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Long-term pumping-induced groundwater quality changes at a brackish-water desalination facility, Sanibel Island, Florida

Natalie J. Harvey[a], Danvers E. Johnston[b], Thomas M. Missimer[a,*]

[a]*Emergent Technologies Institute, U.A. Whitaker College of Engineering, Florida Gulf Coast University, 16301 Innovation Lane, Fort Myers, FL 33913, USA, Tel. 239-590-4538; emails: tmissimer@fgcu.edu (T.M. Missimer), nharvey@fgcu.edu (N.J. Harvey)*
[b]*Department of Civil and Environmental Engineering, U.A. Whitaker College of Engineering, Florida Gulf Coast University, 10501 FGCU Boulevard South, Fort Myers, FL 33965-6565, USA, email: djohnston@fgcu.edu (D.E. Johnston)*

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ABSTRACT

The Island Water Association owns and operates a brackish-water reverse osmosis (BWRO) desalination facility with a treated water capacity of 26,477 m^3/d. The feedwater for the plant is pumped from two different aquifers via 16 production wells (24,888 m^3/d). Both aquifers are semi-confined and they are recharged bottom upwards from the higher leakance lower confining unit, with limited recharge from the low leakage upper confining unit. The aquifer system is density stratified with increasing salinity with depth; the higher salinity water at depth, along with bottom upwards recharge, has led to a slow upward trend in salinity. In operation for nearly 38 y, the facility has increased the quantity of water pumped from the aquifer system. A solute transport model was conducted before the construction of the wellfield in 1982. The model generated a series of curves showing the projected increase in dissolved chloride concentration based on various pumping rates. Projections showed 80 y of increases with pumping and an eventual flattening of the curves. Over the past 20 y, dissolved chloride data collected from the 16 production wells show increase is a range from 0% to 60%. The overall feedwater, a blend of all wells, has shown increases in total dissolved solids from about 2,500 to 2,800 mg/L. These data values are much lower than the original model predicted, with both a lower starting concentration and a lower rate of increase. Based on the collected data, regression analysis, and a 20 y forward projection, the BWRO plant will be able to continue operation without a significant design change in the primary membrane process.

Keywords: Brackish-water reverse osmosis desalination; Groundwater source; Salinity change; Sanibel Island, Florida

1. Introduction

Groundwater is commonly used as a source to supply brackish-water reverse osmosis (BWRO) desalination facilities in many regions of the United States [1]. The most significant density of BWRO desalination plants in the United States is located in Florida where there are more than 140 facilities with a total treatment capacity of about 1.95 million m^3/d (515 MGD) with only 3 being seawater reverse osmosis (SWRO) systems and the others BWRO [2]. Perhaps the highest density of these plants occurs in South Florida, where 38 facilities were operating in 2019 [3]. The total operating capacity of the desalination plants in South Florida, including 38 BWRO and 2 SWRO facilities, is 1.1 million m^3/d (287 MGD) (Fig. 1). All of the desalination facilities use brackish groundwater pumped from mostly the upper part of the Floridan Aquifer System. Because this unit is classified as a leaky aquifer system, pumping of groundwater tends to cause long-term changes in the feedwater salinity, in turn, creating operational challenges [4].

* Corresponding author.

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One of the oldest BWRO facilities in Florida is operated by The Island Water Association, Inc. (IWA), which is a member-owned corporation that supplies water to a franchise area covering the City of Sanibel (Sanibel Island) and Captiva Island, Florida (Fig. 2). The organization was formed in 1966 to provide potable water to the islands with the construction of a distribution system and a 2,896 m subaqueous pipeline connecting Sanibel Island with Pine Island to the east [5]. Initially, the potable water was purchased from the Greater Pine Island Water Association (GPIWA). However, in the early 1970s, the potable water demand of the IWA, combined with deteriorating water quality from the GPIWA, forced IWA to develop an independent water supply system. In October 1972, the IWA contracted with Ionics to build an electrodialysis desalination (ED) plant with a capacity of 4,543 m^3/d which was placed into service in November 1973. The raw water supply was provided by wells tapping Zone III of the Hawthorn Aquifer System [4,6]. The ED plant was expanded to a capacity of 6,814 m^3/d in December 1975.

Because of increased demand and deterioration of feedwater quality, the IWA decided to develop a BWRO desalination facility using the Lower Hawthorn/Upper Suwannee Aquifer as the feed water source [7]. The initial BWRO plant contained a single train with a capacity of 2,271 m^3/d and was placed into service in May 1980. The water supply then consisted of a combination of the ED and BWRO plant outputs. Two additional trains were added to the BWRO plant in April 1981 and January 1982 to increase the overall capacity to 6,813 m^3/d. A series of additional expansions occurred to bring the BWRO plant capacity to 22,331 m^3/d in 1991 [4]. The ED plant was taken out of service in 1992 based on the higher total dissolved solids (TDS) of the feed water. The current IWA reverse osmosis (RO) plant capacity, including some blend of the raw water with the permeate, is 26,477 m^3/d.

The plant operated by the IWA is an excellent example of a continuously operating BWRO desalination facility with increasing salinity of the raw water caused by the pumping of a leaky or semi-confined aquifer system. Predictive groundwater modeling of the aquifer system was conducted in 1981 to estimate future changes in feedwater salinity based on several possible future growth scenarios [8].

A key issue in the successful operation of a BWRO facility is the coordination between the primary process design and the long-term changes in feedwater quality (Missimer [4]). The IWA facility currently uses a thin-film composite polyamide RO membrane manufactured by Dow Filmtec. The facility operates at a pressure of about 11 bar (160 psi) and a conversion rate of about 80%, which allows a blend of permeate with 6% raw water. The RO membranes are capable of treating brackish-water with a TDS up to about 3,500 mg/L (about 1,940 mg/L of dissolved chloride). The process diagram for the facility is shown in Fig. 2.

The objective of this research was to evaluate the measured changes in feedwater quality produced from the feed water supply wells for assessment of the possible need for future process design changes to the membrane treatment.

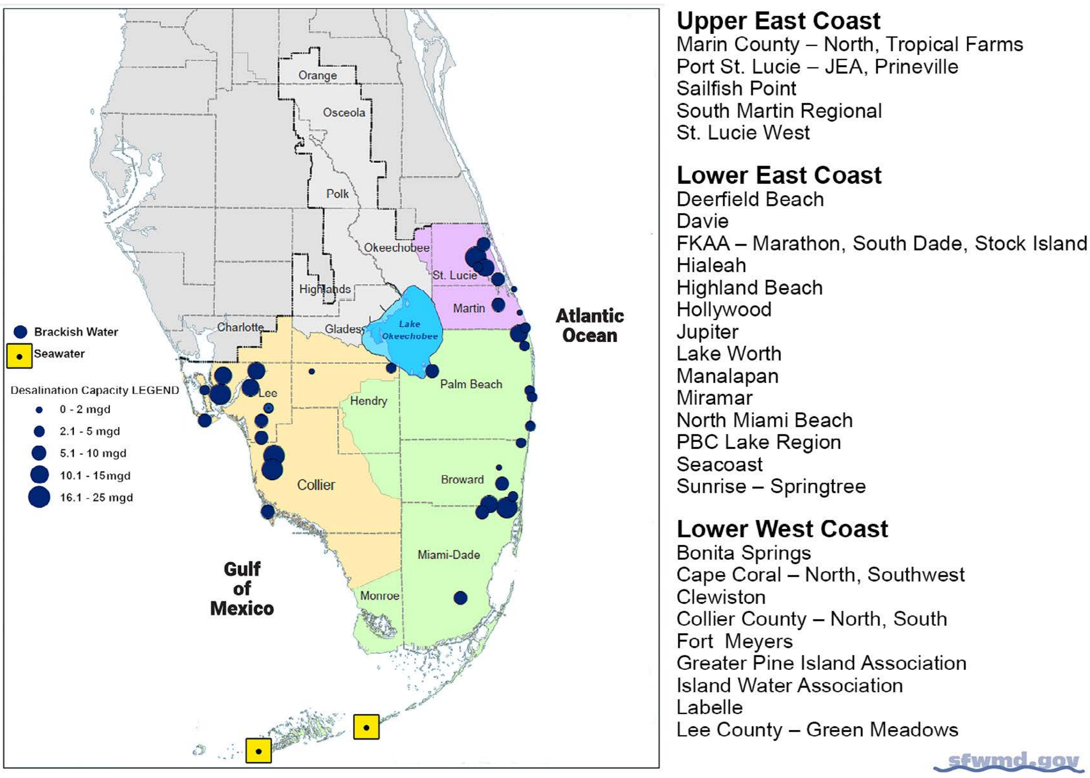

Fig. 1. 2019 facilities using brackish groundwater and seawater in South Florida.
Number of operating facilities 40. Total capacity 287 mgd.

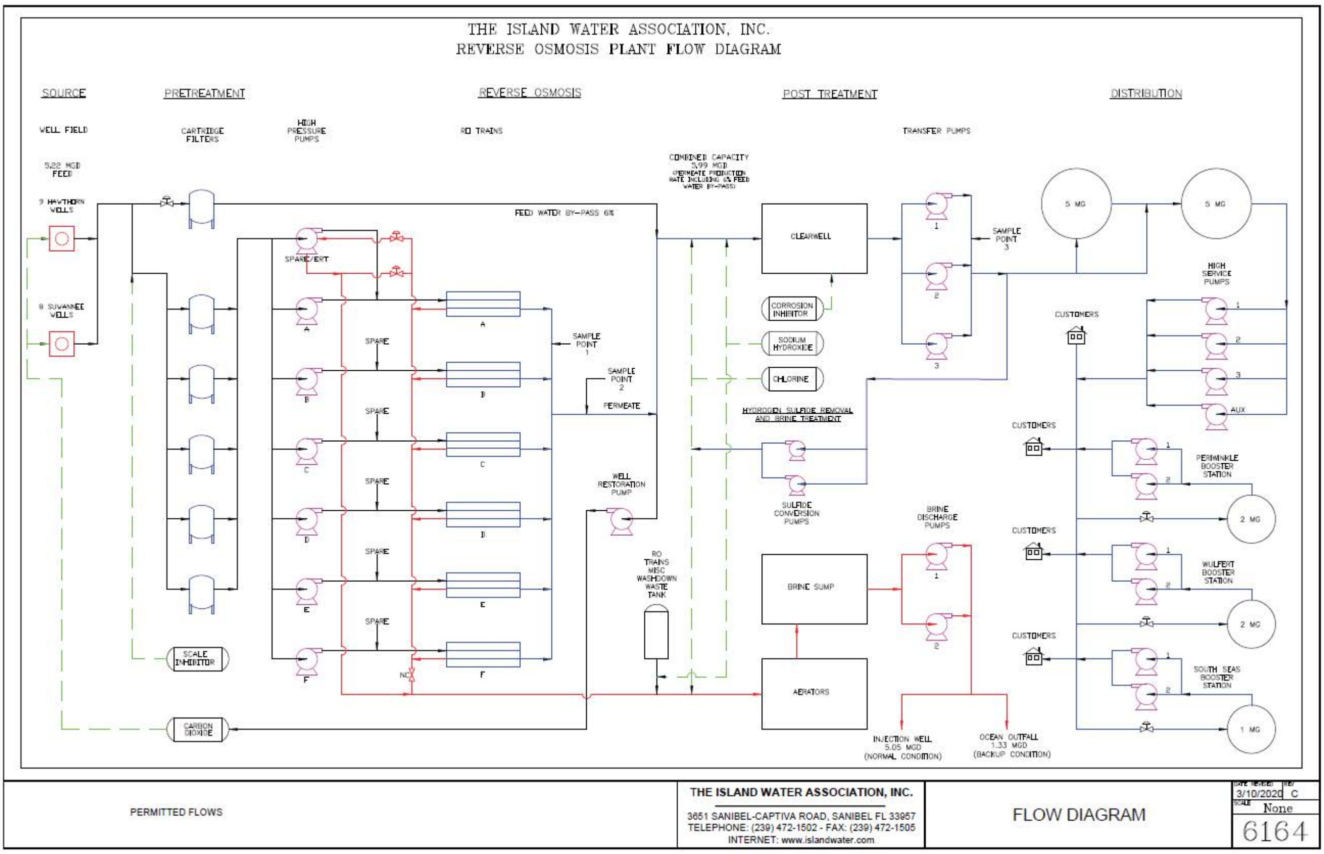

Fig. 2. Process diagram of the Island Water Association, Inc. BWRO plant (modified from the Island Water Association, Inc.).

In addition, the water quality data were used to assess the performance of the initial groundwater modeling. Two previous assessments of the changes in water quality in the wellfield were made, but they did not include a comparison of the pumping-induced water quality changes to the past groundwater modeling [4,9]. The research described in this manuscript provides an improved approach to groundwater development, modeling assessment, and enables a more robust process design assessment. Research of this type will enable more productive BWRO facilities to be constructed with less risk of failure and is applicable worldwide.

2. Hydrogeology of the aquifer system used for feed water

Despite being a relatively small capacity BWRO system, a considerable amount of hydrogeologic information has been collected on Sanibel Island. These data enabled an understanding of the aquifer system and allowed it to be successfully developed [4,6,8,10–23]. A diagram showing the subsurface hydrogeology beneath the island in the original production well S-1 is shown in Fig. 3. The aquifers pumped to feed the facility are Hawthorn-Zone III and the combined Hawthorn-Zone IV and Suwannee-Zone I aquifers. A hydrogeologic cross-section across the wellfield shows a significant variation in the depth to the top of the production zones, which is caused by low-grade tectonic activity that occurred during the Late Miocene time (Fig. 4) [24,25].

Currently, a total of 16 production wells provide the feedwater and blend water for the RO plant. Table 1 shows the construction details of the production wells. All well locations are shown in Fig. 5.

Water quality in the aquifer system varies vertically within the different zones. Permeable hydraulic units above Hawthorn Aquifer System-Zone II contain seawater. Hawthorn Aquifer System-Zone II contains water with a dissolved chloride concentration of greater than 12,000 mg/L. The initial dissolved chloride concentration in Hawthorn Aquifer System-Zones III and IV and Suwannee Aquifer System-Zone I was less than 2,000 mg/L (Fig. 6). Salinity within the aquifer system below Suwannee-Zone I increases until seawater occurs at about 800 m below surface. The general dissolved chloride concentration decreases from east to west in the wellfield. About 500 m to the east of the production H-10 site, a test well showed near seawater concentrations of dissolved chloride associated with a subsurface fault in the production zones [15].

A well inventory of deep, flowing wells on Sanibel Island was conducted by the U.S. Geological Survey [11] (Fig. 7). The dissolved chloride and TDS data do not show any consistent pattern, likely because of variation in well construction and possible corrosion of steel casings over time. Most of these wells were drilled using the cable tool method, which means that no cement grout occurs between the casing and the formation. Most of the wells drilled for the IWA ED plant were also originally drilled using this

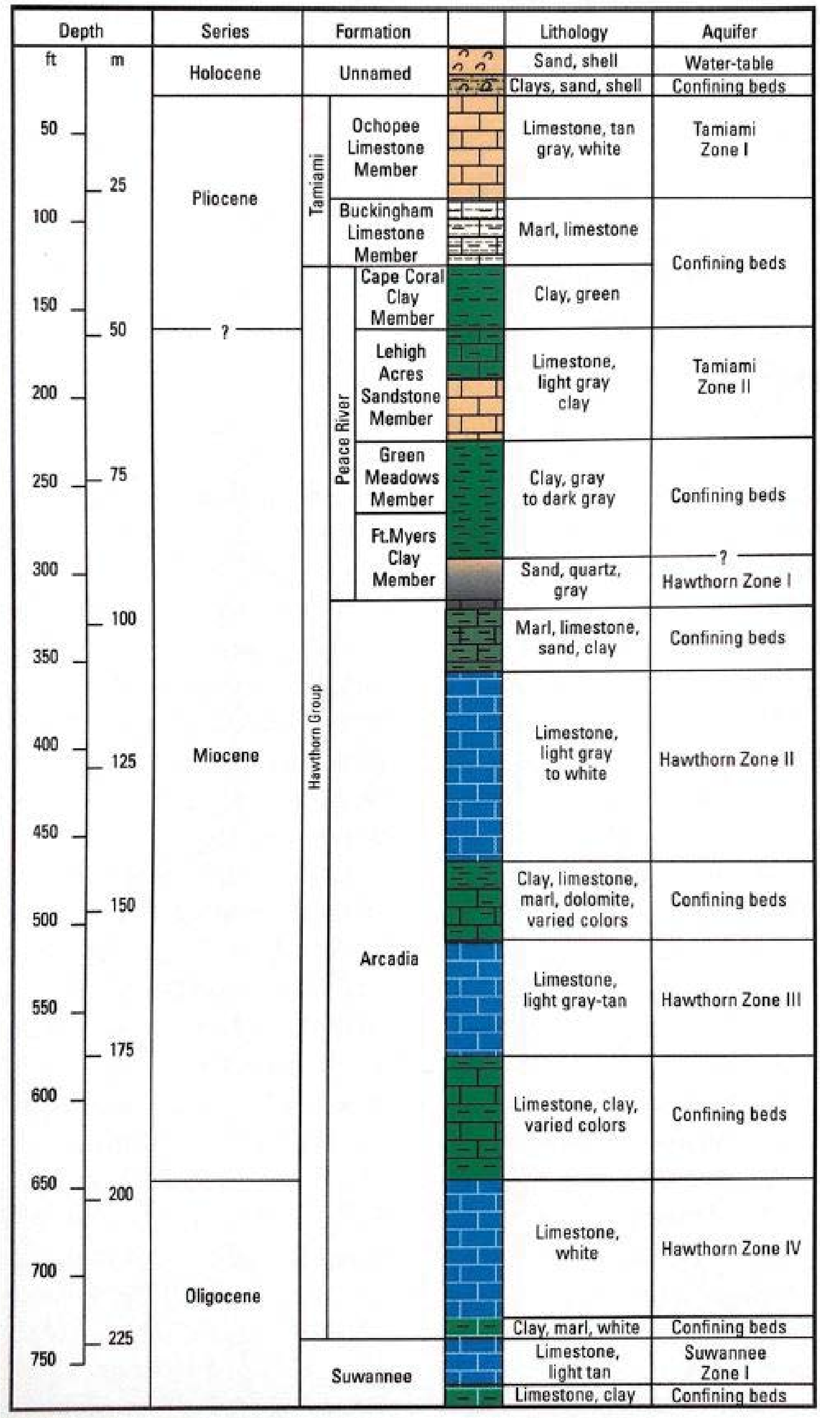

Fig. 3. The aquifer hydrogeology in production well S-1 [4].

method but later were lined with polyvinyl chloride (PVC) casing to mitigate the casing corrosion issue.

Chemical analyses of the water from these wells shows the relationship between the dissolved chloride and TDS concentrations (Fig. 8). The TDS can be calculated from the dissolved chloride concentration by dividing by 0.38.

The aquifer hydraulic properties were measured by conducting several aquifer performance (pumping) tests. The transmissivity of Hawthorn-Zone III ranged from 74 to 195 m^2/d, and Hawthorn-Zone IV (combined with Suwannee-Zone I) ranged from 310 to 994 m^2/d. The storativity of Zone III was about 2×10^{-4}, and Zone IV was 4×10^{-4}. The leakance of Zone III ranged from 6.7×10^{-6} to 5.3×10^{-5} d^{-1}. The leakance measured in Zone IV ranges from 1.3×10^{-4} to 9.4×10^{-4} d^{-1}. The higher leakance of Zone IV is believed to be the result of a lesser degree of confinement at the base of the aquifer

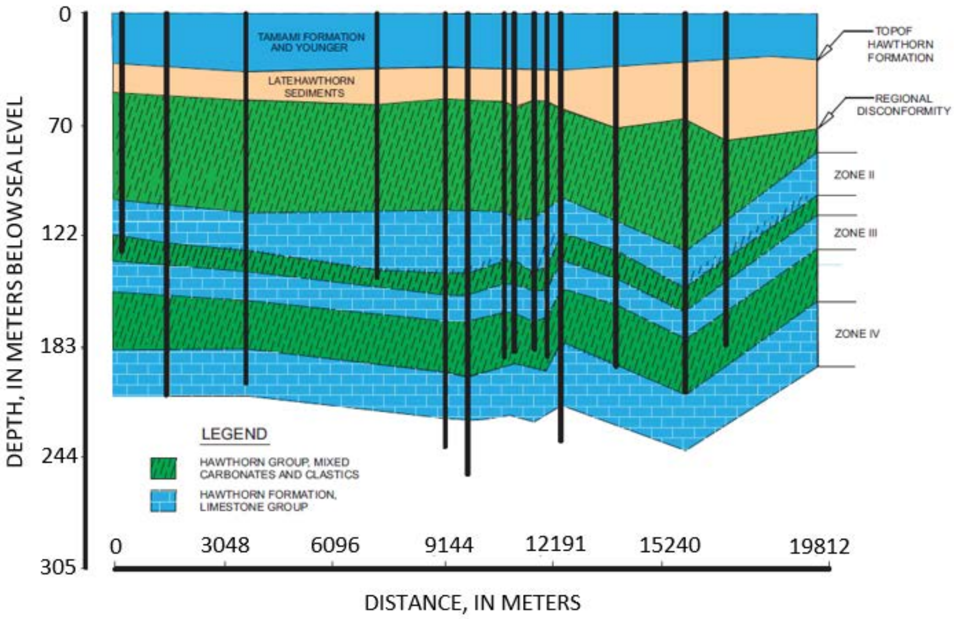

Fig. 4. Geologic section from east to west through the wellfield showing the production aquifer locations. Hawthorn Aquifer System-Zones III and IV are used for the wellfield [4].

Table 1
Construction details of production wells

Well no.	Year drilled	Total depth (m)	Casing depth (m)	Casing diameter (cm)	Casing material
S-1	1978	218.2	201.2	30.5	PVC
S-3	1981	214.9	201.2	25.4	Fiberglass (FRP)
S-4	1984	219.5	203.6	25.4	Fiberglass (FRP)
S-5	1985	234.7	202.4	25.4	Fiberglass (FRP)
S-6	1988	234.7	197.8	25.4	PVC
S-7	1988	234.7	194.8	25.4	PVC
S-8	1991	228.6	188.4	25.4	PVC
S-9	2015	201.2	214.9	30.5	PVC
H-5	1975	206	154.8	15.2	PVC
H-6	1975	213.4	197.2	15.2	PVC
H-7	1975	214	196.6	15.2	PVC
H-8	1975	206.7	154.8	15.2	PVC
H-9	1975	205.7	153.6	15.2	PVC
H-10	1975	190.5	152.4	25.4	PVC
H-12	1977	198.1	185.9	25.4	PVC
H-14	1988	184.4	153.9	20.3	PVC

wherein Hawthorn-Zone IV and Suwannee-Zone I act nearly as a single aquifer.

In 1981, a hydraulic and solute transport model was conducted to project future changes in water quality in Hawthorn-Zone IV based on projected pumping rates [8]. This modeling used a code developed by Missimer & Associates, Inc., which was before the modern development of more complex solute transport programs that consider variable density (e.g., SEAWAT). The model inputs included aquifer hydraulic coefficients, water quality, pumping rates with some assumptions on the capture of some horizontal flow of water passing through the production aquifer [8]. The results of the modeling is shown in Fig. 9. The pumping-induced salinity changes show the steepest changes after 30 to 50 y with eventual stability reached after over 100 y of pumping.

Fig. 5. Well, location map showing existing production wells.

3. Methods

3.1. Collection of pumping and water quality data from production wells and composite feedwater

Operating data from the production wells were collected from the IWA staff. These data include the monthly totalized pumping records and the measured dissolved chloride concentrations from each well by month. These records extend from 1982 to the present. The IWA also measures the TDS of the well water at the end of each month. There is an established relationship between the dissolved chloride concentration and the TDS for the Lower Hawthorn/Suwannee Zone 1 aquifers based on research done on Sanibel Island, which is shown in Fig. 8. The TDS can be estimated from the dissolved chloride data by dividing by 0.38. This is similar to the conversion determined at the same aquifer at the City of Cape Coral North wellfield [26]. The dissolved chloride concentration is divided by 0.5594 to yield the TDS.

The dissolved chloride concentration and TDS of the composite feedwater treated at the plant were also obtained. The operators of the facility tend to rotate the production well usage to maintain a relativity stable inflow water quality to operate the BWRO process with maximum efficiency.

3.2. Statistical analysis of the production of well water quality data

Plots of dissolved chloride concentration vs. time were constructed for each production well and compared with the monthly total cumulative pumping. A trend analysis was conducted to ascertain if the change in dissolved chloride with time is linear or another relationship. A linear regression analysis was conducted in most cases, to assess long-term change. The fit of the data to the regression line was determined (R^2 value), and its statistical correlation was determined by calculation of a p-value (a p-value < 0.05 was used to determine significance). The regression line equations were then used to project water quality changes for periods of 5, 10, 20, and 40 y.

3.3. Comparison of the early solute transport modeling projection to the wellfield performance

The aggregated inflow water quality from the wellfield changes with time as compared to the projected changes as shown in Fig. 9. Some basic observations were made concerning the usefulness of the original projections and the underlying modeling assumptions.

4. Results

4.1. Variation of feed water quality within Hawthorn Aquifer System-Zone IV/Suwannee Aquifer System-Zone I and Hawthorn Aquifer System-Zones III with linear regression analysis

The dissolved chloride values of raw water pumped from the 16 production wells between July 24, 1998, and April 2020 show a generally upward trend in nearly all of the production wells with a few exceptions (Fig. 10). All of the dissolved chloride concentrations vary in linear trends with considerable difference between the aquifers and the individual wells.

Changes in dissolved chloride concentration in the Hawthorn Aquifer System-Zone IV/Suwannee Aquifer System Zone-Zone I wells (S-series in Fig. 10) show shallow slopes with some even declining concentrations. In S-1, the slope of the linear trend is now slightly downward. When this well became active in early 1980, the dissolved chloride concentration was at about 1,250 mg/L and rose to nearly 2,100 mg/L by early 1995. During this time, the heaviest pumping occurred in production wells S-1, S-2, and S-3, all located near the BWRO plant. Well S-1 has been pumped at a lower rate in the last 20 y and is now shows a slight improvement in salinity. The initial trend in dissolved chloride concentration was similar in slope between 1982 and 1999 but has lessened to that shown in Fig. 10. Based on the

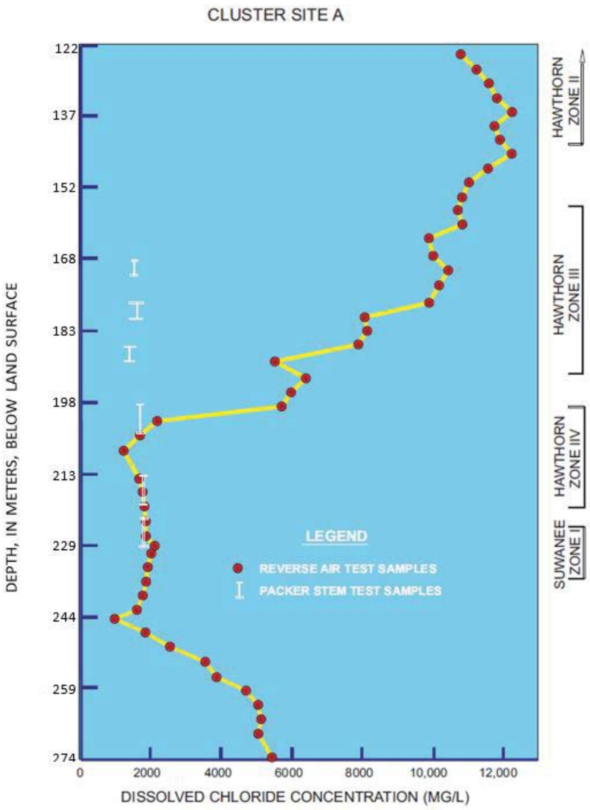

Fig. 6. Dissolved chloride concentration with depth in a well located near the BWRO plant. Note that the water samples were collected during reverse air rotary drilling, which is affected by the hydraulic conductivity of the aquifers being penetrated. The lined-lined zones on the figure indicate the location of packer tests, which produce more accurate water quality data [4].

scatter in collected values, some of which is measurement error, the R^2 value for the linear regression is poor for both wells. In addition, the p-value for well S-1 shows a statistical insignificance ($p > 0.05$). The linear upward trend in the increase of dissolved chloride concentration is similar in all of the other S-series wells, other than S-9. The R^2 values are relatively low and some show p-values > 0.05, which shows a lack of statistical significance of the regression line. Well S-8 had an initial dissolved chloride concentration of about 1,100 mg/L and has risen to about 1,600 over the 28 y operational period. Because of higher chlorides, well S-9 has not been pumped as much as the other S-series wells. With less pumping, the dissolved chloride concentration and has shown a decline in salinity over the past 6 y. During the early years of operation, the S-series wells were used solely to supply the BWRO plant, and the H-series wells supplied the ED plant.

The H-series wells were used exclusively to supply the ED plant up until 1992 when the plant was shut down. At or before this time, all of the pre-existing H-series wells were refurbished by lining the steel casings with PCV to solve the issue of corrosion of the casing and the leakage of higher salinity water into the wells. The modified H-series wells were brought online to feed the BWRO plant and to allow rotation of the wells to produce high-quality feedwater. H-series wells 5, 6, 8, 10, and 14 all have a slightly increasing linear trend in dissolved chloride concentration. In all cases, the R^2 values are low, but in three of the wells, the trend is statistically significant, with the p-values being <0.05. There is a slight upward trend in dissolved chloride concentration in well H-7, but the well is rarely used. Well H-9 has a declining trend in dissolved chloride concentration, which is statistically significant. Well H-12 has a statistically significant increasing trend in dissolving chloride concentration.

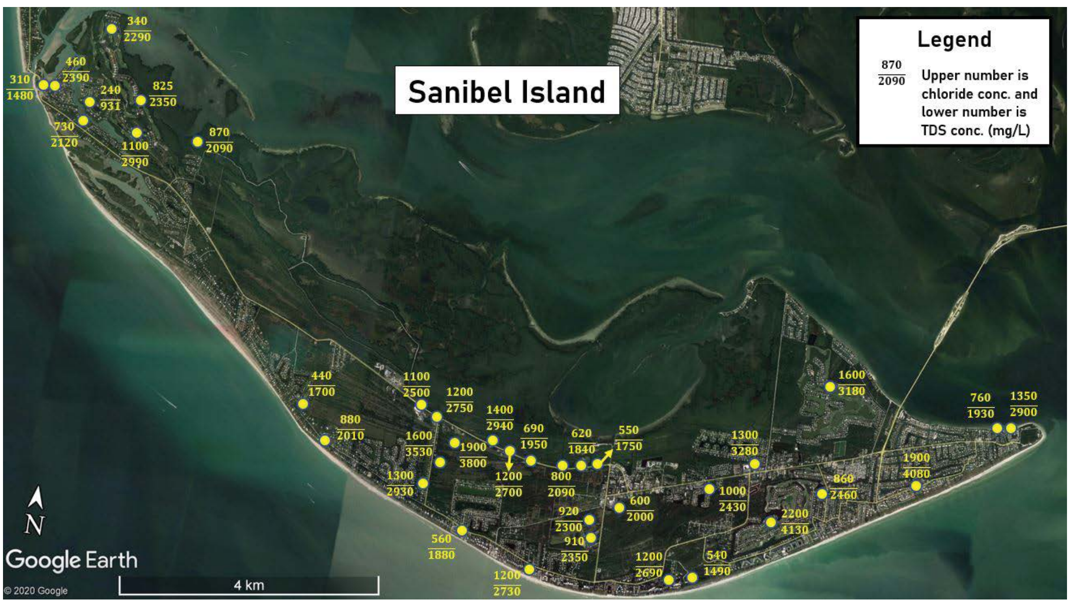

Fig. 7. Lower Hawthorn and Upper Suwannee Aquifer wells on Sanibel Island, Florida, with dissolved chloride and TDS concentrations (modified from Boggess and O'Donnell [11]).

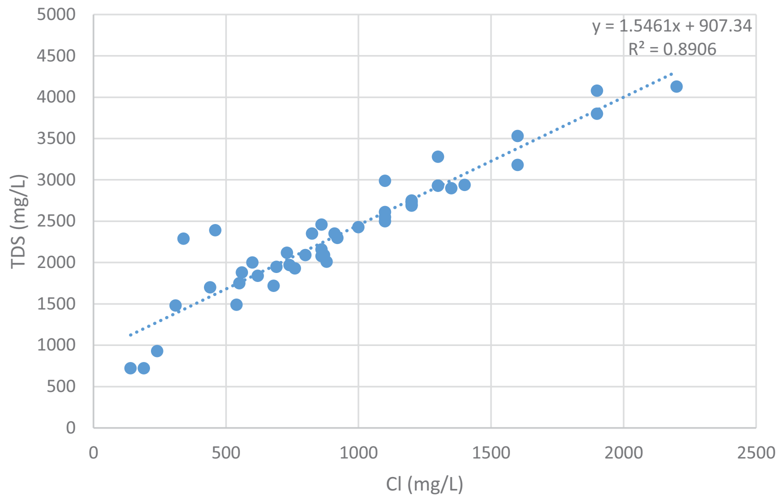

Fig. 8. The plot of the dissolved chloride vs. TDS for the wells on Sanibel and Captiva Islands, Florida (modified from Boggess and O'Donnell [11]).

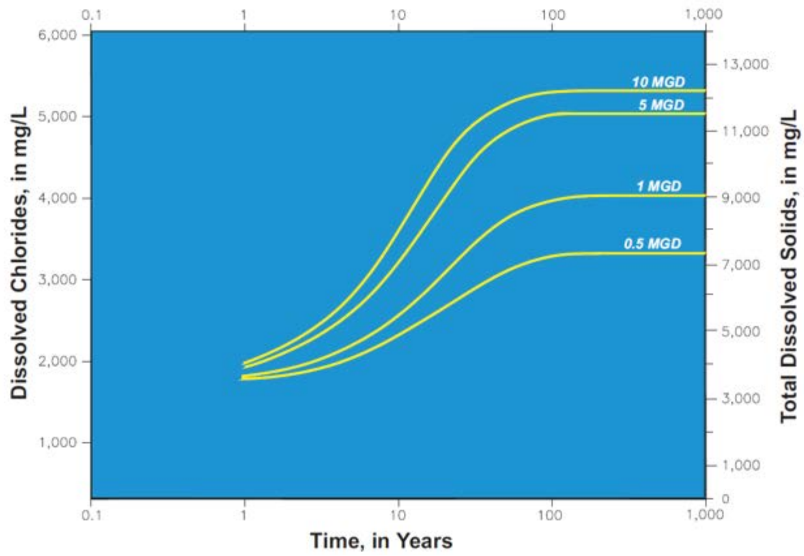

Fig. 9. Results of predictive solute transport modeling conducted by Missimer & Associates, Inc. [8]. The family of curves was developed for four different pumping rates. Because of limited computing capacity at that time, it was not possible to calculate to error envelope using a standard sensitivity analysis.

4.2. Trend in feedwater TDS over the last 20 y of operation

The feedwater to the BWRO plant has been controlled by rotating the use of various production wells during the full operational history of the facility. Since the shut-down of the ED plant in 1998, the addition of the H-series wells has enhanced the ability of the IWA to rotate more wells in the overall operational scheme. A trend of the TDS variation in the last 20 y in the feedwater to the BWRO plant is shown in Fig. 11.

The average TDS of the feedwater entering the facility was about 2,400 mg/L in 2001 and has increased to an average of near 2,900 mg/L in 2020. However, the trend has been nearly flat over the last 5 y.

Based on the increase in dissolved chloride (and TDS) concentrations over the past 20 y, projections were made for changes in 5 to 40 y. The equations developed from the regression analysis of the dissolved chloride measurements in the wells were used to make the projections. The projections within the time range of 5 to 20 y are considered to be reasonable estimates, but the 40 y projection may be problematic.

The projections made in Table 2 are based on the regression analyses, but there are operating circumstances that have influenced the values. The declines in dissolved chloride values projected in wells H-9 and H-10 (highlighted in yellow) are not considered to be reliable because the values are unlikely to go below the original values recorded from the aquifer before pumping began. Therefore, they will

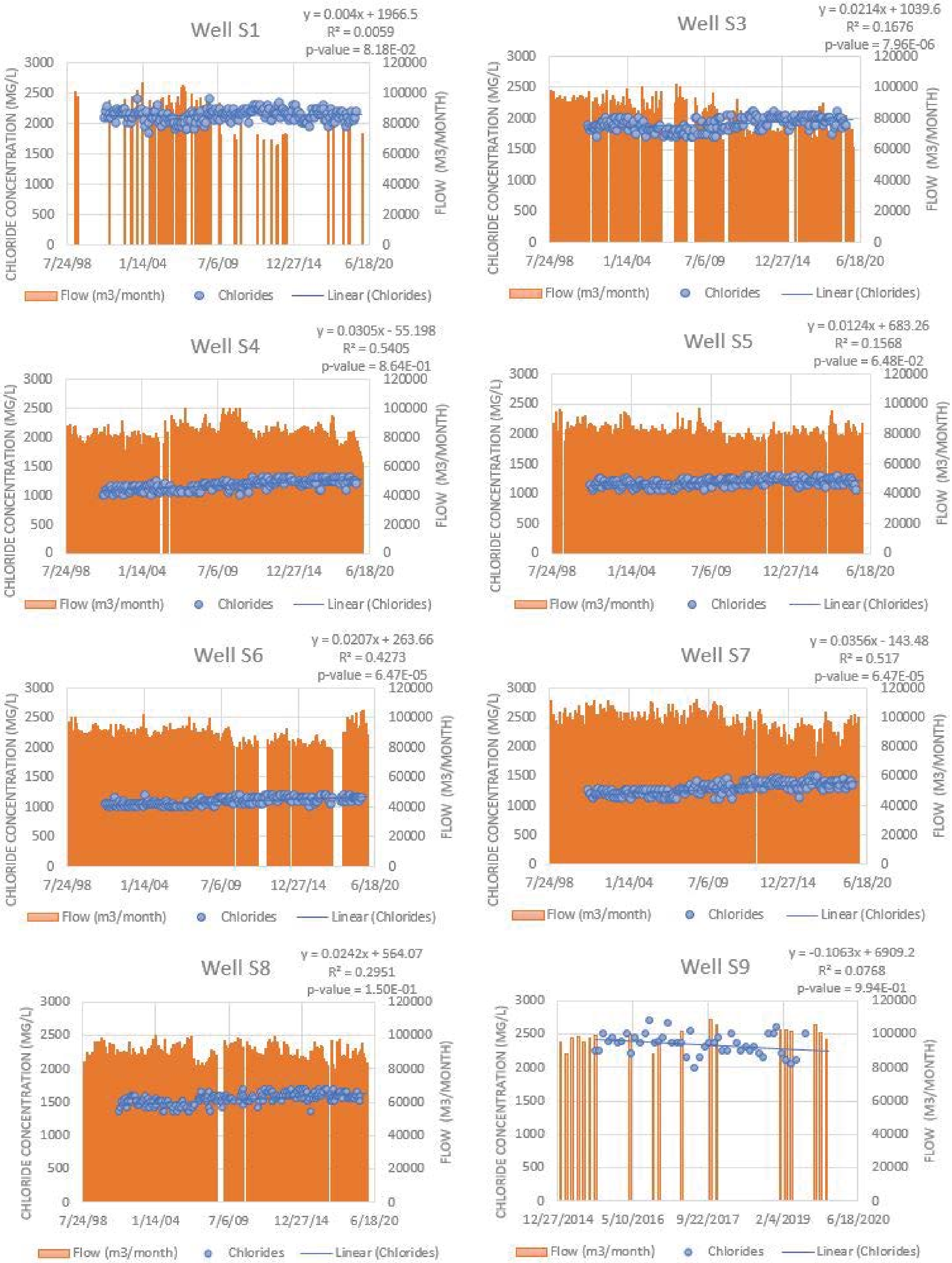

Fig. 10. Graphs showing the trend in dissolved chloride (mg/L) changes in pumped water from each production well (blue dots) and the quantity of pumped water pumped in m³. Note that the sampling frequency is monthly, and the pumpage is aggregated monthly. Wells S1–S9.

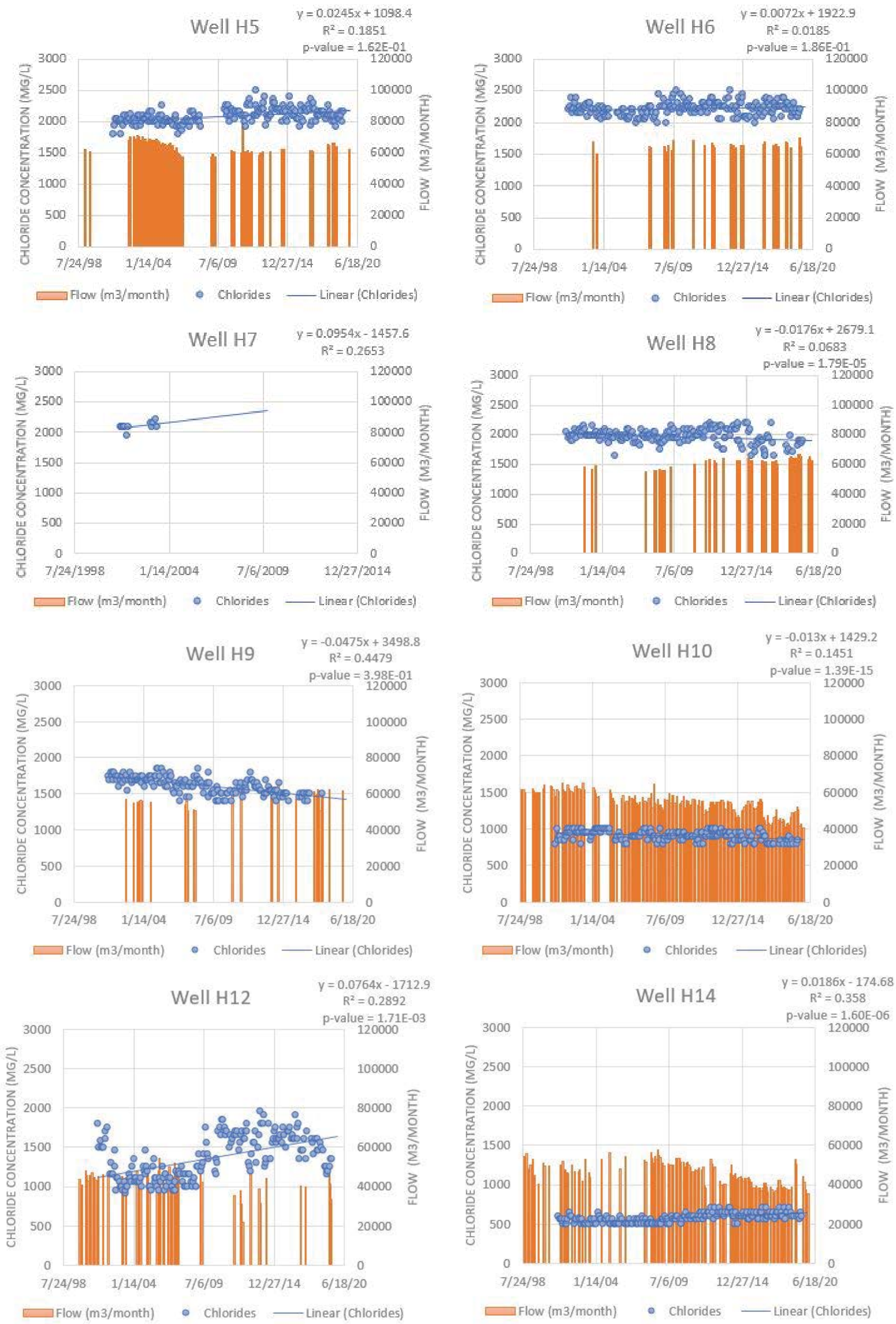

Fig. 10. Graphs showing the trend in dissolved chloride (mg/L) changes in pumped water from each production well (blue dots) and the quantity of pumped water pumped in m^3. Note that the sampling frequency is monthly, and the pumpage is aggregated monthly. Wells H5–H14.

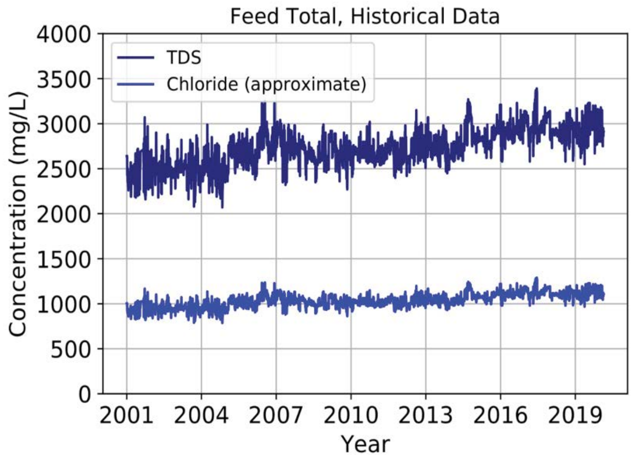

Fig. 11. The trend in the TDS concentration and chloride concentration in mg/L over the past 20 y of the BWRO plant operation.

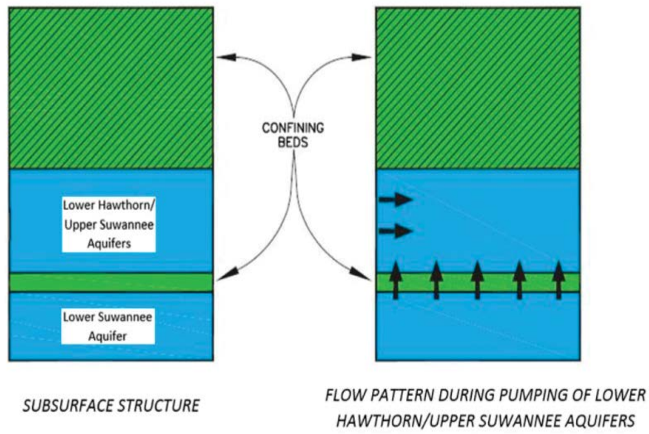

Fig. 12. A conceptual model for evaluation of salinity changes in the Lower Hawthorn/Suwannee Aquifer in Southwest Florida [26–28].

likely stay at or near the 2019 values. Well H-12 (highlighted in blue) has been heavily used to balance the net inflow water quality, so shows greatly variability in concentration.

5. Discussion

5.1. Analysis of the original conceptual model and the analytical groundwater quality model compared to the observed and projected water quality changed based on measurement

The original conceptual model for evaluating future water quality changes at the IWA was similar to that used for other wellfields used to supply brackish-water to BWRO facilities (Fig. 12). The overlying confining unit is thicker and has a much lower leakance compared to the lower confining unit. Therefore, the pumped aquifer essentially recharges for the bottom upwards with some moderation of pumping-induced water quality changes by capturing some fresher horizontal water flow through the aquifer. The aquifer system pumped by the IWA is the combined Hawthorn Aquifer System-Zone III (H-series wells) and the underlying Hawthorn Aquifer System-Zone IV/Suwannee Aquifer System-Zone I (S-series wells). The key boundary is the low leakance confining unit above Hawthorn-Zone III (Fig. 4).

A comparison of the projected dissolved chloride changes in time shown in Fig. 9 to those that occurred is quite great. The actual raw water pumped from the wellfield has varied between 30,303 and 31,061 m^3/d (8 and

Table 2
Projected dissolved chloride concentration of projection wells at 5, 10, 20 and 40 y based on the regression analysis of the wells

Well no.	Starting concentration 2001 (mg/L)	2019 concentration (mg/L)	5 y projection (mg/L)	10 y projection (mg/L)	20 y projection (mg/L)	40 y projection (mg/L)
S-1	2,100	2,200	2,148	2,156	2,171	2,200
S-3	1,900	2,200	2,023	2,073	2,174	2,376
S-4	1,000	1,200	1,347	1,414	1,549	1,817
S-5	1,150	1,050	1,259	1,289	1,348	1,466
S-6	1,050	1,150	1,213	1,258	1,349	1,531
S-7	1,250	1,350	1,473	1,547	1,694	1,989
S-8	1,250	1,500	1,671	1,725	1,832	2,047
H-5	1,800	2,150	2,204	2,250	2,343	2,528
H-6	2,200	2,200	2,257	2,290	2,358	2,494
H-8	2,050	1,550	1,789	1,727	1,604	1,357
H-9	1,750	1,200	1,205	1,071	801	263
H-10	800	850	802	764	690	542
H-12	1,800	1,350	1,730	1,872	2,157	2,727
H-14	600	600	680	721	804	970

8.2 MGD) for the last 10 to 20 y. The composite dissolved chloride concentration has increased from 1,395 to 1,562 mg/L (TDS 2,500 to 2,800 mg/L). Comparing the actual changes in dissolved chloride concentration, including the well database changes for the next 20 y is compared to the original solute transport modeling in Fig. 13. Note that the slope of the projected change is considerably less than projected in the original model.

The original model assumed that solely the Hawthorn Aquifer System-Zone IV/Suwannee Aquifer System-Zone I was going to be used to supply the BWRO plant. This aquifer has a higher leakance value compared to Hawthorn-Zone III, and thereby this higher value was used to generate the curves in Figs. 9 and 13. Based on the model, the original wellfield design was spread out with more wells added to the west and northwest of the plant site. These wells tended to have a lower starting dissolved chloride concentration by a difference of about 800 mg/L on average. Therefore, the starting point for the projection was lower. In addition, the higher leakance value dictated the lower slope of the overall wellfield increase in water salinity.

5.2. Impacts of wellfield water quality on the future operation of the IWA BWRO plant

The BWRO plant membranes are capable of treating feedwater with a TDS concentration of up to 3,500 mg/L (dissolved chloride concentration of 1,940 mg/L) without having to increase the operating pressure or changing the process design. Based on the projected changes in the dissolved chloride values from the wells and the feedwater blend, the BWRO process should be able to continue operation without major design changes for the next 20 y. This means that the plant operation should maintain a conversion rate of 80% and still have the capacity to blend 6% of the raw water with the treated water and still produce the desired treated water quality. This conclusion is based on a minimal increase in the treatment capacity of the plant. If additional raw water is required for future operations, the IWA would need to consider adding production wells with the locations based on a newly developed solute transport model using the SEAWAT code that includes new projected pumping rates.

6. Conclusions

Accurate projection of future groundwater salinity changes is a critical aspect of BWRO system design. The membranes used in these desalination plants have a specific upper limit in the TDS of the feedwater that cannot be exceeded without causing a significant operational issue and potential plant re-design and reconstruction. The Island Water Association has successfully operated a BWRO plant that supplies potable water to Sanibel and Captiva Islands, Florida. The plant design includes membranes in a 2-stage configuration capable of treating raw well water with a maximum TDS concentration limit of 3,500 mg/L. A solute transport model was developed to assess future salinity changes using dissolved chloride concentration as a proxy in 1982. The model showed a rather steep increase in chloride concentration between operating years 10 and 70 and then a stable curve. Monitoring of the production well water quality and the composite feedwater quality to the facility over the past 20 y shows that the increases in wells ranged between 0 and 50%. Still, the composite feedwater increased only about 12%, with the current value averaging about 2,800 mg/L. The model showed a much higher starting salinity and a much higher rate of change. The model results were used to spread out the wellfield with more wells constructed to the west, wherein lower salinity water was found in the aquifer system. This also reduced the vertical head differential across the basal confining units, which tends to reduce the rate of salinity change. In addition, the use of two aquifers for the plant began in 1998 instead of only using the lower one with higher leakance. Based on the monitoring data, the conceptual model on which the solute transport model was designed is correct, but the model code was old and inadequate compared to the SEAWAT code used today, and the input parameters were very conservative. It is important to document audits of solute transport models used in water-supply design projects to allow future improvements.

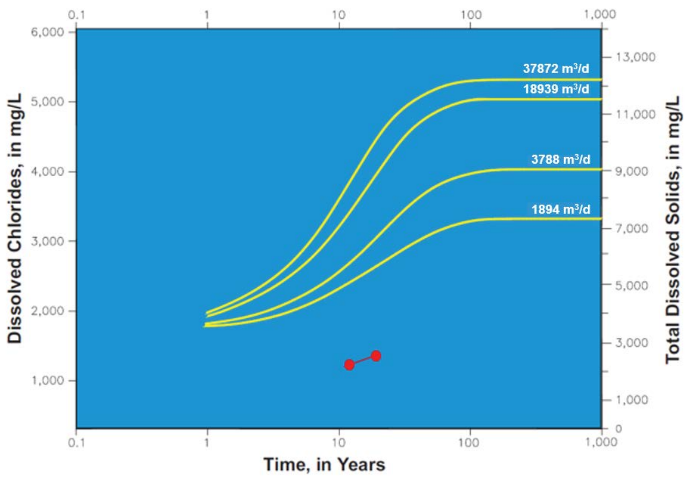

Fig. 13. A comparison of the actual dissolved chloride changes in the original solute transport model to that which has occurred.

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