



Article Pumping-Induced Feed Water Quality Variation and Its Impacts on the Sustainable Operation of a Brackish Water Reverse Osmosis Desalination Plant, City of Hialeah, Florida, USA

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Abstract: Brackish water reverse osmosis (BWRO) desalination of groundwater is believed to be a sustainable method of providing municipal utilities with a high-quality supply in regions where freshwater sources are stressed and not sustainable. A key aspect of water management is the ability to evaluate an aquifer containing brackish water to ascertain future pumping-induced water quality changes and their impacts on the facility operation and economics. The city of Hialeah, Florida, has operated a BWRO facility for the last 9 years. The facility has a maximum design capacity of about 88,000 m^3/d but is currently operating at about 33,000 m^3/d . The facility was designed to treat water with a TDS of up to 10,000 mg/L. A detailed hydrogeologic investigation, including groundwater solute-transport modeling, suggested that the salinity of the source water would remain under 10,000 mg/L of TDS during the 30-year life expectancy of the facility. However, after 9 years of operation, it was found that the rate of salinity increase was much higher than predicted (27.5%), at the low rate of $33,000 \text{ m}^3/\text{d}$. If the faculty was operated at the maximum capacity, the ability of the plant to treat the source water might be between 5 and 10 years. The conceptual model used to guide the solute transport modeling was not accurate for this site because it did not incorporate the apparent enhanced leakance through the basal confining unit below the aquifer. The greater leakance was likely caused by undetected, irregularly distributed fracturing of the underlying confining dolostones. The facility will require a major redesign to upgrade the process to be able to treat seawater at a TDS significantly above 10,000 mg/L in the future, should that occur. While the change will be costly, with a high capital cost to change the process, increased energy consumption, and overall higher water treatment cost, it is still more sustainable and has less environmental impact compared to other alternatives (e.g., treating tidal sources of seawater). The use of electricity from nuclear or solar generation could mitigate the environmental impacts of higher power consumption.

Keywords: brackish-water reverse osmosis desalination; sustainability; Floridan Aquifer System; municipal water supply; groundwater modeling

1. Introduction

The use of fresh groundwater in regions with rapid population growth commonly produces conflicts between public water supply, and agricultural and environmental stakeholders [1]. In addition, freshwater pumping from coastal aquifers can induce saltwater intrusion and impact wetland areas, causing an unsustainable consumption of water resources. Therefore, the desalination of saline water from deep aquifers with treatment by



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). reverse osmosis (RO) is an increasingly used water-supply solution in Florida and many other states within the United States, where there are abundant supplies of brackish ground-water [2]. The U. S. Geological Survey defines brackish water to have a total dissolved solids (TDS) concentration ranging from 1000 to 10,000 mg/L [2].

A key issue in the use of brackish water for desalination with the RO process is sustaining the raw water supply source that is coupled with the treatment process. As aquifers containing brackish water are pumped, the water quality is rarely constant and there is a common trend to observe increases in the salinity of the groundwater over time. The issue of sustainability in the use of brackish water aquifers with changing salinity has been evaluated by Missimer et al. [3]. They concluded that, despite the trends of increasing salinity, the water supply source is not being depleted, but instead, the cost of treatment increases in time based on the requirement to change the primary treatment process which increases the operating pressure that causes greater energy consumption. They point out that the only other alternate water supply source at the sites desalting brackish water is often tidal seawater, which would require much higher energy consumption and a generally higher cost to the consumer.

Successful design and operation of brackish water reverse osmosis (BWRO) desalination facilities are, collectively, an integrated engineering systems design issue requiring detailed understanding of both the water treatment process and the groundwater hydrology of the source aquifer [4]. An important challenge is that the TDS of the feedwater pumped from an aquifer system must remain within the treatment capability of the reverse osmosis process design [4].

BWRO membranes are designed to treat specific ranges in TDS concentrations. Some membranes function most efficiently in the range of 1000 to 3000 mg/L, whereas others produce freshwater from feedwaters with TDS concentrations ranging from 3000 to 6000 mg/L [5]. Once the feedwater TDS concentration exceeds 10,000 mg/L, the membranes required to treat the water will likely be a seawater membrane, requiring higher feed pressure that results in higher energy use [6], higher chemical costs [7–9], lower conversion rates [5], and an overall higher treatment cost to produce potable water [10]. BWRO costs do not significantly increase until the feedwater TDS increases to above 6000 mg/L, based on recent research [11]. However, if the TDS concentration of the feedwater rises above the maximum concentration that the installed membrane can treat, the facility can fail or require expensive retrofitting [12].

To avoid facility failure or expensive retrofitting, there are two possible engineering approaches to the problem. The first is to conduct a more detailed aquifer characterization, including solute transport modeling of the source aquifer to predict future changes in the feedwater TDS concentration, and then engineering the process design based on the upper envelope of the model prediction [4,13]. The success of this approach is based on the quality of the groundwater model developed to evaluate the site, which, in turn, is based to a high degree on the voracity of the hydrogeologic data collected during aquifer characterization [4,13]. The second approach is to use a very conservative process design that specifies a membrane capable of treating a much higher TDS concentration compared to that initially measured in the production wells. This approach does incur some greater costs for pumps (higher pressure and perhaps de-staged) and chemical feed systems that may not be necessary during the early operational stages of the plant. However, this approach may also be risky in that, if the aquifer system produces a rapid change in water quality, a major retrofit could become necessary.

The coordination of the engineering design and the hydrogeological investigations and modeling tends to give a more reliable result, based on several documented case studies [14–17]. Groundwater modeling produces two benefits for the system design, including a hydraulic analysis that assesses the water level (pressure) drawdown in the proposed wellfield, which is used for optimizing well spacing and yields, and the solute transport aspect, which predicts the changes in water quality (TDS or dissolved chloride) with time [4]. The groundwater model developed to evaluate the site-specific conditions needs to match the life expectancy of the BWRO facility, with a common range of 20 to 30 years based on the facility design criteria and the conceptual model of the feedwater source aquifer [13]. The most common conceptual solute transport model used in southern Florida shows that the changes in water quality are caused by the upward movement of higher salinity water during pumping, which is controlled to a large extent by the pumping-induced drawdown in the source aquifer and the leakance of the lower confining unit [18] (Figure 1).



Figure 1. Common conceptual model used in southern Florida to evaluate long-term changes in aquifer water quality for BWRO facilities (from Drendel et al. [18]).

The objective of this research is to document the correlation between the source aquifer solutetransport model prediction and the actual water quality data collected from the operating BWRO facility in the city of Hialeah, Florida (USA). This is an audit of a long-term model prediction and the real operating data, which has rarely been performed and published. It is very important to document case histories, in order to improve approaches to long-term groundwater solutetransport modeling and to assess the sustainability of the BWRO design in relationship to the aquifer behavior during pumping.

2. Background

2.1. Site Location and Background

The city of Hialeah is located in Miami-Dade County, Florida (Figure 2). For decades, the public water supply for all of Miami-Dade County, Florida was obtained by pumping groundwater from the Biscayne Aquifer, which is one of most productive freshwater aquifers in the world [19,20]. However, since this aquifer is heavily developed for water supply and has a very high transmissivity, it is subject to saltwater intrusion, which limits the sustainable yield of the aquifer [21,22]. Therefore, alternative water supplies are being developed to mitigate impacts to the unconfined freshwater aquifer system and to produce a more robust, multi-source water supply for Miami-Dade County [23].

2.2. Hydrogeology of the Upper Part of the Floridan Aquifer System

The source of the brackish water required to supply the BWRO plant is the Upper Floridan aquifer, which is the uppermost aquifer in the Floridan Aquifer System [19]. The Upper Floridan aquifer is 152 to 183 m (500 to 600 ft) thick along the coast of Miami-Dade County [24]. The dissolved chloride concentration in the Upper Florida aquifer ranges from about 1500 to 3000 mg/L and trends to higher values in the southern part of the county [24].

The site-specific geology from land surface to the Middle Confining Unit of the Floridan Aquifer System is shown in Figure 3. The Upper Floridan aquifer occurs in the carbonate rocks of the lowermost section of the Hawthorn Group (Arcadia Formation), a thin section of the Suwannee Limestone, and the upper part of the Avon Park Formation. It is apparent from the geology that the aquifer is extremely well-confined at the top by 92 m (300 ft) of very low permeability sediments within the Hawthorn Group (Figure 3). At the base of the aquifer, it is confined by lower permeability rocks within the Avon Park Formation. The degree of confinement above the top of the aquifer is believed to be much higher compared to the lower confinement. During aquifer pumping, the aquifer behaves as a leaky or semiconfined system, with water rising from the bottom upwards through the basal confining unit, as illustrated in Figure 1.



Figure 2. Location showing the site location of the water supply wells and water treatment plant (heavy red line).

To determine the aquifer hydraulic coefficients, an aquifer pumping test was conducted for about 4.8 days. Drawdown was measured in the test production well and three monitoring wells constructed at distances of 28, 223, and 386 m (93, 730, and 1265 ft) from the test production well. Based on a variety of analytical techniques, the calculated transmissivity at the site ranged from 522 to 604 m²/d (5500 to 6500 ft²/d), the storativity was 5×10^{-4} , and the leakance values were calculated to range from 1.5×10^{-4} to $4.1 \times 10^{-4} d^{-1}$ [19]. The values for leakance are critical in the analysis because the pumping rate, well spacing, and leakance are the principal controls over pumping-induced, long-term changes in water quality [4,13].

0 Sandy fossiliferous limestones (wackestone). MIAMI LIMESTONE. FT. THOMPSON FM. KEY LARGO LMS. SURFICIAL AQUIFER SYSTEM highly transmissive Sandy fossil/forous (mostones (wackostone/pacie/tone) TAMIAMI EM Sandy limestones, calcareous sandstone, clayey silt, silty sands, fossiliferous, silt and sand-sized phosphate grains, light olive gray (10YR 5Y 5/2) INTER-76.2 MEDIATE CONFINING UNIT 333 HAWTHORN GROUP 152.4 101110 Sandy fossiliferous limestones (wackestone). very fine-grained sand sized phosphate grains, light olive gray (5Y 7/1) UNNAMED AQUIFER Depth (meter below land surface) Limestones interbedded with marl and clay, fossiliferous, phosphatic, yellowish gray (5Y 7/2) to light olive gray (5Y 7/1) 228.6 INTER-MEDIATE CONFINING UNIT 304.8 Limestone, fossiliferous (wackestone), dolomitic limestones, clay, phosphatic, yellowish gray (5Y 7/2) to pale yellowish brown (10YR 7/2) SUWANNEE LS UPPER FLORIDAN Limestones (grainstones) and dolomitic RDANAQUIFER SYSTEM 381 limestone, very pale orange (10YR 8/2), cone-shaped dictyoconid foraminifera, and AQUIFER ŰШ centimeter-sized echinoids TH ΠŤ AVON PARK FORMATION Limestones (grainstones) and dolomitic 457.2 WITH limestone, grayish orange (10YR 7/4) F.O MIDDLE CONFINING UNIT

Figure 3. Hydrostratigrahic column for the city of Hialeah wellfield [19].

Since the test production well and the monitoring wells were drilled using the reverse air rotary method, water quality data were collected with depth to assess the variation. As illustrated in Figure 4, the dissolved chloride concentration was relatively constant, at nearly 1200 mg/L between 335 and 396 m (1100 and 1300 ft) below surface and increasing from 1200 to nearly 2200 mg/L from 396 to 534 m (1300 to 1750 ft) below surface.

2.3. Groundwater Modeling to Assess Future Changes in Feedwater Quality

A solute transport model was developed using the SEAWAT code, which simulated density-dependent fluid movement and solute transport [25,26]. The SEAWAT code couples the groundwater flow model code MODFLOW [27] with the MT3DMS model [28]. The conceptual model used is similar to that shown in Figure 1.

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Depth (m)



Figure 4. Dissolved chloride concentration with depth in the test-production well and monitoring wells [19].

Since several large-scale solutetransport models had previously been constructed for this region, these models were utilized to establish the aquifer boundary conditions for the local model used in the city of Hialeah wellfield evaluation. The Phase II Lower East Coast model, developed by Golder Associates [29] for the South Florida Water Management District, was used to assess the boundary conditions. This is a 14-layer model that was calibrated to regional potentiometric surface maps. The local model was centered in the regional model using the telescopic mesh method [30,31]. The local model was calibrated using a transient method tied to the water levels measured during the aquifer test. Additional aquifer performance test data were added to the grid before calibration.

The first step in the groundwater modeling process was to run a groundwater flow model using MODFLOW to assess the drawdowns in the wellfield and optimize the spacing of the production wells. The withdrawals were assumed to be taken from 12 primary wells and 2 backup wells (not shown) (Figure 5). The prediction simulations were run for 30 years. The wellfield pumping rate was $50,492 \text{ m}^3/\text{d}$ (13.33 MGD) for the first 6 years, $64,395 \text{ m}^3/\text{d}$ (10 MGD) for the next 10 years, and $88,371 \text{ m}^3/\text{d}$ (23.33 MGD) for the last 12 years. The simulated drawdowns for model layer 3 (approximately 3330 to 454 m below surface) are shown in Figure 6. Note that the maximum drawdown in the production wells in the center of the wellfield is about 24 m (80 ft).

During the development of the local model from the regional model, the hydraulic parameters were translated from the regional model and preserved in the local model. After the local model was created, the aquifer properties, including the top and bottom layer elevations, and the hydraulic parameters, including the hydraulic conductivity and specific storativity, were revised locally based on the field data collected for this study. In the original model, the bottom of the Upper Floridan aquifer is located at approximately -409 m (-1341 ft) NGVD-29, while the field geologic data indicate that the bottom of the Upper Floridan aquifer is located at approximately -448 (-1470 ft) NGVD-29. The model layer thickness was changed to reflect this difference.



Figure 5. Wellfield design showing the existing production well locations. The test production well is PW-1 [20].

The local model was updated with the water quality data collected during the field program. A constant TDS concentration of 3500 mg/L (equivalent to a dissolved chloride concentration of about 1645 mg/L) was applied to the Upper Floridan aquifer in the vicinity of the proposed wellfield, based on the field data. The TDS concentration assigned to the confining unit (MCU or model layer 6) was 4750 mg/L (dissolved chloride of about 2138 mg/L), which was obtained from the regional model and verified by the field data.

A 30-year model simulation was run using dissolved chloride concentration, because chloride is a non-reactive solute and would require no additional corrections for the removal or reaction of various ions in the water moving through the confining units. A detailed sensitivity analysis was performed for the simulation to create an envelope of error for the 30-year operations period. The final model prediction is shown in Figure 7. It is observed that the error in prediction increases over time, with the upper side of the envelope deviating further away from the base run compared to the lower range value. The base run lies closer to the low range than the high range. The high range is always recommended for use in the process design, with a caveat that unexpected issues can occur when models are conducted for this long period. Any solute transport model prediction using the conceptual model as shown in Figure 1 assumes that the changes in water quality

originate from more saline water leaking upward into the production zone from below. Any variations in water quality within the production aquifer caused by anthropogenic sources of higher salinity water, such as unplugged test wells or old, unplugged oil test wells, cannot be predicted. Other natural issues such as unmapped faults or open karst features also cannot be predicted, but have a low likelihood of occurring. In addition, no consideration is given to the horizontal intrusion of higher salinity water, based on regional data that shows that the anticipated capture zone of the production wells is not far enough seaward to induce high salinity water movement.



Figure 6. Simulated drawdowns (m) in model layer 3 based on 88,371 m³/d (23.33 MGD) from the Upper Floridan aquifer for 30 years [19].

2.4. Design of the Brackish Water Treatment Facility and Water Quality Treatment Limitations

The full design capacity of the BWRO water treatment plant is 64,394 m³/d (17 MGD), with the first phase being 37,879 m³/d (10 MGD) [19]. The design conversion rate for the facility is 75% for the first phase. Therefore, the first phase (6 years) will require 50,492 m³/d (13.33 MGD) of feedwater. At full capacity, in 10 years, the conversion rate is expected to decline to about 73% based on the increase in TDS concentration. Therefore, the required feedwater volume will be 88,371 m³/d (23.33 MGD).

The process design for the maximum TDS that can be treated by the membranes was set at 10,000 mg/L, or a dissolved chloride concentration of about 4700 mg/L. The upper end prediction of the solute transport modeling indicates a maximum dissolved chloride concentration of about 6400 mg/L. If the feedwater TDS would rise above this number, the plant would require a major retrofit that would likely include new membranes, pumps with a higher pressure rating, and a reduced conversion rate. A reduced conversion rate would likely necessitate the addition of more production wells. Additional production wells might also be needed to reduce the average salinity of the feedwater. The reason to



perform pre-design solute transport modeling is to avoid this issue during the operational lifetime of the facility. Should any retrofitting be required, it would likely occur during a membrane replacement cycle, which is commonly 5 to 7 years.

Figure 7. Simulated ranges of dissolved chloride concentrations in mg/L versus time in years [19].

3. Methods

3.1. Water Use and Quality Data Collection

Information on the operation of the BWRO wellfield was provided by Miami-Dade County. The data include monthly pumping rates for the production wells and the water quality parameters, with the most important being the monthly measured dissolved chloride concentrations. These data were plotted to show the variation in dissolved chloride concentration changes over time.

3.2. Statistical Analysis of Data

A regression analysis was performed on the dissolved chloride concentration data to evaluate the trends based on 9 years of actual data. The R^2 and *p*-values were determined to ascertain the quality of the regression match to the data and its statistical significance. Based on previous analyses of this type, the scatter can be significant based on the quality of the analytical technique used to measure the dissolved chloride concentration. The resultant regression equations are considered to be significant if the *p*-values are less than 0.05.

Once the regression equations were obtained for each production well, they were used to project future chloride concentrations at 5, 10, 20, and 30 years. The actual operating data and the projections were then averaged, and compared to the solutetransport model to ascertain its accuracy.

4. Results

Change in Salinity in Wells Used for Water Supply for the Past 9 Years of Operation in the Upper Floridan Aquifer

The current wellfield consists of 10 production wells, as shown in Figure 5. The construction details and the initial dissolved chloride measurements made on these wells are given in Table 1. Note that the geology was rather uniform across the site, which

allowed the casing and total well depth to show very little variation. However, the initial dissolved chloride concentrations varied from 1340 to 1860 mg/L, or a difference of 39%.

Table 1. Construction details and initial dissolved chloride measurements made on water obtained for the wells. Note that wells P-2 to PW-14 contained 40.6 cm of PVC casing to a depth of 45.7 m and 30.5 cm to the base of the casing.

Well	Diameter (cm)	Cased Depth (m bls)	Total Depth (m bls)	Initial Dissolved Chloride Concentration (mg/L)
PW-1	39	329.9	454	1630 (end of APT)
PW-2	40.4–30.5	329.9	443	1710
PW-3	40.4–30.5	329.9	456	1860
PW-4	40.4–30.5	329.9	447	1460
PW-5 *	40.4–30.5	329.9	454	NA
PW-6 *	40.4–30.5	329.9	454	NA
PW-7 *	40.4–30.5	329.9	454	NA
PW-8	40.4–30.5	329.9	458	NA
PW-9	40.4–30.5	329.9	457	1240
PW-10	40.4–30.5	329.9	451	1410
PW-11	40.4–30.5	329.9	452	1340
PW-12	40.4–30.5	329.9	458	NA
PW-13	40.4–30.5	329.9	464	1540
PW-14 *	40.4–30.5	329.9	454	NA

* Permitted but not yet constructed.

For the first 9 years of operation, six production wells were pumped to provide the feedwater, instead of using all 10 wells. The initial data obtained for the dissolved chloride concentration of each well were collected in August 2013, and the last data presented on this water were collected in August 2022. The average daily pumping rate was determined for each year of operation. The original solute transport model was constructed using assumed daily pumping rates of 50,492 m³/d (13.33 MGD) for the first 6 years and 64,395 m³/d (17.01 MGD) for the next 10 years, and an ultimate capacity of 88,371 m³/d (23.33 MGD).

The actual pumping rates and measured dissolved chloride concentration measurements are presented in Figure 8. The correlation of the dissolved chloride concentrations to the regression line best fit lines ranges from R² values of 0.1675 to 0.8687, with an average of 0.5875. The *p*-values range from 5.23×10^{-45} to 2.2×10^{-6} , with an average of 5.84×10^{-26} . While the correlation of the data points to the regression line is rather low, all of the regression curves show statistical significance based on *p*-values of less than 0.05. Changes in the dissolved chloride concentration over time show low slopes in wells 2 and 3 and much higher slopes in wells 1, 4, 5, and 6.

The average starting dissolved chloride concentration of the wellfield was 1588 mg/L, and the ending average after 9 years of pumping at an average of 32,339 m³/d was 2638 mg/L, for an average annual increase of 116.67 mg/L (Table 2). There was significant variation in the rate of change based on the location of the individual wells in the wellfield. Wells 1, 10, and 11 in the northern part of the wellfield showed an average change in dissolved chloride concentration of 178.89 mg/L, compared to wells 2, 3, and 4 at the southern end of the wellfield, which averaged 54.45 mg/L.



Figure 8. Monthly pumping rates and dissolved chloride concentration measurements for nine years of operation. A linear regression line is shown for the chloride data and the statistical fit of the data to the line (\mathbb{R}^2 and *p*-values) is also shown.

Well No.	Starting Dissolved Chlorides (mg/L)	Ending Dissolved Chlorides (mg/L)	Annual Rate of Change (mg/L/yr)	5-Year Proj.	10-Year Proj.	20-Year Proj.	40-Year Proj.
PW-1	1690	3500	201.11	4666	5943	8495	13,600
PW-2	1710	1770	6.67	1855	1934	2092	2409
PW-3	1720	1880	17.78	2114	2306	2689	3455
PW-4	1530	2780	138.89	3303	4062	5579	8613
PW-10	1430	2750	146.67	3711	4637	6487	10,189
PW-11	1450	3150	188.89	4317	5489	7831	12,517
Average	1588	2638	116.67	3328	4112	5529	8964

Table 2. Starting and ending dissolved chloride concentrations for all 6 active production wells, along with a projection of future concentrations based on the regression lines calculated from the data collected from each well. Average values were calculated for the measured and projected concentrations.

5. Discussion

5.1. Projected Changes in Water Quality Based on the Regression Equations Developed from the Monitoring Data

The actual data collected from the wellfield are summarized in Tables 2 and 3. The changes in the dissolved chloride concentration measured varied significantly between the production wells. The pumping rate in the first year of operation averaged close to 22,000 m³/d, and in the 9th year averaged about 33,000 m³/d. The average annual change in the dissolved chloride was 116.67 mg/L for the nine years of operation. The linear regression equations, as approximations, were used to make projections for 5, 10, 20, and 40 years beyond the operational period, as shown in Table 2. It should be noted that these projections are based on current pumping rates, which are only 37% of the ultimate wellfield capacity. Based on the water supply plan, the projected chloride concentration at higher future pumping rates could increase these values between two and three times.

Solute-Transport Model Projection				Actual Data (9 yr) and Regression Equation Projection			
Year	Projected Pumping (m ³ /d)	Avg. Dissolved Chloride (mg/L)		Year	Actual Pumping (m ³ /d)	Avg. Dissolved Chloride (mg/L)	
		Base	High			1588	
1	50,492		Ũ	1	22,070	1705	
2	50,492			2	27,682	1822	
3	50,492			3	29,024	1939	
4	50,492			4	34,618	2056	
5	50,492	1650	1750	5	28,432	2173	
6	50,492			6	33,411	2290	
7	64,395			7	33,662	2407	
8	64,395			8	33,362	2523	
9	64,395			9	32,339	2638	
10	64,395	1700	2000	10	32,339	2755	
15	64,395	1750	2200	15	32,339	3328	
20	88,371	1800	2500	20	32,339	4112	
30	88,371	2000	3100	30	32,339	5529	

Table 3. Comparison of the solute transport projected change in dissolved chloride concentration to actual measurements for the first 9 years of wellfield operation and future projections.

The R^2 values shown in Figure 8 show a wide variation, with three values wellcorrelated, ranging from 0.7922 to 0.8687, with one value with a medium correlated at 0.5299, and two values with rather low correlations at 0.3235 and 0.1675. The variation of these values is likely caused by the method of wellfield operation, as some wells were pumped for longer times than other wells. Additionally, there is some analytical error in the analysis of the chloride concentration in the laboratory. Despite some low R^2 values, all of the regression analyses have very small *p*-values; therefore, all are statistically significant. The varibility in the dissolved chloride values across the wellfield is likely caused by variations in the leakance of the lower confining unit. This issue in further explored in Section 5.3.

5.2. Comparison of the Groundwater Solute-Transport Model Results versus the Actual Measured Changes in Water Quality

A comparison of the actual wellfield data to the past solute transport model projections is shown in Table 3. The measured changes in the dissolved chloride concentrations in the 9th year of operations, at 37% of the full capacity of the wellfield, were already about 27% above the high range for the full wellfield capacity in the 10th year of operation. The solute transport model significantly under-predicted the changes in salinity at the wellfield site. While a long-term aquifer performance test was conducted on the site to obtain accurate values of transmissivity and leakance, there appears to be some feature onsite that has enhanced the upward movement of higher salinity water at a rate above that controlled by the measured leakance (see Section 5.3 for an explanation). No evidence was found that the increase in salinity was impacted by the horizontal movement of higher salinity water within the Upper Floridan aquifer.

5.3. Conceptual Model of the Water Quality Changes

The conceptual model used in creating the solute transport model at the city of Hialeah wellfield has been used successfully in numerous other long-term projections of water quality changes for BWRO system design in Florida [4,12,14–17]. However, one system, the Collier County South wellfield, showed an over-prediction of salinity that required a modification of the standard model to add a downward component of freshwater [32]. The city of Clearwater facility has had extreme increases in the salinity of the feedwater, despite the creation of a pre-design solute transport model [12]. In this case, the area was riddled with open karst features (sinkholes) that made the development of an accurate solutetransport model virtually impossible [12]. Very high rates of feedwater salinity increases have been reported for other BWRO wellfields in Florida, including the North Collier County site [4], North Lee County, the city of Hollywood, and the Lake Region facility in western Palm Beach County.

Based on the comparison of the city of Hialeah monitoring data to the original solutetransport model predictions, the original conceptual model does not accurately predict the observed changes, as shown in Table 3 Therefore, the aquifer system at the site must have a different conceptual model compared to the original model presented in Figure 1.

There are two possible explanations for this aquifer behavior. First, the dolostones constituting the lower confinement between the Upper Floridan aquifer and the underlying aquifer may be fractured, thereby enhancing the leakance value in parts of the wellfield above those measured onsite. Second, there may be karst features that allow the upward movement of higher salinity water within the aquifer system.

The fracturing of the dolostones is the favored explanation for the enhanced upward movement of higher salinity water under pumping conditions. Missimer and Maliva [33] described a tectonic event in the Middle to Late Miocene that placed southern Florida under compressive stress and caused some thin-skinned folding and fracturing of highly competent carbonate rocks, such as the dolostone units that provide confinement beneath the between aquifers within the Floridan Aquifer System. The fractures within the dolostones are likely to be partially annealed, and under a non-pumping condition allow only the minor upward movement of higher salinity water. Under an enhanced hydraulic gradient from pumping, greater upward movement of more saline water would occur, which could explain the 37% variation of the dissolved chloride concentration within the wellfield.

It is quite unlikely that open karst conduits could explain the enhanced upward leakance. It is more likely that karst conduits within the Eocene to Early Miocene carbonate units, if present, are filled with mud that occurs within the upper confining unit. Therefore, the karst features would have a lower hydraulic conductivity compared to the carbonate

rocks forming the aquifer system, and would not influence the upward movement of higher salinity water.

A proposed conceptual model for the Upper Floridan aquifer in the wellfield is shown in Figure 9. The key deviation from the original conceptual model is the enhanced leakance that allows for greater quantities of higher salinity water to enter certain wells within the wellfield (e.g., those showing the highest rates of the dissolved chloride concentration increase). The data from the wellfield suggest that the pattern of fracturing is non-uniform, and may or may not occur near and impact various wells within the wellfield. The slow, low-rate upward migration of more saline water is occurring throughout most of the wellfield areas (as indicated by the initial modeling results), but more rapid migration is occurring near fracture zones (Figure 9).



Figure 9. New conceptual model for the city of Hialeah wellfield.

5.4. Assessment of the Impacts of Water Quality Changes on the Future of the Plant Operation

The BWRO process design was made to have a maximum TDS of the feedwater at 10,000 mg/L for a maximum pumping rate of 88,371 m³/d (23.33 MGD). The design of the process included an estimated recovery of 73%. The life expectancy of the plant was designed to be 30 years. During the solute transport modeling, the relationship between the TDS and dissolved chloride was to be that dissolved chloride was 47% of the TDS. A detailed study of the TDS/chloride relationship in Cape Coral Florida determined that the equation TDS (mg/L) = $1.5934 \times (Cl (mg/L) + 479$ was a more accurate means of estimating TDS from chloride concentration [14]. This equation implies that a dissolved chloride concentration of 5975 mg/L would produce a TDS concentration of 10,000 mg/L. Therefore, the design capacity of the BWRO plant would be exceeded when the dissolved chloride occurred between 4700 and 5975 mg/L, depending on which ratio is correct at this site.

The measured data and the linear regression of the current pumping rate of $33,362 \text{ m}^3/\text{d}$ (8.8 MGD) show that the BWRO process would be sufficient to allow the operation of the facility to the 30-year operational life expectancy, or 21 years from August 2022. However, if the plant was operated at its full capacity of 88,371 m³/d (23.33 MGD), the rate of the dissolved chloride increase could rise to 2.6 times faster than at the current rate.

If the plant output were to be increased slowly to the maximum capacity over 5 years, the BWRO plant would likely have to be retrofitted with a new process (seawater RO membranes) by the end of that period, as the 10,000 mg/L design concentration would be exceeded. This would require high-pressure pumps to be installed, with the ability to increase pressure to 69 bar (1000 psi). In the early years, after the 10,000 mg/L TDS is exceeded, the pumps could be de-staged to run at lower, more economic pressures. The overall plant conversion rate would reduce from a 73% rate in the next several years to 50%, as the TDS approaches 35,000 mg/L in future years. That would require the full 69 bar (1000 psi) pumping pressure to achieve operational efficiency. To produce a product

capacity of 75,758 m^3/d (20 MGD) based on a feedwater TDS of 35,000 mg/L, the wellfield capacity would have to be increased to 151,515 m^3/d (40 MGD). This would require at least 14 new production wells and a near doubling of the desalination plant footprint. In addition, two new injection wells would be required, as the concentration would double.

Salinity in the southwestern corner of the wellfield (wells 2 and 3) has been more stable. The average salinity of the feedwater might be reduced by the construction of additional production wells in that direction.

Based on the discovery of the enhanced rate of leakance, the wellfield should be remodeled using the actual well data for calibration, and some new timeframes for higher-use rates should be carefully planned. The upper limit of the new envelope of error could be used as a guideline, based on a variety of boundary conditions and pumping rates. The capital improvements required to operate the plant can be staged over many years. Improvement plans should be updated based on the observed water quality trends and overall utility needs.

5.5. The City of Hialeah Desalination Facility within the Context of Sustainability

The discovery of the higher than expected increase in the salinity change does not equate to an unsustainable situation. Within the context of the definition of sustainability, it is defined as the pursuit of maintaining the natural system in a condition that will not impact future generations. The issue of sustainability within the operation of a municipal utility also includes an economic factor.

The feedwater quality at the city of Hialeah wellfield will become more saline over a limited period, ultimately necessitating the need to change the process from brackish water membrane treatment to a seawater membrane treatment. The system will have to operate at an increasingly higher pressure as the TDS concentration increases above 10,000 mg/L. This change in process will progressively require more energy to operate the RO process and will require expensive capital costs to upgrade the overall design of the plant, wellfield, and concentrate disposal. The question arises: "Does this change in conditions caused by the pumping of the aquifer constitute a violation of the fundamental principle of sustainable groundwater use?"

First, the desalination of brackish water from the Upper Floridan aquifer was a replacement for using freshwater from the Biscayne Aquifer to prevent the development of a non-sustainable use, in that saltwater intrusion would have damaged the aquifer and environmental impacts could have impacted wetlands and perhaps other natural system habitats. Despite the rise in the cost of water treatment, the water supply in the source aquifer does become more expensive to treat, but is still a viable water supply source for future generations. So, from an environmental view, the increasing salinity does not directly impact the environment and could be defined as sustainable. The change in water salinity, however, causes an increase in the amount of electrical energy consumed to operate the facility, which can be considered as an indirect impact. If this electricity is provided by nuclear or solar power, then there will be a low impact on emissions of carbon dioxide and thus contributions to global warming [33]. Therefore, there is a solution to sustainably operating the facility.

The economics of the facility operation merit some analysis. An analysis of an alternative water supply source for the facility would reveal that tidal seawater could be used to supply this or another seawater reverse osmosis (SWRO) desalination plant. While tidal seawater would not likely exhibit any increase in salinity, it does contain a high concentration of organic material that must be removed during the treatment process, before the water enters the primary membrane process [34]. Although the increase in the TDS concentration of the feedwater will exceed 10,000 mg/L, it is unlikely that the TDS will ever reach a typical seawater concentration of 35,000 mg/L. Even if the feedwater did increase in TDS to 35,000 mg/L, the operation of an SWRO plant using groundwater instead of tidal seawater would cost somewhere between 10 and 25% less, based on the extensive pretreatment processes required to exclude organic material from the primary membrane process and lessen the rate of membrane biofouling [10,35]. In addition, there are other environmental impacts of operating an SWRO desalination plant using a tidal seawater source. The primary impact is the entrainment and impingement of marine organisms [36]. In the case of the city of Hialeah, there would also be the cost of adding a pipeline from the coast and an onshore intake. In both cases, the environmental impacts of the concentration discharge to tidal water could be avoided by using deep well injection for disposal [37]. Therefore, it can be concluded that, despite the increase in water treatment cost that will occur over the next 10 to 15 years, the continued use of the Upper Floridan aquifer at this location is the least costly water supply alternative and must be considered to be economically sustainable.

5.6. Suggested Future Research to Better Define a New Conceptual Model

Some easy and important tests can be done on the production wells to ascertain the origin of the higher salinity water moving into the wellfield. If the water is leaking from a greater depth below the Upper Floridan aquifer in some wells compared to others, there may be some temperature differences that could help indicate the deeper source. Perhaps the wells with the highest rate of salinity increase would have a higher water temperature than those with the lower rate. It is simple to obtain water samples from the wellheads and make accurate field temperature measurements. In addition, it would be prudent to obtain some new geophysical logs of the wells, including temperature, conductivity, and flowmeter logs.

Consideration should be given to running some borehole-to-borehole seismic logs to investigate if fractures can be detected. Some high-resolution, land-based seismic reflection surveys have been run in Miami-Dade County at other locations. It may be useful to reassess the records from some of these surveys to try to determine if any fractured zones occur in the upper 250 m of the Floridan Aquifer System, which would encompass the Upper Florida aquifer and the confining unit immediately below it.

6. Conclusions

The city of Hialeah, Florida operates a brackish water reverse osmosis (BWRO) desalination plant that currently operates at a capacity of about 33,000 m³/d and has an ultimate capacity of 88,000 m³/d. The BWRO plant can treat feed water up to a TDS concentration of 10,000 mg/L (4700 mg/L of dissolved chloride). The feed water is pumped from the Upper Florida aquifer onsite, currently using six production wells. The wellfield contains 14 permitted wells (10 installed) that will be used in the future. A solutetransport model was conducted on the production aquifer for a prediction of water quality changes over 30 years. The model was based on the onsite collection of high-quality hydrogeological data and used the original conceptual model employed for nearly all BWRO wellfields in Florida. The conceptual model predicts a slow increase in groundwater TDS based on the upwards movement of higher salinity water through the basal confining unit. The predicted change in dissolved chloride over 30 years of operation at the base run ranged from 1650 to 2000 mg/L, and at the high range, from 1650 to 3000 mg/L. Actual measured data show that at a pumping rate of $33,000 \text{ m}^3/\text{d}$, the dissolved chloride concentration in the 10th year of operation will reach 2750 mg/L or 27.5% higher than the predicted upper range. If the plant was operated at its anticipated maximum design capacity, the feedwater quality would exceed 10,000 mg/L of TDS, which would render the plant process unable to treat the feed water within 5 to 10 years.

Based on the data and analysis, the Upper Floridan aquifer may contain an enhanced leakance value that was not detected during the aquifer performance test. The likely cause of the higher leakance rate within parts of the wellfield is the undetected fracturing of the confining dolostones underlying the Upper Florida aquifer. Therefore, a revised conceptual model must be used to accurately predict the future changes in pumping-induced water quality at this site. While the most commonly used conceptual model has been used to accurately predict the water quality changes at some other BWRO sites in Florida, in this case, the undetected enhanced vertical connection precluded the ability to accurately predict long-term water quality changes. This is a classic example of the difficulty in making long-term water quality predictions (30 years) for a complex aquifer system.

Despite the increased rate of salinity change, the water pumped from the source aquifer will still be able to be treated with freshwater by changing the treatment process from brackish water membranes to seawater membranes. This change will necessitate a major redesign of the facility and will have a higher energy consumption, resulting in a higher water treatment cost. However, a comparison to other water supply alternatives, such as using more freshwater from the Biscayne Aquifer, or developing seawater from a tidal source, the retrofit of the plant is the only truly sustainable water supply alternative. The indirect impact of the increased electric consumption on sustainability would be the use of nuclear or solar power energy sources to mitigate carbon dioxide discharge to the atmosphere.

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