Significant Water Quality Trends Observed in the Lower Hawthorn Aquifer of Southwest Florida: Occurances & Solutions

E. Edward Rectenwald, Gordon P. Kennedy, Michael L. Weatherby, and George E. Reilly

Most coastal utilities in Southwest Florida use a brackish water supply for reverse-osmosis water treatment plants. Water quality changes observed here should be investigated by utilities located on the east coast and other parts of Florida because the South Florida Water Management District encourages the use of brackish aquifers for public water supply through alternative water supply funding in all of South Florida.

The aquifer most commonly used in Lee and Collier counties is the Lower Hawthorn Aquifer within the Floridan Aquifer System, which typically has chlorides of approximately 1,000 milligrams per liter (mg/L). Significant water quality declines have been noted, however, in several wells in separate municipal wellfields. Isolated occurrences of abnormally high chloride concentration groundwater have also been observed during construction of production wells.

Wellfield water quality declines may be a result of lateral saltwater intrusion, vertical upconing, or bulk flow through localized vertical conduits such as fissures, cracks, or fractures tapping more saline sources of water. These conduits may be a result of naturally occurring aquifer heterogeneity or manmade features such as improperly abandoned agricultural or oil exploratory wells.

This investigation describes the hydrogeologic framework and occurrences of increased chloride concentrations observed in separate wellfields in Southwest Florida. Mass balance calculations using major cations and anions were analyzed to find possible sources for these increased concentrations.

Possible sources must be identified before work can be done to rehabilitate wells or initiate operational changes to the wellfield to minimize effects. If the problem is specific to a well, possible solutions may include relining or back plugging the interval where the higher chloride concentrations may be entering the production zone. If well rehab does not improve water quality and use of the well is severely limited, it may need to be plugged and abandoned and a new well drilled in a different location.

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If the degrading water quality is occurring over most of the wellfield, major infrastructural and operational changes may have to be implemented. These changes could include wellfield expansion or phase-out, operational scheduling to minimize the use of affected wells, and water treatment plant upgrades utilizing improved membrane technology.

This article provides examples of unusual water quality and some approaches that utility operators may take to minimize impacts on facilities and the resource. Historical water quality data was analyzed from two wellfields in Southwest Florida. With permission, data from two Lower Hawthorn aquifer brackish wellfields are presented here: the city of Cape Coral and city of Fort Myers wellfields.

The water quality was collected at varying times between 1988 and 2007, depending on when the wellfield started operation. Figure 1 depicts the location of wellfields in Southwest Florida that utilize brackish water sources.

Figure 1: Map Showing Public Water Supply (PWS) Wellfields used in Southwest Florida

City of Cape Coral: Southwest & North RO Wellfields

Cape Coral was one of the first cities to convert to the Lower Hawthorn Aquifer. In

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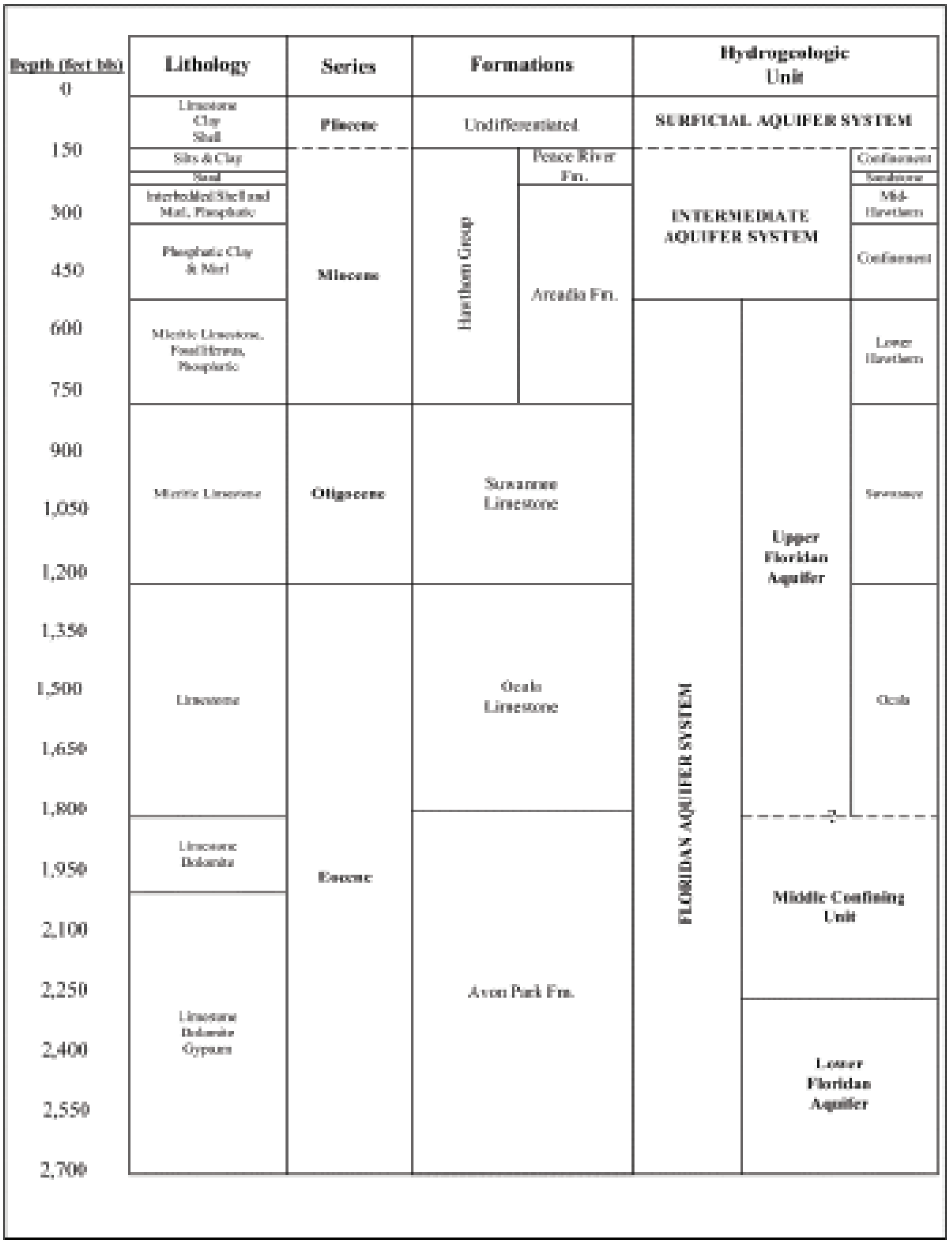
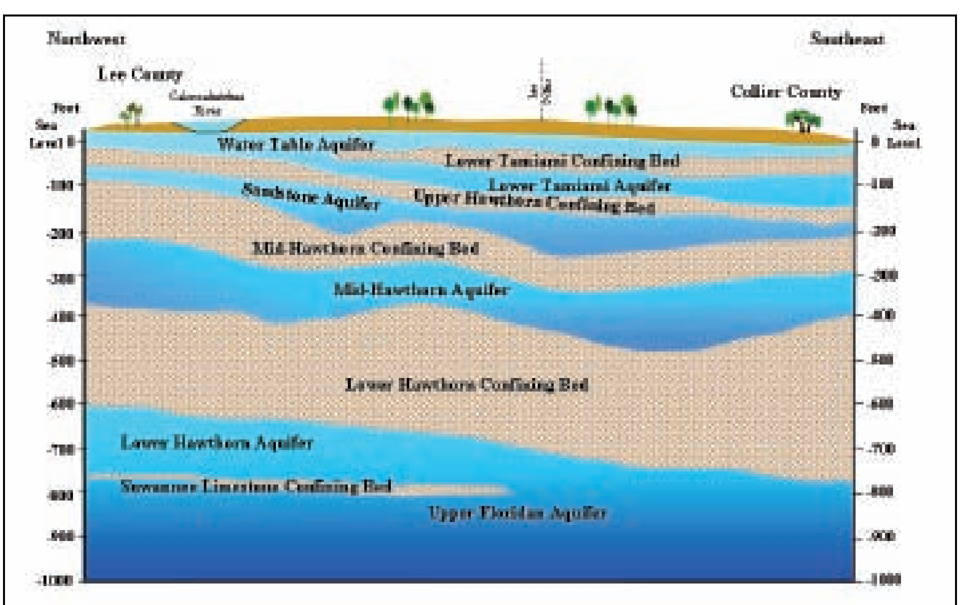


Figure 2: Generalized Hydrostratigraphic Section for Southwest Florida



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1976 the city put into operation a drinking water supply system supplied by wells up to 700 feet deep and a reverse osmosis (RO) water treatment plant with an initial capacity of 3 million gallons per day (MGD). In 1985 the city expanded this system to 15 MGD with 26 production wells in operation. In 2005 the system was further expanded to 17.8 MGD with the construction of eight new production wells.

Casing and total depths of the wells average approximately 400 and 800 feet below land surface (bls), respectively. The design pumping rate for each well was 700 gpm. The city is currently constructing a new RO water treatment plant in North Cape Coral, where 25 production wells are planned to be in production with an initial capacity of 12 MGD.

City of Fort Myers: Brackish Wellfield

Fort Myers converted from a freshwater system using shallow aquifer water to the brackish Lower Hawthorn Aquifer using RO technology for treatment. In 2001 the city put the RO treatment plant into operation with an initial capacity of 6 MGD, initially supplied by seven wells. By 2007 the city had expanded this system to 13 MGD with 16 production wells in operation.

Casing and total depths of the wells average approximately 450 and 750 feet bls, respectively. The design pumping rate for each well was 700 gpm. The city plans to build out the current RO plant with a capacity of 20 MGD of finished water.

Hydrogeology

Three major aquifer systems underlie Southwest Florida: the Surficial Aquifer System (SAS), the Intermediate Aquifer System (IAS), and the Floridan Aquifer System (FAS). These three systems are composed of multiple, discrete aquifers separated by low-permeability "confining" units that occur throughout this Tertiary/Quaternary age sequence.

The aquifers occurring in the upper portion of the FAS are the focus of this study. Figure 2 shows a generalized hydrostratigraphic section of the subsurface in Southwest Florida.

Two types of porosity control groundwater flow patterns in the FAS. Primary porosity is formed at the time of deposition

Figure 3: Generalized Hydrologic Cross-Section of Southwestern Florida

and is from finer-grained material enclosing larger grains. Secondary porosity is formed in the rock after deposition through such processes as dissolution of the carbonate rock matrix, creating voids or fracturing.

Florida is underlain by carbonate rocks that have been altered by karst processes. These limestone and dolomite units are variably affected by fractures; enlarged bedding planes; and geologic contacts, vugs, and caverns of various sizes (Tihansky, 2005). Variability in carbonate aquifer types have been documented by other authors (Hickey, 1982; Robinson, 1995; Knochenmus and Robinson, 1996).

These structural features, formed by fractures associated with larger structural mechanisms, create preferential pathways along which groundwater moves with less resistance (Tihansky, 2005). Well-developed networks of fractures and preferential flow zones facilitate rapid lateral and vertical movement and mixing of groundwater of differing quality (Tihansky, 2005). Figure 3 shows a generalized hydrologic cross-section from northwest to southeast across South Florida.

The FAS is defined as a vertically continuous sequence of permeable carbonate rocks of Tertiary age that are hydraulically connected in varying degrees, and whose permeability is generally several orders of magnitude greater than that of the rocks that bound the system above and below (Miller, 1986). The system is subdivided into the Upper Floridan Aquifer (UFA), the middle confining unit (MCU), and the Lower Floridan aquifer (LFA), based on hydraulic characteristics.

The FAS in the study area of Cape Coral is composed predominately of limestone with lower occurrences of dolomitic limestone and dolomite. The system occurs within the lower Arcadia Formation, Suwannee and Ocala Limestones, Avon Park Formation, and the Oldsmar Formation. The Paleocene Age Cedar Keys Formation with evaporitic gypsum and anhydrite forms the lower boundary of the FAS (Miller, 1986). In this article, hydrogeologic characteristics of the MCU and LFA will not be discussed because of the emphasis concerning water quality trends in the Lower Hawthorn aquifer.

The Lower Hawthorn Aquifer occurs within the lower portion of the Arcadia Formation of the Hawthorn Group and makes up the uppermost part of the UFA. The predominant lithology consists of white to light-gray, quartz sandy, micritic limestone containing minor amounts of dolomites, phosphate grains, and some beds consisting of abundant mollusk and gastropod shell fragments and other fossils (Reese, 2000). Typically, the limestones are moderately hard and have a moderate to high intergranular

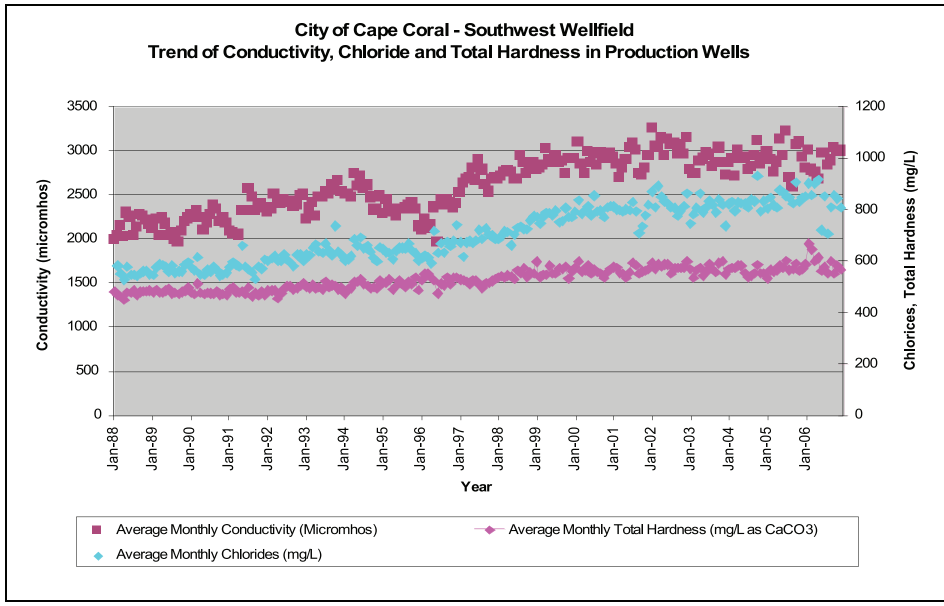

Figure 4: Chloride Trend in Southwest Production Wells Combined

porosity, and the shelly beds can have high moldic porosity.

The Lower Hawthorn Aquifer dolomites or dolomitic limestones typically have a microsucrosic texture, are very hard, and have variable porosities. The top of the aquifer occurs at depths ranging from approximately 400 to 600 feet bls in Southwest Florida and extends to a depth of 700 to 800 feet bls (Missimer and Associates, Inc, 1991).

The top of the Suwannee Limestone is generally estimated to be at approximately 700 to 800 feet bls in Southwest Florida, with variable confinement from the Lower Hawthorn Aquifer above. A regional disconformity separates the Hawthorn Group from the Suwannee Limestone (Reese, 2000).

Confining beds between the two aquifers vary in thickness from a few feet to almost 100 feet and consist of interbedded carbonate clays, marls, and limestones and/or dolomites of variable permeability (Missimer and Associates, Inc., 1991). The contact between the Hawthorn Group and the Suwannee Limestone is marked by an attenuation of the natural gamma activity on geophysical logs. The degree of confinement ranges from moderate to poor and exhibits a hydraulic connection in most instances (Missimer and Associates, Inc., 1991).

The Suwannee Limestone is divided into upper and lower units separated by variable confining units of limestone and marl of low permeability. The upper unit is composed of calcarenitic limestones, while the lower unit is composed of similar limestone, though less permeable because of interbedding and increased lime mud and fine grained material (Missimer and Associates, Inc., 1991).

Production wells penetrating the Lower Hawthorn Aquifer and Suwannee Limestone of the UFA in Southwest Florida have provided information regarding the quality of water contained within the strata. Most wells produce water containing chloride concentrations between 500 milligrams per liter (mg/L) and 2,000 mg/L and total dissolved solids (TDS) concentrations between 1,000 mg/L and 3,000 mg/L. Hardness and sulfate concentrations are approximately 180 mg/L and 250 mg/L, respectively.

Wellfield Water Quality Trends

Water quality trends can occur in two fashions: slow trends over time within the wellfield and fast changes observed in individual wells. Certain mechanisms can be responsible for these trends or quick changes; however, many times the exact answer is not known without intense and potentially expensive investigations.

Several wellfields tapping the Lower Hawthorn Aquifer have shown some type of abrupt water quality declines, including the North Collier Hawthorn Wellfield (CDM, 2005), North Lee County Wellfield (SFWMD Permit Information Files), the city of Cape Coral, and the city of Fort Myers. The latter two utilities gave permission to use their water quality data in this article, which documents water quality declines or unusual occurrences.

City of Cape Coral: Southwest RO Wellfield

Cape Coral began withdrawals from the

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Lower Hawthorn aquifer wellfield approximately 30 years ago. Digital records of monthly well data are available since 1988, providing a 20-year data set available for analysis. The city's records represent the longest-duration withdrawals of a major public water supply utility tapping the UFA in Southwest Florida.

Water quality declines were noted during the first 15 years of operation. At the time of the 1984-1985 wellfield expansion (Wells 11 through 22, now called Wells 211 through 222), chloride concentrations in the wellfield averaged approximately 550 mg/L. Few water quality anomalies were observed in the southwest Cape Coral brackish wellfield.

Changes in chloride concentration over time are presented in Figure 4, showing chloride levels in all wells (combined) increasing from 550 mg/L in 1988 to 850 mg/L in 2006. Similar trends were established for hardness and conductivity. On the other hand, no variations were observed for other parameters, such as alkalinity, pH, hydrogen sulfide, fluoride, and turbidity (Schers et al, 2007).

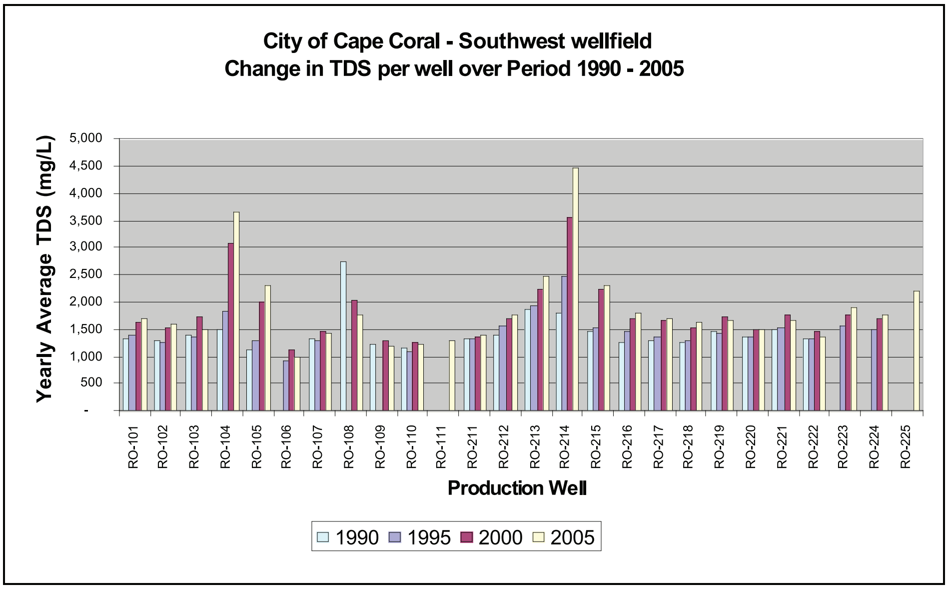

Figure 5: Chloride Trend in Southwest Production Wells Combined

While average salinity levels for all wells combined have steadily increased between 1988 and 2006, differences were observed in individual wells, as presented in Figure 5. It is evident that salinity in certain production wells, with marginal salinity, increases in that period (Well 110 experiences a TDS increase from 1,150 to 1,240 mg/L). Similarly, some wells exhibited dramatic TDS changes, such as Well 214, which exhibited a TDS increase from 1,810 to 3,940 mg/L. The variation in water quality degradation across the wellfield may be sought in localized differences in geology and hydrogeology.

Studies and modeling efforts predicted that water quality declines would continue at a predictable rate in proportion to water production (Missimer & Associates, 1991). Actual data, however, suggest that major infrastructural and operational changes to the city's water supply system and wellfield procedures have stabilized the rate of water quality decline (Schers et al, 2007).

These changes include: 1) implementation of a dual water system for potable and

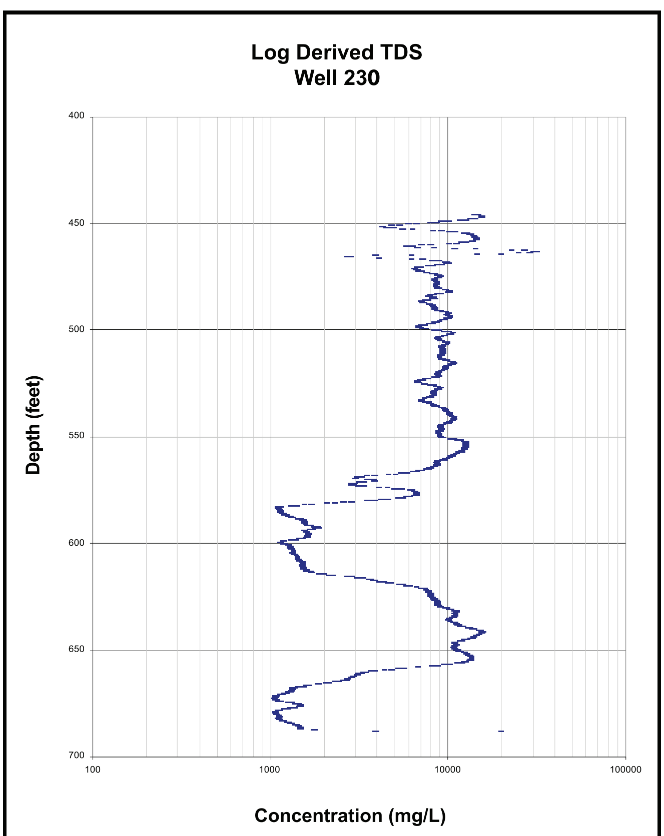

Figure 6: Calculated TDS Plot for Well 230

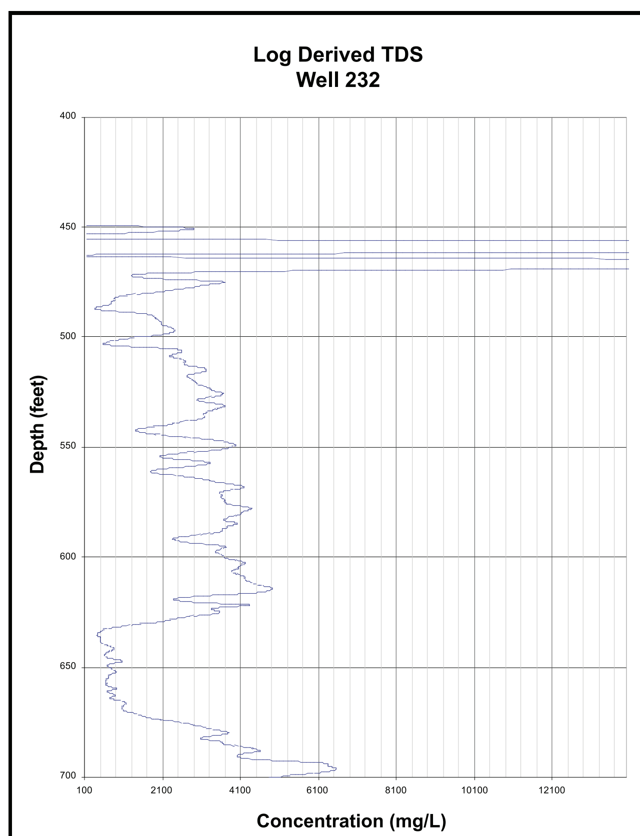

Figure 7: Calculated TDS Plot for Well 232

irrigation uses, 2) wellfield operational scheduling to minimize use of marginal facilities and poorer quality wells, 3) regularly scheduled well rehabilitation and maintenance to increase well efficiency, and 4) use of variable frequency drives coupled with real-time well monitoring to optimize individual well production.

The wellfield improvement strategies minimized stresses on individual wells and wellfield alignments and also minimized the potential for saltwater intrusion and upconing. Water quality of the raw water to the RO treatment plant has increased from about 1,400 mg/l TDS in the late 1980s to around 1,900 mg/l in 2000. Water quality has remained stable since that time in spite of production increases from approximately 300 to 425 million gallons per month.

The data suggest that readily implementable wellfield operational protocols can minimize water quality changes to manageable levels, prolonging the life of the resource and treatment plant operational requirements (Schers et al, 2007).

The relative stability and consistency of water quality in the South Cape Coral Wellfield was shattered during the wellfield's 2005-2006 expansion (Wells 226 through 232). Two of the eight wells exhibited anomalously high chloride concentrations during well construction.

Geophysical logs, the video log, and water quality data collected upon completion of well drilling indicated that unusual conditions were present in Well 230 that had not been encountered previously in Cape Coral within the Lower Hawthorn Aquifer. Upon completion of the open hole drilling, chloride concentrations ranged from 6,250 to 7,120 mg/L.

The well was initially back plugged to prevent potential inter-aquifer flow from the zone below 600 feet bls into shallower portions of the Lower Hawthorn. Derived TDS plots calculated from geophysical log data indicated that the high TDS water was present in the upper portion of the aquifer (Figure 6). The well was therefore subsequently plugged and abandoned.

Although not as severe, a second well encountered anomalously poor water quality. Dissolved chloride concentrations ranging from 2,600 to 2,900 mg/L were observed in Well 232. The calculated TDS plot from this well, however, indicated a distinct transition in water quality from the top to the bottom of the open-hole section of the well (Figure 7). The information obtained from geophysical and video logs indicated the subsurface water quality conditions encountered in Well 232 were of a different character than in Well 230.

Well 232 was subsequently backplugged to isolate the poorer-quality water zone. Significant water quality improvements were observed following backplugging. Dissolved chloride concentrations have decreased from 2,600 to 1,200 mg/l since the well was put back in operation. It is believed that additional pumping will continue to improve the water quality upon flushing the area immediately surrounding the wellbore that may have been contaminated by the poorer-quality water from below.

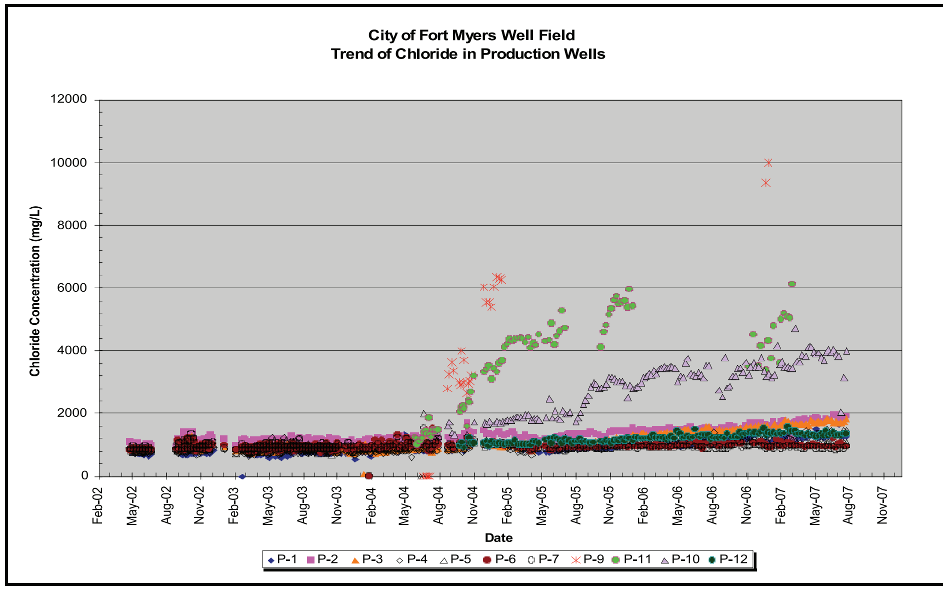

Figure 8: Relationship Between Chlorides and Time for the City of Fort Myers Wellfield

City of Fort Myers Brackish Wellfield

Fort Myers completed construction of its Phase I Wellfield in 2000 (seven wells) and the RO treatment plant and wellfield came on line in 2001. Construction of the Phase II Wellfield (five additional wells) was initiated in 2003.

During the development of the first production well in Phase II, the water quality quickly deteriorated from conductivity of approximately 7,000 microsiemens per centimeter (µS/cm) to 40,000 µS/cm (approximately 20,000 mg/L TDS or 10,000 mg/L chloride). Because of the poor water quality and in concern for the other wells, this well was partially back plugged and converted to a monitoring well. Because of the extreme need for water, construction proceeded carefully with the other wells in the area. Testing during construction did not reveal any water quality issues with the other four wells, which were put on line as soon as they were permitted by the Florida Department of Health.

By mid-October 2004, it was apparent that the high salinity in the first well had begun migrating to the next-closest new production wells, located approximately 850 feet and 1,400 feet away. The poor quality in the well 1,480 feet away degraded to 10,000 µS/cm in 46 days and to 20,000 µS/cm in 176 days, but the well located 960 feet away degraded to 10,000 µS/cm in 234 days, denoting a preferential pathway for lateral migration.

On October 29, 2004, because of the quick, severe change in water quality, the city considered the possibility of using remote sensing to look for improperly abandoned oil exploratory wells in the area of the first well. The city also considered the possibility that the high salinity could be caused by some naturally occurring feature (fractures or other geologic anomalies) within the northern section of the wellfield.

To date, the lateral migration of salt water has impacted three of the five Phase II brackish production wells. Subsequently, two of these wells were shut down in 2006 because they were causing impacts to the recovery efficiency of the RO treatment plant. The third impacted well remains in operation at a reduced flow rate and is used as a capture zone well to protect the fifth well constructed, which has high productivity. Figure 8 shows the water quality impacts.

Construction of Phase III of the brackish wellfield was initiated in late 2006 and completed in mid-2007. These five new wells provided enough water to bring one of the saltwater-impacted wells back on line without causing impacts to the recovery efficiency of the RO water treatment plant.

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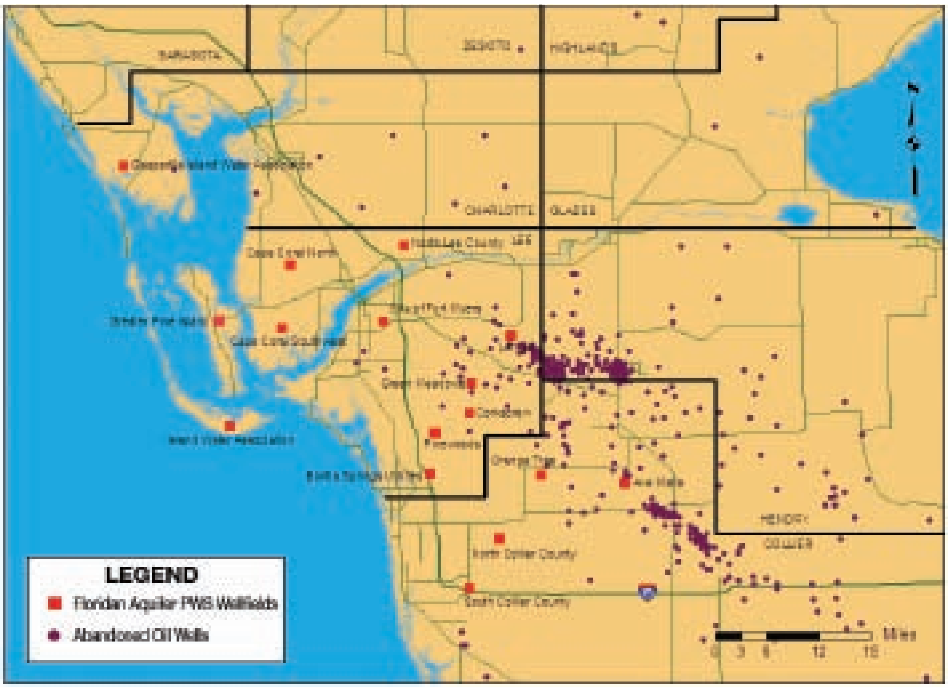

Figure 9: Map Showing the Location of Oil/Gas Wells and Surrounding PWS Wellfields

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Potential Sources of Poor Quality

In general, the quick water quality changes experienced at these utilities seem to be connected to a vertical conduit (vertical fractures or old borehole) that is allowing upward movement of saline water from an underlying aquifer. The changes observed in one or two wells appear to be isolated. The physical mechanism contributing to the water quality changes is unknown. The possibilities are:

- A pocket of poor-quality water below 800 feet in close proximity of certain wells
- A series of vertical conduit intersecting borehole bottoms allowing:
  - Direct connection to well boreholes
  - Quick changes in water quality depending on degree of intersection
- A vertical conduit in close proximity of wells with:
  - Nondirect connection to boreholes (only proximal)
  - Allowing quick changes in water quality, depending on well distance from source (i.e. quick response in certain wells but slower in adjacent wells)

The idea of a pocket of poor-quality water implies the water quality from the well will show evidence of degradation, stabilize, and possibly improve over time, since the trapped connate water is finite in extent and volume. The other two scenarios may or may not have a point of water quality stabilization. Dilution, or the mix between the poor-quality water entering the bottom of the borehole and the water entering into the higher portion of the borehole, may allow the well water quality to stabilize at a specific (reduced) production rate from that well.

Saltwater Intrusion

Lateral and vertical intrusion are the two types of saltwater intrusion that occur in Southwest Florida. Lateral saltwater intrusion occurs when seawater migrates inland from a natural reduction of freshwater heads (drought) or pumping of wells. As population increases, so does the demand of water, so an increase in pumping to meet the demand lowers the hydraulic potential by stressing the aquifer, allowing seawater to move inland at a faster rate.

Fractures, which are also evident in carbonate aquifers of Southwest Florida, may also increase movement of saltwater laterally into these coastal wellfields.

Vertical saltwater intrusion occurs when saline water moves upward through fractures from underlying, more-brackish aquifers. Production wells are occasionally drilled into fractures that are oriented vertically or at high angles. These fractures may act as conduits for high-salinity waters to move upward rapidly, degrading the water quality of some wells soon after they go into production.

Improperly Abandoned Exploratory Oil Wells & Agricultural Wells

After uncharacteristically poor water quality was found following development of the first well at Fort Myers, it was suspected that an improperly abandoned oil or exploratory well might be responsible. It is known that many of these types of wells are located in Lee County (and surrounding counties), originating back in the 1940s and 1950s with the advent of oil and gas exploration in the area. Many of the wells or exploratory holes were not publicly well documented.

Figure 9 provides locations of oil and gas wells and surrounding public water supply wellfields in Southwest and South Central Florida (USGS database). Further review of old aerials and inquiries to state and federal agencies provided no evidence of wells of this type in the immediate wellfield area.

There were also many improperly constructed agricultural wells in Southwest Florida that were not properly documented. In the 1990s, the South Florida Water Management District conducted a well abandonment program that plugged and abandoned many of the documented agricultural wells in Southwest Florida.

Solutions to Minimize Migration

Upward migration of very poor-quality water can have detrimental effects, not only for the individual well, but for the entire wellfield. These effects may only be a trending of observed water quality changes, or the migration could cause severe effects on several wells, significantly decreasing the sustainability of the water supply and wellfield.

Some solutions can be imposed on wells that are experiencing impacts from poor-quality water. At times, multiple solutions should be used simultaneously to achieve the desired effect.

Abandoning a well shall always be the last option available. Reducing the impacts of upward or lateral migration of poor-quality water shall always be the first option, because it is prudent to try to save the high capital investment in today's production wells.

Back Plugging with Cement

t is possible that wells may be usable in the future if they are back plugged. Since wells can have multiple distinct flow zones in the borehole, they can be back plugged to minimize the connection to poorer-quality

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water. Typically, the deep flow zones are responsible for the connection to poor-quality water.

A well's production will decrease after back plugging because of plugging the preferential flow zone where the majority of the flow is originating. Grout can be forced into small fractures, thus plugging off even small conduits outside of the borehole wall.

Back plugging reduces the borehole stresses from the previously exposed vertical conduits, decreasing the possibility of upward migration. If production can be increased by acidizing a less dominant flow zone higher in the borehole, then lower borehole stresses will cause less water to be pulled from the bottom of the borehole.

Hydraulic Control & Water Quality Blending

Since a well may be connected or in close proximity to a vertical conduit, it is quite possible that back plugging may not be completely successful and the well will continue to show signs of degradation, since any vertical conduit will always be within the capture zone (drawdown cone) of this well.

Further operational analysis may show that the well can be used at lower flow rates and the water produced can be diluted into the raw water stream to the RO water treatment plant. This action has a higher chance of success when additional wells exist or are planned in the immediate future. With each new production well added to the wellfield, the dilution capacity of the wellfield will increase.

Groundwater modeling can shed further light on this issue using a particle tracking software package to see which well is capturing the source of poor-quality water and which adjacent well can capture the poor-quality water if the currently affected well is abandoned. Also, groundwater modeling with a solute transport software package can determine if the poor-quality water will be captured by other wells if affected wells are turned off as mentioned above, in addition to potentially locating the source of the poor-quality water by matching field observed water quality data.

It is also possible that affected wells can continue being pumped and discharged to the RO treatment plant's deep injection well for disposal to protect the rest of the wellfield. There are permitting and pipeline considerations with this option; however, it can be a viable option if the current wellfield can not be expanded to increase the blending capacity.

For one wellfield in Lee County, a raw water quality calculation exercise was conducted to determine the potential blending effects for the wellfield if two wells impacted by poor-quality water were operational. A table was created that calculated the blending capacity of the current wellfield with these two wells operating. The results indicated that if the water quality can be marginally improved through back plugging and acidization, these wells could be operational at reduced pumping rates within the current wellfield, and the RO treatment plant would experience only a slight chloride increase.

The study also indicated that the water quality could stay at current levels with reduced pumping rates when the Phase II wellfield is put on line, maintaining hydraulic control on the poor-quality water and preventing it from migrating to adjacent wells, while still providing 1.4 MGD of raw water to the RO treatment plant with minimal increases in the raw water chlorides.

Well Abandonment

A facility could also plug and abandon a well and look for a new location where production could be as good or better without the degrading water quality. If the poor water quality is originating from the upper half of the production interval just below the casing, this may be the only option available. This solution is also not a guarantee and could be more costly if the new location identified the same water quality issues as the well that was plugged and abandoned.

Well abandonment because of severe water quality impacts within an active wellfield will have a much lower chance of success. If the conduit connection to the poor-quality water is not severed and abandonment activities are not successful, then the poor-quality water can be pulled or captured by the next-closest operating well if the poor-quality water is allowed to enter the raw water aquifer.

Well abandonment should be considered as a last option for many reasons. Besides the capital investment in constructing the well and pipeline, abandonment removes all potential for hydraulic control of the migration of poor-water quality, which may migrate artificially through the wellfield by pumping stresses alone.

Conclusions

Significant increases in salinity, which are typically localized, can be caused by natural geologic features such as karst dissolution features, vertical fissures, cracks or fractures, or man-made conduits from abandoned agricultural or oil and gas exploration wells. Several existing wellfields in Lee County and Collier County have exhibited significant water quality changes over time. These changes can affect single wells, multiple wells, or the entire wellfield.

Efforts can be made to minimize effects of significant poor-quality water migration. In some instances, sacrifices must be made to protect the rest of the wellfield. These sacrifices may be a loss of production from back plugging a well with significant water quality changes, abandonment of an affected well, reduced recovery efficiencies because of continued use of an affected well, higher operational costs because of higher operational pressures, or even conversion to use of high-pressure RO trains, as Collier County is planning.

Wellfields in Southwest Florida that utilize the Lower Hawthorn Aquifer may start to degrade over time with an ever-increasing population, raising the importance for RO technology to continue to improve. Water treatment plants currently offer lower operating pressures, higher salt rejection, and longer membrane life, allowing a transition from freshwater aquifer sources to the UFA (brackish aquifers) with manageable impacts on drinking water costs (Schers *et al*, 2007).

Improvements to the wellfield pumping equipment have had substantial impacts on maintaining optimum pumping conditions and on power consumption (Schers *et al*, 2007). Installation of variable frequency drives allows pumping rates to operate individual wells according to up to three set points: based on well drawdown set point, pressure set point, or production flow set point, which in turn lowers the stress on the aquifer (Schers *et al*, 2007).

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