Hydrogeology and Groundwater Salinity of Water Conservation Area 2A (WCA-2A)

Broward and Palm Beach Counties, Florida
Technical Publication WS-54

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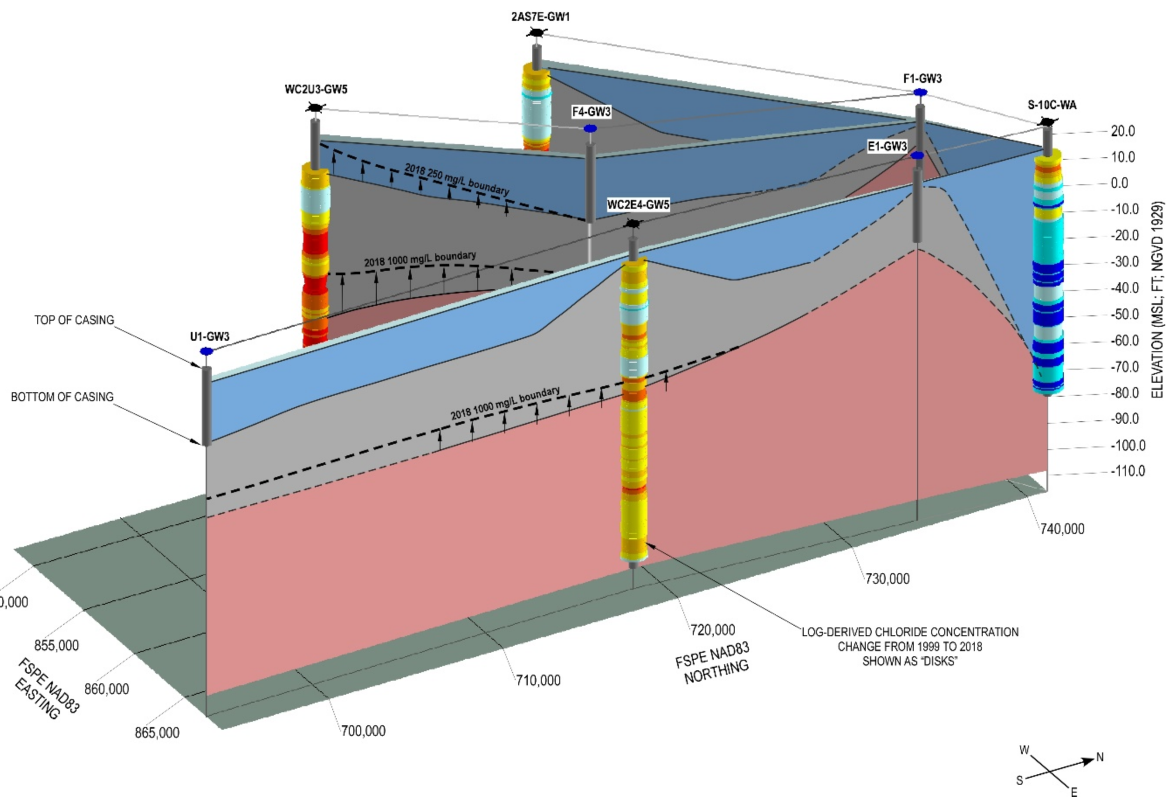

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EXECUTIVE SUMMARY

The Water Conservation Area 2A (WCA-2A) wetland encompasses approximately 105,000 acres in a remnant portion of the Florida Everglades in southeastern Florida and is part of the surface water flow system through South Florida towards the southeastern coastal areas, Florida Bay, and the Gulf of Mexico. Levee construction to enclose WCA-2A began in the 1950s, and the basin was completely enclosed by levees and canals by 1963. Numerous ecological investigations have been conducted focusing on vegetative changes as a result of anthropomorphic changes in surface water flow and water quality; however, groundwater studies were limited until 1997. This study summarizes the hydrogeology of the surficial aquifer system (SAS) within WCA-2 described in previous geological studies. A geophysical investigation also was conducted to assess potential groundwater quality changes in WCA-2A over the past approximately 20 years near the S-10C structure, between WCA-2A and WCA-1, where there have been major changes in vegetative communities related to distance from the levee and structure.

The SAS is approximately 170 to 200 feet (ft) thick in WCA-2A and is underlain by the intermediate confining unit, corresponding to Hawthorn Group sediments. Lithostratigraphic units identified within the SAS in WCA-2A, in descending order, include unconsolidated recent and Holocene sediments; the Pleistocene Fort Thompson and Anastasia formations; and the Pleistocene Tamiami formation, composed of the Pinecrest Sand and Ochopee Limestone members. Three permeable zones (PZ-1, PZ-2, and PZ-3) within the SAS are delineated across the site based on previous publications and through correlation with geophysical and lithologic logs. Each permeable zone consists of highly variable lithology that includes sand and shell, cemented or loosely cemented shell and shell fragments, vuggy or solution-enhanced limestone, or calcareous sandstone, with hydraulic conductivity estimated to range from 100 to 1,000 ft/day. Relatively low-permeability strata, including semi-confining and confining intervals that overlie and are interbedded with permeable zones include an uppermost peat, sand, soil, and marl layer, approximately 2 ft thick, that overlies PZ-1; fine to medium sand, sandstone, and limestone between PZ-1 and PZ-2; and limestone, shelly sand, and clay between PZ-2 and PZ-3. Horizontal hydraulic conductivity estimates range from 0.1 to 100 ft/day for interbedded and semi-confining units and <0.1 ft/day for confining clay intervals, which are very limited.

Geophysical resistivity logging data and chloride concentrations collected from 1997 through 2000 and in 2018 were used to assess salinity changes over the last 20 years. The study included data analysis from three deep SAS monitor wells within the wetland interior of WCA-2A, and one levee well adjacent to the S-10C structure. Resistivity logs acquired in 1997 and 1999 from the deepest well at each cluster were correlated with chloride concentration data to model estimated chloride concentrations with depth. A logging event in September 2018 was conducted at the deep well of each cluster, followed by a chlorides sample from the same well, to develop a model for each cluster representative of 2018 conditions. The 1997/1999 and 2018 chloride curves were compared to identify changes in chloride concentration. Salinity zone boundaries in the WCA-2A wells were chosen where the chloride log trace appeared to cross a key threshold for most of the curve, defined by the United States Geological Survey as fresh water (chloride concentration ≤250 milligrams per liter), saltwater (chloride concentration ≥1,000 milligrams per liter), and brackish water (between those two end members). Geophysical modeling was useful for estimating salinity boundaries that often would not be identified by sampling discrete well screen intervals alone.

The salinity findings in this study are consistent with previous investigations that conceptualized surface water/groundwater exchange beneath the wetlands compartmentalized by the L-39 levee as fresh recharge water from WCA-1 driven downward to a depth of at least 90 ft on the upgradient (headwater) side of the levee, forcing higher salinity water at depth upwards towards the surface in WCA-2A and inducing vertical mixing throughout the upper SAS. The implications of the upward movement of connate (saline) water into shallower zones of WCA-2A – and over time for this water to be observed at land surface – need to be explored and better understood.

Geophysical modeling indicated important changes in salinity since 1997/1999. Each wetland monitor well was brackish in the shallower intervals and transitioned to saltwater at depth in 1997/1999 and 2018. Based on geophysical modeling, the brackish water/saltwater interface in the wetland well clusters rose approximately 4 to 21 ft to depths of 47 to 59 ft from top of casing, respectively, and average chloride concentrations of the saturated interval based on the model increased 7% to 27% from 1997/1999. While near-surface groundwater at two wetland wells was brackish in 1997/1999, the third well changed from fresh to brackish within the upper 10 ft.

Based on the 2018 model and laboratory samples, water in the monitor well next to the S-10C structure was fresh for the total depth of the well. The 1997/1999 model indicated the groundwater was slightly brackish, although laboratory samples indicated fresh water. Infiltration of fresher drilling fluid and a lack of well development may have caused the 1997/1999 model to appear more saline than it was. Chloride concentrations were relatively constant over the entire well depth in both models.

The models appeared more effective at identifying relative changes in chloride concentration than absolute concentrations. A variance between the 1997/1999 modeled estimates, averaged over screened intervals, and laboratory results was observed, in which modeled estimates averaged 124% above, 38% above, and 25% below laboratory results for fresh water, brackish water, and saltwater, respectively. Model uncertainties were identified associated with: the potential presence of drilling fluids during logging in 1997/1999 due to lack of well development; the resistivity log resolution compared to smaller-scale lithology changes; boreholes that were not drilled deep enough to accommodate the logging tools and metallic centralizers that were used in well construction; and different logging methods and borehole conditions (cased versus uncased well) present during the 1997/1999 and 2018 events.

Model uncertainties can be minimized during future logging events by conducting contemporaneous sampling of wells at all depths at each well cluster. This would add multiple data points for modeling, reduce the metallic centralizer effects, and reduce the bottom hole limitations of the deepest wells. Additional wells, if installed, should not include metallic centralizers and should include sumps at the bottom to accommodate logging tools.

Additional recommendations include installation of monitor well clusters inside WCA-1, the northern and western areas of WCA-2, and WCA-3A to facilitate resistivity logging and water sampling. These well clusters would become part of an Everglades sentinel wells program to monitor groundwater salinity changes over time to update density-dependent models.

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ACRONYMS AND ABBREVIATIONS

μS/cm	microsiemens per centimeter
APT	aquifer performance test
bls	below land surface
cm/s	centimeters per second
ft	foot
ft/day	feet per day
K	hydraulic conductivity
K_h	horizontal hydraulic conductivity
K_v	vertical hydraulic conductivity
mg/L	milligrams per liter
NGVD29	National Geodetical Vertical Datum of 1929
ohm-m	ohm-meter
PVC	polyvinyl chloride
SAS	surficial aquifer system
USGS	United States Geological Survey
WCA	water conservation area

1 INTRODUCTION

This investigation is focused on the hydrogeology of the surficial aquifer system (SAS) beneath Water Conservation Area 2A (WCA-2A), located in the Everglades Protection Area in Palm Beach and Broward counties, Florida (**Figure 1**). The area consists of remnant Everglades bounded by canals, levees, and other water management structures. Levee construction to enclose WCA-2A began in the 1950s, and the basin was completely enclosed by levees and canals by 1963 (Harvey et al. 2006). Surface water levels, hydraulic gradients, water quality, and the timing and magnitude of flows have changed as a result of water management. Numerous ecological investigations have been conducted focusing on vegetative changes as a result of anthropomorphic changes in surface water flow and water quality. However, groundwater studies have been limited. Harvey et al. (2000, 2002, 2005, 2006) investigated interactions between surface water and groundwater, including mercury concentrations, within WCA-2A and the Everglades Nutrient Removal Project area, approximately 8 miles north of WCA-2A. This report integrates the Harvey et al. studies with others describing the hydrogeology of the SAS in Palm Beach and Broward counties, including Causaras (1985), Fish (1988), and Reese and Wacker (2007, 2009).

A geophysical investigation was conducted to assess potential groundwater quality changes in WCA-2A over the past approximately 20 years. The study area is near the northeastern levee (L-39) and S-10C structure, between WCA-2A and WCA-1, where there have been major changes in vegetative communities related to distance from the levee and structure (Harvey et al. 2005). Geophysical logging was conducted by RMBaker LLC in September 2018 at four monitoring wells used in the Harvey et al. investigations to evaluate subsurface salinity changes from 1997/1999 to 2018.

2 SITE SETTING AND DESCRIPTION

The WCA-2A wetland encompasses approximately 105,000 acres in a remnant portion of the Florida Everglades and is part of the surface water flow system through South Florida towards the southeastern coastal areas, Florida Bay, and the Gulf of Mexico. The interior of WCA-2A is undeveloped and enclosed by the L-39 and L-6 levees to the north, the L-36 to the east, the L-35B to the south, and the L-38E to the west. WCA-1 is located to the northeast, the Everglades Agricultural Area and Stormwater Treatment Area 2 are to the northwest, WCA-3 is to the southwest, WCA-2B is to the south, and developed areas of Coral Springs and Parkland are to the east.

Surface water flows into WCA-2A from WCA-1 through the S-10A, S-10C, and S-10D structures on the L-39 levee and from the L-6 canal to the northwest via the G-336A through G-336F culverts. Surface water flows from WCA-2A into WCA-3 through the S-11A, S-11B, and S-11C structures; into WCA-2B through the S-144, S-145, and S-146 culverts; and into the L-36 canal through the S-38 culvert. The water surface in WCA-2A generally slopes towards the southwest on a grade similar to land-surface slope, except during water releases through structures when water can flow to the southeast (Harvey et al. 2002).

Average water level difference between WCA-1 and WCA-2A is -2.8 feet (ft) (Harvey et al. 2002). The largest and most rapid fluctuations in surface water level at WCA-2A, up to 4 ft, are caused by water releases from WCA-1 rather than precipitation and evapotranspiration. The largest vertical hydraulic gradient (groundwater) observed in WCA-2A is at the S-10C structure, which temporarily declines by a factor of three when the spillway is open.

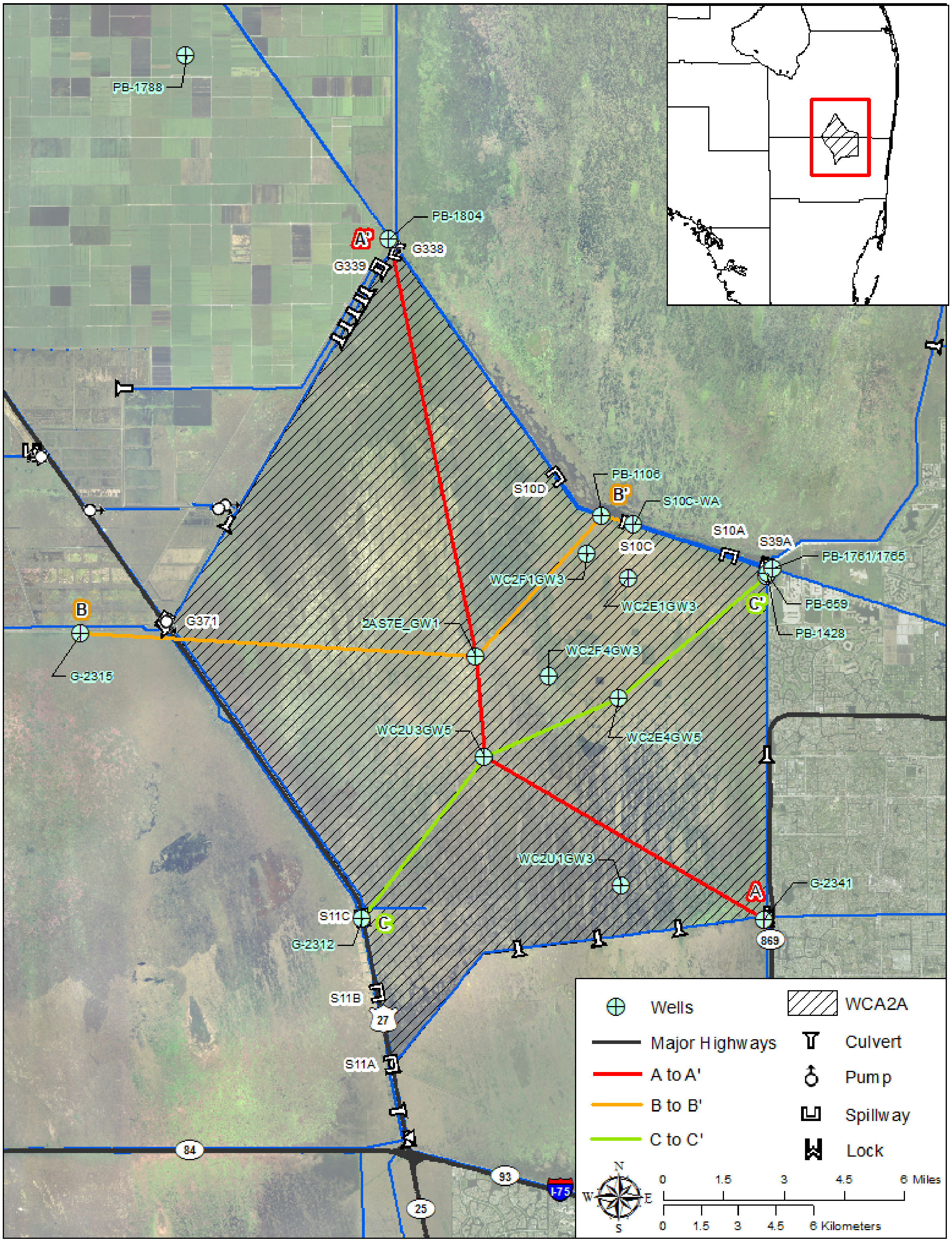

Figure 1. Site map of Water Conservation Area 2A, Palm Beach and Broward counties, Florida.

3 METHODS

The hydrogeologic framework described in this report is based on previous investigations, including Causaras (1985) and Fish (1988) in Broward County, Reese and Cunningham (2000) in Broward and Palm Beach counties, Harvey et al. (2000, 2002, 2005, 2006) in the interior of WCA-2A, and Reese and Wacker (2007, 2009) in Palm Beach County and South Florida. These investigations provided lithology, geophysical logging data, hydraulic test data, and hydrogeologic interpretations, including aquifer thicknesses and structural surfaces. The reviewed data were largely derived from boreholes advanced on the levees adjacent to WCA-2A. Harvey et al. (2000, 2002, 2005, 2006) provided data from wetland interior (WCA-2A) wells. A detailed discussion of data used from each report is presented in **Section 4**. Brief descriptions of the previous investigations reviewed for this study are provided below:

- Causaras (1985) and Fish (1988): The United States Geological Survey (USGS) conducted an extensive field program of SAS testing and water quality sampling from 1981 to 1984. Twenty-seven test wells were advanced in Broward County, including four wells (G-2312, G-2315, G-2341, PB-1428) along the perimeter of WCA-2A. Reverse-air drilling methods and geophysical logging were used to obtain representative samples for lithologic description and formation boundary delineation. Hydrologic observations were made of flow variations during drilling and at 10-ft depth intervals after completing each drill pipe length. Reverse-air pumping was conducted at 10-ft depth intervals to obtain sediment-free samples for water quality analysis. Previously available aquifer test data and specific capacity tests of production wells were compiled for estimation of hydraulic conductivity (K) and transmissivity (T). Hydrogeologic cross-sections showing lithology and K were provided.
- Reese and Cunningham (2000) mapped the extent of the Gray Limestone aquifer in southeastern Florida, including Broward and Palm Beach counties. In addition to previously collected data, 35 new test core holes were advanced, aquifer tests were conducted, and water quality data was obtained to describe the aquifer. The study used previously acquired data within and adjacent to WCA-2A to map the thickness, elevation, and transmissivity of the Gray Limestone aquifer and the thickness and leakance within the upper confining unit.
- Reese and Wacker (2007, 2009) described the hydrogeology of the SAS in Palm Beach County. A framework was developed that included three main permeable zones (from shallowest to deepest: PZ-1, PZ-2, and PZ-3) corresponding to lithostratigraphic intervals primarily defined by the natural gamma ray geophysical log signatures (GR markers). Structural contour and isopach maps as well as hydrogeologic cross-sections were provided.
- Harvey et al. (2000, 2002, 2005, 2006) investigated the SAS to quantify interactions between groundwater and surface water within WCA-2A and the Everglades Nutrient Removal Project area. Within WCA-2A, monitor well clusters were installed at seven wetland sites: WC2F1, WC2F4, WC2E1, WC2E4, WC2U1, WC2U3, and 2AS7E. An additional monitor well cluster, S10C, was installed on the L-39 Canal, adjacent to the S-10C structure between WCA-1 and WCA-2A. The deepest borehole at four sites (WC2E4, WC2U3, 2AS7E, and S10C) were continuously sampled using split-spoon and core sampling for unconsolidated and consolidated sediments, respectively, followed by geophysical logging. Hydraulic properties were estimated via seepage meter analysis, steady-state air permeability tests on limestone cores, field drawdown and bail tests, and grain-size analysis.

Hydrogeologic data from the referenced reports were incorporated into three SAS cross-sections across WCA-2A (**Section 4**). Construction details of levee and wetland monitor wells referenced for cross-section development are shown in **Table 1**.

Table 1. Monitor wells referenced for hydrogeologic cross-sections in this report.

Well Name	County	Latitude (DMS)	Longitude (DMS)	Location (relative to WCA-2A)	Land Surface Elevation (NGVD29)	Drilled Depth[a]	Screen or Open Hole Interval[a]	Diameter (inches)	Geophysical Logs Run
Levee Wells									
G-2312	Broward	26 13 47	80 27 37	L-38 (South)	15	229	207-217	2	No
G-2315	Broward	26 19 58	80 34 21	West of W Corner	20	249	225-235	2	Yes
G-2341	Broward	26 13 43	80 17 58	Cypress Creek Canal (SE Corner)	12	209	126-136	2	No
PB-1106	Palm Beach	26 22 28	80 21 49	Hillsboro Canal (L-39)	23	221	120-130	2	Yes
PB-1428	Palm Beach	26 21 09	80 17 51	Hillsboro Canal (L-39)	13	219	176-188	2	No
PB-1761/ 1765/1803[b]	Palm Beach	26 21 19	80 17 42	Hillsboro Canal (L-39)	10	120	ND	ND	Yes
PB-1804	Palm Beach	26 28 29	80 26 54	North Corner, S-6 Pump Station	12	230	38-188	4	Yes
Interior Wetland Wells									
2AS7E-GW1	Broward	26 19 26	80 24 51	Interior	10	125	123-125	2	Yes
S10C-WA	Palm Beach	26 22 17	80 21 03	Hillsboro Canal (L-39)	22	101	99-101	2	Yes
WC2E4-GW5	Broward	26 18 32	80 21 25	Interior	12	125	123-125	2	Yes
WC2U3-GW5	Broward	26 17 16	80 24 40	Interior	11	125	123-125	2	Yes

DMS = degrees, minutes, seconds; ND = no data; NGVD29 = National Geodetic Vertical Datum of 1929.
[a] All depths in feet below land surface.
[b] PB-1761/1765/1803 – three wells co-located.

A geophysical investigation was conducted as part of this study to assess subsurface salinity changes over the past approximately 20 years. Geophysical logging was conducted by RMBaker LLC at each deep well in four well clusters: 2AS7E, WC2E4, WC2U3, and S10C (adjacent to the S-10C structure). Chloride samples also were collected for correlation and development of modeled chloride curves. Modeled chloride curves were developed using geophysical log and sample data from the same wells acquired from 1997 through 2000. A detailed discussion of methodology and results is provided in **Section 5**.

4 SITE HYDROGEOLOGY

4.1 Lithostratigraphic Framework

Lithostratigraphic units within the SAS in WCA-2A, in descending order, include unconsolidated recent and Holocene sediments peat and marl; the Pleistocene Fort Thompson and Anastasia formations; and the Pleistocene Tamiami Formation, composed of the Pinecrest Sand and Ochopee Limestone members. Pleistocene Pamlico Sand, Miami Limestone, and Caloosahatchee Marl were not identified within WCA-2A in reviewed publications and are not represented in this report. The SAS is underlain by the intermediate confining unit, composed of the Peace River formation of the Miocene Hawthorn Group. Reese and Wacker (2007, 2009) identified four lithostratigraphic correlation markers based primarily on GR markers and secondarily on lithologic characteristics. The GR markers approximate the following lithostratigraphic boundaries: F – within the upper part of the Fort Thompson and Anastasia formations; T – top of the Tamiami Formation (Pinecrest Sand member); O – top of the Ochopee Limestone; and H – top of the Hawthorn Group. Formations and hydrogeologic units included in this report are presented in **Figure 2** and as cross-sections in **Figures 3** to **5**.

Series	Lithostratigraphic Unit		Lithology	Correlation Marker	Hydrogeologic Unit(s)	
Holocene	Peat and Lake Flirt Marl		Peat, marl, organic soil, quartz sand		Surficial Aquifer System	Semi-confining unit
Pleistocene	Fort Thompson Formation		Loosely cemented shell and shell fragments, marine limestone and minor gastropod-rich freshwater limestone, quartz sandstone and sandy limestone	F		Permeable zone 1 and semi-confining units
		Anastasia Formation	Coquina, shell, quartz sand, and sandy limestone			
Pliocene	Tamiami Formation	Pinecrest Sand Member	Quartz sand, pelecypod-rich freshwater limestone, shell, terrigenous sediments, local abundant phosphate grains	T		Permeable zone 2 and semi-confining units
		Ochopee Limestone Member	Pelecypod lime rudsone and floatestone, pelecypod-rich quartz sand and sandstone, moldic quartz sandstone	O		Permeable zone 3 and semi-confining units
Late to Middle Miocene	Hawthorn Group	Peace River Formation	Quartz and, sandstone,clay-rich quartz sand, silt, marl, terrigenous mudstone or clay, diatomaceous mudstone, local abundant phosphate grains	H	Intermediate Confining Unit	

Figure 2. Lithostratigraphic and hydrogeologic units identified in Water Conservation Area 2A (Adapted from: Reese and Wacker 2009).

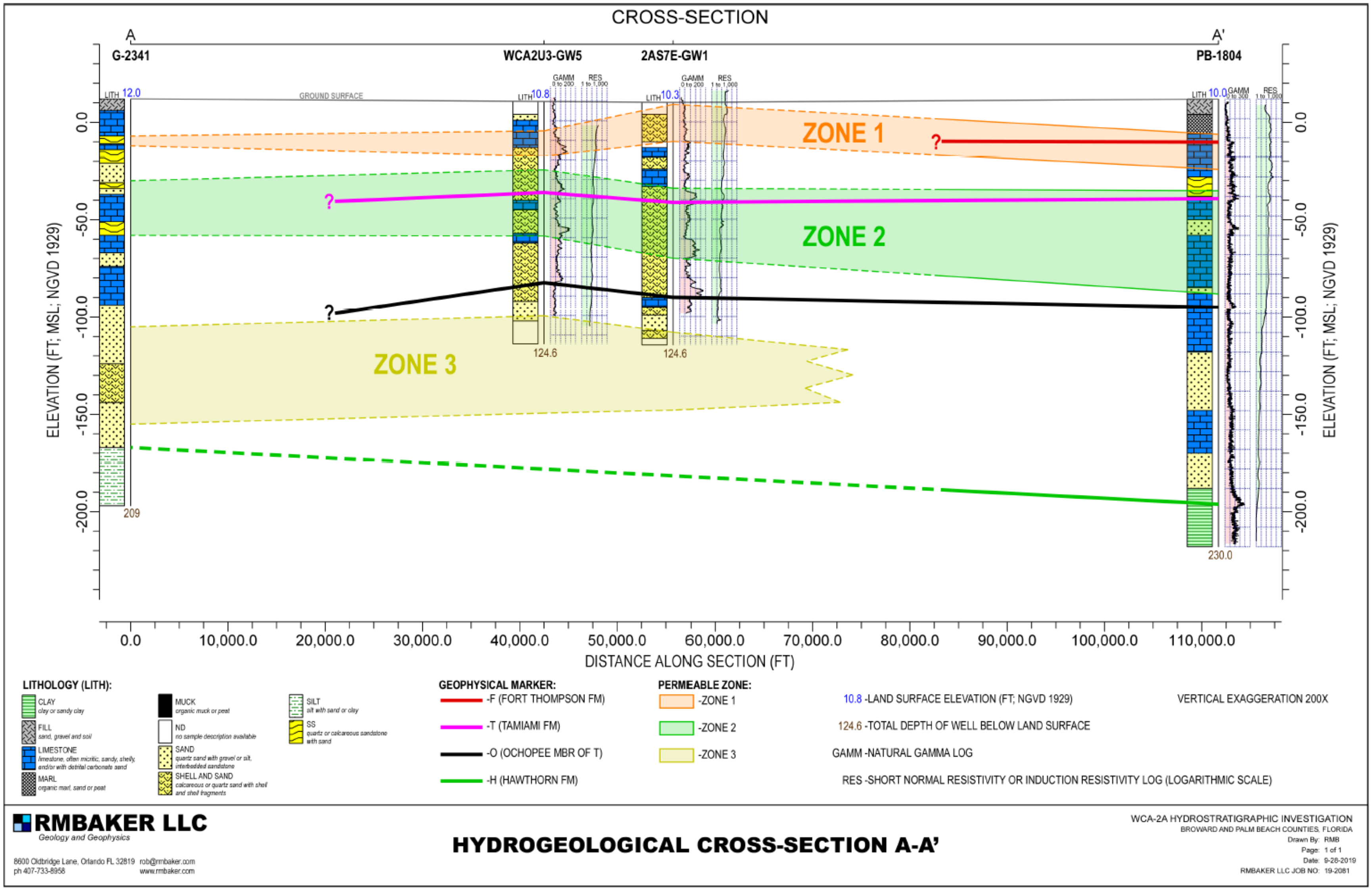

Figure 3. Hydrogeologic cross-section A-A' showing permeable zones, lithology, and gamma ray and resistivity log curves.

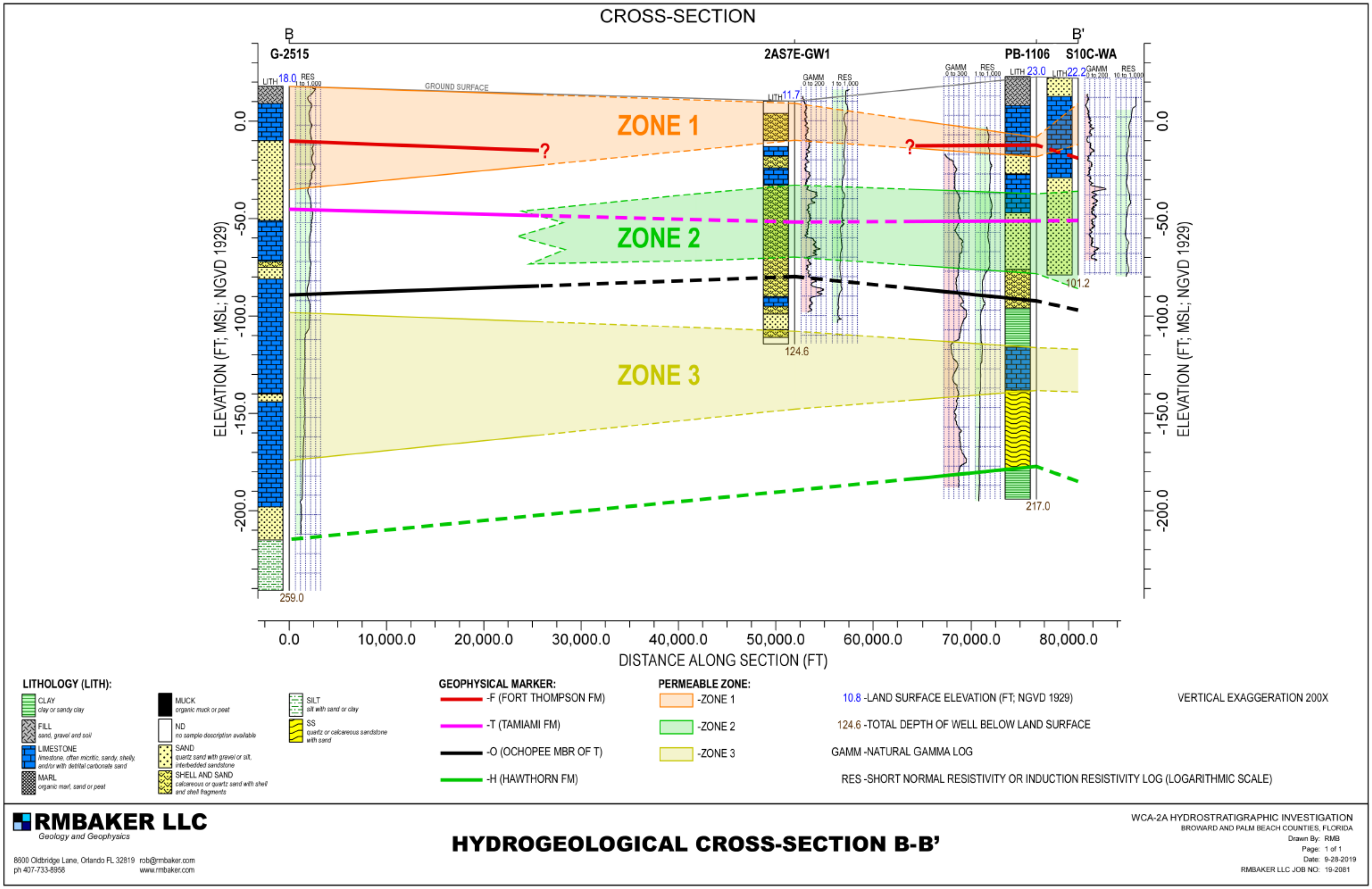

Figure 4. Hydrogeologic cross-section B-B' showing permeable zones, lithology, and gamma ray and resistivity log curves.

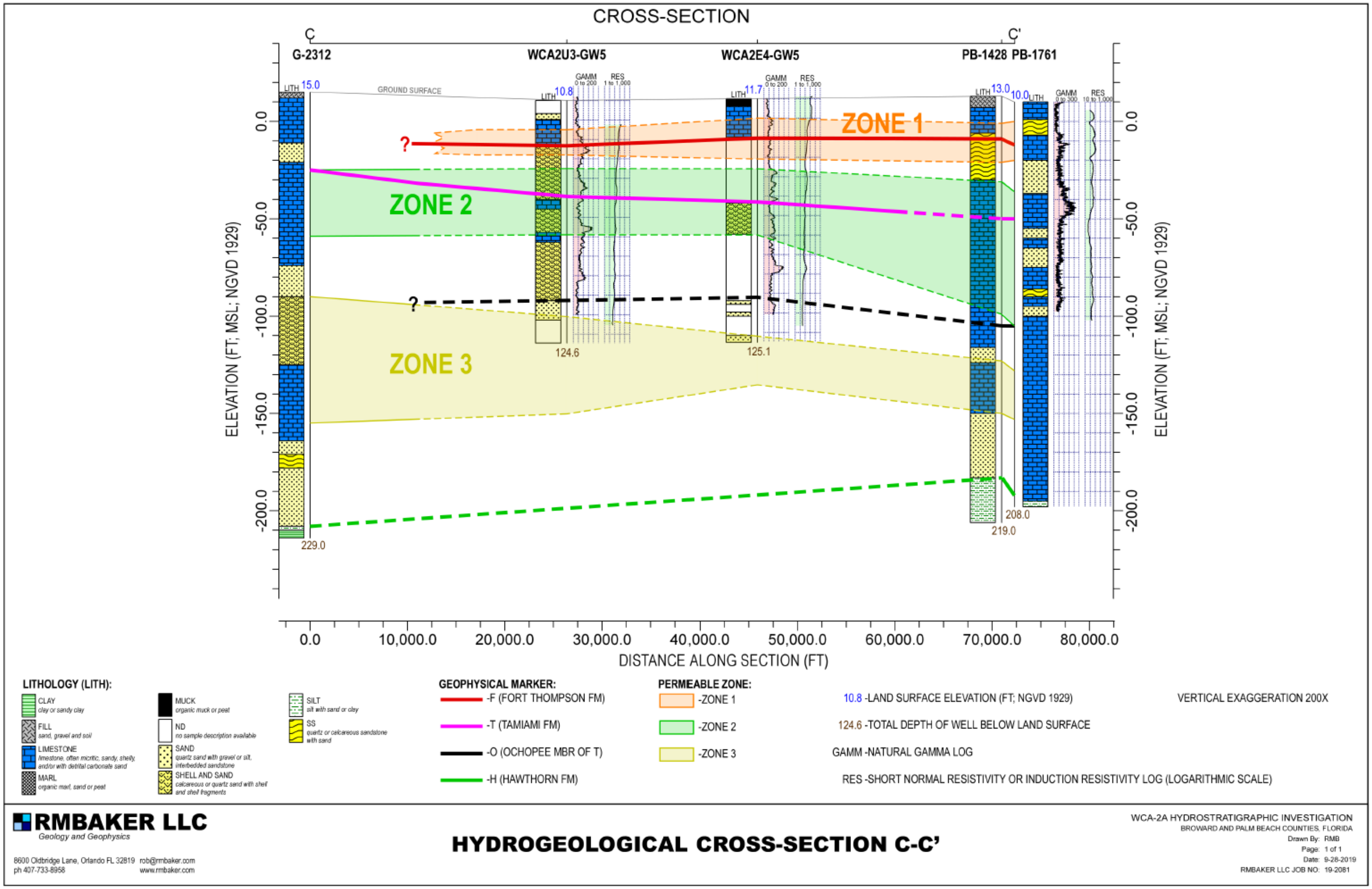

Figure 5. Hydrogeologic cross-section C-C' showing permeable zones, lithology, and gamma ray and resistivity log curves.

Peat (Recent) and Undifferentiated Sand, Soil, and Marl (Holocene to Pleistocene)

Peat (recent) and Holocene to Pleistocene sand, soil, and marl are present in the subsurface beneath wetland areas. Harvey et al. (2002) estimated an average thickness of 2.3 ft of peat underlain by 1 ft of marly sand and sand within WCA-2A, including the marl and sand sediments within the Lake Flirt Marl.

Fort Thompson Formation (Pleistocene)

The Fort Thompson Formation consists of alternating beds of marine limestone and minor gastropod-rich freshwater limestone, quartz sandstone, and sandy limestone. Within WCA-2A, the Fort Thompson Formation extends from Holocene peat and marl to the top of the Pinecrest Sand member of the Tamiami Formation. It is estimated to be up to 55 ft thick within WCA-2A. The formation grades laterally to the east and, in some places, is interbedded with the Anastasia Formation within the southeastern part of WCA-2A. The Fort Thompson Formation includes the upper permeable zone of the SAS (PZ-1) and semi-confining units.

Anastasia Formation (Pleistocene)

The Anastasia Formation consists of alternating offshore bar, beach ridge, and dune system deposits and is contemporaneous with the Fort Thompson Formation (Harvey et al. 2002). It grades laterally to the west and, in some places, is interbedded with the Fort Thompson Formation. Although the lithostratigraphic framework presented by Reese and Wacker (2009) does not differentiate between the Fort Thompson and Anastasia formations, Fish (1988) described up to 100 ft of shelly sand, sandstone, and shelly limestone designated as Anastasia Formation lateral equivalents interbedded with limestone of the Fort Thompson Formation in eastern wells PB-1428 and G-2341, pinching out towards the west. The Anastasia Formation includes the upper permeable zone of the SAS (PZ-1) and semi-confining units.

Tamiami Formation (Pliocene)

The Tamiami Formation includes the Pinecrest Sand and underlying Ochopee Limestone members:

- The Pinecrest Sand member consists of quartz sand, pelecypod-rich quartz sandstone and sandy limestone, shell, and terrigenous mudstone, with locally abundant phosphate grains. Based on the depths of the O and T markers, this member is up to 60 ft thick and occurs between approximately -25 and -57 ft National Geodetic Vertical Datum of 1929 (NGVD29) in WCA-2A. The Pinecrest Sand member includes the middle permeable zone of the SAS (PZ-2) and semi-confining units.
- The Ochopee Limestone member consists of pelecypod lime rudstone and floatstone, pelecypod-rich quartz sand and sandstone, and moldic quartz sandstone. Based on the depths of the O and H markers, the member is up to 130 ft thick and occurs between approximately -80 and -105 ft NGVD29 in WCA-2A. The Ochopee Limestone member includes the lower permeable zone of the SAS (PZ-3) and semi-confining units.

Hawthorn Group/Peace River Formation (Miocene)

The Peace River Formation of the Hawthorn Group is the lower confining unit for the SAS. It consists of clay-rich quartz sand, silt, marl, clay, quartz sand, and sandstone, with locally abundant phosphate grains. Based on the depth of the H marker in WCA-2A, the top of the Hawthorn Group occurs between approximately -170 and -200 ft NGVD29.

4.2 Hydrogeologic Units

The hydrogeologic framework of the SAS described in this report is based on Reese and Wacker (2007, 2009), which named the three main permeable zones: PZ-1, PZ-2, and PZ-3. The term “Biscayne aquifer” is not used in this report because referenced reports limit its extent south and east of WCA-2A. Swayze and Miller (1984) mapped the westernmost extent of the Biscayne aquifer in Palm Beach County approximately 3 miles east of WCA-2. Fish (1988) showed the Biscayne aquifer thinning and pinching out towards the northwest near WCA-2A. Permeability in WCA-2A, as identified in this study, does not satisfy the definition of the Biscayne aquifer provided by Fish (1988), as including a thickness of at least 10 ft of highly permeable strata (K of 1,000 ft/day or more). Reese and Wacker (2009) expanded on Fish’s (1988) work and provided isopach and structural contour maps showing elevation and thickness of permeable zones and interbedded semi-confining units within Palm Beach and Broward counties. Cross-sections showing hydrogeologic units, including permeable zones, semi-confining zones, and confining zones, are shown in **Figures 3** to **5**, and are based on interpolation from Reese and Wacker (2009) for levee monitor wells and Harvey et al. (2000) for wetland monitor wells.

PZ-1 is within the Fort Thompson Formation or the laterally equivalent Anastasia Formation. PZ-1 typically occurs below or within the “F” GR marker and is located at or near the surface (commonly called the water table aquifer). Thickness varies from 20 to 50 ft in the northern and central portions of WCA-2A, to 4 ft in the southeastern portion (G-2341), to not present in the southwestern portion (G-2312). Reese and Wacker (2009) described the lithology of PZ-1 as cemented or loosely cemented shell and shell fragments with high intergranular porosity and permeability. Vuggy limestone or calcareous sandstone also may be present. The overlying, semi-confining peat, sand, soil, and marl layer above PZ-1 is approximately 2 ft thick.

PZ-2 is within the Pinecrest Sand member of the Tamiami Formation, approximately -10 to -35 ft NGVD29. It ranges from 20 to 55 ft thick, except where it pinches out near the western portion of WCA-2A. Lithology of PZ-2 is shelly, highly permeable, well cemented gray limestone and calcareous, quartz-rich sandstone. Large pore spaces are common, and the aquifer often is characterized as “solution riddled”, or as having interconnected vugs or cavities. Interbedded layers of loose quartz sand also are common. PZ-2 is separated from PZ-1 by 6 to 18 ft of semi-confining strata. Overlying and lateral sediments consist of fine to medium sand, hard sandstone and limestone, and sandy marl or clay.

PZ-3 is within the Ochopee Limestone member of the Tamiami Formation and is equivalent to the Gray Limestone aquifer within WCA-2A (Reese and Cunningham 2000). It typically occurs below the “O” GR marker, approximately -90 to -130 ft NGVD29 and varies in thickness from 60 ft in the southern portion of WCA-2A to pinching out in the northern portion. Lithology is commonly gray, sandy lime rudstone or floatstone; calcareous, quartz-rich sandstone; and quartz or carbonate sand. Porosity within PZ-3 is primarily intergranular and moldic with locally distributed solution-enlarged pore spaces. PZ-3 is separated from PZ-2 by 20 to 50 ft of semi-confining strata consisting of limestone, shelly sand, and sand. Approximately 20 ft of clay overlies PZ-3 at PB-1106 in the northeastern portion of WCA-2A, suggesting confinement.

4.3 Hydraulic Properties

Hydraulic property estimates presented in this report are based on regional estimates from Fish (1988) and Reese and Wacker (2009) as well as site-specific tests of interior wetland monitor wells from Harvey et al. (2000, 2002, 2005). Fish (1988) provided hydraulic property estimates in Broward County based on calculation of specific capacities of municipal supply wells, aquifer test results from previous reports, and aquifer and laboratory testing conducted as part of the 1981 to 1984 USGS field program. K was illustrated on eight geologic cross-sections as vertically delineated zones characterized as very low (≤0.1 ft/day), low

(0.1 to 10 ft/day), moderate (10 to 100 ft/day), high (100 to 1,000 ft/day), and very high (≥1,000 ft/day). Wells/borings along the perimeter of WCA-2A included G-2312, G-2315, G-2341, PB-1428.

Reese and Wacker (2009) expanded on Fish's (1988) work and provided maps showing transmissivity estimates of permeable zones within Palm Beach and Broward counties. K estimates herein are based on transmissivity and aquifer thicknesses presented in their report. Reese and Wacker (2009) summarized aquifer performance test (APT) results, including previous testing programs, and geophysical flow-log analysis for wells along the perimeter levees of WCA-2A. APTs were conducted at four sites on levees surrounding WCA-2A: S10C-WA (PZ-1 and PZ-2), G-2312 (PZ-2 and PZ-3), PB-1804 (PZ-2), and PB-1761 (PZ-3). Flowmeter and fluid property logs within PZ-1 were analyzed at PB-1761, identifying one flow zone from 17 to 23 ft below land surface (bls). Flowmeter and fluid property logs within PZ-2 were analyzed at two sites: five distinct flow zones from 47 to 103 ft bls were identified at PB-1761 and three distinct zones from 45 to 100 ft bls were identified at PB-1804. K ranges for permeable zones within WCA-2A and APT results of perimeter wells are shown in **Table 2**. Transmissivities and K based on individual well tests are shown in **Table 3**.

Table 2. Comparison of regional hydraulic conductivity ranges and average aquifer performance test results of perimeter wells adjacent to Water Conservation Area 2A within hydraulic zones.

Hydrogeologic Unit	K Ranges (ft/day)		Aquifer Performance Test Results*
	Prevailing K (Fish 1988)	K Estimates (Reese and Wacker 2009)	K (ft/day) – Aquifer Test Average (Number of Tests)
PZ-1	High (100 to 1,000)	200 to 500	122 (1)
PZ-2	High (100 to 1,000)	500 to 1,000	609 (3)
PZ-3	High (100 to 1,000)	200 to 500	384 (2)
Interbedded and Semi-confining	Low to Moderate (0.1 to 100)	N/A	N/A
Confining	Very Low (≤0.1)	N/A	N/A

ft = foot; K = hydraulic conductivity; N/A = not applicable, no tests were run.
* Based on aquifer thicknesses in report.

Table 3. Transmissivity and hydraulic conductivity derived from aquifer performance tests of Permeable Zones 1, 2, and 3 at perimeter wells.

Permeable Zone	Well	Thickness of Total Interval Tested (ft)	Transmissivity (ft^2/day)	K (ft/day)	Average K per Zone (ft/day)
PZ-1	S10C-WA	32	3,900	122	122
PZ-2	S10C-WA	72	12,000	167	609
PZ-2	G-2312	22	9,000	409	
PZ-2	PB-1804	48	60,000	1,250	
PZ-3	G-2312	34	22,000	647	384
PZ-3	PB-1761*	25	3,000	120	

ft = foot; K = hydraulic conductivity.
* Based on total test interval tested (From: Reese and Wacker 2009, Table 1-9B).

Harvey et al. (2000, 2002, 2005) conducted investigations at seven wetland sites and one levee site (S10C) within and adjacent to WCA-2A. Hydraulic properties, including horizontal hydraulic conductivity (K_h) and vertical hydraulic conductivity (K_v), were estimated using bail tests and seepage meter analysis (for peat), steady-state air permeability tests of cores, field drawdown tests, and sieve analysis.

- K of wetland peat was estimated by two methods: 1) calculation of K from Darcy's law using seepage meter flux measurements and vertical hydraulic gradients, and 2) bail tests in piezometers installed in the peat. According to Harvey et al. (2000), if the peat is anisotropic, then the seepage meter-based analysis would be more likely to estimate K_v and the bail tests more likely to estimate K_h. If isotropic, then the two methods are equivalent. The Darcy's law estimates were based on eight measurements taken at four sites: WC2E4, WC2F1, WC2F4, and WC2U3. Seven bail tests were conducted at the same four sites. Average K was 1.0 and 1.4 ft/day for the seepage meter and bail test methods, respectively (Harvey et al. 2005).
- Steady-state air permeability tests and porosity analyses were conducted on 11 core samples from 5 sites: WC2E1, WC2F1, WC2U1, WC2U3, and S10C. Each sample was predominantly limestone, eight were representative of PZ-1 and three were representative of the semi-confining unit above or below PZ-1. For PZ-1, average K_h and K_v at each site was 241 and 87 ft/day, respectively, and average porosity was 22%. For the semi-confining unit, average K_h and K_v was 19 ft/day for each, and average porosity was 19%. Results for core sample analysis are shown in **Table 4**.
- Fifteen field drawdown tests were conducted at seven sites: WC2E1, WC2E4, WC2F1, WC2F4, WC2U1, WC2U3, and S10C. Tests at all seven sites included PZ-1 and one site, S10C, included PZ-2. The tests consisted of pumping drawdown to depths of 5 ft or more and recording recovery rates. The average K_h per site was 212 ft/day for PZ-1 and 169 ft/day for PZ-2. One test interval was determined to be in the semi-confining unit above PZ-1, with an average K_h of 65 ft/day. Results for field drawdown tests are shown in **Table 5**.
- Sieve analysis of split-spoon samples from monitor wells at S10C were used to estimate K_v and K_h of unconsolidated sediments. The software program MVASKF used 10 equations and grain-size statistics to produce 10 values, which were then arithmetically averaged. A K_h value for the entire set of results was calculated using equations developed by Todd (1980). Twenty-three samples were collected and considered representative of PZ-2 and yielded average K_h and K_v results of 21 and 17 ft/day, respectively. Based on test data from other sources, these results are considered outliers and are not included in hydraulic summaries in this report.

Table 4. Hydraulic conductivity from laboratory core analyses within and adjacent to Permeable Zone 1 (From: Harvey et al. 2002).

Well Name	Sample Elevation (ft NGVD29)	Hydraulic Zone	K_h (ft/day)	K_v (ft/day)	Porosity (%)	Lithologic Description
S10C-WA	-13.6 to -18.6	Below PZ-1	4.1*	8.3*	25*	Limestone, slightly sandy, pin-point porosity
S10C-WA	-7.6 to 12.6	PZ-1	85	16	24	Limestone, fossils, very sandy, pin-point porosity
Average S10C-WA Test Results			**85**	**16**	**24**	
WC2U1-GW3	5.9 to 0.9	PZ-1	61	26	17	Limestone, fossils, sandy, moldic
WC2U1-GW3	-4.1 to -9.1	PZ-1	45	6.1	19	Fine sand
Average U1-GW3 Test Results			**52**	**16**	**18**	
WC2E4-GW3	12.0 to 7.0	Above PZ-1	29*	40*	17*	Limestone, fossils, sandy, limonite
WC2E4-GW3	2.0 to -3.0	PZ-1	450	430	25	Limestone, fossils, sandy, slightly moldic
WC2E4-GW3	-3.0 to -8.0	PZ-1	4.6	16	11	Limestone, some sand, some fractured
Average E4-GW3 Test Results			**227**	**223**	**18**	
WC2F4-GW3	11.5 to 6.5	PZ-1	180	7.5	22	Limestone, sandy, slightly moldic, limonite
WC2F4-GW3	1.5 to -3.5	PZ-1	500	90	19	Limestone, fossils, sandy, pin-point porosity
Average F4-GW3 Test Results			**340**	**49**	**21**	
WC2U3-GW3	1.2 to -3.8	Above PZ-1	24*	8.5*	14*	Limestone, fossils, slightly sandy
WC2U3-GW3	-8.8 to -13.8	PZ-1	500	130	31	Limestone, fossils, slightly sandy
Average U3-GW3 Test Results			**500**	**130**	**31**	
Average of Tests within PZ-1			**241**	**87**	**22**	

ft = foot; NGVD29 = National Geodetic Vertical Datum of 1929; PZ = Permeable Zone.
* Not included in permeable zone average.

Table 5. Results of field drawdown tests within and adjacent to permeable zones (From: Harvey et al. 2000).

Well Name	Test Interval (ft NGVD29)	Permeable Zone	K_h (ft/day)	Average K_h per Site (ft/day)
WC2E1-GW3	-7.17 to -9.17	PZ-1	211	173
WC2E1-GW4	4.36 to 2.36	PZ-1	134	
WC2E4-GW3	-4.41 to -6.41	PZ-1	93	87
WC2E4-GW4	7.58 to 5.58	PZ-1	80	
WC2F1-GW3	-13.99 to -15.99	PZ-1	166	112
WC2F1-GW4	3.83 to 1.83	PZ-1	58	
WC2F4-GW3	-9.92 to -11.92	PZ-1	58	87
WC2F4-GW4	6.52 to 4.52	PZ-1	116	
S10C-C	-7.83 to -9.83	PZ-1	47	47
WC2U1-GW3	-10.11 to -12.11	PZ-1	1,261	647
WC2U1-GW4	-2.58 to -4.58	PZ-1	32	
WC2U3-GW3	-14.97 to -16.97	PZ-1	205	135
WC2U3-GW4	7.89 to 5.89	Above PZ-1	65*	
PZ-1 Average				**205**
S10C-WA	-77.18 to -79.18	PZ-2	130	169
S10C-WB	-39.67 to -41.67	PZ-2	208	
PZ-2 Average				**169**

ft = foot; NGVD29 = National Geodetic Vertical Datum of 1929; PZ = Permeable Zone.
* Not included in permeable zone average.

5 GEOPHYSICAL SALINITY INVESTIGATION

5.1 Purpose

A geophysical model was developed to estimate salinity changes in the upper SAS based on geophysical and chloride sample collection from 1997 through 2000 and in 2018. The study area includes the eastern portion of WCA-2A, from the L-39 levee and S-10C structure to approximately 1 mile north of the L-35N levee, which borders the southeastern side of WCA-2A (**Figure 6**). Surface water recharge and groundwater flow beneath WCA-2A and WCA-1 (north of the L-39 levee) have been modified from pre-development conditions, at least in part due to a water level increase at WCA-1 relative to WCA-2A, and flow through three structures (S-10A, S-10C, and S-10D) on the L-39 levee. Major changes in vegetative communities south of the levee have been observed (Harvey et al. 2005).

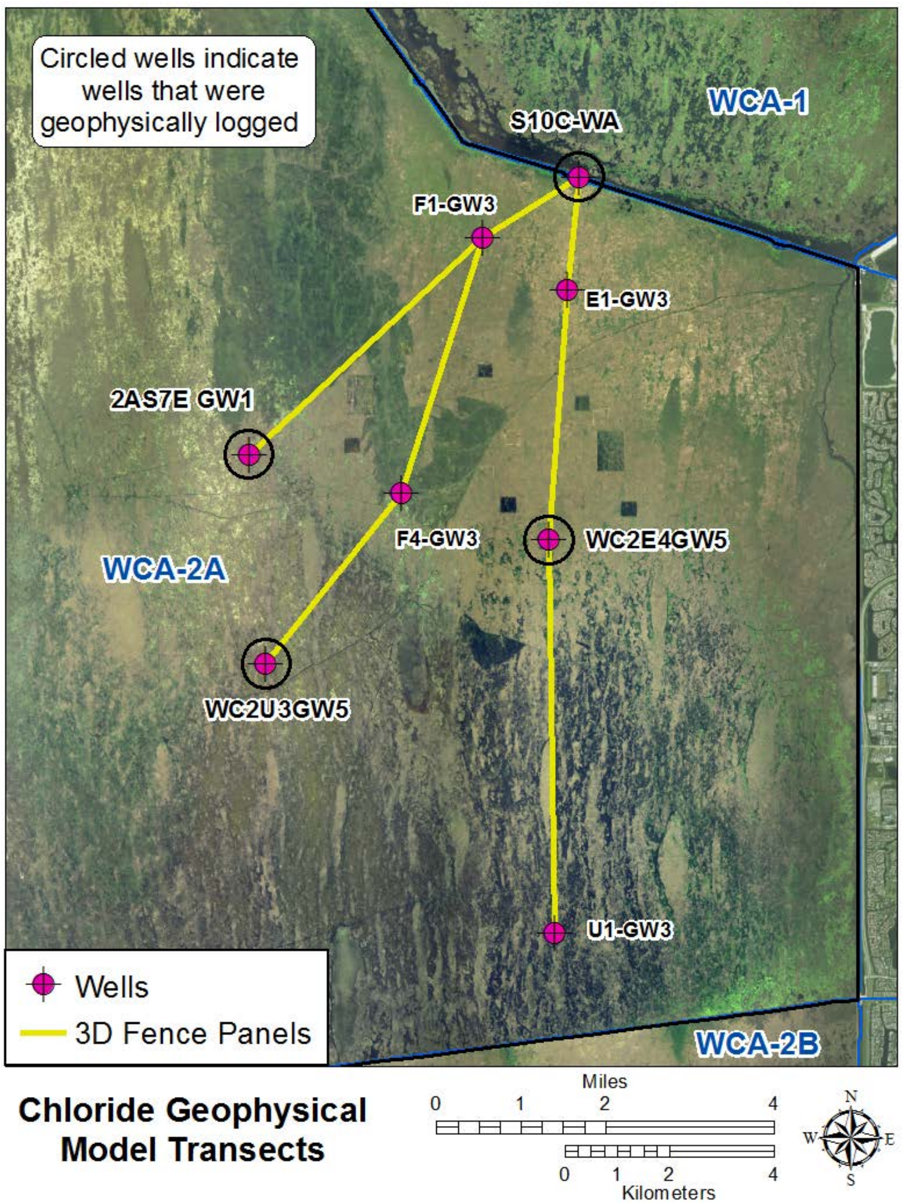

Figure 6. Monitor wells included in the geophysical salinity investigation.

5.2 Methods

Geophysical logging data and chloride concentrations from 1997 to 2000 were reviewed for three monitor well clusters within the wetland interior of WCA-2A, and one monitor well cluster adjacent to the S-10C structure. Resistivity logs acquired in 1997 and 1999 from the deepest well at each cluster were correlated with the chloride concentration data to model estimated chloride concentrations for the saturated interval of each monitor well. A geophysical logging event in September 2018 was conducted at the deep well at each station, followed by a chloride analysis from a water quality sample from the same well, to develop an independent model for each cluster representative of 2018. The 1997/1999 and 2018 chloride curves were compared to identify chloride concentration changes over the saturated interval of the monitor well. Additional chloride concentrations from four shallow monitor wells that were not geophysically logged are included to further characterize subsurface salinity in the study area contemporaneous with geophysical logging in 1997/1999. Construction details for monitor wells used in this study are provided in **Table 6**.

Table 6. Construction information for monitor wells used in the geophysical salinity investigation.

Well Name	Well Installation Date	Latitude (DMS)	Longitude (DMS)	Muck (Ground) Elevation	Top of Casing (ft NGVD29)	Depth from Top of Casing (ft)	Screen Length (ft)	Well Construction Material
Deep Well Clusters								
WC2E4-GW3	12/05/96	26 18 32	80 21 25	11.97	17.29	23.70	2.0	1.5-inch PVC
WC2E4-GW4	12/06/96	26 18 32	80 21 25	11.97	17.28	13.70	2.0	1.5-inch PVC
WC2E4-GW5	10/27/99	26 18 31	80 21 26	11.97	17.74	125.10	2.0	2-inch PVC
WC2E4-GW6	10/29/99	26 18 31	80 21 26	11.97	17.74	64.33	2.0	2-inch PVC
WC2E4-GW7	10/29/99	26 18 31	80 21 26	11.97	17.58	36.54	2.0	2-inch PVC
WC2E4-GW8	11/06/99	26 18 31	80 21 26	11.97	17.56	21.38	2.0	2-inch PVC
2AS7E-GW1	11/11/99	26 19 26	80 24 51	10.19	16.43	124.55	2.0	2-inch PVC
2AS7E-GW2	11/12/99	26 19 26	80 24 51	10.19	16.45	65.25	2.0	2-inch PVC
2AS7E-GW3	11/12/99	26 19 26	80 24 51	10.19	16.46	35.52	2.0	2-inch PVC
2AS7E-GW4	11/13/99	26 19 26	80 24 51	10.19	16.43	20.57	2.0	2-inch PVC
WC2U3-GW3	12/08/96	26 17 14	80 24 42	11.16	17.23	34.20	2.0	1.5-inch PVC
WC2U3-GW5	11/22/99	26 17 14	80 24 42	11.16	18.38	124.60	2.0	2-inch PVC
WC2U3-GW7	11/23/99	26 17 14	80 24 42	11.16	18.38	64.50	2.0	2-inch PVC
WC2U3-GW3	11/17/99	26 17 14	80 24 42	11.16	18.28	36.45	2.0	2-inch PVC
WC2U3-GW8	11/18/99	26 17 14	80 24 42	11.16	18.25	20.10	2.0	2-inch PVC
S10C-WA	03/12/97	26 22 15	80 21 04	22.41	23.15	101.39	2.0	2-inch PVC
S10C-WB	03/13/97	26 22 15	80 21 04	23.12	22.41	64.59	2.0	2-inch PVC
S10C-WC	03/14/97	26 22 15	80 21 04	21.84	21.84	31.47	2.0	2-inch PVC
Shallow Well Clusters								
WC2E1-GW3	12/02/96	26 21 04	80 21 15	12.50	18.03	27.20	2.0	1.5-inch PVC
WC2F1-GW3	12/11/96	26 21 38	80 22 10	11.92	17.96	33.95	2.0	1.5-inch PVC
WC2F4-GW3	12/04/96	26 18 60	80 23 07	11.53	17.38	29.30	2.0	1.5-inch PVC
WC2U1-GW3	12/05/96	26 14 26	80 21 21	10.87	16.79	28.90	2.0	1.5-inch PVC

DMS = degrees, minutes, seconds; ft = foot; NGVD29 = National Geodetic Vertical Datum of 1929; PVC = polyvinyl chloride.

Data Acquisition from 1997 through 2000

Geophysical data consisting of gamma ray and induction resistivity logs, representative of the upper approximately 125 ft of the SAS, were used to generate model curves. The monitor wells were installed by the USGS and the South Florida Water Management District in multiple phases between 1997 and 1999. Geophysical logging was conducted in uncased boreholes in March 1997 at S10C-WA and in October and November 1999 at the three wetland sites (2AS7E-GW1, WC2E4-GW5, and WC2U3-GW5). Boreholes were advanced by rotary drilling, and lithology samples were collected using standard penetration test (SPT) technology for unconsolidated sediments and wire-line coring for consolidated rock. Monitor wells were constructed with 2-inch diameter casings and 2-ft long well screens. Stainless steel centralizers were installed at 15- to 20-ft intervals starting just above the screen interval. The wetland monitor wells are continually submerged and accessed by docks with aboveground polyvinyl chloride (PVC) stick-ups.

Chloride data were obtained from the vertically integrated wells at each well cluster: 2AS7E-GW1 through GW4; WC2E4-GW5 through GW8; WC2U3-GW5 through GW8; and S10C-WA through WC, with well screens between approximately 14 and 125 ft below the top of the casing. The nearest complete sample set to the date of the well logging was used for correlation with geophysical data. For wells at clusters 2AS7E, WC2E4, and WC2U3, installed in October and November 1999, the average of three events conducted from January through September 2000 were used (Harvey et al. 2005). For monitor wells at S10C, installed in 1997, the average of two sample events conducted in January and April 2000 was used (Harvey et al. 2005). Samples were collected 2 to 10 months after well completion for the 3 wetland sites and approximately 3 years after completion for S10C-WA. Additional historical chloride data were obtained for shallow monitor wells at four sites (WC2E1-GW3, WC2F1-GW3, WC2F4-GW3, and WC2U1-GW3) to further characterize historical groundwater conditions.

Data Acquisition in 2018

Geophysical logging and sampling were conducted by RMBaker LLC on September 25 and 26, 2018 at monitor wells 2AS7E-GW1, WC2E4-GW5, WC2U3-GW5, and S10C-WA. A portable wireline system with an integrated and calibrated depth encoder was used to troll a Robertson Geologging Ltd. slimline dual-induction sonde within each tested monitor well. The cased-hole resistivity logs were composed of shallow (20-inch) and deep (32-inch) bulk formation induction resistivity measurements, combined with a natural gamma sensor. The 2018 geophysical logging events were conducted within PVC-cased monitor wells with slotted screens in the bottom 2 ft. Induction resistivity logs were the only resistivity logs that could be performed through existing PVC casing. Prior to field deployment, the dual-induction sonde was bench tested using a calibration coil to confirm suitable measurement precisions were possible with the existing system calibration. Tests for both resistivity data channels were within an acceptable 3% of the calibration value, so a recalibration was not necessary.

The sonde was lowered to the bottom of each cased monitor well, and the total depth was recorded. The total well depths at the time of logging in 2018 typically were within 0.5 ft of the reported depth relative to the surveyed top-of-casing reference elevation. Geophysical logging measurements were performed while rolling the sonde upward from the bottom at a speed of approximately 20 ft per minute. The position of each sensor (vertical offset) from the tip of the sonde often was shallower than the top of the screened interval, sometimes pushed even higher by fine sands accumulated at the bottom of the well. The deepest data points from the logs were used to correlate to the water sample chloride data (referenced to mid-point of screened interval).

Groundwater samples were collected from each deep monitor well after geophysical logging and submitted to the South Florida Water Management District laboratory for total chlorides analysis. Samples were collected using a submersible electric pump and after purging approximately one well volume.

Geophysical Model Development

A USGS methodology (Stumm and Como 2017) was used to directly relate bulk induction resistivity measurements to chloride concentrations from water quality samples. For Stumm and Como (2017), this direct relationship was possible because the lithologies in that coastal study were predominantly quartz sands with little clay content. For this investigation, the bulk resistivity log response was similarly assumed to coincide directly with chloride concentration even though the WCA-2A lithologies were variably composed of limestone, shell and sand, sand, and sometimes sandstone, with sand composed of calcareous or quartz grains and all with widely ranging porosities and resistivity responses irrespective of fluid salinity.

The development of chloride-geophysical models included 1) corrections for depth encoder errors and centralizer effects, 2) a conversion of resistivity to conductivity, 3) a conversion of conductivity to specific conductance normalized to 25°C, and 4) a conversion of specific conductance to a chloride curve using linear regression techniques.

1) The geophysical logs from 1997 and 1999 had notable depth encoder errors. The older geophysical logs spanned very similar depths as the recent geophysical logs with few exceptions, but the depth encoder used at the time of geophysical logging was poorly calibrated (not set to zero at land surface) and gave false depth data as a result. Depth corrections to the resistivity logs were made by curve matching the gamma log peaks from the older data to fit the 2018 gamma logs.

   When the monitor wells were completed in 1997 and 1999, the PVC casing was centralized within the open hole using stainless steel centralizers. The presence of highly conductive metals at discrete intervals caused excessive noise and data spiking during the induction logging performed in 2018, so these portions of the induction logs were removed. The result was a much smoother curve that was more representative of the bulk sediment properties but with some remaining centralizer influences.

2) The short normal resistivity logs from the 1997 and 1999 data and the deep induction resistivity logs from the 2018 data were chosen to model the chloride concentrations because the measured values and the curve shapes were most similar. Both log traces were converted from resistivity to conductivity using the following relationship:

   $$(1/\text{resistivity}) \times 1{,}000 = \text{conductivity}$$

   where resistivity is measured in ohm-meters (ohm-m) and conductivity is measured in millisiemens per meter.

3) A temperature gradient for each deep monitor well was established from a water sampling event in 2000 (Harvey et al. 2005), in which pumped samples were collected and tested for the entire well cluster. These data were used to create a temperature log generally representative of the vertical temperature gradient for WCA-2A. The temperature log was used to convert the raw conductivity logs into normalized specific conductance logs. The following relationship was used for this conversion:

   $$\text{SPCO} = \text{COND}/(1+r[t-25])$$

   where SPCO is specific conductance (measured in microsiemens per centimeter [µS/cm]), COND is measured conductivity (µS/cm), t is temperature (°C), and r is the temperature correction coefficient (0.0191).

4) The geophysical resistivity logs were representative of the bulk properties of the subsurface lithology being investigated. Important components of the bulk properties included mineralogy, porosity, and pore fluid salinity. In water-saturated formations composed of carbonates or quartz sands, relatively clay-free, a form of the Archie (1942) equation can be shown as:

$$R_o/R_w = a/\phi^m$$

where R_o is measured bulk formation resistivity (ohm-m), R_w is formation water resistivity (ohm-m), a is a dimensionless pore geometry coefficient, ϕ is porosity (as a percentage), and m is a dimensionless cementation factor. Establishing values for a, m, and ϕ for the specific lithologies (lithology coefficients) within the WCA-2A monitor wells was not possible for this investigation; therefore, the right side of the Archie equation above was assumed to equal one.

A cross-plot of log specific conductance and sample chloride was created for the 1997 and 1999 data set as well as the 2018 data set. Only the deep monitor well chloride samples and corresponding log values were used in the cross-plots. The 1997 and 1999 data were composed of specific conductance derived from short normal resistivity plotted versus chloride values from samples. The 2018 data were composed of specific conductance derived from deep induction resistivity plotted versus chlorides. Linear regressions performed for each data set enabled conversion of the specific conductance logs into chloride geophysical models, or chloride log traces. The empirical relationships and correlation R^2 values from the linear regressions are shown below.

1997/1999 data: Calculated chloride concentration = 11.323 × SPCO + 213.65 ($R^2 = 0.88$)

2018 data: Calculated chloride concentration = 11.324 × SPCO – 56.102 ($R^2 = 0.95$)

5.3 Presentation of Model Data Sets

The chloride-geophysical model for each monitor well (**Figures 7** through **10**) is a vertical representation of groundwater salinity, with a computed log of chloride concentrations as the basis for interpreting salinity zonation. Each figure shows the following log curves, from left to right: 1997/1999 and 2018 gamma ray curves, specific conductance curves (calculated from resistivity curves), and modeled chloride curves. Chloride concentration results used for each model are shown in data boxes at the top of each figure. Salinity zonation was defined by the USGS (Prinos et al. 2014) as fresh water with a chloride concentration ≤250 milligrams per liter (mg/L), saltwater when the chloride concentration is ≥1,000 mg/L, and brackish water between those two end members. Salinity zone boundaries in the WCA-2A monitor wells were chosen where the chloride log trace appeared to cross a key threshold for most of the curve, even though a higher-order oscillation of the curve might have crossed back. The largest of these oscillations were consistently associated with adverse centralizer noise in the 2018 data.

Fence diagrams (**Figures 11** and **12**) illustrate the horizontal and vertical distribution of chlorides in 1997/1999 and observed changes since then at each monitor well using a color ramp. Fresh water, brackish water, and saltwater within the aquifer are color coded, and the 2018 positions of the fresh water/brackish water and brackish water/saltwater interfaces are shown. A map showing the percent change in chloride concentrations between the 1997/1999 and 2018 sampling events, based on the geophysical models for the entire saturated interval for each monitor well, is provided in **Figure 13**. The interpolated areas of decreasing or increasing chloride concentration are delineated, along with inferred direction of saline water flux.

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Location: Water Conservation Area 2A
County: Broward
State: Florida
Country: USA

Casing Depth: 124.55 ft
Casing Elevation: 17.905 ft (MSL) NGVD 1929
Casing Screen: 122.5-124.5 ft
Ground Elevation: 10.25 ft (MSL) NGVD 1929

WELL ID: **2AS7E-GW1**
Date(s) Logged: *SEP 2018* *NOV 1999*

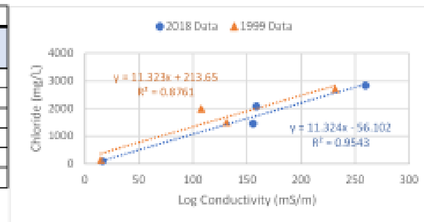
	2018 Data			1999 Data		
Well	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)
2AS7E-GW1	123.6	259.6	2831.0	123.6	231.6	2700.0
				64.3	65.2	1500.0
				34.5	42.6	545.0
				19.6	28.1	290.0

NOTES:

1. The cross-plot included log and chloride data for only the deep wells at 2AS7E-GW1, WC2U3-GW5, WC2E4-GW5 and S10C-GW1.

2. Lab analyses were correlated to the mid-point of the 2-foot screened interval.

3. Where the logs did not overlap with the well screen the deepest log value was used for the cross-plot.



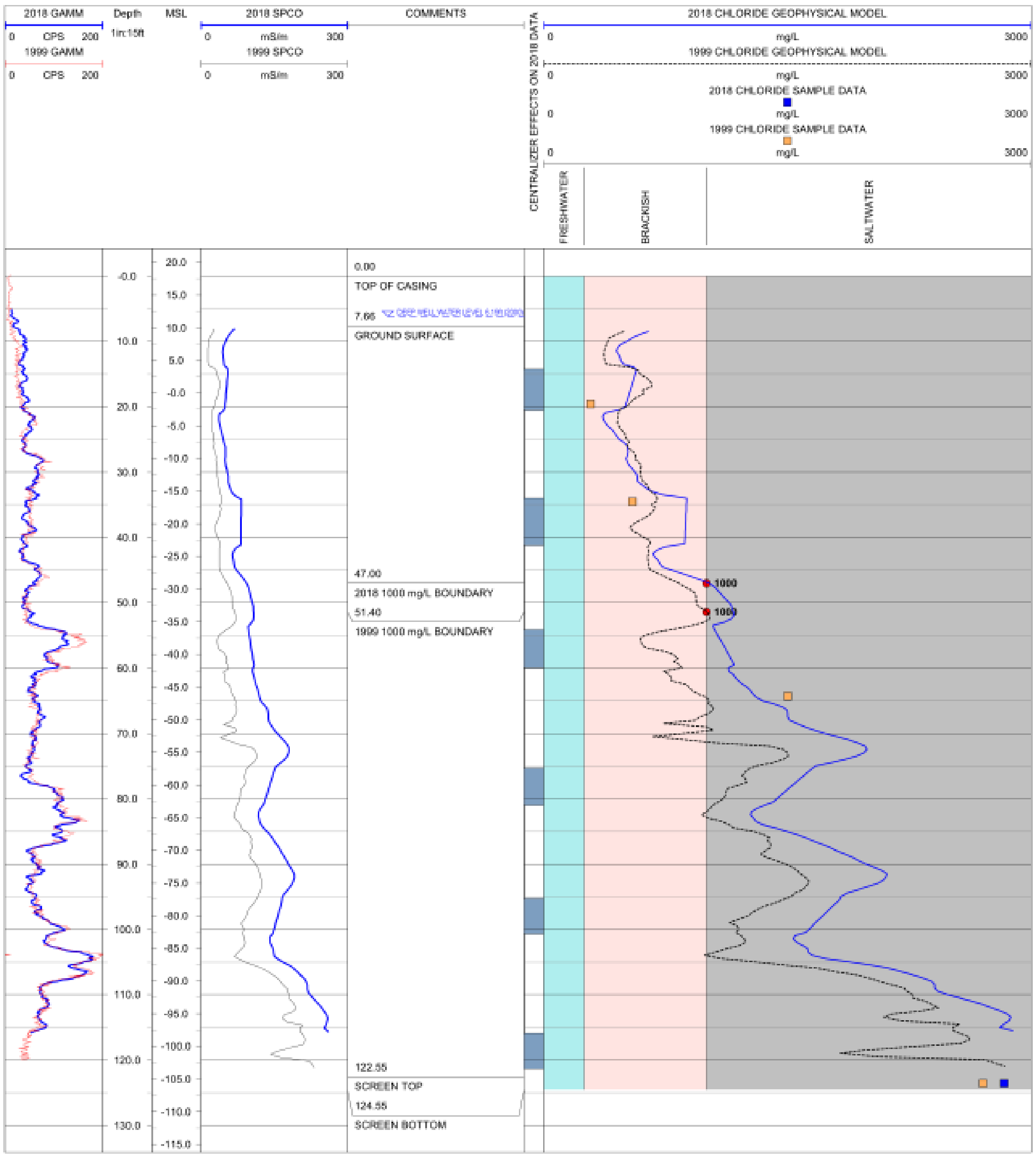


Figure 7. Geophysical model curves and data sets for 2AS7E-GW1.

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Location: Water Conservation Area 2A
County: Broward
State: Florida
Country: USA

Casing Depth: 124.6 ft
Casing Elevation: 18.275 ft (MSL) NGVD 1929
Casing Screen: 122.6-124.6 ft
Ground Elevation: 10.78 ft (MSL) NGVD 1929

WELL ID: WC2U3-GW5
Date(s) Logged: *SEP 2018* *NOV 1999*

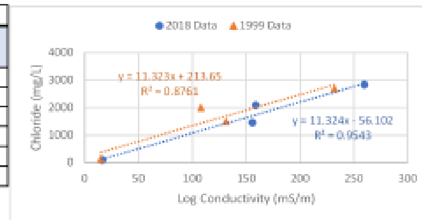
	2018 Data			1999 Data		
Well	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)
WC2U3-GW5	123.6	158.6	2079.0	123.6	107.8	2000.0
				63.5	59.5	1067.0
				34.5	24.3	487.0
				33.2	21.4	467.0
				19.1	6.3	185.0

NOTES:

1. The cross-plot included log and chloride data for only the deep wells at 2AS7E-GW1, WC2U3-GW5, WC2E4-GW5 and S10C-GW1.

2. Lab analyses were correlated to the mid-point of the 2-foot screened interval.

3. Where the logs did not overlap with the well screen the deepest log value was used for the cross-plot.



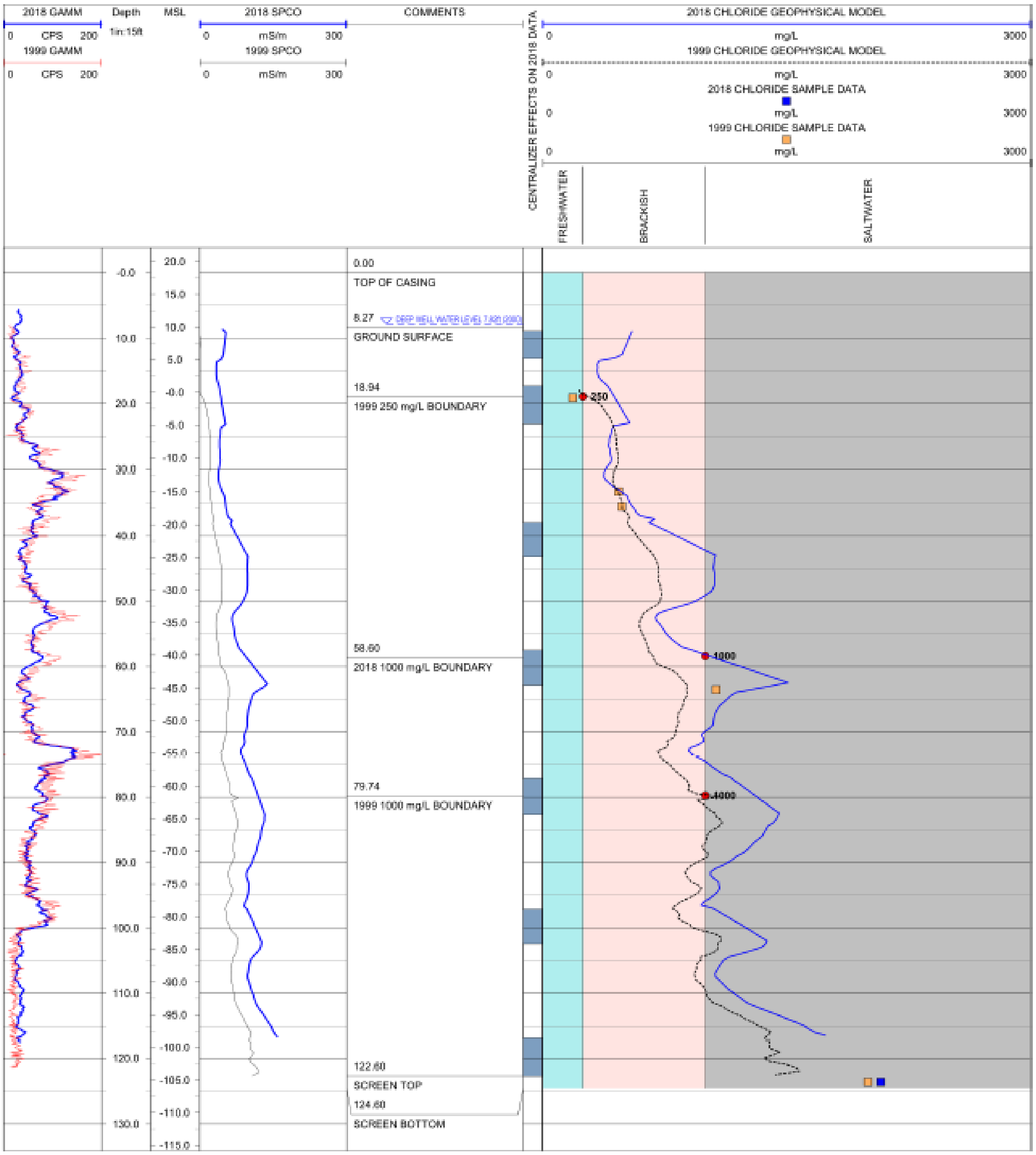
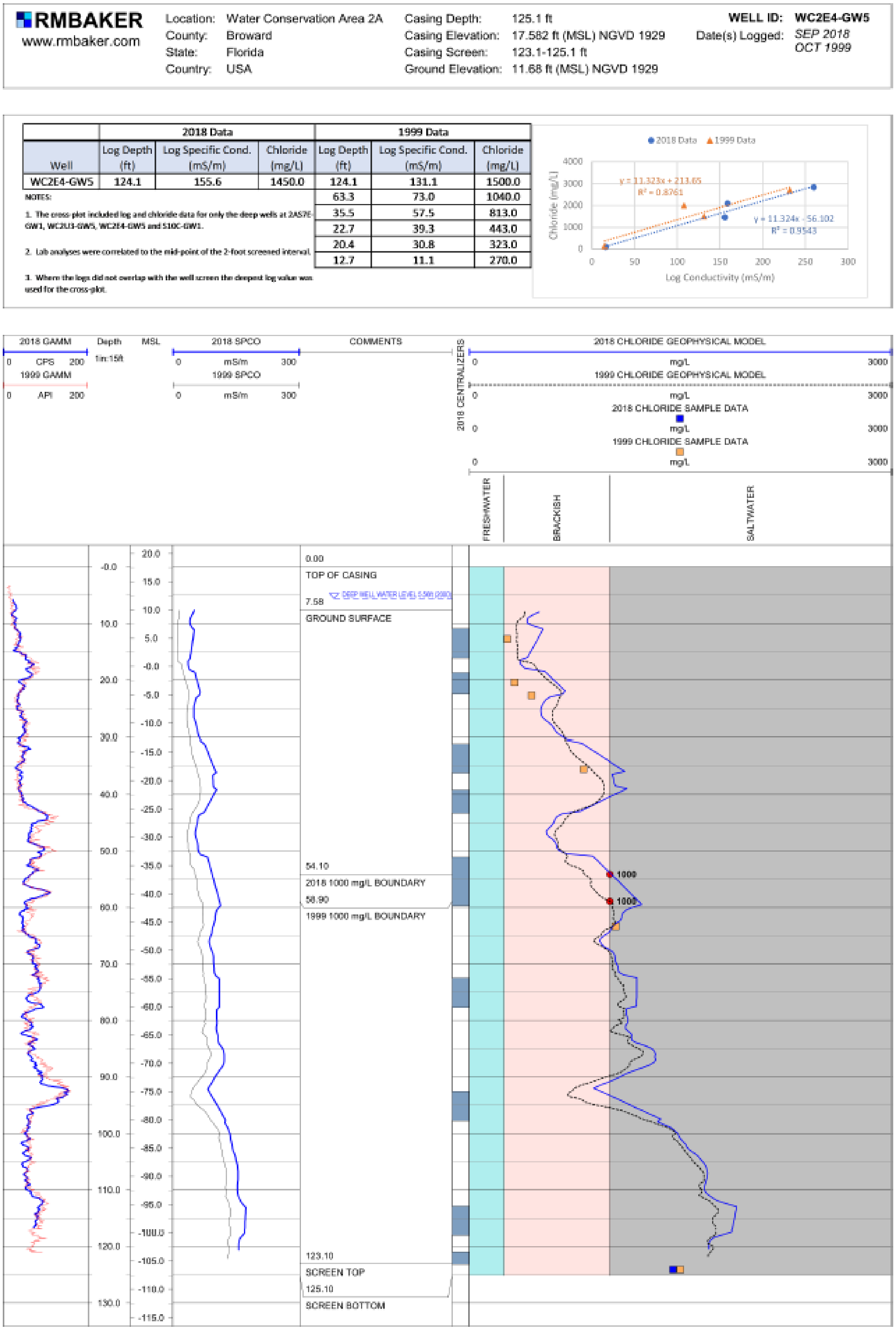


Figure 8. Geophysical model curves and data sets for WC2U3-GW5.



	2018 Data			1999 Data		
Well	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)
WC2E4-GW5	124.1	155.6	1450.0	124.1	131.1	1500.0
				63.3	73.0	1040.0
				35.5	57.5	813.0
				22.7	39.3	443.0
				20.4	30.8	323.0
				12.7	11.1	270.0

Figure 9. Geophysical model curves and data sets for WC2E4-GW5.

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Location:	Water Conservation Area 2A	Casing Depth:	101.2 ft	WELL ID:	S-10C-WA
County:	Palm Beach	Casing Elevation:	22.206 ft (MSL) NGVD 1929	Date(s) Logged:	SEP 2018 MAR 1997
State:	Florida	Casing Screen:	99.2-101.2 ft		
Country:	USA	Ground Elevation:	22.206 ft (MSL) NGVD 1929		

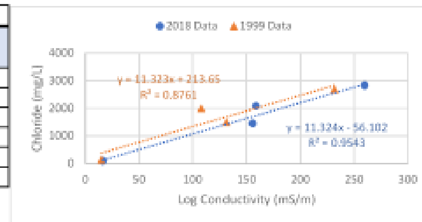
	2018 Data			1999 Data		
Well	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)	Log Depth (ft)	Log Specific Cond. (mS/m)	Chloride (mg/L)
S-10C-WA	100.4	16.2	95.0	100.4	14.4	150.0
				63.6	6.7	120.0
				30.5	9.5	125.0

NOTES:

1. The cross-plot included log and chloride data for only the deep wells at 2AS7E-GW1, WC2U3-GW5, WC2E4-GW5 and S10C-GW1.

2. Lab analyses were correlated to the mid-point of the 2-foot screened interval.

3. Where the logs did not overlap with the well screen the deepest log value was used for the cross-plot.



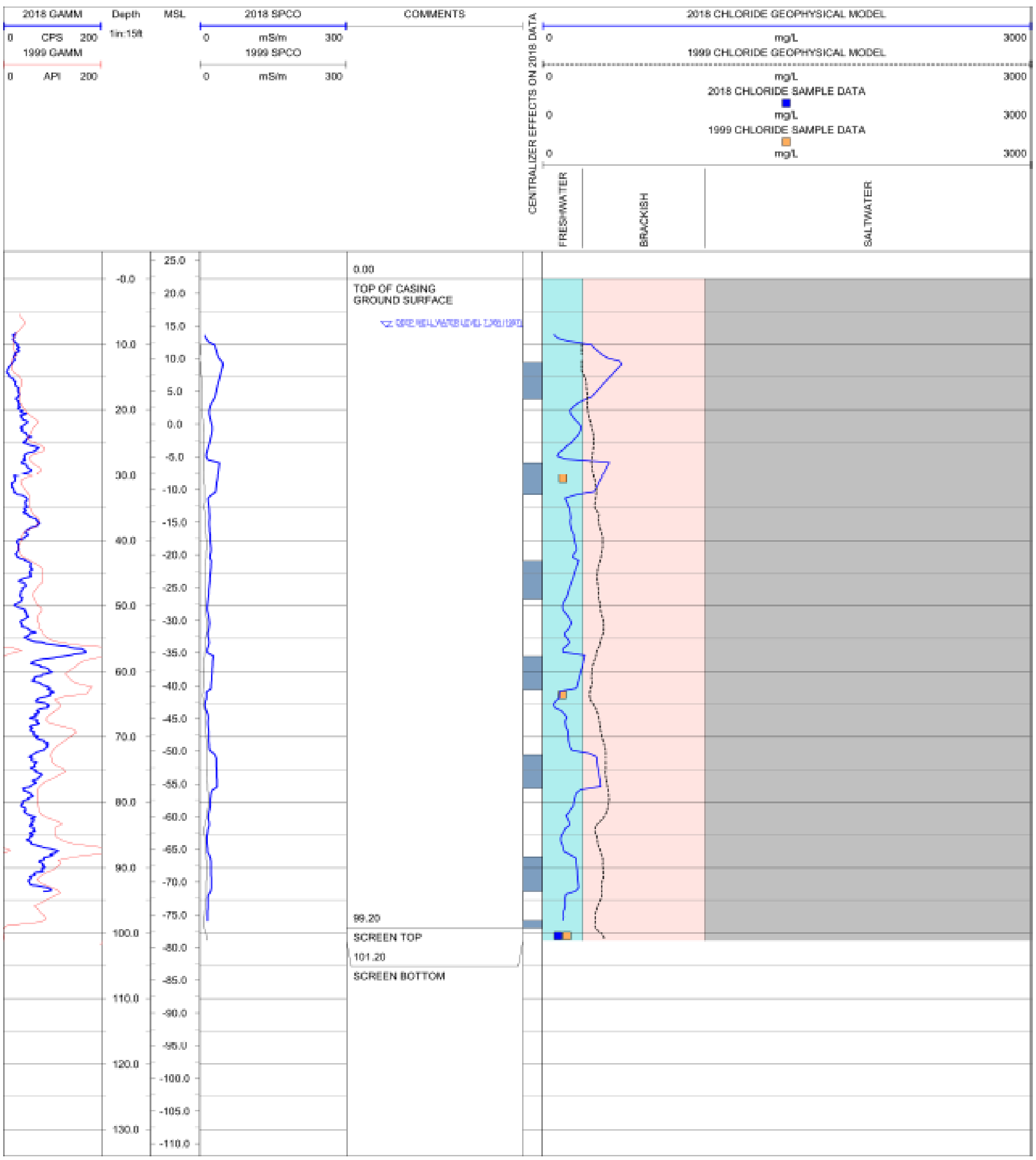


Figure 10. Geophysical model curves and data sets for S-10C-WA.

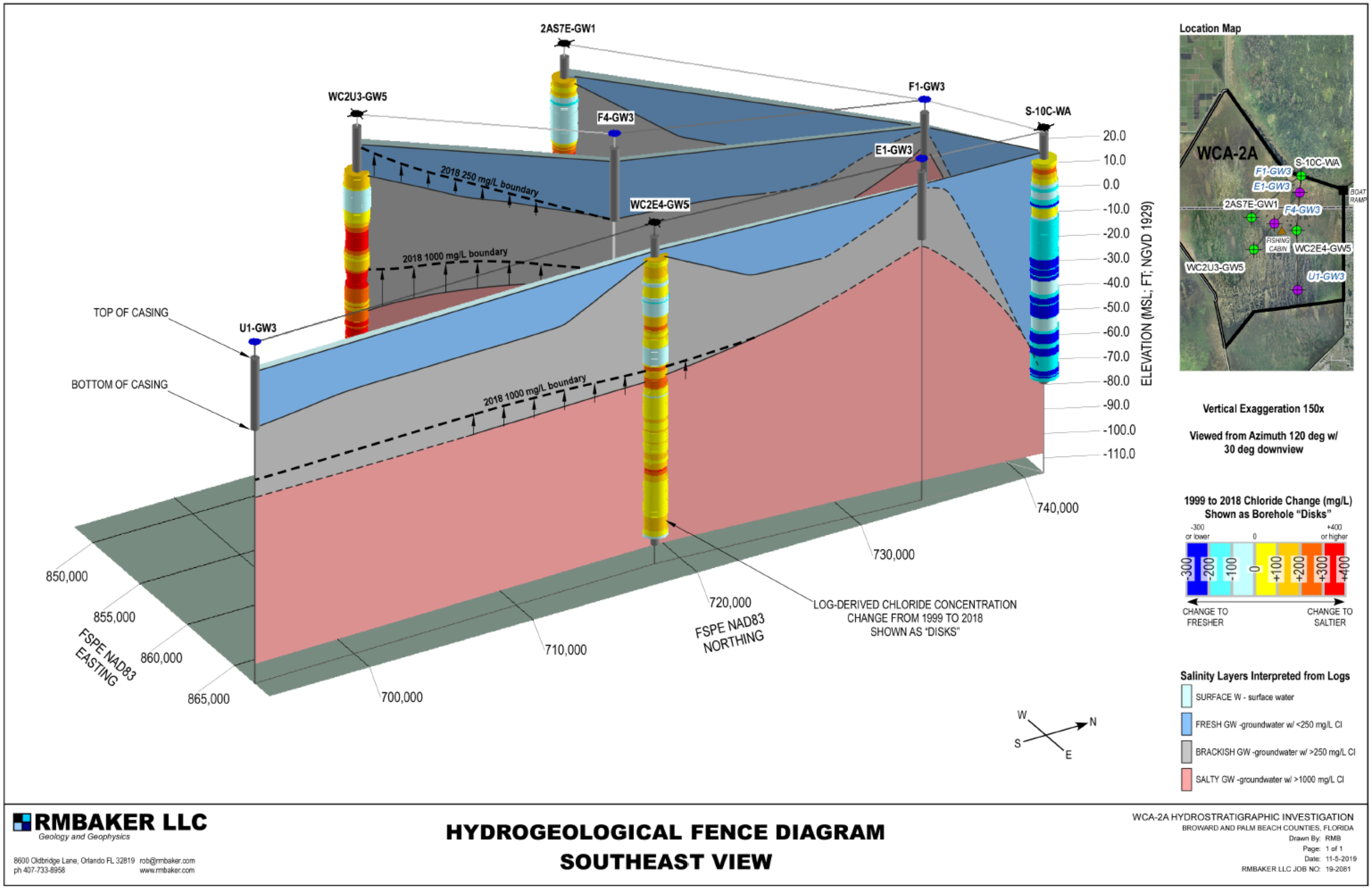


Figure 11. Fence diagram looking west.

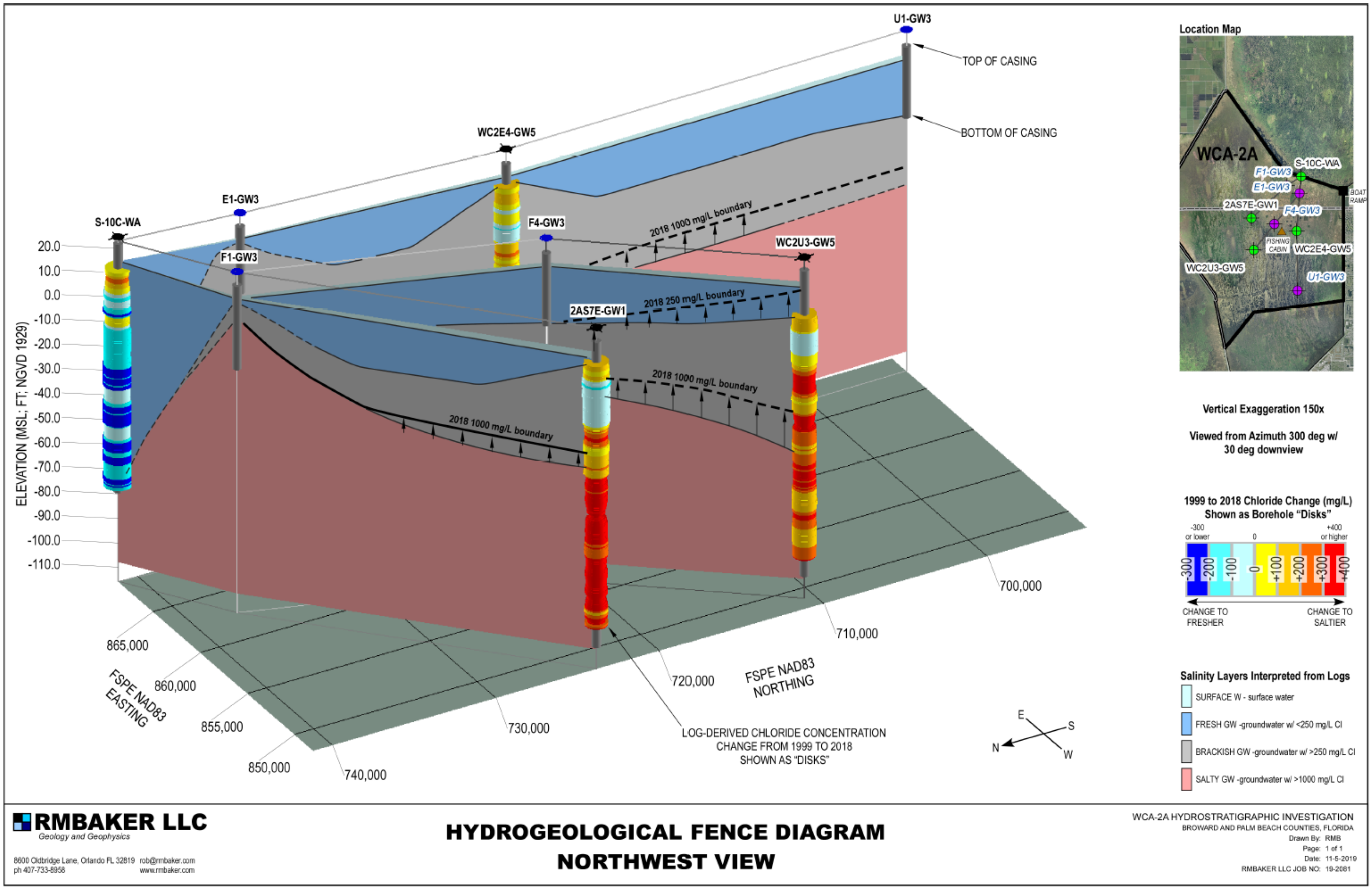


Figure 12. Fence diagram looking east.

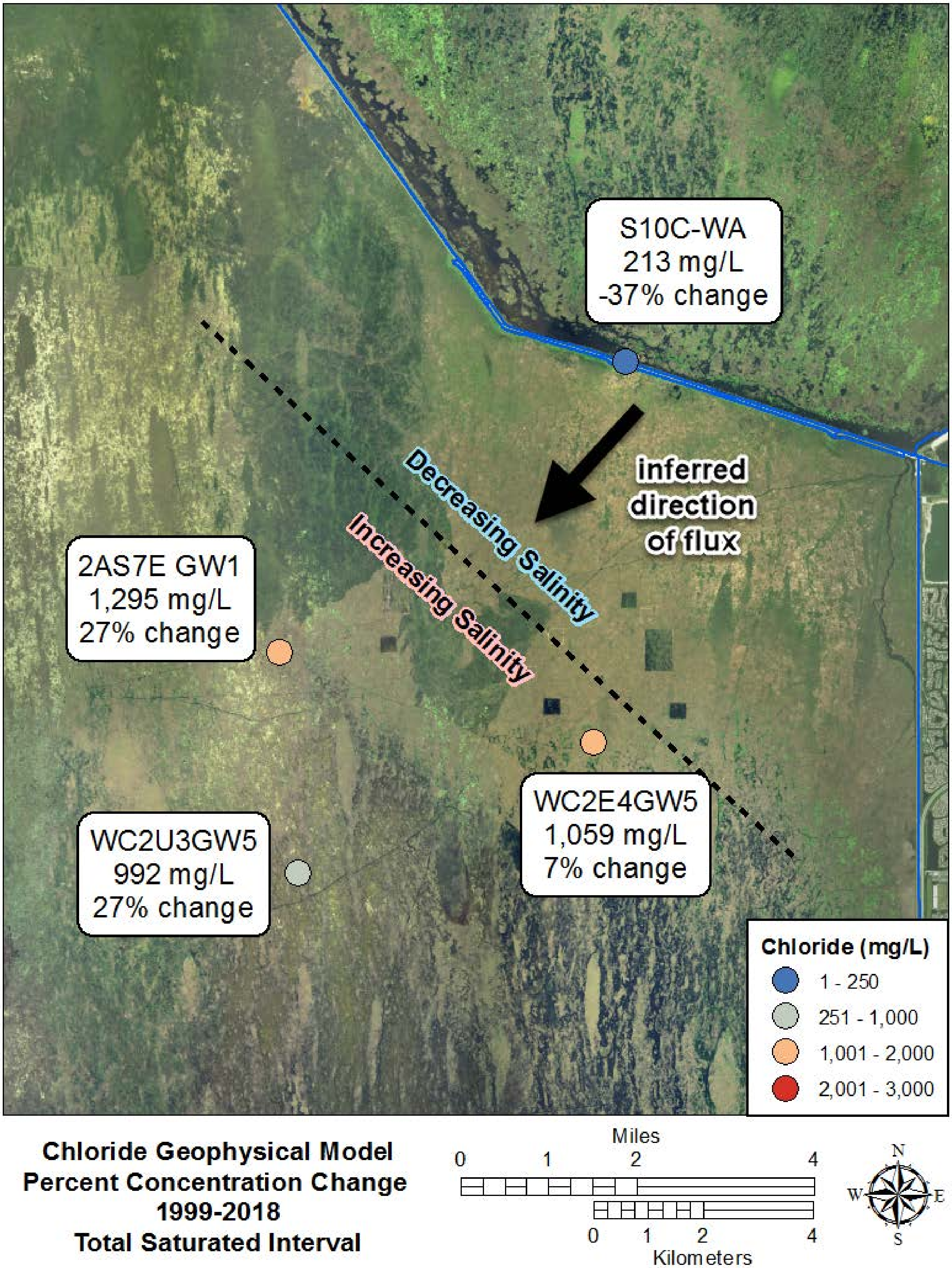


Figure 13. Average chloride concentration change over the saturated interval for tested monitor wells.

5.4 Findings

Modeling has indicated that chloride concentrations have decreased at S10C-WA (on the L-39 levee) and increased in the wetland monitor wells since 1997/1999. At S10C-WA, modeled chloride concentrations, averaged over the saturated interval, decreased by approximately 37% and were relatively constant with depth. The 1997 model indicated S10C-WA was slightly brackish, with an average chloride concentration of 336 mg/L for the saturated interval, compared to an average of 213 mg/L (fresh water) in 2018. Laboratory analysis indicated an average chloride concentration (of three screened intervals) of 132 mg/L in 1999, compared to 2018 concentrations of 95 mg/L (of the deepest screened interval only). The laboratory results were 39% and 45% of the 1997/1999 and 2018 modeled average, respectively. Although the modeled chlorides were higher than the laboratory samples in each event, the change in chloride concentration indicated by each methodology is comparatively similar.

The wetland monitor wells (2AS7E-GW1, WC2U3-GW5, and WC2E4-GW5) were brackish in the shallower intervals, with saltwater at depth during the 1999 and 2018 sampling events. The brackish water/saltwater interface in the three monitor wells rose between 4 and 21 ft to depths between 47 and 59 ft from top of casing, respectively (**Figures 10** and **11**). Average chloride concentrations of the saturated interval of the monitor wells based on the model were between 992 and 1,295 mg/L, an increase from 1999 of 7% to 27% (**Figure 13**). While the near-surface groundwater at 2AS7E and WC2E4 appeared brackish in 1999, the uppermost 10 ft at WC2U3 was fresh. In 2018, the uppermost 10 ft at WC2U3 had transitioned to brackish.

Laboratory chloride concentrations at the nearest shallow monitor well to S10C-WA, WC2F1-GW3 (**Figures 11** and **12**), approximately 0.5 miles south of the S-10C structure, were higher (2,206 mg/L) at shallow depth (approximately -24 ft NGVD29) relative to shallow monitor wells farther south. The brackish water/saltwater interface (1,000 mg/L based on geophysical models) was much deeper in the logged monitor wells further south, between -51 to -80 NGVD29 in deep monitor wells 2AS7E-GW1, WC2E4-GW5, and WC2U3. This may be a consequence of upward flow and mixing of saline groundwater originating from the lower part of the aquifer beneath WCA-1 and reduced upward flow and mixing farther south.

The salinity findings in this study are consistent with the findings of Harvey et al. (2002), who used geochemical evidence and groundwater gradient analysis to conceptualize surface water/groundwater exchange beneath wetlands compartmentalized by the L-39 levee, including at the S-10C structure between WCA-1 and WCA-2A. According to Harvey et al. (2002), the effect of the higher stage behind the levees was to induce fresh water recharge from WCA-1 to a depth of at least 90 ft on the upgradient (headwater) side of the levee and relict seawater forced into the downgradient (tailwater) side of the levee, with upward flow and vertical mixing within WCA-2A.

5.5 Model Uncertainties

Model uncertainties are associated with: 1) the likely presence of drilling fluids during logging in 1997/1999 and the sequence of geophysical logging and water quality sampling relative to well development; 2) relatively broad-scale oscillations of the resistivity curve primarily associated with lithology changes; 3) well construction limitations that precluded geophysical logging of the deepest screen intervals; and 4) use of different geophysical logging methods and borehole conditions (cased versus uncased well) in the 1997/1999 and 2018 events. A detailed discussion of each is presented below.

1) During the 1997/1999 sampling event, the wells were geophysically logged within about a day of drilling and without casing installation and, therefore, were not developed (i.e., the well was not purged of drilling fluids or sediments that are not representative of native water quality). Fresh water was the

major component of the drilling fluid, so the formation water may have been fresher than native water, and the resistivity measurement would have been relatively higher as a result. The laboratory samples for correlation with the logging were collected after well completion and development, and approximately 2 to 10 months after logging for the wetland monitor wells and approximately 3 years after logging for S10C-WA. Therefore, the resistivity logs likely measured fresher water than the samples, with both data sets used to build the chloride model. This would result in a modeled curve that was slightly more saline than the formation was at the time of logging. Additionally, there is the potential for changes in aquifer water quality between logging and sample collection.

2) Important components of the bulk resistivity properties included mineralogy, porosity, and pore fluid salinity, among others. In groundwater salinity studies, it is common to assume nearly constant values for mineralogy and porosity-related coefficients, thereby enabling a direct comparison of the bulk formation resistivity to the resistivity of the water. Such broad assumptions can be less than ideal in WCA-2A where the sediments are highly variable. The chloride geophysical model log traces were, in part, validated by the consistent, concurrent vertical trends of the sampled chloride concentrations. Higher-order oscillations in the log traces most likely were associated with the variabilities of lithology and porosity changes; however, the pore fluid salinity levels appeared to dominate the overall bulk resistivity responses in the logs. Because the same monitor wells were geophysically logged in 1997/1999 and 2018, uncertainties related to lithology and porosity would be expected to have remained relatively constant, reducing uncertainty in comparative analysis between the 1997/1999 and 2018 models. Higher-order oscillations in the log traces, controlled by lithology, dictate the shape of the model curve near sample points and create inherent variances at discrete vertical points (e.g., well screens from which laboratory samples were collected). Higher levels of uncertainty are expected to be associated with absolute chloride concentrations predicted within each model and less associated with the predicted change between the 1997/1999 and 2018 models for each well.

3) For both the 1997/1999 and 2018 geophysical logging events, the depth of the resistivity logs for the three wetland monitor wells was above the screened intervals of the deep monitor wells used for sample collection. The lowest log depth in 1997/1999 was approximately 1 to 2 ft above the screened interval due to the distance between the logging tool sensor and the tip of the tool. In the 2018 model, metallic centralizers were installed immediately above all the deep well screens, rendering the lowest portions of the resistivity curves useless; therefore, the base of the usable portions of the 2018 log curves are effectively 3 to 8 ft shallower than the well screens. An additional source of imprecision was that 1997/1999 geophysical logging runs were performed with poor depth encoder calibrations. Correlation of the 1997/1999 logs with 2018 logs was done using gamma ray correlation, resulting in some uncertainty in the resultant 1997/1999 log depth.

4) The geophysical logging method in 1997/1999 was long (64-inch) and short (16-inch) normal resistivity on an uncased borehole, whereas dual induction (shallow and deep) resistivity on the cased borehole was used in 2018. Short normal and deep induction logs were used to build the chloride models. For short-normal resistivity measurements, a current loop is established between an electrode on the sonde and a remote electrode (at the surface or on a cable bridle), with electrical potential proportional to formation resistivity measured by two other electrodes on the sonde spaced 16 inches apart. For deep induction, transmitter coils in the sonde generate an electromagnetic field that induces current flow within the formation. That current flow yields yet another electromagnetic field detected by receiver coils in the sonde, with the decay of the induced field proportional to the formation resistivity. The use of two different regressions enabled the conversion of two different logging methods, used for an uncased and cased well, into a common relatable data set (two chloride concentration models). This approach greatly reduced the significance of the variable borehole logging methods and borehole conditions present in 1997/1999 and 2018.

6 CONCLUSIONS AND RECOMENDATIONS

A review of previous publications and correlation of geophysical and lithologic logs was conducted to describe the hydrostratigraphy of the SAS in WCA-2A. The SAS is composed of three permeable zones (PZ-1, PZ-2, and PZ-3), consisting of highly variable lithology, including sand and shell, cemented or loosely cemented shell and shell fragments, vuggy or solution-enhanced limestone, and calcareous sandstone. Hydraulic conductivity (K) is estimated to range from 100 and 1,000 ft/day within each zone. Relatively low-permeability strata, including semi-confining and confining intervals that overlie and are interbedded with permeable zones include an uppermost peat, sand, soil, and marl layer, approximately 2 ft thick, that overlies PZ-1, and fine to medium sand, shelly sand, sandstone, limestone, and clay between permeable zones. K_h estimates range from 0.1 to 100 ft/day for interbedded and semi-confining units and <0.1 ft/day for confining clay intervals, which are very limited.

A geophysical investigation of the SAS in WCA-2A was performed to assess salinity changes over the last 20 years. Based on geophysical modeling, the brackish water/saltwater interface in the wetland monitor well clusters rose approximately 4 to 21 ft, and, based on the model, average chloride concentrations increased 7% to 27% between 1999 and 2018. While near-surface groundwater at two wetland monitor wells were already brackish in 1997/1999, the third monitor well changed from fresh to brackish within the upper 10 ft in 2018. Water quality in the monitor well next to the S-10C structure was vertically consistent over the logged interval and appeared slightly brackish based on the 1997/1999 model and fresh in 2018. Infiltration of drilling fluids and a lack of well development may have caused the 1997/1999 model to appear more saline than it was. Chloride concentrations were relatively constant over the entire well depth in both models.

The salinity findings in this study are consistent with the findings of Harvey et al. (2002), who used geochemical evidence and groundwater gradient analysis to conceptualize surface water/groundwater exchange beneath wetlands compartmentalized by the L-39 levee, including at the S-10C structure between WCA-1 and WCA-2A. According to Harvey et al. (2002), the effect of the levees – and the associated higher stages in WCA-1 vs. the downgradient WCA-2A -- was to induce fresh water recharge from WCA-1 to a depth of at least 90 ft on the upgradient (headwater) side of the levee and relict seawater forced into the downgradient (tailwater) side of the levee, with upward flow and vertical mixing within WCA-2A. The implications of the upward movement of connate (saline) water into shallower zones of WCA-2A – and over time for this water to be observed at land surface – need to be explored and better understood.

The model appears more effective at identifying relative changes in chloride concentration than the absolute concentrations. The variance between the 1997/1999 modeled estimates and laboratory results increased as salinity decreased. Much of this variance may be because the boreholes were geophysically logged prior to well construction and development, allowing residual drilling fluids to impact resistivity readings. Model uncertainties can be minimized in future logging events by conducting contemporaneous sampling of wells at all depths at each well cluster. This would add multiple data points for modeling, reduce the centralizer effects, and reduce the bottom hole limitations of the deepest monitor well. Additional monitor wells, if installed, should not include metallic centralizers and should include sumps at the bottom to accommodate logging tools.

Additional recommendations include installation of monitor well clusters inside WCA-1, the northern and western areas of WCA-2, and WCA-3A to facilitate resistivity logging and water sampling. These monitor well clusters would become part of an Everglades sentinel wells program to monitor groundwater salinity changes over time and to update density-dependent groundwater models.

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