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Impacts of projected changes in feed-water salinity on the City of Cape Coral Florida north brackish-water reverse osmosis desalination plant operation

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ABSTRACT

Successful design of brackish-water reverse osmosis (BWRO) desalination systems requires detailed knowledge concerning the source aquifer system to assure that future water quality changes induced by pumping do not adversely impact operations. The City of Cape Coral, Florida has successfully operated two BWRO systems with a combined capacity of 113,632 m^3/d (South Plant: 68,182 m^3/d, North Plant: 45,455 m^3/d) with the North facility being operated for the past 11+ years. An investigation of the salinity changes in the production wells that provide feed water to the North BWRO plant shows that all wells have an increasing salinity based on the standard conceptual model of pumping-induced upwards recharge from the underlying aquifer. The blended average feed water quality has historically increased in dissolved chloride concentration from about 900 to slightly over 1,000 mg/L, which is a total dissolved solids (TDS) change from 1,913 to 2,072 mg/L. This change is within the general range predicted by pre-design groundwater modeling. The projected dissolved chloride value at the 20-year point is 2,007 mg/L (3,860 mg/L TDS) for the low-salinity wells based on current trends. The BWRO membrane process was designed to treat feed water with up to 4,000 mg/L of TDS or a dissolved chloride value of 2,080 mg/L. Based on the evaluation of the changes in dissolved chloride concentration in all the production wells, the facility will be able to operate below the maximum treatable salinity over the next 20 years which will allow any necessary process upgrades to be made in a planned manner. This is an example of good coordination between planning, plant design, and operation of a BWRO facility where increases in feed water salinity with time are known to occur.

Keywords: Brackish-water reverse osmosis desalination; Groundwater source; Groundwater salinity; City of Cape Coral; Florida

1. Introduction

The City of Cape Coral, Florida is currently the third-largest city geographically in Florida (274 km^2) with an estimated population of 189,343 in July 2018 [1]. The City operates two brackish-water reverse osmosis (BWRO) desalination facilities to meet 100% of its total potable water supply-demand. The total capacity of the two BWRO plants combined is 113,637 m^3/d. Desalination is not new to the City with the first BWRO facility (South Plant) beginning operations in 1976 and eventually expanding to a capacity of 68,182 m^3/d [2]. Rapid population growth in the 1990s necessitated that the City add a second BWRO plant with a capacity of 45,455 m^3/d in 2009 [2]. The use of desalination has allowed the City of Cape Coral to maintain a high-quality water-supply system despite a population growth rate of nearly 60% in the 1990s. The City developed a long-term water master plan to meet future demands in an organized and scheduled manner in the late 1980s [3,4].

With regard to history, in 1976, the City put into operation a BWRO water supply system with six production wells up to 215 m deep into the Floridan Aquifer System [5]. A BWRO

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treatment plant with an initial capacity of 11,364 m^3/d was also installed and is the oldest continuously operating BWRO treatment facility in the world. By 1985, the City of Cape Coral Southwest reverse osmosis (RO) Plant was expanded to a capacity of 56,818 m^3/d to supply potable water for the growing population [2,6]. At this time, Cape Coral had the largest low-pressure RO plant in the world. By 2005, the City needed to expand the Southwest Plant to a capacity of 68,182 m^3/d that was completed in 2008. The new North BWRO Plant was designed and subsequently brought online in March 2010 at a capacity of 45,455 m^3/d [6].

Both BWRO facilities operated by the City obtain raw water from the Lower Hawthorn/Suwannee Zone I Aquifer which is the uppermost aquifer in the Floridan Aquifer System. The South BWRO Plant uses 33 wells and the North BWRO Plant has 22 wells that all tap this aquifer (Table 1). The northern wells are located around Kismet Parkway, Diplomat Parkway, Chiquita Boulevard North, and Del Prado Boulevard North (Fig. 1). The locations of the production wells, the injection well, the monitoring wells, and the North BWRO treatment plant are shown in Fig. 2. Three of the 22 wells in North Cape Coral were drilled in 1990 during the hydrogeologic investigation conducted for the development of the water master plan [4]. The other wells supply additional brackish water and were all completed by March 2008 [7].

The most important advancement in water treatment in the last 50 years was the ability to economically desalt water to produce potable freshwater from either brackish or seawater sources [8]. BWRO treatment technology has become an affordable treatment technology that has been implemented in many systems in Texas, California, and Florida including the North Cape Coral BWRO facility [9]. RO is accomplished by applying pressure to a concentrated salt water solution and forcing the pure water to flow through the semi-permeable membrane [6]. Pretreatment of the raw water from the wellfield starts with a combination of sulfuric acid to reduce the pH and polyacrylic acid as a scale inhibitor [1]. The raw water passes through cartridge filters to

Table 1
North Cape Coral production wells construction details

Well number	Casing depth (m, bls)	Total depth (m, bls)
RO 302	138.1	217.7
RO 303	138.1	204.9
RO 304	145.1	217.1
RO 305	134.1	193.9
RO 306	135.7	196.6
RO 307	140.2	187.2
RO 308	154.0	214.0
RO 309	153.4	214.0
RO 310	158.5	220.1
RO 311	175.3	244.5
RO 312	130.5	158.6
RO 313	165.2	245.4
RO 318	199.7	263.4
RO 319	142.7	163.4
RO 320	180.5	256.1
RO 321	172.3	243.9
RO 322	192.1	256.1
RO 323	192.1	253.7
RO 324	196.0	264.0

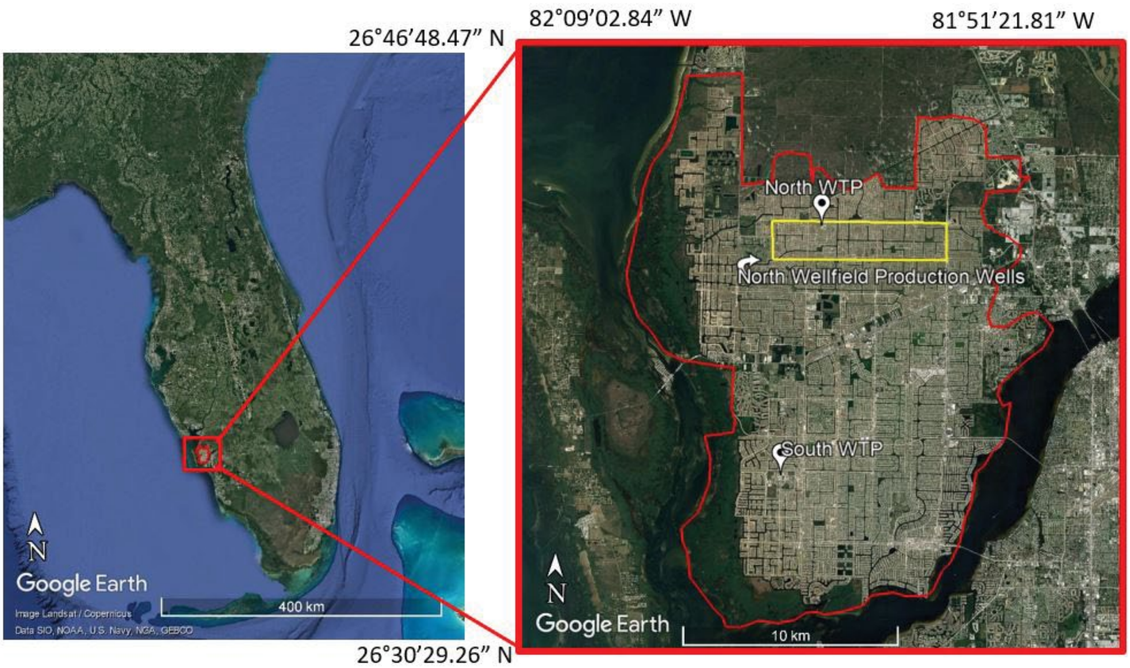

Fig. 1. Location map of the North Cape Coral BWRO plant, production wells and injection wells.

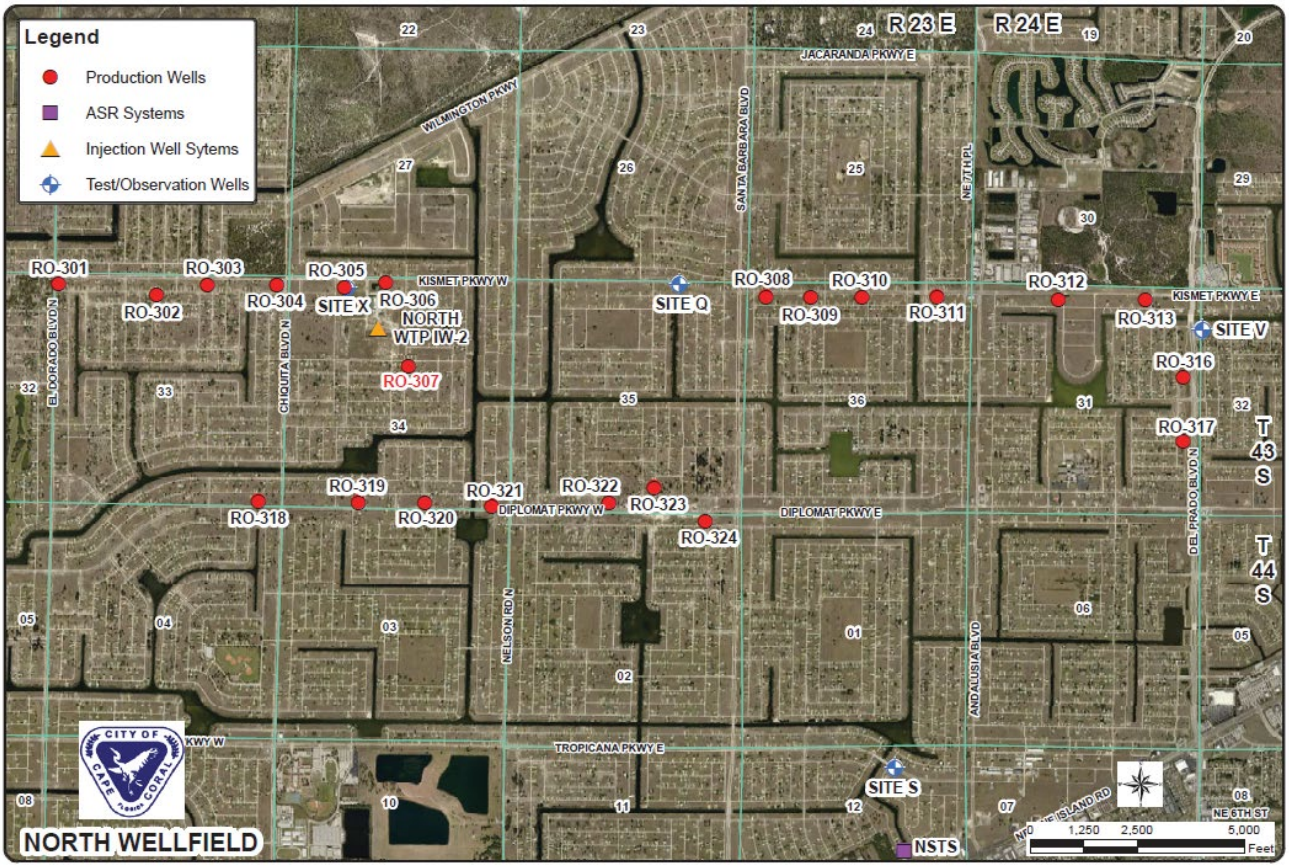

Fig. 2. Location and numbers of the North Cape Coral production wells, BWRO plant.

remove any particulates before entering the primary membrane process, which consists of pumping the pretreated water under a pressure of 11 bar (160 psi) through BWRO membranes. The recovery efficiency of the system, defined as the volume of finished water divided by the volume of raw water (in percent), is approximately 80%. The product water is blended with about 15% of raw water, which saves money and reduces the amount of post-treatment chemicals needed to stabilize the water. A diagram showing the process is given in Fig. 3.

A critical aspect of the design and operation of any BWRO plant is the coordination between the quality of the raw water supply with its variation in time and the process design of the desalination plant [8,11,12]. Most of the BWRO plants located in Florida use brackish water extracted from close to the top of the Floridan Aquifer System [12,13]. Most commonly, the total dissolved solids concentration (TDS) in the upper part of the Florida Aquifer System is relatively low and increases in concentration with depth in the aquifer system [8,9]. The confining units within the Floridan Aquifer System below the uppermost confining unit are relativity thin and leaky. When the production aquifer (Lower Hawthorn Aquifer) is pumped, it is recharged primarily from the bottom upwards (Fig. 4). Since the aquifers underlying the pumped aquifer contain higher concentrations of TDS, the production aquifer exhibits an increase in salinity with time.

The design of the BWRO plant is linked not only to the initial water quality from the production wells that tap the aquifer but also on the anticipated long-term change in water quality that is induced by pumping [8]. Commonly, a groundwater solute transport model is constructed and calibrated based on data collected during field investigations conducted on the production and underlying aquifers. This model is then used to assess the long-term, pumping-induced changes in water quality and the error range in that assessment [8].

It is the purpose of this research to assess the actual changes in water quality (TDS) that have occurred in the North City of Cape Coral wellfield and compare them to past estimates of changes based on the collected hydrogeologic data and the modeling. In addition, the changes in water quality are used to assess BWRO plant operation in the future based on the facility design.

2. Hydrogeology of the aquifer system

The hydrogeology of the Floridan Aquifer System in Lee County and the North Cape Coral area has been studied in detail in a series of U.S. Geological Survey reports [15–18], South Florida Water Management District reports [19–21], and consultants reports [3,4,7,22–32]. A generalized hydrogeologic section of the saline-water aquifer system beneath the area is shown in Fig. 2.

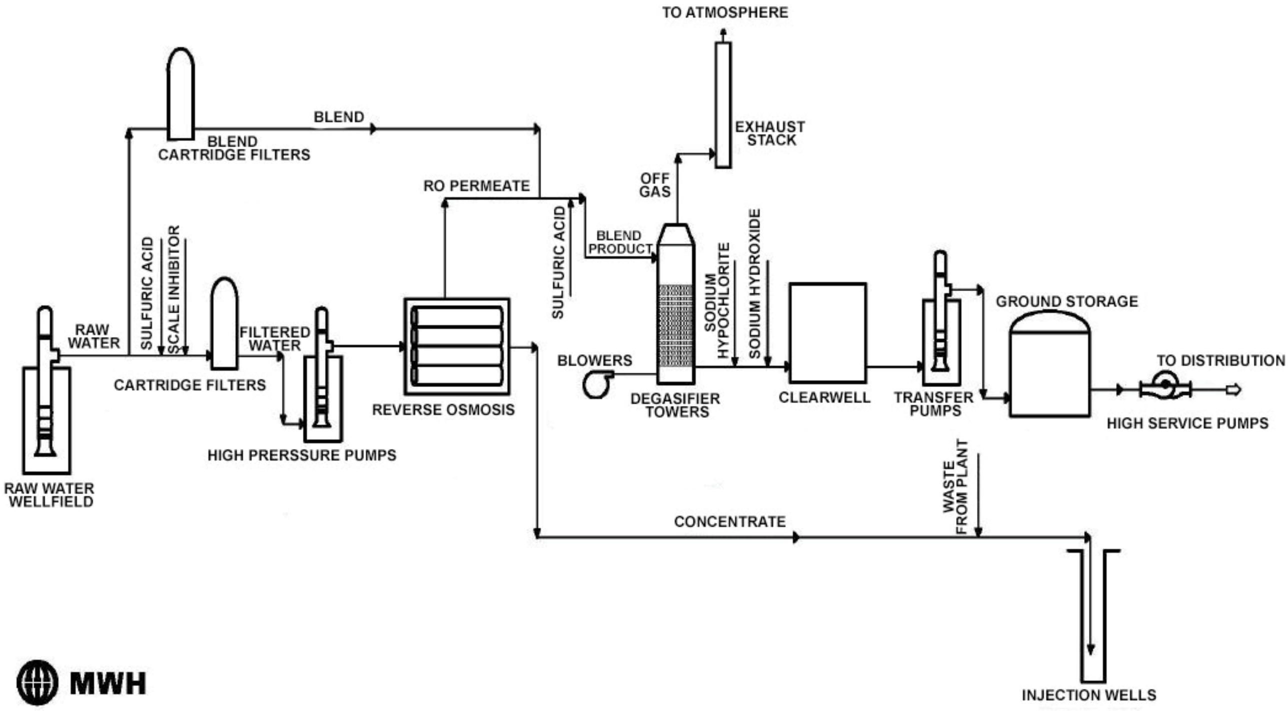

Fig. 3. Process diagram for the North Cape Coral BWRO from MWH [10].

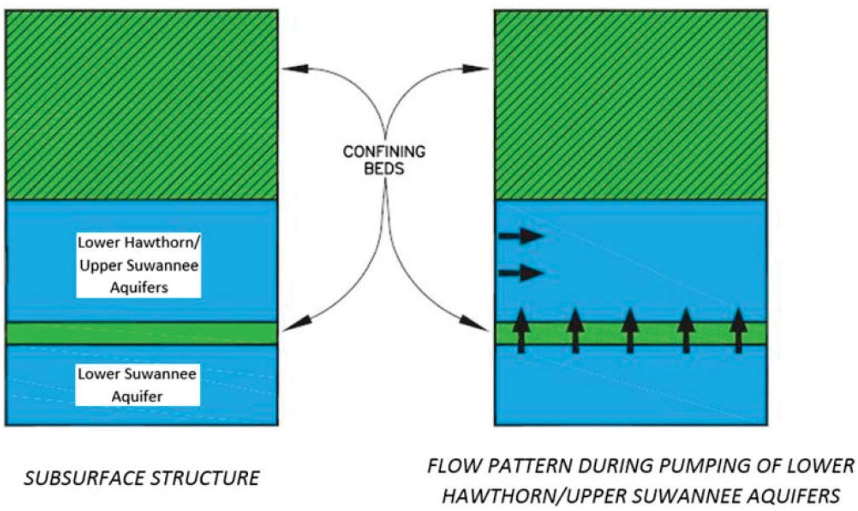

Fig. 4. General model of groundwater flow during aquifer pumping showing the upwards recharge of the pumped aquifer [14].

Wells used to produce the raw water for the BWRO facility tap the Lower Hawthorn/Suwannee Zone I Aquifer which is considered to be the upper part of the Floridan Aquifer System in this region [33]. As shown in Fig. 5, at least 8 separate aquifers are underlying the North Cape Coral area, each having a unique potentiometric surface and water quality. All of these aquifers are classified as semi-confined or leaky aquifers as defined by Walton [34] and Kruseman and DeRidder [35]. The thickest confining unit in the system overlying the Lower Hawthorn Aquifer occurs above it and separates the Florida Aquifer System from the Intermediate Aquifer System [20]. Therefore, when the Lower Hawthorn/Suwannee Zone I Aquifer is pumped, the primary recharge is upwards from the underlying aquifer with each subsequently deeper aquifer being impacted with upward movement of higher salinity water. This means that as the production aquifer is pumped it will take on the chemical characteristics of the underlying aquifer which has greater salinity. The TDS of the aquifer will increase in time based on the hydraulic characteristics of the aquifer and the underlying aquifer system water quality (Fig. 4).

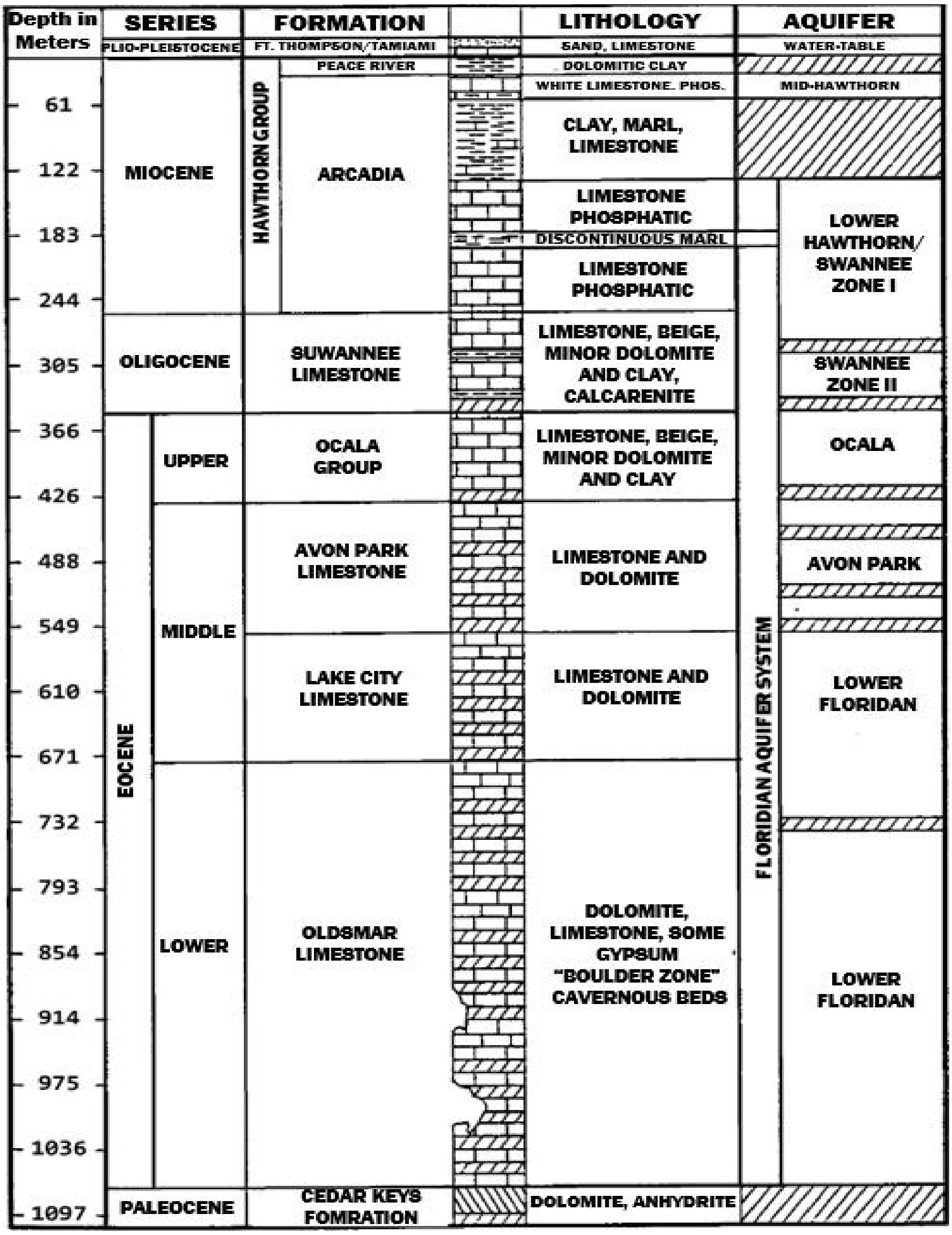

Fig. 5. Generalized hydrogeology beneath North Cape Coral, Florida (Missimer & Associates, Inc., [3,4]).

There are three important hydraulic coefficients which define the hydraulic properties of the Lower Hawthorn/ Suwannee Zone I Aquifer which include the transmissivity, storativity (storage coefficient), and leakance. Based on testing completed during the water supply master plan investigation [3,4], the range of expected transmissivity values is 300 to 900 m^2/d, the storativity ranges from 5.7×10^{-5} to 2.0×10^{-4} (dimensionless), and the leakance ranges from 3.4×10^{-3} to 1.1×10^{-1} 1/d. Note that Suwannee Aquifer Zone I has a transmissivity range of 621 to 844 m^2/d, a storativity of 2.5×10^{-4} (dimensionless), and a leakance of at least 0.071/d [4]. Because of the very high leakance of the both the Lower Hawthorn Aquifer and Suwannee Aquifer Zone I, they are treated as one aquifer and in many locations where there is no significate confinement. The depth and thickness of the production aquifer varies within the constructed production wells (Fig. 6). Depth to the top of the aquifer also varies (Fig. 7).

Prior to aquifer development, the potentiometric surface of the Lower Hawthorn/Suwannee Zone I Aquifer ranged between 12 and 15 m above sea level and the flow of water through the aquifer was from the northeast to the southwest [16]. Beginning in the 1980s, the potentiometric surface was reduced due to the pumping in the southern part of Coral Coral and the general flow direction in the aquifer was altered toward the pumping center of the wellfield. The

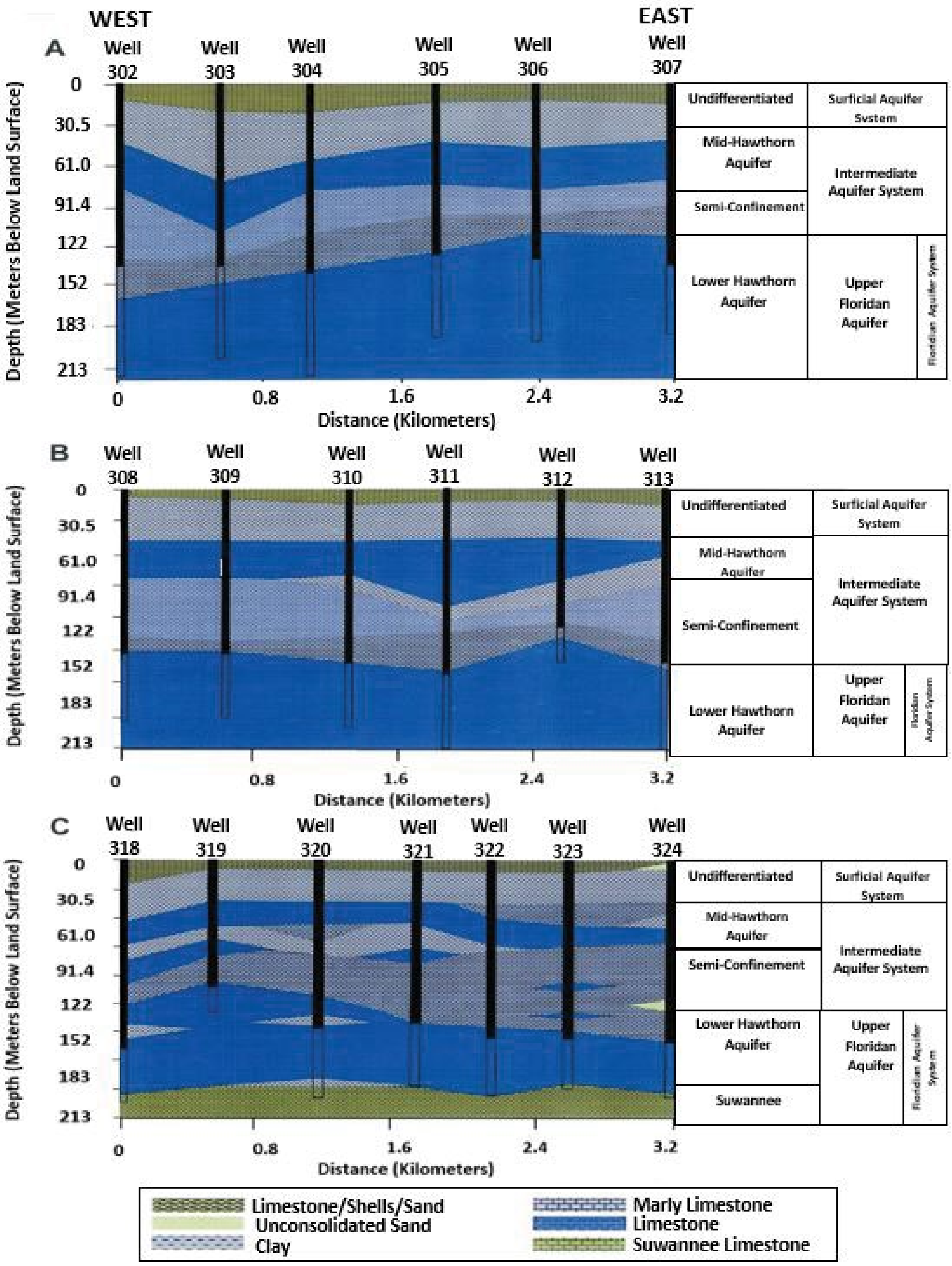

Fig. 6. Hydrogeology of the North Cape Coral Wellfield (modified from [7]).

aquifer still has a general northeast to southwest flow direction in areas located away from the Cape Coral Wellfields [4].

The pre-pumping dissolved chloride concentrations in the North Cape Coral area in the Lower Hawthorn Aquifer ranged from 600 to 1,000 mg/L based on an inverse-square smoothing method [4]. The pre-pumping dissolved chloride concentration in Upper Suwannee Aquifer (Zone I) ranged from 1,000 to 2,000 mg/L [4]. In the Lower Suwannee Aquifer, the dissolved chloride concentration was estimated to range from 2.000 to 7,000 mg/L [4]. The dissolved chloride concentrations in the underlying Ocala Aquifer were estimated to be 3,000 to 15,000 mg/L [4]. In all of the aquifers investigated, the dissolved chloride concentrations increase from northeast to southwest (in the direction of groundwater flow). The depth to the 10,000 mg/L total dissolved solids concentration, defined by regulation as the base of the

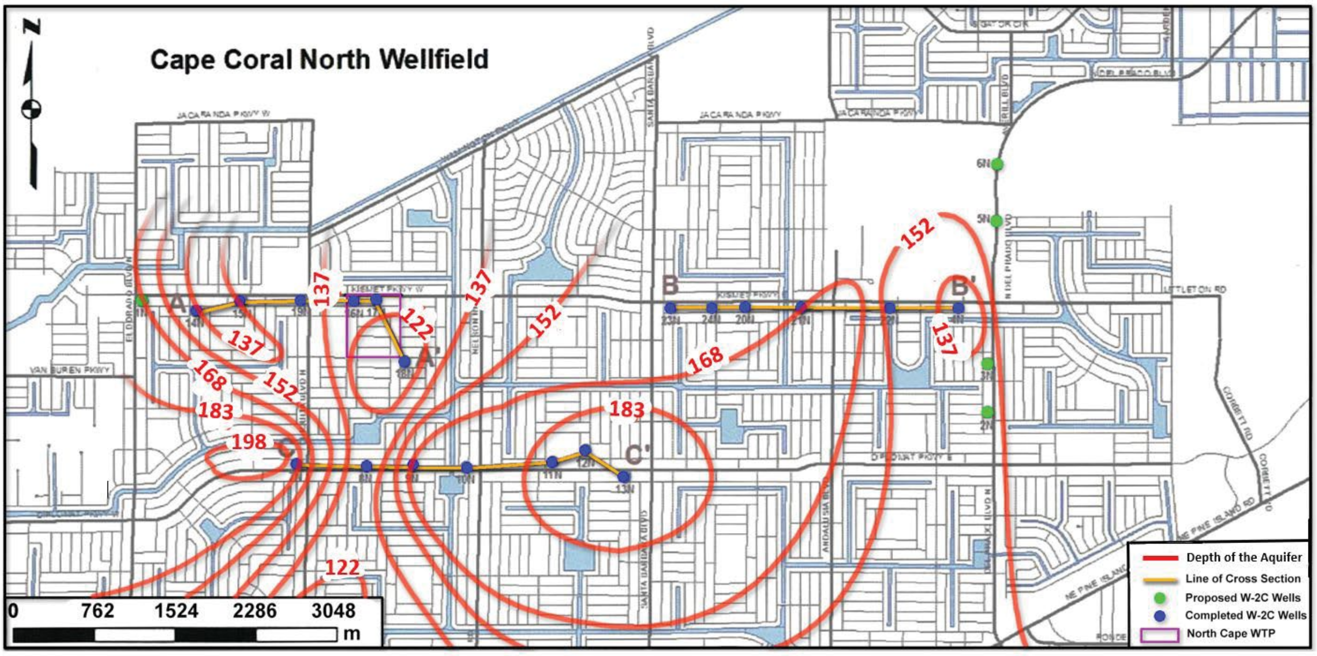

Fig. 7. Depth in meters to the depth of the Lower Hawthorn/Suwannee Zone I Aquifer (red contours) and the locations of the hydrogeologic sections in Fig. 6 (modified from [7]).

Underground Source of Drinking Water (USDW), was measured at the North Cape Coral injection well site to lie 375 m below surface [32] (Fig. 8).

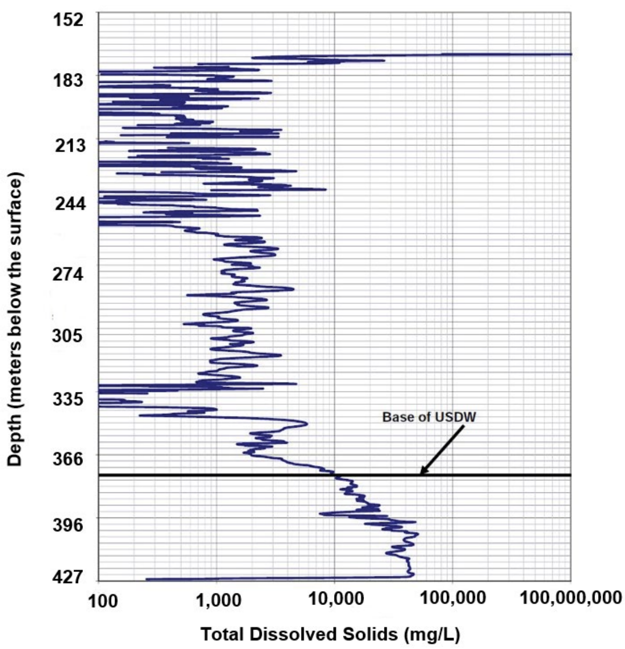

Fig. 8. North Cape Coral log derived TDS plot (from MWH [32]).

3. Materials and methods

3.1. Collection of pumping and water quality data from the North Cape Coral production wells

Historical data were obtained from the City of Cape Coral North Wellfield utility operating staff. Monthly chloride concentrations and pumping rates were obtained from March 2010 through December 2018. The water quality data were collected monthly and the pumping rates were continuously monitored and summed.

The ratios between the major ions in seawater are known to be consistent [36,37]. In brackish groundwater, the ratios are different because of rock and water interactions, but the seawater ratios are good proxies for ratios such as dissolved chloride/TDS. An estimate of TDS concentration from dissolved chloride data can be made by dividing the dissolved chloride concentration by 0.5594. The relationship of dissolved chloride concentration to TDS for the Lower Hawthorn/Suwannee Zone I aquifer is shown in Fig. 9. This shows that the relationship is closer to a division of 0.52.

3.2. Analysis of the production of well-dissolved chloride data

The dissolved chloride concentration data were plotted for each production well as well as the combined plant influent and effluent dissolved chloride concentrations. The dissolved chloride concentration versus time was plotted and a trend line demonstrating a linear regression (in most cases) was developed. The plots included the dissolved chloride concentration change in relation to the pumping rates for each well. This data set was analyzed, and an equation was developed to allow a future projection to be made of the dissolved chloride based on the current pumping rates in the wells. In some cases, the relationship between the dissolved chloride concentration and time was not linear and followed another curve. This curve was then

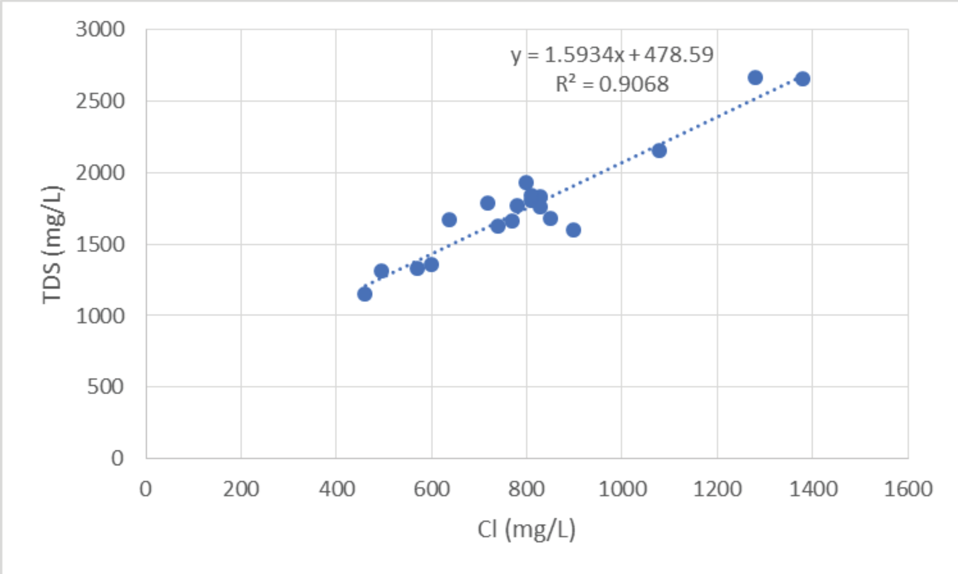

Fig. 9. Cross plot of the dissolved chloride concentration versus the TDS taken from chemical analyses of production well water samples from the Lower Hawthorn Aquifer [7].

used to make future projections. In all cases, the degree of the match between the data and the regression analysis line or curve was calculated (R^2 values) and was tested for statistical significance by calculating a p-value. The p-value had to be <0.05 for the linear regression to be considered to be significant.

Projections for future dissolved chloride concentration were made for 5, 10, 20, and 40 years based on the observed trends. Dissolved chloride was used for the projection rather than TDS because it is considered chemically conservative and essentially non-reactive. Some components within the TDS, such as calcium and magnesium, may react when passing through aquifer confining materials.

4. Results

4.1. Variation in feed water quality in association with pumping rates

The analyses of the water quality changes with pumping and time are shown in Fig. 10 and a summary of the statistical characteristics of the data are contained in Table 2. Based on the data, most of the wells show the dissolved chloride concentration increasing as a linear trend with a variable slope depending on the location. The statistical correlation of the data is very good for these wells with generally high R^2 values and a p-value indicating the trends are truly statistically significant (Table 2).

There is a tendency for the wells located in the western part of the wellfield to show a higher dissolved chloride concentration and an accompanying greater rate of change. This is caused by the high leakance between the Lower Hawthorn Aquifer and the Suwannee-Zone I Aquifer which can be collectively treated as one aquifer. The Suwannee-Zone I has a greater salinity compared to the Lower Hawthorn Aquifer moving from east to west beneath the wellfield which causes the greater salinity change. However, there is a cluster of wells occurring close to the BWRO treatment plant and injection well, numbers 305, 306, and 307 that show an exponential increase in dissolved chloride concentration. In addition, well 324 also shows an exponential increase in dissolved chloride concentration with time. Pumping from these wells has been discontinued or reduced significantly. The behavior of the dissolved chloride concentration in well 307 appears to have started as a linear trend and transitioned to exponential, perhaps based on proximity to wells 305 and 306. The trend in well 304 may also be changing as shown in Fig. 10.

4.2. Use of linear regression to predict long-term water quality based on the measured trend

A map showing contouring of the initial dissolved chloride concentration in the production wells indicates that the dissolved chloride concentration is generally higher in the western part of the wellfield and decreases to the east (Fig. 11a). The results of using the individual well data to project future changes in dissolved chloride based on current pumping rates are shown in Table 3. Projections of the water quality over 20 years for those wells with a linear trend is considered to be reasonably valid based on the aquifer type. However, the 40-year projection is less certain, and a better approximation would require three-dimensional solute transport modeling. A comparison between the initial dissolved chloride concentration in the wells and the 20-year projection is shown in Figs. 11a and b.

Projection of the dissolved chloride trend in the problem wells that show an exponential increase based on past pumping rates and the wells are currently not pumped. Any projection of water quality in these wells cannot rise above seawater because that is the worst quality water underlying the wellfield. The average values for the dissolved chloride projection include the use of the linear trending wells and

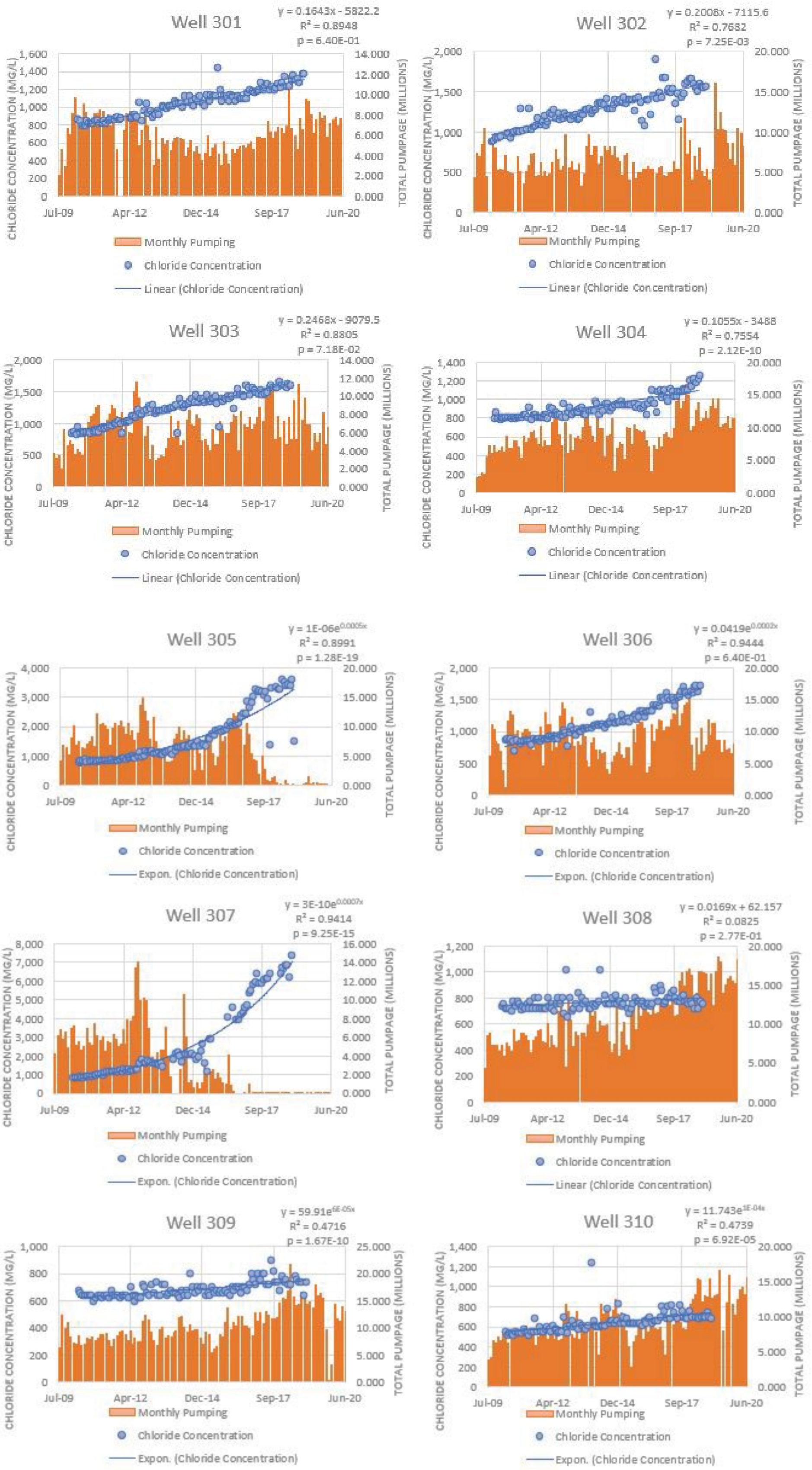

Fig. 10. Continued

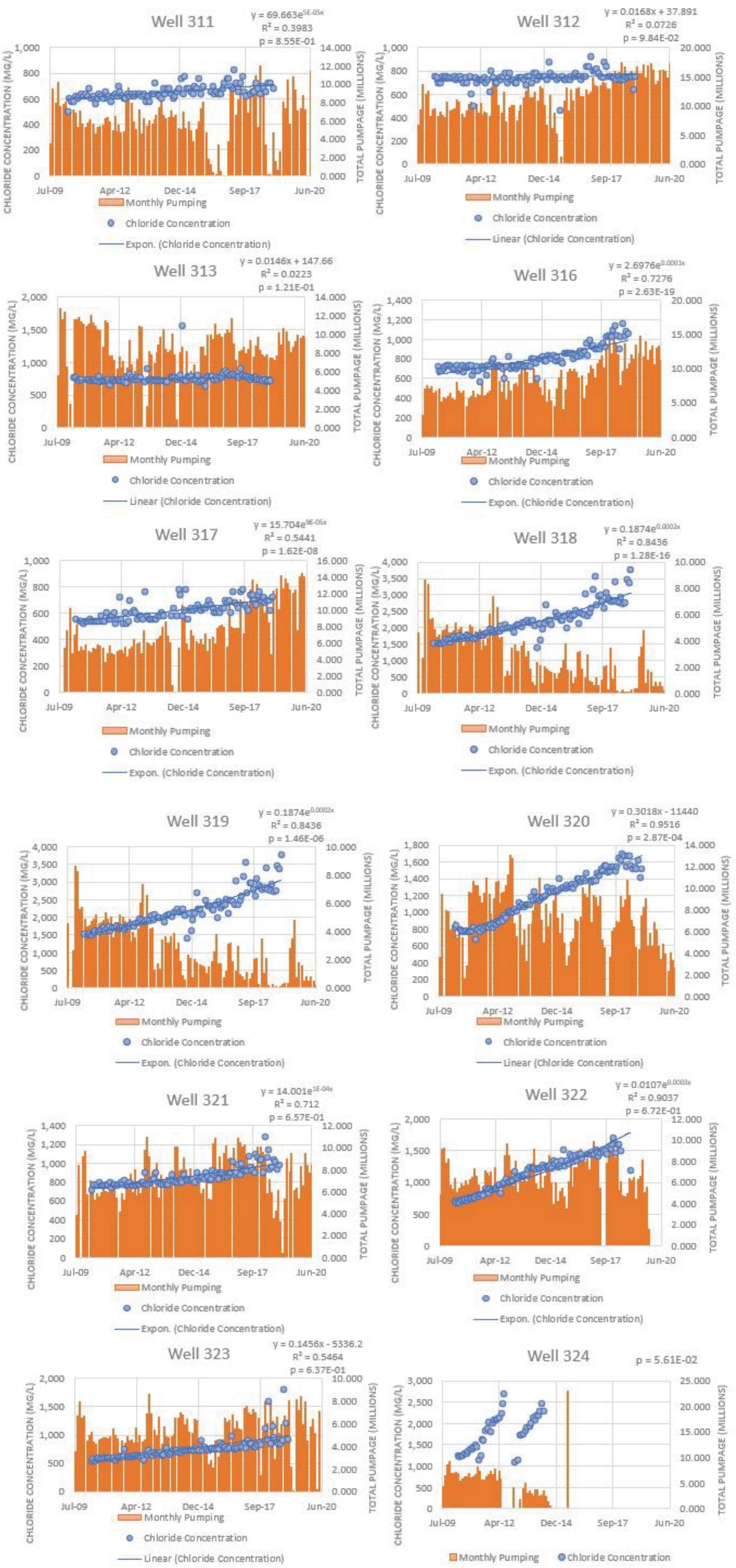

Fig. 10. Graphs showing the increase in dissolved chloride concentrations in time with the monthly pumpage data from all production wells. Note that the vertical scales are not the same on all graphs because of the space limitations for publication.

Table 2
Pre-pumping, monitoring data and projections of dissolved chloride concentration with time

Well No.	Pre-pumping[a] (mg/L)	2010 (mg/L)	End of 2018 (mg/L)	5-years projection (mg/L)	10-years projection (mg/L)	20-years projection (mg/L)	40-years projection (mg/L)
301		860	1,220	1,318	1,858	2,458	3,658
302	830	880	1,480	1,611	2,271	3,004	4,470
303	850	840	1,500	1,646	2,457	3,358	5,161
304	810	800	1,080	1,097	1,444	1,829	2,600
305[c]	800	800	3,320	3,066	5,887	9,021	15,289
306[c]	810	860	1,560	1,622	2,561	3,605	5,693
307[c]	830	820	6,400	6,080	12,519	19,675[b]	19,675[b]
308	600	740	800	795	851	913	1,036
309	740	680	780	751	884	1,033	1,329
310	495	560	760	743	941	1,160	1,599
311	570	500	660	711	826	953	1,208
312	720	760	740	768	823	884	1,007
313	638	760	740	781	829	883	989
316		720	1,040	988	1,362	1,777	2,609
317		560	740	709	888	1,087	1,485
318	1,380	1,540	2,840	3,009	4,663	6,502	10,179
319	1,280	1,280	1,580	1,525	1,761	2,023	2,548
320	900	820	1,700	1,680	2,672	3,775	5,980
321	770	720	1,040	1,001	1,288	1,607	2,245
322	780	700	1,600	1,675	2,669	3,774	5,984
323	460	540	920	992	1,471	2,008	3,066
324[c]	1,080	1,240	–	3,234	5,175	7,332	11,644
Average	808	760	1,049	1,134	1,548	2,007	2,926
Average with good wells	808	817	1,477	1,627	2,550	3,576	4,975

[a]Data from wellfield completion report by MWH [7].
[b]Dissolved chloride value cannot exceed the seawater concentration in the boulder zone.
[c]These wells are not pumped, so the projections are likely to be incorrect with the dissolved chloride concentration going to seawater.
[d]The blue colored data were considered higher salinity wells and not averaged into the first average line.

the bad quality wells. In addition, all the wells would have to be pumped at the same rate and duration to make the values useful. A second set of averages was calculated without the use of the poor-quality wells. Management of the wellfield is evaluated in the discussion.

5. Discussion

5.1. Conceptual model causing increased groundwater salinity in time

The conceptual model used to evaluate nearly all wellfields used to feed BWRO facilities in Florida is similar to that shown in Fig. 4. This conceptual model assumes that the primary means of recharge is upwards leakage induced by pumping because the production aquifer is a leaky or semi-confined unit that has a greater degree of confinement at the top and a lesser degree of underlying confinement. In addition, the natural flow of lower salinity water in the aquifer moves from northeast to southwest [16] and part of that flow is captured to moderate salinity changes [8]. The pattern of water quality change found in the production and monitoring data suggests that most of the wellfield follows the general conceptual model based on the linear change in dissolved chloride concentration with the slope differences being caused by position in the wellfield which affects the vertical gradient (total aquifer drawdown) combined with variations in localized upward leakance.

Several complicating factors appear to influence the pattern of water quality change. First, the western side of the wellfield produces water with a higher dissolved chloride concentration as previously documented [3,4,16]. Second, there is a source of higher salinity water located near the center of the wellfield near the BWRO plant and the injection well. There is another localized source of higher salinity water located near well 324. There are several potential causes of the anomalous high salinity areas which have the potential to impact future wellfield and BWRO treatment operations. However, in the southern Cape Coral wellfield, several wells show a similar pattern to that found in well 324. This phenomenon is likely a hydrogeological issue from localized higher leakance possible associated with a lack of basal confinement or localized fracturing [8].

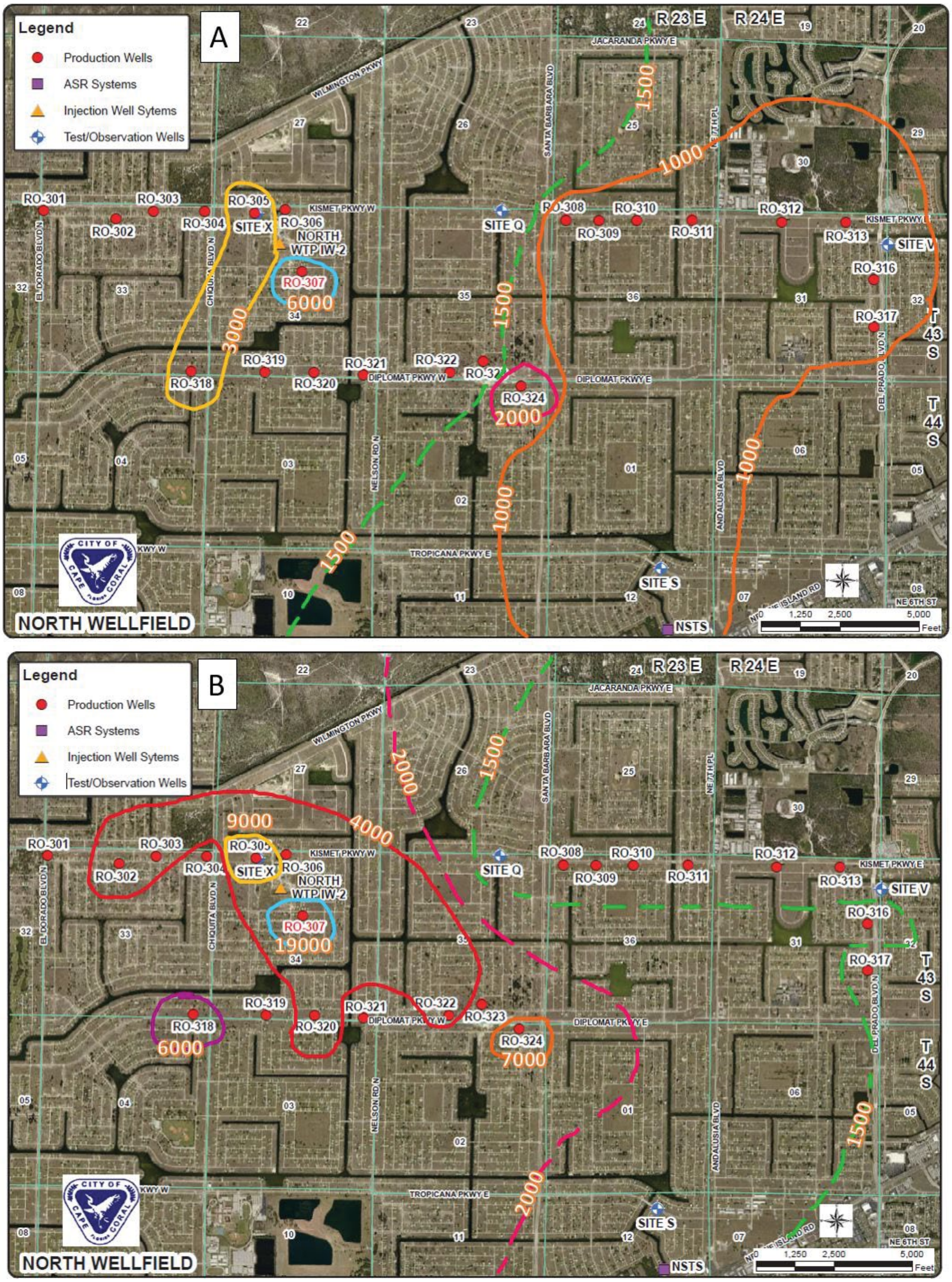

Fig. 11. (a) Chloride concentration (mg/L) contours created from 2018 chloride concentration data and Missimer and Associates Master Water Supply Plan [4]. (b) 20-year future projections used to create contours. Dashed contour lines are estimated based on surrounding contours and chloride concentration measurements.

5.2. Comparison of actual versus modeled changes in water quality during pumping

A solute transport model was conducted as part of the water master plan for both the north and south wellfields [4]. The model was constructed by making a series of assumptions concerning the projected potable water use rates, the efficiency of the BWRO treatment, and the locations of future wells. The FTWORK Code was used to construct the solute transport model [38]. The planning model is somewhat difficult to apply to the existing North Cape Coral Wellfield due to differences in actual wellfield design and operation, but a comparison of the gross pumping of the south and north wellfields appears to show an increase in the probable range of dissolved chloride concentration in the North Wellfield from about 1,000 to 1,800 mg/L during the 10 years of operation [4]. The maximum range in projected dissolved chloride concentration was from about 1,250 to 2,300 mg/L. In both the average and high range projections, the starting salinity values were lower than those found in the final designed wellfield. It does appear that the slope of the projected change in water quality is similar in the aggregated well data. The major difference is the unexpected high dissolved chloride changes in the central and western portions of the wellfield.

Based on the linear regression analysis of actual water quality data collected over the past 9 years in the low-salinity wells, the average dissolved chloride concentration in 20 years will be 2,007 mg/L if all the low-salinity wells are pumped at their current rates. This projection matches reasonably well with the initial solute transport modeling. However, if the dissolved chloride concentration in all the wells (good and bad) are averaged, the projected values would be 3,576 mg/L. Therefore, it is important to manage the wellfield wisely and take remedial action to protect the good wells.

5.3. Impact of long-term measured increase in feed water TDS concentrations on the facility design and operation

The projected values of dissolved chloride given in Table 3 show that most of the production wells have a rather constant increase in dissolved chloride concentration with time following the general conceptual model. If it is assumed that all the wells are being pumped equally, excluding the high salinity wells, then the increase in dissolved chlorides will be slow and should not impact the ability of the North BWRO plant to treat the raw water. The key issue is wellfield management and careful selection of the wells being pumped to optimize North BWRO plant operation.

There are several fundamental issues about the North BWRO plant operation which include the maximum salinity the membrane process is designed to treat, the optimal brackish-water to freshwater conversion percentage, and the optimal blend of bypassed brackish water for blending. The North BWRO plant was designed to treat a maximum TDS concentration of 4,000 mg/L which is equivalent to a dissolved chloride concentration of 2,080 mg/L. Based on the operation over the past 10 years, the inflow raw water dissolved chloride concentration has been controlled as shown in Fig. 12. The raw water dissolved chloride concentration has varied predominantly between ±20% of the average concentration. This has been achieved by carefully managing the wellfield. If the wells were to be pumped equally in the future, without using the high salinity wells, the increase in overall dissolved chloride concentration to the North BWRO plant would be near 2,000 mg/L as shown in Table 3. This concentration is close to the maximum that can be treated by the BWRO plant membrane process design. If all wells were to be pumped equally, the projected dissolved chloride concentration would be 3,576 mg/L which would exceed the ability of the BWRO plant to treat the raw water. The current recovery rate is approximately 80%. With proper wellfield management, that rate can be maintained for the current

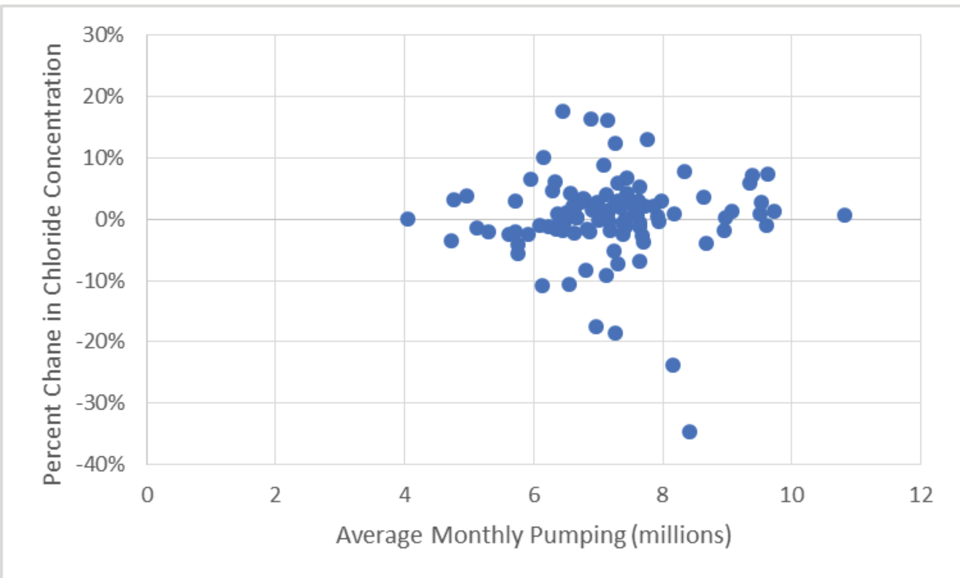

Fig. 12. Variations in the dissolved chloride concentration of the blended raw water pumped from the wellfield versus the total monthly pumping in m^3/d.

wellfield pumping recovery rates, but some important remedial measures must be taken to protect the good wells. The average annual change in dissolved chloride concentration in the production wells is shown in Fig. 13.

5.4. Assessment of the wells producing higher salinity feedwater compared to the other wells and possible management options

There are higher than anticipated dissolved chloride concentrations in the western part of the wellfield as previously discussed. However, a few wells located in the central part of the North BRWO wellfield are a primary management concern to the long-term operation of the wellfield. Several possible sources of the higher salinity water should be considered, but each would suggest a different mitigation measure. Since the affected wells are clustered at one location and solitary at the second location, they are analyzed separately.

The high dissolved chloride concentrations from the wells located near the BWRO plant could be the result of localized fracturing in the aquifer system below the production zone, the occurrence of an old production well that was previously used for agricultural irrigation, or less likely from some issue that occurred during injection well construction. If the issue is related to deep, subsurface fracturing, the movement of high salinity water upward into the Lower Hawthorn/Suwannee Zone I Aquifer could be attenuated by the plugging of problem wells with cement. If the problem is related to an old, deep well that may be cut off below the land surface, the high salinity water could still be entering the aquifer. Inter-aquifer contamination with high salinity water of this type was documented by Boggess et al. [39]. If the connection of the production aquifer is by a well conduit, then the wells should be continuously pumped in the future. The issue is what to do with the higher salinity water. Since there is no viable freshwater source to allow blending to reduce the salinity of the water before membrane treatment, then the water could be pumped to waste into the injection well or the City could consider building one or two seawater treatment trains to treat the water for blend with the BWRO water. If the problem is related to the injection well construction, the plume of high salinity water would eventually be "mined" from the aquifer based on pumping without affecting any other wells. There is evidence that the higher salinity water may be impacting well 304 based on a reduced correlation coefficient in the regression analysis and an upward trend toward the end of the monitoring period. Therefore, some remedial action should be considered.

The issue with well 324 is likely caused by localized, naturally enhanced upward leakance. In this case, the prudent action would be to plug the well with cement to avoid the issue of it becoming a point source of upward-moving high salinity water. There is evidence that the saline water from this well may be impacting well 323 based on the low correlation coefficient which is not statistically significant (high p-value). If additional raw water is required for plant operations, one or more wells could be constructed in the eastern part of the wellfield, where salinities are lower. Management of salinity in the raw water can be used to keep the blend in a salinity range that allows BWRO plant operation well beyond 20 years.

5.5. Future risk of abrupt or unanticipated changes in water quality from the wellfield in comparison with other BWRO facilities in southern Florida

The North Cape Coral BWRO facility and wellfield were carefully designed to minimize the risk of incompatibility with the raw water source. The Water Master Plan hydrogeologic investigation and modeling showed that there was some certainty in the water quality well before the BWRO plant was designed. There were some groundwater quality anomalies, as was suggested in the operation of the South Cape Coral wellfield, which showed several production wells with higher than average increases in salinity [4]. Operational data from the North BWRO plant demonstrated that the raw water quality has been managed by selective pumping of various wells to maximize the plant efficiency.

Based on the operational data collected to date, the overall TDS concentration of the raw water will get close to

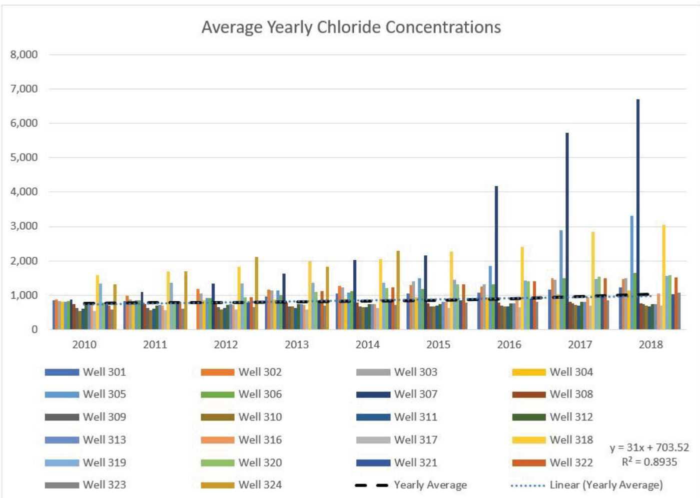

Fig. 13. Increase in the yearly average chloride concentration for selected wells in time.

the treatment maximum design of the BWRO process over the next 20 years. This is based on the current plant capacities of 68,561 m^3/d for the south plant and 45,455 m^3/d for the north plant [40]. These plant capacities require 85,701 and 56,818 m^3/d of raw water respectively based on an 80% conversion rate [40]. During the next 20 years, it is likely that there will be some additional production wells constructed to the east of the BWRO facility in an area with known lower salinity in the production aquifer and remedial measures will be taken to reduce salinity changes at problem well sites. These wellfield management approaches will allow the BWRO plant to continue operation unabated.

Based on the current population projection, the next expansion of the North Cape Coral BWRO plant should occur in 2040 or before this time [40]. While the building that houses the BWRO facility has the capacity to expand production to meet the build-out demand for the City, process equipment will have to be replaced as it reaches its useful life expectancy. As equipment replacement occurs, the process design and production well salinities could be evaluated to accommodate the salinity changes at the time and into the future. The BWRO process in the future may require a higher operating pressure and lower conversion rate if the salinity is higher or projected to be higher. Technological advances in membrane technology could mitigate the need for higher pressure based on rapid past improvements in membrane performance.

A comparison with other local operating BWRO facilities shows that the North Cape Coral BWRO is similar to the Bonita Springs Utilities and the Island Water Association facilities which have experienced minimal operational issues involving increases in production well salinity [6,9]. The North Lee County and the City of Fort Myers BWRO facilities have had more serious issues with groundwater quality in their wellfields and may require some redesign of the primary process at an earlier time compared to the North Cape Coral BWRO facility [41]. The Lake Regional BWRO facility in Palm Beach County, Florida had some unexpected major increases in raw water quality which have impacted operations [9]. The most serious BWRO design issue occurred at the City of Clearwater facility which has a treatment capacity of 37,879 m^3/d. In that case, the primary membrane process was unable to treat the raw water from the wells within the first few months after startup. That facility is currently under redesign. Based on the examples given, the design of the primary membrane treatment process must be sufficiently robust to be able to treat groundwater that could have a significant increase of salinity over time.

6. Conclusions

The total treatment capacity of the City of Cape Coral makes it one of the world's largest BWRO facilities. It has been operated successfully over the past 11 years and is projected to do so in the future based on the adopted operational protocols. Some key conclusions from evaluation of feed water quality changes at the North Cape Coral BWTO facility wellfield over the past decade include: (1) the City authorized completion of a Water Master Plan that included a hydrogeologic investigation and detailed groundwater modeling years before the BWRO plant was designed, (2) the City has conducted detailed groundwater monitoring of water quality, pumping and water levels (potentiometric surface measurements) beginning in the south wellfield in the 1980's, (3) the membrane process designed for the north plant is sufficiently robust to operate at the current pumping rates for 30 years based on the uncertainty in future groundwater quality (based on past collected information), (4) the operation of the facility uses an optimized approach to utilization of the production wells which are sufficiently abundant to allow rotation and control of the inflow water quality, and (5) the City recognizes that management of the groundwater pumping rates in the wellfield affects the operation of the BWRO plant and actively manages the wellfield. A current water quality issue is that the operation of some production wells will need to be mitigated to allow continued optimized use of the wellfield. The City of Cape Coral is conducting groundwater investigations to assure future coordination between the BWRO process and anticipated feedwater salinity.

The design of the BWRO process requires a different approach compared to seawater reverse osmosis (SWRO) facilities in that the groundwater used as feed water in BWRO systems has a high potential for salinity change over the useful life expectancy of the facility, while SWRO feed water usually has a relativity constant salinity. An evaluation of the uncertainty in predicting the future feed water quality must be factored into the design [42,43]. If planners decide not to perform extensive hydrogeologic investigations and solute transport modeling prior to process design, the risk is greater, necessitating the need to design greater flexibility into the system. This could include the use of membranes with a greater tolerance to high salinity water along with de-staged high-pressure pumps. This will likely be accompanied by a larger building footprint if the salinity increase would cause higher pressure operation with lower recovery percentages.

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