Rising Tides and Sinking Brines: Managing the Threat of Salt Water Intrusion

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The Florida Keys Aqueduct Authority (authority) has adapted its Biscayne Aquifer monitoring plan to track changes to the saline water interface and to address a growing threat from a localized hypersaline plume in southeast Miami-Dade County. The authority's Biscayne Aquifer wellfield in Florida City is located about 10 mi west of Biscayne Bay and about 5 mi east of Everglades National Park. The authority currently monitors a network of 16 Biscayne Aquifer wells within an area of approximately 30 sq mi south and east of its Florida City wellfield as part of a saline water intrusion monitoring (SWIM) program. Continued inland movement of the saline water interface towards the authority's wellfield has necessitated changes in its monitoring program to include six new wells inland of the saline water interface and to cease monitoring at eight existing wells.

At least two distinct sources of saline water have been identified as impacting the authority's SWIM network: 1) hypersaline density driven seepage from the Florida Power and Light (FPL) cooling canal system at Turkey Point east of its wellfield, and 2) seawater encroachment via seepage from the C-111 and other nearby canals south of the wellfield. The FPL salinity source has been confirmed by its tritium signature within the surrounding groundwater monitoring network.

The leakage of seawater from tidally influenced canals has been indicated by correlation of salinity variation with canal stage data. Recent Comprehensive Everglades Recovery Plan (CERP) projects involving improvements to canal control structures and the plugging of canals have begun to have a measurable impact in the form of decreasing chlorides at some wells adjacent to canals in the western half of the SWIM network. All of the monitor wells located in the eastern half of the network exhibit increasing chloride level trends and also have the highest levels measured in the network.

In order to facilitate optimization of the SWIM network, the authority's historical records of chloride concentrations at multiple well sites and multiple depths within the Biscayne Aquifer were graphed and mapped using a geographic information system (GIS). The data were evaluated to determine trends in existing wells that had previously experienced saline water invasion and to identify target areas where monitoring coverage was lacking. New well sites were chosen within the target areas based on estimates of the rate of intrusion and logistical factors, such as accessibility, land ownership, utilities, and right of way concerns. The depths for sampling points in each new well were chosen to fill gaps in data from neighboring wells. The new well construction design generally matches that of existing SWIM wells and includes provisions for continuous salinity profiling across the vertical extent of the Biscayne Aquifer, as well as discreet sampling at separate and distinct intervals within the well. The design facilitates continuity of sampling and monitoring procedures within the network and provides for a variety of approaches to characterize the movement of saline water within the aquifer.

Time series plots of chloride levels at a number of the SWIM wells have exhibited variable degrees of saline water influence, ranging from highly fresh and stable to exponentially increasing salinity. Several wells with multiple discreet sample depths have demonstrated pronounced density-controlled stratification, which indicates that the saline water interface has moved preferentially along the bottom of the aquifer, while water in the upper portion of the aquifer has remained relatively fresh.

This stratification has been occasionally reversed with wells showing episodic increases in salinity within the upper sampling interval, while deeper samples remained fresh. This inversion of the normal salinity distribution has been transient and indicates transient encroachment of saline surface water. The accuracy and integrity of the SWIM program is critical to the management and sustainability of the authority's Biscayne Aquifer wellfield. Continued improvements and optimization of the monitoring program ensures long-term viability of the critical Biscayne Aquifer groundwater resource.

Historical Overview

The 1935 Labor Day Hurricane destroyed the Florida Overseas Railroad and halted the transport of large quantities of fresh water to the Florida Keys via railroad tank cars. The lack of a dependable water supply prompted the Florida Legislature to create the Florida Keys Aqueduct Commission (FKAC) in 1937, which was the predecessor of the authority. The U.S. Navy reopened its naval base in Key West in 1939 and entered into an agreement with FKAC in 1941 to build a water supply pipeline from the mainland to Key West, with the federal government paying two-thirds of the cost.

The Navy acquired 353 acres of land in Florida City in 1941 and contractors began drilling wells, building pump stations, and laying approximately 128 mi of 18-in. ductile steel pipe to bring water to Key West. Water pumped from three 10-in. Biscayne Aquifer wells at the Florida City Navy wellfield first reached Key West on Sept. 22, 1942. Due to the high level of calcium hardness in the water, which caused excessive buildup of lime scale in pipes, a filtration and lime softening water treatment plant was added to the Florida City facility in 1944.

In the late 1980s, a new lime softening/filtration water treatment plant was built and then expanded to meet the demands of growth and tourism in the Florida Keys and Monroe County. Although alternative and emergency water supply systems have been developed, including reverse osmosis treatment plants at Florida City, Stock Island, and Marathon, the primary source of fresh water for the Florida Keys remains groundwater from the Biscayne Aquifer pumped from the Navy wellfield in Florida City.

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Saline Water Intrusion Monitoring Program Background

The Central and Southern Flood Control District, later to become the South Florida Water Management District (SFWMD), originally issued the authority's Water Use Permit Number 13-00005-W in 1974 for 13.5 mil gal per day (mgd) of Biscayne Aquifer water. Under two SFMWD programs, entitled Saline Water Intrusion Monitoring and Management (SWIMM) and Multidepth Potentiometric Head Monitoring Program (MUD-POHMP), the original permit required that the permittee collect water samples from canals and wells for analyses of dissolved chloride concentrations and other parameters.

The permit required the construction of one onsite and two offsite monitor wells to be equipped with monitoring devices, and records to be submitted monthly. In 1974 the U.S. Geological Survey (USGS) entered into a cooperative agreement with the U.S. Navy to assess the adequacy of the water supply and to evaluate potential impacts of seawater intrusion in response to U.S. Navy and authority concerns that increased withdrawals from the wells could cause seawater to move inland and contaminate the wellfield. An early USGS saline water intrusion map as it relates to the Navy wellfield is excerpted as Figure 1.

In 1980, the authority entered into a joint funding agreement with USGS to perform water level monitoring and dissolved chloride analysis of wells owned by the authority, as well as other USGS wells in established monitor well networks. Several of these wells remain in the SWIM network and continue to be maintained by USGS. Under cooperative funding between the authority and USGS, two of these wells provide real-time water level data that are available on the USGS website.

During the water use permit renewal process in 1990, SFMWD required an update of the SWIM monitoring program due to increases in salinity observed in several wells. The authority implemented changes to the monitoring program, namely by addition of six new monitor wells, designated as FKS-1 through FKS-6, and by conductivity profile monitoring in addition to the previously required chloride and water level data. In 2001, SFWMD again required updates to the monitoring plan and the authority responded by the addition of three more monitor wells, FKS-7 through FKS-9, by 2004.

As part of a wellfield protection study conducted in 2010, the authority's consulting engineer recommended a number of changes to the program, including the addition of seven new monitor wells and ceasing monitoring at four existing wells. In 2015, the authority requested that Water Science Associates (WSA) reevaluate the previous consultant's recommendations, provide an updated analysis, and design and implement modifications to the SWIM program.

Geographic Information Systems and Data Evaluation

As part of the initial evaluation of the SWIM program, WSA assembled the files of monitored data from the authority for the 16 monitor wells in the network. These data encompassed monthly

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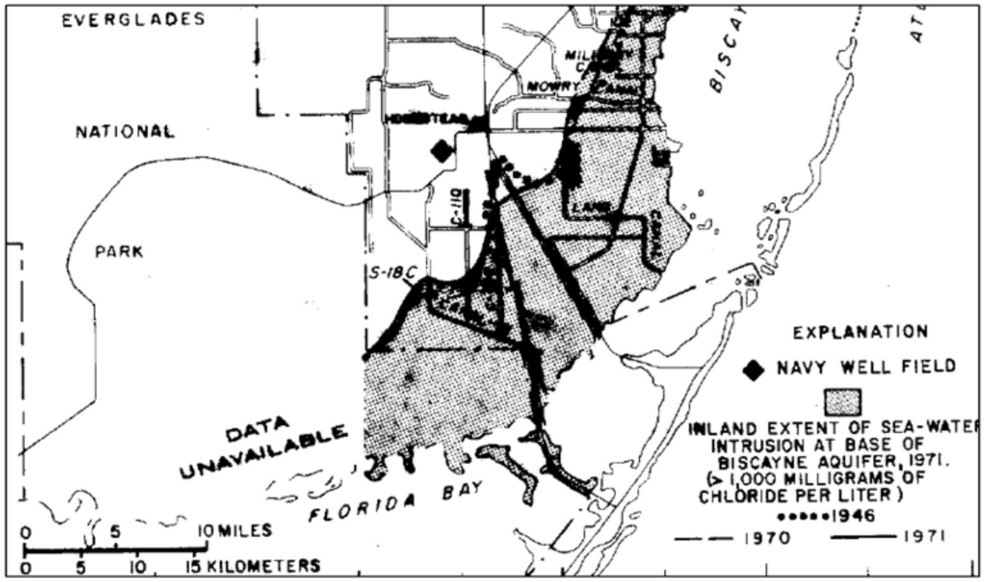

Figure 1. Inland Extent of Seawater Intrusion for 1946, 1970, and 1971 (Meyer, F.W., 1974)

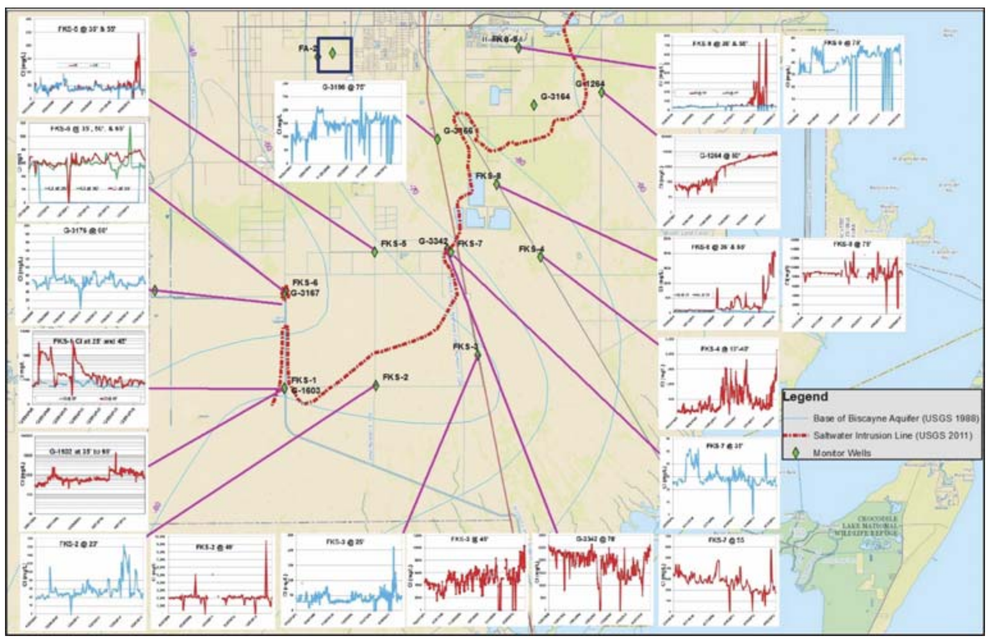

Figure 2. Map Showing Saline Water Intrusion Monitoring Wells and Chloride Levels Over Time

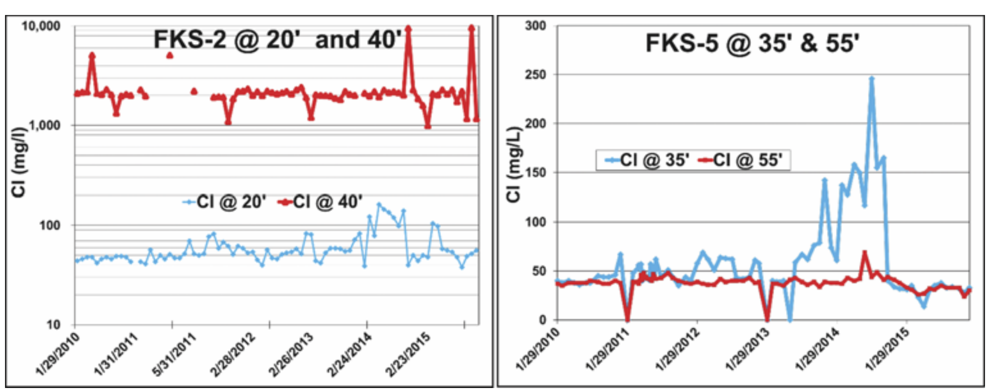

Figure 3. Chloride Levels in Upper and Lower Zones of Monitor Wells FKS-2 and FKS-5

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sampling events from 1991 through 2016. The chloride levels in all of the wells were plotted as time series and positioned on a GIS map of the network, as shown in Figure 2. Additional mapped information included a 2011 representation of the approximate extent of the 1000 mg/l isochlor based on work conducted by USGS (Prinos 2011) and a GIS contour map showing the base of the Biscayne Aquifer (Ramirez, J., 1990).

A review was conducted by WSA of CERP work that included SFWMD and U.S. Army Corps of Engineers (USACE) projects as they pertain to the effectiveness and spatial distribution of the SWIM network. Projects that were evaluated included the SFWMD's C-111 Spreader Canal Western Project, the USACE's C-111 South Dade Project, and the USACE's Biscayne Bay Coastal Wetlands Project.

Perhaps the most significant CERP project impacting the SWIM program is the plugging of several canals that previously have served as conduits for direct inland movement of seawater during dry periods and have allowed rapid drainage and reduced groundwater recharge during wet periods; specifically, wells FKS-2 and FKS-5 are located adjacent to a recently plugged section of the C-110 canal. As shown in Figure 3, over a period of several months in 2014, FKS-2 and FKS-5 experienced elevated chlorides in their upper zones, while the lower zones did not show corresponding increases. This pattern of salinity indicates that the canal and upper zones of the wells were intruded by surface water rather than groundwater.

The lowering of the water table elevation in the immediate vicinity of canals also produced localized areas of reduced hydraulic head within the aquifer that facilitate saline water intrusion in the groundwater system. This effect is believed to have caused transient intrusion of saline water into FKS-1 and adjacent G-1603 during two low-stage episodes that occurred in April 2009 and May 2011. During drought conditions, the canal stage on the C-111 adjacent to the two wells was lowered to about 1-ft National Geodetic Vertical Datum (NGVD), and chloride levels in FKS-1 and G-1603 experienced corresponding dramatic increases on the order of 3000 to 4000 mg/l, as shown in Figure 4.

This correlation of wellfield water levels and chlorides with the canal stage had previously been established by a detailed statistical analysis in 2013 by one of the authors (Martin, 2013). The study concluded that canal-stage levels had a much more significant impact on observed groundwater levels and chlorides than withdrawals from the wellfield by the authority or other nearby users. This conclusion was further bolstered by the current evaluation and was subsequently used as a basis for a permit modification linking dry-season Biscayne Aquifer water use restrictions to actual groundwater levels in USGS monitor well G-613, rather than the calendar-based criteria previously imposed. The G-613 is located about 2 mi southeast of the authority's wellfield.

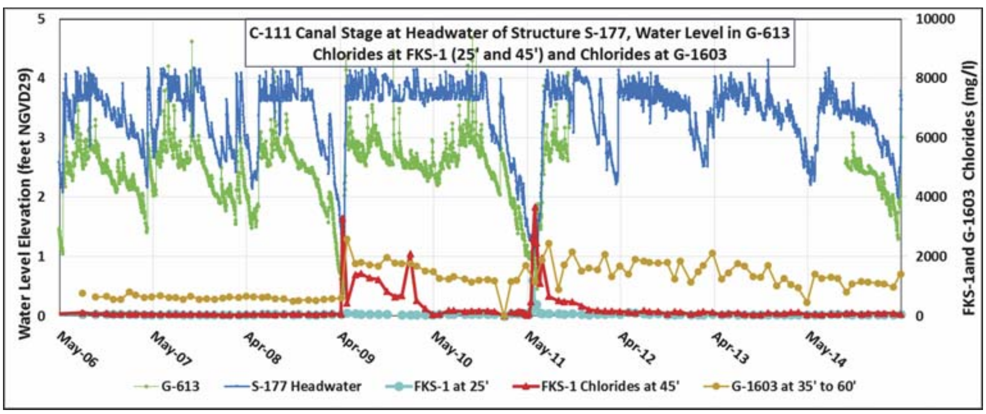

Figure 4. Canal Stage Correlation With Salinity Increases at FKS-1 and G-1603

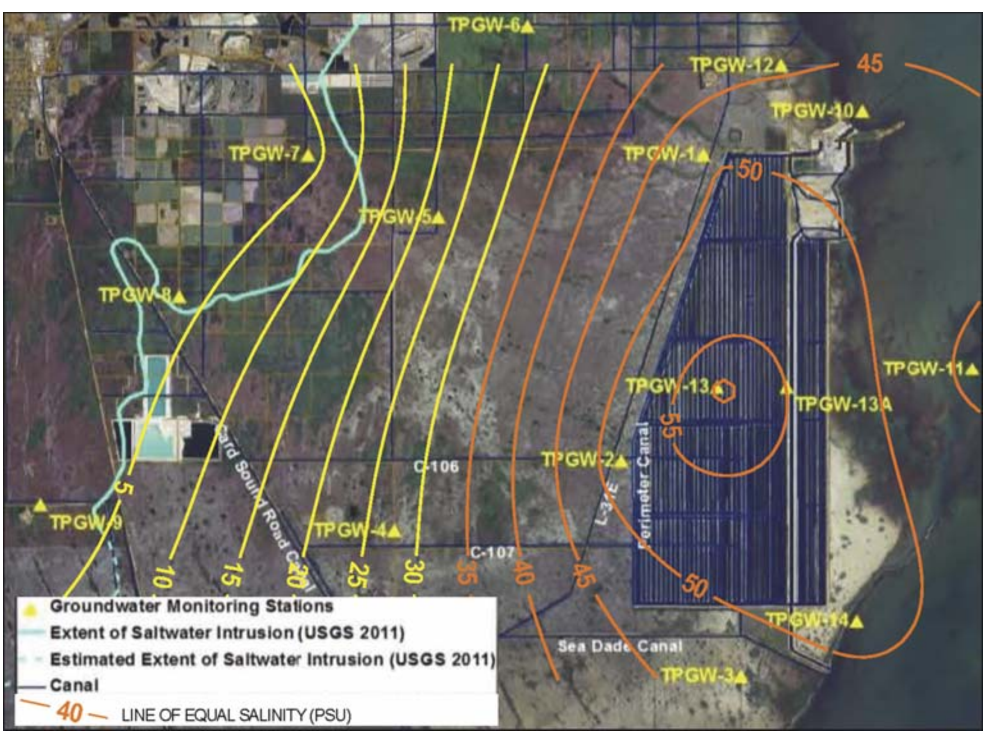

Figure 5. Contour Map of Salinity in Deep Bicayne Aquifer Groundwater: Average December 2014 Practical Salinity Units (PSU) Values

Florida Power and Light Hypersaline Plume

The FPL maintains a cooling canal system (CCS) for operation of power generation units at its Turkey Point power generation facility in southeast Miami-Dade County. The western boundary of the CCS is located about 9.5 mi east of the authority's wellfield and about 5.5 mi east of FKS-9. The CCS consists of some 6,000 acres of canals through which water is circulated for dissipation of heat created by the power generation units. The CCS is characterized as a "closed-loop" cooling system, in that the same water is circulated through the extensive canal network without direct input of new water to the system; however, the CCS does not function as a closed-loop system hydrologically in that, as the warmed water is circulated, evaporation losses to the atmosphere remove freshwater from the canal sys-

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Ralph Braun (standing) discusses collection system trends with Nick Wagner, Superintendent of Lift Stations.

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tem, causing a concentration of salinity that exceeds typical ocean salinities by a factor of two or more. This increased salinity is accompanied by a corresponding increase in water density that causes hypersaline water to migrate downward into the underlying groundwater system and radially outward beneath the CCS (Figure 5).

Tritium and total dissolved solids concentrations in groundwater samples show that hypersaline water emanating from the CCS has moved westward of the L-31E Canal more than 2 mi and is influencing movement of the saline water interface within the Biscayne Aquifer more than 4 mi inland. Currently, FPL is under a consent order to remove the hypersaline plume and has begun operation of a recovery and injection system designed to remove hypersaline water from the Biscayne Aquifer and inject it into the Boulder Zone via a deep injection well. The SFWMD has permitted FPL to capture 5.475 bil gal per year (15 mgd) of hypersaline water from the Biscayne Aquifer and the Florida Department of Environmental Protection (FDEP) has granted FPL an underground injection control (UIC) permit to inject up to 15.59 mgd of water into a deep injection well.

Monitoring Network Upgrades

Discontinuation of monitoring at eight existing wells was recommended by WSA, based on several factors, including proximity of the saline front, existing monitoring by others, and previous chloride trends. The locations of existing SWIM wells, including those where monitoring is proposed to cease and the proposed new wells, are shown in Figure 6.

Construction of six new SWIM wells, designated as FKS-10 through FKS-15, was recommended based on perceived gaps in the spatial distribution of the network, particularly in areas where the saline water had advanced inland beyond an existing site. Because the saline water interface has moved northward of FKS-2 at depth, but has not yet reached FKS-5, an intermediate well FKS-13 was proposed to monitor the movement of the salinity front between those two wells. The FKS-10, 11, and 12 are positioned along US Highway 1 to intercept the front that has previously moved inland of FKS-4, 7, and 8. Because FKS-7 and 8 have upper monitor intervals that are fresh, these wells remain useful for determining the vertical extent and inferred motion of the front, as is evidenced by chlorides at different depths and conductivity profiles.

The area to the east of Card Sound Road and south of the Florida City Canal, historically referred to as Model Land, required additional wells due to the rapid encroachment of the hypersaline plume in this area. Prolonged elevated salinity has rendered G-1264 not useful and well G-3164 was lost in 2009 (Figures 7a and 7b). Because G-3164 was relatively fresh when it was last monitored in 2009, a well situated between G-3164 and G-1264 was initially proposed; however, a lack of road access and pre-existing groundwater monitoring by the operator of a nearby mine dictated that the proposed location for FKS-14 be shifted southwest of the original location.

Salinity monitoring data in the vicinity of FKS-9 indicates that the salinity front is approaching from the east in this area and potentially intruding the upper portion of the Biscayne Aquifer via surface flow in the Florida City Canal or from an abandoned rock pit adjacent to the well. Data from G-1264 indicate that chlorides began to rapidly increase at this site beginning in June 2001. Chloride levels at an FPL monitor well TPGW-7 (Figure 8) located about 1.3 mi west of G-1264, started to increase in December 2013. Based on the time span of about 12.5 years between salinity level surges at G-1264 and TPGW-7, the saline front is estimated to have moved at a rate of approximately 475 ft per year in this particular area.

Well Design

The basis of design for the new monitor wells included consideration of many factors, including cost, effective life span, functionality,

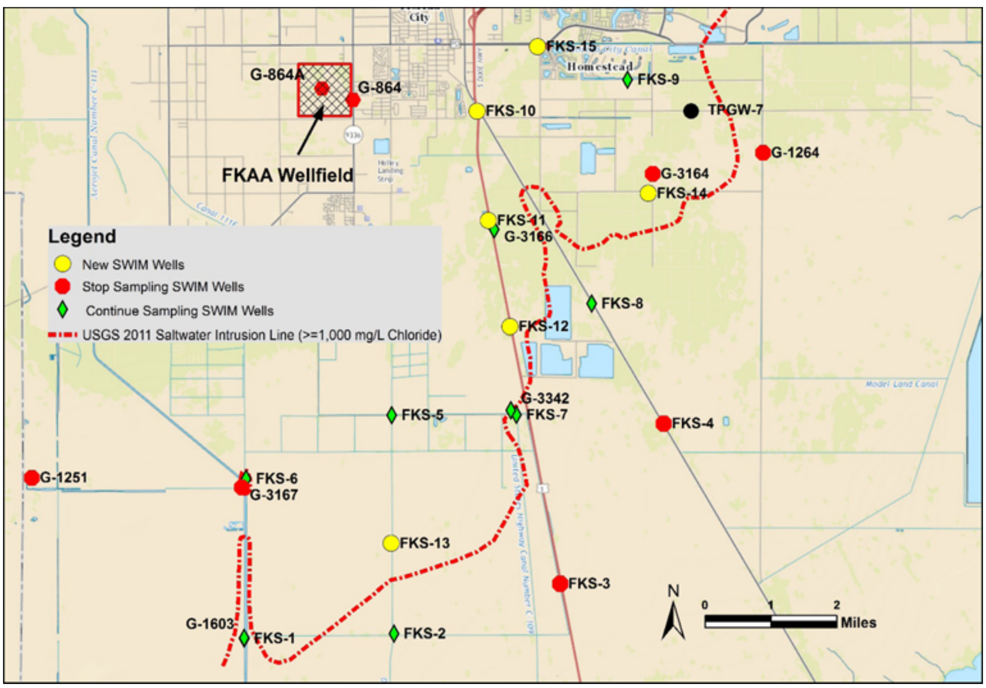

Figure 6. Map of Existing and Proposed Authority Saline Water Intrusion Monitoring Wells and Florida Power and Light Monitor Well TPGW-7

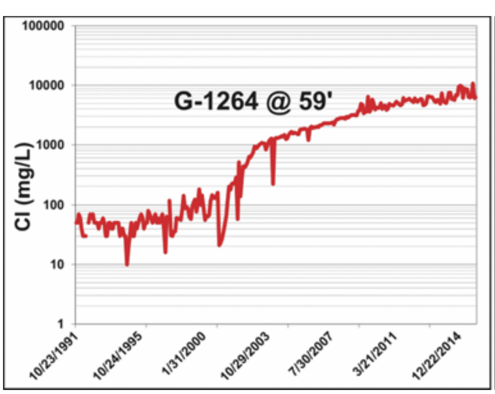

Figure 7a. Chloride Data from G-1264

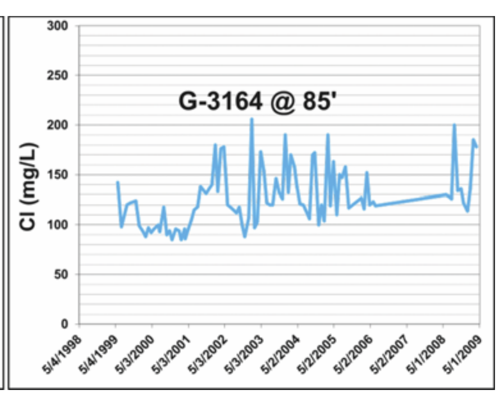

Figure 7b. Chloride Data from G-3166

nearby well coverage (both vertical and horizontal), accessibility, security, property ownership, easement availability, and consistency with historic data collection. Based on the authority's long-term success with sampling and record keeping of its existing multizone FKS wells, the choice was simple: keep the well design consistent with that of the pre-existing wells. Although more complicated alternative well designs involving multiple discrete interval wells at each location were considered, the theoretical benefits of discrete sampling from isolated wells do not outweigh the additional costs that would be incurred by the authority.

Consideration was also given to a well design using individual screened sampling tubes gravel-packed and grouted over discreet vertical intervals to be identified by geophysical logging; however, the risks of sand and grout loss to create such "nested" wells in a single borehole and time and costs for logs and tailoring each well were deemed excessive for the intended purpose of detecting the saline front. The inferred risk of upward interborehole flow is insignificant at most of the SWIM wells given the density stratification inherent to the saline water interface, especially in a highly transmissive aquifer setting.

Currently there are no significant withdrawals from the Biscayne Aquifer in the immediate vicinity of any of the wells that might disrupt the static density equilibrium between separate and highly permeable zones within the aquifer; however, a salinity barrier system proposed by the nearby mine operator that involves pumping up to 7 mil gal per day of water from a single large shallow well into a north-south linear array of deeper injection wells has the potential to impact FKS-14, which is within 0.5 mi of the barrier wells. Increased hydraulic head in a lower flow zone and simultaneous reduction of head in the upper zone could potentially induce upward flow through a connected penetration, such as a borehole or mine pit excavation.

The chosen monitor well design includes multiple small diameter (1- and 2-in.) polyvinyl chloride (PVC) tubes secured from the top by means of a compressive well seal inside of a larger diameter (6-in.) PVC surface casing with an open borehole beneath the surface casing to total depth (Figure 9).

This design allows discrete sample collection from upper and lower depths via the 1-in. open-ended pipes and for continuous vertical conductivity profiling in the 2-in. screen over the entire open-hole portion of the well. A 1-ft-long screened interval at the base of each sample tube was included in case plugging of the bottom of the tube was to occur. Protective measures at the

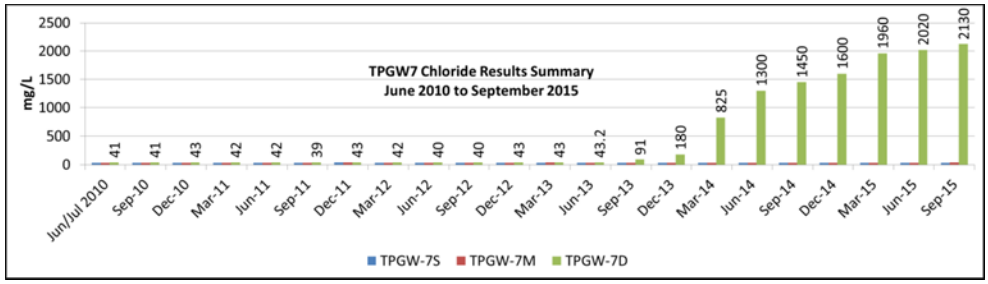

Figure 8. Chloride Level in Florida Power and Light
TPGW-7 Well Nest (D) = Deep = Screened from -77 to -81 ft (NGVD 1929)

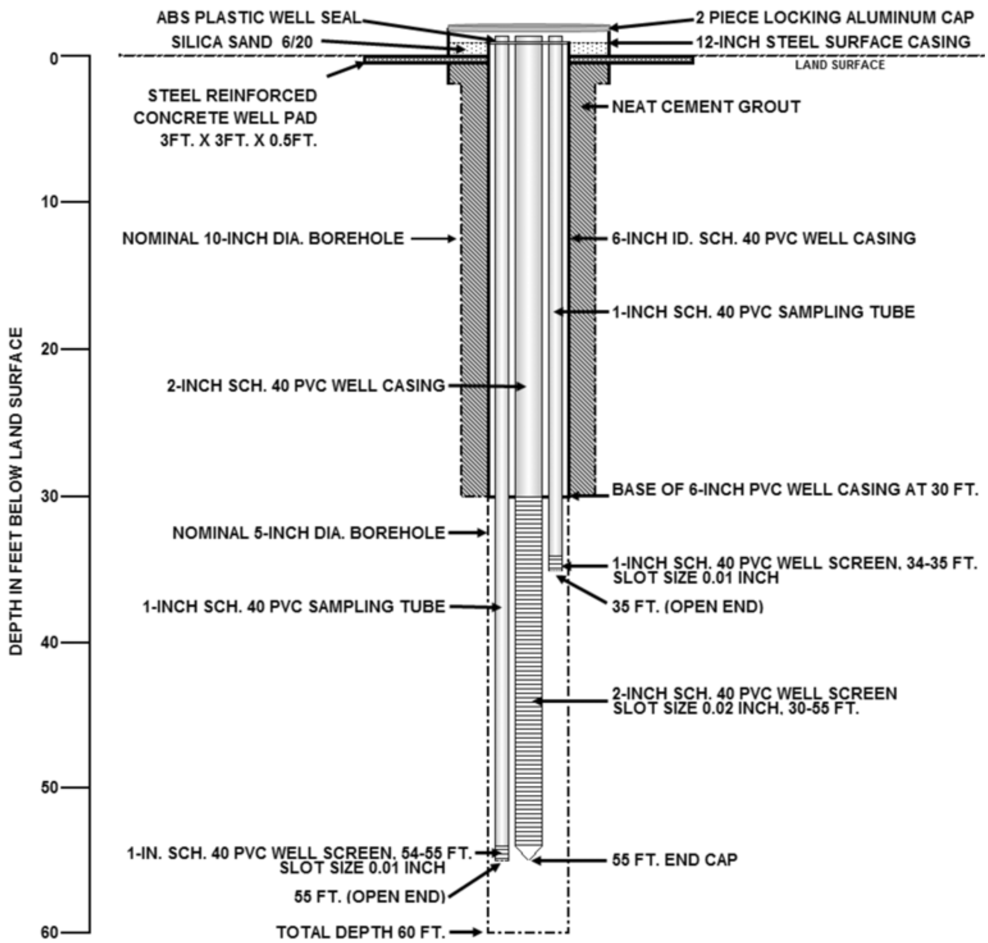

Figure 9. Schematic of Typical Saline Water Intrusion Monitoring Well Profile

wellheads include 12-in. diameter-schedule 40 steel casings, locking well caps, steel reinforced concrete well pads, and cement-filled 4-in. steel pipe corner bollards at each pad. There is a high risk of vandalism in the Model Lands area and the protective features are likely to be challenged.

Permitting

The various permits and agreements obtained for modification of the SWIM program and construction of the new wells include the following:

- SFWMD Water Use Permit No. 13-00005-W, Application No. 160317
- Florida Dept. of Health Well Construction Permits 13-59-13036 to 13-59-13040
- Miami Dade Department of Transportation (DOT) and Public Works Permits 2016005628, 2016005629, 2016005630
- SFWMD Right of Way Occupancy

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Permit/General Permit No. 14687

- SFWMD Revocable Right of Entry/License Agreement
- Memorandum of Agreement between Florida DOT and FKAA finalized in April 2017

Conclusions

Salinity data reviewed in this study suggest that the authority's Biscayne Aquifer wellfield in Florida City has not been currently impacted by saline water intrusion, nor have wellfield operations contributed to regional saltwater encroachment. The recent modifications to the SWIM program are a proactive response to man-made groundwater problems, namely drainage canals lowering groundwater heads and providing direct conduits and the hypersaline plume originating at Turkey Point.

Although control structures and plugs now exist on most of the canals that have acted in the past as conduits for salt water intrusion, canals continue to pose risk for saline intrusion in the region due to their high potential to convey saline water rapidly inland toward the wellfield during storm surges, king high-tide events, and extreme drought and low water conditions. Eleven of the 16 chloride monitoring wells in the current SWIM network are positioned within 100 ft of a major canal and are the most likely to exhibit salinity impacts. These canals include the C-111, C-110, Card Sound Canal, and the Florida City Canal. The SWIM wells FKS-7 and G-3342 are also located on a likely flow path for saline water, which is the abandoned Florida East Coast Railway borrow ditch extending south from the wells to the C-111 canal. The close proximity of these wells to the main pathways of intrusion ensures early detection and allows rapid response if any water management actions can be taken to arrest the problem.

Apart from naturally occurring seawater, the single most damaging source of groundwater pollution threatening the authority's wellfield is the FPL cooling canal system at Turkey Point. Because of the intense public and regulatory scrutiny focused on the hypersaline plume and remediation efforts being undertaken by FPL and others to halt and reverse the intrusion, future data from FKS-9, FKS-14, and FKS-15 will provide ever more valuable intelligence for the community of professionals involved in this issue.

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