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Groundwater quality change impacts on a brackish-water reverse osmosis water treatment plant design: the City of Clearwater, Florida

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ABSTRACT

Brackish-water reverse osmosis (BWRO) water treatment facilities commonly utilize groundwater for feed water supply. An increase in feed water salinity over time is common due to upward recharge of the production aquifer caused by higher salinity water occurring in deeper aquifers and upwards leakage or upconing of that water during pumping. The rate of change is based on the leakance value of the lower confining unit and the overall wellfield design and pumping rate. The City of Clearwater Reverse Osmosis Water Treatment Plant Number 2 utilizes feed water from the upper part of the Floridan Aquifer System and the overlying Surficial Aquifer System. The design capacity for the facility was set at 23,674 m^3/d (6.25 MGD). The BWRO process was designed to treat feed water with a total dissolved solids (TDS) of 1,500 mg/L. Soon after startup of the BWRO plant, the feed water TDS increased to a range between 2,400 and 3,300 mg/L. Based on the feed water quality the facility has been able to produce only about 9,470 m^3/d or about 40% of the design capacity. The groundwater model used to estimate changes in groundwater quality with time produced an inaccurate result, which was based on the choice of an inappropriate conceptual model, selection of the boundary conditions, and some other issues in the model structure. An analysis of the individual production well pumping rates and associated changes in salinity show that the confining units between the aquifers are likely breached by karst conduits. These localized breaches caused rapid and unpredictable increases in feed water salinity under pumping conditions. The BWRO facility will require a re-design of the treatment process with a number of options available to produce the desired product water. Because of the inability to accurately predict long-term changes in feed water quality, there is high risk in the design and operation of BWRO facilities using a karstic aquifer system as a feed water source. The location of the specific vertical conduits that allow upward movement of higher salinity water cannot be accurately predicted in the aquifer system.

Keywords: Brackish-water reverse osmosis desalination; Groundwater quality; Aquifer characteristics; City of Clearwater; Florida

1. Introduction

Initial water quality and stability of the feed water supply are critical aspects in the design of all brackish-water reverse osmosis (BWRO) desalination plants [1]. The design of the BWRO process must be sufficiently robust to assure that it will operate properly during the full life expectancy of the facility based on anticipated variations in the feed water quality [2].

Prior to the design of the RO process, hydrogeologic studies of the production aquifer are commonly conducted to gather sufficient data in order to model the anticipated solute transport and aquifer water quality changes in

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time caused by the pumping of the production wells [1]. A conceptual model of the production aquifer (or system) and subsequent design scenarios for the wellfield are tested using a groundwater model developed from the collected data. The resultant model findings and recommendations have an inherent error range, which when projected 20 to 40 y into the future can cause significant uncertainty in the projected water quality changes. However, hydrogeologic studies generally provide a successful design approach since engineers can conservatively interpret model error ranges and build in future facility process design features to accommodate water quality changes [2,3].

The purpose of this research is to assess a BWRO facility that was designed based on a series of assumptions that contained a very high degree of uncertainty in projected water quality changes. Inaccurate predictions of future water-quality changes in a BWRO facility can result in major design and financial consequences. The water-quality changes of the investigated BWRO facility have necessitated design modifications before the anticipated design life span of the facility was realized. Bromate formation, groundwater supply shortfalls, and increases in groundwater TDS concentrations have dramatically reduced the production of potable water from the facility. An analysis of this issue and the necessary design modifications are included in this research.

Most published research in engineering focuses on innovative designs and documentation of successful projects that operate well within the original design parameters. However, this research documents a facility that has had operational difficulties caused by unexpected water-quality changes, which perhaps could not be accurately predicted using existing published methods and modeling techniques. While the groundwater model used and the associated design of the BWRO plant are documented herein, it is not the purpose of this research to criticize the groundwater or engineering work performed on the project. Rather, the purpose is to use the data to provide design solutions to feed water supplies developed from karst aquifer systems. Another objective of this research is to develop a new conceptual model that can be applied to highly karstic areas where BWRO facilities have not been previously constructed.

2. Materials and methods

2.1. Background of BWRO facility

The City of Clearwater, Florida (City), has had to subsidize its potable water supply through wholesale purchases from Pinellas County to satisfy the water demand. In order to reduce dependence on outside sources, improvements to three water treatment plants (WTPs) operated by the City were planned and designed [4]. The source of raw water supply to the City WTPs is groundwater pumped from different aquifers within the underlying Floridan Aquifer System. The raw water sources are divided into three wellfields to supply the WTPs, which are termed Reservoirs 1, 2, and 3, corresponding to WTP numbers 1, 2, and 3. The BWRO facility investigated in this research is limited to the Reverse Osmosis Water Treatment Plant Number 2 (RO WTP No. 2), which corresponds to the wellfield bounded by Reservoir 2 [5] (Fig. 1). The water quality issues encountered at WTP-2 do not impact the other water treatment facilities operated by the City of Clearwater to a significant degree.

A series of pre-design hydrogeologic assessments were conducted on the target aquifer for the water supply development to RO WTP Number 2. No groundwater modeling was conducted to make water quality predictions for the water sources used at the WTP-1 and WTP-3 facilities. The hydrogeologic evaluations included test drilling, aquifer hydraulic testing, and groundwater flow and solute transport modeling using the MODFLOW/SEAWAT code [5]. In addition, a technical memorandum update to the City water master plan was produced [6], a wellfield operation schedule was developed [7], and a preliminary design report for the BWRO plant was completed [8]. A wellfield management plan update was also developed [9]. A subsequent system evaluation technical memorandum was prepared after the BWRO plant was constructed to assess why it was underperforming, which was supported by six separate technical memoranda [10].

2.2. Description of the BWRO facility

The City of Clearwater BWRO WTP No. 2 was designed originally to produce 23,674 m^3/d (6.25 MGD) of product water. The facility construction was completed in 2014, but the production in 2018 was limited to approximately 9,470 m^3/d (2.5 MGD) due to increased TDS concentrations in the feed water and other operational challenges. The freshwater iron removal filter system (using shallow groundwater as feed water) was designed to contribute 3,788 m^3/d (1.0 MGD) with the BWRO system producing the remaining 19,886 m^3/d (5.25 MGD).

The plant process includes two cartridge filter systems in parallel, three RO feed pumps, a two-stage RO skid configuration, an ozonation process, and deep injection well for concentrate disposal (Fig. 2). During a 2018 system evaluation, the wellfield capacity was indicated to be deficient, the RO feed pumps were undersized, two of the three RO skids were not operational, the ozonation process created excessive bromate, the clean-in-place (CIP) system was undersized, and the caustic storage and feed systems were not fully functional [10].

The BWRO process design criterion for the feed water was for a maximum TDS of 1,500 mg/L. However, soon after startup, the water pumped from the production wells had a TDS range of 2,400 to 3,300 mg/L with only two of the three RO skids operational. The operation of some of the skids was made possible by only pumping the wells with the lowest salinity concentration. Bromate concentrations in the product water were found to range from 11.6 to 29.7 μg/L instead of the design criteria of less than 10 μg/L. The supply of brackish water had a substantially higher TDS compared with the design criterion of 1,500 mg/L and the TDS concentrations in water being pumped from the production wells continued to rise [10].

Twelve production wells were designed and constructed to feed the BWRO plant. Since the wellfield lies within an urban area, the selection of acceptable well locations was a difficult task. The individual well pumping rates were set

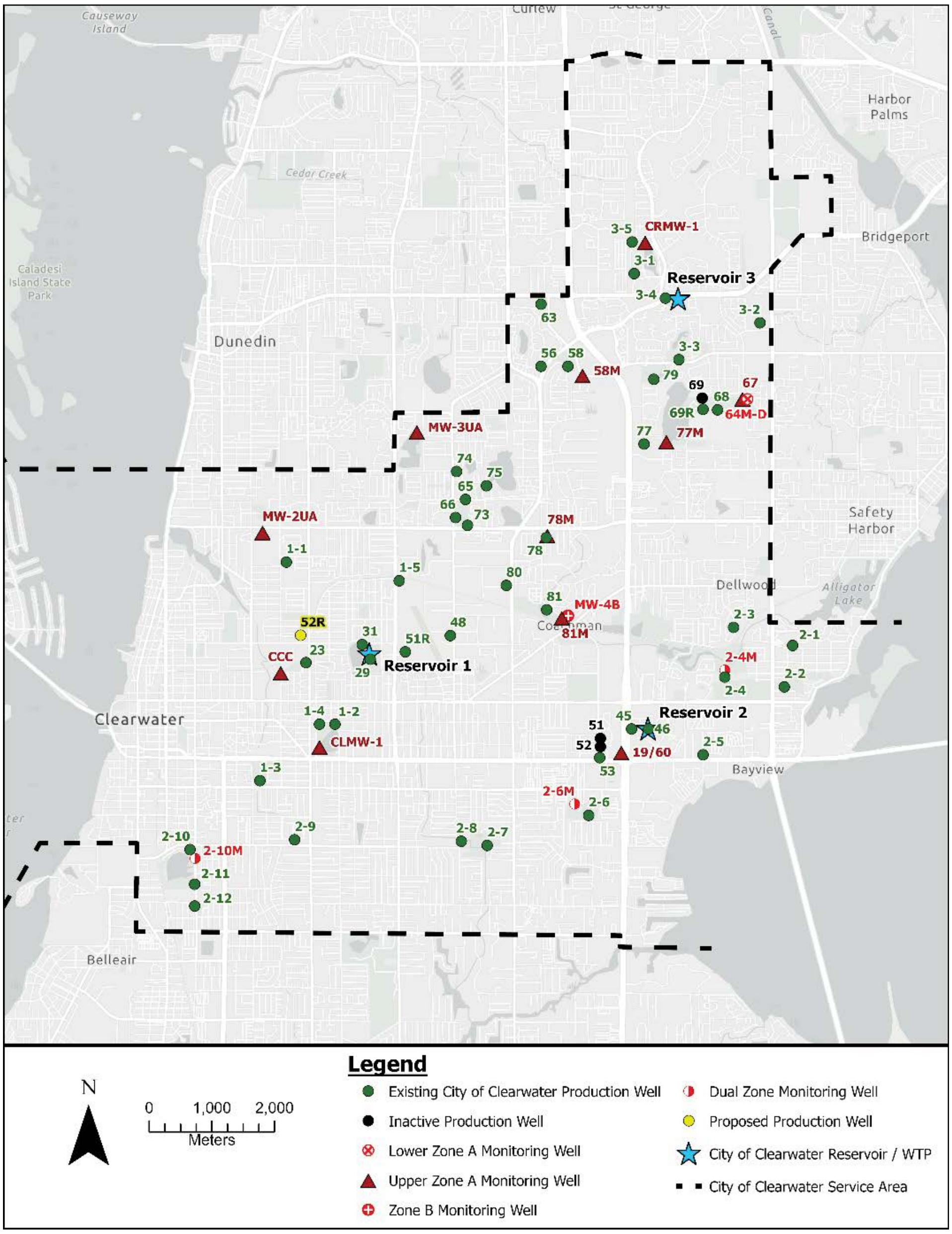

Fig. 1. Map showing the locations of the WTPs and wellfields used for water supply [9].

based on the yields of the formations at the individual sites, and on the overall BWRO plant requirements.

2.3. Analysis of pumping water quality data

Dissolved chloride concentration data were analyzed on water samples collected from the feed water production wells by City staff. These data were extracted from the annual reports prepared by the City as per the requirements of the Southwest Florida Water Management District (SWFWMD) consumptive use permit conditions. The dissolved chloride measurements were compiled and plotted vs. time to demonstrate the trends. The relationship between the cumulative monthly pumpage and the concentration of dissolved chlorides was evaluated to determine the rates of dissolved chloride changes in time along with the statistical trends.

2.4. Evaluation of the groundwater modeling performed to project future water-quality in the water supply wellfield

A three-dimensional, groundwater flow and solute transport model was conducted to evaluate the upper part of the Floridan Aquifer System during the BWRO plant design [5]. The development of the flow and solute transport model and the data used in it were reviewed to assess the accuracy of the model and how the outputs were used in the BWRO process design. In addition, the use of the model outputs was assessed in terms of how these outputs were presented to the engineers.

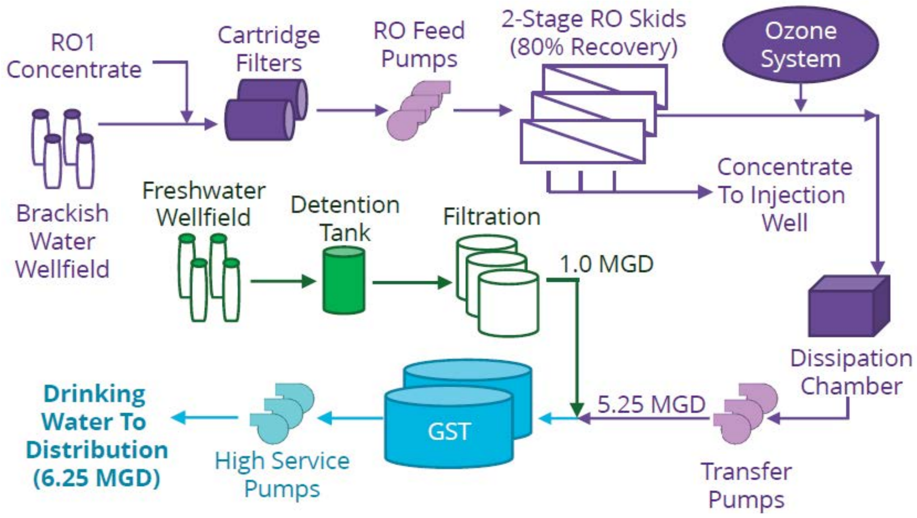

Fig. 2. Process flow diagram for the City of Clearwater BWRO water treatment facility [10].

3. Results

3.1. Wellfield design and hydrogeology

Twelve brackish-water production wells (numbered 2–1 through 2–12) and two freshwater wells (numbered 51 and 52) in Reservoir 2 were designed and constructed to supply feed water to RO WTP No. 2 (Fig. 1). The two aquifers within the wellfield area include the Surficial Aquifer System (SAS) and the upper part of the Floridan Aquifer System (FAS), which are separated by an intermediate confining unit [11] (Figs. 3 and 4). The Upper Floridian Aquifer was subdivided into four permeable Zones A through D, which are also separated by semi-confining units as demonstrated in a geological cross section of central Pinellas County through the Clearwater area (Fig. 4). Note that the FAS is a regional aquifer system and is recharged in areas lying over 80 km to the northeast in central Florida. The water quality in the FAS generally becomes more saline near the coast away from the recharge area and increases with depth in the aquifer system. A conceptual hydrostratigraphic cross section of Reservoir 2 was also developed during the preliminary design assessment modeling. The water quality in Zone A transitions between fresh and brackish water. In Zone B, there is vertical stratification of salinity with brackish water at the top and increasing to higher salinity with depth. Water in Zone C is of seawater quality with a TDS of between 35,000 and 36,000 mg/L.

The existing production wells used to feed the BWRO plant are constructed into Zones A and B of the Floridan Aquifer System with the wells 30.5 to 61 m deep most likely tapping Zone A and wells at depths of 61 and 91.5 m tapping Zone B. Well construction details are given in Table 1. Note that the total depth and casing depths vary greatly in terms of the aquifer penetrated and the open hole available for groundwater inflow.

Aquifer transmissivity, storativity, and leakance were measured for the Upper and Lower Zone A aquifers. Note that this hydrogeologic nomenclature deviates from that developed by the U.S. Geological Survey (compare Figs. 3 and 5). Upper Zone A extends approximately 24.4 to 42.7 m below land surface and Lower Zone A from 61 to 94.5 m below land surface. The transmissivity, storativity, and leakance were, respectively, 870 m^2/d, 1.9×10^{-4}, and $2.67 \times 10^{-3}\ d^{-1}$ for Upper Zone A and 435 m^2/d, 1.1×10^{-4}, and $1.3 \times 10^{-3}\ d^{-1}$ for Lower Zone A [5]. Since it was expected that recharge to the wellfield in Zones A and B would be predominantly from the bottom upwards from deeper zones though the semi-confining layers, the dissolved solids and salinity of the produced water were expected to increase over time.

Table 1
Well numbers and construction details

Well no.	Total depth (m)	Casing depth (m)	Casing diameter (cm)
2–1	90.9	68.6	40.6
2–2	76.2	50.3	40.6
2–3	99.1	20.1	25.4
2–4	122.0	61.0	30.5
2–5	93.3	67.7	40.6
2–6	94.8	53.4	25.4
2–7	85.1	63.1	40.6
2–8	93.3	63.1	40.6
2–9	147.3	61.0	40.6
2–10	76.8	57.3	30.5
2–11	105.5	68.3	40.6
2–12	110.7	73.8	40.6

3.2. Evaluation of the groundwater modeling performed to project future water quality in the water supply wellfield

A three-dimensional, groundwater flow and solute transport model was developed using the USGS code SEAWAT to evaluate the upper part of the Floridan Aquifer System during the BWRO plant design [5]. The development of the solute transport model and the data used in

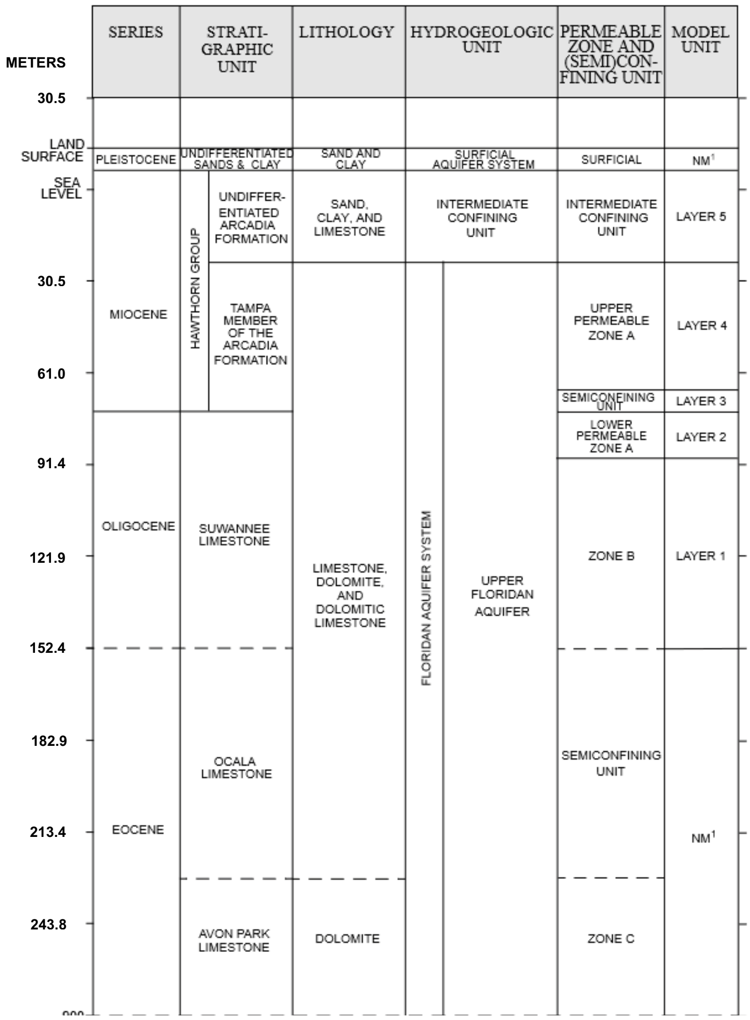

Fig. 3. Generalized hydrogeology of the aquifer system beneath the central Pinellas County/City of Clearwater area [11].

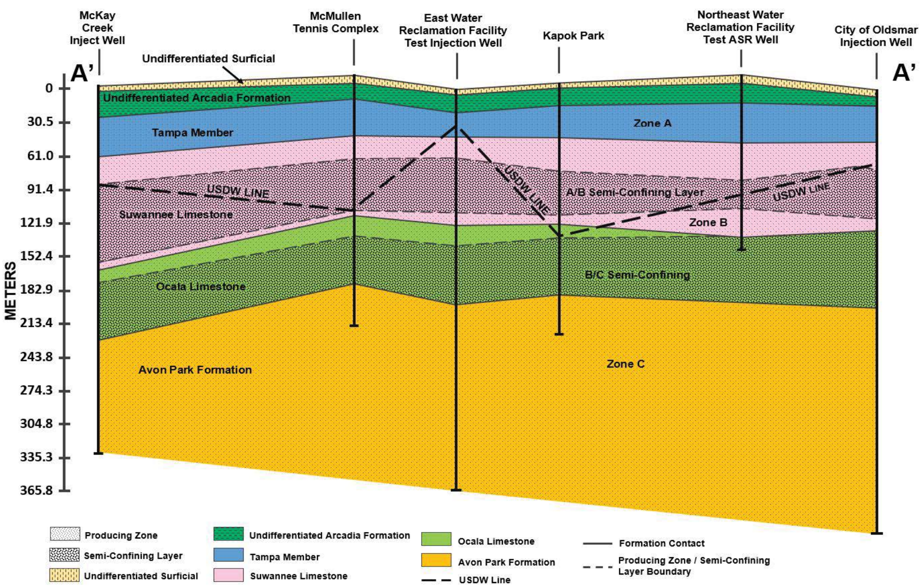

Fig. 4. Hydrogeologic cross-section showing the zones within the Floridan Aquifer System in the study area [5].

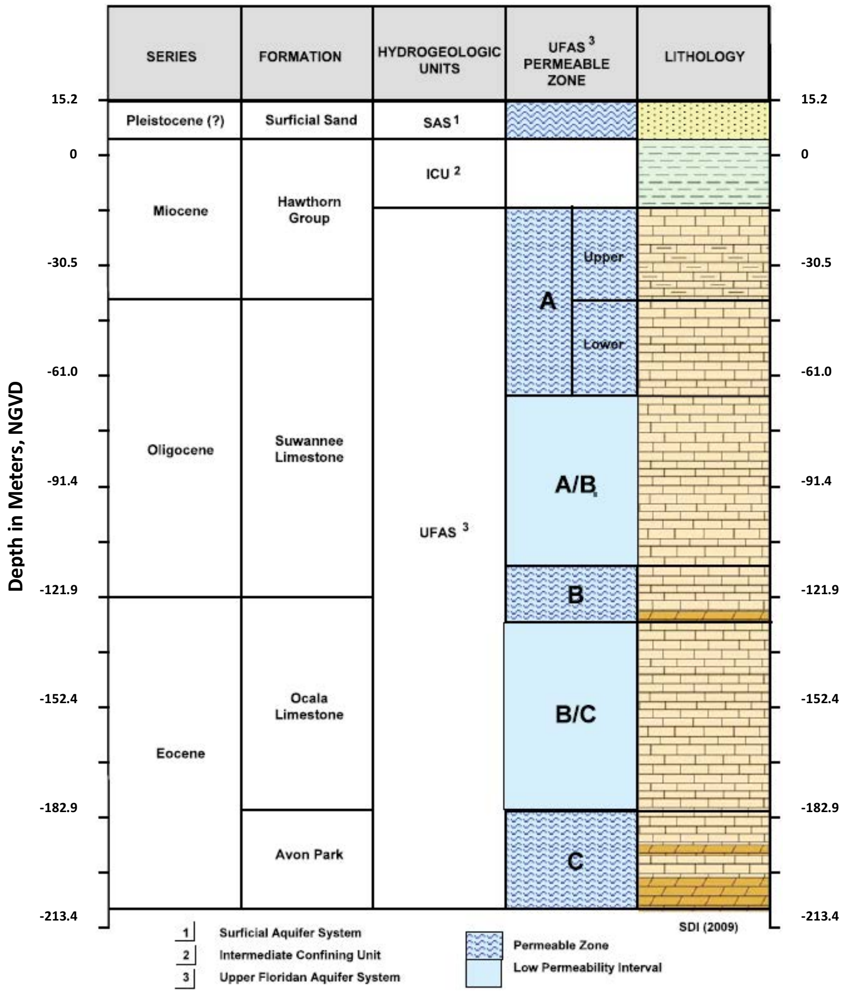

Fig. 5. Generalized Reservoir 2 area hydrostratigraphy, which contains the production wells for RO WTP No. 2 [5].

it were reviewed to assess the accuracy of the model and how the outputs were used in the BWRO process design.

The final version SEAWAT model developed for the BWRO plant design had a uniform grid spacing of 187.5 m (600 ft) in both the row and column directions as shown in Fig. 5 [5]. Vertically the model contains 21 layers, representing the hydrostratigraphic sequence (Fig. 6) from the surficial aquifer (SA) to Zone C of the FAS (Fig. 7).

The SAS was simulated as an unconfined aquifer. All layers within the ICU and UFAS were simulated under confined conditions. Constant head and constant concentration boundaries were specified around most of the model perimeter for the SAS and Zone A (layers 3–10), Zone B (layers 14–15), and Zone C (layer 21). General Head Boundaries (GHB) boundaries were used for an area on the coast of Tampa Bay and the Gulf of Mexico. The locations of the GHB and constant head and constant concentration boundary cells are shown in Fig. 8.

Yearly stress periods were used for 2012 through 2014 followed by a 30-y stress period for the water-quality impact analysis, which corresponds to the period 2015 through 2045. The predicted changes in dissolved chloride concentration with time in the brackish-water wells (Floridan Aquifer System) and the freshwater wells (Unconfined aquifer) are shown in Fig. 9.

The design criterion for the feed water TDS was set by the City of Clearwater to be 1,500 mg/L. The design of the BWRO plant was supposed to be based on the salinity prediction by the SEAWAT model (Fig. 9). However, the starting water TDS in the upper part of the FAS was near 1,300 mg/L. The modeled design criterion was assumed to be offset by mixing with freshwater in the SAS with a TDS of about 200 mg/L at plant startup.

The model predicted a steady increase of dissolved chloride concentration from about 700 mg/L in 2012 to approximately 1,600 mg/L in 2045. The TDS concentrations were about 1,300 mg/L at the start and increased to 3,000 mg/L by 2045. Based on actual data collected from the production wells, the model prediction significantly under-predicted the feed water salinity in both the FAS (brackish water wells) and SAS (freshwater wells).

3.3. Irregularity in pumping rates and feed water quality

Because of unexpected changes in water quality and the resultant operational difficulties at the BWRO plant,

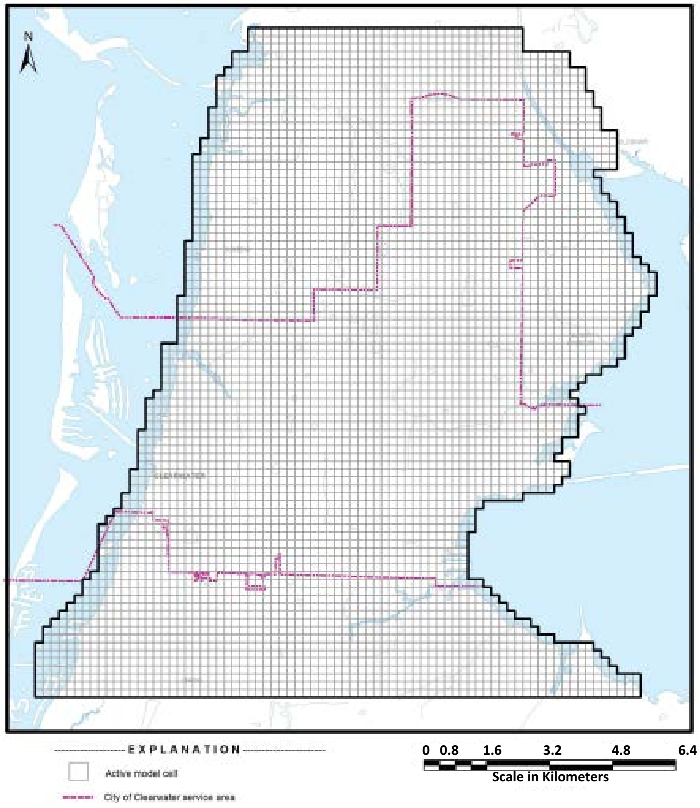

Fig. 6. City of Clearwater SEAWAT Model Active Grid [5].

Hydrostratigraphic unit	Interval thickness, m	SEAWAT model layer number
SAS	0.3 to 49.4	1
ICU	0.3 to 22.9	2
Upper zone A	4.3 to 18.0	3
		4
Less permeable zone	3.0 to 11.3	5
		6
		7
Lower zone A	14.0 to 51.8	8
		9
		10
		11
		12
Semi-confining A/B	10.7 to 80.8	13
		14
		15
Zone B	21.3	16
		17
		18
Semi-confining/C	30.5 to 57.9	19
		20
Zone C	45.7	21

Fig. 7. Summary of hydrostratigraphic intervals within the UFAS and SEAWAT Model Layers [5].

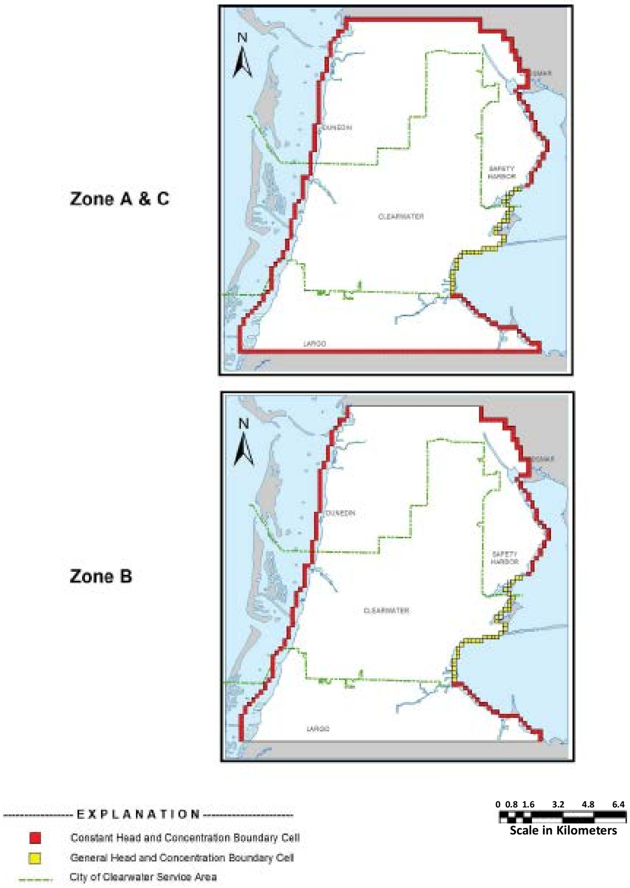

Fig. 8. Location of Constant Head and General Head Boundary Cells [5].

the pumping rates of the individual production wells have been quite irregular. Attempts were made by the facility operators to obtain a blend of well discharges to meet the plant operational requirements. The changes in dissolved chloride concentration and the associated pumping rates are shown in Fig. 10.

Production wells 51 and 52 tap the SAS, which is supposed to contain a stable freshwater quality. These wells have exhibited a linear upward trend in dissolved chloride concentration (Fig. 10). Well 51 had a starting dissolved chloride concentration of 50 mg/L and after about 2 y of pumping, it was up to about 350 mg/L. Well 52 had a starting dissolved chloride concentration occurring between 100 and 200 mg/L and after 4 y of variable pumping, the concentration was just above 300 mg/L (Fig. 10). If well 52 is assumed to have started at 100 mg/L, the rate of the rise in dissolved chloride concentration these wells averaged 71.25 mg/L per year. The model predicted rate of rise in the dissolved chloride concentration rate for the SAS wells for the 30-y model period was 4.2 mg/L per year.

Within the FAS production wells, there are a variety of behavior types with extreme differences in the rate of rise in dissolved chloride concentrations (Fig. 10). In all cases, a comparison of the change in dissolved chloride concentration and the corresponding rate of change shows that salinity increases during pumping conditions and reduces during periods of non-pumping.

The most consistent increase in dissolved chloride concentration in time was found in wells 2–11 and 2–12, which have monitored changes of 216 and 192.5 mg/L per year, respectively, with an average of 204 mg/L per year. The model predicted a change rate of 30 mg/L per year.

Perhaps the most extreme variation of dissolved chloride concentration with pumping occurs in well 2–1. Relatively short pumping durations produce extreme increases with subsequent recovery to near the baseline with cessation of pumping. Based on the slope of the increases, an annualized rate would be nearly 5,000 mg/L per year. Similar behavior to well 2–1 was found in wells 2–4, 2–5, 2–6. The observed rate of increase in dissolved chloride concentration during a pumping cycle was about 500; 2,800 and 707 mg/L per year, respectively. Well 2–3 has the most consistent behavior with an average annual increase of only 12.5 mg/L based on a 2-y pumping cycle. The dissolved chloride concentration during the 2-y pumping cycle never rose above 125 mg/L, which is extremely unusual for an FAS production well. The other production wells have such extreme variations that no pumping cycle rate of increase could be estimated with any degree of accuracy.

4. Discussion

4.1. Typical conceptual model for evaluation of salinity increase with time in BWRO systems in Florida

A large number of BWRO systems are operated in Florida [12]. Most of these facilities exhibit wellfield performance with a long-term and reasonably predictable increase in salinity caused by pumping [1]. A series of recently published papers has documented the variability in some of the feed water source wellfields [3,13–15]. In all of these BWRO systems, there is a degree of consistency based on a conceptual model that assumes that the production

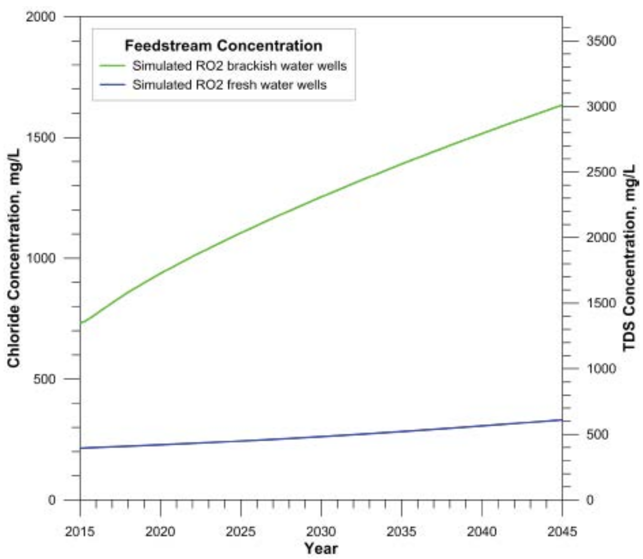

Fig. 9. Simulated feed water quality to the RO2 facility over 30 y [5].

aquifer is semi-confined, the confining units have a near constant thickness and leakance, the area of the confinement is infinite, and recharge is upwards from deeper aquifers containing higher salinity water (Fig. 11). Some variations in the general model have been attributed to the influence of localized vertical conduits that allow some water to leak upwards, therefore not primarily controlled by leakage through the basal confining unit. Such behavior during pumping can be caused by the presence of unplugged, abandoned wells [16] or faults [17]. Within the wellfields studied, the number of production wells influenced by localized conduits is generally small relative to the total number of production wells. This is not the case at the City of Clearwater.

4.2. Problems with the SEAWAT model used for prediction of future water quality changes

There are many possibilities that could lead to incorrect model prediction, including the construction of the model, model boundaries, initial aquifer conditions, input parameters (e.g., aquifer hydraulic properties), and use of an inaccurate conceptual model. Model calibrations typically last short time periods, therefore the effect of incorrect boundary locations, initial conditions, and leakance values can lead to incorrect model predictions.

One potential problem with a SEAWAT model is the selection of proper boundary conditions. A constant head-concentration boundary along the beach applied to model layer 1 (unconfined aquifer) was reasonable as it represents the Gulf of Mexico. However, a similar boundary condition applied to the same location (along the beach) in deep layers (in Zone B of the FAS), as used in the SEAWAT model for this BWRO plant design is shown in Fig. 8 [5], is not appropriate. Since the aquifer system extends offshore, it is unlikely that there is a constant head and constant dissolved chloride concentration boundary at the shoreline in this complex aquifer system. Under the pre-development condition, it is likely the fresher water moved into the aquifer below the Gulf of Mexico caused by up-gradient recharge from precipitation and horizontal flow. A saltwater/freshwater interface may also be found at some offshore location within the semi-confined aquifer. Groundwater withdrawals may reduce the hydraulic pressure inland, thus the position of the interface may shift landward. The magnitude of this shift is dependent on the groundwater pumping rates, aquifer hydraulic coefficients, and other factors. An artificially aligned constant head and constant salinity concentration boundary in the deep aquifer along the beach location would force the salinity of the inflow to assume the values specified along the boundary. Therefore, it is likely for the model to under-predict the salinity change over time based on this boundary position.

Another issue is how the modeling results were used. Groundwater modeling results always contain various degrees of uncertainty, so it is risky to apply the modeling results directly for an engineering design of the wellfield. The model prediction is made based on the available data when the model was built. The uncertainty of the data, conceptualization (conceptual model), assumptions, simplifications, etc. will all affect the modeling results. Also, the uncertainty likely grows with time during long-term predictions.

A sensitivity and uncertainty analysis should be performed to better understand the model and its results. In sensitivity analysis, the input parameters are varied within the ranges of their values to investigate the sensitivity of modeling results based on those input parameters. The results of model prediction then should be given as a possible range instead of a single set of values in a curve (uncertainty envelop). The range should include all possible results from the sensitivity runs (Fig. 12). The process is similar to use of the so-called spaghetti plots in hurricane prediction. It should be noted that those limits are determined from a series of simulation runs performed during the sensitivity analysis and they may not cover all possibilities. The actual concentrations predicted are bounded by the prediction limits. In an ideal world, one solution to the problem is to validate the model periodically and recalibrate it, if necessary, during the wellfield operation. The design of the BWRO plant may have to be modified, if the revised prediction causes issues with wellfield operation. In the real world, if the BWRO plant design is based on the model, the upper limit of the prediction should be used. This assumes that the conceptual model is accurate.

The City of Clearwater BWRO plant was designed to treat feed water with a TDS of 1,500 mg/L with a corresponding dissolved chloride concentration of about 800 mg/L. Based on the well data showing the dissolved chloride concentrations in the production wells (Fig. 10), it is quite clear that the design concentration was exceeded soon after plant startup. In addition to the construction and use of the model, there was also a problem with the conceptual model used for the model development. It should be noted that at the time the modeling was conducted, the "normal" conceptual model applied by to these types of simulations is that shown in Fig. 11.

4.3. New conceptual model for the upper FAS with pumping at the City of Clearwater site

There were two "surprises" discovered during the early operation of the City of Clearwater Reservoir 2 facility. First, water quality in the unconfined aquifer (SAS) was not constant and rapidly increased in salinity during pumping. Second, the wells tapping the uppermost zone of the FAS exhibited severe changes of salinity induced by pumping. In addition, there were considerable differences in the rate of salinity changes in the water pumped from the different production wells. The assumption that the unconfined aquifer wells had no significant source of higher salinity water within their cone-of-depression was incorrect. The assumption that the upper FAS wells would be sufficiently confined to have a relatively uniform leakance value was also wrong. Therefore, the conceptual model used in virtually all of the BWRO wellfields in other areas of Florida does not apply to the City of Clearwater site, which requires the use of a different conceptual model.

A new conceptual model for the area surrounding the City of Clearwater Reservoir 2 wellfield must include an explanation of why salinity increases were quite rapid after initiation of pumping and why there is so much variability in the rate of salinity change. The City of Clearwater lies in the north half of Pinellas County, Florida, which

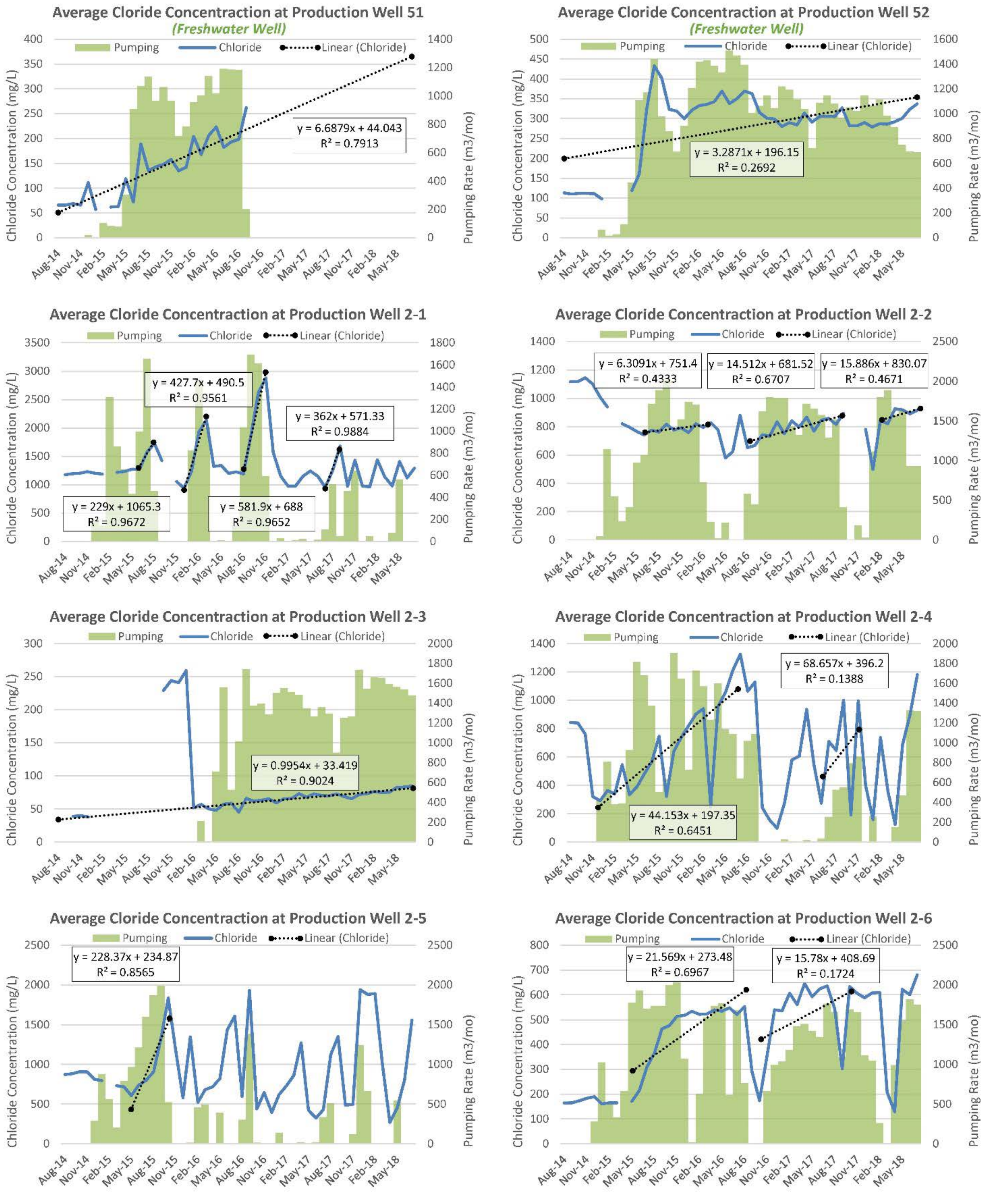

Fig. 10. Continued

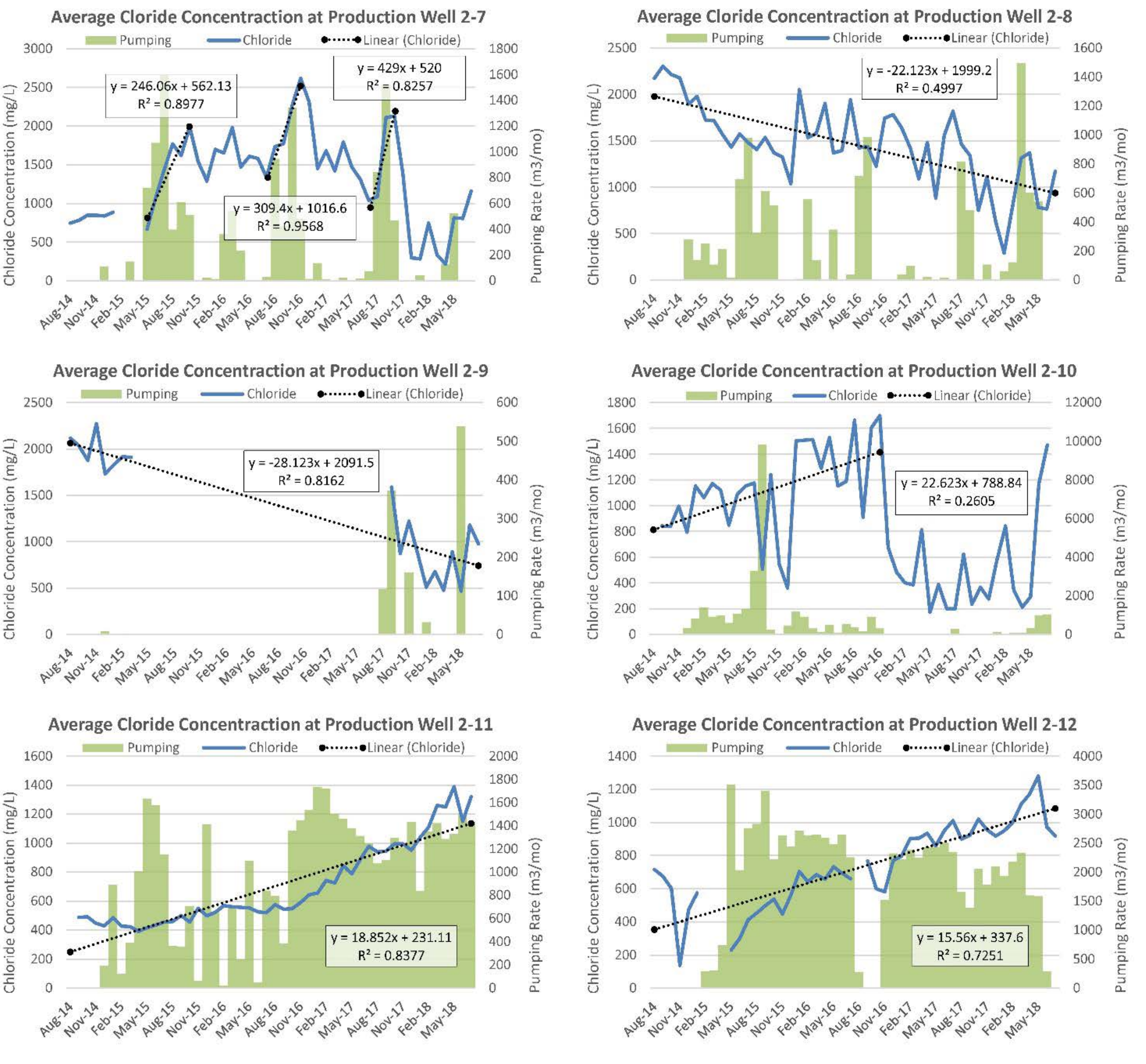

Fig. 10. Graphs depicting the pumping and dissolved chloride concentration for each production well from August 2014 through July 2018 with the associated pumpage for each month. Note that the green bars represent the monthly pumping volumes and the blue values are the measured dissolved chloride concentrations. The regression equations and R^2 values are shown. Note that wells 51 and 52 are freshwater wells that became brackish when pumped. Pumping of well 51 was curtailed due to the high rate of salinity change.

is a well-known sinkhole prone area. A map showing the location of sinkholes in or near the Reservoir 2 wellfield is shown in Fig. 13. The outline of the wellfield area is generally shown in red on the figure. Therefore, it is possible that the confining units in and near the City of Clearwater are perforated by karst conduits that interconnect various zones within the FAS and perhaps up into the SAS.

Based on the assumption that the integrity of the confining units within the aquifer system is open to question based on karst conduit issues, a new conceptual model is proposed and shown in Fig. 14. This conceptual model explains all of the changes in aquifer salinity during a pumping condition. Karst conduits could occur at various positions throughout the wellfield in varying distances to the production wells. The conduits could connect different zones within the FAS (A, B or C) and Zone A to the base of the SAS. The distance of a given production well to a conduit could determine the rate of salinity change with pumping. Where the distance is large, the wells would exhibit a slow rate of change related mostly to the aquifer leakance and well pumping rate (e.g., wells 2–11 and 2–12). The closer a production well is to a vertical conduit, the greater the rate of salinity increase (wells 2–1, 2–2, 2–4). Other wells showing extreme changes in water quality could occur in locations where higher

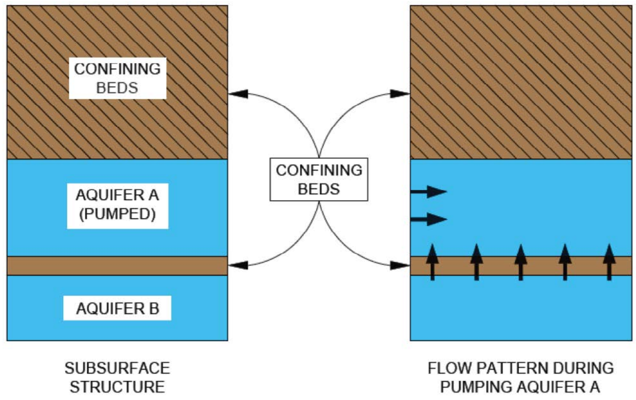

Fig. 11. Diagram of the upward recharge flow pattern of a brackish-water aquifer during pumping [3].

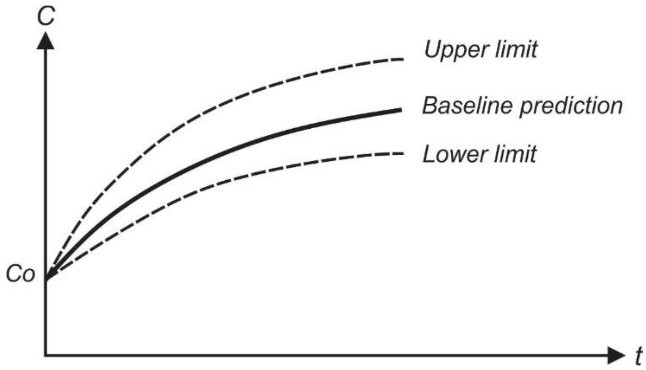

Fig. 12. Schematic of model predicted concentration with upper and lower limits based on the sensitivity analysis. C_o is the initial concentration.

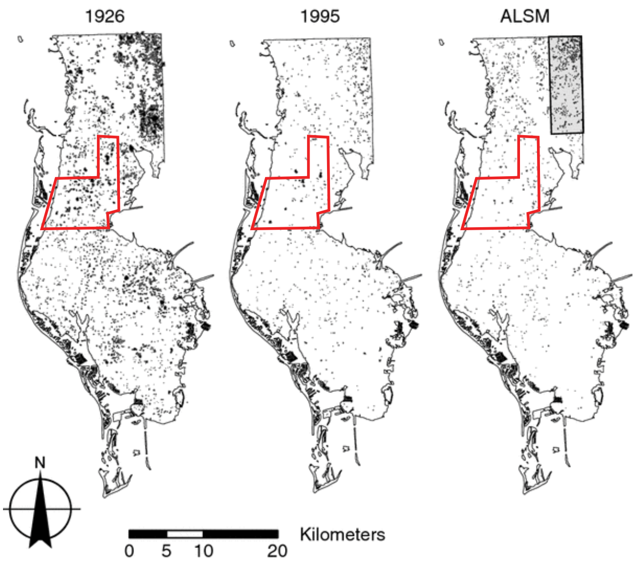

Fig. 13. Sinkholes found in Pinellas County, Florida in 1926, 1995, and Airborne Laser Swath Mapping (ALSM) [18–20]. The wellfield area is outlined in red.

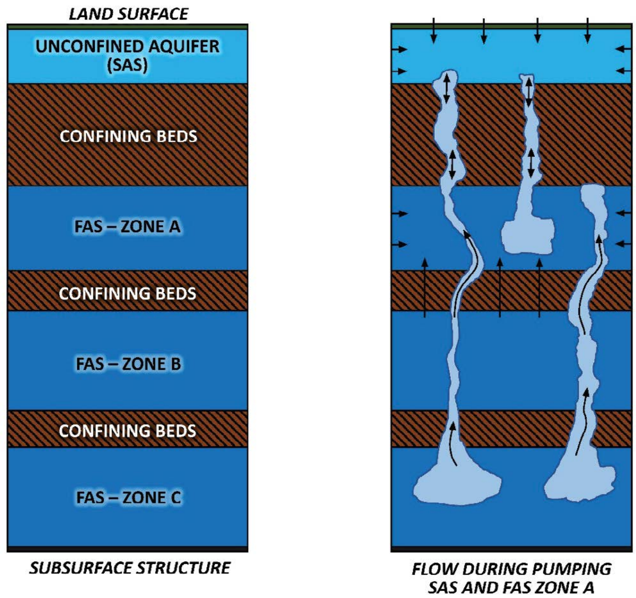

Fig. 14. Possible conceptual model for the City of Clearwater Reservoir 2 wellfield. Note that flow through the connecting karst conduits is based both on natural differences in head between zones and aquifers, on the production well pumping rate, and on the distance between a production well and the conduit.

salinity water has been moving upward and displacing less saline water in the production aquifer over time.

Based on the principle of non-uniqueness, the conceptual model shown in Fig. 14 may not be the only explanation for the behavior of the wellfield during pumping. An alternative conceptual model may involve possible horizontal saltwater intrusion from either the Gulf of Mexico or the bay into the unconfined aquifer to cause the quality change. In addition, the pumping-induced changes in water quality found in the FAS could be explained by the karst conduit model. However, the conceptual model shown in Fig. 14 may be the only one that could explain all of the pumping-induced changes within a single concept. There may be a variety of other conceptual models that could be considered based on multiple causalities, including density stratification within one or more hydrogeologic units.

Even if a solute transport model was constructed that utilized proper boundary conditions, another key observation of the modeling effort is that application of the new conception model (Fig. 14) would still likely underestimate groundwater salinity changes. It is unlikely that any solute transport model could be developed that would accurately predict groundwater quality changes in an aquifer system having the conceptual model shown in Fig. 14 impacts of the implied model on the BWRO plant design and operational challenges.

If the implied new conceptual model of the hydrogeology of the wellfield is accurate, the impacts on the process design of the BWRO plant would be extreme. There will be a need to increase the ability of the plant to treat feed water with a much higher salinity, which could require the use of seawater membranes in the future for some or all of the feed water.

Three possible strategies should be considered for the process design modification. One option would be to use several different sources of feed water for operation of the BWRO plant. Based on the past consulting reports, there are several possible combinations of sources that could be used. This approach to providing feed water to the BWRO membranes is shown in Table 2. This strategy would produce the desired 23,674 m^3/d (6.25 MGD), but would require a considerable amount of pipeline modifications, which could be quite expensive. In addition, the controls for the system would be costly. There will be considerable uncertainty in the feed water TDS concentration for the seawater RO skids based on the choice of which production wells to pump and the desired pumping rates. The TDS could range between 10,000 and 36,000 mg/L. Therefore, a very conservative conversion would be 50%, but would be up to 65% if the TDS concentration at the extremes of the range.

The second option would be to create a hybrid BWRO/SWRO facility that would use two different feed water sources. Various wells could still be used in the system to meet the overall blend required to provide potable quality water. This option would require at least two feed water pipelines based on the choice of production wells and/or the addition of some new production wells. Operation of the plant would be complex with the possible need for a blend tank to assure the desired TDS and hardness of the product water would be achieved.

The third option would be to abandon the BWRO process and replace it with SWRO. All of the existing production wells could be used, but the lower recovery percentage would necessitate a larger number of skids to be constructed and a larger footprint for the plant. Because the feed water quality will be brackish for many years of operation before it becomes seawater, the recovery rates would be as high as 65% in the early years and lessen to 50% when the TDS exceeds about 30,000 mg/L. This option would require a doubling of the plant footprint, but would not require new piping. Based on the selection of production wells used, the plant operation could be complex due to variable feed water TDS.

One of the key findings of this research is that karst aquifer systems are very difficult to accurately predict and evaluate future water-quality changes induced by pumping. The standard model of uniform occurrence of the confining units, uniform leakance, and lack of vertical conduits for enhanced vertical flow cannot be assumed. Therefore, the desalination solution may be to use a seawater membrane design with the ability to operate the facility at variable pressures, depending on water quality changes.

5. Conclusions

Groundwater used to supply BWRO plants typically exhibits a long-term increase in the TDS of the feed water. To project the change for design of the BWRO process, groundwater flow and solute-transport modeling of the source aquifer are conducted to assess changes in water quality over a 20 to 30-y operational period. Considerable reliance is commonly placed on the modeling results to assure that the plant will operate successfully for its useful life expectancy, usually 20–30 y.

The RO WTP No. 2 facility at the City of Clearwater, Florida, was designed to treat a feed water quality TDS of 1,500 mg/L. After a short operational period, the feed water TDS exceeded the design criterion with an observed range of 2,400 to 3,300 mg/L. Finished water bromate concentrations of 11.6 to 29.7 mg/L were also well above the design criterion of 10 ppb. Because of the higher than expected feed water TDS, the plant could only produce 9,470 m^3/L (2.5 MGD) of product water instead of the design capacity of 24,621 m^3/d (6.5 MGD), only 40% of the required capacity.

There were a series of flaws in the groundwater modeling used to establish the process design criterion of 1,500 mg/L. Three major issues were found, including the boundary conditions in the model were not set correctly, the wrong conceptual model of the aquifer system was used, and the model presentation produced only a single projected curve without containment by an envelope of error established by conducting a sensitivity analysis. Even if the modeling was conducted using proper boundary conditions, it was based on the "standard" conceptual model, which has been demonstrated to be inaccurate, and therefore, would have under-predicted water quality changes. Since design of the BWRO process was guided by only the single curve projection, it was insufficiently robust to deal with the higher salinity of the feed water.

Table 2
Feed water source and treatment scheme to meet the desired water supply quantity

Source	Flow (m^3/d; MGD)	TDS (mg/L)
WTP wells (BWRO)	9,545 (2.52)	1,820
Iron system filtrate (BWRO)	4,621 (1.22)	1,300
WTP-1 concentrate (BWRO)	2,424 (0.64)	3,000
Total feed water(BWRO)	16,591 (4.38)	1,836
Permeate (BWRO)	13,258 (3.5)	35
Blend from WTP-1 wells (BWRO)	1,894 (0.5)	700
Blend from WTP-2 wells (BWRO)	1,894 (0.5)	3,500
Total treated water (BWRO)	18,485 (5.38)	350
Seawater RO	6,591 (1.74)	10,000–36,000 (?)
Total treated water	23,674 (6.25)	250

The typical conceptual model that was used in the development of the solute-transport model of production aquifer assumes that pumping-induced recharge is from the bottoms upward. An infinitely wide confining unit with a relatively uniform thickness and leakance were also assumed. The pressure gradient across the confining bed was caused by a combination of natural head differences, the hydraulic properties of the production aquifer, and the wellfield pumping rate. The extreme changes in produced water from the wells indicate that the described conceptual model, which is used in the design of most wellfields that produce feed water for BWRO systems in Florida as described, is not valid. The most likely conceptual model includes a significant numbers of breaches in the confining units, which allows rapid upward movement of higher salinity water into the overlying aquifer during pumping of the production wells. The breaches in the confining aquifers are likely caused by karst conduits, either filled or open, which are pathways that allow the flow of water at lower resistance compared with the lower permeability confining units.

Use of karst aquifer systems containing conduits that connect aquifers as a feed water supply source for BWRO systems may be inappropriate. Even with the development of a sophisticated groundwater solute-transport model to assess future changes of water quality, the inherent uncertainty in the model predictions would necessitate a desalination plant design that can treat seawater. Because of the reduced pretreatment costs, the use of high-salinity groundwater as a feed water source would still be cost effective, as compared with using a seawater surface source.

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