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Changes in Pumping-Induced Groundwater Quality Used to Supply a Large-Capacity Brackish-Water Desalination Facility, Collier County, Florida: A New Aquifer Conceptual Model

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Abstract: Brackish-water reverse osmosis (BWRO) desalination facilities are designed to treat feedwater within a fixed range in salinity. If the salinity and ion concentrations of the feedwater rises above the maximum design concentrations, then the plant may ultimately fail. BWRO plants typically use groundwater as a feedwater source. Prior to the process design, a detailed groundwater assessment is made to characterize the source aquifer system and to develop a solute-transport model that is used to project the changes in water quality over the expected useful life of the facility. Solute transport-modeling performed for the Collier County (Florida) South BWRO facility, which was designed to produce 30,303 m^3/d with an expansion to 75,758 m^3/d, used an aquifer system conceptual model that assumed upwards migration over time of brackish waters with higher salinities into the production zones. This conceptual model is typical of how most BWRO systems developed in the United States operate. The original solute transport model predicted a range of increases in dissolved chloride concentrations over a 20-year period from a low of 5 mg/L/yr, a mid-range of 35 mg/L/yr, and a high range of 85 mg/L/yr. Actual data collected over a 11- to 13.5-year period showed that the dissolved chloride concentration average of the feed water decreased by 16 mg/L/yr. The original conceptual model was found to be inaccurate in that it suggested an upwards recharging system, whereas downward leakage (or perhaps lateral migration) of fresher water appears to be occurring in the system. This is an example of a long-term solute-transport model audit, which is rarely performed, in which a new conceptual model was found to be applicable to an aquifer system used to feed a BWRO facility.

Keywords: hydrogeology; pumping-induced water quality changes; brackish-water desalination; aquifer conceptual models; Collier County; Florida

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1. Introduction

Freshwater shortages plague many regions of the world, particularly in high-population growth areas and arid regions [1]. While conventional sources of water supply are often quite limited, including fresh surface water bodies and fresh groundwater sources, brackish groundwater is abundant in many areas, especially the United States [2]. Brackish water is defined by the U.S. Geological Survey to have a total dissolved solids (TDS) concentration lying between 1000 and 10,000 mg/L [2]. The lower range of brackish-water, between TDS concentrations of 1000 and 3000 mg/L, can replace some uses of freshwater, particularly for irrigation of salt-tolerate plants and some industrial applications [3,4]. The U.S. Environmental Protection Agency defines underground sources of drinking water to have a TDS of less than 10,000 mg/L [5]. Brackish water, however, cannot be used directly as drinking water based on the drinking water quality standards [5].

Brackish water can be treated economically to freshwater using the reverse osmosis process [6–9]. In 2010, there were 649 active desalination plants in the United States with a treatment capacity of about 1.5 million m^3/day [10]. Mickley [11] found that in 2017 there were 295 brackish-water reverse osmosis desalination (BWRO) plants in the United States that had capacities of over 95 m^3/day. This is about a 20% increase in the number based on comparison to a 2012 survey [12]. Most of the BWRO treatment facilities today use brackish water with a TDS concentration of less than 5000 mg/L. Generally, as the salinity of the water source increases, the overall cost of treatment increases, particularly when the TDS rises above 6000 mg/L [13]. Once the TDS concentration increases above about 10,000 mg/L, a seawater-type membrane is required rather than a brackish-water membrane with a reduced conversion rate and a significantly higher overall treatment cost [14].

While BWRO has been increasing in use in the United States, there have been challenges in the development, design, and operation of wellfields used to supply feedwater to BWRO facilities [15–19]. Water quality changes are induced by pumping of the production wells, the rate of which depends on local hydrogeologic conditions [19]. The changes in water quality can occur as a steady, slow increase in TDS over time, such as occurred at the IWA facility on Sanibel Island, Florida [16,17], at the Bonita Springs Utilities system, Florida [20], the City of Cape Coral North Plant, Florida [21], the Town of Jupiter, Florida [22], and the City of Clewiston, Florida [23] or a more rapid rate such as at the Dare County, North Carolina facility [15], the City of Fort Myers facility, Florida [24], and the North Collier County, Florida BWRO facility [19].

In addition to the importance of feedwater TDS increases to BWRO plant design and potential process failure, other operational difficulties can occur because of the overall change in water chemistry. The associated increase in feedwater hardness can reduce the plant conversion efficiency and increase scaling potential, which collectively increase treatment costs [25–29].

The TDS of the feedwater for a BWRO plant is of considerable importance because the successful operation of the plant is based on the ability of the plant to treat the water originating in the wellfield [19]. BWRO plant design is based on the feedwater remaining within a specific envelope of TDS values and ion concentrations over time. If the TDS of the raw water exceeds the design parameters, then the freshwater production will decrease and the plant may eventually fail. The remedy to this type of failure can be exceeding costly and require a re-design of the treatment process with major retrofitting of the water treatment plant and/or the construction of additional production wells to try to capture fresher water. In fact, one facility, the City of Clearwater, Florida BWRO plant, was unable to operate at full capacity at the initial startup due to a very rapid rise in the TDS concentration of the feedwater [30].

Based on the critical nature of the coordination between the BWRO design and the wellfield performance in terms of water quality, solute-transport modeling is necessary to quantify the pumping-induced water quality changes in the production wellfield to assure the long-term viability of the overall system [19]. Development of a groundwater model to assess TDS changes over an operational period of 20 to 30 years requires considerable field data collected on the aquifer water quality and hydraulic characteristics along with a viable conceptual model [31]. Many of the existing BWRO systems that have been modeled show that changes in TDS are caused primarily by upwards movement of higher salinity water through confining layers based on the production aquifer being semi-confined with the upper confining layer having a considerably lower leakance compared to the lower confining unit [20] (Figure 1).

The purpose of this research was to perform a post-audit of the solute-transport modeling initially performed for an operational BWRO in southern Collier County, Florida, that utilizes two aquifers, one tapping the lower aquifer in the Intermediation Aquifer System and the lower one tapping the upper unit of the Floridan Aquifer System. Key issues examined are the accuracy of the initial solute-transport modeling and the appropriateness of the initial and alternative possible conceptual models. This research is very important to gaining fundamental knowledge on how best to coordinate the design of wellfields in relationship to BWRO process design.

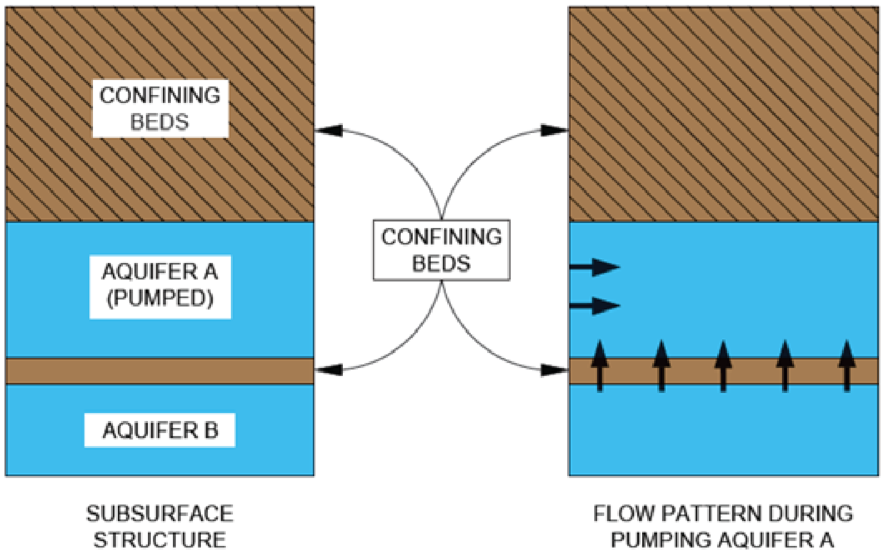


Figure 1. General conceptual model applied to wellfields being used to provide feedwater to BWRO plants in southern Florida (from Drendel et al. [20]).

2. Background

2.1. Hydrogeology of the Aquifer System

The Collier County South BWRO facility was originally designed to contain 14 production wells with individual well capacities of 3818 m^3/d (700 gpm). Ten wells tap the Hawthorn Aquifer System-Zone I and four wells tap the Lower Hawthorn Aquifer. Additional production wells, 24 completed in Hawthorn Aquifer Zone I and three wells in the Lower Hawthorn Aquifer, were subsequently added for a plant capacity expansion.

The hydrogeology of the production wellfield area is summarized in Figure 2. Hawthorn Aquifer Zone 1 is a brackish-water aquifer lying within the Intermediate Aquifer System [32]. Zone 1 is confined from the overlying Surficial Aquifer System by a semi-confining unit lying within the Peace River Formation of the Hawthorn Group at the top and is confined below a semi-confining unit lying at the base of the Intermediate Aquifer System. The overlying aquifers contain freshwater and the underlying Lower Hawthorn Aquifer contains brackish water. The Lower Hawthorn Aquifer is the uppermost aquifer in the Floridan Aquifer System [33,34]. Note that the aquifer system shows some degree of stratigraphic variability, and a minor aquifer does occur within the confining unit separating the two aquifers (Figure 3).

Characterization of the Hawthorn Aquifer Zone 1 was reported in CDM [32]. The aquifer consists of porous limestone with a moderate degree of heterogeneity. Test drilling for geologic characterization of the Hawthorn Zone 1 aquifer found that it occurred between 91.5 and 137 m below surface. The thickness of the aquifer ranged from 30.5 and 45.7 m. An aquifer performance test was conducted from which transmissivity, storativity, and leakance values of 248 to 1242 m^2/d, 1×10^{-4} to 1×10^{-5}, and 2.2×10^{-3} d^{-1}, respectively, were obtained. The dissolved chloride concentration in the aquifer ranged from 1800 to 2800 mg/L with an approximate TDS concentration ranging from 3350 to 4940 mg/L. The approximate TDS values were obtained from chloride data based on the relationship in this aquifer system [21].

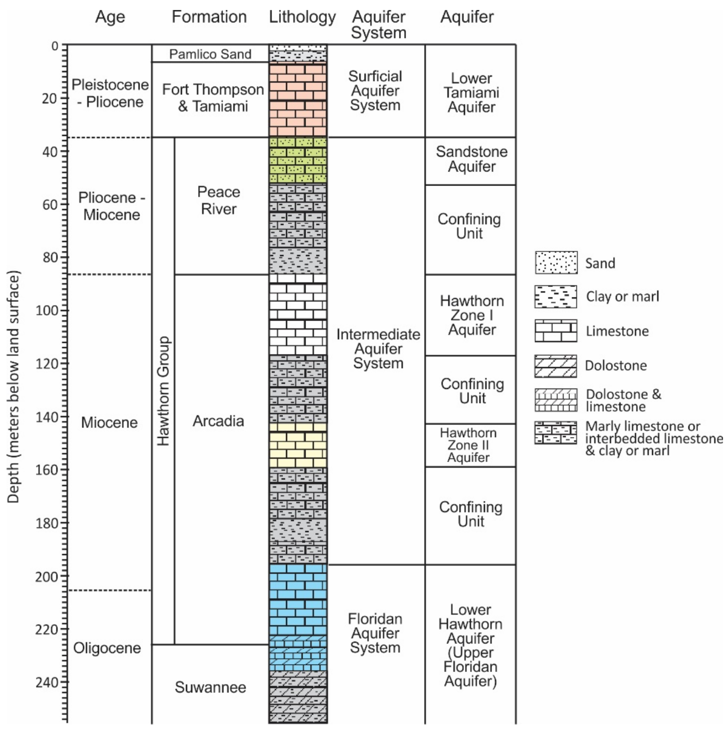


Figure 2. Hydrogeology of Hawthorn Aquifer Zone 1 and the Lower Hawthorn Aquifer [32].

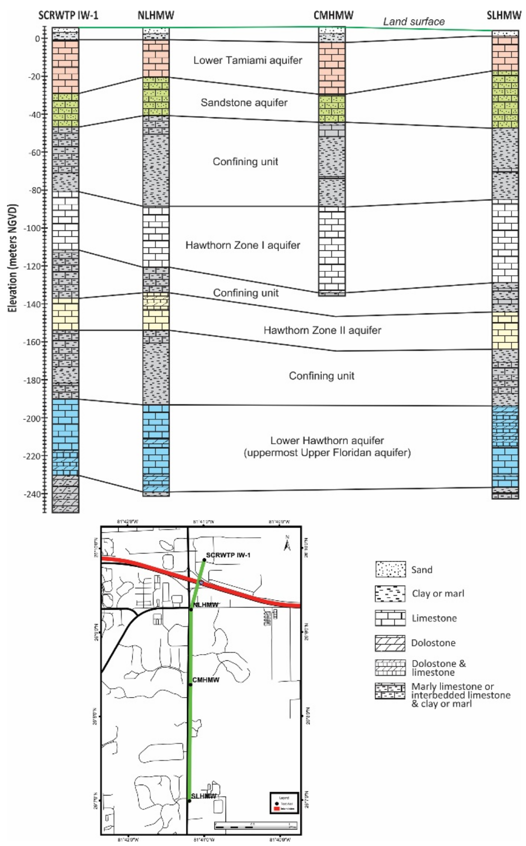


Figure 3. Stratigraphic cross-section showing the variability in depths and thicknesses of the two production aquifers [32].

The Lower Hawthorn Aquifer consists of porous limestone and dolomite units that exhibit considerable heterogeneity [32]. The aquifer occurs between 198 and 244 m below surface with a relatively uniform thickness of 46 m. Due to the extreme heterogeneity, the aquifer has a range in measured transmissivity of 124 to 3229 m^2/d. The measured storativity is near 1×10^{-4}, and the leakance was estimated to be about 7×10^{-3} d^{-1}.

Based on the geology, aquifer testing results, and groundwater modeling, it was demonstrated that the pumping of the upper aquifer will have little impact on the overlying freshwater aquifer system because of the confinement and the stark contrast in water quality across the confining unit. If the potentiometric surface in the aquifers is all converted to freshwater heads, the potentiometric surface of the Hawthorn Aquifer Zone 1 containing brackish water is 3 to 5 m above the potentiometric surfaces of the Lower Tamiami Aquifer and the water-table aquifer, which both contain freshwater. No potentiometric surface data are available from the Sandstone Aquifer that overlies Hawthorn Aquifer Zone 1. The measured leakance value for Hawthorn Aquifer Zone 1 is therefore predominantly unidirectional and directed upward from the Lower Hawthorn Aquifer. The leakance measured in the Lower Hawthorn Aquifer is likely bi-directional with some skewing toward bottom-upward water movement during a pumping condition as there is a lesser degree of confinement at the base compared to the top of the aquifer. The head differential between the Lower Hawthorn Aquifer and the overlying Hawthorn Aquifer Zone 1 shows an upward directed difference of 0.3 to 1.2 m. Groundwater leakage into Lower Hawthorn Aquifer from below would tend to cause an increase in salinity. Data collected during construction of the injection well disposal system at the BWRO plant site indicate that the dissolved chloride concentration in Middle Confining Unit is up to 5500 mg/L, which is equivalent to a TDS of 10,000 mg/L.

Groundwater solute-transport modeling was conducted on the combined two-aquifer system using the SEAWAT code [35]. With a pumping rate at 41,666 m^3/d divided between the two aquifers, the maximum drawdown in Hawthorn Aquifer Zone 1 was estimated to be about 15 m in the center of the cone of depression and maximum drawdown in the Lower Hawthorn Aquifer was simulated to be 12 m in the center of the cone of depression. Based on a 20-year period of operation at a pumping rate of 41,666 m^3/d, the dissolved chloride concentration was projected to increase from the initial dissolved chloride concentration of 2600 mg/L to an average of 3500 mg/L [32]. This range of values equates to a TDS concentration range of 4622 to 6000 mg/L. The calculated chloride and TDS concentrations are considered best-estimated projections based on measured aquifer hydraulic data. The results of a sensitivity analysis indicated that the chloride concentration could rise as high as 4250 mg/L and TDS as high as 8100 mg/L. The groundwater modeling also included pumping of the North Collier Regional Water Treatment Plant Wellfield, which provides feedwater to another BWRO facility.

2.2. Design of the Brackish-Water Treatment Facility and Water Quality Treatment Limitations

The South Collier County BWRO facility was originally designed and constructed to meet a potable water production capacity of 30,303 m^3/d (8 MGD). The projected conversion efficiency of the plant is about 80%, which means that of the raw water that is pumped into the BWRO plant, 80% produced becomes potable water and the remaining water is concentrate (brine). Therefore, the feedwater source must supply about 41,667 m^3/d (11 MGD) to produce the desired quantity of potable water. Eleven production wells were constructed to meet the feedwater demand, each producing 3788 m^3/d (1 MGD). The plant was brought online in 2004. An expansion of the plant to bring the capacity to 75,758 m^3/d (20 MGD) was completed and brought into production in 2007. The expanded wellfield contained a total of 41 production wells with 35 in Hawthorn Aquifer Zone 1 and 6 production wells in the Lower Hawthorn Aquifer. The wellfield capacity was in excess of the minimum feedwater pumping rate required of 101,023 m^3/d (26.67 MGD) as excess well capacity has been built into the system as backup to account for well or well pump failure. The locations of the production wells are given in Figure 4 and the production well construction details are contained in Table 1. The engineers assumed a slight reduction in the conversion rate, otherwise the wellfield capacity would have been 94,698 m^3/d (25 MGD). The design criteria were based on a solute-transport model for the initial phase of the wellfield and SWRO plant, which projected at 20 years that TDS concentration might range up to 7650 mg/L for the 30,303 m^3/d pumping rate. Simulations were not performed for the full 101,023 m^3/d (26.67 MGD) capacity.

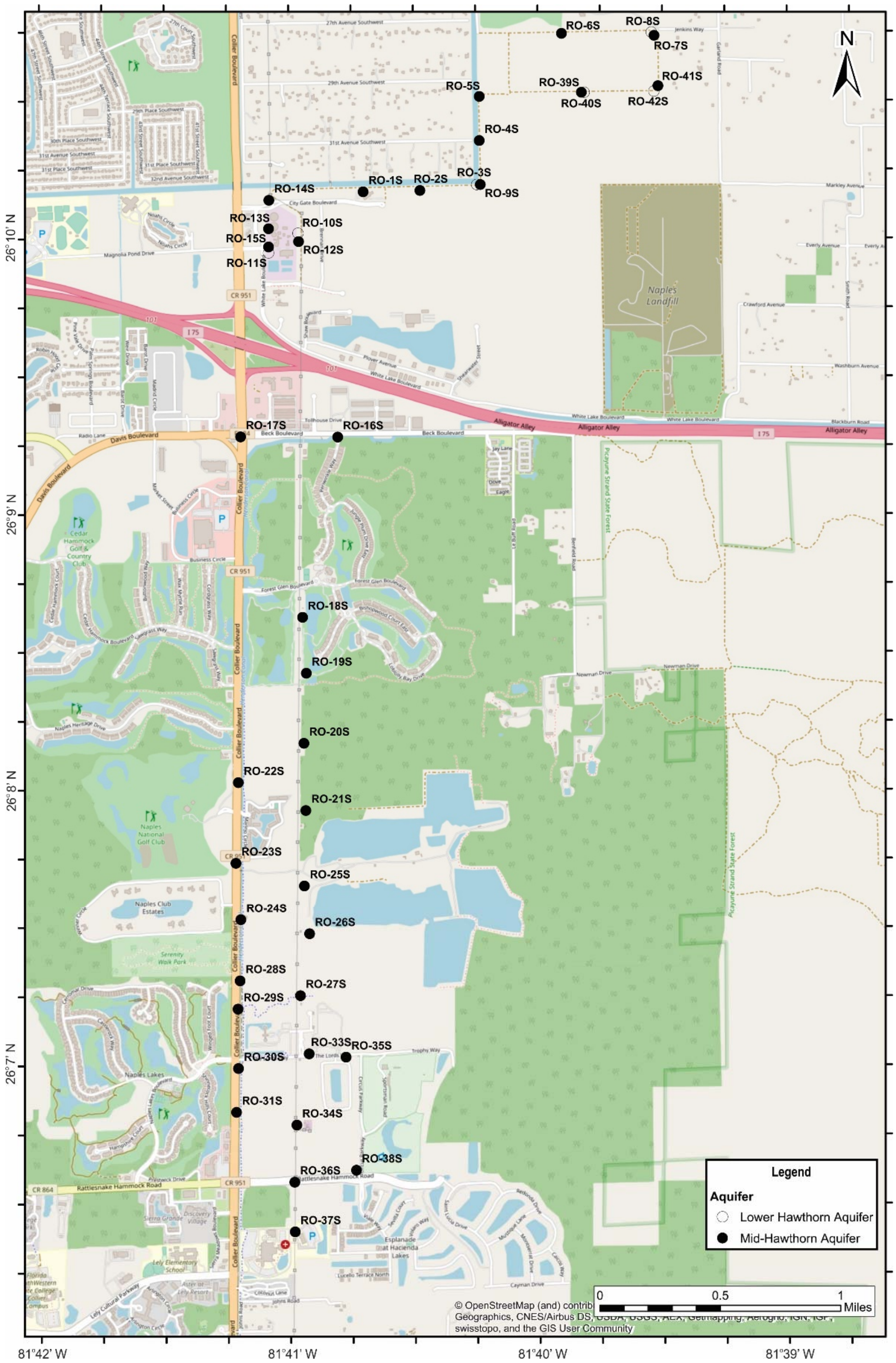


Figure 4. Map showing the location of production wells.

Table 1. Construction details on the production wells.

Well	Casing Diameter (cm)	Total Depth (m)	Casing Depth (m)	Aquifer
RO-1S	40.64	128.0	95.1	Hawthorn-Zone I
RO-2S	40.64	122.0	89.0	Hawthorn-Zone I
RO-3S	40.64	122.9	89.3	Hawthorn-Zone I
RO-4S	40.64	122.6	100.9	Hawthorn-Zone I
RO-5S	40.64	122.6	90.6	Hawthorn-Zone I
RO-6S	40.64	128.4	96.6	Hawthorn-Zone I
RO-7S	40.64	134.8	100.0	Hawthorn-Zone I
RO-8S	40.64	299.4	201.2	Lower Hawthorn
RO-9S	40.64	207.9	192.1	Lower Hawthorn
RO-10S	40.64	256.7	192.1	Lower Hawthorn
RO-11S	40.64	293.6	199.1	Lower Hawthorn
RO-12S	40.64	128.7	91.2	Hawthorn-Zone I
RO-13S	30.48	122.0	89.9	Hawthorn-Zone I
RO-14S	40.64	128.7	90.9	Hawthorn-Zone I
RO-15S	40.64	122.6	89.9	Hawthorn-Zone I
RO-16S	40.64	128.0	91.5	Hawthorn-Zone I
RO-17S	40.64	128.0	91.5	Hawthorn-Zone I
RO-18S	40.64	128.0	91.5	Hawthorn-Zone I
RO-19S	30.48	128.0	91.5	Hawthorn-Zone I
RO-20S	30.48	128.0	91.5	Hawthorn-Zone I
RO-21S	30.48	128.0	91.5	Hawthorn-Zone I
RO-22S	30.48	128.0	91.5	Hawthorn-Zone I
RO-23S	30.48	128.0	91.5	Hawthorn-Zone I
RO-24S	30.48	128.0	91.5	Hawthorn-Zone I
RO-25S	40.64	128.0	91.5	Hawthorn-Zone I
RO-26S	40.64	128.0	91.5	Hawthorn-Zone I
RO-27S	40.64	128.0	91.5	Hawthorn-Zone I
RO-28S	40.64	128.0	91.5	Hawthorn-Zone I
RO-29S	40.64	128.0	91.5	Hawthorn-Zone I
RO-30S	40.64	128.0	91.5	Hawthorn-Zone I
RO-31S	40.64	128.0	91.5	Hawthorn-Zone I
RO-32S	40.64	128.0	91.5	Hawthorn-Zone I
RO-33S	40.64	128.0	91.5	Hawthorn-Zone I
RO-34S	40.64	128.0	91.5	Hawthorn-Zone I
RO-35S	40.64	128.0	91.5	Hawthorn-Zone I
RO-36S	40.64	128.0	91.5	Hawthorn-Zone I
RO-37S	40.64	128.0	91.5	Hawthorn-Zone I
RO-38S	40.64	128.0	91.5	Hawthorn-Zone I
RO-39S	40.64	122.0	91.5	Hawthorn-Zone I
RO-40S	40.64	304.9	213.4	Lower Hawthorn
RO-41S	40.64	122.0	91.5	Hawthorn-Zone I
RO-42S	40.64	304.9	213.4	Lower Hawthorn
RO-43S	40.64	304.9	213.4	Lower Hawthorn (not in operation)
RO-44S	40.64	304.9	213.4	Lower Hawthorn (not in operation)
RO-45S	40.64	304.9	213.4	Lower Hawthorn (not is operation)

The BWRO plant was designed to treat a feedwater with a maximum TDS of between 8000 and 9000 mg/L with a corresponding dissolved chloride concentration of between approximately 4000 and 4900 mg/L [36]. If the salinity of the feedwater becomes higher than the ability of the BWRO process to treat the raw water, a major modification of the process would be required. The treatment process upgrade could include higher pressure pumps, new membranes, and an increase in raw water capacity caused by a reduced conversion rate. An upgrade of the treatment system to handle higher salinity water might increase the footprint of the plant and increase the concentrate flow to the injection wells.

3. Methods

3.1. Water Use and Quality Data Collection

Collier County Utilities monitors the pumping rate and dissolved chloride concentration in each production well. The monthly totalized pumping data for all production wells and the monthly measured dissolved chloride concentration were obtained. These data were graphically analyzed to assess the changes in pumping (bar graphs) and dissolved chloride concentration. Additionally, the combined feedwater into the BWRO plant is monitored continuously for conductivity, which can be converted to TDS. The data for the years 2018 to 2020 were compiled for comparison to the individual well water salinity changes.

3.2. Statistical Analysis of Data

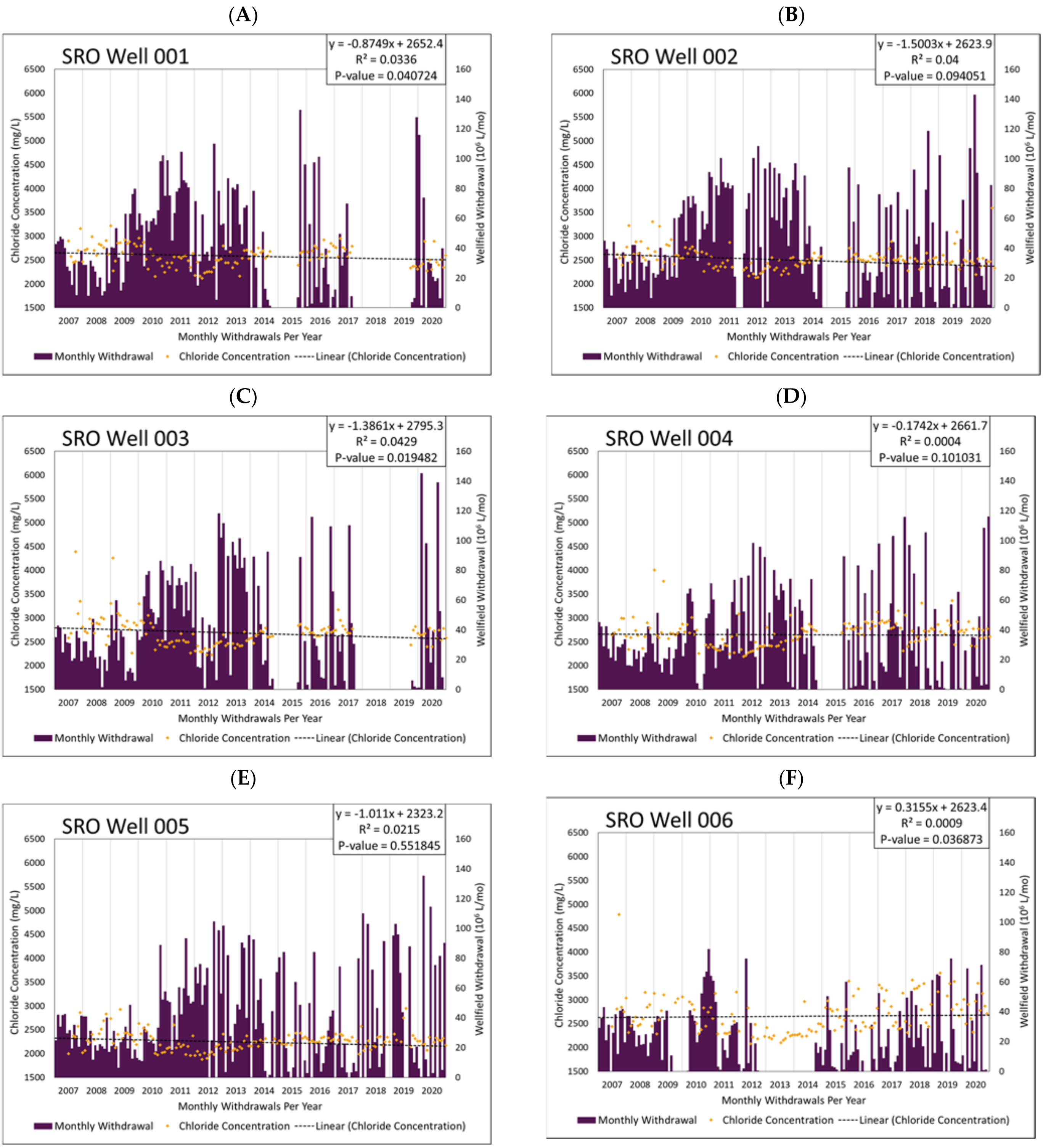
The trends in dissolved chloride changes were assessed by a regression analysis of the dataset for each production well. The R^2 and p-value were calculated for each regression to evaluate statistical significance. The regression lines were then used to project changes in dissolved chloride concentration into the future at 5, 10, 20 and 40 years for the current design pumping rate of 56,818 m^3/d. The projected change in water quality was then evaluated in comparison to the maximum design capacity of the BWRO plant. Many wells that tap Hawthorn Aquifer Zone 1 show a declining trend. The projected trends from the operational data were compared to the results of previously performed solute-transport modeling. The statistical analysis does not take into consideration any future increase in plant capacity. This type of analysis would require a new, expanded solute-transport model to assess expanding aquifer pumping impacts on water quality.

4. Results

4.1. Changes in Salinity in Wells Used for Water Supply for 13 Years of Operations in Hawthorn Aquifer Zone 1

Data obtained from 35 production wells tapping Hawthorn Aquifer Zone 1 were graphed to show the monthly aggregated pumpage and the dissolved chloride concentration (Figure 5). There is considerable variation in the R^2 values, which define the tightness of the data fit to the trend line. R^2 values range from 7×10^{-6} to 0.1393. The very low R^2 values are indicative of extreme scatter in the dissolved chloride data, which is likely caused by inaccuracies in the laboratory method used to measure dissolved chloride concentrations and operator error, along with the variable pumping schedules in the wellfield. In total, 43% of the wells have a p-value > 0.05 and 57% wells gave a value of <0.05. The p-values below 0.05 are considered to indicate that the regression is statistically significant, whereas trends with higher values are not considered significant.

The period of record for the dissolved chloride data is given in Table 2. Note that many of the wells had data on monthly pumpage, while other wells did not for the early period of record. The starting and ending dissolved chloride measurements for all the Hawthorn Aquifer Zone 1 wells are given in Table 3 along with the estimated annual rate of change based on these measurements. Note that the period of record is not the same for all production wells, because a larger number of wells was required after the BWRO plant was expanded. To normalize the data, the annual rate of change in the dissolved chloride concentration was calculated. The linear regression analysis for all the production wells show that the intercept of the y-axis does not correlate well with the starting measurement for dissolved chloride concentrations due to the error within the measurements (Table 3). Dissolved chloride concentration increased in only three wells and decreased in 32 wells based on the linear regression. The average rate of change using the starting and ending dissolved chloride concentration was 17 mg/L/yr.



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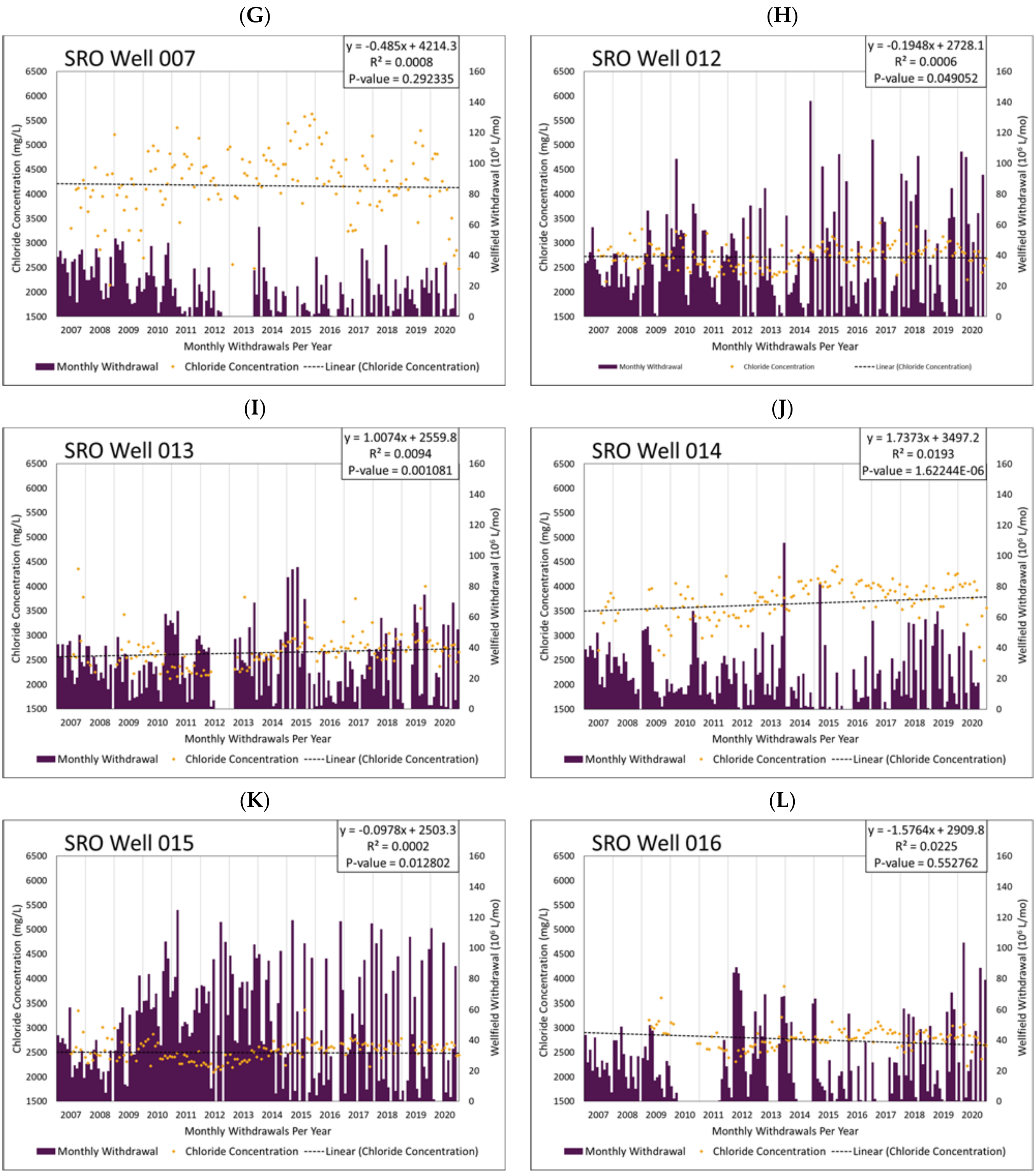

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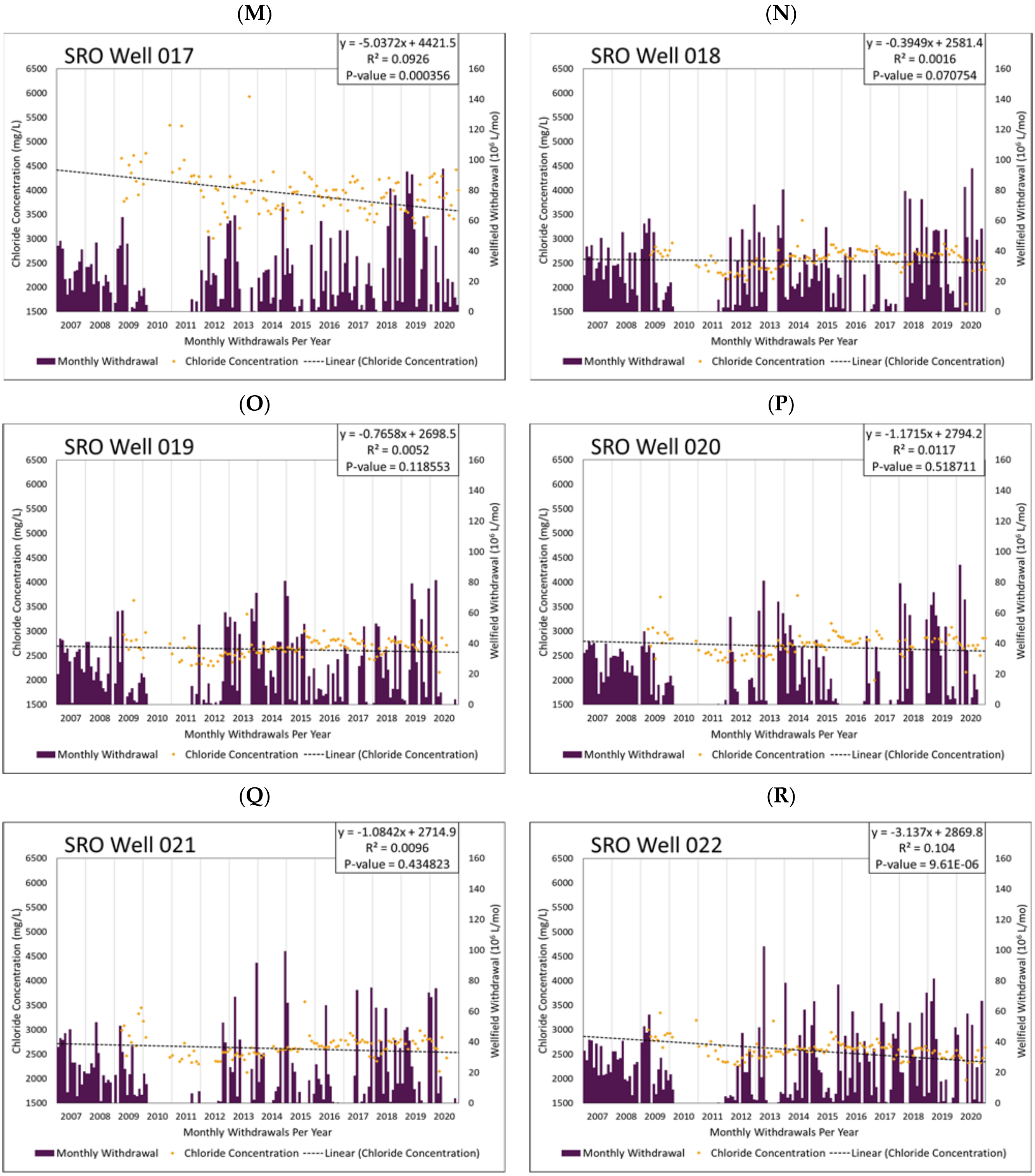

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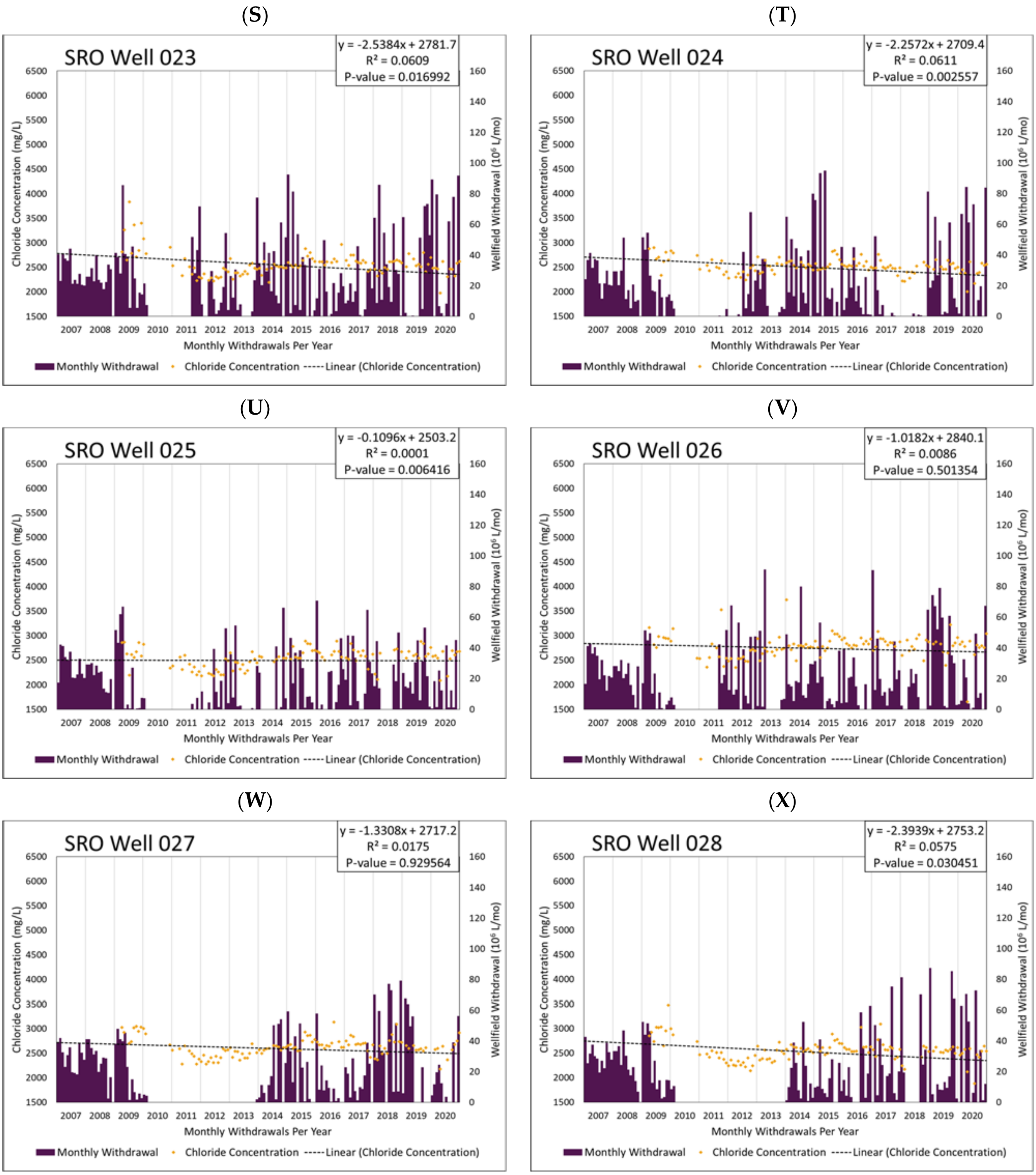

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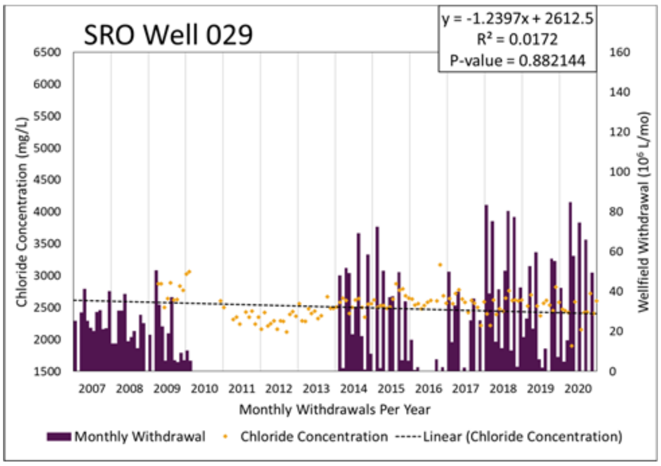

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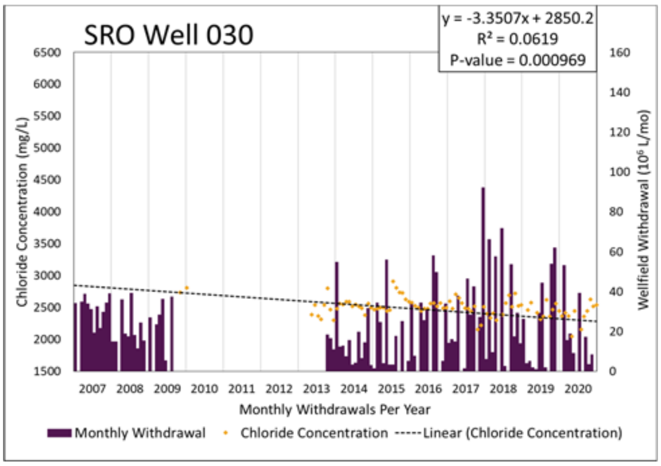

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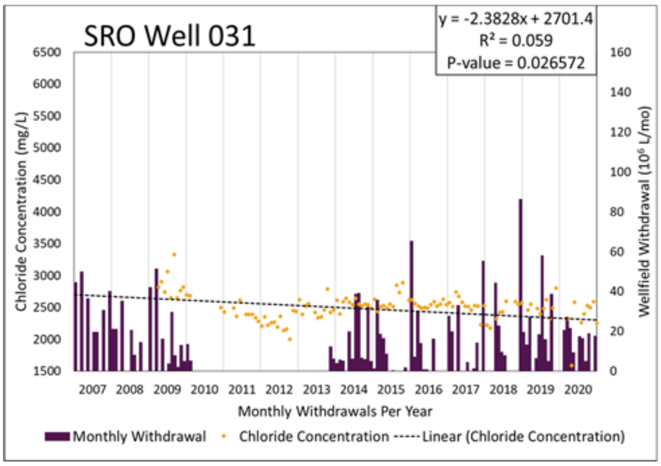

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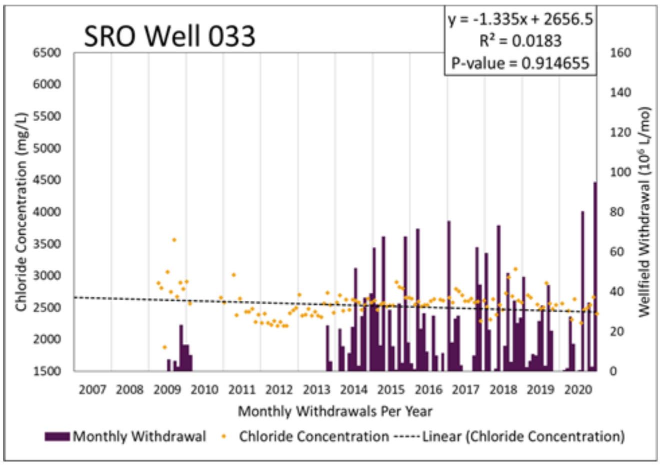

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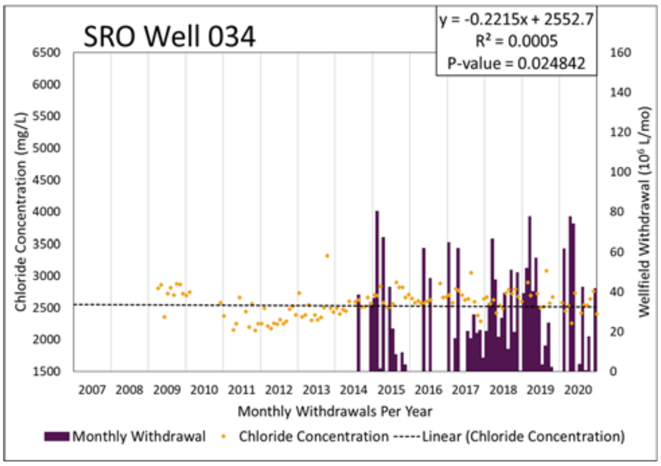

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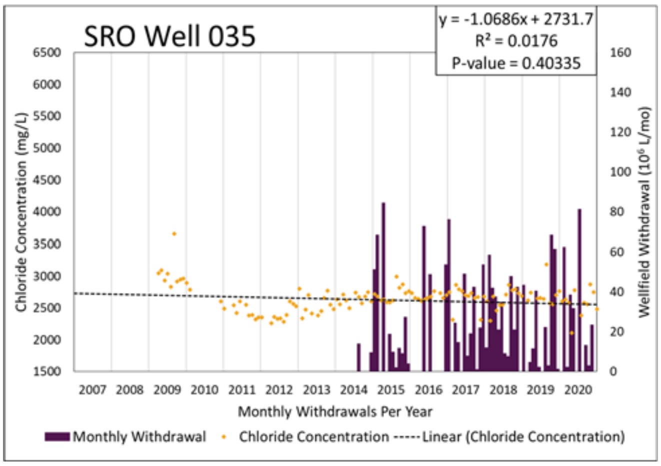

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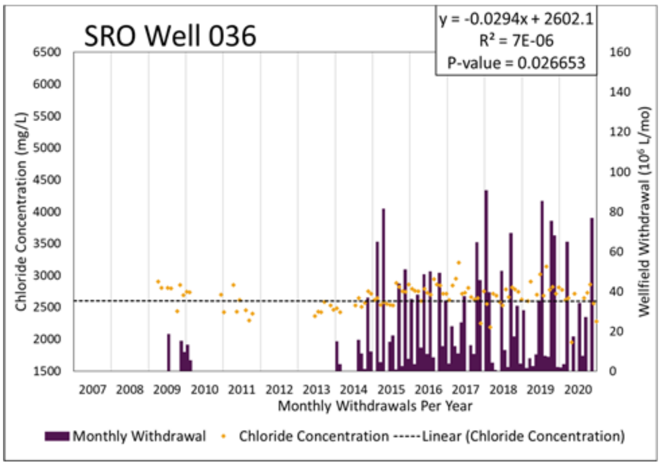

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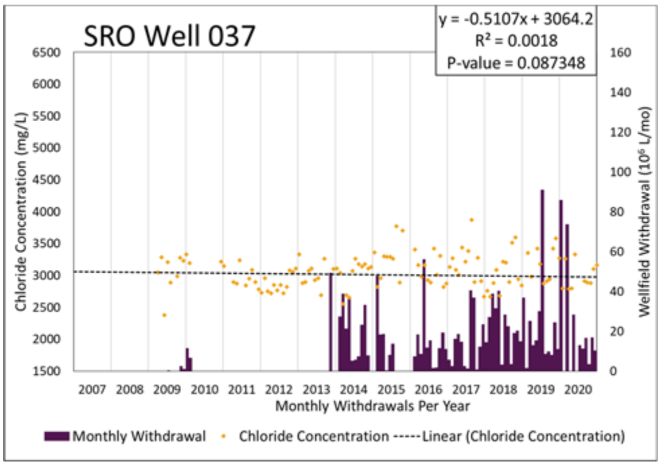

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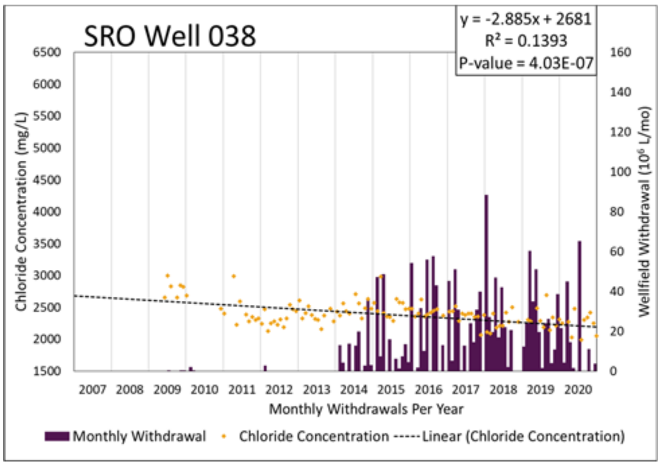

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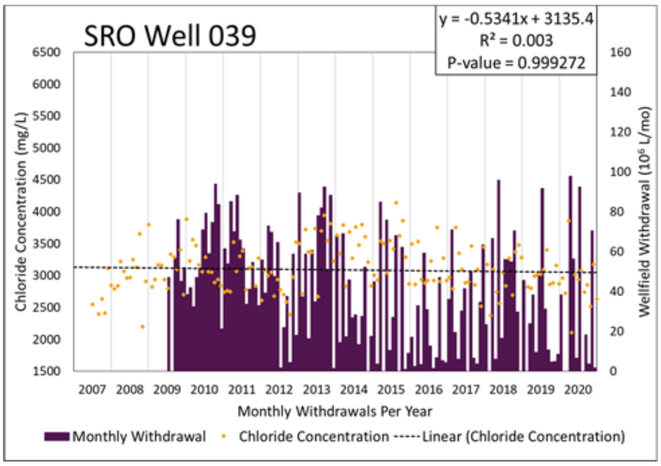

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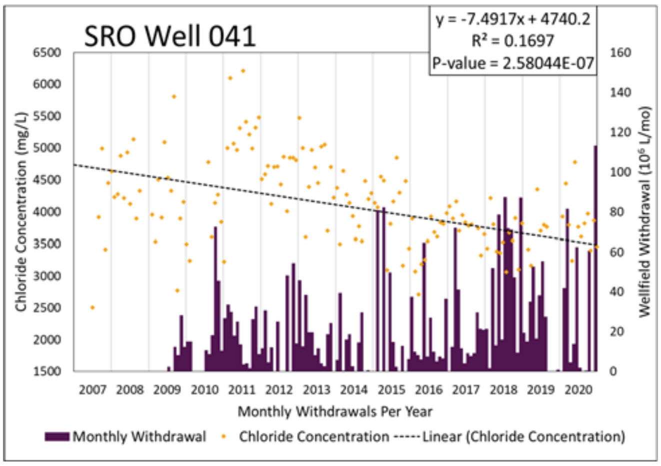

Figure 5. Plots of dissolved chloride concentration with time, monthly cumulate pumping, the calculated values of R^2 and *p*-values and the regression equations for the trend line for Hawthorn Aquifer Zone 1 production wells.

Table 2. Hawthorn Aquifer Zone 1 production wells period of recorded for starting and ending dissolved chloride concentrations measurements.

Well No.	Months of Data	Starting Dissolved Chloride Concentrations (mg/L)	Ending Dissolved Chloride Concentrations (mg/L)
RO-1S	162	July 2007	December 2020
RO-2S	162	July 2007	December 2020
RO-3S	162	July 2007	December 2020
RO-4S	162	July 2007	December 2020
RO-5S	162	July 2007	December 2020
RO-6S	162	July 2007	November 2020
RO-7S	162	July 2007	December 2020
RO-12S	162	July 2007	December 2020
RO-13S	162	July 2007	December 2020
RO-14S	162	July 2007	December 2020
RO-15S	162	July 2007	December 2020
RO-16S	141	April 2009	December 2020
RO-17S	141	April 2009	December 2020
RO-18S	140	May 2009	December 2020
RO-19S	140	May 2009	December 2020
RO-20S	141	April 2009	December 2020
RO-21S	141	April 2009	December 2020
RO-22S	141	April 2009	December 2020
RO-23S	141	April 2009	December 2020
RO-24S	141	April 2009	December 2020
RO-25S	141	April 2009	December 2020
RO-26S	141	April 2009	December 2020
RO-27S	141	April 2009	December 2020
RO-28S	141	April 2009	December 2020
RO-29S	141	April 2009	December 2020
RO-30S	134	November 2009	December 2020
RO-31S	141	April 2009	December 2020
RO-32S		No Record	No Record
RO-33S	141	April 2009	December 2020
RO-34S	141	April 2009	December 2020
RO-35S	141	April 2009	December 2020
RO-36S	141	April 2009	December 2020
RO-37S	141	April 2009	December 2020
RO-38S	139	June 2009	December 2020
RO-39S	162	July 2007	December 2020
RO-41S	162	July 2007	December 2020

Table 3. Hawthorn Aquifer Zone 1 production wells annual rate of change in dissolved chloride concentrations with 5, 10, 20, and 40-year projections.

Well No.	Starting Dissolved Chlorides (mg/L)	Ending Dissolved Chlorides (mg/L)	Annual Rate of Change (mg/L/yr)	Intercept Starting Dissolved Chlorides (mg/L)	5-Year Proj.	10-Year Proj.	20-Year Proj.	40-Year Proj.
RO-1S	2901	2600	−23	2652	2458	2405	2300	2090
RO-2S	2620	2330	−22	2623	2291	2201	2021	1661
RO-3S	2584	2580	0	2795	2487	2404	2238	1905
RO-4S	2640	2610	−2	2661	2623	2613	2592	2550
RO-5S	1996	2170	13	2323	2099	2038	1917	1674
RO-6S	2436	2710	21	2623	2693	2712	2750	2826
RO-7S	3300	2470	−64	4214	4106	4077	4019	3903
RO-12S	2852	2680	−13	2728	2685	2673	2650	2603
RO-13S	2558	2660	8	2560	2784	2844	2965	3207
RO-14S	2695	3560	67	3497	3883	3987	4195	4612
RO-15S	2475	2440	−3	2503	2481	2475	2463	2440
RO-16S	3160	2640	−44	2910	2593	2499	2309	1931

Table 3. *Cont.*

Well No.	Starting Dissolved Chlorides (mg/L)	Ending Dissolved Chlorides (mg/L)	Annual Rate of Change (mg/L/yr)	Intercept Starting Dissolved Chlorides (mg/L)	5-Year Proj.	10-Year Proj.	20-Year Proj.	40-Year Proj.
RO-17S	4660	4000	−56	4422	3414	3112	2503	1294
RO-18S	2664	2360	−26	2581	2506	2483	2439	2349
RO-19S	2924	2710	−18	2699	2546	2500	2408	2225
RO-20S	3039	2860	−15	2794	2559	2488	2348	2066
RO-21S	2988	2420	−48	2715	2497	2432	2302	2042
RO-22S	2998	2640	−30	2870	2239	2051	1675	922
RO-23S	2815	2640	−17	2782	2272	2119	1815	1206
RO-24S	2876	2560	−27	2709	2255	2120	1849	1307
RO-25S	2,857	2680	−15	2503	2481	2474	2460	2434
RO-26S	3164	3040	−11	2840	2635	2574	2452	2208
RO-27S	3030	2920	−9	2717	2450	2370	2211	1891
RO-28S	2852	2540	−27	2753	2272	2128	1841	1266
RO-29S	2873	2600	−23	2613	2364	2289	2141	1843
RO-30S	2740	2540	−18	2850	2177	1975	1573	769
RO-31S	2919	2250	−48	2701	2222	2079	1793	1221
RO-33S	2883	2400	−41	2657	2389	2308	2148	1828
RO-34S	2808	2400	−35	2553	2508	2495	2469	2415
RO-35S	3045	2480	−48	2732	2517	2453	2325	2068
RO-36S	2903	2280	−63	2602	2596	2594	2591	2584
RO-37S	3048	3160	10	3064	2961	2931	2869	2747
RO-38S	2658	2050	−53	2681	2107	1934	1588	895
RO-39S	2546	3460	7	3135	3016	2984	2920	2792
RO-41S	2507	3460	85	4740	3077	2627	1728	500 [2]
Average	2855	2659	−17 [1]	2880	2607	2527	2367	2065

[1] This number is corrected for the period of record differences between a maximum of 13.5 years and a minimum of 11.17 years. [2] This is the lowest number possible for reduction in dissolved chloride concentration based on the overlying aquifer chemistry.

4.2. Changes in Salinity in Wells Used for Water Supply for 13 Years of Operation in the Lower Hawthorn Aquifer

The wellfield produces feedwater from six Lower Hawthorn Aquifer wells. Monthly pumpage and measured dissolved chloride concentrations are shown in Figure 6. The period of record of dissolved chloride data for each of the Lower Hawthorn Aquifer production wells is given in Table 4. There are some differences in the length of time the wells have been operated. A key observation is that that the changes in the dissolved chloride concentrations over the period of record are minimal (Table 5). Of the six wells, four show a downward trend in dissolved chloride concentration and two show an upward trend. The largest increase is in well RO-10S at about 101 mg/L per year. The largest decrease in concentration occurred in well RO-8S, which was 35 mg/L per year. The overall change in dissolved chloride concentration over the full operating period is a slight increase of 1 mg/L per year based on the starting and ending measurements during the period of record. Note that the intercept of the y-axis that defines the beginning of the trend line does not match the starting dissolved chloride measurement. This is caused by the laboratory error and the changes in pumping rates over time.

Table 4. Lower Hawthorn Aquifer period of record for starting and ending dissolved chloride concentration measurements.

Well No.	Months of Record	Starting Dissolved Chlorides Concentration (mg/L)	Ending Dissolved Chlorides Concentration (mg/L)
RO-8S	162	July 2007	December 2020
RO-9S	162	July 2007	December 2020
RO-10S	162	July 2007	November 2020
RO-11S	162	July 2007	December 2020
RO-40S	162	July 2007	December 2020
RO-42S	161	September 2007	December 2020

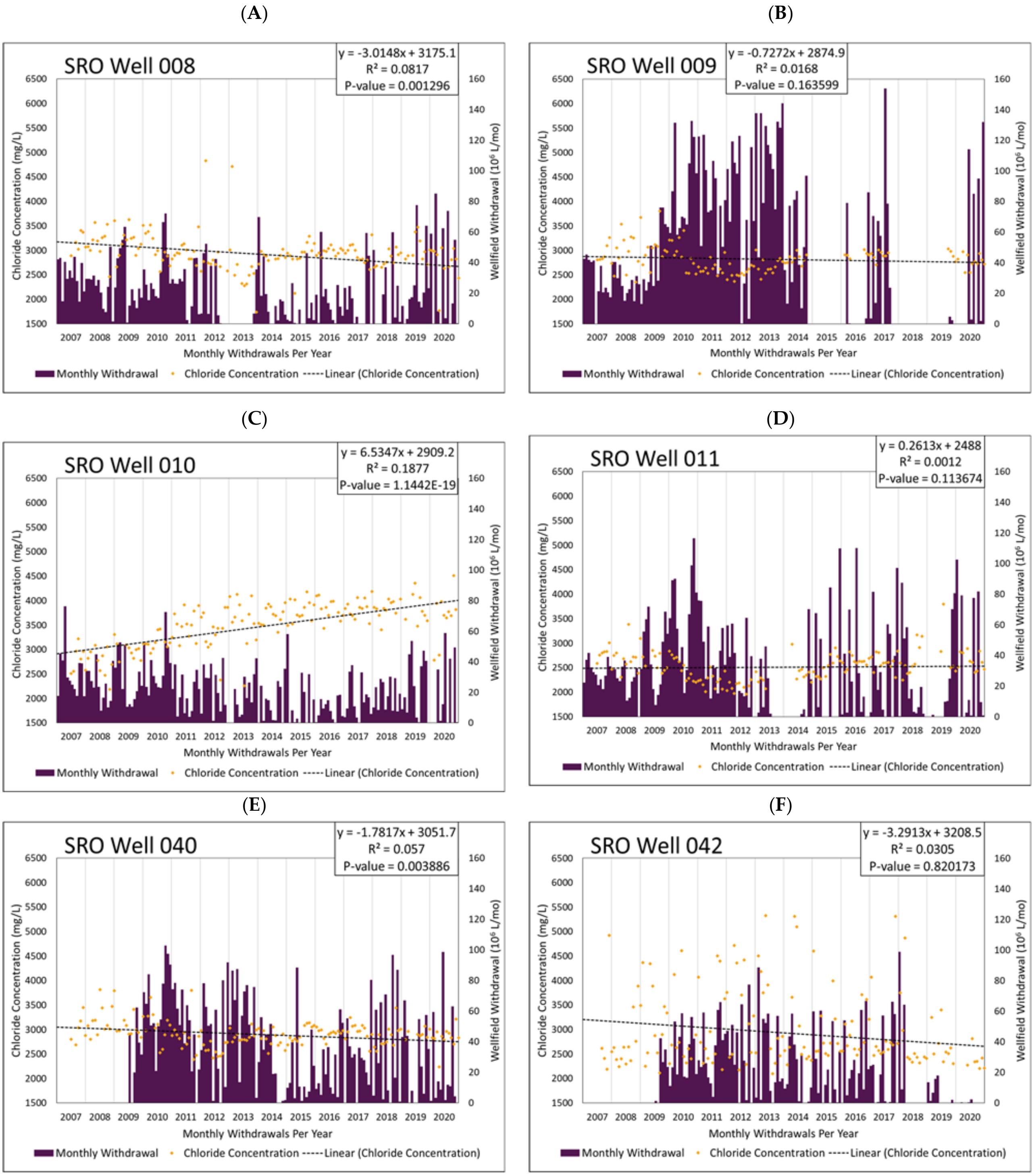

Figure 6. Plots of dissolved chloride concentrations with time, monthly cumulate pumping, the calculated values of R^2 and p-values and the regression equations for the trend line for the Lower Hawthorn Aquifer production wells.

The scatter plots of the dissolved chloride concentrations with time show very low R^2 values. Only half (50%) of the linear regression-based trend lines meet the test of statistical significance as indicated by p-values of less than 0.05. Of the six wells, four show a downward trend in dissolved chloride concentration and two show an upward trend.

Table 5. Lower Hawthorn Aquifer starting and ending dissolved chloride concentrations with 5, 10, 20, and 40-year projections.

Well No.	Starting Chlorides (mg/L)	Ending Dissolved Chlorides (mg/L)	Annual Rate of Change (mg/L/yr)	Intercept Starting Dissolved Chlorides (mg/L)	5-Year Proj.	10-Year Proj.	20-Year Proj.	40-Year Proj.
RO-8S	2887	2430	−35	3175	2506	2325	1960	1239
RO-9S	2805	2720	−7	2875	2714	2670	2583	2408
RO-10S	2507	3820	101	2909	4359	4752	5536	7104
RO-11S	2585	2470	−9	2488	2546	2562	2593	2656
RO-40S	2805	2830	2	3052	2656	2587	2336	1885
RO-42S	2611	2210	−34	3209	2482	2284	1885	1099
Average	2700	2747	1	2951	2905	2863	2820	2732

4.3. Combined Projection for Water Quality Changes for 5, 10, 20, and 40 Years into the Future

The 5-, 10-, 20-, and 40-year projections of water quality change based on the regression equations are given for all projection wells in Tables 3 and 5. The dissolved chloride concentration is decreasing in 35 of the 41 production wells. The average change in dissolved chloride concentration in the Hawthorn Aquifer Zone 1 wells, using the y-axis intercept as a reference concentration, is projected to decrease by 9.5% in 5 years, 12.3% in 10 years, 19.2% in 20 years, and 28.3% in 40 years. The 5- and 10-year projections are supported by a dataset of 11.2 to 13.5 years and are considered reliable. The longer projections are based on the trend lines and have low statistical reliability.

The dissolved chloride concentration in the Lower Hawthorn Aquifer is also projected to decrease over time, but to a lesser degree than Hawthorn Aquifer Zone 1. The average decrease in concentration is 1.6% in 5 years, 3.0% in 10 years, 4.4% in 20 years, and 7.4% in 40 years. Again, the 5- and 10-year projections are considered reliable.

If it is assumed that all the production wells are pumped at equal rates into the future at the pumping rate occurring at the end of 2020, then there will be a continued decline in dissolved chloride concentration. The dissolved chloride vales based on the data for all 41 production wells would be 2650 mg/L in 5 years, 2576 mg/L in 10 years, 2433 mg/L in 20 years, and 2163 mg/L in 40 years. As pumping is increased to meet future increased demand, the overall feedwater could decrease or increase based on the conceptual model used to explain the changes.

5. Discussion

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

An initial solute transport model was conducted to assess salinity changes at a pumping rate of 41,667 m^3/d, which was sufficient to produce the desired 30,303 m^3/d of potable water [27]. The model was developed using the SEAWAT code [35] and water quality changes were projected over a 20-year period (Figure 7). It was assumed the initial wellfield would have eight wells tapping the Hawthorn Aquifer Zone 1 and three wells tapping the Lower Hawthorn Aquifer. The most probable change in water quality expected occurred within the shaded area in Figure 7. The modeling projected an increase in dissolved chloride concentration from the starting value of 2600 to the best estimate of 3300 mg/L in the line within the blue shaded area. This equates to a dissolved chloride increase of about 35 mg/L/yr (TDS of 63 mg/L/yr) over 20 years. Note that the various sensitivity analysis runs produce two sets of possible dissolved chloride concentration outcomes with the first being 3500 mg/L at the top of the shaded area (i.e., best estimate range) or as high as 4250 mg/L for more unfavorable hydrogeological conditions. The range of projections consider the variability in the aquifer hydraulic coefficients, the variability of water quality within the two aquifers (Figures 8 and 9), and the interaction during pumping of the aquifers. Therefore, the highest rate of pumping-induced change in dissolved chloride concentration would be 1650 mg/L in 20 years or 82.5 mg/L/yr. Note that a no-flow boundary was assumed to be at the top of Hawthorn Aquifer Zone I within the confining bed separating it from the Sandstone Aquifer. This fits with the conceptual model, which accurately describes most of the wellfields used in Florida for BWRO source water (Figure 1).

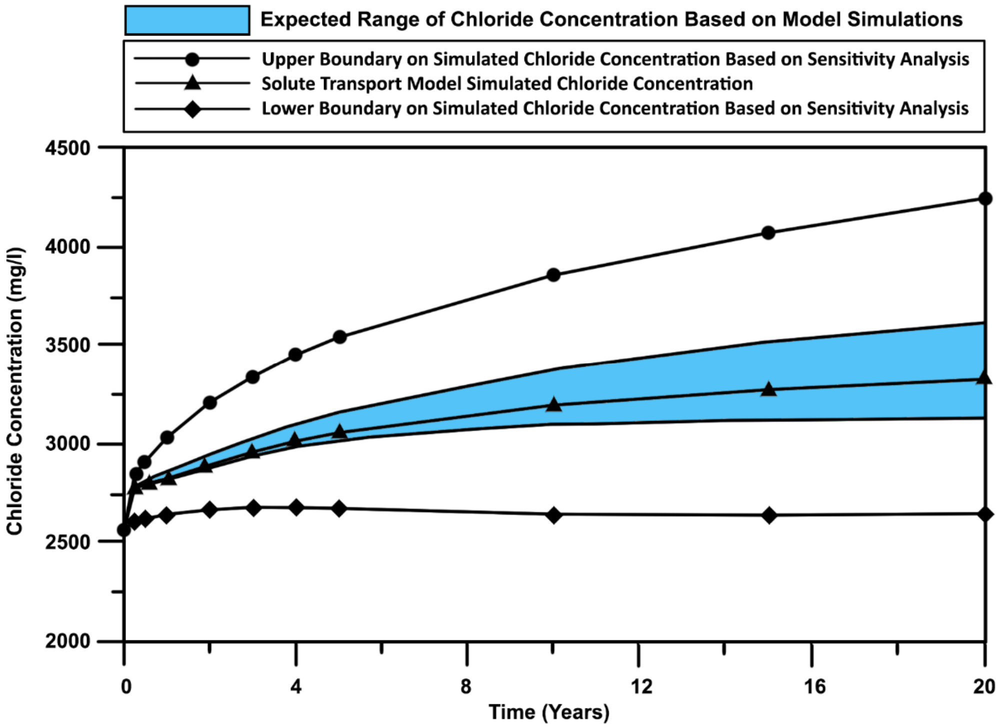

Figure 7. Original solute transport model for the South Collier County Wellfield based on a pumping rate of 41,667 m^3/d (11 MGD) [32].

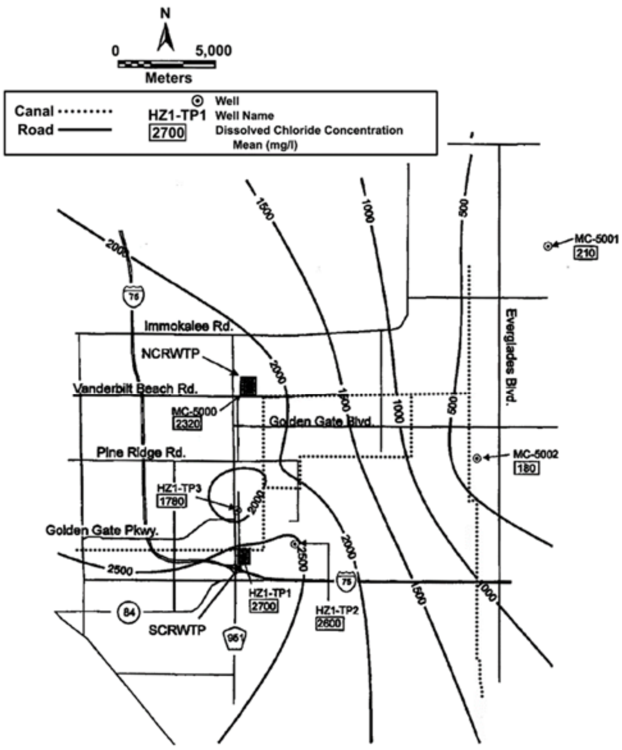

Figure 8. Dissolved chloride concentration distribution in Hawthorn Aquifer System Zone 1 [32].

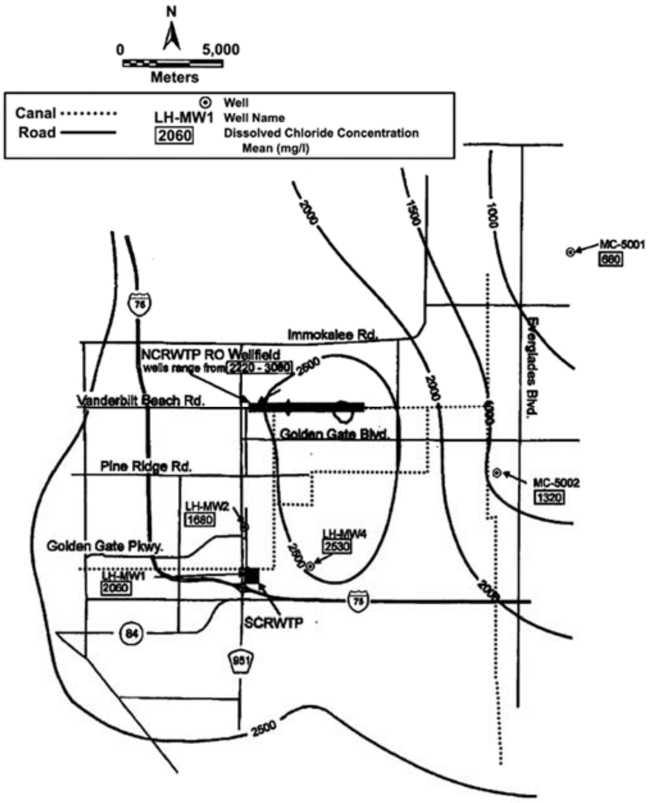

Figure 9. Dissolved chloride concentration distribution in the Lower Hawthorn Aquifer [32].

Based on the data collected from the production wells, the annual rate of change in dissolved chloride concentration in Hawthorn Aquifer Zone 1 is an average decrease of about 17 mg/L/year and the Lower Hawthorn Aquifer average increase is 1 mg/L/yr. The combined change based on relative aquifer use is a 16 mg/L/yr decline. The operational data indicate that the water quality is very stable and occurs just below the lower range of the shaded area of the solute-transport model projection. However, the trend in concentration is generally down and not up.

In general, the modeling results predicted a relatively minor increase of dissolved chloride concentration change over a 20-year period and this seems to be reasonably accurate. However, the model over-predicted the increase of chloride concentration at this wellfield. The field data indicate the dissolved chloride concentration is decreasing in 85% of the wells.

A possible explanation of the discrepancy between the model prediction and actual water quality data may be that the model under-estimated the leakance from above, from the Sandstone Aquifer, which has a low chloride concentration. The model had five layers, and the topmost layer is Hawthorn Zone 1 aquifer. Per MODFLOW/SEAWAT convention [37], the model had a no-flow boundary condition above this aquifer by default. If this default assumption is invalid, the aquifer would receive some recharge, likely of better quality, from the overlying Intermediate Aquifer System (Sandstone Aquifer). Another possibility is that fresher water within Hawthorn Aquifer Zone 1 is being captured and causing some reduction is the concentration (Figure 8). Hawthorn Aquifer Zone 1 contains freshwater water to the north of South BWRO wellfield. This option does not seem to be supported by the water quality data, which shows rather uniform decrease in chloride concentration. If the capture mechanism would be the predominant process, then the northeast part of the wellfield would have the highest reductions in concentration. Therefore, the actual chloride concentration may become more stable than the trends predicted by the model.

5.2. Conceptual Model of the Aquifer System Based on the Changes in Salinity

The conceptual model for the South Collier BWRO wellfield is different compared to the typical conceptual model used to evaluate most aquifers utilized to produce feed water in Florida and in other parts of the United States [19–25]. Nearly all the BRWO plants wellfields in the United States pump brackish water from a single aquifer. The South Collier County Wellfield has unique hydrogeology that allows water to be pumped from two different aquifers that have some degree of interaction based on their leaky nature (Figure 10). In most of the Florida BWRO wellfields, the recharge to the production aquifer is from the bottom upwards. The aquifers underlying the production aquifer contain higher salinity water, which tends to cause a long-term increase in salinity (Figure 1). The Lower Hawthorn Aquifer does behave in this manner to a degree in that 40% of the production wells show an upward trend. However, the aquifer also interacts with the overlying Hawthorn Aquifer Zone 1, which tends to contain less saline water. Hawthorn Aquifer Zone 1 contains fresher water towards the northeast (Figure 8), which corresponds with the regional flow direction as defined in CDM [32]. Since the pumping occurs in both aquifers the upwards movement of higher salinity water into the Lower Hawthorn Aquifer is offset by the production of less saline water from Hawthorn Aquifer Zone 1. In addition, the upper aquifer does capture some of the lower salinity water from the regional flow.

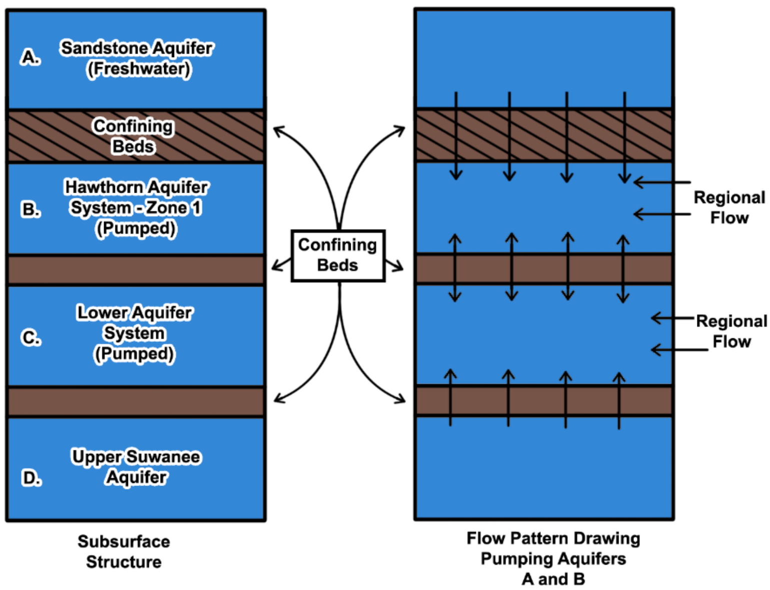

Figure 10. Conceptual model for the South Collier BWRO Plant Wellfield.

In the case of Hawthorn Aquifer Zone 1, some recharge of the aquifer moves downward across the upper confining unit from the Sandstone Aquifer. Therefore, the conceptual model that fits the water-quality behavior of the production wells involves the interaction between a lower high salinity source, the Suwannee Aquifer System, and a freshwater source, the Sandstone Aquifer, with additional interaction across the confining unit between the two production aquifers. It appears that the influx of freshwater into the two-aquifer system from the top is the predominant factor controlling long-term change in water quality. Therefore, the suggested conceptual model is as shown in Figure 10. This is a new conceptual model not found in any previous evaluation of BWRO source-water aquifers.

5.3. Implications of the Groundwater Quality Data for the Future Operation of the Desalination Facility

A key aspect of this research shows that the design of the South Collier County BWRO plant is sufficiently robust to be able to treat the feed water produced from the wellfield using a two-aquifer system over its projected lifespan. The plant can treat raw water with a TDS concentration of 8000 to 9000 mg/L or a dissolved chloride concentration of 4400 to 5000 mg/L. Based on the monitored water quality in the two aquifers, and the monitored blended feedwater for two recent years (Figure 11), the BRWO plant will be able to treat the raw groundwater for its 20-year life cycle without undergoing any major changes in process design. During the 2019–2020 period, the average dissolved chloride concentration of the composite water into the plant was about 2585 mg/L or a TDS concentration of about 4700 mg/L. Based on the well data projection, the dissolved chloride concentration at 20 years into the future will likely be close to 2400 mg/L or a TDS concentration of about 4360 mg/L.

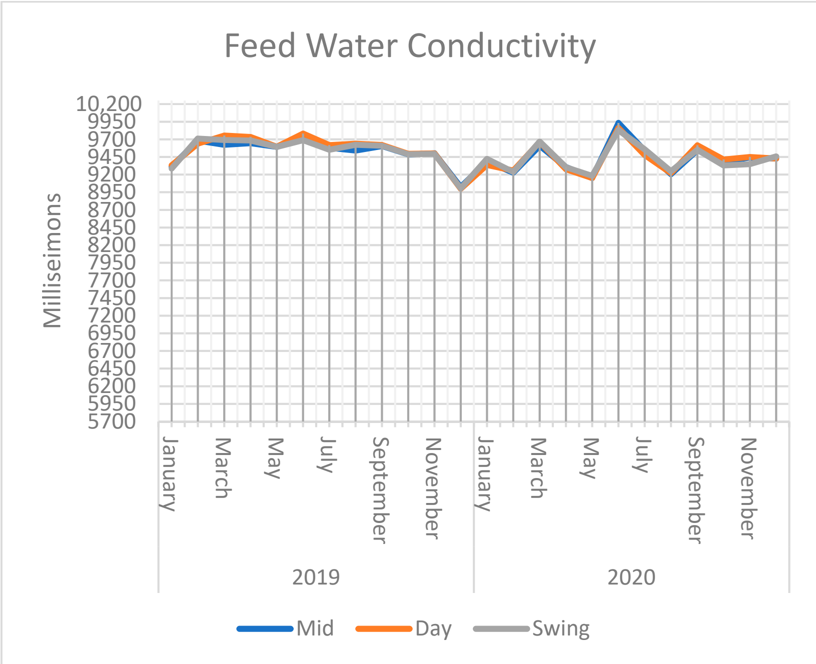

Figure 11. Conductivity of the feed water for 2019 and 2020. The mean is near 9400 millisiemens, which is an estimated TDS of 4700 mg/L or a dissolved chloride value of about 2585 mg/L.

5.4. Implications for the Future Operation of the BWRO Plant

Since the plant has been designed during the expansion to treat a TDS range of 8000 to 9000 mg/L, the projected reduction of the TDS in the future will allow the plant to operate without any modification over its life expectancy. In fact, the plant should be able to increase the blend of raw water into the finished water, therefore reducing future water treatment cost.

6. Conclusions

Most brackish-water reverse osmosis (BWRO) desalination plants use a groundwater source that tends to increase in salinity with time based on aquifer hydraulics and the mechanism of recharge during pumping. The reason that the salinity of the feedwater increases is the use of a single, leaky aquifer into which water recharges by upwards movement from a deeper aquifer that contains higher salinity water. The key operational issue is that the TDS of the feedwater must not exceed the ability of the RO process design to treat the water to potable standards during the life-expectancy of the facility.

The Collier County Florida South BWRO plant has a capacity of 75,758 m^3/d, which requires about 101,023 m^3/d of raw water to be pumped from an aquifer system based an approximate 70% conversion rate. The wellfield taps two different aquifers that contain brackish water. The original groundwater solute-transport model predicted a moderate to low rate of dissolved chloride increase with a mid-range of 35 mg/L/yr based on the conventional upward recharge conceptual model. The high range of change was

85 mg/L/yr over a 20-year period, while the low range was 5 mg/L/yr. The model was constructed with a no flow boundary placed at the top of the first brackish-water aquifer with no freshwater inflow simulated to occur. The actual operational data show a decrease in the average chloride concentration of the feedwater of about 16 mg/L/yr over the past 11 to 13.5 years and regression analysis suggests that the decrease will continue to occur. The key finding is that the uppermost confining unit is sufficiently leaky to allow some downward movement of freshwater to cause a slight downward trend in chloride concentration.

This case study produced a new conceptual model for evaluation of a two-aquifer wellfield with complex vertical water movement induced by pumping. This is a rare case where a groundwater solute-transport model could be audited to assess if the model is accurate over a long time-period and what changes in model structure would be required to make it more accurate.

Author Contributions: Q.L.A. did the graphs of the water quality changes and pumpage with the regression analysis and worked on the text. Z.R.K. did the statistical analysis. R.G.M. worked on the hydrogeology and revised the text. W.G. worked on the groundwater modeling and conceptual model. W.S.M. worked on the hydrogeology. T.M.M. drafted the final text and obtained project funding. All authors have read and agreed to the published version of the manuscript.

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