Saltwater Interface Monitoring and Mapping Program

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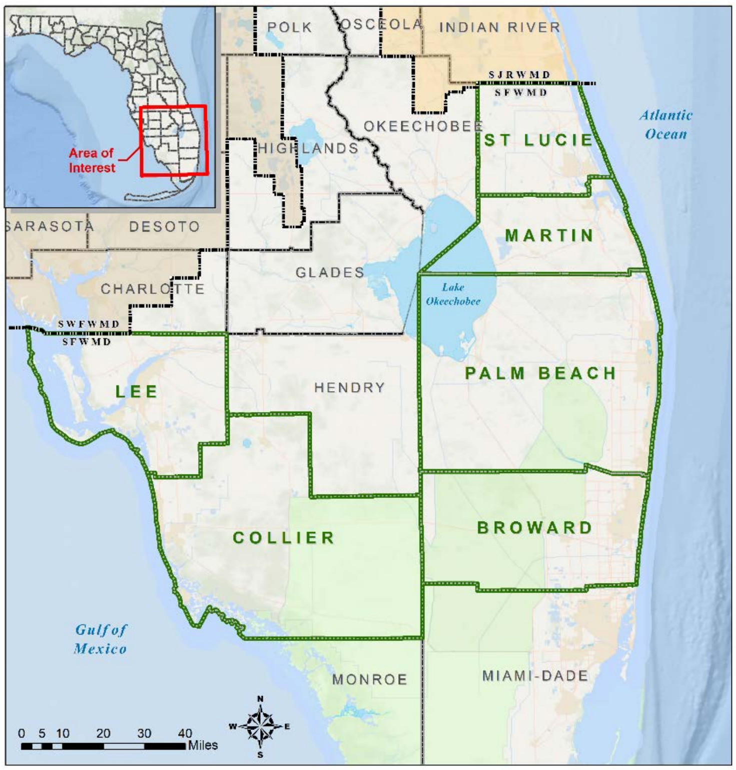

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ACRONYMS AND ABBREVIATIONS

District	South Florida Water Management District
FDEP	Florida Department of Environmental Protection
IAS	intermediate aquifer system
mg/L	milligrams per liter
SAS	surficial aquifer system
SFWMD	South Florida Water Management District
USGS	United States Geological Survey
WIN	Watershed Information Network

1 INTRODUCTION

In 2019, the South Florida Water Management District (SFWMD or District) documented and mapped the saltwater interface in coastal aquifers within St. Lucie, Martin, Palm Beach, Broward, Collier, and Lee counties (**Figure 1**). The United States Geological Survey (USGS) conducts saltwater interface mapping for Miami-Dade and Monroe counties. The SFWMD developed maps for each aquifer within the surficial and intermediate aquifer systems (SAS and IAS). The SFWMD began mapping the approximate location of the saltwater interface in 2009, with updated maps every 5 years. Given the observed effects of sea level rise, this monitoring and mapping program is an essential part of the SFWMD's adaptation strategies.

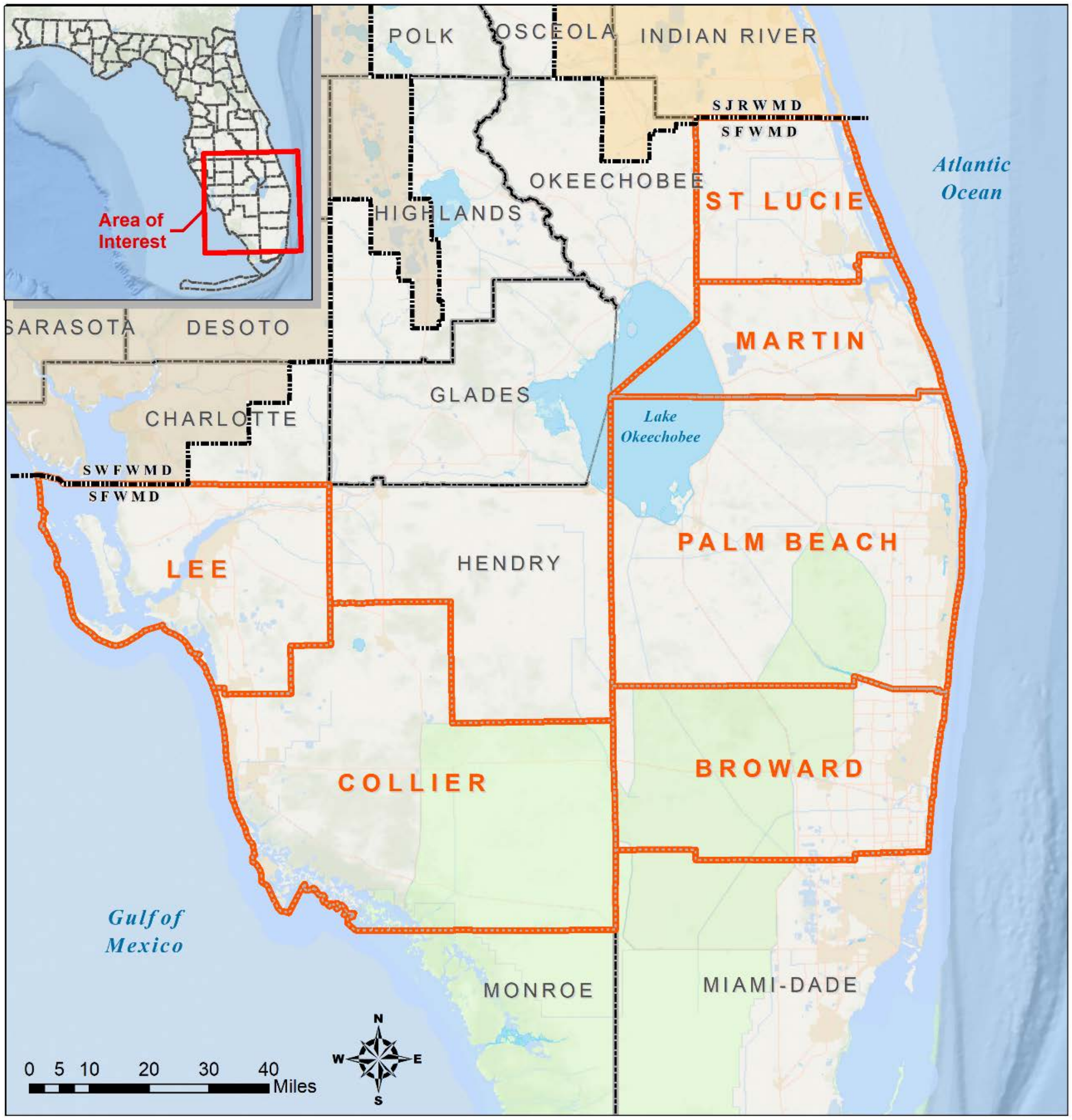


Figure 1. Counties within the SFWMD saltwater interface mapping program.

This report documents the methodology for the preparation, data gathering, and production of saltwater interface maps for each coastal aquifer in 2019. Inferences may be drawn on the movement of the saltwater interface compared to the 2009 and 2014 maps.

2 BACKGROUND AND PURPOSE

2.1 Project Introduction

The saltwater interface monitoring program was established to evaluate the extent of seawater encroachment into aquifers along the South Florida coastline. Water quality (e.g., chlorides, total dissolved solids, specific conductance) data are collected and analyzed every 5 years, and the saltwater interface is mapped for the SAS (including the Biscayne aquifer) on the east coast of Florida and for the Water Table, Lower Tamiami, Sandstone, and Mid-Hawthorn aquifers on the west coast. SFWMD regulatory staff use the mapped position of the saltwater interface as part of the water use permitting review process. Coastal utilities also use these maps to monitor for potential impacts to public supply wellfields and must plan accordingly.

Water quality data are compiled from multiple sources to generate the saltwater interface maps. The SFWMD maintains a cooperative agreement with the USGS, and part of the monitoring program includes sampling groundwater wells completed in the SAS and IAS for chlorides during the dry season. Broward and Collier counties provide chloride data from their groundwater monitoring networks to the SFWMD. The City of Naples also provides chloride data from its monitoring program, and additional water quality data are downloaded from the Florida Department of Environmental Protection (FDEP) Watershed Information Network (WIN) database. Sampling from these networks follows the FDEP SOP-001/01. In addition to these data sets, certain water use permittees are required to submit chloride data, which is stored in the SFWMD's Regulation database. Chloride data from more than 1,000 wells were used to create the 2019 saltwater interface maps.

2.2 Planning and Permitting

Water supply plan updates are completed every 5 years for each planning area within the District, as required by Chapters 373 and 187, Florida Statutes. Saltwater intrusion monitoring is an important component of water management, and movement of the saltwater interface is an important component of water supply planning. For example, if coastal wellfields are over pumped, saltwater can be drawn into wells, resulting in the need to shut down operations, relocate wellfields, or look for alternative water supplies.

The SFWMD Water Use Bureau uses the saltwater interface maps when evaluating applications for water use permits. Projects located in vulnerable zones are required to implement a saline water monitoring program and periodically report chloride concentrations from wells to the SFWMD. Saline water intrusion is considered harmful when it occurs above and beyond seasonal fluctuations (SFWMD 2015).

2.3 Project Objectives

The main objective of this mapping effort is to evaluate movement of the saltwater interface over 5-year intervals. The saltwater interface corresponds to a chloride concentration of 250 milligrams per liter (mg/L), which represents the primary drinking water standard for chloride. The collected chloride data are used to map the extent of saltwater intrusion, examine changes that have occurred over the past 5 years, and possibly determine the causes of those changes. Because wells included in this mapping effort are selected based on their location and depth, improvements to the monitoring program as well as spatial data gaps are assessed with each 5-year update. This is an ongoing data collection and mapping project that may be refined based on water supply planning, regulation, and groundwater modeling needs in the future.

2.4 Common Sources of Saltwater Intrusion

2.4.1 Lateral Intrusion from the Coast

Lateral intrusion from the coast is the most likely type of saltwater intrusion, particularly along Florida's coastline (**Figure 2**). The boundary between fresh groundwater and saltwater is known as the saltwater interface. Fresh groundwater discharging to the coast prevents landward encroachment of saltwater. If too much fresh water is pumped from the system, typically from municipal water supply wellfields, then saltwater can migrate laterally and induce saltwater intrusion. If pumping wells are too close to the saltwater interface, saltwater may enter the well and contaminate the water supply. For example, certain coastal wellfields in Broward County were impacted by lateral intrusion of saltwater and had to be abandoned.

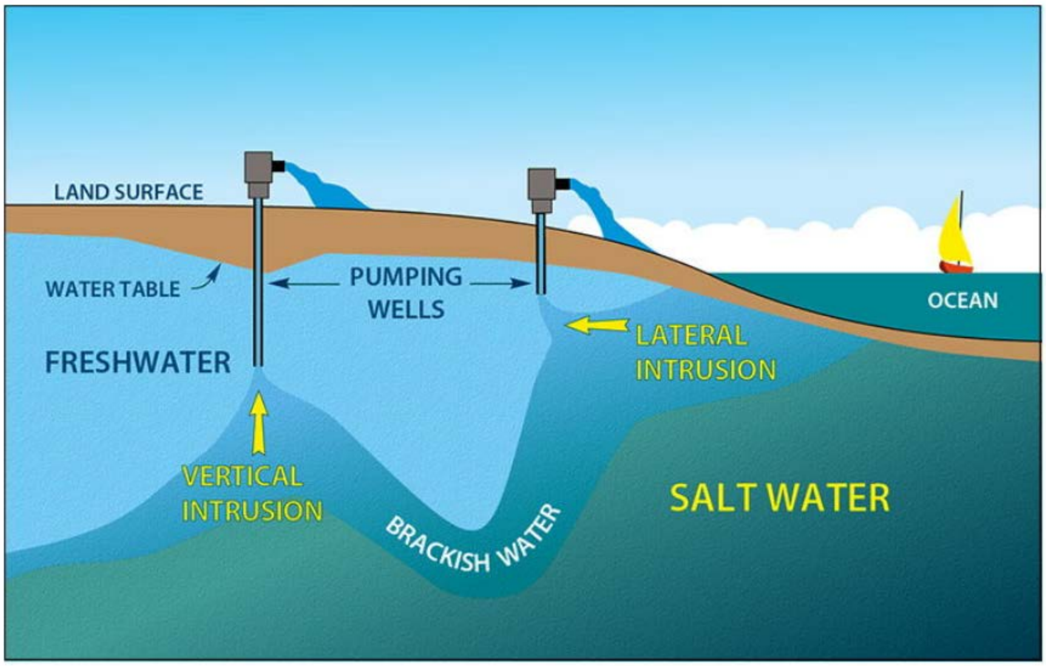


Figure 2. Conceptual drawing of lateral and vertical saltwater intrusion near coastal aquifers (From: Feltgen 2015).

2.4.2 Vertical Intrusion

Vertical intrusion is caused by the lowering of the freshwater head, which allows deeper saltwater to move upward, typically under the influence of pumping (**Figure 2**). This may occur more frequently during droughts when the water table declines due to lower rainfall.

2.4.3 Surface Infiltration

Surface infiltration comes from saltwater pits, ponds, or lagoons that are connected to the aquifer. The denser saltwater can "sink" into the freshwater aquifer, causing saltwater intrusion. Another source of surface infiltration that is found in Broward County is inland saltwater canals that are not protected by salinity control structures, allowing boats access to the ocean. Such canals are in direct contact with the freshwater aquifer and can facilitate saltwater intrusion.

2.4.4 Relict Seawater

Relict seawater is found in various regions of Florida due to changes in sea level over geologic time. As sea level lowers, “pockets” of saltwater may be trapped in the overlying sediment due to layers of lower permeability. Eventually, overlying sediments are recharged with fresh water via rainfall. Wells near this relict, trapped saltwater may be fresh until the head is reduced by pumping and relict seawater is tapped and enters the well.

2.5 Importance of Saltwater Monitoring

Groundwater salinity monitoring of the Biscayne aquifer goes as far back as 1939 (Prinos et al. 2014). The saltwater intrusion issue has persisted through the decades, and water managers continue mitigation efforts to address the problem. The boundary between fresh water and saltwater occurs about 40 feet below sea level for each foot the fresh groundwater table is above sea level, known as the Ghyben-Herzberg principle. Water table elevations in coastal areas must be maintained high enough to prevent saltwater from entering the local groundwater and contaminating nearby wellfields. To help protect wellfields and prevent inland movement of saltwater via coastal canals, salinity control structures can be constructed on some canals. These structures raise the canal head (stage) and the surrounding water table, particularly during the dry season, to hold back saltwater.

Prinos (2013) examined saltwater intrusion in the SAS aquifers of southwestern Florida and determined that the existing saltwater intrusion monitoring network lacked the necessary organization, spatial distribution, and design to properly evaluate saltwater intrusion. As understanding of the SAS and IAS aquifers increased, it became apparent that some monitor wells were open to multiple aquifers or had incorrect aquifer designations. Saltwater was found in canals close to coastal wellfields, and in some instances, saltwater was found upstream from salinity control structures. These factors led to an incomplete picture of the extent and threat of saltwater intrusion in southwestern Florida. Prinos (2013) discussed a plan to improve the hydrostratigraphic and geospatial network coverage using additional monitoring, surface geophysical surveys, and geospatial network coverage. These improvements have been implemented to the greatest practicability for the SFWMD’s saltwater intrusion mapping program in this region.

Over time, coastal wellfields, particularly those seaward of salinity control structures, have been replaced by wellfields farther inland as the saltwater front moves landward. Significant increases in population in South Florida over the last 80 years and the associated increase in water use present challenges for water supply and require careful monitoring of saltwater interface movement. The effects of sea level rise are more readily observed in recent years, emphasizing the need to monitor and document the position of the saltwater interface so adaptation strategies can be developed and implemented.

3 SALTWATER INTERFACE MAPPING

3.1 Strategy

Due to the relatively slow movement of groundwater, and through review of historical movement of the saltwater interface, it was determined that the appropriate interval for the preparation of saltwater interface maps would be every 5 years. Since the SFWMD's mapping effort began in 2009, three sets of maps have been produced: 2009, 2014, and 2019. This has confirmed that the 5-year interval is adequate to compare the position of the saltwater interface over time, note areas of concern, and adjust monitoring, as necessary.

Data were collected from the USGS, SFWMD sampling programs, the SFWMD Regulatory database, and coastal counties with saltwater intrusion monitoring programs. Much of the data are contained into the District's DBHYDRO database. The Regulation database was queried for permittee-provided saltwater intrusion monitoring data.

The SFWMD maps the farthest inland extent of the saltwater interface, which typically occurs at the end of the dry season (between March and May). In most cases, the farthest inland extent is represented by the highest chloride concentration reported during that 3-month period.

3.2 Limitations and Other Considerations

There are several challenges to mapping the 250 mg/L isochlor (i.e., the saltwater interface). First, the saltwater interface is a three-dimensional surface that must be represented on a two-dimensional map. Second, the interface is a dynamic surface, moving with changes in pressure and concentration, and a fixed point in time has to be selected to represent the isochlor. Third, there is a diffuse front in the aquifer where fresh water and saltwater mix that must be represented by a single line at the surface. Lastly, there are different pathways for saltwater intrusion, as discussed in **Section 2.4**. However, while there may be one or more causes contributing to the monitoring results, they all are considered as a single source of intrusion when mapped.

There are some practical challenges related to the data obtained for the isochlor mapping effort. Wells used in previous maps sometimes are not available 5 years later, making comparisons more challenging. In many cases, monitor wells are lost due to development, road construction, lack of access, etc. Conversely, new wells become available that are relevant to mapping the saltwater interface, but no previous data exist for direct comparison. New wells can alter the position of the isochlor and change the interpretation from previous maps. Finally, the availability and distribution of wells that sufficiently represent the saltwater interface are not adequate in places to interpolate the line from one region to another. Certain assumptions must be made to interpolate the isochlor's position and determine potential causes for changes from previous maps.

There are several factors that relate to data quality and how well the data represent the position of the saltwater interface within an aquifer. One factor relates to well construction. Wells consist of a cased segment that prevents groundwater from entering. Attached to the casing (typically at the bottom) is a screened segment that allows groundwater to enter the well. The true representation of the saltwater interface may be affected by the placement and length of the screen within the aquifer. A sample collected at the surface is a composite of all the groundwater entering the well.

The FDEP has standard methods for sampling monitor wells; however, the methods for saltwater intrusion monitoring may not be consistently implemented. This is unavoidable due to the challenges mentioned earlier. Depending on the placement of the well screen and other factors, how a well is purged and the pumping method may not provide the most representative sample. Additionally, not all samples are analyzed for the same parameters. In addition to chloride concentration, specific conductivity, and salinity data were collected and converted to chloride concentrations as supplemental data points for mapping purposes.

Finally, there is the issue of sampling frequency. As mentioned, an ideal sample would be collected between March and May of the sampling year. However, not all wells are sampled during this period. Therefore, some wells may be missed; otherwise, upon more detailed examination, a sampling result from outside this time frame must be used.

3.3 Data Gathering and Evaluation Process

The flow chart in **Figure 3** shows the data gathering and evaluation process for the saltwater interface mapping effort. Water quality data from surface water bodies (i.e., canals, streams, estuaries, and control structures) and groundwater wells were collected primarily from the District's DBHYDRO and Regulation databases. Additional groundwater data were obtained from the USGS National Water Information System, from which data are uploaded periodically to DBHYDRO by the SFWMD's Data Management Unit. Limited surface water and groundwater data were obtained from local and regional governments when available. In 2019, surface water and groundwater quality data were obtained from Broward County, the City of Naples, and the Loxahatchee River District. The FDEPWIN database is a repository for environmental data provided by federal, state, and local agencies as well as academic institutions, volunteer organizations, private laboratories, among others. A comparison of groundwater data in WIN against data gathered from the SFWMD's databases and external sources showed that most of the data in WIN already are captured in the initial query. Therefore, to prevent duplication, WIN data were not included in the 2019 mapping effort. All data retrieved for this analysis (chloride, specific conductance, and salinity) covered the entire period of record available (January 1950 to May 2019) for each monitoring station.

During the 2014 saltwater intrusion analysis, the SFWMD identified various areas with groundwater data gaps. To supplement the existing groundwater data, several wells were added to the SFWMD's monitoring network (**Table 1**). The added wells were sampled by the SFWMD for water quality parameters, and samples were submitted to the District's laboratory for analysis. Groundwater from these wells was sampled and analyzed during April and May 2019.

Surface water and groundwater data retrieved from DBHYDRO and the Regulation database were scrutinized for duplicates, consistency of parameters, reporting units, qualifiers, and missing information. All external sources were inspected to eliminate possible duplication of records and data inconsistencies. Records with potential data quality issues were identified and removed. All data variables such as station names, water quality parameters, reporting units, county name, aquifer name, and data type (groundwater and surface water) were unified under a single attribute name. Geographic coordinates were converted to state plane (x and y), where needed. All well depth (cased depth and depth drilled) information was reported in feet. Subsequently, all data sources were merged into a single database to include the entire period of record.

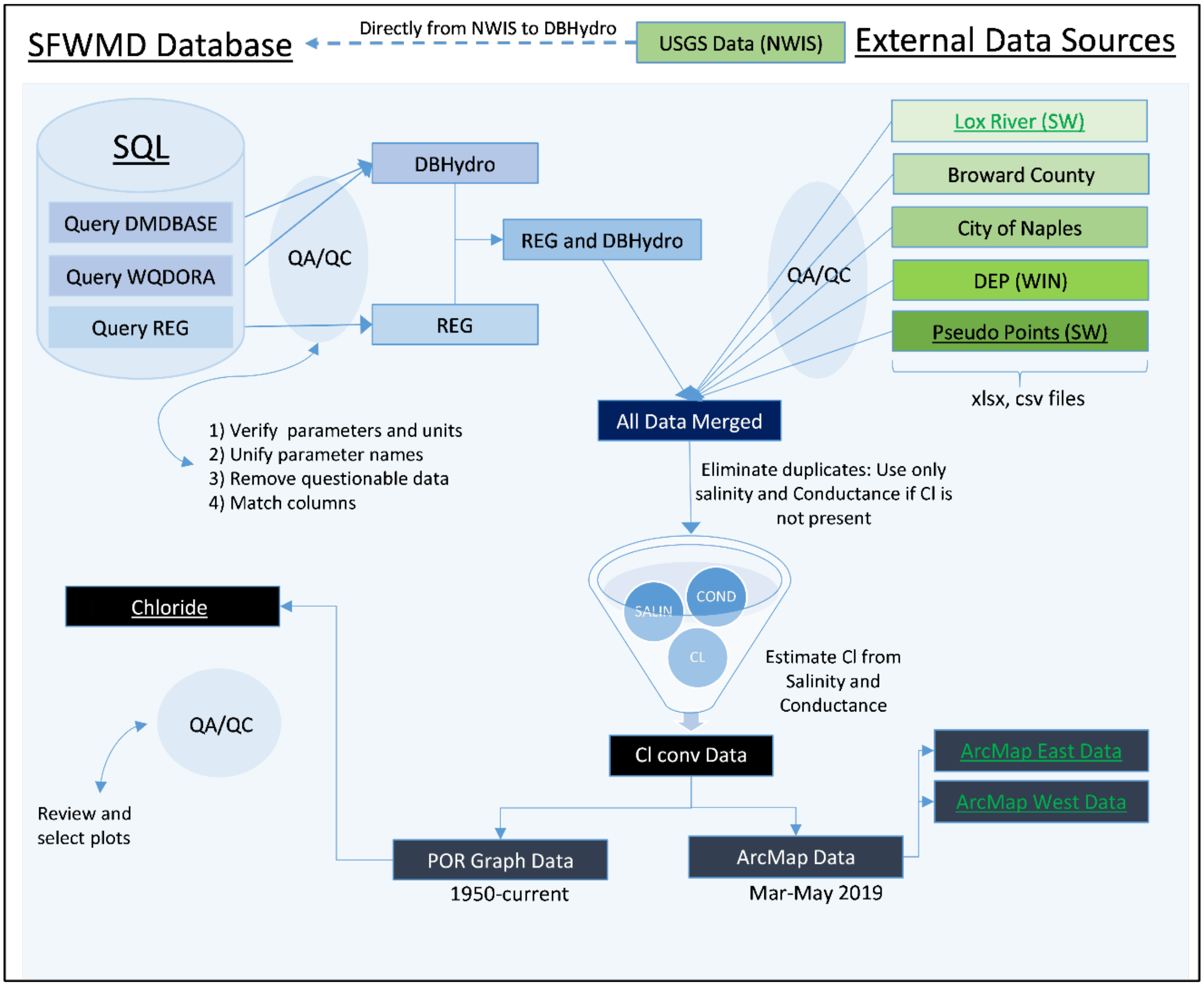


Figure 3. The data gathering and evaluation process for the saltwater intrusion evaluation.

Table 1. Groundwater wells sampled to supplement chloride data for the saltwater intrusion evaluation.

Station	X Coordinate	Y Coordinate	County
C-1062_G	394635.7	663669.8	Collier
L-1976	423498.4	872914.0	Lee
L-721_G	316765.7	860925.2	Lee
M-1073	943555.8	978075.3	Martin
PB-99 2	963281.5	850663.2	Palm Beach
STL-172	880325.6	1110772.0	St. Lucie
STL-177	897780.0	1078485.0	St. Lucie
STL-266R	860222.2	1171490.0	St. Lucie
STL278	884653.5	1098165.0	St. Lucie

The data collection and evaluation effort focused primarily on groundwater chloride concentrations. However, not all groundwater wells are monitored for chloride; however, in many cases, specific conductance and salinity data were available. Therefore, specific conductance and salinity were converted to chloride concentration to increase the number of wells and observations available for this analysis.

Specific conductance and salinity measurements were converted to chloride concentration using the equations described in Iricanin (2017). Specific conductance was converted to practical salinity assuming a water temperature of 25°C. The chloride concentration then was derived from the resulting practical salinity value based on the relationship between salinity and chlorinity, as described by Wooster et al. (1969) and Iricanin (2017). The derived chloride concentration was adjusted for density using the approximate density of seawater (1.02 grams per cubic centimeter) at 25°C. The final chloride concentrations obtained from this conversion scheme were approximations considered suitable for this application.

In 2019, active monitor wells were selected by screening wells with observations available between March and May. However, as discussed earlier, not all wells are routinely sampled during this period. Therefore, some wells may have been missed, or upon more detailed examination, a sampling result from outside of this time frame may have been used. In many cases, chloride observations were available for all 3 months. Because the objective of this analysis is to map the worst-case scenario of the saltwater interface extent, only the highest chloride concentration reported during the 3-month period was used.

Chloride data for each active monitor well were plotted to show the period of record of observations. These time-series plots show trends in chloride concentration over time as well as the movement of the saltwater interface if it passes through the monitor well. The selected wells for 2019 were individually evaluated using the time-series plots. Plots showing changes in chloride concentration were generated for select monitor wells over the period of record. An example of a time-series plot is shown in **Figure 4** taken from a monitor well near Hallandale in Broward County. Improvements (i.e., decreases in chloride concentration) may be apparent where pumpage has been reduced or demand has shifted to being met with alternative water supplies. Select plots were placed alongside the saltwater interface maps to provide a different perspective regarding movement of the interface. A 250 mg/L dashed line is shown across the vertical axis of the plots to highlight when this chloride concentration has been reached in the monitor well.

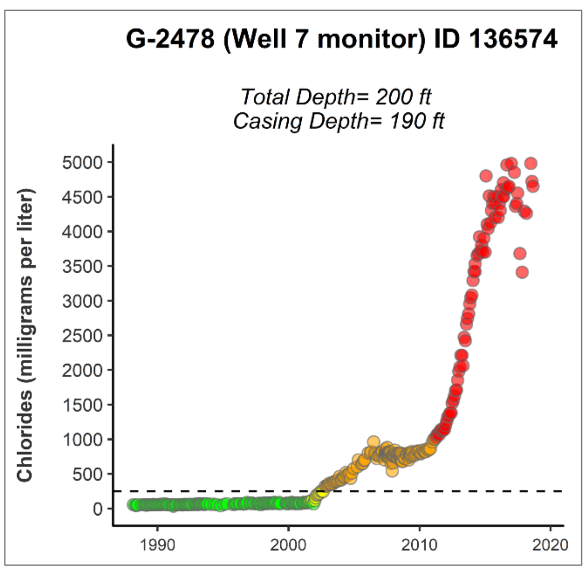


Figure 4. Time-series plot of chloride concentrations at G-2478.

The processed 2019 groundwater data, including surface water data, were divided and formatted into two different files for the west coast and east coast to include all necessary fields for spatial analysis. These steps are illustrated in **Figure 3**. All data processing, analyses, and well time-series plots were performed using R programming language (version 3.5.1, R Development Core Team 2018, Vienna, Austria).

3.4 Mapping Process

The saltwater interface mapping process is shown in **Figure 5**. The 2019 west coast and east coast processed chloride data were imported into ArcGIS for spatial analysis. West coast data were further divided to represent each corresponding aquifer (Water Table, Lower Tamiami, Sandstone, and Mid-Hawthorn). Surface water stations with chloride data included in the processed file were used to enhance the isochlor mapping process; these data values are considered pseudo-chloride points and are derived from surface water measurements and samples collected at established monitoring stations in canals, streams, estuaries, and control structures near coastal areas. Salinity control structures were identified and used as reference points for the saltwater interface extent. Additional pseudo-chloride points were added along the intracoastal area and in the open coastal region, where chloride concentrations were expected to be greater than 16,000 mg/L. These points were manually added using ArcGIS, exported, and merged into the 2019 database as shown in **Figure 3**. The pseudo-chloride points helped fill spatial data gaps but were used with caution because they were derived from surface water data and not groundwater data, upon which the saltwater interface maps are based.

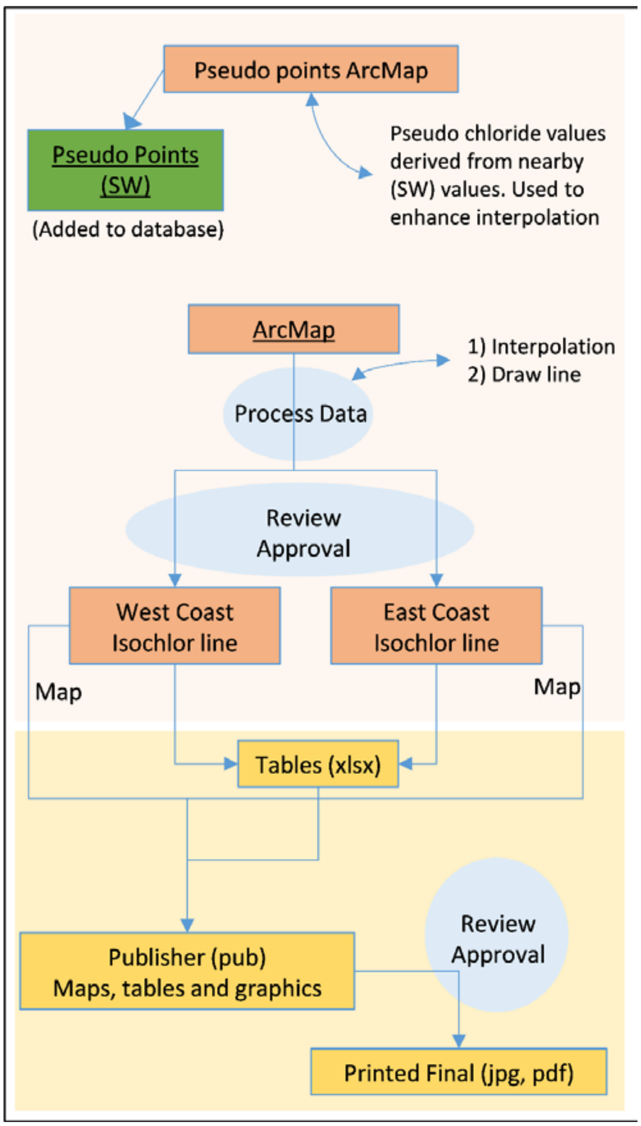


Figure 5. Flow-chart of the saltwater interface mapping process.

Pseudo-chloride points were used to provide additional control during the spatial interpolation process. The Radial Basis Function, or Spline with Tension Function, was used to interpolate or estimate chloride concentrations using observed chloride concentrations or input points. This process produced a continuous, smooth surface that passed through the input points. Subsequently, interpolated maps showing chloride concentrations below and above 250 mg/L were created and compared against the 2009 and 2014 isochlors. Based on this comparison, the new 2019 isochlor was drawn and manually adjusted. All pseudo-chloride points then were removed from the map, leaving only the groundwater chloride data. Each well affecting the shape of the isochlor was manually checked for accuracy and potential movement/correction of the line based on site-specific information. Consequently, one line was drawn for the east coast counties, and one line was drawn for each of the SAS and IAS aquifers on the west coast. Individual maps were created for each county and corresponding aquifer, showing the previous (2009 and 2014) and current (2019) isochlors, all wells used for the 2019 isochlor, the most recent well field boundaries, county lines, main hydrography (water bodies and structures), and other spatial reference layers (e.g., transportation, wetlands, cities). Isochlor lines were differentiated by year to show any movement of the saltwater interface landward (worsening) or seaward (improving). Interpretations of these movements for each map are provided in **Section 5**.

3.5 Map Rendering

Once all the data were gathered and evaluated, the components of each map were combined in a final map rendering. **Table 2** summarizes the saltwater intrusion maps by county and aquifer for 2009, 2014, and 2019. In previous years, the Mid-Hawthorn aquifer map was plotted separately for the west coast counties of Lee and Collier. For 2019, the Lee and Collier county Mid-Hawthorn aquifer data were combined into one map, resulting in a total of eight maps covering five aquifers in six District coastal counties.

Table 2. List of saltwater interface maps.

County	Aquifer	2009	2014	2019
Martin and St. Lucie	Surficial	X	X	X
Palm Beach	Surficial	X	X	X
Broward	Surficial	X	X	X
Lee	Water Table	X	X	X
Lee	Mid-Hawthorn	X	X	
Lee and Collier	Sandstone	X	X	X
Lee and Collier	Lower Tamiami	X	X	X
Collier	Water Table	X	X	X
Collier	Mid-Hawthorn	X	X	
Lee and Collier	Mid-Hawthorn			X

Note: Miami-Dade County mapping performed by the United States Geological Survey.

There are several components to the final map rendering: a legend, period of record time-series graphs, a reference table, and the 2009, 2014, and 2019 isochlors plotted on a county map.

The legend describes various features on each map (**Figure 6**). A notable part of the legend explains that each colored dot on the map is followed by a number with another number in parentheses. The first value is a map identification number (which follows numerically) and the second value is the chloride concentration. Each 250 mg/L isochlor shows the saltwater interface for 2019 (solid red line), 2014 (dashed green line), and 2009 (dotted black line). Other useful features (e.g., wellfields, freshwater bodies, saline water bodies, mangrove and saltwater marches) also are identified on the legend.

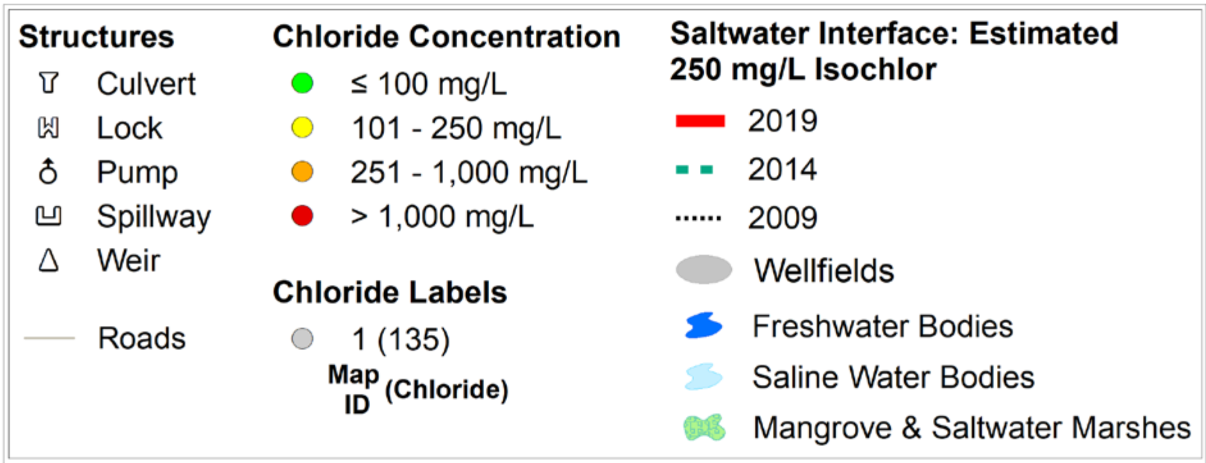


Figure 6. Legend identifying data layers in the 2019 saltwater interface maps.

Monitor wells included on the maps were categorized and differentiated (i.e., color coded) based on chloride concentration ranges. Green represents chloride concentrations ≤100 mg/L; yellow represents 101 to 250 mg/L; orange represents 251 to 1,000 mg/L; and red represents >1,000 mg/L. These are the same color codes used for the time-series plots. The chloride value shown on the map is the highest chloride concentration observed between March and May 2019. **Figure 7** is an example of a map layout showing the 2009, 2014, and 2019 estimated positions of the saltwater interface in Martin and St. Lucie counties.

Along the bottom of each saltwater interface map is a reference table, which serves as a key to identify wells using a map identification number (Map ID). In addition to the well name, the reference tables provide specific well information such as project name, coordinates, and well depth. The reference table can help identify the data source, which can be reviewed on a well-by-well basis. For the rare occasion when the chloride value used fell outside the March to May time frame, the value is identified with an asterisk and found at the end of the reference table. A total of 1,134 wells were used to plot the 8 saltwater interface maps prepared for 2019.

All spatial analyses and map layouts were performed using the ArcGIS v10.4.1 Spatial Analyst tool software (Environmental Systems Research Institute, Redlands, California). The final maps, including data tables and time-series plots, were prepared using Microsoft Publisher and converted to PDF files for final review, management approval, and distribution. Following final review, the maps were generated at a plot size of approximately 36 inches wide by 60 inches long (**Figure 8**). The maps are available on the SFWMD's website at https://www.sfwmd.gov/documents-by-tag/saltwaterinterface.

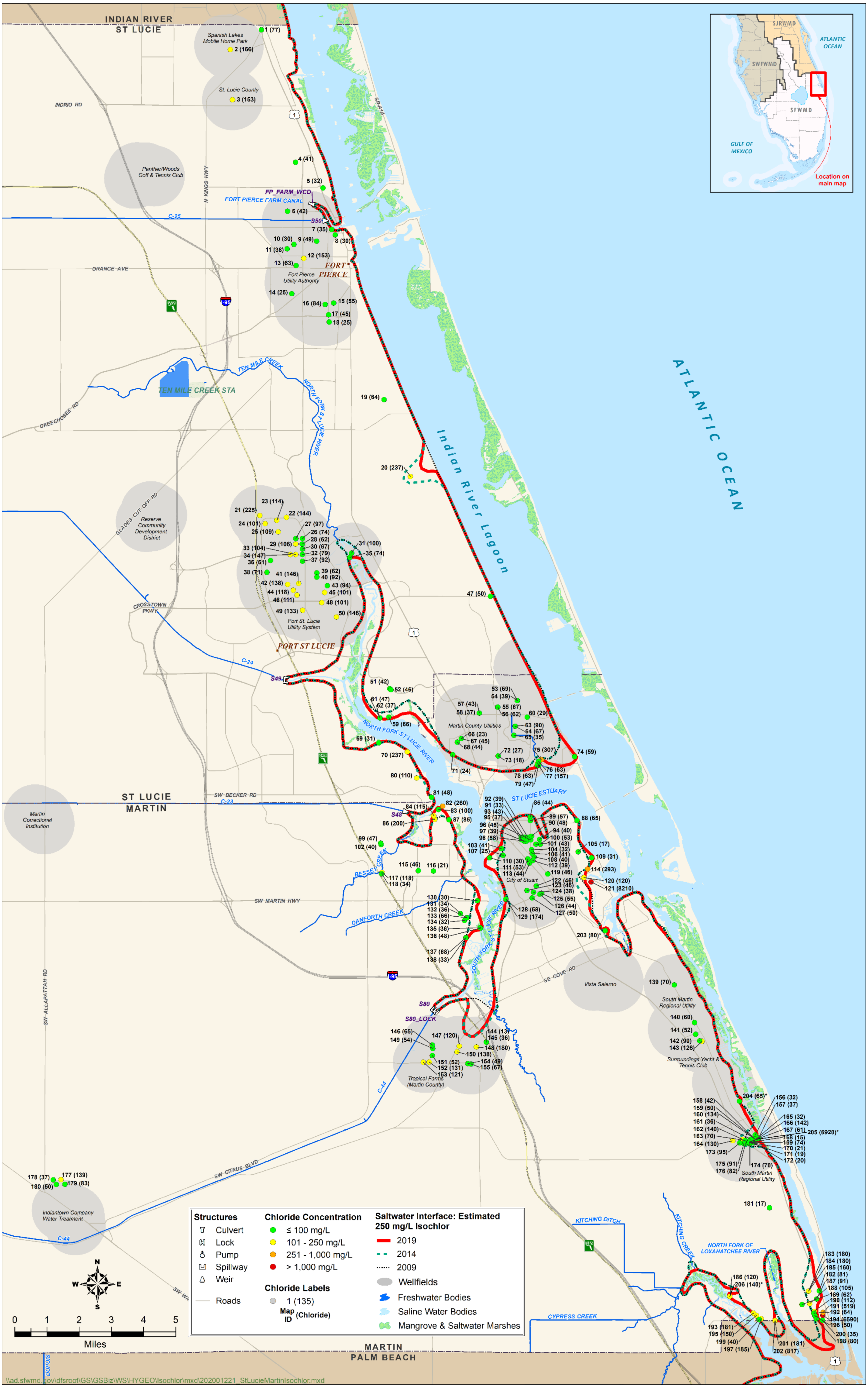
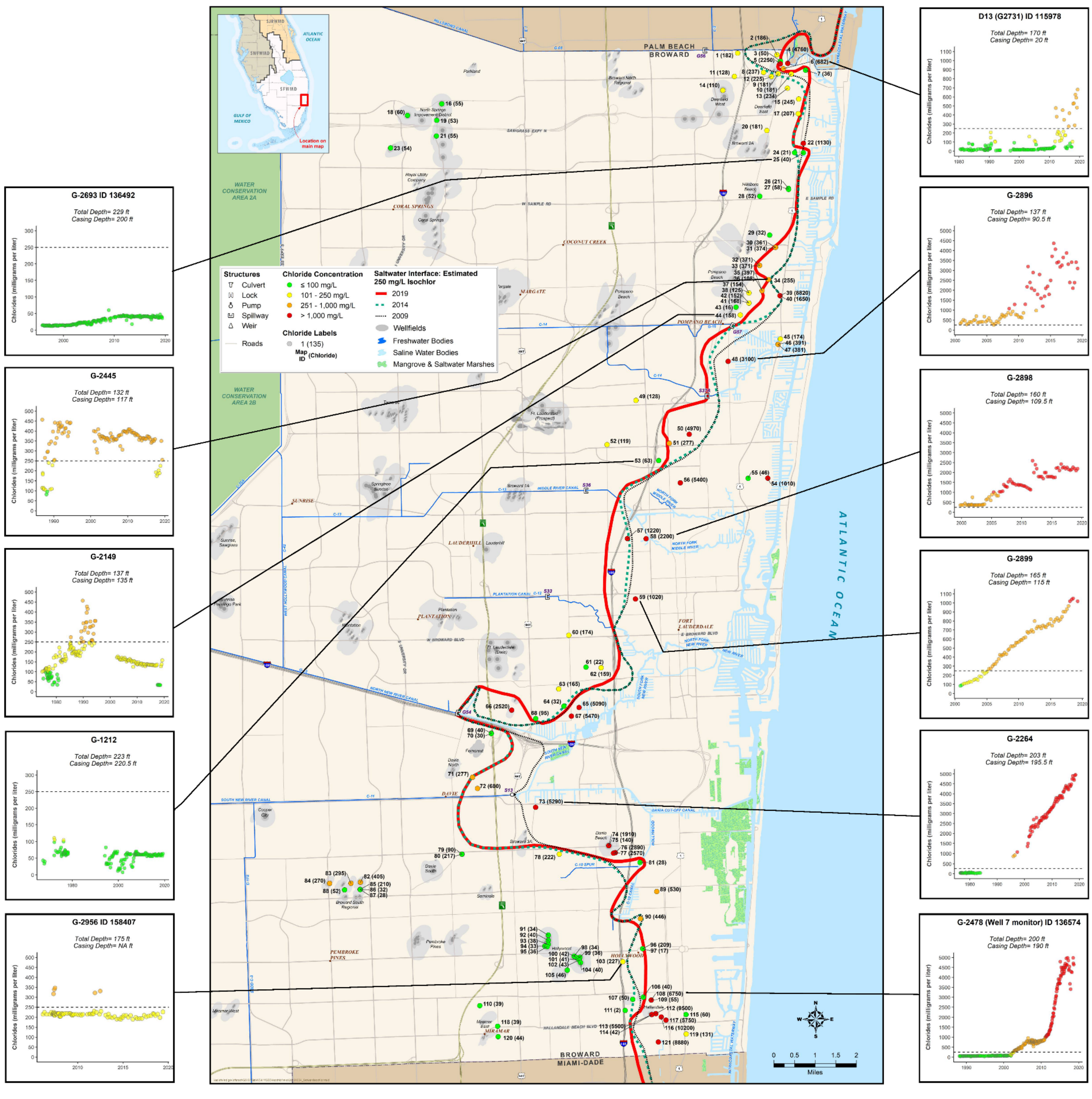


Figure 7. Map of the 2009, 2014, and 2019 estimated positions of the saltwater interface in Martin and St. Lucie counties.

Broward County
Estimated Position of the Saltwater Interface
Surficial Aquifer System
March/April/May 2019

Prepared by: Water Supply Bureau



Map ID	SFWMD Facility ID	Project Name	Well Name	XCOORD	YCOORD	Cased Depth (feet lbs)	Total Depth (feet lbs)	Chloride (mg/L)
1	115935	DEERFIELD BEACH PUBLIC WATER SUPPLY	D1-A (G2718)	944746	725422	100	150	182
2	149498	DEERFIELD BEACH PUBLIC WATER SUPPLY	D11 (G2729)	949765	725218	20	180	186
3	115984	DEERFIELD BEACH PUBLIC WATER SUPPLY	CWI	950221	724407	150	160	50
4	115976	DEERFIELD BEACH PUBLIC WATER SUPPLY	D12 (G2730)	951147	724120	20	180	4760
5	115985	DEERFIELD BEACH PUBLIC WATER SUPPLY	CWD	950198	724065	190	200	2250
6	115978	DEERFIELD BEACH PUBLIC WATER SUPPLY	D13 (G2731)	950594	723439	20	170	682
7		BROWARD COUNTY / USGS	FP MW-1 (G-2892)	953429	723245	108	155	36
8	149548	DEERFIELD BEACH PUBLIC WATER SUPPLY	D10 (2728)	948052	722957	20	180	237
9	115943	DEERFIELD BEACH PUBLIC WATER SUPPLY	D7 (G2725)	949983	722800	60	170	181
10	115979	DEERFIELD BEACH PUBLIC WATER SUPPLY	D14-A (G2733)	951596	722753	100	150	181
11	115936	DEERFIELD BEACH PUBLIC WATER SUPPLY	D2-A (G2719)	944329	722439	100	150	128
12	115982	DEERFIELD BEACH PUBLIC WATER SUPPLY	D17 (G2737)	949053	722435	100	150	225
13	115980	DEERFIELD BEACH PUBLIC WATER SUPPLY	D15-A (G2735)	951110	720940	100	150	234
14	115983	DEERFIELD BEACH PUBLIC WATER SUPPLY	DR-1 (G2738)	942847	720664		170	110
15	115981	DEERFIELD BEACH PUBLIC WATER SUPPLY	D16 (G2736)	952549	719549	10	260	245
16	6428	NORTH SPRINGS IMPROVEMENT DISTRICT	4	906867	718939	80	130	55
17	115942	DEERFIELD BEACH PUBLIC WATER SUPPLY	D6 (G2724)	952492	717676	60	180	207
18	6431	NORTH SPRINGS IMPROVEMENT DISTRICT	9	902493	717446	80	130	60
19	6424	NORTH SPRINGS IMPROVEMENT DISTRICT	6	906227	716828	80	130	53
20	115973	DEERFIELD BEACH PUBLIC WATER SUPPLY	D9 (G2727)	948468	715524	80	180	181
21	6425	NORTH SPRINGS IMPROVEMENT DISTRICT	7	906186	714820	80	130	55
22	136498	BROWARD COUNTY 2A/NORTH REGIONAL P W S	G-2893	953145	713873	167	177	1130
23	6423	NORTH SPRINGS IMPROVEMENT DISTRICT	2A	900319	713297	80	130	54
24	136493	BROWARD COUNTY 2A/NORTH REGIONAL P W S	G-2694	952025	712690	85	125	21
25	136492	BROWARD COUNTY 2A/NORTH REGIONAL P W S	G-2693	953145	712686	200	229	40
26		USGS	G-2752	951245	708113	250	255	21
27	136873	TOWN OF HILLSBORO BEACH	HBBSW1 (39th Street)	951253	707989		257	58
28	136872	TOWN OF HILLSBORO BEACH	HBBMP1 (plant 110)	947573	707104		110	52
29		BROWARD COUNTY / USGS	FP MW-3 (G-2277)	948831	702139	131	131	31.6
30	136306	POMPANO BEACH PUBLIC WATER SUPPLY	SWI4-D	949590	700570		200	361
31	136307	POMPANO BEACH PUBLIC WATER SUPPLY	SWI4-S	949590	700570		120	374
32	136193	POMPANO BEACH PUBLIC WATER SUPPLY	SWI1D	947553	698254		200	371
33	136299	POMPANO BEACH PUBLIC WATER SUPPLY	SWI1-S	947553	698253		120	371
34		USGS	G-2445	948675	696456	117	132	255
35	136326	POMPANO BEACH PUBLIC WATER SUPPLY	SWI6-D	947869	695024		200	397
36	136327	POMPANO BEACH PUBLIC WATER SUPPLY	SWI6-S	947869	695024		120	108
37	136308	POMPANO BEACH PUBLIC WATER SUPPLY	SWI5-D	946184	694743		200	154
38	136325	POMPANO BEACH PUBLIC WATER SUPPLY	SWI5-S	946184	694743		120	125
39	136304	POMPANO BEACH PUBLIC WATER SUPPLY	SWI3-D	950151	694392		180	8820
40	136305	POMPANO BEACH PUBLIC WATER SUPPLY	SWI3-S	950151	694392		120	1650
41	136302	POMPANO BEACH PUBLIC WATER SUPPLY	SWI2-D	946184	693444		180	168
42	136303	POMPANO BEACH PUBLIC WATER SUPPLY	SWI2-S	946184	693444		120	152
43		BROWARD COUNTY / USGS	FP MW-2 (G-2447)	944522	692920		135	16.1
44		USGS	G-2149	945075	691914	135	137	158
45	136301	POMPANO BEACH PUBLIC WATER SUPPLY	SWI10-S	950207	688843		130	174
46	136332	POMPANO BEACH PUBLIC WATER SUPPLY	SWI9-D	949904	688166		140	391
47	136333	POMPANO BEACH PUBLIC WATER SUPPLY	SWI9-S	949913	688160		130	381
48		USGS	G-2896	943520	685987	90	137	3100
49	212901	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW2	931728	680983	5	200	128
50	212914	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW9	938539	676654	5	200	4970
51		USGS	G-1232	935983	675497	203	205	277
52	212899	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW1	928026	675331	5	200	119
53		USGS	G-1212	934631	673297	220	223	63
54	136868	CORAL RIDGE COUNTRY CLUB	CRCCMW1	948594	671037	5	85	1010
55	136869	CORAL RIDGE COUNTRY CLUB	CRCCMW2	946082	671022	5	95	46
56		USGS	G-2897	937402	670438	126	136	5400
57	212913	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW8	930628	663304	5	260	1220
58		USGS	G-2898	933021	663290	110	160	2200
59		USGS	G-2899	931657	655577	115	165	1020
60	212902	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW3	923133	650934	5	200	174
61		USGS	G-2902	925324	646854	180	190	22
62	212912	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW7	927267	646780	5	200	159
63	212903	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW4	921841	644062	5	200	165
64		USGS	G-2957	922510	641858		190	32
65		USGS	G-2352	924445	641698		171	5090
66	212900	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW6	915819	641353	5	270	2520
67		USGS	G-2904	923467	640582		126	5470
68	212904	FORT LAUDERDALE PUBLIC WATER SUPPLY	MW5	918895	640281	5	200	95.2
69	136755	FERNCREST WATER TREATMENT PLANT	MW5	913211	638392	10	20	40
70	136756	FERNCREST WATER TREATMENT PLANT	MW6	913211	638355	72	82	30
71	137073	TOWN OF DAVIE WATER PLANT SYS I, III, AND V	MW-4 (Veterans Park DW-4)	910816	632765	165	175	277
72	137072	TOWN OF DAVIE WATER PLANT SYS I, III, AND V	MW-1 (Potters Park DW-1)	911455	631337	170	180	680
73		USGS	G-2264	918886	628920	196	203	5290
74	136784	DANIA BEACH P W S	DCMW-B	928240	624011	94	99	1910
75	136783	DANIA BEACH P W S	DCMW-A	928256	624011	63	68	140
76	136785	DANIA BEACH P W S	DEH	929087	623115	110	117	2890
77		USGS	G-1697	928848	623048	117	126	2570
78		USGS	G-2785	921917	622924	195	200	222
79	137075	TOWN OF DAVIE WATER PLANT SYS I, III, AND V	MW-3 (Stirling West DW-3)	909446	622918	110	120	90
80	137074	TOWN OF DAVIE WATER PLANT SYS I, III, AND V	MW-2 (Stirling East DW-2)	909472	622918	140	150	217
81	277399	OAKWOOD PLAZA	WELL-1	932243	621886	70	100	28
82	136920	BROWARD COUNTY SOUTH REGIONAL WELLFIELD	G-2930	896469	619361	127	132	405
83	148533	BROWARD COUNTY SOUTH REGIONAL WELLFIELD	G-2933	895252	619224	117	122	295
84	148532	BROWARD COUNTY SOUTH REGIONAL WELLFIELD	G-2934	892521	619216	115	120	270
85	148535	BROWARD COUNTY SOUTH REGIONAL WELLFIELD	G-2931	896426	618441	121	130	210
86	163816	BROWARD COUNTY SOUTH REGIONAL WELLFIELD	G-2958	896448	618420	116	121	32
87	163817	BROWARD COUNTY SOUTH REGIONAL WELLFIELD	G-2959	896449	618420	76	81	28
88	148534	BROWARD COUNTY SOUTH REGIONAL WELLFIELD	G-2932	894434	618383	110	115	52
89	138201	HOLLYWOOD WATER TREATMENT PLANT	G-2612	934377	618174	272	273	530
90	138200	HOLLYWOOD WATER TREATMENT PLANT	G-2441	932300	614708	180	181	446
91	29894	HOLLYWOOD WATER TREATMENT PLANT	36 Chaminade	920503	612592	90	112	34
92	29896	HOLLYWOOD WATER TREATMENT PLANT	38 Chaminade	920503	611924	128	150	40
93	29897	HOLLYWOOD WATER TREATMENT PLANT	39 Chaminade	920503	611404	135	155	38
94	29899	HOLLYWOOD WATER TREATMENT PLANT	41 Chaminade	920062	611178	139	150	33
95	29898	HOLLYWOOD WATER TREATMENT PLANT	40 Chaminade	920879	611121	125	145	36
96		USGS	G-2425	932576	610854	198	203	209
97	138199	HOLLYWOOD WATER TREATMENT PLANT	G-2426	932576	610854	86	91	17
98	29902	HOLLYWOOD WATER TREATMENT PLANT	32 South	923808	609899	55	80	34
99	29900	HOLLYWOOD WATER TREATMENT PLANT	30 South	924555	609764	60	95	36
100	29901	HOLLYWOOD WATER TREATMENT PLANT	31 South	924012	609763	60	80	42
101	29903	HOLLYWOOD WATER TREATMENT PLANT	33 South	924374	609559	69	90	41
102	29904	HOLLYWOOD WATER TREATMENT PLANT	34 South	924441	609413	70	86	43
103	158407	HOLLYWOOD WATER TREATMENT PLANT	G-2956	930047	609189	175	185	227
104	29937	HOLLYWOOD WATER TREATMENT PLANT	35 South	924634	609073	60	77	40
105	29907	HOLLYWOOD WATER TREATMENT PLANT	28 South	922937	608111	60	75	46
106	20882	HALLANDALE BEACH PUBLIC WATER SUPPLY	7	932668	604656	66	97	40
107	20883	HALLANDALE BEACH PUBLIC WATER SUPPLY	8	931316	604380	101	107	50
108	136574	HALLANDALE BEACH PUBLIC WATER SUPPLY	G-2478 (Well 7 monitor)	933686	604281	190	200	6750
109	136613	HALLANDALE BEACH PUBLIC WATER SUPPLY	G-2477	933685	604280	75	80	55
110	136633	CITY OF MIRAMAR PUBLIC WATER SUPPLY	MCMW3	911739	603569	30	120	39
111	279320	HALLANDALE BEACH PUBLIC WATER SUPPLY	9	930838	602958	80	100	2
112	136612	HALLANDALE BEACH PUBLIC WATER SUPPLY	G-2410	934275	602550	205	206	9500
113	192981	HALLANDALE BEACH PUBLIC WATER SUPPLY	G-2965 (Well 3 monitor)	933757	602427	165	175	5500
114	20878	HALLANDALE BEACH PUBLIC WATER SUPPLY	3	933750	602425	61	81	42.5
115	136611	HALLANDALE BEACH PUBLIC WATER SUPPLY	G-2409	938125	602425	83	84	60
116	136581	HALLANDALE BEACH PUBLIC WATER SUPPLY	G-1435	934961	602118	190	195	10200
117	136610	HALLANDALE BEACH PUBLIC WATER SUPPLY	G-2294	935565	601715	135	139	5750
118	136629	CITY OF MIRAMAR PUBLIC WATER SUPPLY	MCMW1	914018	600927	30	120	39.2
119	14672	GULFSTREAM PARK	2	938150	599939	16	45	131
120	136630	CITY OF MIRAMAR PUBLIC WATER SUPPLY	MCMW2	914088	598598	30	120	43.9
121		USGS	G-2903	934584	598920	146	156	8880

Well and chloride information was obtained from the USGS, local governments and SFWMD records. Chloride values are given in milligrams per liter (mg/L). Map data represents the maximum chloride value for the period of March/April/May 2019. Graphs of selected wells represent the period of record for each well through May 2019. The solid red isochlor line marks an approximation of the farthest inland extent of the saltwater interface as defined by the 250 mg/L chloride concentration in groundwater and/or the farthest inland extent of saline surface water. The dashed green line corresponds to the 2014 data and the dashed black line corresponds to 2009 data.

Figure 8. Example of the final map layout for the 2019 estimated position of the saltwater interface in Broward County, including selected time-series plots and the reference table.

4 WATER SUPPLY PLANNING

Saltwater interface monitoring and mapping is an important component of water supplying planning, particularly in coastal water supply planning areas. Within the District, these planning areas are: Upper East Coast, Lower East Coast, and Lower West Coast. The SFWMD publishes water supply plans for these regions, which recognize that declines in inland groundwater levels and groundwater flow towards the ocean (or Gulf of Mexico) may allow saltwater intrusion in some coastal areas. Installation of coastal canal salinity control structures has helped stabilize the saltwater interface, but there is evidence of inland migration in some areas, particularly coastal Broward and Miami-Dade counties. A few coastal public supply wellfields located seaward of salinity control structures are no longer operating due to saltwater intrusion (SFWMD 2018).

Sea level rise is recognized as a force that can increase inland migration of the saltwater interface. As sea level continues to rise, some coastal wellfields may have to relocate farther inland, change treatment processes, or be replaced with alternative water sources (SFWMD 2018). An important management strategy is to continue to collect and analyze water level and water quality data, including information about saltwater intrusion.

4.1 Upper East Coast

The most recent water supply plan update for the Upper East Coast Planning Area was published in 2016, prior to completion of the 2019 saltwater interface maps. The plan recognized that the 2009 and 2014 maps can be used to track the saltwater interface over time, identify areas of concern that require additional monitoring, and suggest changes in wellfield operations. The saltwater interface is regionally dynamic, with inland movement in some areas and seaward movement in other areas. Local-scale investigations of the saltwater interface position could be warranted in areas of concern, depending on the network of available monitor wells, the proximity of saltwater sources to wellfield locations, and withdrawal rates. The plan concluded that the SAS historically has served as the primary source of water for urban demands in the Upper East Coast Planning Area and expansion of SAS withdrawals is limited due to wetland impacts and the increased potential for saltwater intrusion. Alternative water sources such as the Floridan aquifer system may be required to reduce demand on the SAS and the increased potential for saltwater intrusion (SFWMD 2016).

4.2 Lower East Coast

The water supply plan for the Lower East Coast Planning Area was most recently updated in 2018, prior to completion of the 2019 saltwater interface maps. Comparing the 2009 and 2014 saltwater interface maps, there were a few locations where noticeable inland movement of the saltwater interface occurred in Broward and Miami-Dade counties. These data, in addition to the 2019 results, are important to calibrate groundwater models designed to simulate future saltwater movement.

With increased impacts of sea level rise, local governments, utilities, and private entities may be required to develop adaptive strategies to combat further saltwater intrusion (as well as regional flood protection). Strategies include construction of defensive barriers and pumping systems, improvement of infrastructure, and changes to land use. With the inland movement of the saltwater interface, local-scale investigation of the interface position could be warranted in some areas, depending on the network of monitor wells available, the proximity of saltwater sources to wellfield locations, and withdrawal rates.

The 2018 water supply plan recommended utilities design wellfield locations, configurations, and pumping regimes to avoid saltwater intrusion. Implementation of groundwater recharge systems could help prevent inland movement of the saltwater interface. The SFWMD, USGS, and local governments should continue to coordinate saltwater intrusion monitoring efforts to delineate the location and movement of the saltwater interface and identify areas of concern. Meanwhile, the SFWMD should periodically review existing groundwater monitoring networks and enhance them, as appropriate (SFWMD 2018).

4.3 Lower West Coast

The most recent update to the Lower West Coast Water Supply Plan was published in 2017, prior to completion of the 2019 saltwater interface maps. The plan noted that the monitoring networks used for saltwater intrusion, aquifer assessment, and groundwater modeling are a hybrid of regional programs and monitoring required or performed by water use permittees. Efforts should be made to identify locations considered critical to long-term monitoring and modeling to ensure wells are constructed, maintained, or replaced, as necessary. SAS and IAS wellfield operating plans should be reviewed and revised by utilities to maximize withdrawals while avoiding harm to natural systems and potential impacts from saltwater intrusion.

The 2017 water supply plan recognized that future increases in SAS and IAS withdrawals are limited by, among other things, the potential for saltwater intrusion. In the Lower West Coast Planning Area, monitoring of chloride concentrations is crucial to the protection of fresh groundwater due to inland migration of the saltwater interface and upward movement (upconing) of saline groundwater. Another potential saltwater source is improperly abandoned wells. As noted in other water supply plans, local-scale investigation of the saltwater interface position could be warranted in some areas, depending on the network of available monitor wells, the proximity of saltwater sources to wellfield locations, and withdrawal rates. By tracking the movement of the saltwater interface every 5 years, areas of concern may be identified that require additional monitoring and/or may need changes in wellfield operations (SFWMD 2017).

5 2019 ISOCHLOR INTERPRETATION

5.1 St. Lucie and Martin Counties – Surficial Aquifer System

There were 206 monitor wells used in the St. Lucie and Martin counties saltwater interface map for the SAS. There has been little movement of the saltwater interface in this region, as evidenced by all three isochlor lines (2009, 2014, and 2019) overlapping throughout most of the mapped area. The time-series plots of wells landward of the saltwater interface remain relatively flat. However, one well (Map ID 24) in Port St. Lucie has an upward slope approaching 250 mg/L. Several wells seaward of the saltwater interface continue to show chloride concentrations in excess of 250 mg/L. Monitor well M-1132 in the City of Stuart is approaching a chloride concentration of 10,000 mg/L.

5.2 Palm Beach County – Surficial Aquifer System

There were 305 wells used in the Palm Beach County saltwater interface map for the SAS. There has been no apparent landward movement of the saltwater interface in Palm Beach County. Due to the clustering of monitor wells in certain areas, the Palm Beach County map has insets to enlarge the scale for closer observation of the 250 mg/L isochlor. Around the City of Lake Worth Beach and the City of Lantana there is an area of seaward migration of the saltwater interface (**Figure 9a**). This also is evident in the time-series plot for Map ID 167 representing USGS monitor well PB-1717 (**Figure 9b**). These improvements (seaward movements) to the saltwater interface may be due to the shifting of pumpage among certain wells within a wellfield or the reduction of pumpage from SAS wells in favor of Floridan aquifer system wells.

(a)
(b)

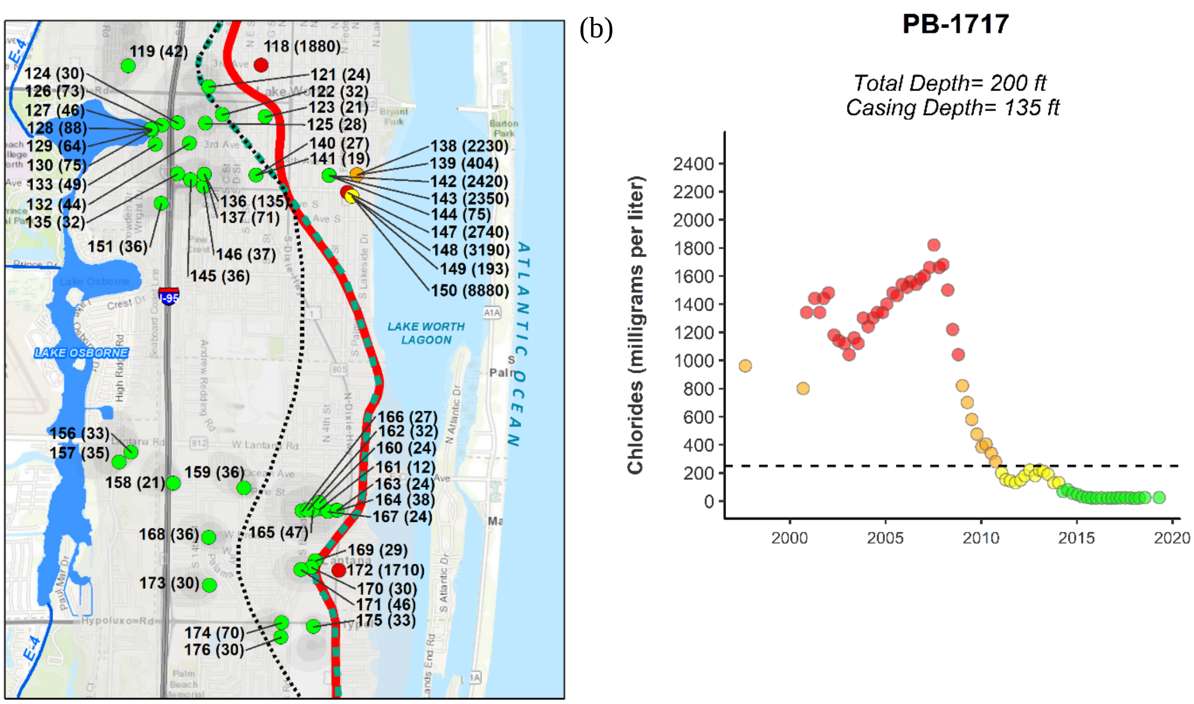


Figure 9. (a) Evidence of eastward saline migration around Lake Worth Beach and Lantana; (b) Time-series plot for monitor well PB-1717, showing a decline in chloride concentrations.

5.3 Broward County – Surficial Aquifer System

There were 126 wells used in the Broward County saltwater interface map for the SAS. Broward County had some significant landward movement of the saltwater interface in 2019 compared to the 2014 and 2009 maps. This is evident in **Figure 10a** where the three isochlors are progressively moving west in Pompano Beach. In some cases, there is evidence of saltwater encroachment in the time-series plot for a single monitor well. For example, in **Figure 10b**, Map ID 48, representing USGS monitor well G-2896, the chloride concentration was approximately 750 mg/L in 2009, approximately 2,000 mg/L in 2015, and approximately 4,000 mg/L in 2019. These data represent the movement of the saltwater interface through a monitor well as the wedge of saltwater moves inland.

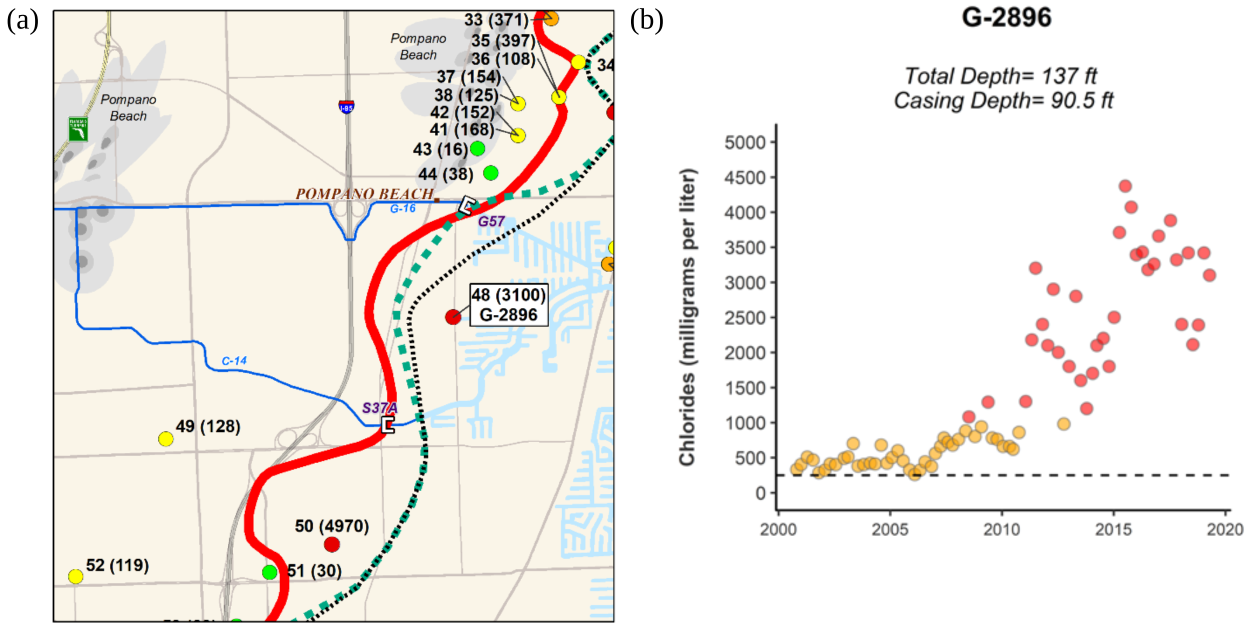


Figure 10. (a) Evidence of westward saline migration in Pompano Beach; (b) Time-series plot showing the saltwater interface passing through monitor well G-2896.

In southern Broward County, most of the Dania Beach wellfield had to be taken out of service as the saltwater interface moved into and beyond the wellfield. **Figure 11a** shows chloride concentrations in several wells (Map IDs74 to 77) exceed 2,000 mg/L. Farther south, the Hallandale Beach wellfield is another impacted area where westward migration of the saltwater interface is observed (**Figure 11a**). The time-series plot (**Figure 11b**) shows monitor well G-2478 (Map ID 108) was fresh prior to 2002, but as the saltwater interface moved westward, chloride concentrations increased to approximately 1,000 mg/L in 2009, approximately 2,500 mg/L in 2014, and is greater than 6,000 mg/L in 2019. This also is an example of where a worst-case scenario was chosen as nearby Map ID 109 has a much lower chloride concentration (55 mg/L). The two monitor wells are close and the green dot (Map ID 109) overlies the red dot (Map ID 108), but Map ID 109 is only 80 feet deep while Map ID 108 is 200 feet deep and the higher concentration was used to interpret the location of the saltwater interface.

(a) (b)

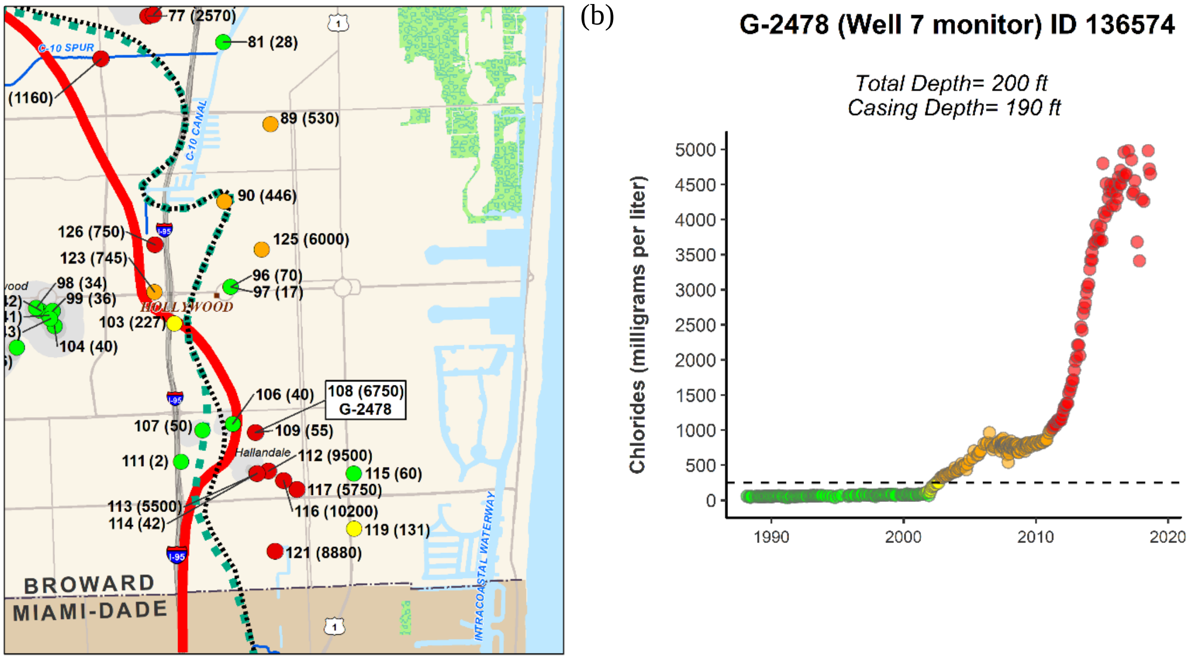


Figure 11. (a) Westward movement of the saltwater interface impacting Dania Beach and Hallandale wellfields; (b) Time-series plot showing the saltwater interface passing through monitor well G-2478.

There is a concerning situation near the Peele-Dixie wellfield in Fort Lauderdale (**Figure 12**). The 2009 and 2014 maps showed the 250 mg/L isochlor south of the wellfield. However, in 2019, the monitor wells used to determine potential saltwater intrusion in the wellfield were examined more closely. New data points (Map IDs 66 and 122) and an additional monitor well sampled outside of the March to May time frame showed significant encroachment in the vicinity of the wellfield. The City of Fort Lauderdale plans on installing replacement wells; however, careful monitoring is required.

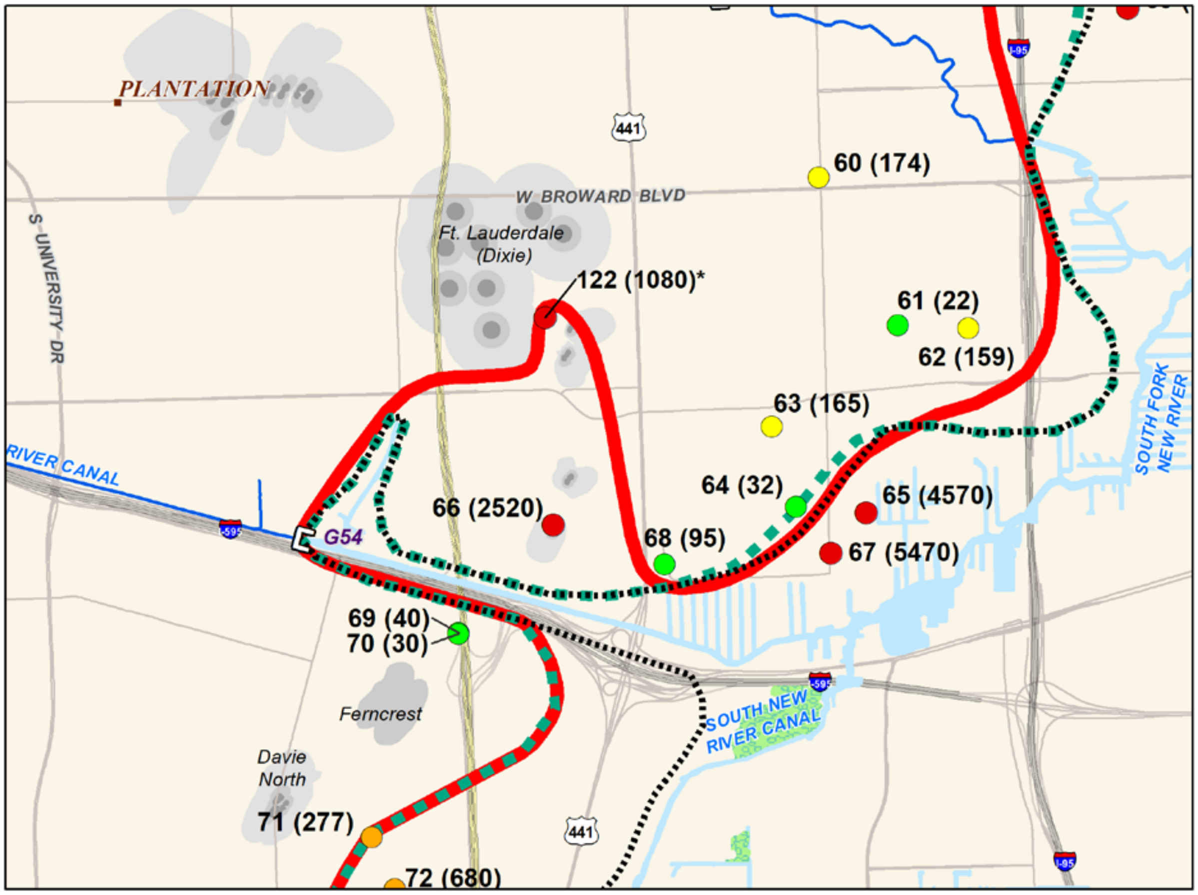


Figure 12. Changes in the saltwater interface position around the Fort Lauderdale Peele-Dixie wellfield.

There was one area near Deerfield Beach where the isochlor was adjusted using new data points. In conjunction with wellfield management, the saltwater interface appears to be retreating seaward in this area.

5.4 Lee County – Water Table Aquifer

There were 96 wells used in the Lee County saltwater interface map for the Water Table aquifer. The 2019 isochlor remained relatively stable compared to 2009 and 2014. One area near Cape Coral showed improvement as the isochlor shifted seaward with the addition of a new data point in an area of limited monitoring.

5.5 Lee and Collier Counties – Sandstone Aquifer

There were 77 wells used in the Lee and Collier counties saltwater interface map for the Sandstone aquifer. There was one area near Lehigh Acres where a new data point suggests the saltwater interface has moved inland compared to 2009 and 2014 (**Figure 13**).

5.6 Lee and Collier Counties – Lower Tamiami Aquifer

There were 148 wells used in the Lee and Collier counties saltwater interface map for the Lower Tamiami aquifer. The isochlor remained relatively stable near the Naples Coastal Ridge wellfield. The saltwater interface moved landward in the Bonita Springs area and northern Collier County. There was slight landward movement in a portion of Collier County where relict seawater is believed to exist (**Figure 14**).

5.7 Collier County – Water Table Aquifer

There were 78 wells used in the Collier County saltwater interface map for the Water Table aquifer. Unlike on the east coast of Florida where salinity control structures are present and often act as a divide to prevent saltwater from freely flowing inland, the Lower West Coast Planning Area typically does not have such structures. Thus, areas adjacent to freshwater creeks such as Haldemen Creek, Lely Canal, and Henderson Strand typically exhibit landward movement of the saltwater interface (**Figure 15**). However, additional movement of the saltwater interface was noted in the Lely Canal area in Collier County. The area around the Lely Canal outfall is a coastal natural habitat influenced by tidal changes. Recent development in the area has occurred and possibly has caused some inland movement of the saltwater interface. There appears to be a natural flushing of fresh to saline water depending on the season and tides in coastal Collier County. As noted, the data used for these maps were collected during the dry season. Wells in this area do not have a long enough period of record for time-series analysis but should be carefully monitored in the future.

5.8 Lee and Collier Counties – Mid-Hawthorn Aquifer

There were 98 wells used in the Lee and Collier counties saltwater interface map for the Mid-Hawthorn aquifer. There was only one area near Fort Myers where changes in water quality suggest the saltwater interface has moved inland (**Figure 16**).

Figure 13. Position of the saltwater interface in the Sandstone aquifer in Lee and Collier counties.

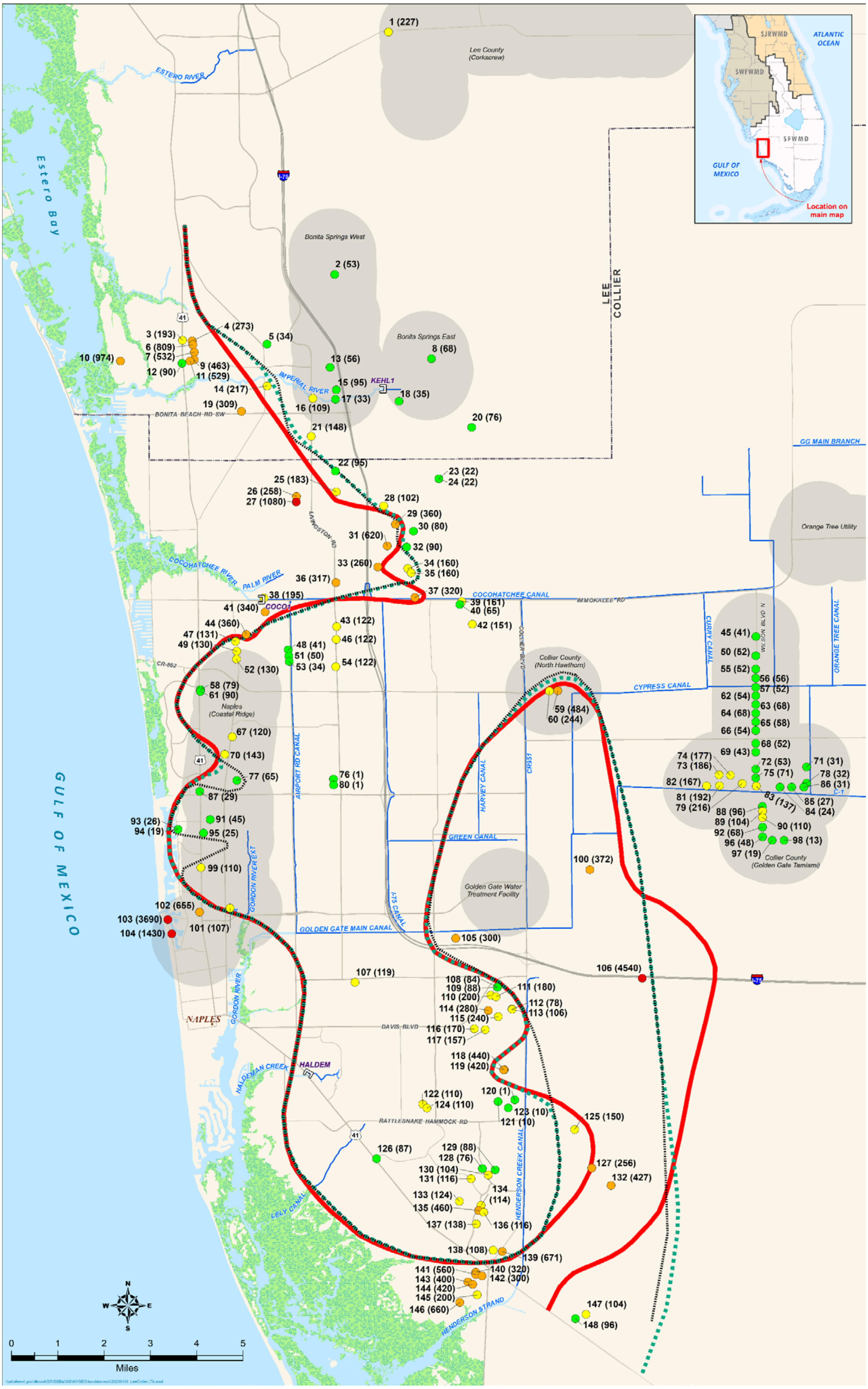


Figure 14. Position of the saltwater interface in the Lower Tamiami aquifer in Lee and Collier counties.

Figure 15. Position of the saltwater interface in the Water Table aquifer in Collier County.

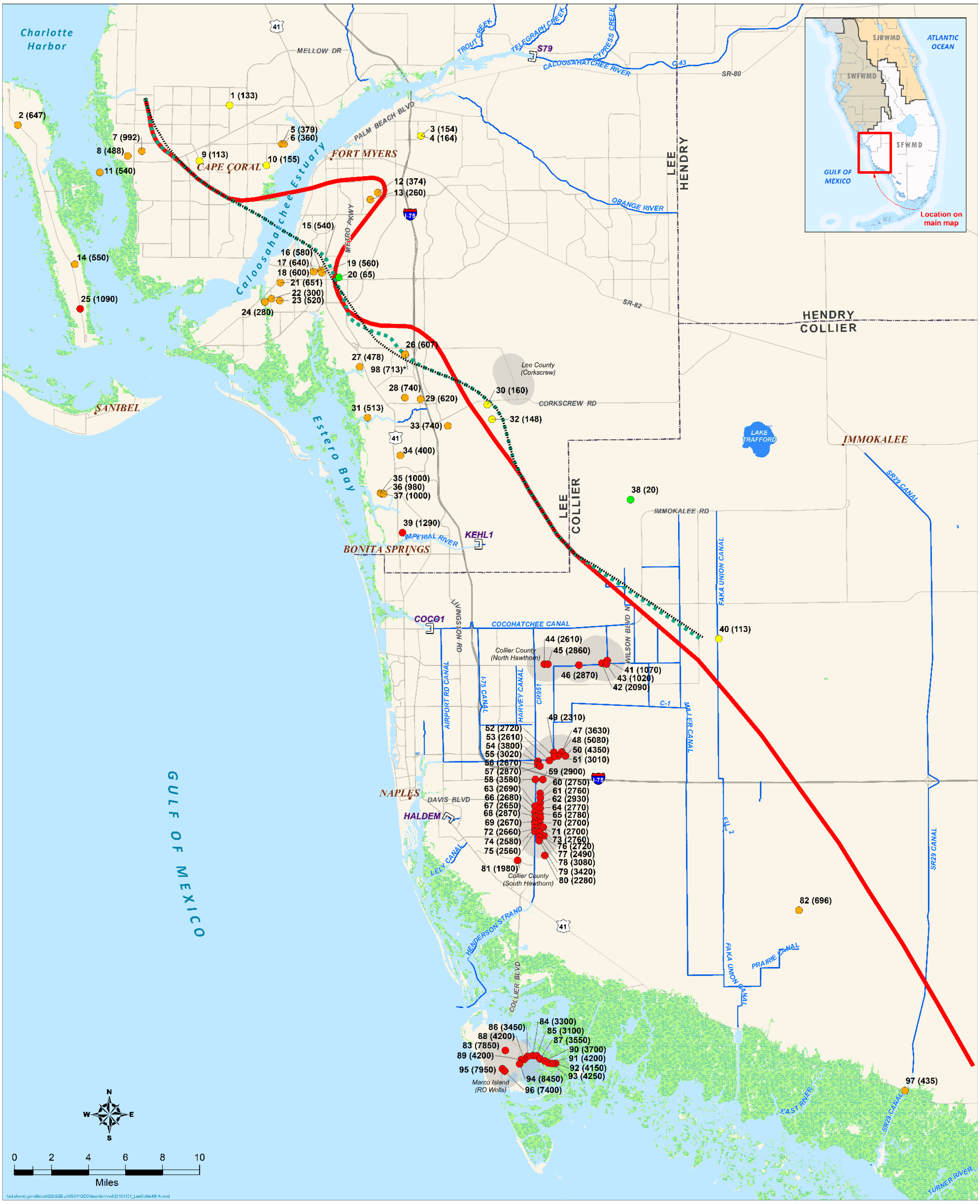


Figure 16. Position of the saltwater interface in the Mid-Hawthorn aquifer in Lee and Collier counties.

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