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Production aquifer water salinity change impacts on brackish-water reverse osmosis desalination facility process design and operation: the City of Clewiston, Florida

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ABSTRACT

The successful management of a brackish-water reverse osmosis (BWRO) desalination facility depends on understanding future expected water-quality changes and how these changes may affect the operational reliability of the water treatment plant. Because most production aquifers that supply feed water for BWRO facilities are leaky to some extent, long-term water quality changes are expected. To assess the rate of feed water quality changes, two commonly used approaches are groundwater solute transport modeling and various engineering and statistical assumptions. The design of a BWRO facility, RO membrane type, and operational pressure range must be robust enough to treat a range in projected feed water concentrations of total dissolved solids (TDS). The initial water quality and stability of the production aquifer are critical components that guide the design of all BWRO facilities. Inaccurate prediction of the wellfield future water-quality changes can result in major operational and financial consequences. The rate of salinity change in production wells is determined by the hydraulic characteristics of the aquifer (transmissivity, storativity, and leakance), well design, the configuration of the wellfield, and the rate of pumping. The City of Clewiston BWRO facility was designed to produce 11,356 m^3/d of potable water from the upper Floridan aquifer. The membrane process was designed to treat feed water with a TDS maximum of 3,588 mg/L. The initial TDS concentration in 2008 was 2,786 mg/L. The observed 12-y historic average increase in dissolved chloride concentration was 301 mg/L (579 mg/L TDS) with the projected average 20-y increase being 611 mg/L (1,174 mg/L TDS) by the year 2040. The projected 20-y average TDS concentration is anticipated to reach 4,540 mg/L by the year 2040, exceeding the upper design limit. Treatment process design modifications, wellfield management alteration, and capacity expansion will likely be required for the facility to operate until the year 2040. Based on this analysis, groundwater solute-transport modeling is recommended before the design of even moderate-capacity BWRO facilities.

Keywords: Brackish-water reverse osmosis desalination; Groundwater quality; Aquifer characteristics; Feed water quality change; City of Clewiston, Florida

1. Introduction

In designing brackish-water reverse osmosis (BWRO) desalination facilities, hydrogeological studies are commonly performed on the production aquifer. Sufficient data are collected to allow development of groundwater solute-transport models to evaluate anticipated water-quality changes caused by pumping of the production wells over time. A hydrogeologic conceptual model is developed to represent water-quality changes in the production aquifer.

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The potential magnitude of increase in feed water salinity over time is analyzed through a series of simulations of various hydrogeological and design model scenarios. Although hydrogeologic studies and associated modeling generally provide a successful design approach, modeling results and recommendations include an inherent error range. When projected 20–40 y into the future, model errors can cause significant uncertainty in estimating water-quality changes. Conservative engineering judgment is required to interpret model error ranges when choosing a BWRO design schematic that is robust enough to accommodate future water-quality changes for the lifespan of the water treatment facility [1]. However, the use of groundwater modeling is not always performed prior to the design of smaller capacity BWRO systems. In this case, the design engineer is forced to design a treatment process based on assumed future changes in feed-water quality over the expected life cycle of the facility.

The initial water quality and stability of the production aquifer are critical components that guide the design of all BWRO facilities [2]. Inaccurate prediction of the future water-quality changes of the wellfield can result in major operational and financial consequences [3]. BWRO feed water from aquifer sources does not typically exhibit rapid changes in water quality over time. However, the salinity of pumped feed water from production aquifers is documented to gradually increase over time by migration from underlying more saline aquifers through confining layers [4]. The rate of salinity change in the production aquifer is determined by the hydraulic characteristic of the aquifer (transmissivity, storativity, and leakance), the design of the production wells, configuration of the production wellfield, and the rate of pumping [5].

The purpose of this research is to assess the long-term water quality changes of a moderate-capacity BWRO facility and assess if process design or operational protocols require alteration to utilize the water treatment facility for the intended 30-y operational lifespan. This facility design was not guided by the use of a groundwater solute-transport model. This research will help guide the creation of improved groundwater models that can be successfully used to evaluate long-term changes in groundwater quality and guide the design of more robust BWRO systems to meet the issue of changing water quality. In addition, this research will also be useful to design engineers that are provided with limited data in terms of future water-quality forecast.

2. Materials and methods

2.1. Background of the BWRO facility

Before 2007, the City of Clewiston purchased potable water from the U.S. Sugar Corporation. The raw surface water supply for the U.S. Sugar water treatment plant was withdrawn from Lake Okeechobee. The City began exploring future water supply alternatives in 2003 with the onset of reliability issues associated with seasonal droughts, taste and odor problems related to algae blooms in Lake Okeechobee, and a conflict of interest with the South Florida Water Management District policy on the management of Lake Okeechobee water levels [6]. A 2003 report evaluated three alternatives and recommended that a new upper Floridan aquifer system raw water supply and low-pressure reverse osmosis water treatment plant was the best solution to meet the future potable water supply demands. The City consultants completed the design of the new low-pressure BWRO treatment process in 2005 (Fig. 1). U.S. Sugar Corporation informed the City of their desire to discontinue the sale of potable water to the City in 2006, thus the construction of the City water treatment facility was expedited, and completed in December 2007. The water distribution system is also owned and operated by the City of Clewiston [7].

2.2. Description of the BWRO facility

The water treatment plant is located next to the City public works facility in the southern part of the City (Fig. 2). The BWRO plant was designed to provide 11,356 m^3/d of potable water [9]. The raw water system includes four upper Floridan aquifer wells, submersible well pumps, wellhead assemblies, transmission piping, and corresponding electrical and instrumentation components. A Class I deep injection well [10] was constructed about 2.4 km south of the BWRO facility at the City wastewater treatment plant site for combined concentrate and wastewater disposal [11]. The BWRO treatment process has a raw water bypass blending rate of up to 7.5% and a design recovery rate of 75%. A 5,678 m^3 finished water storage tank is located within the Public Works Complex, as well as four high service pumps each having a 6.1 m^3/min capacity. Product water degasification allows for the removal of carbon dioxide and hydrogen sulfide. Chemical post-treatment includes pH adjustment, disinfection, stabilization, and application of a corrosion inhibitor [7]. The locations of the City of Clewiston Public Works Complex, concentrate disposal injection well, and BWRO plant feed water production wells are shown in Fig. 2.

2.3. Analysis of groundwater quality data

City of Clewiston staff collects feed water samples for measurement of the dissolved chloride concentrations and other chemical parameters. Continuous data are also collected on the pumping rates of the production wells. The monitoring data are reported to the South Florida Water Management District (SFWMD) as required by the water use permit [13]. The dissolved chloride data from the production wells were compiled and plotted vs. time for comparison with the cumulative monthly pumpage. Total dissolved solids (TDS) concentrations were estimated by dividing the dissolved chloride concentration by 0.52, which is estimated to be an appropriate ratio for the upper part of the Floridan Aquifer System in the southern Florida area [14]. A regression of the dissolved chloride data was conducted to assess the trend in change as data variation is commonly linear in nature [15]. A trendline of the dissolved chloride concentration change over time was obtained for each well, as well as the associated regression equation, R^2 value to assess the quality of the data fit to the trendline, and p-value to assess the statistical significance of the trendline. Utilizing the historical trending water quality changes, projections

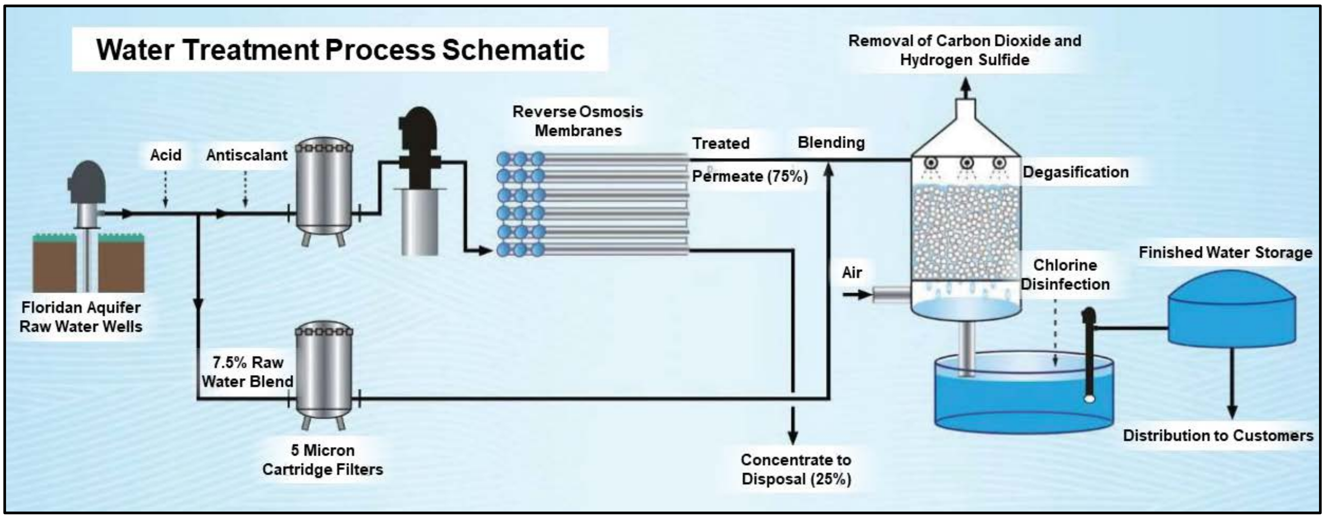

Fig. 1. City of Clewiston brackish-water reverse osmosis water treatment process schematic [8].

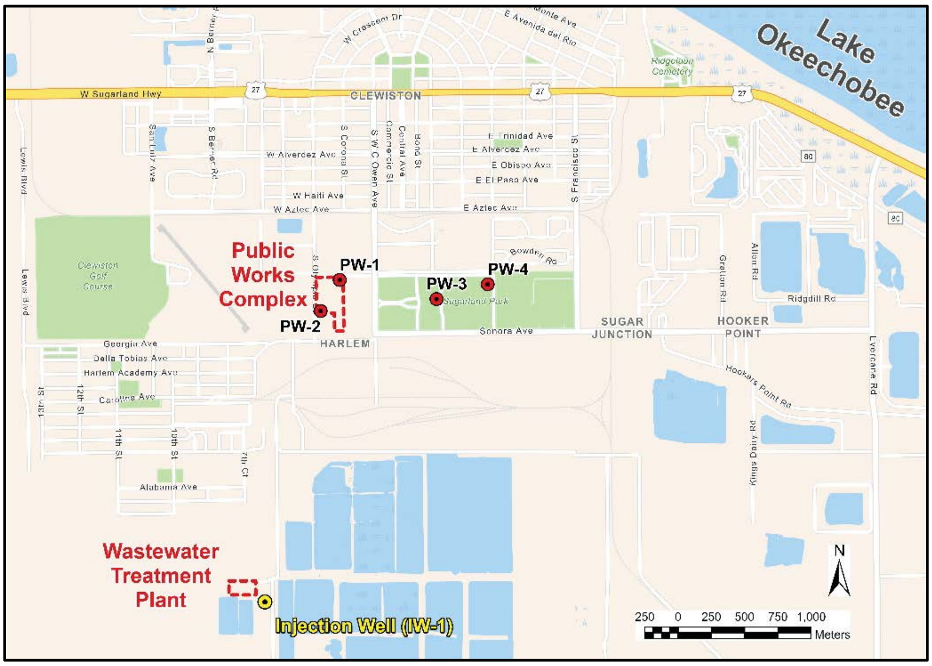

Fig. 2. Identification numbers and location of City of Clewiston brackish-water reverse osmosis plant production wells [12].

were forecasted at increments of 5, 10, 20, and 40 y past 2020 to assess if the plant design, operation, or wellfield design (e.g., well spacings) will require modification for the facility to operate for the intended design life expectancy.

3. Background

3.1. Wellfield design and hydrogeology

Four upper Floridan aquifer production wells supply raw water to the BWRO plant. Each production well has a design capacity of about 3.63 m^3/min. Most of the water production comes from between 213 and 244 m below land surface (bls). The strata underlying the production zone is documented to contain lower-salinity waters with chloride concentrations measured from 420 to 800 mg/L. The initial chloride concentrations of PW-1 and PW-2 were approximately 1,300 mg/L. These wells are located within the Public Works Complex and constructed about 244 m apart. PW-3 and PW-4 were constructed later at a distance of about 660 m to the east of PW-1 with about a 354 m separation between the two wells [9]. The construction details of the production wells are given in Table 1. To produce the 11,356 m^3/d of potable water, about 14,536 m^3/d (10.2 m^3/min) of brackish groundwater supply is required. The conversion rate of raw to product water is about 78%.

Normally, brackish water aquifer systems are density-stratified with salinity increasing with depth. However, a zone of fresher water in the upper Floridan Aquifer lying

Table 1
City of Clewiston production wells construction details [16]

Well number	Total depth (m, bls)	Casing depth (m, bls)	Well Diameter (cm)
PW-1	402.3	213.3	40.6
PW-2	365.7	213.3	40.6
PW-3	365.7	213.3	40.6
PW-4	365.7	213.3	40.6

below the upper part of the aquifer appears to be widespread in the southern Lake Okeechobee area [17]. The data from a reverse-air drilling test show that chloride concentrations are highest near the top of the aquifer and decrease with depth to approximately 396 m bls. Chloride concentration increases with depth below 396 m bls. The underlying relatively low salinity strata were initially thought to act as a buffer against upwards migration of saline water [9]. The geology and hydrogeology were documented at the Clewiston water treatment plant through analysis of well-cuttings and geophysical logs. Cuttings from wells PW-1 and PW-2 were collected at 3-m intervals and at major lithological changes [9]. A stereomicroscope was utilized to create the lithologic column given in Fig. 3.

3.2. Aquifer description, performance, and initial water quality

Use of the Surficial Aquifer System is uncommon in eastern Hendry County and western Palm Beach County because the aquifer has high color and surface water is readily available [18]. The Surficial Aquifer System in the Lake Okeechobee region also locally has high salinities. The Surficial Aquifer System at the Clewiston facility extends to the top of the Intermediate Confining Unit at approximately 51.8–59.7 m bls. Relative to the upper part of the Surficial Aquifer System strata, there is a significant decrease in the average hydraulic conductivity at the base of the Surficial Aquifer System [9].

The boundary between the Surficial Aquifer System and Intermediate Confining Unit coincides with the top of the Hawthorn Group in eastern Hendry County and western Palm Beach County [19]. The base of the Intermediate Confining Unit at the Clewiston WTP site occurs at approximately 207 m bls. At this depth, there is a decrease in phosphate and clay concentration with resistivity increasing below 204 m bls [9].

The Floridan Aquifer System in southern Peninsular Florida is subdivided into the upper Floridan aquifer, the middle confining unit, and the lower Floridan aquifer [20]. The Clewiston WTP production wells only penetrate the upper Floridan aquifer. While the Suwannee Limestone was not positively identified at the Clewiston WTP site, the Ocala Limestone appears to be present from 207 m bls to approximately 305 m bls. The top of the Avon Park Formation occurs at approximately 305 m bls and extends downwards through the total depth of well PW-1 (442 m bls) [9].

In 2007, a step-drawdown test using varying pumping rates and an aquifer performance test (APT) were performed at the City of Clewiston wellfield to determine hydraulic coefficients for the upper Floridan Aquifer [21]. The test results were utilized to calculate the well efficiency and skin effects of the production well. Results from the APT analyses indicate that the transmissivity of the aquifer is about 2,211 m^2/d, the storativity of the aquifer is about 3.2×10^{-4}, and the leakance is approximately 3.4×10^{-4} d^{-1}. The major axis of anisotropy is oriented along the north-east direction and the minor axis of anisotropy is oriented along the north-west direction. The transmissivity along the major axis of anisotropy, oriented along the north-east direction, was calculated to be about 6,782 m^2/d. Oriented along the northwest direction, the transmissivity along the minor axis was calculated to be about 929 m^2/d. An average skin factor of 22 was calculated for production well PW-3, and the efficiency of the wells was estimated to be about 30% [12].

The initial dissolved chloride concentrations in the wells ranged from about 1,280 to 1,640 mg/L (TDS = 2,461 to 3,154 mg/L) within the production aquifer. Based on the water quality data collected during the deep test drilling for construction of the injection well IW-1 (Fig. 4), the TDS concentration averages about 995 mg/L from a depth of 404 to 515 m bls. An irregular water quality increase was observed from 515 to 655 m bls with TDS concentrations ranging from 1,346 to 3,077 mg/L. Beginning at 655 m bls, a rapid increase in TDS from 3,077 to 40,769 mg/L occurs until a depth of about 701 m bls where the average TDS concentration of 40,319 was measured from 701 to 1,061 m bls. The change in TDS begins within the lower part of the Ocala Limestone, which has a low to moderate hydraulic conductivity, and the greatest increase occurs within the Avon Park Formation [22].

Water quality within the production aquifer system varies across the wellfield. The initial dissolved chloride concentrations in the eastern wells (PW-3 and PW-4) were about 250 mg/L higher than the western wells (PW-1 and PW-2). The highest initial salinity was found in PW-4, which is the easternmost well located the closest to Lake Okeechobee (Fig. 2).

4. Results

4.1. Variation in the feed water quality and pumping rate over time

The historic monthly total dissolved chloride concentrations and pumping rates were graphed over time (Fig. 5). From the past 12-y period of operation, 2008–2020, the highest increase in dissolved chloride change occurred in eastern wells PW-3 and PW-4. The lowest rate

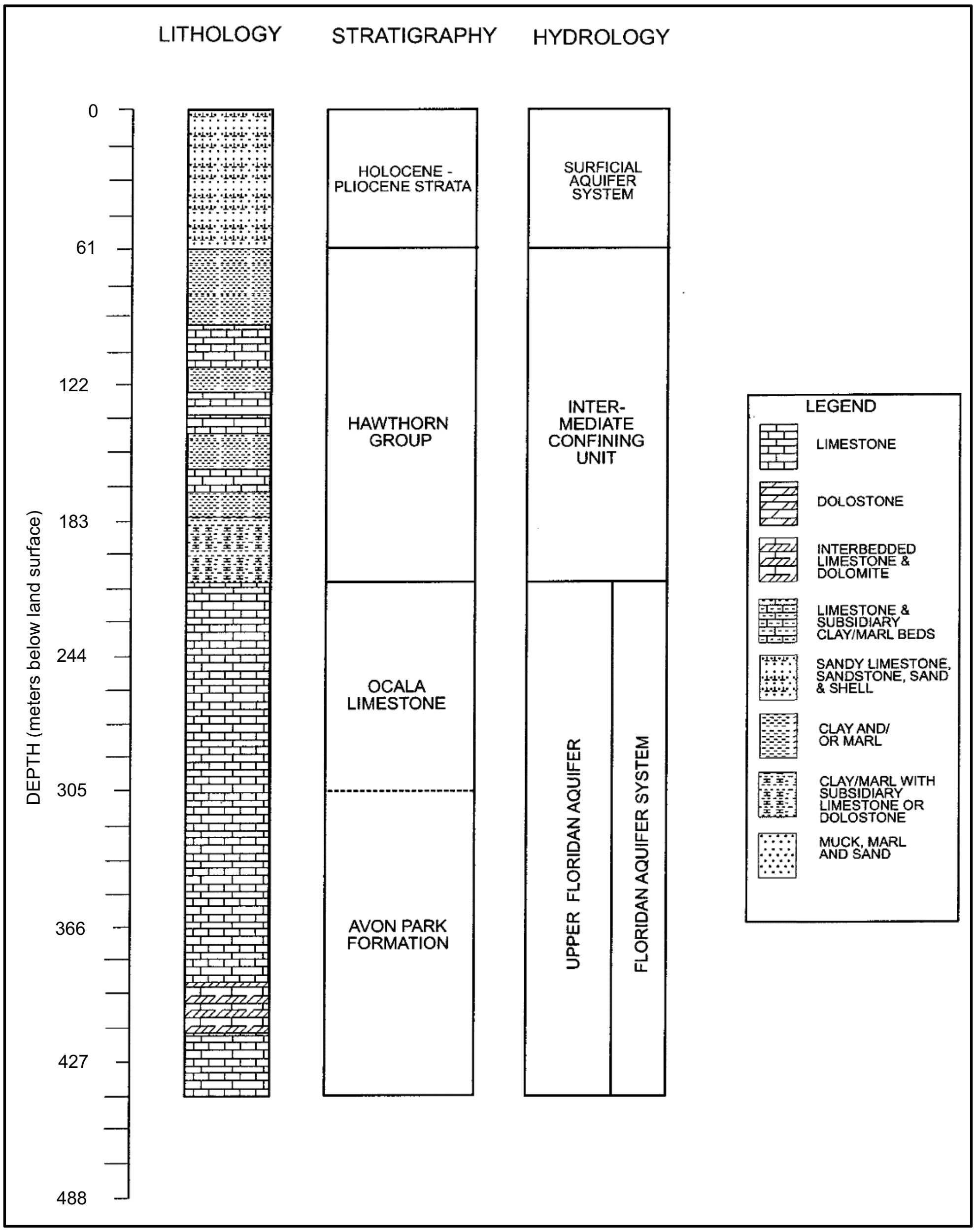

Fig. 3. Production well PW-1 hydrogeology [9].

of dissolved chloride change was found in well PW-2, which is located in farthest from Lake Okeechobee (Fig. 2). As the relationship between dissolved chloride concentration and monthly pumpage is generally linear [24], groundwater salinity change projections were performed based upon linear regression analyses of the data and extending the trend in time. The linear regression equations shown in Fig. 5 were used to estimate the water quality changes of the production wells beginning early 2020 and extending 40 y forward in time (Table 2).

The R^2 values of the regression lines on the graphs are rather low based on the scatter in the dissolved chloride measurements. Regardless of the low R^2 values, the *p*-values for all but well PW-2 show that the trend is statistically significant based on the value being less than 0.05. Therefore, the general downward or stable trend in dissolved chloride concentration is not statistically significant. Since the other wells have significant trends, the aggregated analysis for projections of future changes in water quality is considered to be statistically significant.

5. Discussion

5.1. Conceptual hydrogeologic model for the increase of groundwater salinity over time

The upper Floridan aquifer is semi-confined or leaky. Since the thickness of the confining strata above the aquifer

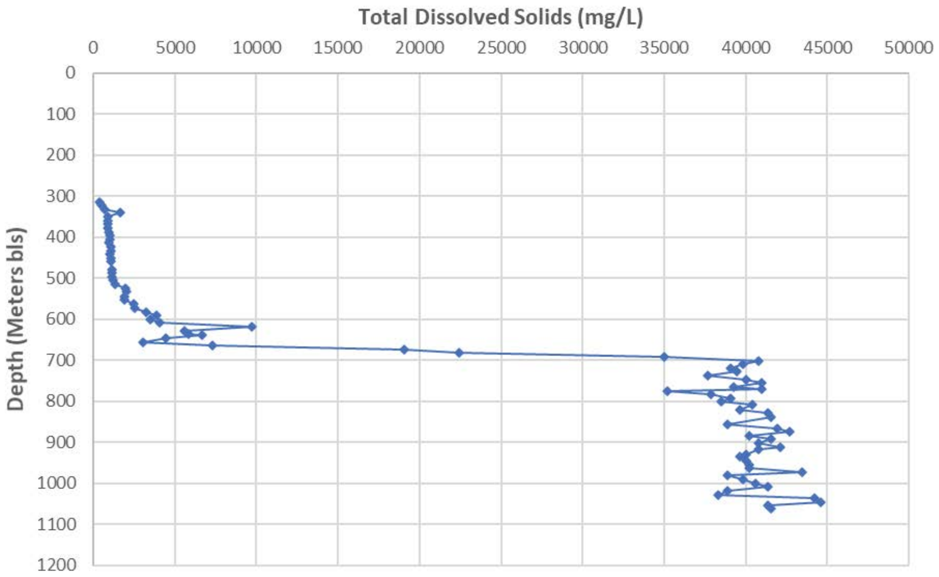

Fig. 4. Water quality variation with depth at the injection well test site IW-1 [23].

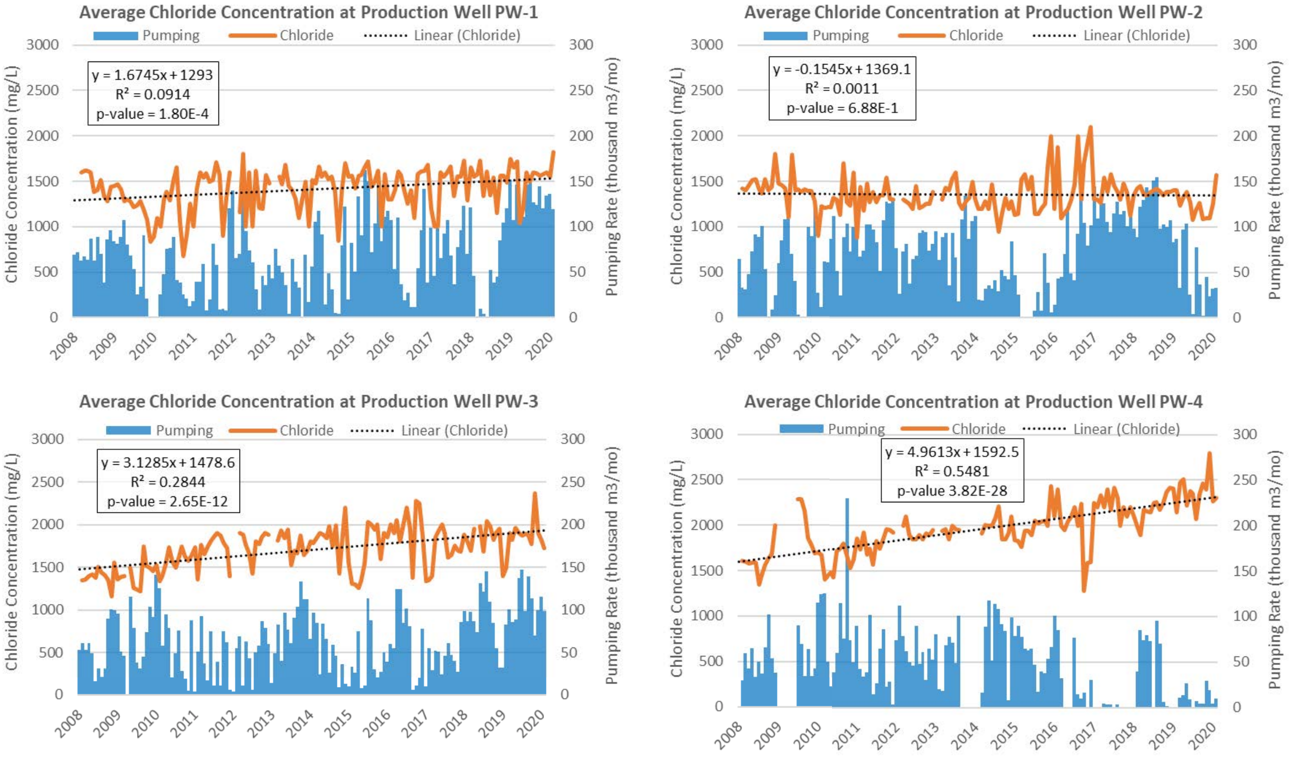

Fig. 5. Graphs depicting the changes in dissolved chloride concentrations (in mg/L) in time with the monthly pumpage data from all production wells.

is considerably greater than the confining strata below the aquifer and the overlying Hawthorn Group contains very low permeability clays, during pumping induced recharge to the production aquifer is primarily upwards. There is a degree of enhanced lateral flow induced by the cone of depression at equilibrium. A simplified diagram of the conceptual model is shown in Fig. 6, which assumes no breaches of the confining unit or significant changes in the hydraulic properties of the aquifer occur within the spatial area of the wellfield. During pumping, the conceptual model assumes that primary recharge of the production aquifer occurs upwards from the underlying aquifer having

Table 2
Dissolved chloride and TDS concentrations in the water from the production wells at the beginning of production, at the beginning of 2020, and projections to 40 y

Well No.	2008, CL- (mg/L)	2008, TDS (mg/L)	2020, CL- (mg/L)	2020, TDS (mg/L)	5 y, CL- (mg/L)	5 y, TDS (mg/L)	10 y, CL- (mg/L)	10 y, TDS (mg/L)	20 y, CL- (mg/L)	20 y, TDS (mg/L)	40 y, CL- (mg/L)	40 y, TDS (mg/L)
PW-1	1,280	2,462	1,550	2,981	1,638	3,150	1,738	3,343	1,939	3,730	2,341	4,502
PW-2	1,370	2,635	1,250	2,404	1,337	2,572	1,328	2,554	1,309	2,518	1,272	2,447
PW-3	1,505	2,894	1,900	3,654	2,123	4,083	2,311	4,444	2,686	5,166	3,437	6,610
PW-4	1,640	3,154	2,300	4,423	2,615	5,028	2,912	5,600	3,508	6,745	4,698	9,035

TDS: total dissolved solids.

a higher TDS concentration. No pre-design solute transport modeling was conducted on this site to make any long-term water quality projections.

Based on the conceptual model, the water quality of the production aquifer will gradually change based on the amount upward leakage into the aquifer and the salinity of the underlying groundwater. Since a gradual increase in feed water salinity from the individual production wells is historically observed, the conceptual model assumptions appear to be satisfied. This conceptual model applies to the behavior of many other BWRO systems in southern Florida, but not all of them. The Bonita Springs facility appears to operate with a similar conceptual model [22], whereas the City of Clearwater BWRO facility has a different proposed conceptual model for feed water supplies that are developed from karst aquifer systems [25]. From Fig. 4, the controlling higher salinity within the wellfield area appears to be about 5,040 mg/L of dissolved chloride at a depth of 619 m bls, which corresponds to a TDS concentration of about 9,692 mg/L.

5.2. BWRO design and operational impacts due to the long-term increase in feed water salinity

From monitoring well data, the rate of salinity increase of water from the production wells is known (Fig. 5). The original BWRO plant was designed to treat feed water with a TDS concentration of up to 3,319 mg/L. The future ability to treat up to 3,588 mg/L was anticipated in the design, although the timeframe of the future condition was not specified [6]. A summary of the feed water, product water, concentrate, and discharge characteristics are provided in Table 3.

Table 3
Characteristics of the facility feed water, product water, concentrate, and discharge [6]

Parameter	Initial	Future condition
Raw well water supply		
Flow, m^3/d	15,142	15,142
TDS, mg/L	3,319	3,588
RO system product water		
Flow, m^3/d	10,410	11,129
TDS, mg/L	70	75
Blended product		
Flow, m^3/d	11,356	11,356
TDS, mg/L	332	357
RO system concentrate		
Flow, m^3/d	3,785	3,785
TDS, mg/L	13,074	14,085

TDS: total dissolved solids.

The initial average dissolved chloride concentration in the four production wells was 1,449 mg/L (2,786 mg/L TDS) in 2008. The 12 y historic average increase in dissolved chloride concentration was observed to be 301 mg/L (579 mg/L TDS) with the average dissolved chloride concentration of 1,750 mg/L (3,365 mg/L TDS) in early 2020. Projecting 20 y in time from early 2020, dissolved chloride concentrations are anticipated to increase on average by 611 mg/L (1,174 mg/L TDS) to reach an average dissolved chloride concentration of 2,361 mg/L (4,540 mg/L TDS) by the year 2040. Since the plant was designed to treat a TDS concentration of up to 3,588 mg/L, treatment process design modification and/or wellfield capacity expansion may be required to treat the projected average TDS of 4,540 mg/L if the BWRO facility intends to operate until the year 2040. Wells PW-3 and PW-4 are particularly concerning, as they are projected to reach TDS concentrations of 5,166 and 6,745 mg/L respectively, and are in closest proximity to Lake Okeechobee. It is noted that wells PW-1 and PW-2 project TDS concentrations of 3,730 and 2,518 mg/L, respectively, by the year 2040, which are much closer to the design treatment capacity of the plant as compared with PW-3 and PW-4.

These projections were analyzed through linear regression of the data. For each well, a trendline of the dissolved chloride concentration change over time was obtained, as well as the associated regression equation, R^2 values, and p-values to assess the statistical significance of the regression line fit to the data. The dissolved chloride data scatter is somewhat significant, which results in generally low R^2 values. However, excluding well PW-2, the p-values are <0.05, which indicates that the trendlines calculated from the regression analysis are statistically significant. The use of the regression equations is, therefore, a reliable means of estimating projected water quality changes.

5.3. Risk of abrupt feed water salinity changes effect on future facility operation

An abrupt change in feed water quality that exceeds the capacity of the design treatment process poses a great operational risk for any BWRO facility [24]. To meet the projected increase in demand, future expansion of the wellfield will need to be carefully planned to draw feed water from parts of the aquifer system that perform similar to the general conceptual model (Fig. 6). Based on the observed salinity increase in the wellfield, the possibility of an abrupt change in water quality is low as the past 12 y of data generally agree with the conceptual model. However, the anisotropy in the aquifer transmissivity with a factor of 7.3 in the vicinity of the wellfield does raise some issues [12]. Another issue is the rather strong relief of the top of the aquifer between the injection well and some of the production wells indicative of subsurface deformation (Fig. 7). The anisotropy, subsurface relief, and fracturing of underlying strata were identified after the treatment system was designed.

The combination of aquifer anisotropy, high relief, and a very high degree of fracturing in the underlying strata detected during drilling of the deep injection well create a higher potential risk compared with other areas of southern Florida. At two other areas where these conditions exist, the Lake Region BWRO Plant on the east side of Lake Okeechobee and at the North Collier County BWRO plant, rather rapid upward movement of high salinity water occurred. While no evidence to date has been found at the City of Clewiston facility, continued, detailed monitoring should be conducted to assess any changes of feed water salinity.

6. Conclusions

The successful management of BWRO facilities depends on understanding future expected water quality changes and how these changes may affect the operational reliability of the water treatment plant. Since most production aquifers that supply feed water for BWRO facilities are leaky to some extent, long-term water quality changes are expected. Solute-transport and groundwater flow modeling of the wellfield and production aquifer are commonly performed to project the change in feed water quality characterization over a 20–40-y period, but in small to moderate capacity systems, modeling is commonly not performed, and estimates are made for the design of the membrane process. The design of a BWRO facility, membrane type, and operational pressure range must be robust enough to treat a range in projected feed water TDS.

The City of Clewiston BWRO facility was designed to treat up to 3,588 mg/L TDS. The 12-y historic average increase in dissolved chloride concentration was observed to be 301 mg/L (579 mg/L TDS) with the average 20-y increase being 611 mg/L (1,174 mg/L TDS) by the year 2040. Since the projected average 20-y TDS concentration is anticipated to reach 4,540 mg/L TDS by the year 2040, treatment process design modification, wellfield management alteration, and capacity expansion will likely be required for the facility to operate until the year 2040.

Since the rate of feed-water salinity increase is projected to exceed the treatment ability of the current membrane process, the City of Clewiston BWRO operation is an important research example of a site where the TDS concentrations are anticipated to exceed the BWRO plant design to treat the water. More detailed hydrogeologic analysis (e.g., groundwater solute transport modeling) and a more robust design approach are required for even small to moderate capacity BWRO facilities. Water quality projections through modeling or other means should consider the potential impacts of adverse hydrogeological conditions whose presence may not be evident at the time of treatment system design.

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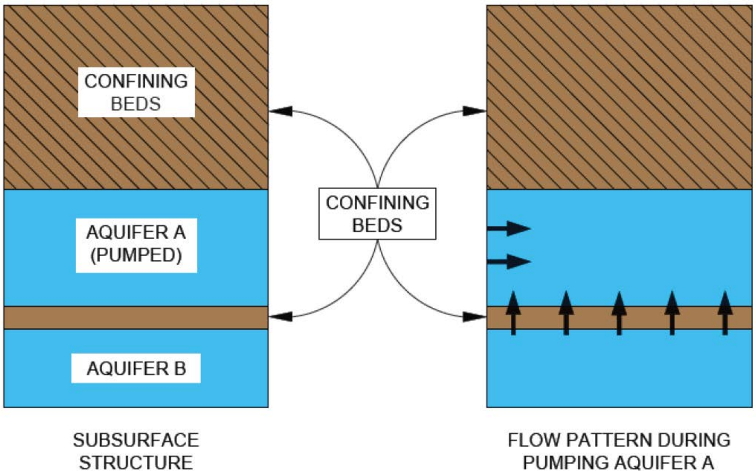

Fig. 6. Diagram of the upward recharge flow pattern of a brackish-water aquifer during pumping [25].

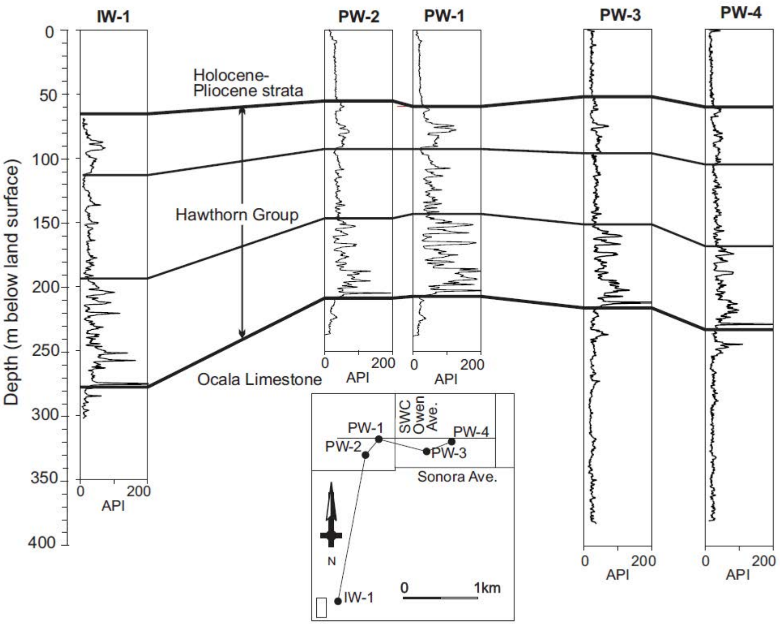

Fig. 7. Geological cross-section of the City of Clewiston site showing considerable relief on top of the upper Floridan aquifer.

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