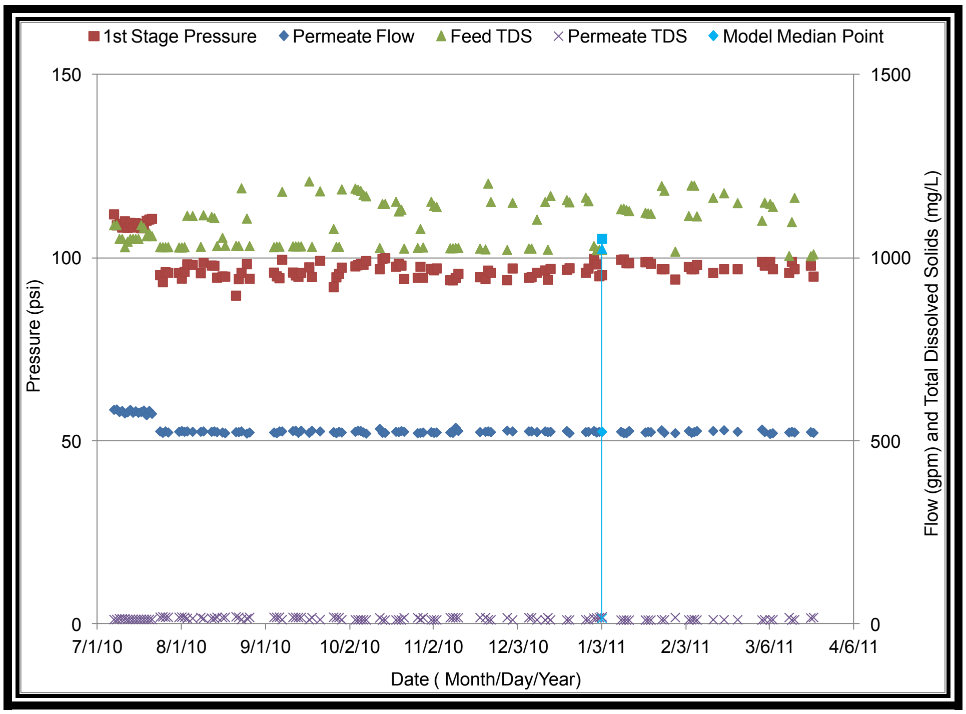


Figure 6.9: Full-scale operational data with model median point for Clay Center Train A.

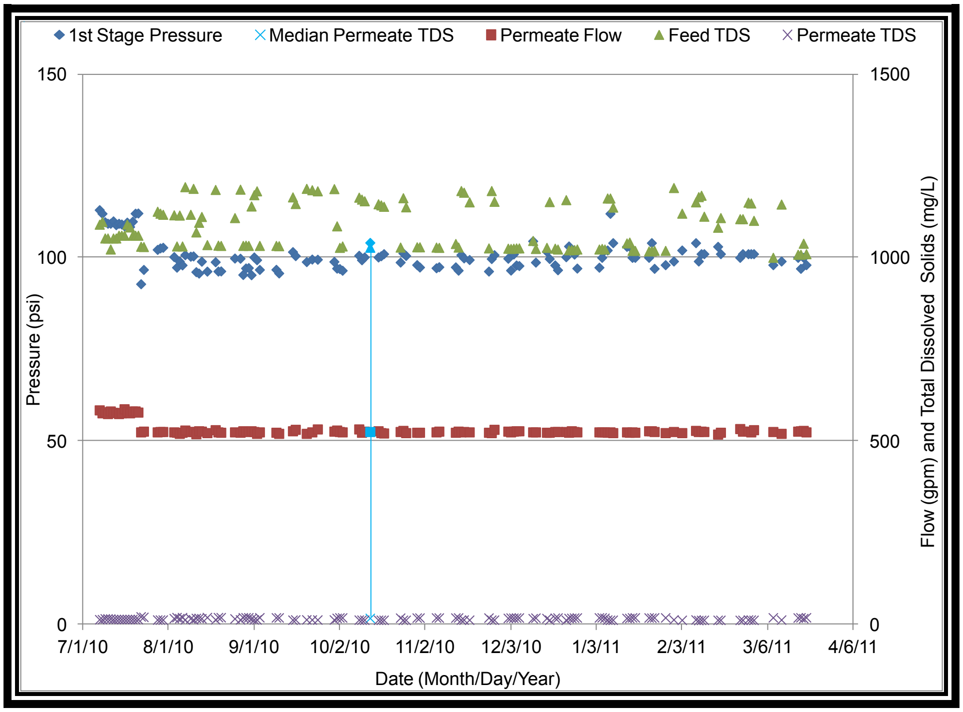


Figure 6.10: Full-scale operational data with model median point for Clay Center Train B.

6.1.3.2 Hardinsburg

The Hardinsburg data set is from a 2.0 million gallon per day reverse osmosis water treatment plant located in Hardinsburg, Kentucky. In June 2007 operation was initiated with two trains in service at 80 % recovery and consists of two stage array configuration of 14 by 7 with seven elements in each pressure vessel. Membranes installed are the ESPA 2 in the first stage and ESPA 1 in the second stage. The ESPA 2 has an active area of 400 square feet, a permeate flow of 9,000 gallons per day, and a salt rejection of 99.6%.

Water quality sampled during the performance test was available for three source wells and Train A and B permeates. A discrepancy observed in the analysis is that the specified total dissolved solids concentration is smaller than the summation of listed ions and the model's estimate, where the model's estimate is equal to the ion summation. In the analysis bicarbonate alkalinity is given as calcium carbonate. In order to input to the model the alkalinity is converted to bicarbonate by multiply by a factor of 1.22. Conductivity is given as the total dissolved solids measurement in the startup data at each data point. Thus, a TDS factor and ion ratio is calculated

to proportionally adjust the water quality. For this case study the feed water is not balanced, because if the data points are balanced they required a substantial addition of sodium or chloride and when comparing model feed concentrations of sodium and chloride to the plant's the concentrations were greater and they should be equal. Acid is added to the raw water prior to entering the membrane system, where the raw water pH is 7 and is lowered to pH 5.7 to 5.8. The model is able to simulate the pH adjustment.

Permeate throttling is used to manage stage one and two permeate flows. First stage permeate throttling is estimated by the model as 38.8 psi on average in contrast to the actual permeate pressure of 9 or 18 psi. Feed pressures are over predicted by an average of 5.9 % for both Train A and B. First stage concentrate pressure is over estimated by 2.4 % and under estimated in the second stage by 1.8 %. Table 6.4 summarizes the percent error of various pressure parameters for Trains A and B.

Model total dissolved solids rejections for Trains A and Train B are 98.3% and 95.4% for full-scale. The average percent error for TDS rejection is 3.1%. In general, the model under predicted calcium, silica, and nitrate pass rejections while over predicting sodium, chloride, sulfate, and bicarbonate rejections. Table 6.5 lists the percent error for specific ion pass rejections. Neither scale nor design warnings were generated by the model for any of the data points.

Figure 6.11 and Figure 6.12 illustrate the four days of full-scale operation data available for Trains A and B, respectively. Conductivity profiles of all pressure vessels in the reverse osmosis system for Trains A and B are shown in Figure 6.13 and Figure 6.14. Similarly to other projects, the variability in conductivity does not have an effect in rejection of the membrane as demonstrated in Figure 6.15 and 0.

Table 6.4: Relative error summary of pressures for Hardinsburg.

	Percent Error (%)		
Train/ Point	Feed Stage 1	Concentrate Stage 1	Concentrate Stage 2
A Min	3.2	0.2	-4.2
A Median	7.1	1.6	-3.5
A Max	3.5	-0.8	-4.4
B Min	7.7	5.6	0.9
B Median	6.9	3.9	0.1
B Max	7.0	3.9	0.2

Table 6.5: Relative error summary of specific ion rejections for Hardinsburg.

	Percent Error (%)							
Train/ Point	Sodium	Calcium	Chloride	Sulfate	Nitrate	Silica	Bicarbonate	TDS Pass
A Min	33.0	-0.4	2.7	>3.3	-3.2	-1.3	4.5	3.3
A Median	38.6	-0.4	2.9	>3.1	-3.1	-1.2	4.7	3.4
A 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
B Median	33.6	-0.4	3.2	>3.3	-2.6	-1.1	3.5	2.9
B Max	33.5	-0.4	3.2	>3.5	-2.3	-1.1	3.7	2.9

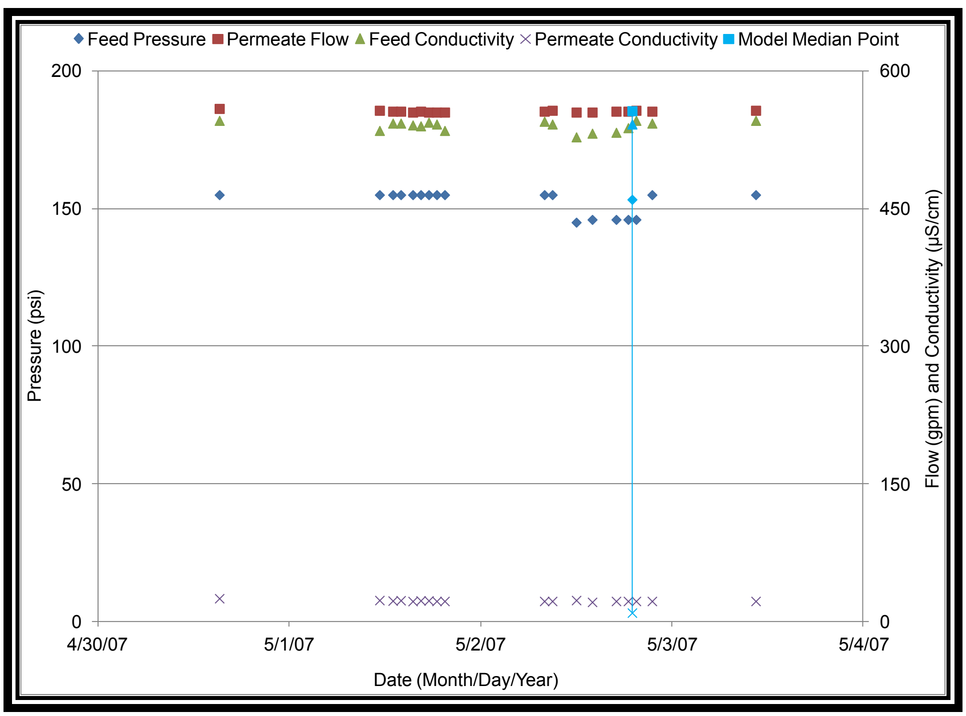


Figure 6.11: Full-scale operational data with model median point for Hardinsburg Train A.

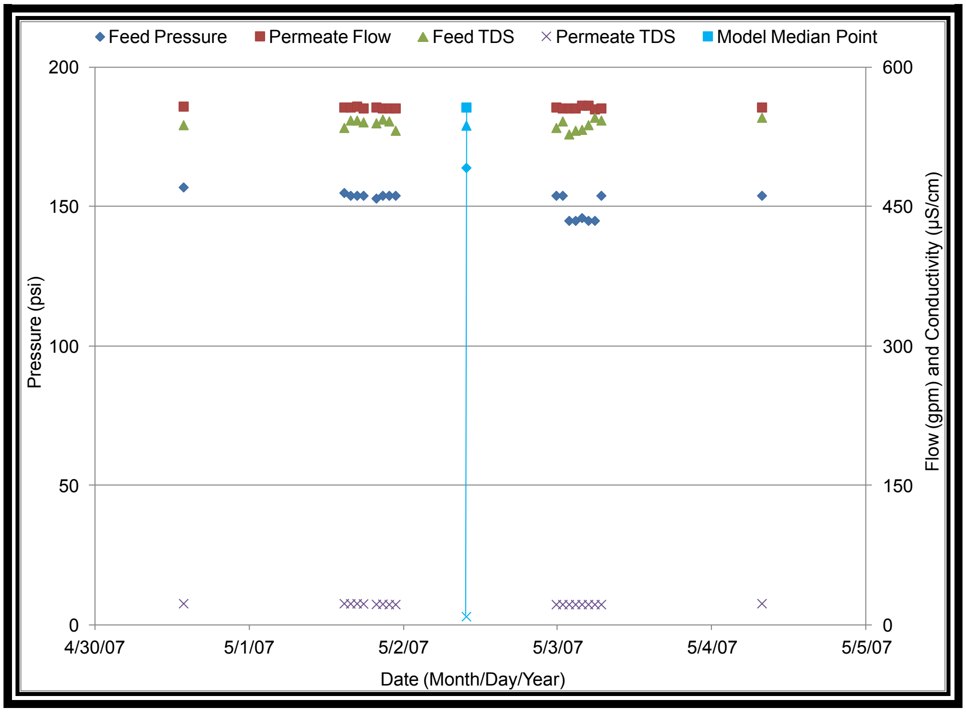


Figure 6.12: Full-scale operational data with model median point for Hardinsburg Train B.

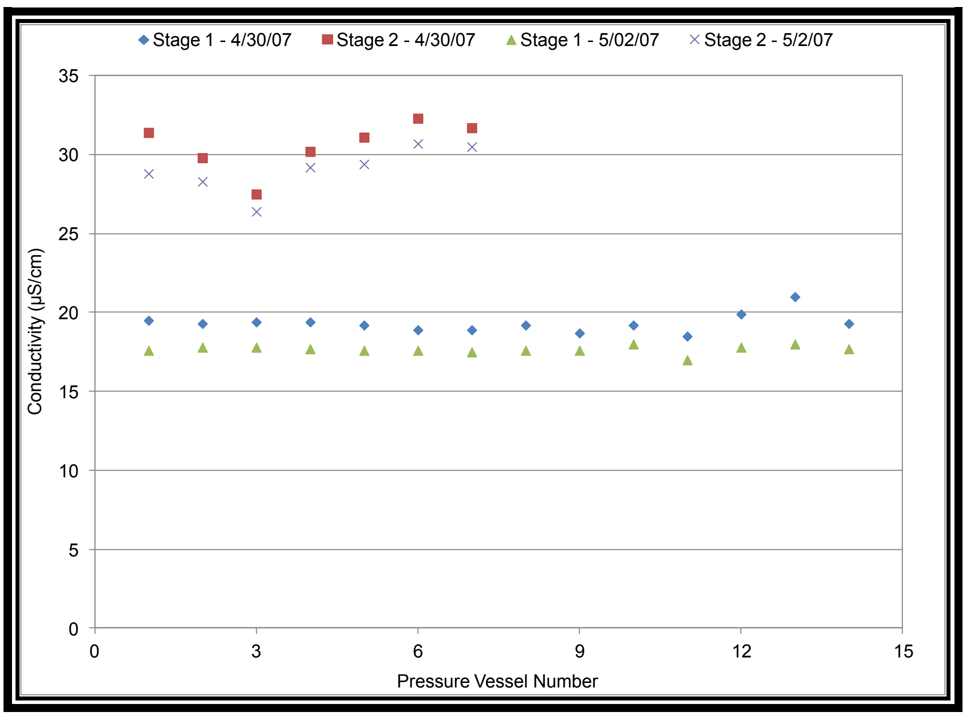


Figure 6.13: Pressure vessel water conductivities for Stage 1 and 2 of Train A in Hardinsburg.

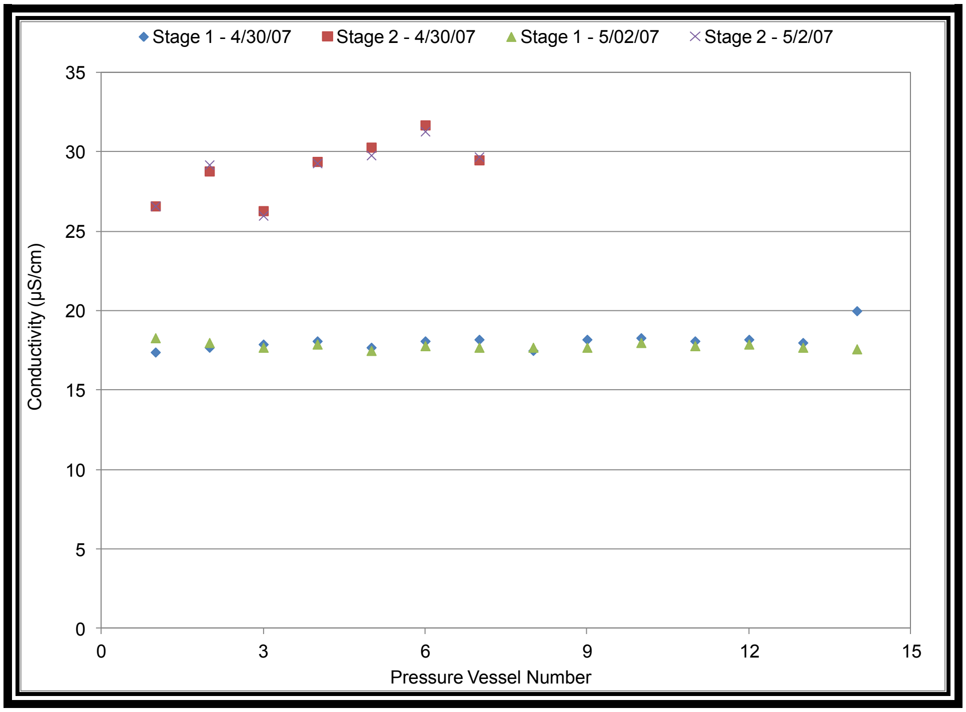


Figure 6.14: Pressure vessel water conductivities for Stage 1 and 2 of Train B in Hardinsburg.

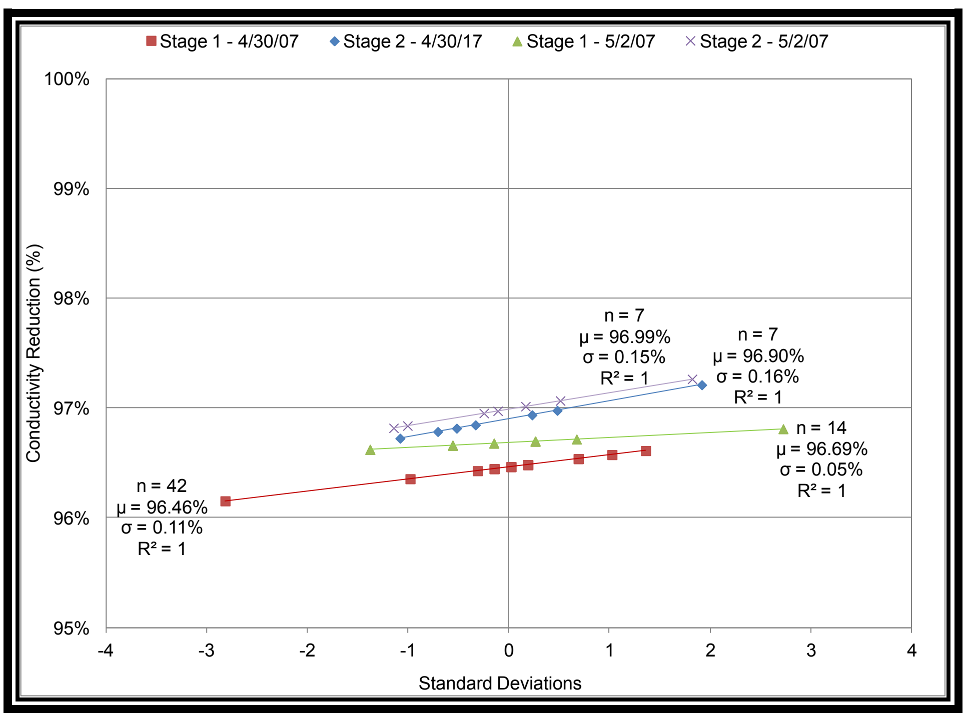


Figure 6.15: Standardized z-value of water conductivity for the pressure vessels in Train A of Hardinsburg.

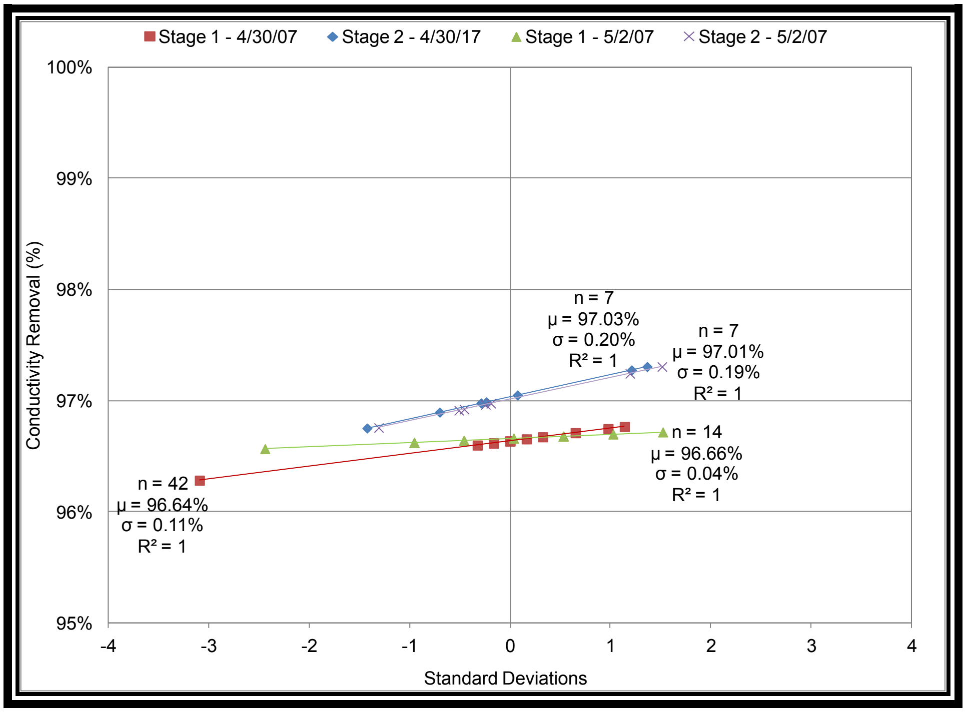


Figure 6.16: Standardized z-value of water conductivity for the pressure vessels in Train B of Hardinsburg.

6.1.3.3 Kay Bailey Hutchinson Zero Year Operation

Kay Bailey Hutchison Desalination Plant startup data includes system data at zero year operation with the same array configuration as describe in the five-year operation. A difference from the initial operation is the initial system recovery is 70 %. Permeate throttling pressures for first and second stages were on average 21 psi and 4 psi, respectively.

A complete set of water quality is not available for the initial operation in July 2007. The TDS factor which is equaled to the slope of the linear relationship between conductivity and total solids concentration for five year operation. The same five-year TDS factor is applied in zero-year and then an ion ratio is calculated and ion concentrations of the five-year operation are proportionally adjusted for each data point.

In the model, the second stage permeate throttling pressure is maintained the same as in actual plant conditions and the first stage pressures is iterated to match the plant's fluxes. As a result all the error is placed on the first stage instead of spreading the error between both stages.

Operational data overlapped with the model median point for Trains A, B, C, D, and E and as illustrated in Figure 6.17 through Figure 6.21.

In general the model over predicts pressures and salt rejections for the system which are listed in Table 6.6. Feed pressures are over estimated by 16.0 % which is the average percent error of all five trains. Similarly, first and second stages are over predicted with a percent error of 16.0% and 13.0%, respectively. The model's first stage permeate throttling pressure estimate is 30 psi in contrast to the plant's actual permeate pressure of 21 psi.

Total dissolved solids rejections are also over predicted by the model. The model's average system TDS rejection for all five trains is 88.9% with a standard deviation of 1.4% contrasted to the plant's rejection of 85.9%. Average percent error of all trains for system TDS rejection is 3.6%, and first stage TDS rejection is 2.5%. Design and solubility warnings are not generated by the model for any of the data points.

Table 6.6: Relative error summary of pressures and total dissolved solids for Hardinsburg.

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

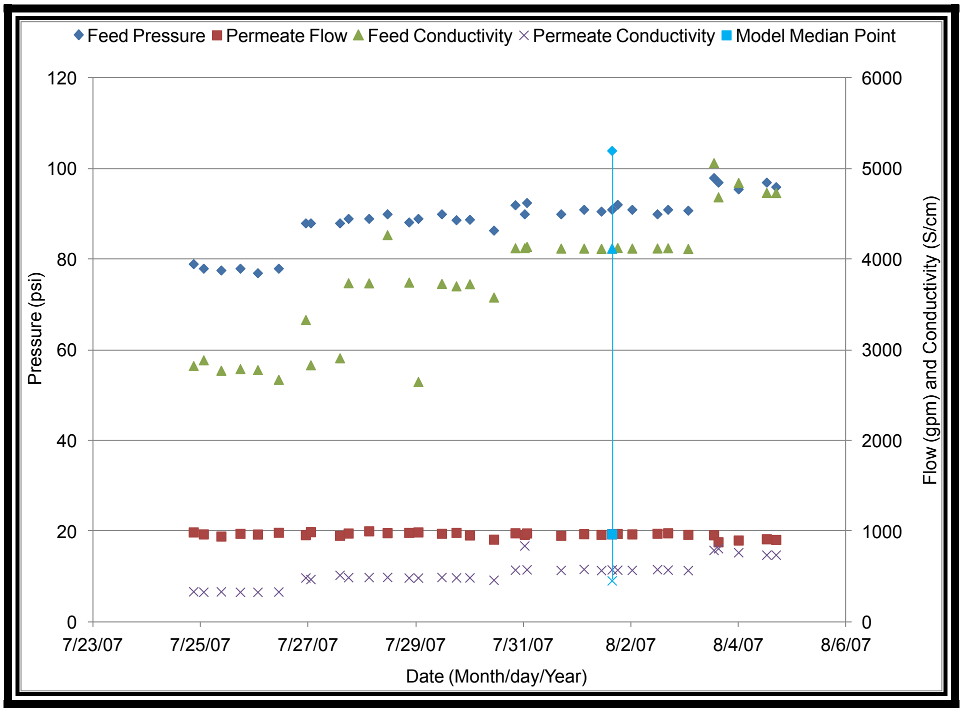


Figure 6.17: Full-scale operational data with model median point for KBH Train A.

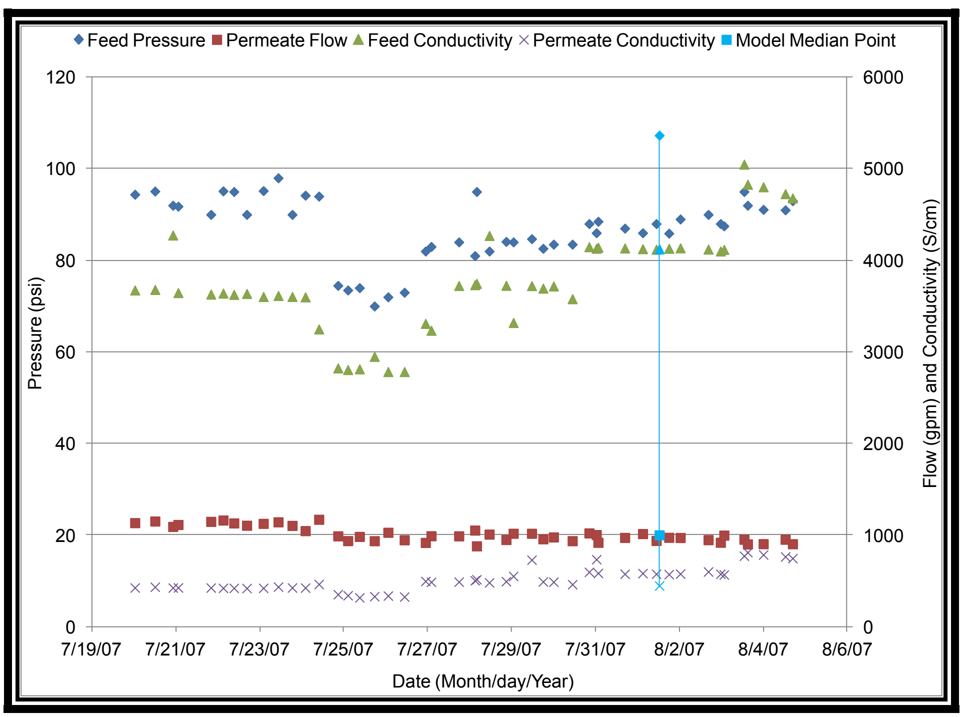


Figure 6.18: Full-scale operational data with model median point for KBH Train B.

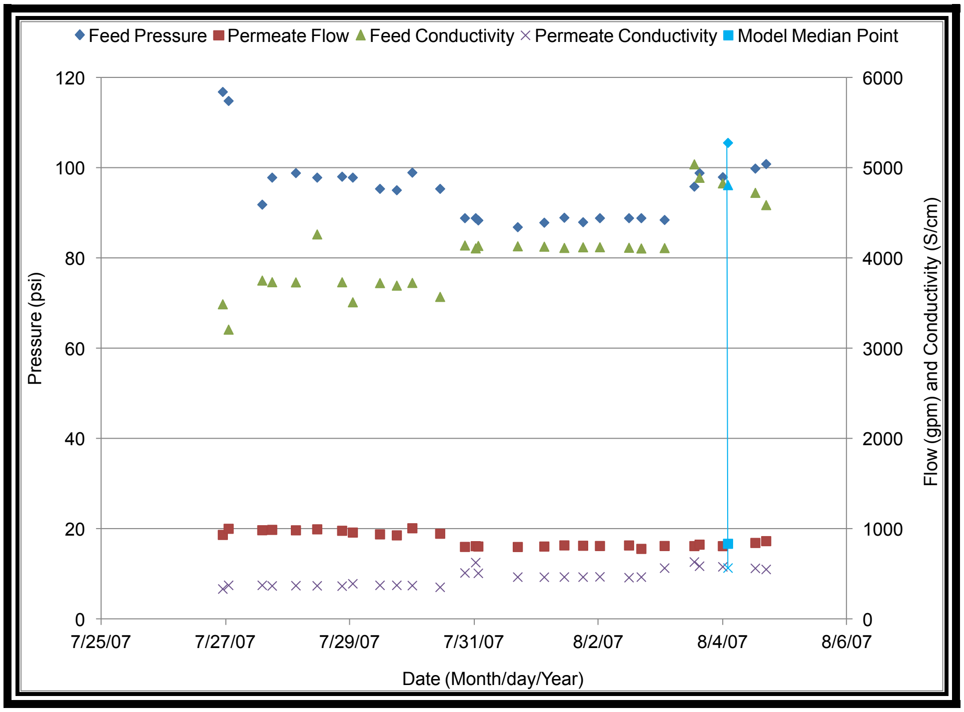


Figure 6.19: Full-scale operational data with model median point for KBH Train C.

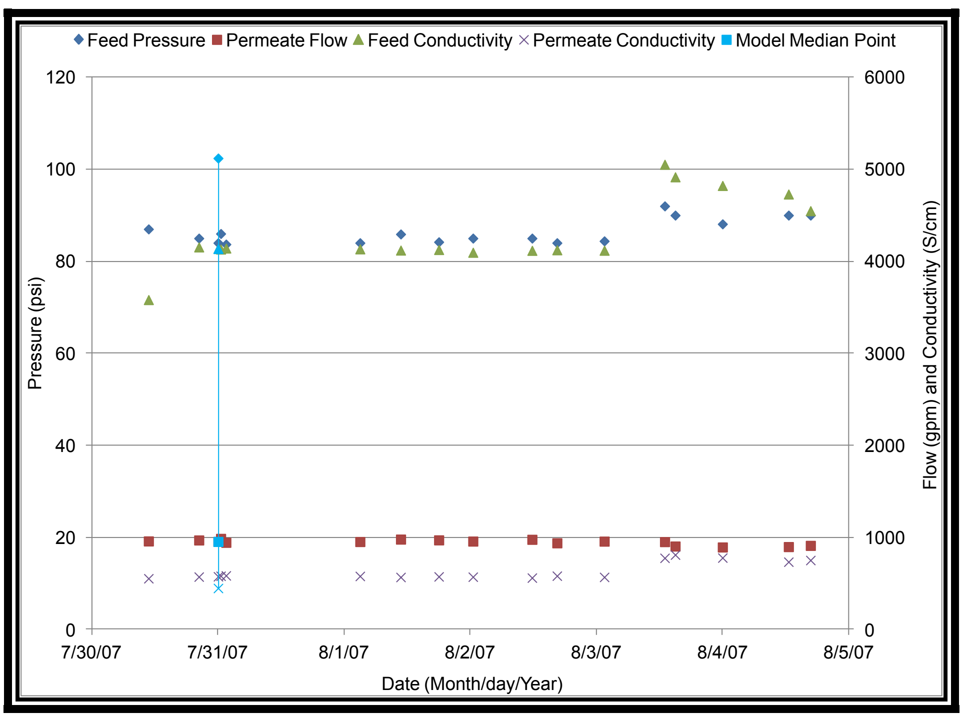


Figure 6.20: Full-scale operational data with model median point for KBH Train D.

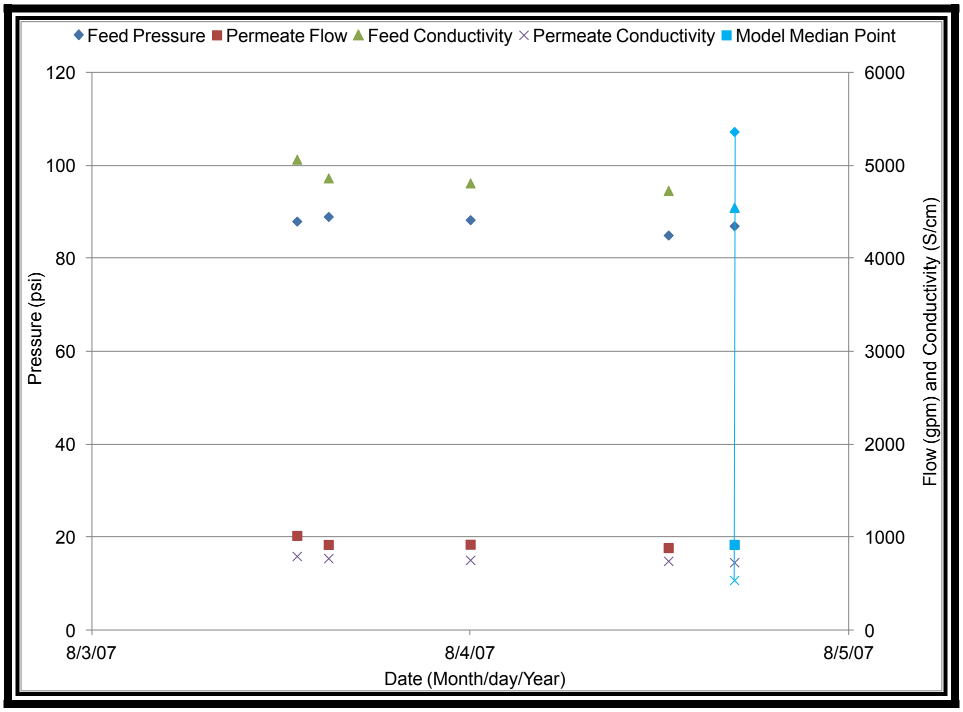


Figure 6.21: Full-scale operational data with model median point for KBH Train E.

6.1.3.4 Kay Bailey Hutchinson Fiver Year Operation

The Kay Bailey Hutchison Desalination Plant has design capacity of 27.5 million gallons per day making it the largest operating inland desalination plant in the world. The reverse osmosis membrane system consists of five trains which produce a total of 15.5 million gallons per day of permeate. Each train operates at 83% recovery and consists of a two stage array configuration of 48 by 24 with seven elements in each pressure vessel. The membrane installed is the Hydranautics ESPA1 with a membrane area of 400 square feet, a permeate flow rate of 12,000, and a salt rejection of 99.3 %.

On June 7, 2012 at 11:00 AM, the total, first stage, and second stage permeate are sampled along with the concentrate and feed water. Trains in operation that day are Train A, C, D, and E and Train B is offline. Water quality analyses were performed at the Center for Inland Desalination Systems Lab at The University of Texas at El Paso. The measured total dissolved solids are plotted against feed water conductivity of the plant to determine the TDS factor between all trains. Figure 6.22 shows the linear relationship between TDS and conductivity has a

slope of 0.5179. The membrane age is specified in the model as 5 years with a flux decline of 7.0 % per year and a salt passage increase of 10.0 % per year.

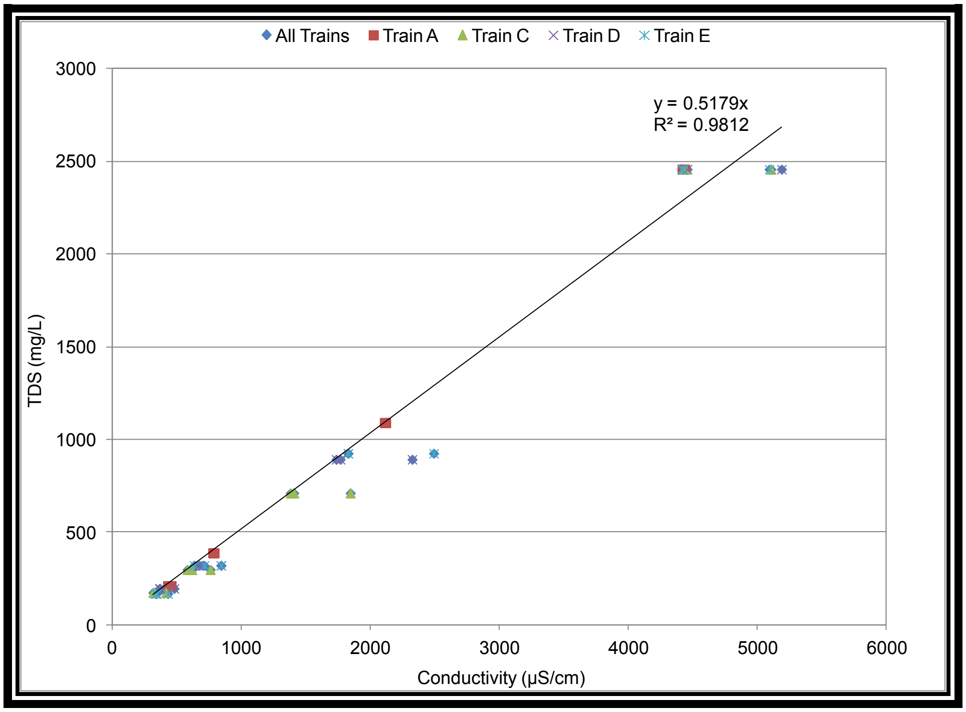


Figure 6.22: Total dissolved solids and water conductivity at five year operation for KBH Train A, C, D, E.

In the model simulation the plant's second stage permeate throttling pressure is matched, and the first stage permeate throttling pressure iterated to match the flux and/or permeate flow. The average full-scale first stage permeate pressure is 37.4 psi compared to the model's prediction of 48.5 psi which results in average difference of 11.1 psi or 30.2 % error. Feed, first stage concentrate, and second stage concentrate are over estimated by an average percent error of 21.9%, 28.3, and 30.2%, in that respective order. Table 6.7 presents a percent error for all train pressures.

For all four trains, the average model system TDS rejection is 88.4% and plant's actual TDS rejection is 86.6%. Table 6.8 presents the percent error for various ion rejections of interest. Sodium and chloride are over predicate by the model, while calcium, sulfate, magnesium, and

fluoride are under predicted. Figure 6.23 shows pressure, flow, and TDS concentrations of model performance with respect to each train.

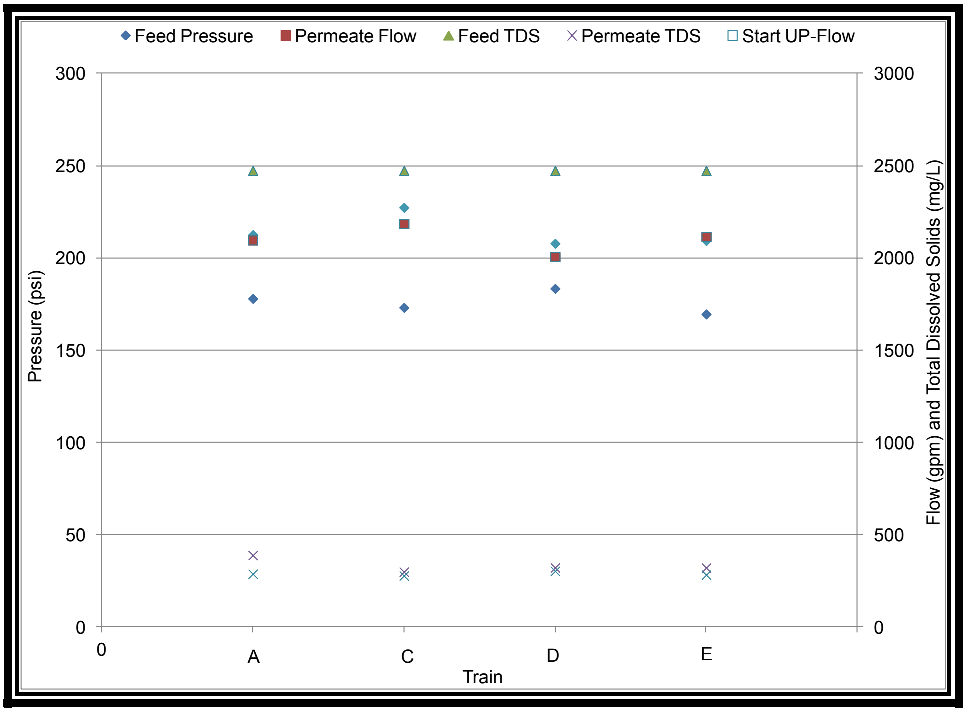


Figure 6.23: Model and operation data for Train A, C, D, E of KBH.

Design warnings were not generated by the model for the data points. Only one scale warning is produced stating that the concentrate Langelier Saturation Index of 1.95 is greater than 1.80. Saturation limits listed by the model for various salts in the concentrate are the following: 6000% for barium sulfate, 230% for calcium sulfate, 800% for Strontium sulfate, and 100% for silica.

Table 6.7: Relative error summary on various pressures for KBH at five year operation.

	Pressure Percent Error (%)		
Train/ Point	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 6.8: Relative error summary of specific ion rejections for KBH at five year operation.

	Percent Error (%)						
Train/ Point	Sodium	Calcium	Chloride	Sulfate	Magnesium	Fluoride	TDS
A Median	8.3	-1.9	10.0	-3.6	-2.2	-13.3	4.8
C Median	2.4	-2.3	4.6	-3.4	-2.4	-10.8	1.0
D Median	3.4	-2.5	5.7	-3.7	-2.7	-16.2	0.8
E Median	4.2	-2.1	6.2	-3.4	-2.4	-14.3	1.8

6.1.3.5 North Lee County

Located in Lee County, Florida, North Lee County water treatment plant has a capacity of 11.0 million gallons per day. The reverse osmosis system operates at 80% recovery and consists of a two stage array configuration of 38 by 17 with seven elements in each pressure vessel. The membrane installed is the Dow Filmtec LE-440i which has an active area of 440 square feet, a permeate flow of 12,650 gallons per day, and salt rejection of 99.3%. Startup performance data were collected in 2011 from January 11 to 13 for Train A and from January 10 to 13 for B.

Conductivity is provided in the startup data. A TDS factor of 0.520 is used in the pilot data and also applied when modeling the various data points. An ion ratio is also required and used to proportionally adjust the feed quality from the projection model at each data point. Sulfuric acid is added to the feed water prior to entering the membrane system. The addition is modeled in the projection and the model estimates the chemical dose.

Permeate throttling pressure of 5 psi in both stages and interstage boost are used to control the permeate flow between stages where the permeate pressures are maintained the same

and the boost pressure is iterated to match the flux. Boost pressure from the startup data is calculated by subtracting the second stage feed from first stage concentrate pressure.

Overall the model under predicts feed and concentrate pressures. Feed pressures are under predicted by an average of negative 1.4% and concentrate by negative 10.7 %. Boost pressure is over predicted by the model by a 5.4 %. In general TDS rejections are over predicted by the model. Train A and Train B have an actual average TDS rejection of 93.3% and 94.2% compared to model predictions of 95.3% and 95.4%. Table 6.9 summarizes the percent errors for various pressures and TDS rejections. Figure 6.24 illustrates all seven startup data points for both Train A and B plus each train's model median points.

Conductivity information for all pressure vessels sampled on two different days is available for both trains. First stage and second stage conductivity profiles for Train A and B are shown in Figure 6.26 and Figure 6.28 and demonstrate that the conductivity entering each pressure vessel varies. To determine if the variability impacts the rejection of the membrane, z-values for first and second stage rejections are calculated and then plotted against each pressure vessels rejection as exemplified in Figure 6.27 for Train A and in Figure 6.29 for Train B. A R-squared value of 1 indicates that conductivities entering the pressure vessels are normally distributed.

All modeled data points do not create design warnings except for median point of Train 4 where the maximum recommended permeate flow of 6.94 gpm is exceeded for the first element in the second stage. Solubility warnings generated for all data points for barium sulfate, strontium sulfate, and calcium fluoride have exceeded saturation limit of 100%. The software warns the user that an antiscalant may be required and to contact antiscalant manufacturer for chemical dosing and limits on system recovery.

Table 6.9: Relative error summary of pressures and total dissolved solids for North Lee County

	Percent Error (%)							
	Pressures					Rejections		
Train/ Point	Feed	Concentrate Stage 1	Feed Stage 2	Concentrate Stage 2	Interstage Boost	TDS Pass	TDS Stage 1	TDS Stage 2
A Min	-1.2	-10.3	-4.9	-8.3	9.2	2.5	2.2	1.9
A Median	-0.2	-9.6	-3.7	-7.4	12.2	2.7	2.29	1.9
A Max	-8.5	-19.3	-17.0	-22.7	-6.4	1.7	1.6	1.5
B Min	0.3	-8.9	-4.9	-8.6	7.6	1.9	1.9	1.7
B Median	-0.1	-8.4	-5.9	-8.9	4.4	2.3	1.9	1.7
B Max	-1.3	-9.3	-6.3	-14.2	6.6	2.8	2.2	2.4

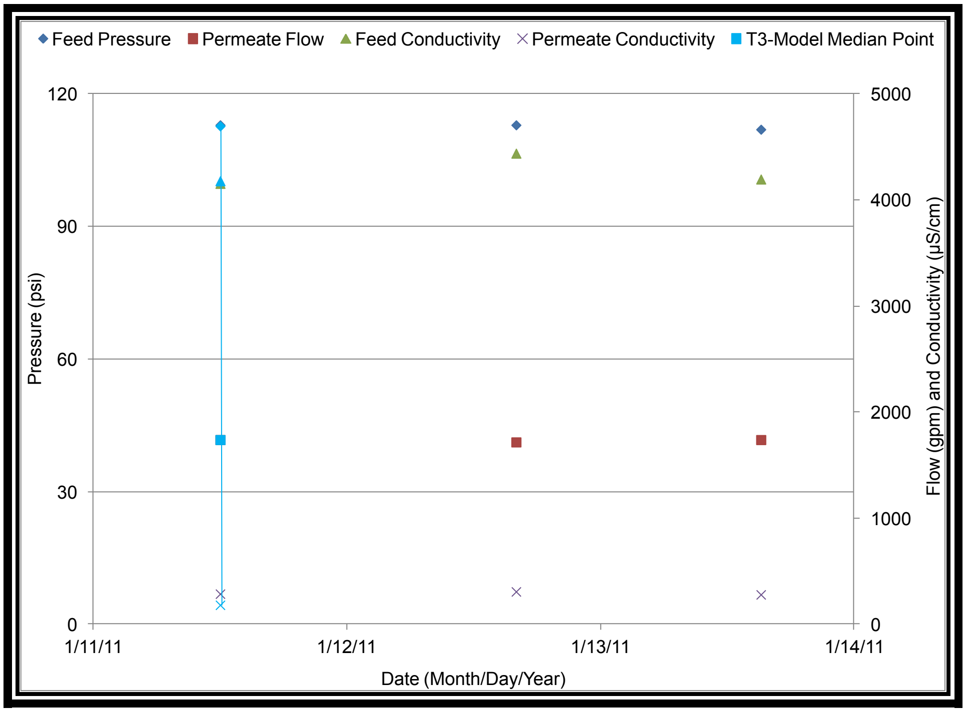


Figure 6.24: Full-scale operational data with Train A model median point for North Lee County.

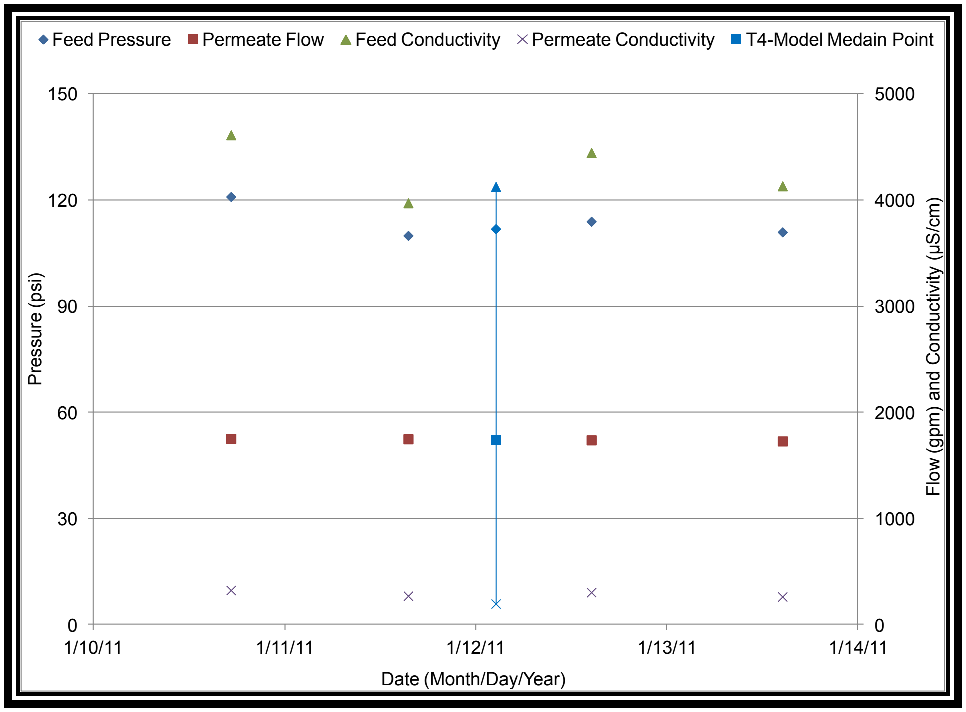


Figure 6.25: Full-scale operational data with Train A model median point for North Lee County.

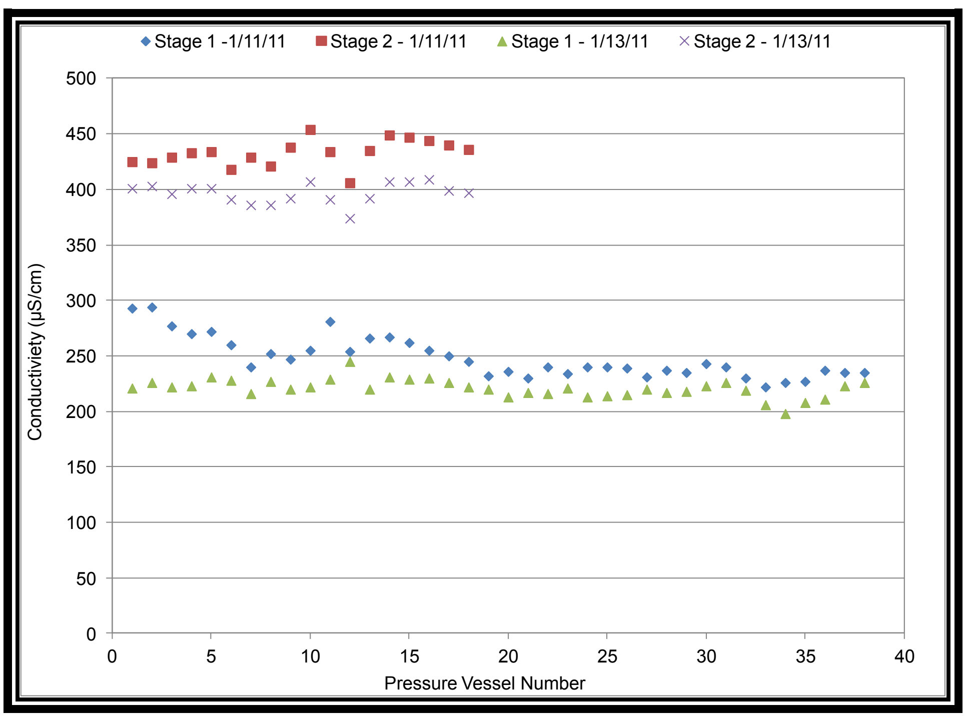


Figure 6.26: Pressure vessel water conductivities for Stage 1 and 2 of Train A in North Lee County.

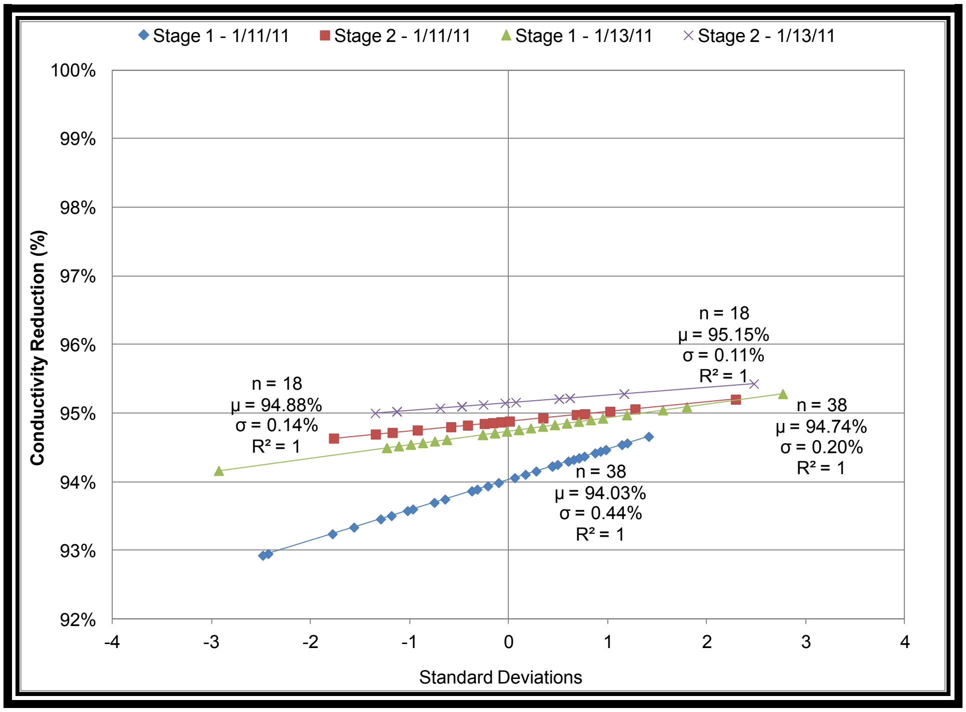


Figure 6.27: Standardized z-value of water conductivity in Train A pressure vessels of North Lee County.

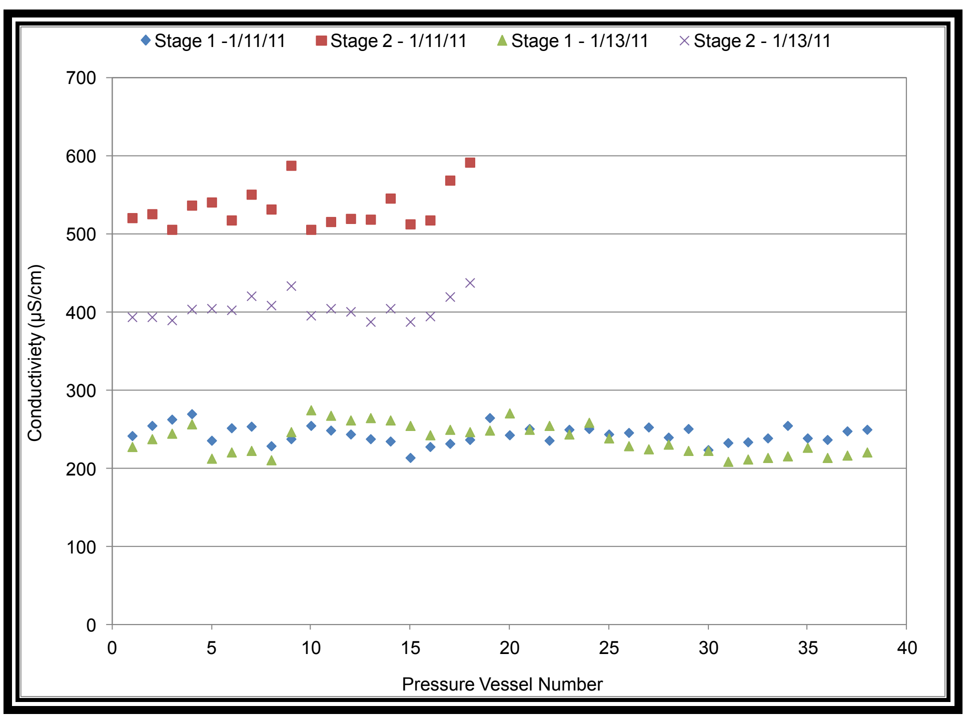


Figure 6.28: Pressure vessel water conductivities for Stage 1 and 2 of Train B in North Lee County.

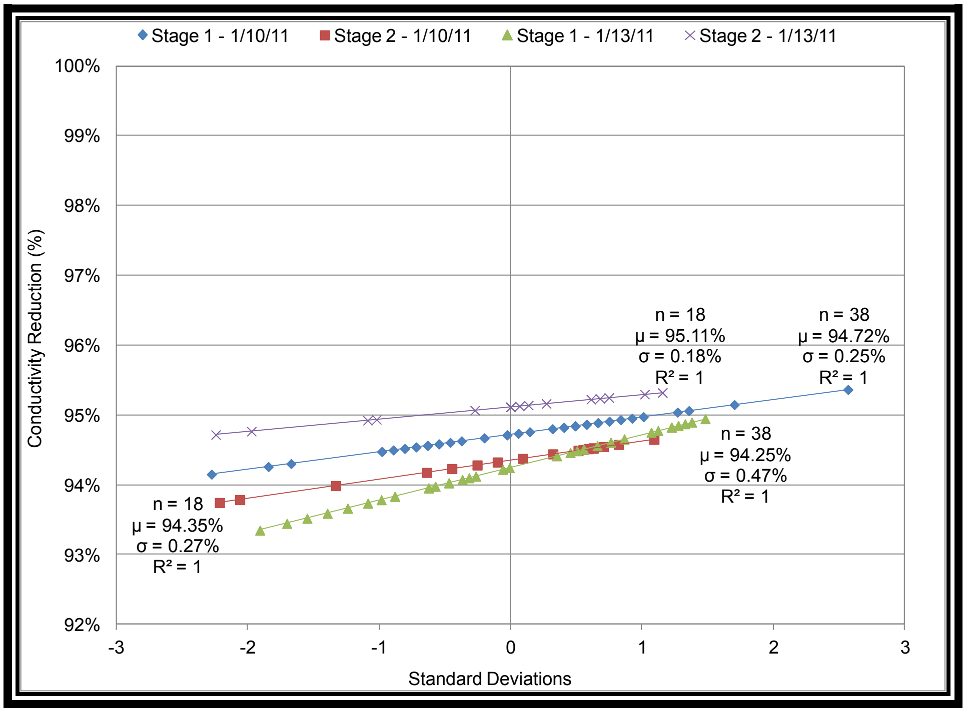


Figure 6.29: Standardized z-value of water conductivity in Train B pressure vessels of North Lee County.

6.2 Precision

A precision analysis demonstrates the confidence of reproducing the same model for six different membrane manufactures using similar membranes. Results for precision are presented in relative percent differences, (i.e., the difference between a manufacture's model and the average of all models divided by the average of all models.) Five data sets were evaluated on precision for the following: a new membrane, a five year old membrane, and a combination of an aged membrane and high total dissolved solids concentration.

Another method used to compare variability of a set of data is the coefficient of variation, which is equal to the standard deviation divided by the average. The coefficient of variation allows comparing data sets with different testing conditions, units, and means. A greater coefficient of variation means the standard deviation is larger relative to the mean value.

6.2.1 Clay Center

For precision analysis of the Clay Center data set, the selected point for assessment is the median flow value from Train A which occurred on January 3, 2011. A low energy RO membrane, DOW XLE-440, was installed in the RO system which has an area of 440 square feet, a nominal permeate flow of 12,700 gallons per day, and a reported salt rejection of 98.0%. 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 6.10. Testing for all membranes was performed at a temperature of 25 degree Celsius, a recover y of 15%, and a pH range of 6.5-7.5.

Table 6.10: Membrane element information for membranes comparable to DOW XLE-440.

RO Model	Membrane Model	Area (ft2)	Permeate Flow (gpd)	Stabilized Salt Rejection (%)	Solution	Solution Concentration (mg/L)	Feed Pressure (psi)
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	2000	125
CSMPRO 4.1	RE8040-BLF	400	11,500	99.2	NaCl	500	100
IMSdesign 2011.19	ESPA4 Max	440	13,200	99.2	NaCl	500	100

Koch and CSM do not have 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 the pass permeate flows were reduced by a factor of 0.9090 (i.e., 400/440). Identical system configurations and feed quality were entereed into all six models. In the Clay Center array design, back pressures and interstage boost were used in the membrane system. As with the accuracy analysis, the permeate back pressures were matched and the boost pressure was

iteratively changed to match the first and second stage fluxes. By matching first and second stage fluxes of the median-flow operation point, flows and recovery were also matched, and pressures and rejections can be compared.

The average first stage feed pressure of all the models is 104.1 psi with a standard deviation of 7.8 psi, which results in a coefficient of variation of 7.5%. Figure 6.30 shows a side by side comparison of models simulating the Clay Center median flow point. In general the graph shows that variation is greater in the feed pressure predictions compared to concentrate where the standard deviation is 14.5 for first stage and 11.5 for second. Table 6.11 presents the relative percent differences for first stage and second stage feed and concentrate pressures and interstage boost. The average of the boost pressures is 36.6 psi with a standard deviation of 5.4 psi which is approximately 34.8 % (i.e., 36.6/104.1) of the average feed pressure.

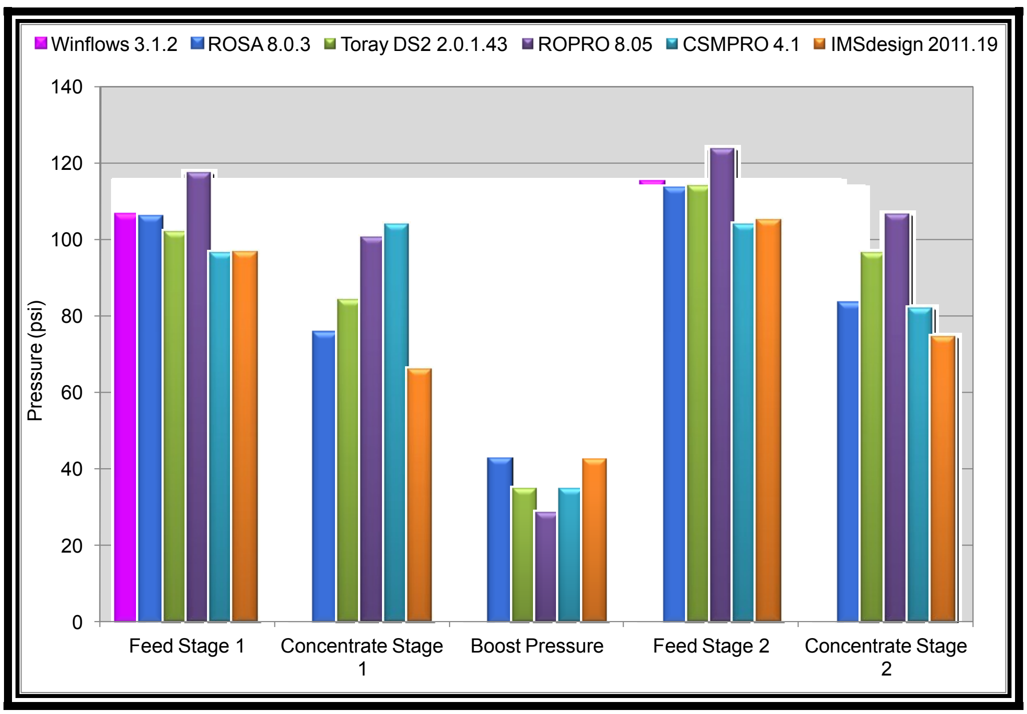


Figure 6.30: Comparison of pressures in RO models simulating Clay Center operation.

Table 6.11: Summary of relative differences in RO system pressures for Clay Center simulation.

RO Model	Relative Difference (from the mean in %) 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	21.5	-5.4	-7.7	-8.2
IMSdesign 2011.19	-7.1	-23.0	15.7	-6.5	-16.3
Average (psi)	104.1	85.5	36.6	85.5	89.0
Standard deviation (psi)	7.8	14.5	5.4	14.5	11.5
Coef. of Variation (%)	7.5	16.9	14.8	6.4	12.9

The average TDS rejection is 98.1% with a standard deviation of 0.8%. When model rejections are compared side by side as in Figure 6.31, overall TDS rejections are similar, but noticeable deviations include sodium for ROPRO and bicarbonate for IMSdesign. A summary of relative differences for specific ion rejections is in and Table 6.12.

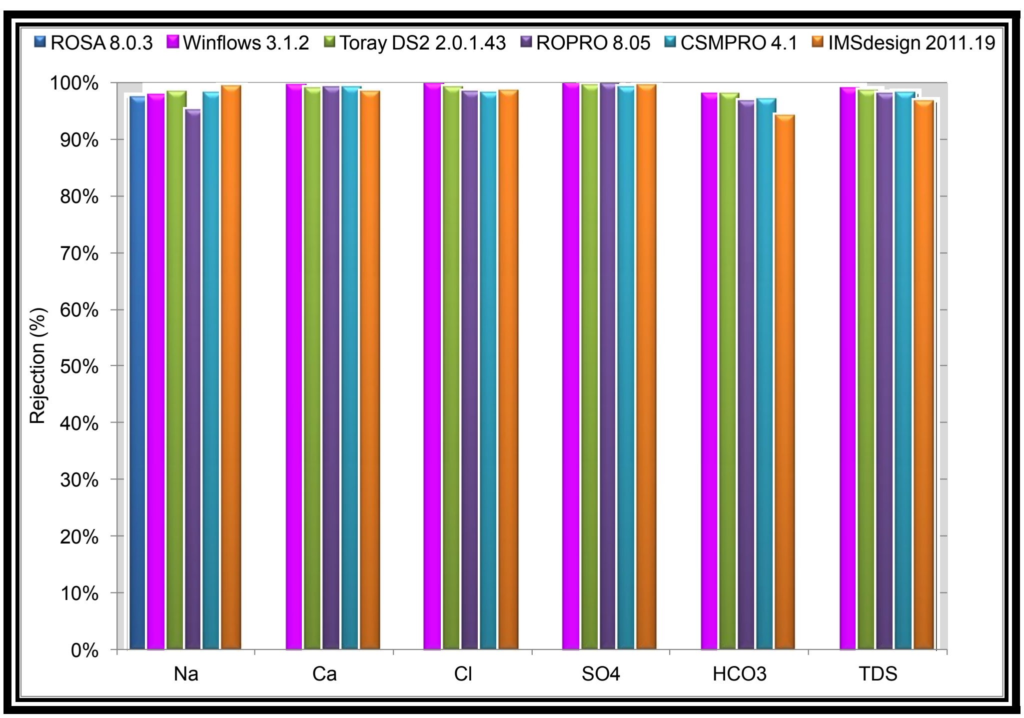


Figure 6.31: Comparison of rejections in RO models simulating Clay center operation.

Table 6.12: Summary of relative differences in RO system rejections for Clay Center simulation.

RO Model	Relative Difference (from the mean in %)					
	Na+	Ca2+	Cl-	S042-	HCO3-	TDS
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 (%)	97.7	99.0	98.6	99.5	97.0	98.1
Standard deviation (%)	1.4	0.3	0.7	0.3	1.5	0.8
Coefficient of Variation (%)	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 generates solubility warnings stating that the Langelier Saturation Index (LSI) and Stiff-Davis Stability Index are greater than zero. Also, the barium sulfate and silica percent saturations are greater than 100%. Similarly, ROPRO, Winflows and CSM also generate the same scale warnings. IMSdesign only generates a silica scale warning indicating the concentrate saturation is 116%, which is greater than the 100% limit.

6.2.2 Kay Bailey Hutchinson Desalination Plant-Five Year Operation

The data point selected for modeling comparison was Train 4 observed on June 7, 2012 at 11:20 am, which is taken as the average day data. The Kay Bailey Hutchinson analysis allows exploring membrane aging in the models to learn how aging is simulated and the parameters required. With time a membrane is affected by two factors: water and salt permeability. All models allow for simulating effects on water permeability due to aging, but only four models can simulate both factors. (For additional information on membrane aging refer to Section 3.3.4Membrane Aging within this report.) Along with a membrane age of five years, a flux decline of 7% per year and scale increase of 10% per year was entered to every model. For the TorayDS2 model, flux decline was entered as a fouling allowance factor, which is equivalent to 0.70 for this analysis. Table 6.13 lists membrane specifications and testing conditions for all

membranes in this analysis where testing is performed at a temperature of 25 degree Celsius, a recovery of 15%, and a pH range of 6.5 to 7.5.

Table 6.13: Membrane element information for comparable membranes to ESPA1.

RO Model	Membrane Model	Area (ft2)	Permeate Flow (gpd)	Stablized Salt Rejection (%)	Solution	Solution Concentration (mg/L)	Feed Pressure (psi)
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 used in the KBH operation; as in the accuracy analysis, the second stage back pressure of 8 psi was matched and the first stage permeate throttling pressure was iteratively changed to match the fluxes. A pressure loss of 5 psi was applied for inter-stage manifold losses in Toray and CSM models, but IMSdesign uses a 3 psi loss embedded in the program. By matching first and second stage fluxes, flows and recovery were also matched, so that pressures and rejections can be compared.

Among the four models, an average feed pressure of 222 psi was observed with a standard deviation of 25.2 psi, which corresponds to a coefficient of variation of 11.4%. The average permeate pressure of 39.5 psi with a standard deviation of 16.9 psi, which 18.9% of the mean feed pressure. Figure 6.32 displays first and second stage pressures for feed, concentrate, and permeate throttling of all three models. Table 6.14 presents a summary of the relative percent differences of the pressures.

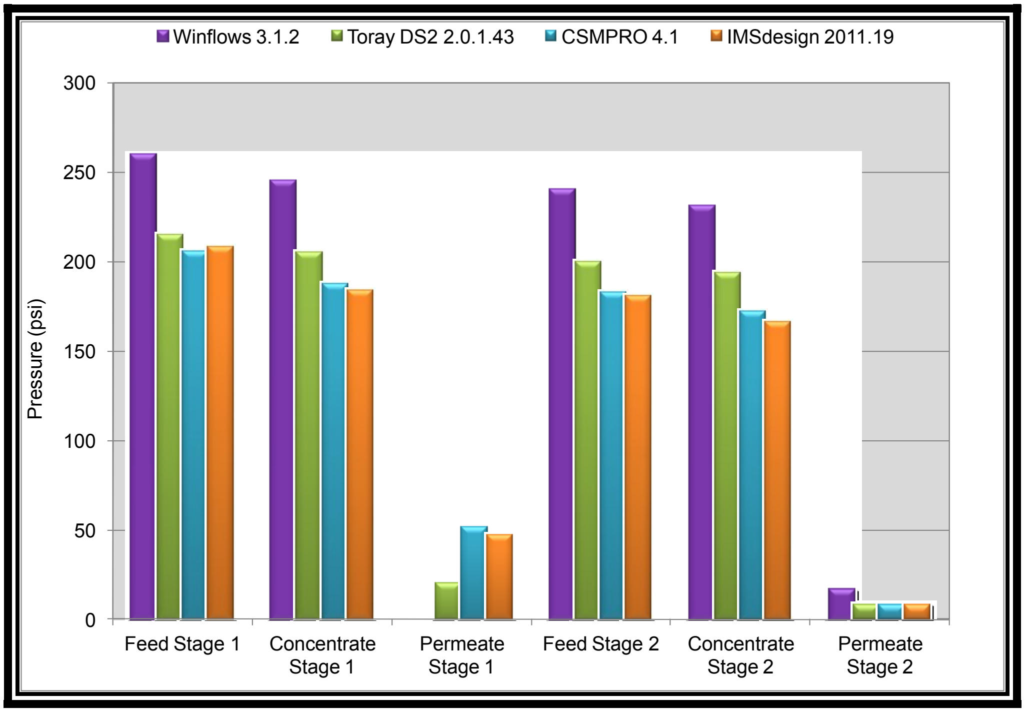


Figure 6.32: Comparison of pressures in RO models simulating KBH (5-yr) operation.

Table 6.14: Summary of relative differences in RO system pressures for KBH simulation.

RO Model	Relative Differences (from the mean in %)				
	Feed Stage 1	Concentrate Stage 1	Throttling Stage 1	Feed Stage 2	Concentrate Stage 2
Toray DS2 2.01.43	2.5	6.6	-49.0	6.5	9.2
CSMPRO 4.1	-1.7	-2.3	30.1	-2.7	-2.7
IMSdesign 2011.19	-0.8	-4.3	18.9	-3.8	-6.4
Average (psi)	222.0	205.2	29.7	200.7	190.4
Standard deviation (psi)	25.2	27.9	24.1	27.5	29.2
Coefficient of Variation (%)	11.4	13.6	81.3	13.7	15.3

Similarly to other precision analysis, bicarbonate and total dissolved solids varies in a small amount from model to model because of the different alphas/coefficients model's use to calculate the bicarbonate system. The average model TDS rejection is 92.4% with a standard deviation of 4.3%. The ion with greatest deviation is bicarbonate with average rejection of 81.9% and standard deviation of 17.8%. Figure 6.33 displays the rejections and Table 6.15 lists the relative percent differences of the rejections for all four models.

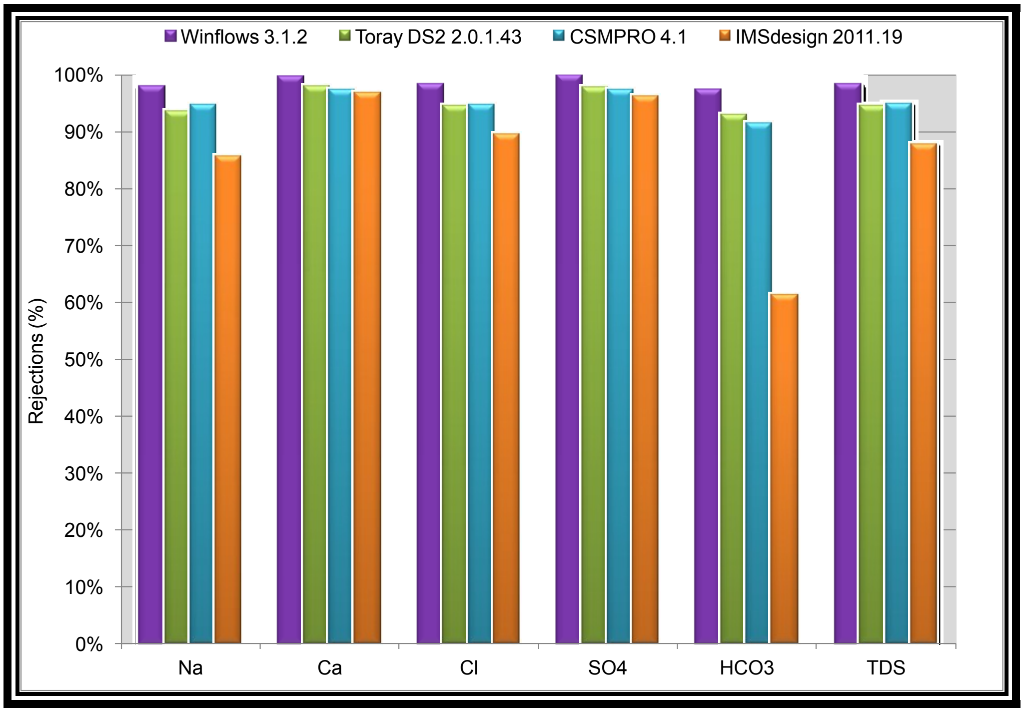


Figure 6.33: Comparison of rejections in RO models simulating KBH (5-yr) operation.

Table 6.15: Summary of relative differences in RO system rejections for KBH simulation.

RO Model	Relative Difference (from the mean in %)					
	Na^+	$Ca2^+$	Cl^-	$S0_4^{2-}$	HCO_3^-	TDS
Toray DS2 2.01.43	2.4	0.6	1.7	0.6	13.6	2.3
CSMPRO 4.1	3.8	-0.1	2.0	0.3	11.7	2.7
IMSdesign 2011.19	-6.1	-0.5	-3.7	-0.9	-25.3	-5.0
Average (%)	91.3	97.4	92.9	97.1	81.9	92.4
Standard deviation (%)	4.9	0.6	2.9	0.8	17.9	4.0
Coefficient of Variation (%)	5.3	0.6	3.2	0.8	21.9	4.3

6.2.3 Capitan Reef Aquifer Model

The Capitan Reef is a brackish Texas aquifer that is being considered for use as a water source. This analysis allows studying the effects of aging and high total dissolved solids concentration (6,000 mg/L) has, if any, on model precision. The membrane selected for the modeling was ESPA2-LD. Membrane specifications and testing conditions for the ESPA2-LD and equivalents are listed in Table 6.16.

Table 6.16: Membrane element information for comparable membranes to ESPA2-LD.

RO Model	Membrane	Area (ft2)	Permeate Flow (gpd)	Stabilized Salt Rejection (%)	Solution	Solution Concentration (mg/L)	Feed Pressure (psi)
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

Permeate back pressures of 15 psi were assumed for both stages, and an interstage boost pump was used to control first and second stage permeate fluxes. Among the four models simulate for Capitan Reef, the average model first stage feed pressure was 188.6 psi with a standard deviation of 19.9 psi and a coefficient of variation of 10.6 %. The average interstage boost pressure is 79.6 with a standard deviation of 5.6 psi, which is 3.0% of the average feed pressure. Figure 6.34 displays various pressures for each model and indicates, overall, that Winflows as a whole predicts higher pressures than other models. Table 6.17 shows the relative difference in pressures of the models.

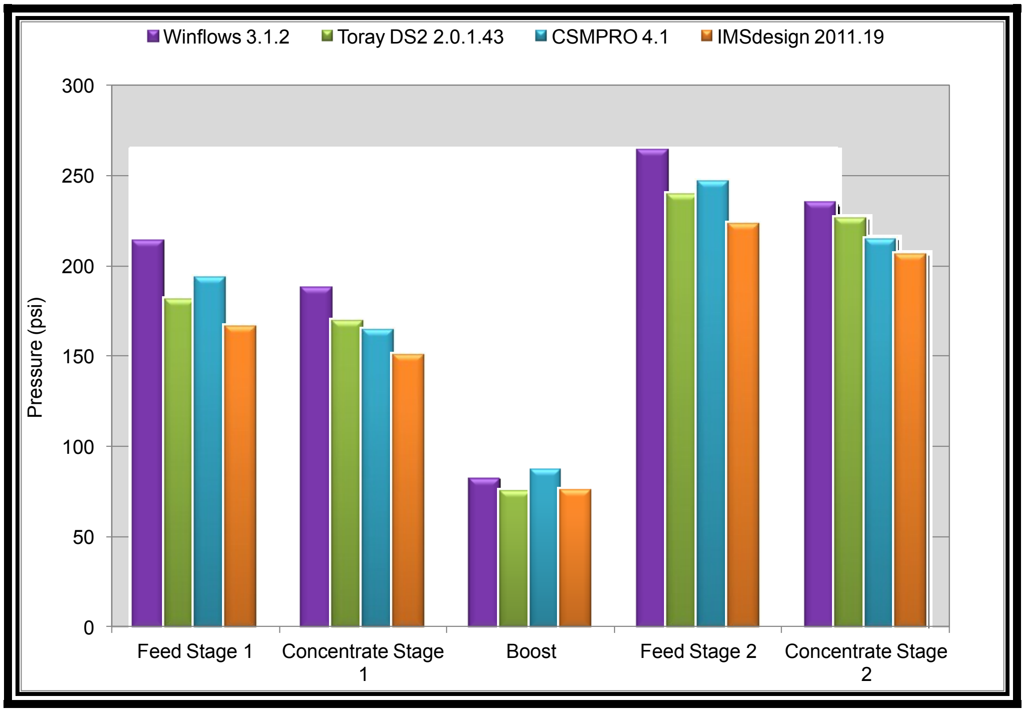


Figure 6.34: Comparison of pressures in RO models simulating Capitan Reef operation.

Table 6.17: Summary of relative differences in RO system pressures for Capitan Reef simulation.

RO Model	Relative Differences (from the mean in %)				
	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 (psi)	188.6	168.0	79.6	243.1	220.2
Standard Deviation (psi)	19.9	15.1	5.6	16.8	12.5
Coefficient of Variation (%)	10.6	9.0	7.1	6.9	5.7

A side by side model comparison for specific ion rejections is shown in Figure 6.35. The model average TDS rejection is 97.7% with a standard deviation of 0.9%. Bicarbonate rejections have a greater spread with an average rejection of 94.8% and a standard deviation of 2.8%. The larger spread can be due to the different methods that models use internally to calculate the bicarbonate system and pH adjustment. Sulfate rejection has the least spread with an average

rejection of 98.9% and a standard deviation of 0.6%. Table 6.18 lists the relative percent differences for various ion rejections.

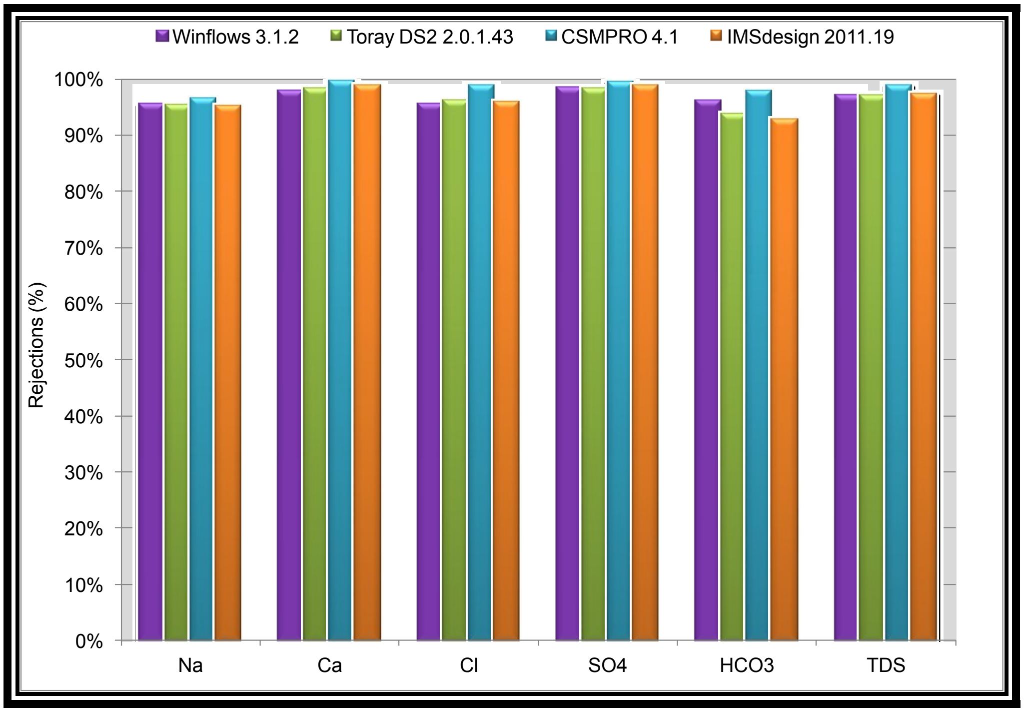


Figure 6.35: Comparison of rejections in RO Models simulating Capitan Reef operation.

Table 6.18: Summary of relative differences in RO system rejections for Capitan Reef simulation.

RO Model	Relative Difference (from the mean in %)					
	Na+	Ca2+	Cl-	S042-	HCO3-	TDS
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	2.7	2.7	0.9
Coefficient of Variation	0.8	0.7	1.7	2.8	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 (LSI) and Stiff-Davis Stability Index are greater than the limit, and a scale inhibitor or pH

adjustment is required. Winflows generates design warnings indicating that the elements limits were exceeded for permeate flux, recovery, and flow rate.

6.3 Pilot versus Full-Scale Operation: North Lee County

The data set for North Lee County contained system information from a pilot study that was performed for a year and four months, along with three days of full-scale data. The accuracy analysis of this study quantified the error in the model with respect to full-scale membrane performance. In addition, this data set permits investigating how the pilot compared to full-scale performance, as well as how the model compared to pilot and full-scale operation.

The net driving pressure is the difference between the average feed-concentrate pressure and the average feed-concentrate osmotic pressure, this net driving pressure is the effective force that is causing water to permeate through the membrane. First and second stage net driving pressures for the pilot, model, and full-scale start-up are shown in Figure 6.36. (Net driving pressure values for the full-scale start-up are calculated from average daily pressures.) The net driving pressures at the beginning of the pilot study were approximately equal to the net driving pressures observed in the full-scale start-up. The model over-predicted the required net driving pressures for the first stage of the pilot during the latter part of the pilot study.

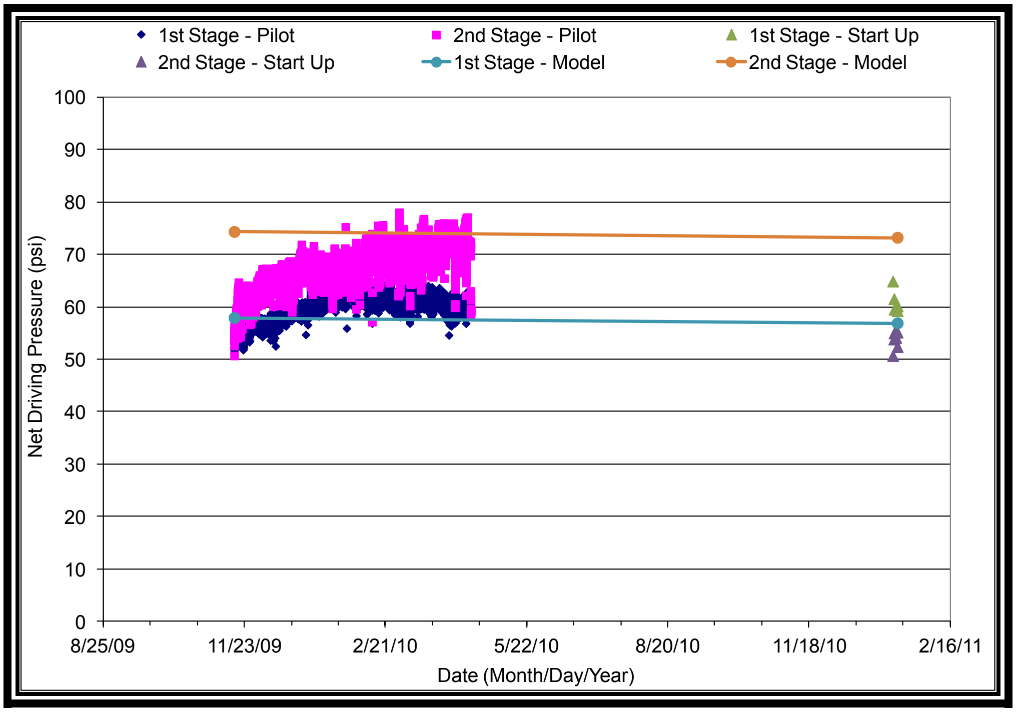


Figure 6.36: Net Driving Pressure comparison of model, pilot, and full-scale.

The specific flux is way of comparing the performance of membranes over variations in temperature and osmotic pressure, and it is calculated by normalizing the flux by temperature. Figure 6.37 shows the first and second stage specific flux for pilot testing, full-scale start-up, as well as the full-scale models. The specific flux of the beginning of the pilot study is comparable to full-scale start-up performance. The specific flux of the first stage of the model is approximately the same as full-scale, but the second stage specific flux is under predicted by the model. The model specific flux is greater than the long-term specific flux of the first stage of the pilot, but the specific flux of the second stage is comparable between the model and the pilot.

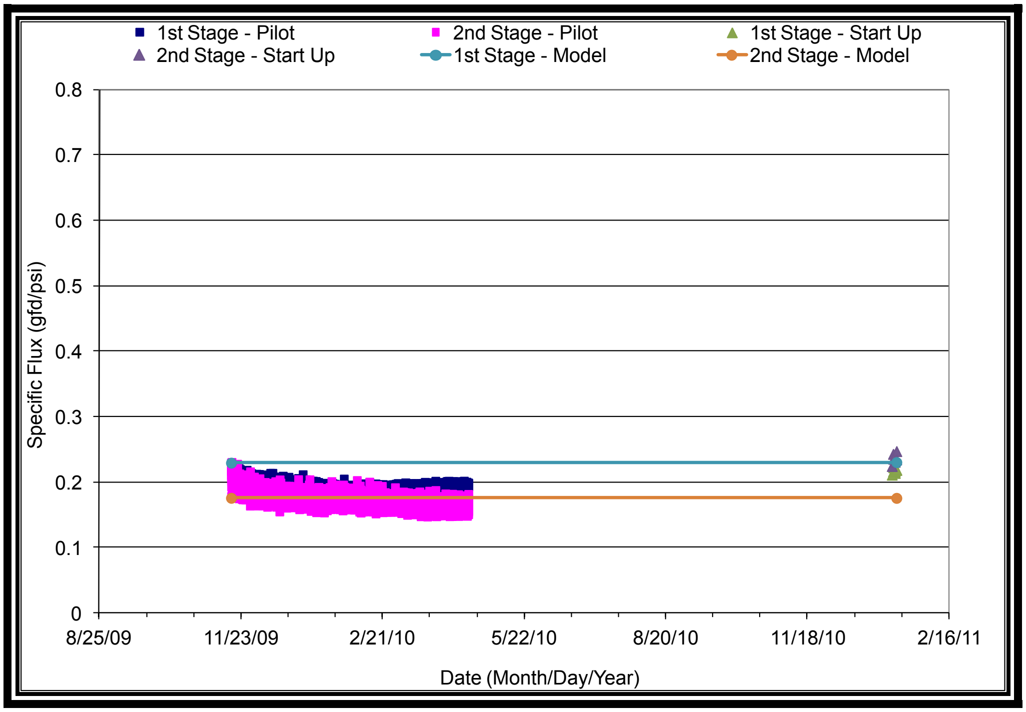


Figure 6.37: Specific flux comparison of model, pilot, and full-scale.

Total dissolved pass rejection for model, pilot, and full-scale startup operation is shown in Figure 6.38. 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.

The normalized salt rejection is way of comparing the performance of membranes over variations in feed water quality, and it is calculated by normalizing rejection by a reference condition such as initial system performance and temperature. Figure 6.39 presents normalizes salinity rejections for pilot testing, full-scale start-up, as well as the full-scale models. Normalized salinity rejections are similar between pilot and full-scale membrane performance, and the predicted rejections by the model are comparable.

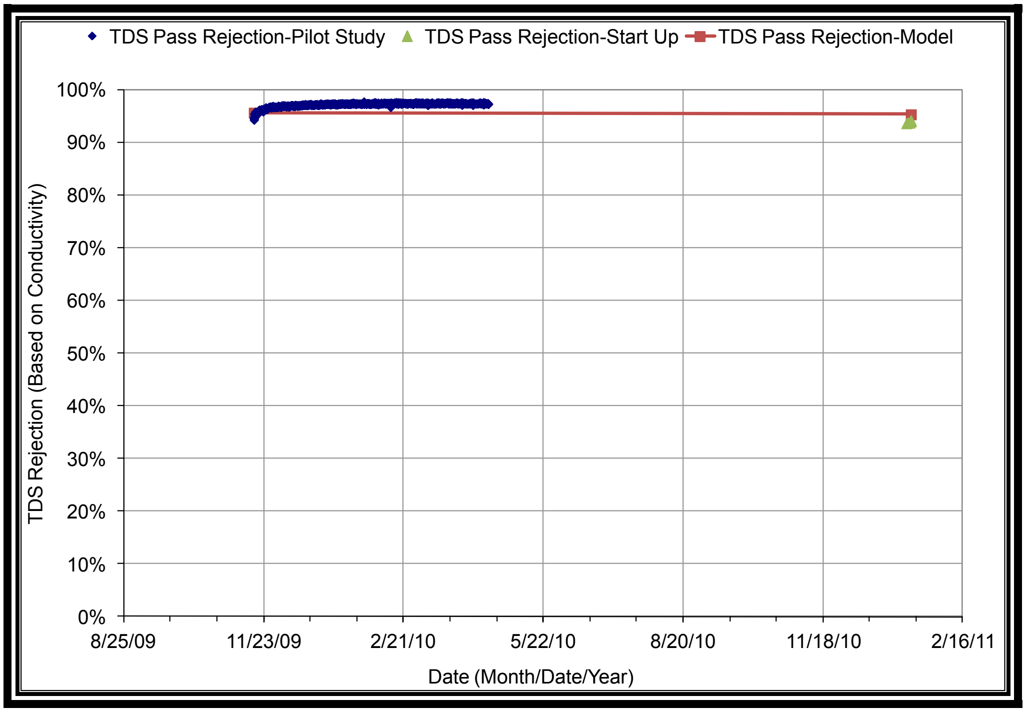


Figure 6.38: Total Dissolved Solids rejection comparison of model, pilot, and full-scale.

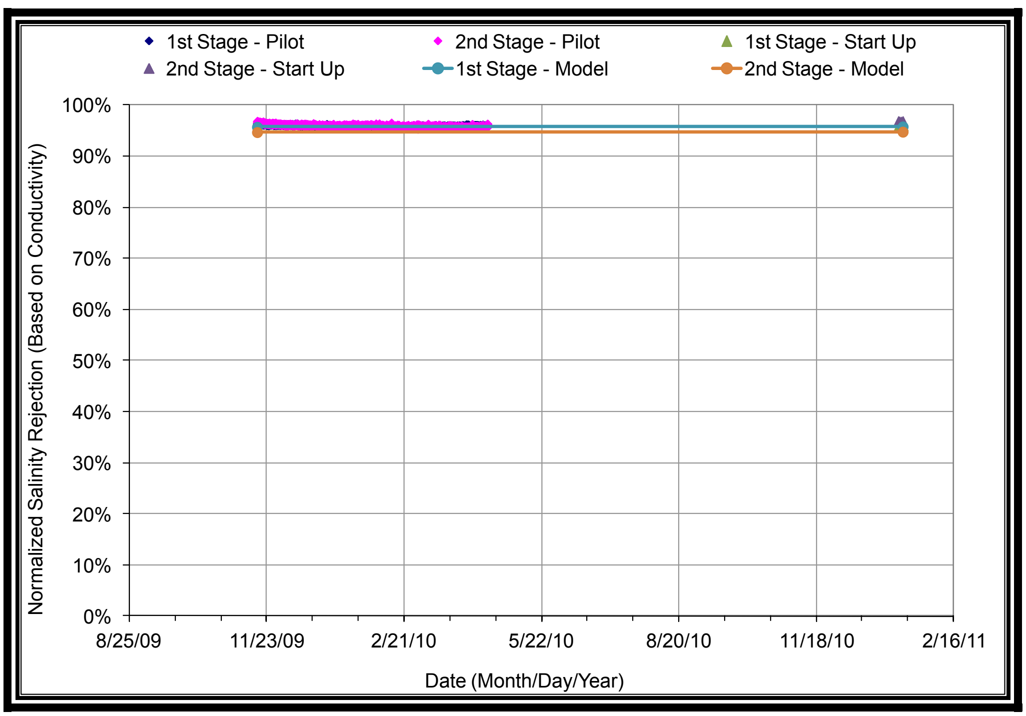


Figure 6.39: Normalized Salinity rejection comparison of model, pilot, and full-scale.

Chapter 7: Conclusions

7.1 Trends

A key finding of this research is the acknowledgement of the predictive value of reverse osmosis models. While, reverse osmosis models may not be perfectly accurate, the predictive value assists engineers, researchers, and regulators in the design of water treatment. General trends observed in the accuracy and precision analyses are discussed here followed by a more specific discussion on the spread of percent error and relative difference for the eight project data sets.

Acknowledgement of the cumulative error throughout the process from data collection to the analysis is important. Before initiating the analyses the data received from manufacturers likely contained some human error derived from keying manual readings, as well as data systems malfunctions, or a mistaken valve adjustment. While, a systematic procedure was implemented for the accuracy and precision analyses, erroneous data may add to the reported error. A goal of the research is to objectively present the data, procedure, and results, and in no way is any particular manufacture given preference.

The safety factor included in the models could be impacting how well the model predicts full-scale performance by making the model less accurate, since a safety factor is inherently conservative. Models being conservative maybe good, but can have a negative impact by oversizing feed pumps and as a result requiring more capital than needed. A primary factor that affects precision analyses is the categorization/selection of membrane. The main factor affecting accuracy is a complete and clear set of data.

A general trend observed in the accuracy analyses is that required feed pressures and reduction of total dissolved solids are over-predicted by the model. The over-prediction is greater for operating pressure (as high as 31%), compared to over prediction of salinity rejections (as much as 5%). The greatest magnitude of relative error was noticed in the boost and permeate throttling pressures. However, relative error can be inaccurately representing the results since a

30 psi difference from the original pressure (of 20 psi) is estimated to be 150% error. If the boost or permeate throttling pressure is taken as a fraction from the feed pressure the error is put more in perspective of the total pressure required. The spread of the relative differences in the precision analyses of pressure is greater compared to ion rejections.

7.2 How accurate and precise are the models' predictions?

7.2.1 Accuracy

For accuracy the relative error between model and full-scale performance of feed pressures ranged from under-predication of 7.4% to over-prediction of 31.3%. The second stage concentrate pressure had a relative error ranging from -13.2% to +47.7%. Total dissolved rejections were typically over-predicted by the model and varied from 0.1% to 5.9%. Table 7.1 lists the percent error for all project data sets for various operating pressures. Figure 7.1 is box-whisker-plot that illustrates the spread for pressures and TDS rejection. From the graph the spread and error bars are observed to be greater for pressures than TDS rejections.

7.2.2 Precision

Table 7.2 and Table 7.3 list the relative differences about the mean for pressures and ion rejections from the precision results, respectively. Figure 7.2 shows that the relative difference for second stage concentrate and inter-stage boost pressure is greatest and first and second feed pressures have the smallest. Figure 7.3 shows the relative differences of rejections for sodium, calcium, chloride, sulfate, bicarbonate, and TDS. The spread of relative differences and error bars for calcium and sulfate are the smallest among the various ions. The greater relative difference for sodium, chloride, and total dissolved solids may be an artifact of those salts being commonly used to balance the feed water and in return change the total dissolved solids concentration. The ion that stands out in the box plot is bicarbonate due to the large error bars. The larger spread of bicarbonate may be due to the different methods that the carbonate system equilibrium is calculated among the various models.

Table 7.1: Summary of percent error in RO system pressures and TDS rejections for accuracy analyses.

Data	Train	Feed Stage 1	Feed Stage 2	Concentrate Stage 1	Concentrate Stage 2	Permeate Stage 1	Boost	TDS	TDS Stage 1	TDS Stage 2
1	A	6.1	5.5	-	7.9	-	-	1.2	1.2	-
	B	12.1	10.8	-	13.3	-	-	1.4	1.3	-
2	A	-7.4	-	-7.7	-13.2	17.0	-	0.64	-	-
3	A	-4.6	-	-	-	-	-	0.3	0.5	-
4	A	11.0	1.3	18.1	3.9	-	-10.8	0.2	0.6	-0.3
	B	6.4	-1.4	7.8	-0.1	-	-4.2	0.1	0.4	-0.3
5	A	7.1	-	1.6	-3.5	209.4	-	3.4	-	-
	B	6.9	-	3.9	0.1	145.6	-	2.9	-	-
6	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	-
7	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	-	-
8	A	-0.2	-	-9.6	-7.4	-	12.2	2.7	2.3	1.9
	B	-0.1	-	-8.4	-9.0	-	4.4	2.3	1.9	1.7

Table 7.2: Summary of relative differences in RO system pressures for precision analyses.

Analysis	Manufacture	Feed Stage 1	Concentrate Stage 1	Permeate Throttling Stage 1	Boost	Feed Stage 2	Concentrate Stage 2
1	Dow	1.7	-11.6		16.6	0.7	-6.5
	GE	2.3	-2.9		1	2.3	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
2	Toray	2.5	6.6	-49		6.5	9.2
	CSM	-1.7	-2.3	30.1		-2.7	-2.7
	Hydranautics	-0.8	-4.3	18.9		-3.8	-6.4
3	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

Table 7.3: Summary of relative differences in RO system rejections for precision simulations.

Analysis	Manufacture	Na^+	Ca^{2+}	Cl^-	$S0_4^{2-}$	HCO_3^-	TDS
1	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
2	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
3	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

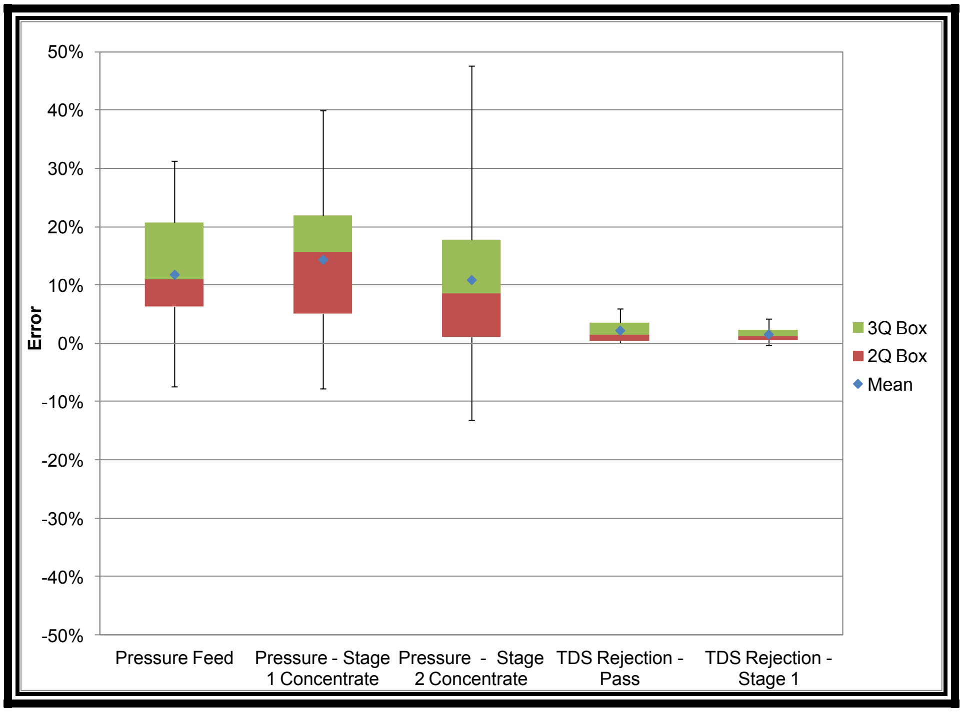


Figure 7.1: Error for pressures in the accuracy analyses.

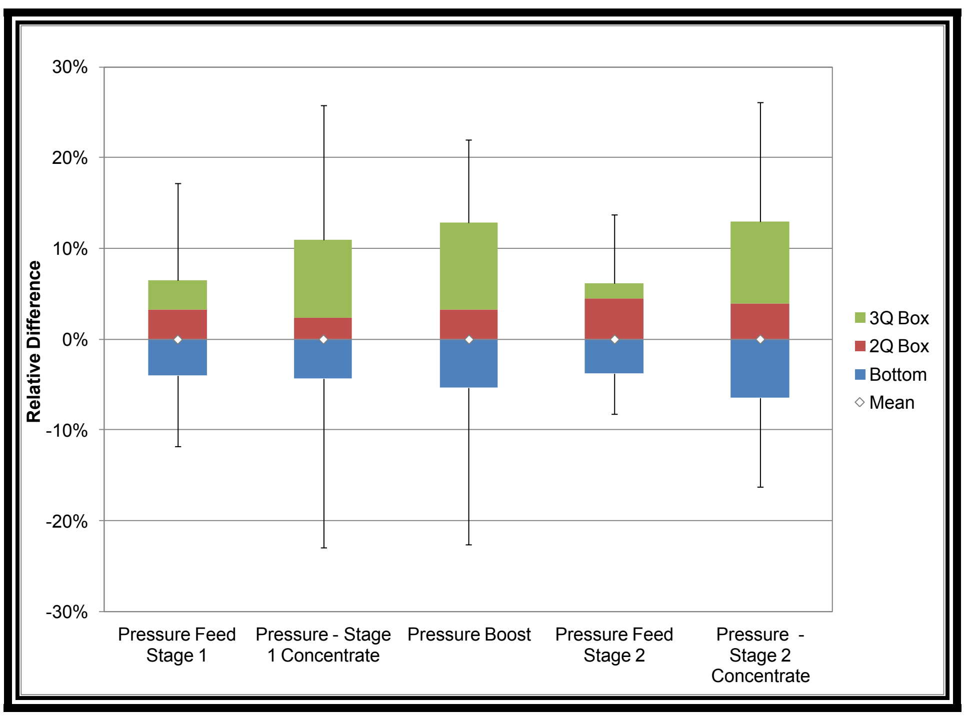


Figure 7.2: Relate difference for pressures in the precision analyses.

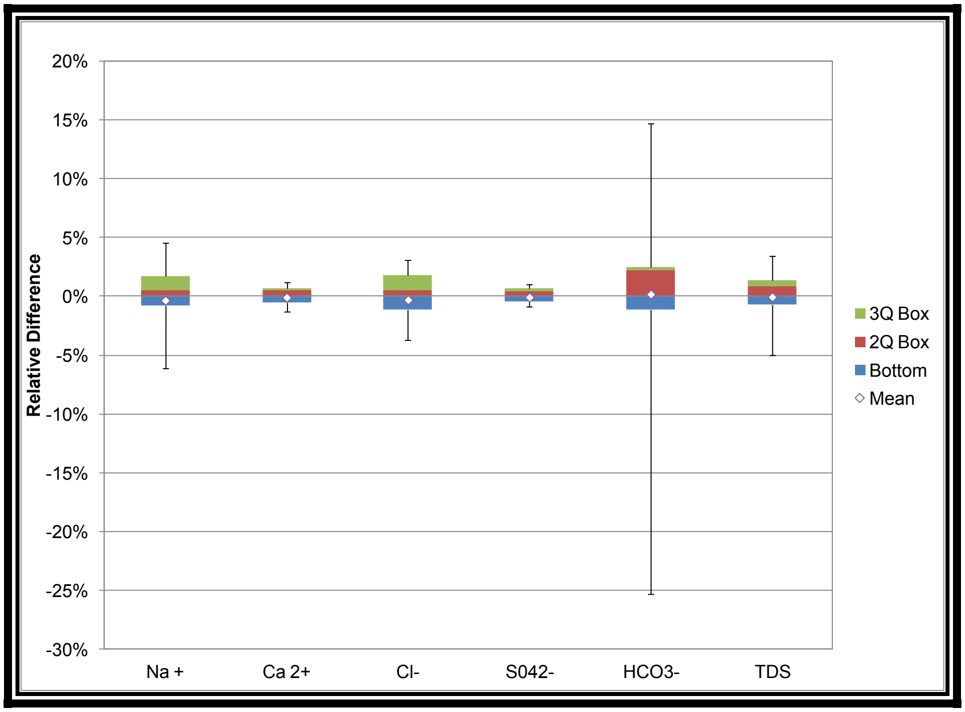


Figure 7.3: Relative difference for ion rejections in the precision analyses.

7.3 Regulations

The Texas Commission on Environmental Quality (TCEQ) has a defined process for approving membrane technologies, which is intended to provide consistency in the design and piloting of membrane treatment facilities in Texas. When compared to federal and other state requirements, particularly as it applies to groundwater sources, the requirement to demonstrate membrane performance with pilot testing is a conservative requirement which is intended to bolster the reliability of the treatment plant's capacity and filtered water quality. TCEQ is open to reviewing details and requirements of the permitting process to consider improving it without jeopardizing the public's health. TCEQ and Texas Water Development Board (TWDB) are working together to identify areas for improvement and gather information on the state of the art technology and current practices. With continued collaboration, the development of a more efficient and effective approval process for membrane treatment systems may be possible.

The performance of membranes in full-scale water treatment plants may be evaluated and predicted by several methods. Four categories of performance prediction and testing are: (1)

computer modeling, (2) hollow-fiber testing (for low-pressure) or flat-sheet testing (for low-pressure or desalting), (3) single-element testing, and (4) demonstration-scale pilot testing. These methods are used (often in combination) to aid in design and operation of full-scale membrane water treatment plants. Each method is uniquely valuable for predicting aspects of full-scale performance (e.g., product water quality or hydraulic characteristics), with tradeoffs in the investment of design time and financial cost. All four prediction methods mentioned above are not perfectly accurate and have certain limitations, which need to be considered when weighing the benefits of each testing methods.

A review of federal drinking water regulations for public water systems is important to understanding the hierarchy of the regulations and their implications on state code. Surface Water Treatment Rules (SWTR) and Ground Water Rule are subparts of the primary drinking water regulations and all have the same class level. Each rule has subset requirements that are at a lower hierarchy level. Pilot testing of membrane filtration is required under the SWTR and thus a lower grade level. The SWTR does not specifically address membrane technologies because at the promulgation of the rule, membrane technology was a new concept in the application of surface water (USEPA, 2001b). An important observation from the review is that pilot testing is not required for groundwaters that use membrane filtration, even though the Ground Water Rule lists membrane filtration as an option to meet 4-log removal of viruses and compliance monitoring. Additional information on the use of nanofiltration and reverse osmosis for virus reduction credit under the GWR can be found in Appendix E of the USEPA Membrane Filtration Guidance Manual.

National Secondary drinking water regulations are non-enforceable guidelines at the national level, except in a few states, Texas being one of them. Total dissolved solids is a secondary regulation; that is enforced in Texas as a primary regulation For example, the reduction of total dissolved solids in water can be performed using desalting membranes. However, Texas requires piloting testing since a membrane technology is being utilized, but at the national level there are no pilot testing requirements

The principal disadvantage of the current TCEQ permitting process for membrane treatment systems is that the requirement for piloting may, in some cases, be unnecessarily slow, and thereby delay or deter the construction process for communities in desperate need of new drinking water sources. As a result, the extra time, cost and permitting process steps required for the use of membrane technologies in water treatment facilities can deter owners and public water systems from developing new and much needed water supplies.

Another disadvantage of the current TCEQ permitting process for membrane treatment systems is that the requirement for demonstration piloting may unnecessarily encumber significant financial costs for the design. Pilot testing cost varies from project to project. Components that affect pilot costs include availability of appropriate facilities, laboratory analysis costs, size, and number of processes in the treatment train, and testing schedule. Including the setup, labor, supplies, and water quality testing, the total cost of piloting a membrane system ranges from $50,000 to $100,000 (Vickers, 2005). Based on recent projects in Texas that are ongoing with TWDB, the cost of pilot testing ranges from $75,000 to $2,690,945.

While the objective of TCEQ's pilot testing requirement is to protect public health and safety by demonstrating the reliability of membrane treatment processes, public health and safety may actually be at risk by the requirement if water supplies become inadequate to meet the needs of the community due to the time and cost of developing new water supplies. TCEQ's requirements can provide some assurance to the water system that the purchased treatment process will be effective. However, TCEQ approval does not constitute a guarantee.

Some are of the opinion that proper engineering consideration necessitates demonstration testing to prove process performance, and a pilot study can accomplish this objective. However, evaluation of membrane performance and the design of reliable membrane treatment systems (especially brackish water desalination) can be executed with proper engineering consideration, which may exclude demonstration-scale pilot testing (as in other States). Dialogue is occurring among engineers and state regulators to develop more streamlined procedures for developing key water treatment systems without comprising the safety and health of the public.

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Appendix

8.1 Texas regulations for membrane treatment

8.1.1 Texas Administrative Code

In 30 TAC §290.42(g) addresses other treatment processes:

> *(g) Other treatment processes. Innovative/alternate treatment processes will be considered on an individual basis, in accordance with §290.39(l) of this title. Where innovative/alternate treatment systems are proposed, the licensed professional engineer must provide pilot test data or data collected at similar full-scale operations demonstrating that the system will produce water that meets the requirements of Subchapter F of this chapter (relating to Drinking Water Standards Governing Drinking Water Quality and Reporting Requirements for Public Water Systems). Pilot test data must be representative of the actual operating conditions which can be expected over the course of the year. The executive director may require a pilot study protocol to be submitted for review and approval prior to conducting a pilot study to verify compliance with the requirements of §290.39(l) of this title and Subchapter F of this chapter. The executive director may require proof of a one-year manufacturer's performance warrantee or guarantee assuring that the plant will produce treated water which meets minimum state and federal standards for drinking water quality. (Texas Commission on Environmental Quality, 2011).*

In 30 TAC §290.42(g) (3), Paragraph (3) of Subsection (g) specifically addresses membrane filtration systems:

> *(3) Membrane filtration systems or modules installed or replaced after April 1, 2012 and used for microbiological treatment, can receive Cryptosporidium and Giardia removal credit for membrane filtration only if the systems or modules meet the criteria in subparagraphs (A) - (F) of this paragraph.*
>
> *(A) The membrane module used by the system must undergo challenge testing to evaluate removal efficiency. Challenge testing must be conducted according to the criteria established by 40 CFR §141.719(b)(2) and the executive director.*
>
> *(i) All membrane module challenge test protocols and results, the protocol for calculating the representative Log Removal Value (LRV) for each membrane module, the removal efficiency, calculated results of LRVC-Test , and the non-destructive performance test with its Quality Control Release Value (QCRV) must be submitted to the executive director for review and approval prior to beginning a membrane filtration pilot study at a public water system.*
>
> *(ii) Challenge testing must be conducted on either a full-scale membrane module identical in material and construction to the membrane modules to be used in the system's treatment facility, or a smaller-scale membrane module identical in*

material and similar in construction to the full-scale module if approved by the executive director.

(iii) Systems may use data from challenge testing conducted prior to January 5, 2006, if prior testing was consistent with 40 CFR §141.719, submitted by the system's licensed professional engineer, and approved by the executive director.

(iv) If a previously tested membrane is modified in a manner that could change the removal efficiency of the membrane product line or the applicability of the non-destructive performance test and associated QCRV, additional challenge testing to demonstrate the removal efficiency of the modified membrane and determine a new QCRV for the modified membrane must be conducted and results submitted to the executive director for approval.

(B) The membrane system must be designed to conduct and record the results of direct integrity testing in a manner that demonstrates a removal efficiency equal to or greater than the removal credit awarded to the membrane filtration system approved by the executive director and meets the requirements in clauses (i) - (ii) of this subparagraph.

(i) The design must provide for direct integrity testing of each membrane unit.

(ii) The design must provide direct integrity testing that has a resolution of 3 micrometers or less.

(iii) The design must provide direct integrity testing with a sensitivity sufficient to verify the log removal credit approved by the executive director. Sensitivity is determined by the criteria in 40 CFR §141.719(b)(3)(iii).

(iv) The executive director may reduce the direct integrity testing requirements for membrane units.

(C) The membrane system must be designed to conduct and record continuous indirect integrity monitoring on each membrane unit. The turbidity of the water produced by each membrane unit must be measured using the Hach FilterTrak Method 10133. The executive director may approve the use of alternative technology to monitor the quality of the water produced by each membrane unit.

(D) The level of removal credit approved by the executive director shall not exceed the lower of:

(i) the removal efficiency demonstrated during challenge testing conducted under the conditions in subparagraph (A) of this paragraph, or

(ii) the maximum removal efficiency that can be verified through direct integrity testing used with the membrane filtration process under the conditions in subparagraph (B) of this paragraph.

(E) Pilot studies must be conducted using membrane modules that will meet the requirements of this section.

(F) Membrane systems must be designed so that membrane units' feed water, filtrate, backwash supply, waste and chemical cleaning piping shall have cross-connection protection to prevent chemicals from all chemical cleaning processes from contaminating other membrane units in other modes of operation. This may be accomplished by the installation of a double block and bleed valving arrangement, a removable spool system or other alternative methods approved by the executive director (TCEQ, 2011).

8.2 Wisconsin regulations

8.2.1 NR811.50 Membrane filtration.

(1)Treatment objectives. The selection of the specific membrane process shall be matched to the desired treatment objectives. The department shall be contacted to determine inactivation/removal credits for the specific membrane and treatment objective membranes to be used in treatment of surface water or groundwater under the direct influence of surface water.

(2)Water quality considerations. A review of historical source raw water quality data, including turbidity or particle counts or both, seasonal changes, organic loading, microbial activity, and temperature differentials as well as other inorganic and physical parameters shall be conducted. The data shall be used to determine feasibility and cost of the system and the degree of pre-treatment. Design considerations and membrane selection at this phase shall also address the issue of target removal efficiencies and system recovery versus acceptable transmembrane pressure differentials. On surface water supplies, pre-screening or cartridge filtration may be required. The source water temperature shall be considered when establishing the design flux of the membrane under consideration and the number of treatment units to be installed. Seasonal variation of design flow rates may be based on documented lower demand during colder weather.

(3)Pilot testing. Prior to initiating the design of a membrane treatment facility, pilot testing shall be conducted. The pilot plant study shall be designed to identify the best membrane to use, need for pre- treatment, type of post- treatment, cold and warm water flux, backwash optimization, chemical cleaning optimization, fouling potential, operating and transmembrane pressure, integrity testing procedures, bypass ratio, amount of reject water, system recovery, process efficiency, particulate or organism removal efficiencies, and other design and monitoring considerations, each where applicable. The duration of the pilot testing shall be 9 to 12 months for microfiltration and ultrafiltration on surface water supplies and 2 to 7 months for reverse osmosis and nanofiltration on groundwaters. The general protocol and sampling schedule shall follow the US EPA Membrane Filtration Guidance Manual, EPA 815-R-06-009, November 2005.

(4)Challenge Testing. Membranes treating surface waters or groundwater under the direct influence of a surface water shall be challenge tested to establish a product specific maximum Cryptosporidium and Giardia Lamblia log removal credit. Challenge testing shall meet the requirements of s. NR 810.45 (2).

(5)Pretreatment. Pretreatment shall be as follows:

(a)Microfiltration and ultrafiltration. Pretreatment shall be designed to remove suspended solids and large particulate matter. The pretreatment may consist of a screen or strainer with a 200 to 500 micron rating. Chemicals used for pretreatment shall be certified for compliance with ANSI/NSF Standard 60.

(b)Reverse osmosis and nanofiltration. Pretreatment shall be provided where appropriate for turbidity reduction, iron or manganese removal, stabilization of the water to prevent scale formation, microbial control, chlorine removal for certain membrane types, and pH adjustment. At a minimum, cartridge filters shall be provided for the protection of the reverse osmosis or nanofiltration membranes against particulate matter.

(6)Membrane materials. Two types of membranes may be used for reverse osmosis and nanofiltration. These are cellulose acetate based and polyamide composites. Microfiltration and ultrafiltration membranes may be organic polymers such as: cellulose acetate, polysulfones, polyamides, polypropylene, polycarbonates or polyvinylidene. The physical configurations may include: hollow fiber, spiral wound or tubular. Membrane materials shall be compatible with any pre-oxidants.

(7)Useful life of membranes. The life expectancy of a particular membrane under consideration shall be evaluated during the pilot study or from other relevant available data.

(8)Backwashing. Automated periodic backwashing shall be provided for microfiltration and ultrafiltration on a timed basis or once a target transmembrane pressure differential or a high resistance have been reached. Back flushing volumes may range from 5 percent to 15 percent of the permeate flow depending upon the frequency of flushing or cleaning and the degree of fouling. The back flushing volumes shall be considered in the treatment system sizing and the capacity of the raw water source. For systems using pressurized air, the compressors shall utilize food grade oil and filters shall be provided to prevent oil from reaching the membranes. Chemically enhanced backwash systems shall be protected from cross connections and shall be followed by a regular backwash. Backwash wastes shall be disposed of in accordance with subch. XII.

(9)Membrane cleaning. A means shall be provided to allow for periodically cleaning the membrane. Cleaning shall include a soak type cleaning and may also include more frequent maintenance cleans. The cleaning process shall protect the raw and finished water from contamination. Cleaning chemicals, frequency and

procedure should follow membrane manufacturer's guidelines. Some cleaning solutions require heated water. Cleaning chemicals shall be NSF/ANSI Standard 60 certified. Membrane cleaning shall be initiated by the operator. Waste streams from chemical cleaning shall be discharged to the sanitary sewer. Adequate space shall be provided for different or additional chemicals which may be required to adequately clean the membranes in the future.

(10)Membrane integrity testing. A means shall be provided to conduct direct and indirect integrity testing to routinely evaluate membrane and housing integrity and overall filtration performance. Direct integrity testing may include pressure and vacuum decay tests for microfiltration and ultrafiltration and marker-based tests for nanofiltration and reverse osmosis. The direct testing method shall allow for conducting tests at least once per day and may be required 3 times per day. Indirect monitoring options may include particle counters or turbidity monitors or both and shall allow for testing continuously. The testing methodology shall be approved by the department during startup procedures.

(11)Monitoring. Equipment shall be provided to monitor water quality, flow rates, and water pressure.

(a) Water quality. Sampling taps shall be provided to allow monitoring of water quality from the source water, from the water after any pretreatment, from the filtrate of each membrane unit, from the combined filtrate of all membranes, from the backwash, and prior to the entry to any clearwell.

(b) Flow monitoring. Water meters shall be provided to allow flow measurement from the source water, from the filtrate of each unit, from the combined filtrate of all units, from the backwash source, from any recirculation line, and from any waste line.

(c) Pressure monitoring. Pressure gauges shall be provided prior to the membrane units, after each membrane unit, and on the combined effluent of all membrane units.

(d) Additional monitoring. Additional monitoring points shall be provided as necessary to satisfy integrity testing requirements and operational reporting requirements of sub. (10) and s. NR 810.07.

(12)Cross connection control. Cross connection control considerations shall be incorporated into the system design, particularly with regard to chemical feeds and waste piping used for membrane cleaning, waste stream and concentrate. Protection may include block and bleed valves on the chemical cleaning lines and air gaps on the drain lines.

(13)Redundancy of critical components. Redundancy of critical control components including but not limited to pumps, valves, air supply, chemical feed equipment and computers shall be provided.

(14)Post treatment. Post treatment of water treated using reverse osmosis or nanofiltration shall be provided. Post treatment may consist of degasification for carbon dioxide, if excessive, and hydrogen sulfide removal, if present, pH and hardness adjustment for corrosion control, and disinfection as a secondary pathogen control and for distribution system protection.

(15)Bypass water. The design shall provide for a portion of the raw water to bypass the unit to maintain stable water within the distribution system and to improve process economics as long as the raw water does not contain unacceptable contaminants. Alternative filtration shall be provided for bypassed surface water or groundwater under the direct influence of surface water.

(16)Reject water. Reject volumes shall be evaluated in terms of the source availability and from the waste treatment availabilities. The amount of reject water from a unit may be reduced to a limited extent by increasing the feed pressure to the unit. Waste disposal from reverse osmosis or nanofiltration reject water shall discharge to a municipal sewer system, to waste treatment facilities, or to an evaporation pond.

(17)Treatment efficiency. The design treatment efficiency shall be determined by pilot testing.

(18)Power consumption. The power consumption of a particular membrane under consideration shall be evaluated during the pilot study or from other relevant data.

(19)Control systems.

(a) Back-up systems. Automated monitoring and control systems shall be provided with back-up power and operational control systems consisting of the following:

1. Dual running programmable logic controllers (PLCs) with synchronized programs and memory, or spare PLCs loaded with the most current program.

2. Spare input/output (I/O) cards of each type.

3. A minimum of 2 human machine interfaces (HMI).

4. Backup power supply including uninterruptible power supply (UPS).

(b) Remote or unmanned operational control. Systems designed for remote or unmanned control shall be provided alarms, communication systems, and automatic shutdown processes. The department shall be contacted to determine the extent of operational control required. At a minimum the following alarms shall be provided:

1. High raw or filtrate turbidity.

2. Pump failure.

3. High pressure decay test.

4. High transmembrane pressure.

5. PLC failure.

6. Membrane unit shutdown.

7. Clearwell level high or low.

8. Equipment failure.

9. High or low chlorine residual.

10. Low chemical level.

11. Power failure.

12. Building intrusion

13. Building low temperature. (WDNR, 2011b)

8.2.2 NR 811.09- Specific requirements for waterworks, plans, specifications and engineering reports.

(1)Plans.

(a) General. The detailed construction plans shall contain appropriate plan and profile views, elevations, sections and supplemental views which together with the specifications provide all necessary information for construction of the improvements. The elevations shall be based on sea level datum or local datum when a conversion to sea level datum is provided. Manufacturer's drawings are not acceptable as construction plans and will not be approved. Other state and local codes, including those of the department of safety and professional services, the public service commission, and the department of health services, shall be consulted for other requirements where applicable.

(b) Wells.

1. A general plan shall be submitted which shows the location of the proposed well and its relation to proposed or existing water supply facilities. It shall show all features of sanitary significance which could have an effect on water quality. A separate well site plan shall be submitted which shows the property lines, contours or an appropriate number of spot elevations so that drainage can be determined, surficial features, structures, and any other relevant data. The well site plan shall also show the locations of all the observation wells, monitoring wells, test wells, treatment wells, or other wells to be constructed in relation to the well site and all permanent supply wells to be constructed on the site. A detailed well cross-section shall be submitted which shows the size and depths of drill holes and casings, depth of grout, and geological formations to be penetrated.

2. A copy of a well site investigation report shall be submitted as required in sub. (4) prior to or along with the plans submitted to the department for all final wells or applicable test wells as described in s. NR 811.12 (1) (g) 2. Based upon a review of the submitted well site investigation report, the department may perform an on-site inspection of the well site. Wellhead protection criteria conforming to s. NR 811.12 (6) shall be considered when siting wells. In addition, drawdown effects from the pumping or test pumping of test wells and final wells shall be considered during well siting and design. Information on possible drawdown effects on nearby private wells, public wells, or surface water bodies from pumping test wells or final wells and the means to be provided for measuring the effects shall be included with all submittals to the department where significant drawdown may occur or when required by the department.

3. Plans and specifications shall be submitted prior to the construction of any test well to be pumped at a rate of 70 gallons per minute or more for a duration of 72 hours or more. When it is known with reasonable certainty that any proposed test well will be converted to a final well the plans and specifications for the final well shall be submitted for department approval prior to construction of the test well.

(c) Surface water intakes.

1. `Location plan.' Plans shall show the location of the intake pipeline and crib relative to the low lift pumping facility. The pipeline shall be referenced by bearing and distance, and the crib location shall be defined by latitude and longitude.

2. `Detailed plans.' A profile of the proposed pipeline and crib shall be provided in addition to construction plans.

(d) Treatment plants.

1. `Location plan.' The location plan shall show the location of the treatment plant in relation to the remainder of the water system and the water source or intake.

2. `Layout.' The general layout plans shall include a contour map of the site, the site size, the size and location of plant structures, a schematic flow diagram indicating the various plant units, the piping layout, and a hydraulic profile at gravity plants.

3. `Detailed plans.' The detailed construction plans shall include the location, dimensions, elevations and details of all existing and proposed plant units or equipment.

(e) Chemical feed equipment. The plan shall include a layout of the waterworks structure and piping. All of the following locations and details of the proposed equipment shall be included:

1. Descriptions and specifications of feed equipment, including anti-siphon devices and feed ranges.

2. Location of feeders, piping layout and points of application.

3. Storage and handling facilities.

4. Specifications for chemicals to be used.

5. Operating and control procedures.

6. Description of testing equipment and procedures.

7. Well or booster pump discharge rates and pressures.

8. Emergency eyewash and shower units.

(f) Pumping facilities. The plan shall show a general layout of the pumping equipment, pump bases, suction and discharge lines and related appurtenances.

(g) Buildings. The plans shall show the locations of all buildings and other site improvements in relation to the site property boundaries. The following details shall be included, where applicable:

1. Building dimensions, profiles, elevations, architectural details, plumbing details, HVAC details, security details, and other building appurtenances.

2. Property site contours.

3. The diameter and locations of all water mains, water service laterals, and appurtenances such as valves and hydrants.

4. The diameters and locations of all floor drains, building drain, building sewer, and POWTS components.

5. The location, elevations, construction details, and appurtenances of any on-site storm water retention or detention ponds.

6. Construction details for any non-water system related improvements to be located or constructed on the property.

(h) Water mains.

1. `Location plan.' The plan shall show the proposed water main extensions in relation to existing facilities. A map, such as required by s. NR 810.26 (2), of the existing system or a portion thereof with the proposed extensions shown will satisfy this requirement.

2. `Detailed plans.' The plans shall show the location of the proposed water main within the street right-of-way or easement; the location of other utilities, such as sanitary or storm sewers; elevations at intersections and hydrants or a profile of

the proposed water main; location of proposed appurtenances; details or special features and connection to the existing system. Profiles showing the ground surface, the proposed water main, the proposed sanitary or storm sewer and rock depths are necessary when approval of a common trench is requested in high bedrock areas. The size of proposed and existing water mains shall also be shown.

3. `Worksheet submittal.' Complete information as requested on any required worksheet shall be provided. The forms shall be completed for all water main projects including revisions to existing projects, upgrading of existing mains and resubmittals of projects previously approved by the department.

(i) Storage facilities.

1. `Location plan.' The plan shall show the location of the proposed facility in relation to existing facilities.

2. `Detailed plans.' Plans shall show contour lines at the site and complete construction details. Overflow elevations for existing and proposed facilities shall be noted.

(2) Specifications. Complete, detailed material and construction specifications shall be supplied for all phases of the proposed project. Specifications shall contain a program for keeping existing waterworks facilities in operation during construction of additional facilities so as to minimize interruptions of service. Specifications shall be included for controlling erosion on the construction site as a result of construction activity as specified in subch. V of ch. NR 151.

Note: Department approved Construction Site Erosion and Sediment Control Technical Standards can be found on the department's internet web site.

(3) Engineering report. An engineering report shall be submitted with all reviewable projects with the exception of water main extensions. The engineering report, required by s. NR 108.04 (2) (a), shall contain the controlling assumptions made and the factors used in determining the functional design of the proposed waterworks improvements as a whole and of each of the component parts or units. Where applicable, the report shall make reference to available regional, metropolitan, county or local water supply or water quality management plans and shall clearly indicate whether the proposed project is in conformance with the plans.

Note: It is recommended that the report also include an energy efficiency analysis.

(4) Engineering report requirements. The engineering report required under sub. (3) shall, in all cases, indicate the basis of design and shall include the following specific data, if applicable:

(a) Description. A brief description of the project and the need for improvements.

(b) Location. A description of the geographic location of the project, including reference to maps or exhibits and the location of existing facilities.

(c) Topography. A brief description of the topography of the general area and its relation to the area involved in the project.

(d) Population. Past census data and estimated future projection to the design year for the area involved in the project.

(e) Design period. The design period being used for sizing major system components, based on the population projection.

(f) Investigations. The results of any investigations, such as soil borings, test wells, pilot tests, water quality data, and fire flow tests.

(g) Flooding. Any areas of the project which are located within the floodway or floodplain as defined in ch. NR 116 shall conform to the requirements of that chapter.

(h) Wetlands. Any areas of the project which are to be located within a wetland, pass through a wetland or may impact a wetland shall be identified.

Note: Copies of the Wisconsin wetland inventory maps are available for inspection at the office of the department of natural resources and may be purchased through the department's internet web site. The department of natural resources is in the process of placing the wetland inventory maps on the department's internet web site.

(i) Recommendations. After discussion of alternatives, the recommendations for improvements shall be listed and a statement of the reasons for selection of the recommended alternative shall be provided. A discussion of estimated capital costs and estimated annual operation and maintenance costs shall be included.

(j) Specific information. The report shall, in addition, include specific information relevant to the type of project. The specific information required for each type of project is as follows:

1. `Groundwater sources — Well site investigation reports.' A copy of a well site investigation report shall be submitted for department review and approval prior to the department approving the construction of a permanent well as required in sub. (1) (b) 2., or where there is reasonable certainty that the location of any test well will be the location of the permanent well. If no test well is to be constructed, site approval may be obtained simultaneously with department approval of plans for the final well. The investigation shall include a field survey of the well site and the surrounding area. The investigation shall consist, at a minimum, of a map and report indicating:

a. The well location by quarter quarter section, township, range, county, latitude, and longitude.

b. The boundaries of the site and the location of the well on the site.

c. The topography of the site.

d. The regional flood elevation.

e. The past and present use of the proposed site.

f. The potential contamination sources within 1/2 mile of the well location summarized in a table or list including distance and direction from the well site and also shown on a map surrounding the well site. The table or list shall include an assessment of the potential for the contamination sources to impact a well constructed on the site and shall include information obtained by checking the department's database of contaminated properties, established in accordance with ss. 292.12 (3), 292.31 (1), and 292.57, Stats., and the department of safety and professional services Storage Tank Database.

Note: The department's database of contaminated properties, established in accordance with ss. 292.12 (3), 292.31 (1), and 292.57, Stats., can be found on the department's Bureau for Remediation and Redevelopment internet web site. The Bureau for Remediation and Redevelopment Tracking System (BRRTS) is an on-line database that provides information on areas of known contaminated soil or groundwater and tracks the status of the cleanup actions. RR Sites Map is the program's geographic information system that provides a map-based system of contaminated properties in Wisconsin. Information that appears on the RR program's database and GIS applications can also be obtained by contacting the regional drinking water staff person responsible for the water system. The department can be contacted to obtain a copy of A Guide For Conducting Potential Contaminant Source Inventories For Wellhead Protection. The department of safety and professional services Storage Tank Database Information can be found on the department of safety and professional services internet web site.

g. The specific geologic formation or formations from which water will be pumped or withdrawn.

h. The test or final well construction details, or both, including the descending order and depths of the specific geologic formations to be penetrated.

i. The proposed test or final well pumping capacity in gallons per minute, or both, as applicable.

j. The direction of groundwater flow in the specific geologic formation or formations from which water will be pumped or withdrawn.

k. The zone of influence of the proposed well consisting of the distance to one foot of aquifer drawdown at the anticipated final pumping rate when pumpage of the well is assumed to be continuous without recharge for 30 days. The zone of influence shall be calculated using the Theis Method with or without computer

modeling unless another method is approved by the department. The aquifer transmissivity (T) and storage (S) coefficients used shall be provided.

L. The recharge area for the well. The recharge area shall be calculated using the Uniform Flow Equation or a computer generated groundwater model unless another method is approved by the department.

Note: A copy of A Template For Preparing Wellhead Protection Plans For Municipal Wells, in which use of the Uniform Flow Equation is discussed, may be obtained from the department.

m. The results from any previous test wells including details of test well location and construction, water quality, pumping conditions including drawdown effects, if applicable, on other nearby wells or surface water bodies, geologic borings, and seismic, resistivity or other groundwater investigations.

n. The anticipated annual volume of water to be withdrawn and the compatibility with the existing water supply facilities.

o. The location and data from any piezometers.

p. The location of any nearby wetlands.

q. The distance and direction from the proposed well to the nearest existing well serving another water utility.

r. The distance and direction from the proposed well to the nearest neighboring private wells within 1,200 feet of the well site.

s. The location and distance to surface water and springs.

t. The locations of alternate well sites for the proposed well and other information such as test pumping or modeling as requested by the department in order to conduct a review under ch. NR 820 to justify the proposed well location if the well will be pumped at a rate equal to or greater than 70 gallons per minute and the department determines that the proposed well will be located within a groundwater protection area as defined in s. 281.34 (1) (a), Stats., or that operation of the well could result in significant adverse impacts to springs as defined in s. 281.34 (1) (f), Stats.

u. A summary evaluation of the site including advantages and disadvantages and the need for any possible water treatment.

2. Surface water sources. To assess the water available at the source, the engineering report shall include a survey and study of the source, including obtaining samples from a number of locations and depths in order to select the best intake site. Sampling shall be sufficient to adequately determine the water quality characteristics. The report shall summarize information on hydrological data, such as safe yield, maximum and minimum water levels or flows, the quality of raw water with special emphasis on results of testing programs, fluctuation in

water quality, including seasonal variations and effects, the presence of befouling organisms, and existing and future potential sources of contamination.

3. Water treatment or chemical addition processes. The engineering report shall include a summary establishing the adequacy of the proposed processes for the treatment of the specific water under consideration. The report shall include any data from pilot or full scale plant studies and describe the method of disposal of any wastes and any possible effects on the environment.

4. Pumping facilities. The engineering report shall include a description of the area to be served and the basis for design, including maximum and minimum discharge heads and flows, pump operational controls, and provisions for emergency operation.

5. Water storage facilities. The engineering report shall include a description of the high to low static pressure range which the proposed facility will provide for existing and future service areas and the volume of domestic and fire storage required within the design period. The report shall explain how the proposed and existing facilities will meet these requirements. The report shall also relate the compatibility of the proposed facilities with existing facilities and any changes that will have to be made to the existing facilities.

History: CR 09-073: cr. Register November 2010 No. 659, eff. 12-1-10; correction in (1) (a), (4) (j) 1. f. made under s. 13.92 (4) (b) 6., Stats., Register December 2011 No. 672.

Vita

Erika Mancha graduated from Smith College in Northampton, Massachusetts in 2005 and received a Bachelor of Science degree in engineering. In summer 2004, she interned at Brock and Bustillos, Inc., a civil engineering firm located in El Paso, Texas. After graduation, she began working at Kimley-Horn and Associates, Inc. in the land development group. She later went on to work with HDR Engineering, Inc. in the power distribution department. While contemplating graduate school, she began working as substitute math teacher and learned she enjoyed teaching and has continued to the present time. In summer 2011, she entered graduate school and started working in the Center for Inland Desalination Systems group as research assistant. In fall of 2012 she graduated with a master of science in civil engineering and received the honor to serve as the Banner Bearer for the Graduate School in the Fall Commencement.

Permanent address: 6416 Mohawk Ave.
El Paso, TX, 79925

This thesis/dissertation was typed by Erika Mancha.