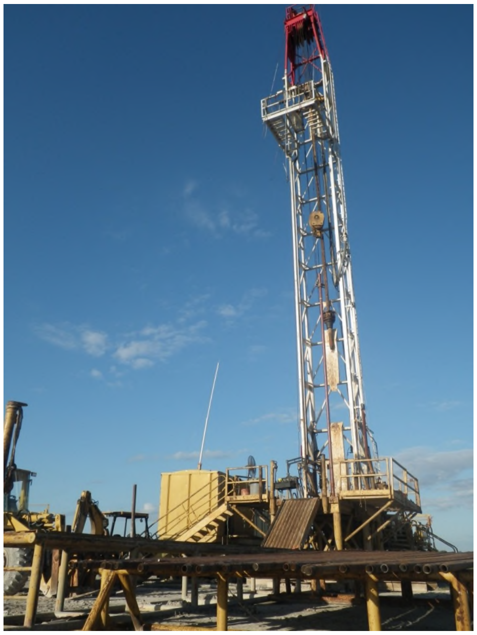
SOUTH FLORIDA WATER MANAGEMENT DISTRICT

Hydrogeologic Investigation for the Kissimmee Basin Lower Floridan Aquifer Reconnaissance Project, Site C

Osceola County, Florida
Technical Publication WS-34



E. Richardson P.G., J. Janzen P.G.,
A. Bouchier P.G., and A. Dodd P.G.

South Florida Water Management District
Hydrogeology Unit
3301 Gun Club Road
West Palm Beach, Florida 33406
September 2014

sfwmd.gov

ACKNOWLEDGEMENTS

This work could not have been accomplished without the help of many people.
Thank you all!

SFWMD On-Site Hydrogeologists

Cindy Bevier
Aurora Bouchier
Brian Collins
Anne Dodd
Liz Geddes
Steve Krupa
John Janzen
Emily Richardson

SFWMD Construction Management Support

Tony Rosato
Houston Tripp

All Webbs Enterprises Drilling Team

Tom Toy
Justin Sullivan
Dave Robbars

SFWMD Groundwater Modeling Support

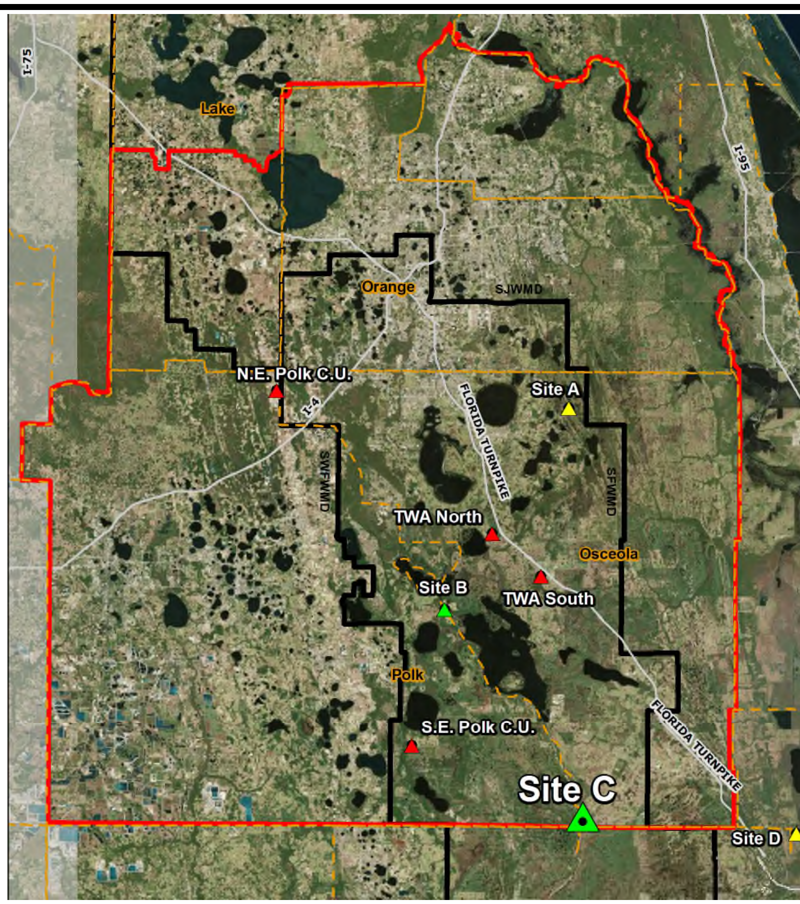
Jefferson Giddings
Ligia Jurado

EXECUTIVE SUMMARY

The Lower Floridan aquifer (LFA) has been targeted as a key source of alternative water supply as part of the Central Florida Water Initiative (CFWI) in the Kissimmee Basin planning area. However, there are many hydrogeologic uncertainties associated with development of the LFA that affect the suitability and sustainability of its use as a long-term water supply source.

The South Florida Water Management District (SFWMD) developed a five-year plan, the Lower Floridan Aquifer Investigation, Kissimmee Basin (LFAKB) Project, for a hydrogeologic reconnaissance of the LFA within the Kissimmee Basin region, with the express purpose of addressing uncertainties in LFA development. The LFAKB Project was first funded in Fiscal Year 2011.

A major component of the LFAKB Project was drilling and testing exploratory wells at four sites to bridge the largest data gaps within the LFA. This report documents the results from the second of those sites, LFAKB Site C.



Lower Florida Aquifer Investigation, Kissimmee Basin Project study area with proposed exploratory drilling sites (green markers) shown in relation to planned Lower Floridan aquifer production wellfields (red markers).

The Site C testing program included:

- Construction and testing of a new dual-zone monitor well (OSF-109) in the uppermost two producing zones of the LFA.
- Modification and testing of an existing Floridan aquifer system well (OSF-105) for aquifer performance testing.
- Determination of water quality with depth and sampling for field and laboratory analysis of formation waters during:
    - Drilling (drill-stem and interval test sampling)
    - Straddle-packer testing from four select zones
    - Aquifer performance testing
    - Development of completed monitor zones
- Implementation and analysis of aquifer performance tests discretely evaluating the Avon Park permeable zone (APPZ) and a portion of the LFA.

Drilling at Site C for the LFAKB Project penetrated to a maximum depth of 2,000 feet below land surface (ft bls). Major findings from the drilling and testing program include:

- The following boundaries of the major hydrogeologic units at this location based on lithology, geophysical logs, and water quality, water level and hydraulic data:
    - Top of the intermediate confining unit (ICU): 85 ft bls
    - Top of the Floridan aquifer system (FAS): 258 ft bls
    - Top of the Ocala-Avon Park Lower Permeability Zone (OCAPLPZ) confining unit between the upper permeable zone (UPZ) and the APPZ: 560 ft bls
    - Top of the APPZ: 916 ft bls
    - Top of the Middle confining unit (MC2) between the APPZ and the LFA: 1,254 ft bls
    - Top of the LFA: 1,480 ft bls
    - The base of the Floridan aquifer system/top of the sub-Floridan confining unit is below the maximum explored depth at this site (> 2,500 ft bls from a previous study)
- Three discrete productive intervals, or flow zones, with varying degrees of confinement between them were identified within the LFA at Site C. For ease of reporting, these zones are numbered sequentially, from shallowest to deepest (LF1–LF3)

Flow Zone	Top Depth (ft bls)	Base Depth (ft bls)	Relative Productivity Estimate
LF1	1,480	1,600	Low - Moderate
LF2	1,640	1,754	Moderate
LF3	1,890	1,954	Low - Moderate

- Formation water sampling and analysis yielded the following distribution of dominant ions and total dissolved solids for the hydrogeologic units sampled:

Station Test ID	Hydrogeologic Unit	Sample Depth (ft bls)	Total Dissolved Solids (mg/L)	Dominant Ion Pairs
POS-2	SAS	20–30	493	Ca-HCO3
POS-3	SAS/ICU	75–90	330	Ca-Na-HCO3-Cl
POH-1	ICU	180–200	310	Ca-Na-Mg-HCO3-Cl
OSF-104U	UFA-UPZ	330–550	212	Ca-Mg-Na-HCO3-Cl
OSF-104M	APPZ	930–1,150	248	Na-Mg-Cl-HCO3
OSF-109	APPZ	920–1,250	302	Ca-Na-Mg-Cl-HCO3-SO4
OSF-109U	LF1	1,489–1,573	2,722	Na-Ca-Cl
OSF-109PT4	LF1	1,545–1,575	2,904	Na-Ca-Cl
OSF-109PT3	LF2	1,689–1,719	6,933	Na-Cl
OSF-109PT2	LF3	1,837–1,867	22,520	Na-Cl
OSF-109PT1	LF3	1,890–1,920	25,322	Na-Cl
OSF-104L	LFA	2,000–2,300	34,121	Na-Cl

SAS: surficial aquifer system
UFA: Upper Floridan aquifer

Discrete, NGVD29 referenced water level measurements within the hydrogeologic units identified at Site C were taken at different points during construction and testing. With completion of this project, a very comprehensive vertical transect of the aquifers above and within the Floridan aquifer system is available. From these data, it appears that the highest heads are in the UFA, decreasing both above and below that unit. There is an approximate 2-foot head drop between the APPZ and LFA at this site, and an additional 35-foot drop within the LFA between the shallowest and deepest measurements.

Aquifer	Depth (ft bls)	Well/Zone	Median Head [ft NGVD29]
SAS	20–30	POS-2	43.58
SAS	75–90	POS-3	45.82
ICU	180–200	POH-1	47.84
UFA-UPZ	330–550	OSF-104U	45.71
APPZ	930–1,150	OSF-104M	45.65
LF1	1,489–1,573	OSF-109U	43.84
LF2	1,694–1,745	OSF-109L	38.48
LF3	1,890–1,920	OSF-109	17.15
Undifferentiated LFA	2,000–2,300	OSF-104L	8.20

Hydraulic testing yielded the following results:

- A 48-hour aquifer performance test (APT) of the APPZ using wells open from 920–1,250 ft bls was completed. The results of drilling and testing at Site C indicated the APPZ is highly productive at this location with transmissivity in excess of 400,000 ft^2/day and a storage coefficient of 1×10^{-6}.

- Interval testing within the Lower Floridan aquifer yielded the following transmissivity estimates from calculated specific-capacity for LF1, LF2, and LF3:

Hydrogeologic Unit	Specific Capacity (gpm/ft)	Transmissivity (ft^2/d)
LF1	14.85	3,970
LF2	36.57	9,780
LF3	28.07	7,500

gpm: gallons per minute

- An extended APT of LF1 resulted in a slightly lower transmissivity estimate of 2,470 ft^2/day, and an estimated leakance between the LF1 and LF2 producing zones of 0.06 – 0.008 per day.

The results of drilling and testing at Site C confirm the presence of several productive intervals within the LFA. The two uppermost intervals, LF1 and LF2, are above the base of the underground source of drinking water (USDW; defined as an aquifer with less than 10,000 mg/l TDS), and can be considered as a potential alternative water supply source. Their suitability for that purpose is most easily assessed by comparison to other lower Floridan sites.

Testing results at site C show a continuation of the trend of decreasing permeability in the lower Floridan aquifer from north to south within the CFWI region. The combined productive capacity of LF1 and LF2 at site C is about a quarter of that at site B, 25 miles to the north. Site C capacity is commensurate with, but slightly less than that of the recently permitted southeast Polk wellfield, which lies approximately 19 miles west and north of Site C. Although southeast Polk appears to be withdrawing from the equivalent hydrogeologic units, there is a major increase in salinity over that distance (TDS increase from a maximum of 1,100 mg/l at the southeast Polk to over 5,000 mg/l at site C). Given that the position of the USDW is less than 10 feet below the base of LF2, it is reasonable to expect that, even with careful wellfield design, that salinity will increase even more under prolonged pumping stress. It is possible that the less brackish LF1 could be targeted independently, but its productivity alone is not really sufficient justify the expense, and the confining unit which separates it from LF2 is sufficiently leaky that it too would see increased salinity over time. Comparatively poor productivity and water-quality make the lower Floridan around site C a poor candidate for alternative water supply development at this time.

ABBREVIATIONS AND ACRONYMS

°C	degrees Celsius
API	American Petroleum Institute
APPZ	Avon Park permeable zone
APT	aquifer performance test
AWE	All Webbs Enterprises, Inc.
BDL	below detection limit
BHCS	borehole-compensated sonic log
BHV	borehole video
bls	below land surface
CFWI	Central Florida Water Initiative
CRDT	constant rate discharge test (constant rate portion of an APT)
DI	dual induction
DST	drill-stem test
FAS	Floridan aquifer system
FGS	Florida Geological Survey
FMI	Formation Micro-Imaging
FRP	fiberglass reinforced plastic
ft	feet
gpd	gallons per day
gpm	gallons per minute
ICU	intermediate confining unit
K	hydraulic conductivity
KTIM	FMI-derived permeability log
LF1 – LF5	permeable zones in the LFA, from shallowest to deepest
LFA	Lower Floridan aquifer
LFAKB	Lower Floridan Aquifer Investigation, Kissimmee Basin Project
MC1	Confining unit between the UPZ and APPZ
MC2	Floridan confining unit between the APPZ and LFA
MCU	middle confining unit
mg/L	milligrams per liter
NAVD88	North American Vertical Datum of 1988

NGVD29	National Geodetic Vertical Datum of 1929
OBI	optical borehole image
OCAPLPZ	Ocala-Avon Park Low Permeability Zone (Floridan confining unit between the UFA and APPZ)
psi	pounds per square inch
PT	packer test
Q	pumping or discharge rate
ROP	rate of penetration
RSW	relict sea water
s	drawdown
S	storativity
SAS	surficial aquifer system
SFWMD	South Florida Water Management District
SP	spontaneous potential
T	transmissivity
TDS	total dissolved solids
TRSW	transitional seawater
UFA	Upper Floridan aquifer
UPZ	Upper permeable zones
USDW	underground source of drinking water
USGS	Unites States Geological Survey
VDL	Variable Density Log
YSI	Yellow Springs Instruments
μS/cm	microsiemens per centimeter

CONTENTS

EXECUTIVE SUMMARY iii
INTRODUCTION 1
1.1. Background 1
1.2. Purpose 3
1.3. Project Description 3
EXPLORATORY DRILLING AND WELL CONSTRUCTION 5
2.1. OSF-109 Well Construction: Phase I 5
2.2. OSF-105R Well Construction 6
2.3. OSF-109 Well Construction: Phase II 9
STRATIGRAPHIC FRAMEWORK 13
3.1. Holocene, Pleistocene, and Pliocene Series 13
3.2. Miocene Series 13
3.2.1. Peace River Formation 14
3.2.2. Arcadia Formation 14
3.3. Oligocene Series, Suwannee Limestone 15
3.4. Eocene Series 15
3.4.1. Ocala Limestone 15
3.4.2. Avon Park Formation 15
3.4.3. Oldsmar Formation 17
HYDROGEOLOGIC FRAMEWORK 21
4.1. Surficial Aquifer System (SAS) 23
4.2. Intermediate Confining Unit (ICU) 23
4.3. Floridan Aquifer System (FAS) 24
4.3.1. Upper Floridan Aquifer (UFA) 24
4.3.2. Middle Confining Unit (MCU) 30
4.3.3. Lower Floridan Aquifer (LFA) 30
HYDROGEOLOGIC TESTING 39
5.1. Geophysical Logging 39
5.2. Water Quality and Inorganic Chemistry 42
5.2.1. Drill Stem Water Quality Sampling 42
5.2.2. Discrete Water Quality Sampling 44
5.3. Aquifer Performance Testing 52
5.3.1. APT#1 (Avon Park Permeable Zone: 920–1,250 ft bls) 52
5.3.2. Interval Testing (Lower Floridan Aquifer: 1,489 –2,000 ft bls) 58
5.3.3. APT 2 (Lower Floridan Aquifer from: 1,489–1,573 ft bls) 60
5.4. Packer Testing 65
5.4.1. OSF-109 Packer Test 1 (1,890 to 1,920 ft bls) 67
5.4.2. OSF-109 Packer Test 2 (1,837 to 1,867 ft bls) 67
5.4.3. OSF-109 Packer Test 3 (1,689 to 1,719 ft bls) 67
5.4.4. OSF-109 Packer Test 4 (1,545 to 1,575 feet bls) 67
5.5. Hydraulic Heads 68
SUMMARY 71
REFERENCES 75

FIGURES

Figure 1-1. The LFAKB Project study area with existing and proposed exploratory drilling sites in relation to planned Lower Floridan aquifer production wellfields. 2
Figure 1-2. Site C general layout.. 4
Figure 2-1. Pre-project OSF-105 and OSF-105R as-built well construction.................................8
Figure 2-2. OSF-109 as-built well construction. 10
Figure 2-3. Final wellheads, Site C. 11
Figure 3-1. BHV view of lamination near top of Oldsmar Formation at approximately 1,948 ft bls. 18
Figure 3-2. BHV view of chert nodules near the top of the Oldsmar Formation at approximately 1,971 ft bls. 19
Figure 4-1. A nomenclature comparison of the hydrogeologic units within the Floridan aquifer system. 21
Figure 4-2. Representative hydrogeologic section for Site C. 22
Figure 4-3. Differential caliper logs, indicating variation in fracture intensity within the APPZ across Site C. 27
Figure 4-4. BHV view of brecciation in OSF-105 (987 ft bls). 28
Figure 4-5. BHV view of fractures bounding a cavity in OSF-105 (982 ft bls).............................28
Figure 4-6. BHV view of large cavity in OSF-105 (1,182 ft bls). 29
Figure 4-7. Image of cavity from BHV logging of OSF-109. 32
Figure 4-8. BHV view of cavity in OSF-109 with flow into borehole 33
Figure 4-9. BHV view of cavity in OSF-109 at a depth of 1,912.9 ft bls in LF3. 35
Figure 5-1. Drill-stem water quality variation with depth. **A:** Field specific conductance; **B:** Laboratory chlorides and sulfates...43
Figure 5-2. Langelier plots of major cation/anion correlations from the Site C samples showing three distinct groupings of waters: A: Surficial/Intermediate, B: Upper Floridan, C: Lower Floridan. 47
Figure 5-3. Water type classification of Site C sample data (after Frazee 1982). 49
Figure 5-4. Configuration of wells for APT#1, Site C 52
Figure 5-5. Bierschenk's graphical solution for laminar and turbulent well loss terms.............54
Figure 5-6. Time-series drawdown data from the step-drawdown test on OSF-109. 55
Figure 5-7. Time for the peak of the first pressure wave to travel from OSF-109 to OSF-105 and OSF-104M. 55
Figure 5-8. Configuration of wells for APT 2, Site C. 61
Figure 5-9. Time drawdown in production well OSF-109U. 62
Figure 5-10. Cooper-Jacob analysis of drawdown data for the linear portion of the test. 63
Figure 5-11. Time-series drawdown from OSF-109L during APT#2. 63
Figure 5-12. Model configuration for estimation of leakance from APT#2. 64
Figure 5-13. Variation in total hydraulic head with depth in the FAS at Site C............................68
Figure 5-14. Long-term water level relationship between the SAS, ICU, and Upper Floridan at Site C. 69
Figure 5-15. Correlation between FAS wells (October 21, 2013–November 6, 2013).................70

TABLES

Table 1-1. Well completion information, Site C. 4
Table 2-1. Monitor interval for remodeled OSF-105. 8
Table 2-2. Monitor intervals for dual-zone LFA monitor well OSF-109. 10
Table 5-1. Summary of the geophysical logging program at Site C (2012). 41
Table 5-2. State of well construction. 44
Table 5-3. Summary of samples collected and analyzed at Site C. 45
Table 5-4. Summary of Site C major ion water chemistry from shallowest to deepest sample. 46
Table 5-5. Description of Frazee (1982) water types. 48
Table 5-6. Water classification summary for the site C samples. 49
Table 5-7. Range of ionic composition from Site C groundwater in comparison to surface water from the adjacent Kissimmee River and typical range from modern seawater. Ions are arranged from most to least abundant. 51
Table 5-8. Site C samples exceeding secondary drinking water standards. 51
Table 5-9. Transmissivity estimations from calculated specific capacity. 53
Table 5-10. Diffusivity estimated from pressure wave travel time, Site C. 56
Table 5-11. Optimized model results for hydraulic properties of Site C based on observation data from the June 2012 test. 57
Table 5-12. Summary of interval test results, Site C. 58
Table 5-13. Approximate estimates of productivity and salinity from discrete sections of the borehole within the lower Floridan aquifer, derived from the interval test results, Site C. 60
Table 5-14. Leakance results from the model. 64
Table 5-15. OSF-109 Packer test depth summary, Site C. 65
Table 5-15. Summary of packer test hydraulic data from OSF-109, Site C. 66
Table 5-16. Summary of vertical distribution in total hydraulic head at Site C 69

APPENDICES

Appendix A. Well Construction Details A-1
Appendix B. Lithologic Description B-1
Appendix C. GeophysicalLogs C-1
Appendix D. Aquifer Performance Test Data D-1
Appendix E. Final Survey and As-Built Drawings E-1
Appendix F. Down-hole Video F-1

1 INTRODUCTION

1.1. Background

The Lower Floridan aquifer (LFA) has been targeted as a key source of alternative water supply for the Central Florida Water Initiative (CFWI) in the Kissimmee Basin planning area. However, there are many uncertainties associated with development of the LFA. These include:

- Its productivity south of Orange County, Florida
- The extent and quality of 'fresher' water zones being targeted for water supply
- The extent of the high capacity Boulder Zone for disposal of brine from reverse osmosis water treatment facilities or as a potential water supply source
- The degree of confinement between the LFA and the Upper Floridan aquifer (UFA) and overlying water bodies that the water management districts involved in the CFWI are trying to protect
- The extent to which the LFA currently receives recharge

Each of these uncertainties affects the suitability and sustainability of the LFA as a long-term water supply source.

In 2010, the South Florida Water Management District (SFWMD) developed a five-year plan for a hydrogeologic reconnaissance of the Lower Floridan aquifer within the Kissimmee Basin region to address uncertainties in LFA development. This plan was funded in Fiscal Year 2011 and became the Lower Floridan Aquifer Investigation, Kissimmee Basin (LFAKB) Project. A major component of the LFAKB Project is drilling and testing exploratory wells at four sites to bridge the largest data gaps within the Lower Floridan aquifer (**Figure 1-1**). The first of these exploratory sites (Site B) was completed in 2011 and is documented in SFWMD Technical Publication WS-33. This report documents the results from Site C drilling and testing.

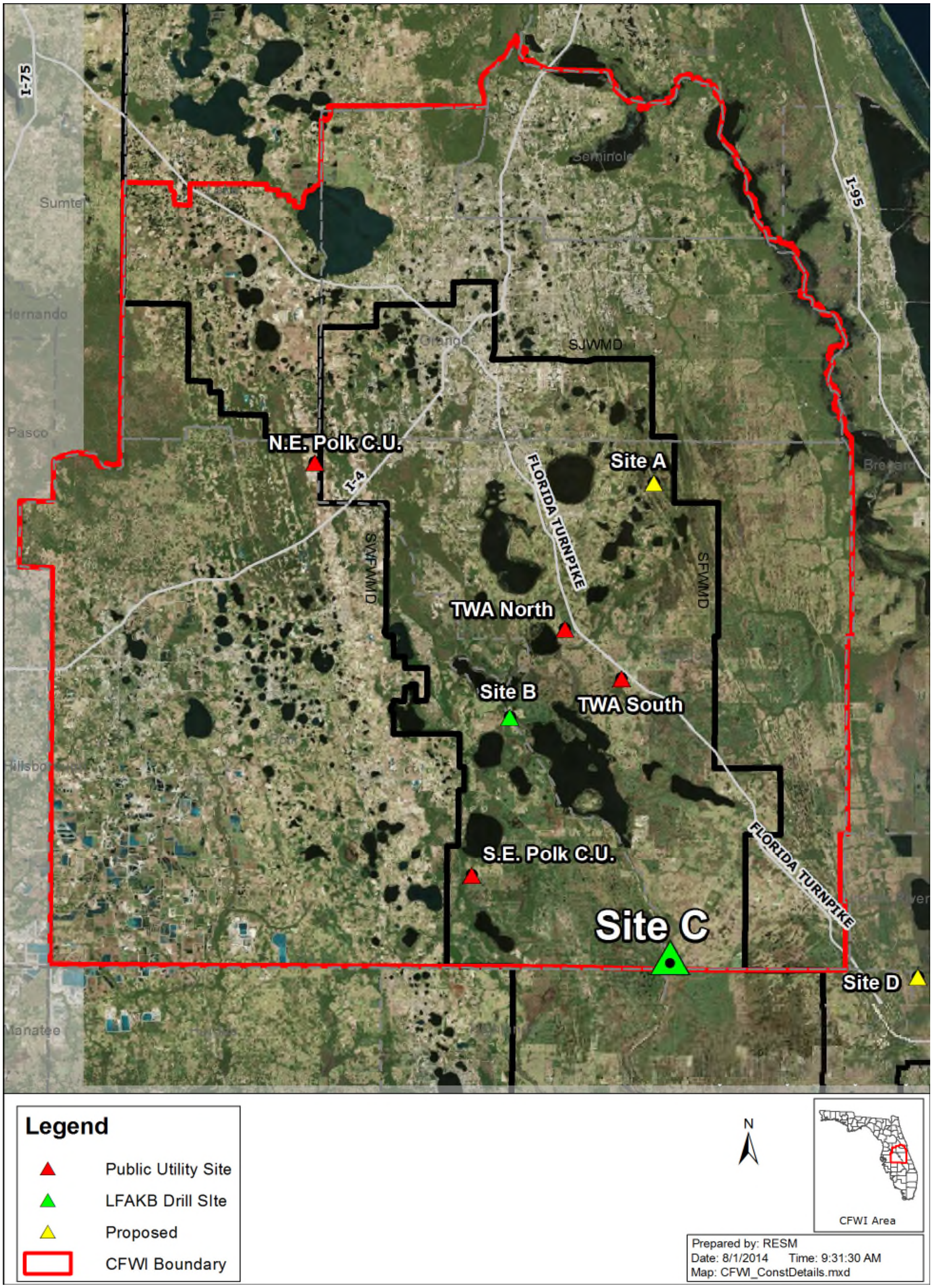


Figure 1-1. The LFAKB Project study area with existing (green markers) and proposed (yellow markers) exploratory drilling sites in relation to planned Lower Floridan aquifer production wellfields (red markers).

1.2. Purpose

Site C is located on the east bank of the Kissimmee River in southwestern Osceola County at the S65A locks south of Lake Kissimmee (**Figure 1-1**). The site is situated at the southern boundary of the CFWI Planning Area.

This site was selected for multiple reasons, including the following:

- The presence of existing on-site hydrogeologic data and monitor wells that could be leveraged to reduce the cost of exploratory well construction and aquifer performance testing
- Given its location, the quality of water in the uppermost zone of the LFA was expected to be nearing the limits of salinity that are desirable for low-pressure reverse osmosis treatment
- Establishing the bounds of that area is one of the overall goals of the LFAKB project
- While there was general information from previous exploration of the position of the top of the LFA at this location, its productivity in this area was unknown but of considerable interest to local utilities

This site, on the floodplain of the Kissimmee River, was also targeted for a detailed evaluation of confinement between the producing zones of the Floridan aquifer system (FAS) and the overlying ecosystem. At the time of this writing, the public supply wellfields at Cypress Lakes and Southeast Polk have been permitted but have not been implemented. Site C will provide a monitoring location to track changes in the LFA and overlying units as those wellfields are activated.

1.3. Project Description

The SFWMD contracted with All Webbs Enterprises, Inc. (AWE) for drilling, testing, and construction of wells at Site C (CN#6000000497). The original scope of the investigation at Site C involved exploratory drilling, testing, and construction of one dual-zone FAS test well (OSF-105R) and one FAS test production well (OSF-109). The relative positions of these and other existing wells at the site are illustrated in **Figure 1-2**. Problems encountered during the construction of OSF-105R forced significant changes to this plan. Well locations, actual drilled depths, and construction duration are provided in **Table 1-1**. Unless otherwise specified, all depths in this report are in units of feet below land surface (ft bls).

Specific objectives for this site included identifying any productive horizons within the LFA above the underground source of drinking water (USDW) and evaluating water quality in those horizons; evaluating the hydraulic properties of LFA zones of interest; and evaluating the degree of confinement between the LFA and overlying units. Construction of the wells was sequenced to facilitate these testing objectives.

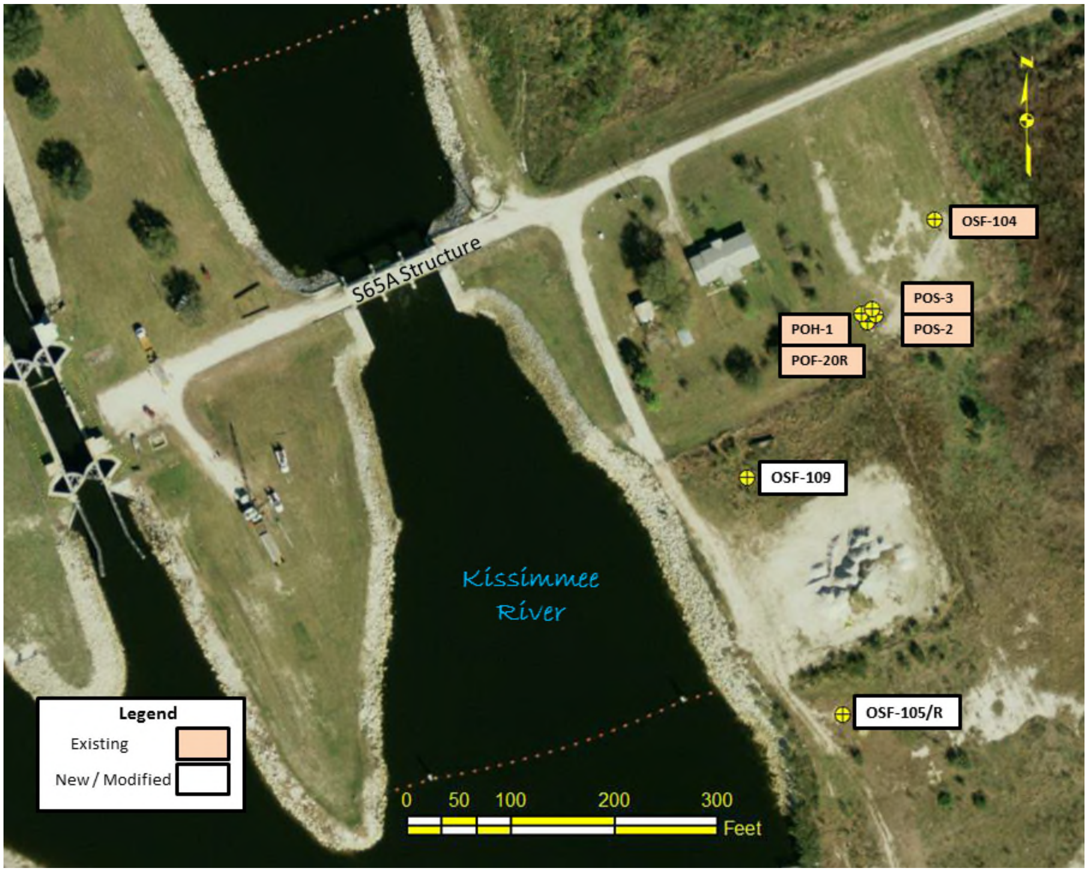


Figure 1-2. Site C general layout.
Note: Wells POF-20R, POH-1, POS-2, POS-3, and OSF-104 are located in Osceola County but were mislabeled as being in Polk County during installation. The names have stayed the same.

Table 1-1. Well completion information, Site C.

Well	Latitude (NAD83)	Longitude (NAD83)	Land Surface Elevation* NGVD29 (NAVD88)	Total Drilled Depth (ft bls)	Completion Date
OSF-109	273932.25	-810759.86	52.14 (50.9)	2000	November 9, 2012
OSF-105R	273929.28	-810758.68	49.34 (48.1)	1750	October 12, 2012
OSF-104	273934.74	-810757.83	54 (52.76)	2500	August 14, 2006
POF-20R	273933.77	-810758.55	55.35 (54.11)	397	2005
POH-1	273933.83	-810758.60		200	2005
POS-2	273933.83	-810758.46		30	2005
POS-3	273933.88	-810758.49		90	2005

*The offset between NGVD29 and NAVD88 is 1.24 ft at Site C.
NAD83: North American Datum of 1983
NGVD29: National Geodetic Vertical Datum of 1929
NAVD88: North American Vertical Datum of 1988

2

EXPLORATORY DRILLING AND WELL CONSTRUCTION

2.1. OSF-109 Well Construction: Phase I

After preparing the site and installing 40 ft of pit casing to support the rig, drilling of well OSF-109 commenced on April 5, 2012. The well was drilled via the mud-rotary method to a depth of 300 ft bls, which was identified by Bennett (2008) as the top of the FAS at this location. Lithologic cuttings were collected and geophysical logs were run on the pilot hole. The pilot hole was then reamed to a nominal 32-inch borehole. The unconsolidated sediments of the intermediate confining unit (ICU) were sealed off by cementing in place a 26-inch diameter carbon steel casing to a depth of 300 ft bls and the rig was reconfigured for reverse-air drilling.

A 12-inch pilot hole was advanced via the reverse-air method to a depth of 920 ft bls, near the anticipated top of the Avon Park permeable zone (APPZ). Formation and production logs were conducted on the pilot hole, which was then reamed to a nominal 26-inch diameter. A 20-inch diameter carbon steel casing was installed to a depth of 915 ft bls and grouted to the base of the uppermost permeable zone of the FAS, providing a temporary annular zone for later hydraulic testing. From the base of this casing to 1,270 ft bls, the approximate base of the APPZ, the borehole was advanced with a nominal 20-inch-diameter drill bit to facilitate aquifer performance testing of the APPZ.

At this point, construction was halted temporarily, and a 48-hour, constant rate discharge test (CRDT) was conducted on the APPZ. The open hole on OSF-109 (915–1,270 ft bls) served as the production well for this test. OSF-105 and OSF-104M provided production zone observation wells. POF-20R and the temporary annular zone on OSF-109 provided data from the overlying producing zone. Results of this CRDT are presented in **Section 5**.

Upon completion of this test, AWE reinstalled the drill-string and continued to advance the nominal 20-inch diameter borehole to 1,490 ft bls, the expected top of the LFA (Bennett, 2008). Formation and production logs were conducted on this borehole, then using the left-hand back-off method, a 12-inch-diameter steel casing was installed from 889 to 1,489 ft bls. The formation behind this casing was characterized by several highly fractured, grout-consuming intervals. These had to be filled with gravel to enable the grout seal to be completed. This casing served to isolate the LFA from the fresher waters of the overlying aquifers.

After installation of the 12-inch diameter casing, AWE reinstalled the drill string with a nominal 12-inch bit. AWE experienced difficulty getting past the back-off with this bit, and switched to a nominal 10-inch bit. They were able to drill out the cement plug with this bit assembly, but metal shavings in the cuttings return indicated some damage was done to the top of the back-off casing.

A 10-inch nominal diameter pilot hole was drilled from the base of the 12-inch casing to a total depth of 2,000 feet bls. At three points during this phase of construction, the drilling was stopped to allow short-term specific capacity testing of various intervals within the LFA. These interval tests were conducted when the pilot hole was at 1,635 ft bls, 1,762 ft bls, and 2,000 ft bls to provide rough estimates of incremental change in productivity during drilling. Results from the interval testing are documented in **Section 5.3**.

At the total well depth (2,000 ft bls), the drill string was removed and the hole was prepared for logging. Initial logging attempts failed when the logging tool was unable to enter the 12-inch casing. A down-hole video survey revealed that the top of the casing was torn, and a portion of it bent inward at approximately 906 ft bls. At this point, the testing program was halted while AWE performed a series of repairs on the well and test equipment. These culminated in the installation of a temporary funnel-shaped liner at the position of the damaged back-off to facilitate entry into the 12-inch casing. Final logging and packer-testing were conducted through this liner.

Based on the logging results, four intervals were selected for straddle-packer testing, focusing primarily on delineating water quality variation within apparent productive intervals (see **Section 5.4**). Upon completion of the packer testing operations, the bottom of the nominal 10-inch diameter pilot hole was permanently back-plugged. Based on the testing results, the final completion interval of 1,490 to 1,745 ft bls was selected with the intent that upon completion of a matching monitor interval in well OSF-105, OSF-109 would serve as the production well for aquifer performance testing of this portion of the lower Floridan aquifer. The pilot hole was filled with crushed limestone gravel to a depth of 1,760 ft bls and capped with ASTM Type II neat cement to a final depth of 1,745 ft bls. The rig was demobilized from OSF-109 and set up over the existing well OSF-105.

2.2. OSF-105R Well Construction

Well OSF-105 was originally drilled in 2006, when it served as the production well for aquifer performance testing of the UFA. At the start of this project, OSF-105 was a 12-inch diameter well, steel-cased to 930 ft bls and open to a highly fractured section of the APPZ. Bennett (2008) documents the construction and testing of this well and reports the total well depth as 1,217 ft bls. Prior to mobilizing the rig over OSF-105, an optical borehole image (OBI) log was conducted by the United States Geological Survey (USGS) to document the condition of the open-hole interval. The USGS log revealed the APPZ in OSF-105 to be significantly more fractured and cavernous than the same interval in well OSF-109, but in apparently stable condition (see **Appendix C**).

On September 5, 2012, AWE began reverse-air drilling of the pilot hole at OSF-105 with a nominal 10-inch drill-bit from the previously drilled depth (1,217 ft bls) to 1,350 ft bls. At this depth, the drill string was removed and reconfigured to facilitate coring operations. Based on the testing results from OSF-109 and the previously drilled OSF-104, four 10-foot intervals were selected for collection of rock cores. Core selections focused on identifying the nature and quality of apparent confining zones.

AWE lowered a nominal 4-inch diameter core barrel to 80 ft off bottom where it refused to advance. Three times through the day and night, AWE tripped out with the core barrel, then back in with the drill bit to wipe the hole to the bottom. The driller could feel large rocks being pushed down the borehole by the drill bit. When the core barrel was lowered, there was again an obstruction. Based on this, it was decided to abandon attempts to core at this depth. The pilot hole was advanced to the second core target at 1,423 ft bls.

Given the difficulties with caving rocks encountered during the first core attempt, it was deemed prudent to perform an additional logging survey (camera, caliper, and borehole deviation) to determine the exact location of the caving zone and potential for further problems. This concern proved well founded. Logging proceeded to a depth of only 1,100 ft bls before the borehole was blocked once again by a fallen boulder. After review of logs and video, SFWMD and AWE concurred that there was an abundance of loose rock material in the borehole and prospects for successful coring operations were poor. The decision was made to abandon further core attempts and resume reverse-air drilling. AWE reinstalled the nominal 10-inch bit, advanced the borehole to a total drilled depth of 1,750 ft bls, conditioned the borehole for geophysical logging, and then removed the drill string to facilitate geophysical logging.

Logging operations were again blocked by fallen rock, this time at a depth of 1,225 ft bls. AWE reinstalled the drill-bit assembly and completed a second wiper run to total depth. Logging operations were attempted a second time, and this time were blocked by fallen rock at 1,144 ft bls. At this point, work on OSF-105 was stopped while SFWMD and AWE considered options for moving forward with the project.

The severe instability in the formation throughout the open APPZ interval of OSF-105 forced major changes to the project plan. In addition to preventing the collection of rock core and geophysical logs, project specifications called for completion of OSF-105 as a dual-zone APPZ/LFA monitor well, to be used for aquifer performance testing and long-term monitoring of the LFA. This required the installation of 1,490 feet of 4-inch diameter FRP tubing to the top of the LFA. The chances of hanging and cementing that tubing successfully under the current borehole conditions were very poor. Neither SFWMD nor AWE were willing to undertake this risk. The risks, costs, and benefits were weighed for several possible options for completing the project as designed. Ultimately, a change order was issued to AWE authorizing a modified approach to completing the site. The redesign described in the following record was selected to maximize the data value and minimize the chances of continued borehole issues at OSF-105.

In order to provide a complete geophysical log record of the formation, particularly the middle confining unit where the large-diameter borehole in OSF-109 precluded quality log acquisition, AWE mobilized larger (6 5/8 inch) drill pipe to the site. This pipe was installed to a depth of 1,750 ft to clear the borehole of fallen debris, then moved up to 1,218 feet and held in place as a protective casing. Final logging (AWE: formation and static fluid logs, USGS: OBI) was conducted through this drill-pipe. Upon completion of logging, the borehole was backfilled with limestone gravel to a depth of 1,312 ft, then capped with 12 ft of neat cement to seal off communication between waters of the APPZ and LFA. The final completion of the remodeled OSF-105 (OSF-105R) is illustrated in **Figure 2-1** and detailed in **Table 2-1**.

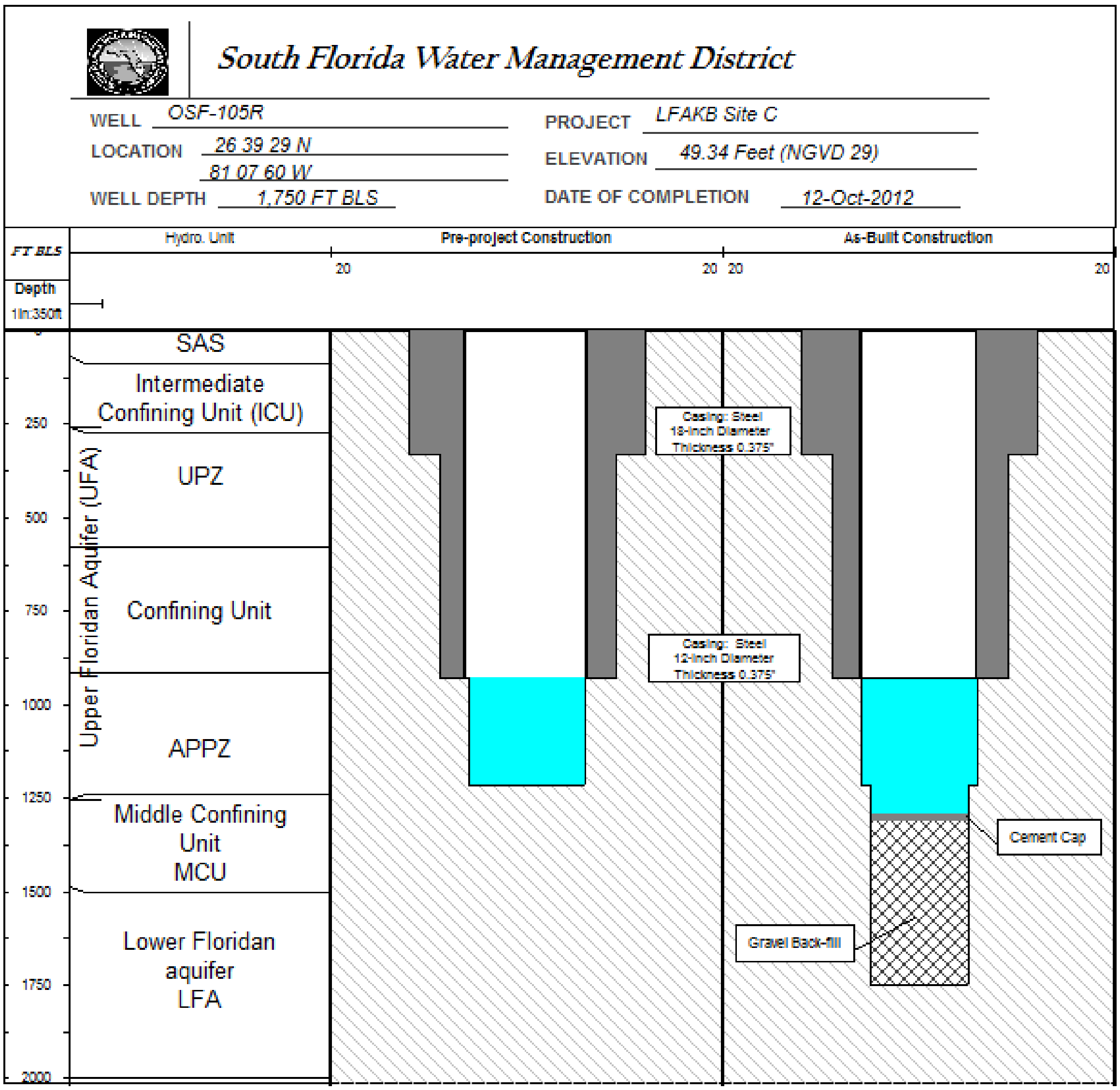


Figure 2-1. Pre-project OSF-105 and OSF-105R as-built well construction.

Table 2-1. Monitor interval for remodeled OSF-105.

Identifier	Monitor Interval (ft bls)	Completion Method	Aquifer
OSF-105R	93 1,300	Open Hole	APPZ

2.3. OSF-109 Well Construction: Phase II

The original plans for OSF-109 were to leave it as completed at the end of phase I construction and utilize it as a production well for an aquifer performance test (APT) of the Lower Floridan aquifer above the USDW. The unstable borehole conditions in OSF-105R prevented completion of that well as a LFA monitor well, however, limiting the planned APT to a single-well test, which would provide little value over the short-term specific capacity testing conducted during construction. Initial testing during the drilling of OSF-109 indicated the LFA above the USDW was characterized by two producing zones separated by a significant confining interval. This was indicated by pronounced differences in head and water-quality. Since 1,500 ft of FRP tubing remained after the problems at OSF-105R left, it was decided that the best use of this resource and the remaining project funds would be to purchase another 200 ft of FRP tubing and reconstruct OSF-109 as a dual-zone well to discretely monitor these two LFA producing zones.

Prior to ordering the additional tubing, a pressure test was conducted on OSF-109 to ensure that the well had suffered no loss of mechanical integrity due to the damage incurred at the top of the back-off casing. The temporary liner at the top of the damaged back-off was removed and a packer was installed in the 12-inch steel casing below the damaged area, at a depth of 922 ft bls. The well was filled with fresh water and pressurized to 30 pounds per square inch (psi). The wellhead was shut in for one hour with no measurable drop in pressure so the well was approved for further repair. AWE fabricated and installed a permanent adaptor to ensure there would be no impediment to logging tools at the position of the damaged back-off. This final repair was verified by a borehole video (BHV) log and approval was given to proceed with the modified construction plan for OSF-109.

Upon completion of backfill operations in OSF-105R, the rig was broken down and reconfigured over OSF-109. Next, 1,700 feet of 4-inch diameter FRP tubing was hung in OSF-109 and grouted back to a depth of 1,573 ft bls using cement baskets. When grouting operations were complete, a packer was set in the FRP tubing and a temporary well header was placed on the tubing in preparation for mechanical integrity (pressure testing) operations. The well was filled with fresh water and pressurized to 51 psi. The wellhead was shut in for one hour with less than 1 percent drop in pressure, well within the specified 5 percent tolerance level.

When mechanical integrity testing was complete, the lower zone of the completed well was developed until clear of visible turbidity and water quality field parameters (pH, temperature, and specific conductance) stabilized. A turbine pump was then installed in the annular zone of the well (first permeable zone of the LFA) and a single-well aquifer performance test was performed on this interval. Results of this aquifer performance test are documented in **Section 5**.

After all on-site testing was complete, the temporary annular zone monitor interval (300–580 ft bls) was backfilled with a 12 percent bentonite grout slurry and final wellheads and pads were installed on OSF-109 and OSF-105R. **Table 2-2** and **Figure 2-2** show the monitor intervals and completion details for OSF-109. The final wellhead configuration of OSF-109 is shown in **Figure 2-3**. A complete construction chronology and additional details on the work are provided in **Appendix A**.

Table 2-2. Monitor intervals for dual-zone LFA monitor well OSF-109.

Identifier	Monitor Interval (ft bls)	Completion Method	Aquifer
OSF-109U	1,489–1,573	Annular Zone	Lower Floridan
OSF-109L	1,694–1,745	Open Hole	Lower Floridan

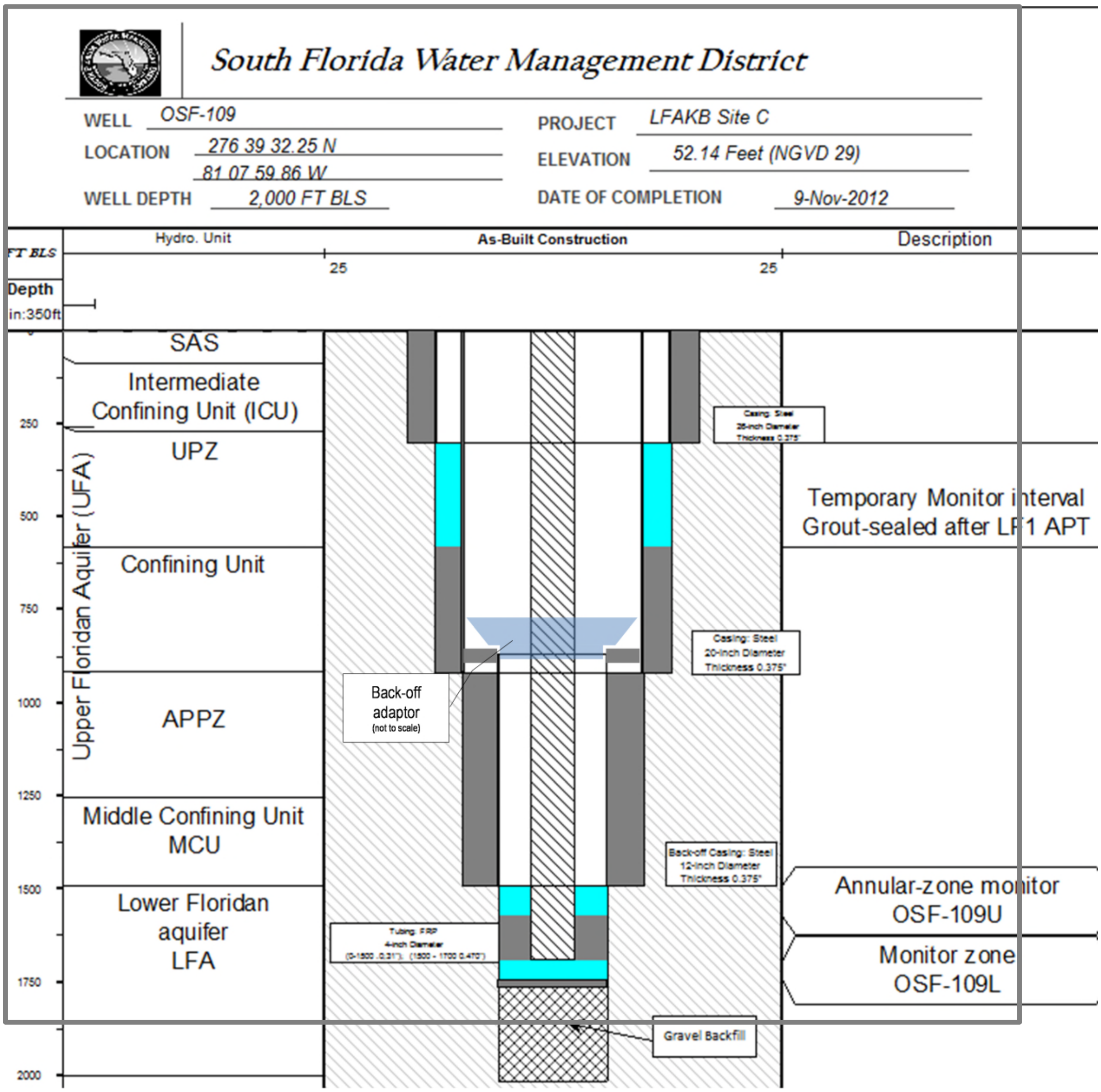


Figure 2-2. OSF-109 as-built well construction.

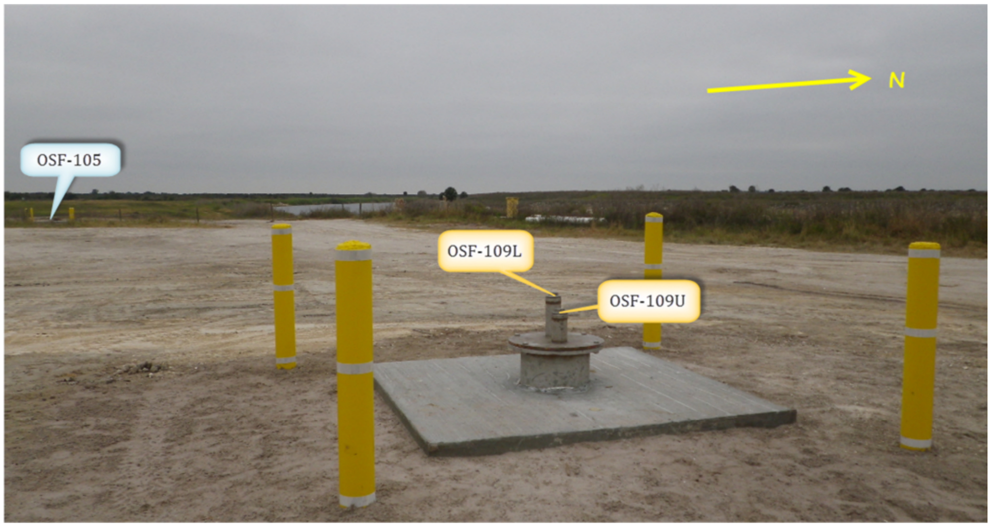


Figure 2-3. Final wellheads, Site C.

3 STRATIGRAPHIC FRAMEWORK

SFWMD staff collected geologic formation samples (well cuttings) from the pilot hole during the drilling of OSF-109 and described them with a focus on dominant lithologic and textural characteristics. The samples were described using the Embry and Klovan (1971) classification for carbonates. The sample descriptions and photographs of lithologic samples are presented in **Appendix B**. An additional description of the site lithology was published by Bennett (2008), who describes the construction and testing of OSF-104, drilled to a depth of 2,531 ft bls in 2005, and OSF-105, drilled to a depth of 1,220 ft bls from 2006 through 2007. The referenced report includes description of drill cuttings prepared by the Florida Geological Survey (FGS). Site lithology described here in this report is primarily based on drill cuttings from OSF-109 from land surface to a depth of 2,000 ft bls and OSF-104 from 2,000 to 2,500 ft bls, unless otherwise stated.

Geophysical logs, BHV logs, OBI logs, and the Formation Micro-Imaging (FMI) log (OSF-104) were also helpful in describing the geologic formations encountered during drilling. BHV logs were reviewed from approximately 300 to 2,000 ft bls at OSF-109, 933 to 1,221 ft bls at OSF-105, and 333 to 1,510 ft bls at OSF-104. OBI logs were reviewed for depth intervals 1,487 to 1,708 ft bls at OSF-109 and 922 to 1,732 ft bls at OSF-105. The FMI log was reviewed from 343 to 2,531 ft bls at OSF-104.

3.1. Holocene, Pleistocene, and Pliocene Series

Undifferentiated sediments of Holocene, Pleistocene, and/or Pliocene age occur from land surface to approximately 85 ft bls at the site based on the first presence of olive-gray silt and phosphatic sand in drill cuttings, indicative of the Hawthorn Group. These undifferentiated sediments consist of pale yellowish-brown to very pale orange, medium- to coarse-grained quartz sand with silt and up to 50 percent shell fragments, olive-gray calcareous clay, and shell beds with silt and clay. The borehole diameter increased significantly in the lower 25 ft corresponding to a zone washed out during drilling operations.

3.2. Miocene Series

The Hawthorn Group is composed of a heterogeneous mixture of silt, clay, calcareous clay, quartz sand, phosphatic sand and silt, limestone, and dolostone. Scott (1988) elevated the

Hawthorn Formation to group status in Florida. It consists of the Peace River Formation, composed of predominantly siliciclastic material, and the underlying Arcadia Formation, composed principally of carbonates.

3.2.1. Peace River Formation

The top of the Peace River Formation is present at a depth of approximately 85 ft bls at the site and consists of olive-gray, unconsolidated, and poorly indurated sand and silt with minor (less than 20 percent) phosphatic sand and gravel and up to 10 percent carbonate mud. Unconsolidated sediments consisting of shell, sand, and silt with phosphatic sand and gravel are present to the base of the formation at approximately 135 ft bls. The Peace River Formation is approximately 50 ft thick at this site.

Deposition of the Peace River Formation sediments began in the Middle Miocene when siliciclastic sediments overran Florida's carbonate bank environment (Scott, 1988). As sea level rose during this period, large amounts of siliciclastic material made their way to southern Florida, restricting carbonate sedimentation. Although the sediments of the Hawthorn Group show significant reworking, it appears that the depositional setting was a shallow to marginal marine environment.

3.2.2. Arcadia Formation

A lithologic change from predominately siliciclastic to mixed siliciclastic-carbonate sediments differentiates the Arcadia Formation from the overlying Peace River Formation. The contact is transitional/gradational (Bryan et al., 2011) and is placed where carbonate beds are more abundant than siliciclastic beds. A distinctive lithologic change occurs at the site at a depth of approximately 135 ft bls, where a poorly indurated, light olive-gray to dark gray dolostone and dolomitic mudstone with calcareous clay, shell, and phosphatic sand first occurs. It is the predominant lithology to the base of the formation. This carbonate interval is evidenced by a sharp gamma ray increase on geophysical logs and an irregular natural gamma log signature due to varying phosphatic sand content. Bennett (2008), placed the top of the Arcadia Formation at this site at 175 ft bls based on a change in lithologic character from a fine-grained quartz sand unit intermixed with limestone to a phosphatic, arenaceous limestone (wackestone) based on description of cuttings from OSF-104. However, drill cuttings from OSF-105 indicate a similar lithology change as observed in OSF-109 at approximately 140 ft bls. Natural gamma logs at all three wells indicate an increase in gamma log response, indicative of increased phosphate, at 130 to 140 ft bls, suggesting that the samples described for OSF-104 from this depth interval may not have been representative of the formation. The Arcadia Formation is approximately 145 ft thick at this site.

The Arcadia Formation developed during the Lower Miocene in a carbonate bank environment with the deposition of siliciclastics from a southward flowing, longshore current (Scott, 1988). The depositional setting appears to have been a quiet water (low energy) lagoon, similar to the environment currently present in Florida Bay (King, 1979).

3.3. Oligocene Series, Suwannee Limestone

The Suwannee Limestone was not present at this location.

3.4. Eocene Series

3.4.1. Ocala Limestone

The upper Eocene Ocala Limestone is identified at a depth of approximately 285 (OSF-105) to 296 ft bls (OSF-104) at the site. The upper contact of the unit with the Arcadia Formation is characterized by a change in lithology from light olive-gray dolostone and dolomitic mudstone to very pale orange, highly fossiliferous grainstone, a sharp reduction in gamma ray response from approximately 280 to 75 American Petroleum Institute (API) units, and the first occurrence of the diagnostic microfossil *Lepidocyclina*. The predominant lithology of the Ocala Limestone consists of a poorly indurated, very pale orange to grayish-orange, highly fossiliferous, skeletal packstone, grainstone, and rudstone with moderate to good intergranular porosity. Grain size ranges from medium sand to fine gravel, and commonly appears as loose aggregate in drill cuttings. Fossil types include the foraminifera *Lepidocyclina* and *Numulities*, echinoid spines, and bryozoa. The sonic log indicates very well developed porosity throughout the formation, with the greatest development from approximately 310 to 372 ft bls at OSF-109. Porosity logs at OSF-104 indicated high porosities from the base of the casing at 333 ft bls to approximately 350 ft bls. Little evidence of large-scale secondary porosity features such as cavities and fractures were observed on the BHV and OBI/FMI logs. The natural gamma log indicates a gradual reduction in gamma response throughout the formation to approximately 40 API units at its base. The Ocala Limestone is approximately 105 ft thick at this site.

The Ocala Limestone was deposited on a warm, shallow carbonate bank, similar to the modern day Bahamas (Miller, 1986). This low-energy environment probably had low to moderate water circulation (Tucker and Wright, 1990).

3.4.2. Avon Park Formation

The top of the middle Eocene Avon Park Formation is identified from lithologic samples at a depth of 390 ft bls, based on the first occurrence of *Cushmania* (formerly *Dictyconus)* and *Neolagnum* in OSF-105 (Bennett, 2008) and *Neolagnum* in OSF-109, both diagnostic microfossils used as biostratigraphic indicators for the Avon Park Formation (Bryan et al., 2011). A significant change in lithology was not noted in drill cuttings at this depth. A gradual decrease in gamma ray response is observed from approximately 40 API units in the overlying Ocala Formation (OSF-109) to approximately 30 to 25 API units in the Avon Park Formation. The FGS places the top of the Avon Park Formation at OSF-104 at 490 ft bls, based on the first occurrence of a diagnostic benthic foraminifera (*Fallotella*) (Bennett, 2008). Geophysical log correlation of the three boreholes indicates gamma ray characteristics are at approximately equivalent stratigraphic depths; therefore, the depth intervals of drill cuttings at OSF-104 may have been incorrectly labeled.

The upper 90 ft of the formation is predominantly a very pale orange, well-indurated foraminiferal grainstone with a sparry calcite matrix and low to moderate visible intergranular porosity. Fossil constituents include *Fallotella,* abundant in the upper 15 ft, *Neolagnum*, miliolids, echinoid and algal fragments, and fossil molds. Sonic logs in OSF-109 and OSF-104 indicate relatively high porosity, up to 65 to 75 percent, through this section and the caliper log indicates significant and irregular washout in the borehole. Below this section to a depth of approximately 595 ft bls, the lithology consists of interbedded wackestone, packstone, and grainstone, very pale orange in color with poor to moderate induration, and moderate to good intergranular and vuggy porosity. Abundant foraminifera throughout this section include *Fallotella* and *Cushmania*, in addition to miliolids and echinoid fragments. Sonic porosity is reduced to approximately 55 to 65 percent. The caliper log indicates a regular signature with the borehole diameter decreasing slightly. BHV and OBI/FMI logs through this interval show little evidence of significant large scale secondary porosity development, and porosity appears to be primarily intergranular and vuggy in nature.

The lithology between approximately 595 and 890 ft bls changes to interbedded, moderately indurated wackestone, packstone, and dolomitic limestone with relatively low primary and secondary porosity. Common fossils include abundant foraminifera (*Fallotella, Lepidocyclina, Cushmania, Numulities, Fabularia,* and miliolids) and fragments of echinoids, mollusks, and algae. Sonic porosity is gradually reduced in this section to approximately 35 percent in the lower portion. From approximately 890 to 916 ft bls, the lithology changes to interbedded, very pale orange wackestone with good intergranular porosity and well-indurated, yellowish-brown, microcrystalline to sucrosic dolostone with few fossils and little visual porosity. Natural gamma increases from approximately 20 to up to 50 API units from approximately 905 to 916 ft bls, and sonic porosity is reduced to as low as 15 percent. Little large-scale secondary porosity development is evident at the site from the top of the Avon Park Formation to approximately 916 ft bls based on geophysical and BHV logs.

At approximately 916 ft bls, lithology changes to a dark yellow-brown to pale yellow-brown, microcrystalline to sucrosic, well-indurated dolostone that is present to a depth of approximately 1,445 ft bls. A marked reduction in rate of penetration (ROP) was observed in OSF-109 at the top of this unit, from approximately 0.6 ft/minute in strata above to approximately 0.2 ft/minute in strata below (**Appendix A**). The dolostone unit typically includes visible vuggy, fossil moldic, and pinpoint porosity with evidence of fractures in drill cuttings, and interbeds of dark brown lamination. Large-scale, secondary porosity features such as fractures, cavities, and brecciated zones are evident from approximately 916 to 1,391 ft bls at the site based on geophysical, video, and OBI/FMI logs (discussed in more detail in **Section 4.3.1.2** of this report).

The lithology changes at approximately 1,445 ft bls to 1,530 ft bls to a very pale orange to grayish-orange, moderately indurated dolomitic limestone (wackestone) with a fine-grained, sucrosic texture and little visible pinpoint, fossil moldic, and vuggy porosity. An increase in ROP was observed in OSF-109 from approximately 0.1 ft/minute in strata above 1,435 ft bls to approximately 0.3 ft/minute in strata below (**Appendix A**). Relatively little large-scale secondary porosity development is evident at the site from approximately 1,390 to 1,490 ft bls based on BHV and/or OBI/FMI logs**.**

At a depth of 1,530 ft bls, the unit grades to a grayish-orange to moderate yellowish-brown, moderately indurated dolostone with fine-grained sucrosic texture and poor to good pinpoint, vuggy, and fracture porosity. Brown lamination is present at depth of 1,535 to 1,545 ft bls and 1,555 to 1,560 ft bls. From approximately 1,620 to 1,750 ft bls, lithology consists of a predominately moderately yellowish-brown to grayish-orange, well-indurated, sucrosic dolostone and moderate to good intergranular, pinpoint, vugular, and fracture porosity. Dolomitized foraminiferal grainstones are abundant from approximately 1,640 to 1,720 ft bls and 1,745 to 1,750 ft bls. Significant secondary porosity development, such as brecciation, fracturing, and numerous solution cavities, is evident on the BHV and OBI/FMI logs from approximately 1,490 to 1,650 ft bls and 1,660 to 1,750 ft bls (discussed in more detail in **Section 4.3.1** of this report).

From approximately 1,750 to 1,835 ft bls, lithology consists of predominately moderately yellowish-brown to grayish-orange, well-indurated, sucrosic dolostone with moderate to good visible intergranular, pinpoint, vugular, and fracture porosity. Dolomitized foraminiferal grainstones are abundant from approximately 1,750 to 1,765 ft bls and 1,805 to 1,830 ft. bls. The borehole-compensated sonic (BHCS) logs, BHV logs, and OBI/FMI logs indicate well-developed secondary porosity throughout this section.

From approximately 1,835 to 1,940 ft bls, lithology consists of grayish-orange, moderately indurated dolomitic limestone and well-indurated moderate yellow-brown sucrosic dolostone with moderate to high pinpoint and vugular porosity. Sample cuttings from approximately 1940 to 1950 ft bls indicate the lithology consists of very pale orange, moderately indurated limestone and dolomitic limestone with moderate pinpoint porosity, diagnostic of the top of the Oldsmar Formation. The top of this limestone unit is 1,947 ft bls on the geophysical logs in OSF-109. Numerous cavities and fractures, with lessor intervals of brecciation, were observed throughout most of this section through the base of the Avon Park Formation (discussed in further detail in **Section 4.3.1** of this report).

The Avon Park Formation is present to a depth of approximately 1,947 ft bls at the site and is approximately 1,560 ft thick. The abundance of dolostone, larger foraminifera, and sedimentary structures within the Avon Park Formation indicate peritidal to shallow, open marine deposition (Bryan et al., 2011).

3.4.3. Oldsmar Formation

The top of the early Eocene Oldsmar Formation is placed at 1,947 ft bls at OSF-109, at the transition to an approximately 10-foot-thick section of very pale orange, moderately indurated, fossiliferous limestone (packstone) and dolomitic limestone. The natural gamma response and lithology logs correlate well with OF-104, where the top of the Oldsmar Formation was placed at 1,948 ft bls (Bennett, 2008). A reduction in the ROP was observed in OSF-109 in the Oldsmar Formation, from approximately 0.3 ft/minute in strata above 1,930 ft bls (17 ft above the top of the Oldsmar Formation) to approximately 0.16 ft/minute in strata below 1,930 ft bls (**Appendix A**). The upper limestone unit has microcrystalline texture with dark gray lamination and moderately to well-developed pinpoint and vuggy porosity (**Figure 3-1**). This unit grades into microcrystalline dolostone and dolomitic limestone from approximately 1,960 to 1,980 ft bls, with up to 50 percent chert and 5 percent gypsum from approximately 1,970 to 1,980 ft bls (**Figure 3-2**). Lithology changes from 1,980 to 1,995 ft bls to a poorly indurated, very pale orange dolomitic limestone with poor porosity, and from 1,995 to 2,000 ft bls (total depth) to a yellowish-gray calcilutite with no observed porosity. Numerous cavities and fractures with lessor intervals of brecciation are observed from the top of the formation to approximately 1,994 ft bls in the BHV (OSF-109) and OBI/FMI logs.

Site lithology below 2,000 ft bls is based on lithologic and geophysical logs from OSF-104. The interval from approximately 2,000 to 2,020 ft bls consists of moderately indurated dolomitic limestone and good secondary porosity development. The interval from approximately 2,020 to 2,107 ft bls consists of moderately indurated mudstone with good primary porosity development based on BHCS and compensated neutron log analysis. The FMI log did not show evidence of large-scale secondary porosity development within the intervals described above.

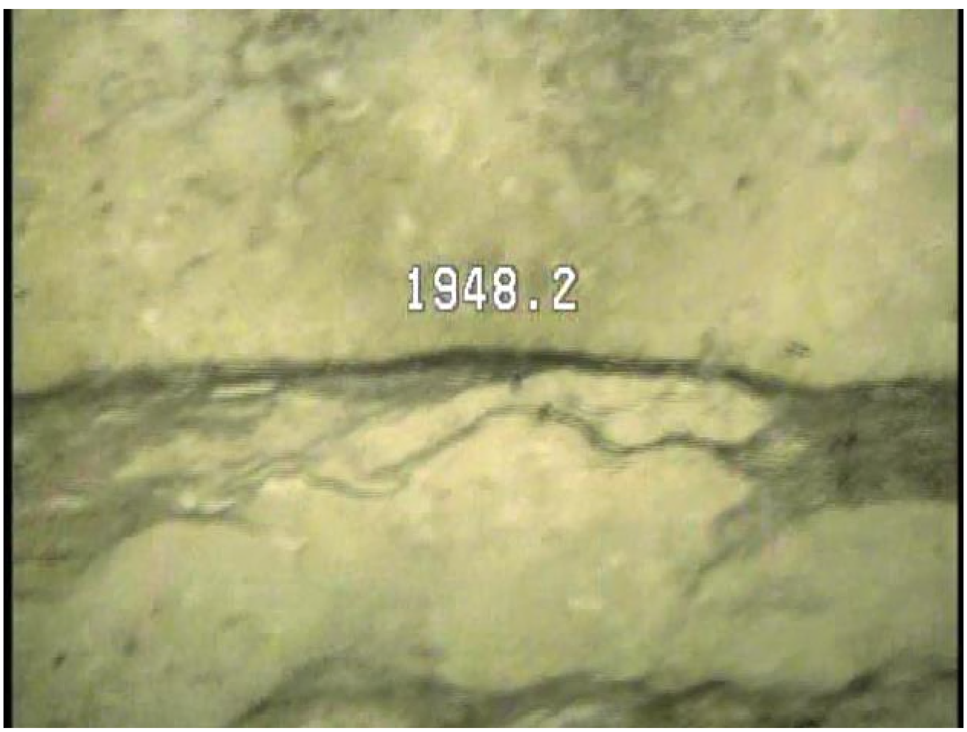


Figure 3-1. BHV view of lamination near top of Oldsmar Formation at approximately 1,948 ft bls.

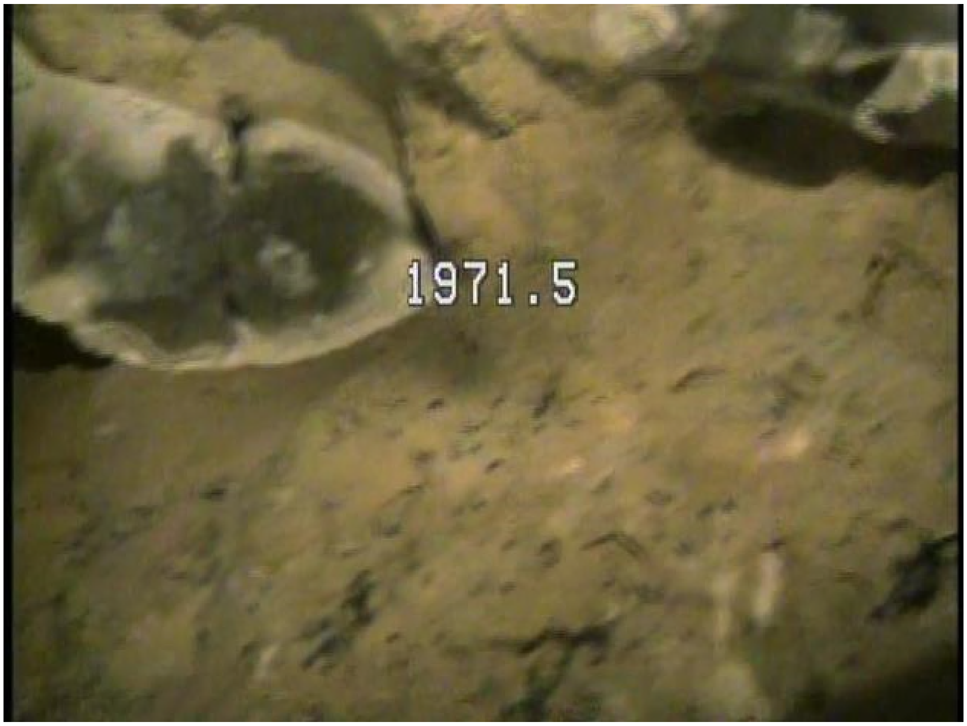


Figure 3-2. BHV view of chert nodules near the top of the Oldsmar Formation at approximately 1,971 ft bls.

Bennett (2008) describes the interval from 2,100 through 2,200 ft bls as composed of moderately indurated packstone and grainstone with good primary porosity development, becoming progressively more dolomitic, better indurated, and less porous from 2,200 through 2,240 ft bls. Little evidence of large-scale secondary porosity is observed on the FMI log. A potential flow zone at the base of this interval is evident based on an apparent cavernous zone visible on the FMI log from 2,242 through 2,251 ft bls.

The interval from 2,251 through 2,531 ft bls (total depth) consists predominantly of well-indurated, microcrystalline to crystalline dolostone with little visible porosity. Few large-scale solution features such as caverns and fractures were observed on the FMI log from 2,251 through 2,453 ft bls. The interval from 2,453 through 2,531 ft bls (total depth) includes well-developed secondary porosity evident on the FMI log.

The sediments of the Oldsmar Formation were deposited on a warm, shallow carbonate bank (Miller, 1986) or tidal flat (Duncan et al., 1994) environment.

4

HYDROGEOLOGIC FRAMEWORK

Two major aquifer systems underlie this site within the Quaternary/Tertiary sequence, the surficial aquifer system (SAS) and the Floridan aquifer system (FAS). The FAS is the primary focus of this investigation. Aquifers within the FAS are composed of multiple discrete zones of moderate to high permeability, many characterized by karst solution and fracturing. These productive zones are separated by lower permeability units of various degrees of confinement. These sub-units of the FAS are not consistently labeled in the literature. **Figure 4-1** presents a comparison of commonly used nomenclature. A representative hydrogeologic section, with hydrogeologic units conforming most closely to Site C conditions, is presented in **Figure 4-2**.

	Miller, 1986	SWFWMD (after Horstman, 2011)	SJRWMD (after Davis & Boniol, 2011)	SFWMD (after Reese & Richardson, 2007)
Floridan aquifer system	Upper Floridan aquifer	Upper Floridan aquifer: Suwannee permeable zone	Upper Floridan aquifer: Upper permeable zone	Upper Floridan aquifer
		Ocala low-permeability zone	Ocala / Avon Park low-permeability zone	Middle confining / semi-confining unit 1
		Avon Park permeable zone	Avon Park permeable zone	Avon Park permeable zone
	Middle confining unit (I, II or VI)	Middle confining unit (I, II or VI)	Middle confining unit I Middle confining unit II	Middle confining unit 2
	Lower Floridan aquifer	Lower Floridan aquifer (below middle confining unit I, II or VI)	Lower Floridan aquifer: Upper permeable zone confining unit Lower permeable zone Boulder zone Fernandina zone	Lower Floridan aquifer
Sub-Floridan confining unit				

Figure 4-1. A nomenclature comparison of the hydrogeologic units within the Floridan aquifer system.

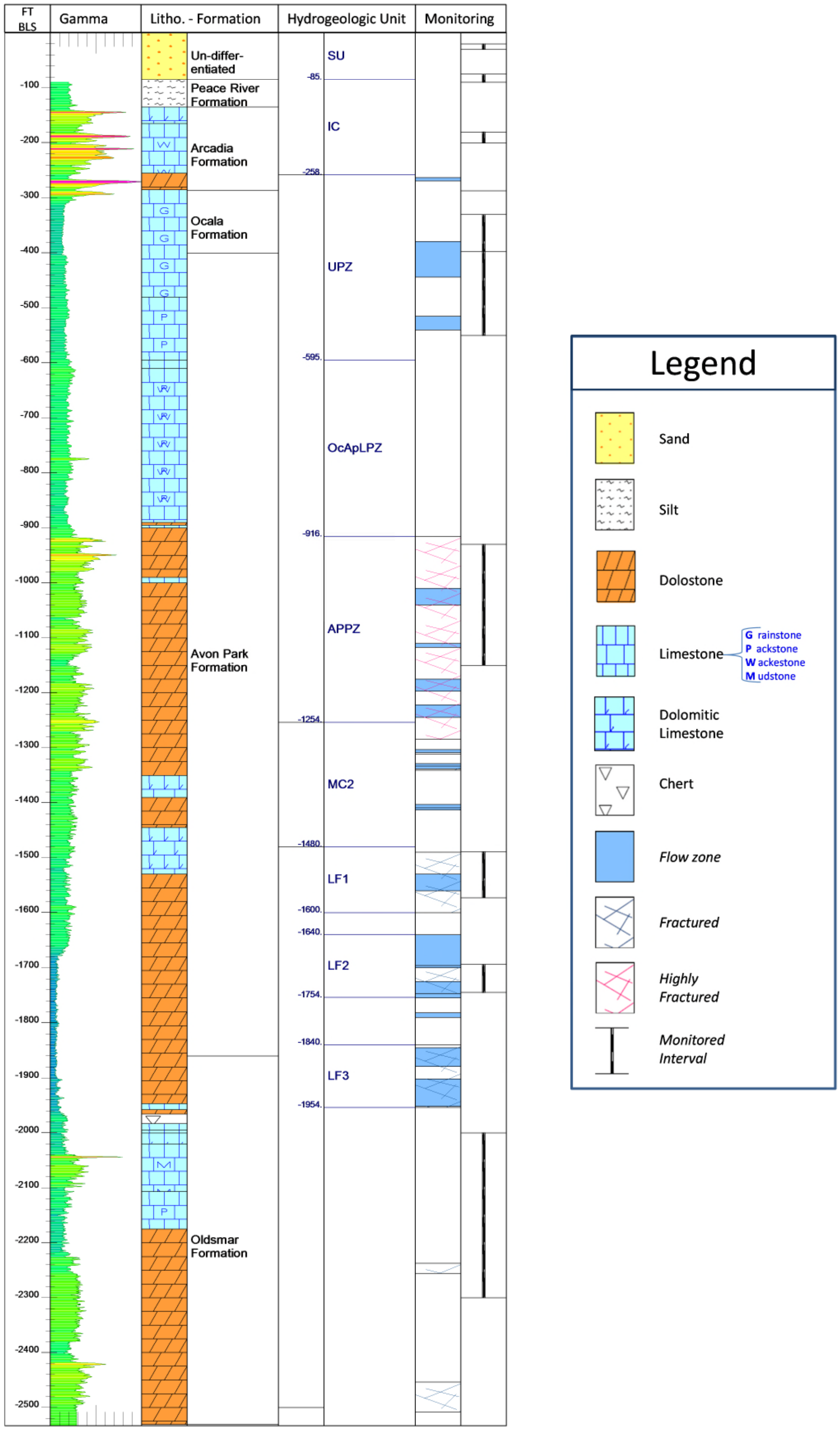


Figure 4-2. Representative hydrogeologic section for Site C.

4.1. Surficial Aquifer System (SAS)

The SAS varies from approximately 100 to 150 ft thick in southeastern Polk County (Spechler and Kroening, 2007). At this location, the SAS consists of undifferentiated Holocene sediments that occur from land surface to a depth of approximately 85 ft bls (OSF-109) and 110 ft bls (OSF-105). The sediments consist of pale yellowish-brown to very pale orange, medium- to coarse-grained quartz sand with silt and up to 50 percent shell fragments, olive-gray calcareous clay, and shell beds with silt and clay. The SAS is not a major source of potable water in the Kissimmee Basin. Two SAS monitoring wells were installed at Site C prior to the LFA investigations: POS-2 is screened from 20 to 30 ft bls, and POS-3 is screened from 75 to 90 ft bls, which includes the SAS and approximately 5 feet of the upper ICU.

The ion chemistry of POS-3 is more similar to POH-1, which is screened in the ICU from 180 to 200 ft bls, than POS-2 (for more information, see Section 5.2). Frazee (1982) characterizes both of those wells as having recharged through a clay-silt estuarine depositional environment high in sodium bicarbonate ($NaHCO_3$). These results imply some degree of vertical confinement between POS-2 and POS-3.

4.2. Intermediate Confining Unit (ICU)

The ICU in southeastern Polk County is approximately 200 ft thick (Spechler and Kroening, 2007). At this location, the ICU extends from approximately 85 to 258 ft bls. One ICU monitoring well, POH-1, with a screen interval from 180 to 200 ft bls, was installed at Site C prior to the LFA investigations.

Hawthorn Group sediments that make up the ICU consist of unconsolidated and poorly indurated sand and silt with phosphatic sand and gravel of the Peace River Formation, and poorly indurated dolostone and dolomitic mudstone and phosphatic sand and silt of the Arcadia Formation. The base of the ICU at Site C is approximately 30 ft above the base of the Arcadia Formation. Spechler and Kroening (2007) describe sediments within the Hawthorn Group in western Polk County with sufficient permeability to warrant being referred to as an aquifer system (intermediate aquifer system). This has not been reported as far east as Site C and significant permeability was not observed during the drilling and testing here.

The sediments of this unit act as a confining unit, separating the FAS from the overlying SAS. Background water levels indicate distinct head differences, implying confinement between these two aquifer systems, but there is evidence of significant leakage through the ICU under pumping stress. An aquifer performance test (APT) was conducted at Site C in 2006 (Bennett, 2008) utilizing the interval from 330 to 550 ft bls in the UFA at OSF-105 as the production zone, and water level response to that pumping stress was observed in SAS (POS-3) and ICU (POH-1) monitoring wells. Consequently, the ICU is characterized as semi-confining at Site C.

4.3. Floridan Aquifer System (FAS)

The FAS consists of a series of Tertiary limestone and dolostone units. At this site, the system includes permeable sedimentary strata of the Arcadia Formation, Ocala Limestone, Avon Park Formation, and Oldsmar Formation. The base of the FAS occurs in the Paleocene Cedar Keys Formation, not encountered at Site C, which includes massive beds of gypsum and anhydrite (Miller, 1986).

4.3.1. Upper Floridan Aquifer (UFA)

At Site C, the UFA includes permeable zones within the Arcadia Formation, the Ocala Formation and upper portions of the Avon Park Formation, and the Avon Park Permeable Zone within the middle portion of the Avon Park Formation. The top of the UFA occurs at depths of approximately 258 ft bls at OSF-109 and 263 ft bls at OSF-104.

4.3.1.1. Upper Permeable Zones (UPZ)

Three productive zones are present near the top of the FAS to a depth of approximately 560 ft bls (OSF-109).

The upper zone consists of an approximately 2-ft thick bedding plane, which is a cavernous zone within a dolomitic limestone unit interbedded with phosphatic silt, sand, and clay of the lower Arcadia Formation. This zone was evident during drilling of OSF-109 based on a 2-ft drop in the drill bit and lost circulation of approximately 8,000 gallons of drilling fluid at depths from 258 to 260 ft bls. Geophysical logs indicate this zone is characterized by an increase in borehole diameter and relatively low gamma ray response just above a sharp increase in the gamma ray log. FMI-derived permeability log (KTIM) analysis (OSF-104) indicates this high permeability interval occurs at approximately 263 to 269 ft bls. This portion of the aquifer was not included in subsequent testing.

The interval beneath the uppermost permeable zone to a depth of approximately 379 ft bls (OSF-109) and 387 ft bls (OSF-104) consists of relatively low permeability dolostone and phosphatic silt, sand, and gravel of the Arcadia Formation and skeletal packstone, grainstone, and rudstone of the Ocala Formation. Few large-scale karstic solution features are observed on the BHV and OBI/FMI logs. Although sonic porosity logs and cutting descriptions indicate over 50 percent intergranular porosity within the Ocala Formation, geophysical log analysis and the flow log (OSF-109) indicate little permeability or flow. Analysis of the KTIM log (OSF-104) indicates an apparent confining interval based on log-derived hydraulic conductivity of less than 0.1 ft/day from 358 to 387 ft bls, coincident with the presence of kaolinite clay up to approximately 20 percent. Additionally, Bennett (2008) observed that while drilling OSF-104, the interval from 300 to 370 ft bls appeared non-productive based on insufficient formation water production during reverse-air drilling.

Two productive intervals are evident on the dynamic flow log (using caliper corrected flow) from OSF-109, which indicates diffuse flow from approximately 379 to 444 ft bls and 515 to 540 ft bls. These intervals correspond to moderately to well-indurated grainstone and packstone, respectively, with moderate to low visual porosity evident in drill cuttings. Productivity of these zones was confirmed by the results of the APT conducted in 2006 at OSF-105, which pumped the interval from 330 to 550 ft bls and yielded a transmissivity of 11,423 ft^2/day and a storage coefficient of 5.5 x 10^{-3} (Bennett, 2008). Data from the 2006 test was incorporated into modeling analysis of APT#1 (see **Section 5.3.1**), yielding a reduced estimate for transmissivity of this interval. The SFWMD (Bennett, 2008) selected the depth interval of 330 to 550 ft bls in OSF-104U for long-term monitoring and hydraulic testing.

Published testing results of the upper permeable zone of the UFA (equivalent to Zone A of the UFA in older publications) in Polk County have reported a wide range of transmissivity values, from greater than 100,000 ft^2/day in the northwest to less than 5,000 ft^2/day in the east and southeast. Productivity of the UPZ at the site is consistent with the lower values observed in the southeastern portion of the county.

An interval of low permeability was encountered from the base of the lower UPZ to the top of the underlying APPZ. The lithology of this interval is characterized by an increase in fine-grained sediments (wackestones and mudstone) with low intergranular porosity, increased dolomitic limestone, and dolostone interbeds in the lower portion. Few significant large-scale solution features, such as cavities and fractures, are present and sonic porosity is significantly reduced. Limited confining capacity is suggested by the minor diffuse flow evident on the dynamic flow logs (OSF-109), a minimal head drop of -0.06 ft (median difference over six-year period of record) between the overlying UPZ and the underlying APPZ (described in **Section 5.5**), and similar water quality characteristics of the two zones as demonstrated in samples from OSF-104U (UPZ) and OSF-104M (APPZ) (described in **Section 5.2**). This low permeability zone was described at Site C by Bennett (2008) as Middle Confining Unit 1 (MC1), a regional confining unit in central and southern Florida above the underlying APPZ (Reese and Richardson, 2007). Regionally, the MC1 thickens and becomes increasingly confining in southern Florida, but it may be absent altogether in northern central Florida. This regional variability has led often to conflicting nomenclature. Where present within the CFWI area, MC1 is most often considered a subunit of the UFA. In many areas of western Florida, it consists almost entirely of rocks of the Ocala Limestone. Many recent publications now refer to this unit as the Ocala low permeability zone (Horstman, 2011; Sepulveda et al., 2012) or Ocala-Avon Park low permeability zone (Davis and Boniol, 2011). Based on its stratigraphic position and the limited confining characteristics described in this investigation, this report refers to this interval as the Ocala-Avon Park low permeability zone.

4.3.1.2. Avon Park Permeable Zone (APPZ)

Reese and Richardson (2007) describe the APPZ as lying between the Upper and Lower Floridan aquifers and correlate the unit across central and southern Florida. In central Florida, where overlying confinement may be weak or absent, the APPZ is considered a part of the Upper Floridan aquifer. Older publications from the central Florida region tend to refer to this unit as Zone B of the Upper Floridan aquifer, but the term APPZ is now in common usage. The APPZ is characterized by dolostone or interbedded dolostone and dolomitic limestone, with a high degree of secondary permeability. Permeability is primarily associated with fracturing, but cavernous or karstic, intergranular, and intercrystalline permeability can also be present (Reese and Richardson, 2007).

The APPZ consists predominantly of moderate to dark yellow-brown, microcrystalline to sucrosic, well-indurated dolostone. The top of the APPZ is coincident with the top of the first, thick sequence of dolostone at the site. Vuggy and fossil moldic porosity is observed in drill cuttings throughout most of the section. The high porosity and permeability of the APPZ at this site is primarily due to large-scale secondary porosity features such as brecciation, solution-enhanced fractures, and large cavities, rather than primary porosity features or smaller-scale secondary porosity features such as vugs.

The top of the APPZ at Site C occurs at depths of approximately 924 ft bls at OSF-104, 916 ft bls at OSF-109, and 920 ft bls at OSF-105. The base is placed at a depth of approximately 1,254 ft bls based on fracture/solution cavity development, flow log analysis at OSF-109, and changes in water quality below this depth. This is the base of freshwater influx to the borehole. The SFWMD selected the depth intervals of 925 to 1,222 ft bls in OSF-104 (OSF-104M) for long-term monitoring and 930 to 1,300 ft bls for hydraulic testing because this interval includes the significant productive intervals of the APPZ.

The vertical extent and distribution of permeable strata varies significantly between each of the wells as illustrated in **Figure 4-3** by the differential caliper[1] logs for each well. OSF-105 exhibits the greatest vertical extent and density of large-scale secondary porosity development observed at the site. This contributed to difficulties experienced during construction of the well and impacted interpretation of aquifer performance testing in this aquifer. BHV, OBI, and caliper logs indicate a nearly continuous section of brecciated, cavernous, and/or fractured strata from approximately 930 to 1,254 ft bls at OSF-105 (**Figure 4-4** through **Figure 4-6**; see **Appendix C** for image logs). BHV, FMI, and caliper logs at OSF-104 indicate brecciation, fractures, and numerous large cavities from approximately 946 to 1,285 ft bls. Similar features were observed in video and geophysical logs at OSF-109 from 916 to 938 ft bls, and two distinct zones with numerous cavities and fractured strata were observed from1,075 to 1,137 ft bls and 1,213 to 1,262 ft bls.

[1] Caliper Diameter (in) – Nominal Borehole Diameter (in)

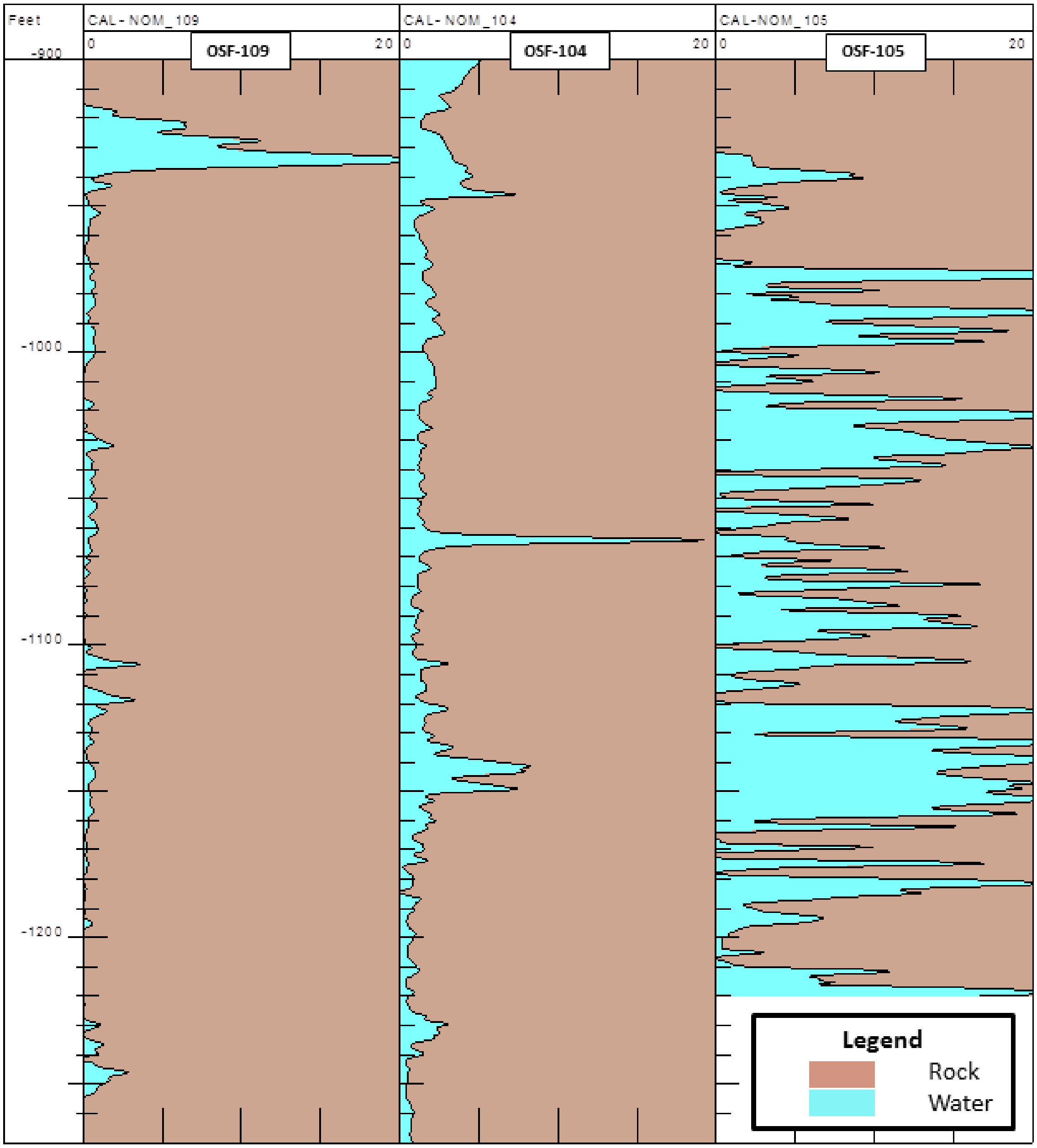


Figure 4-3. Differential caliper logs, indicating variation in fracture intensity within the APPZ across Site C.

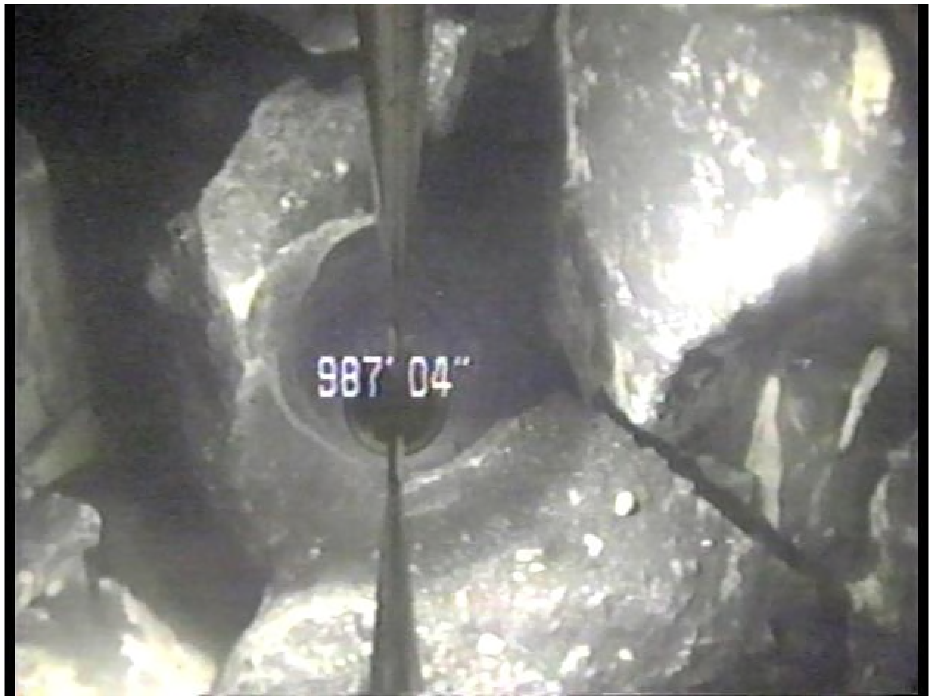


Figure 4-4. BHV view of brecciation in OSF-105 (987 ft bls).

Figure 4-5. BHV view of fractures bounding a cavity in OSF-105 (982 ft bls).

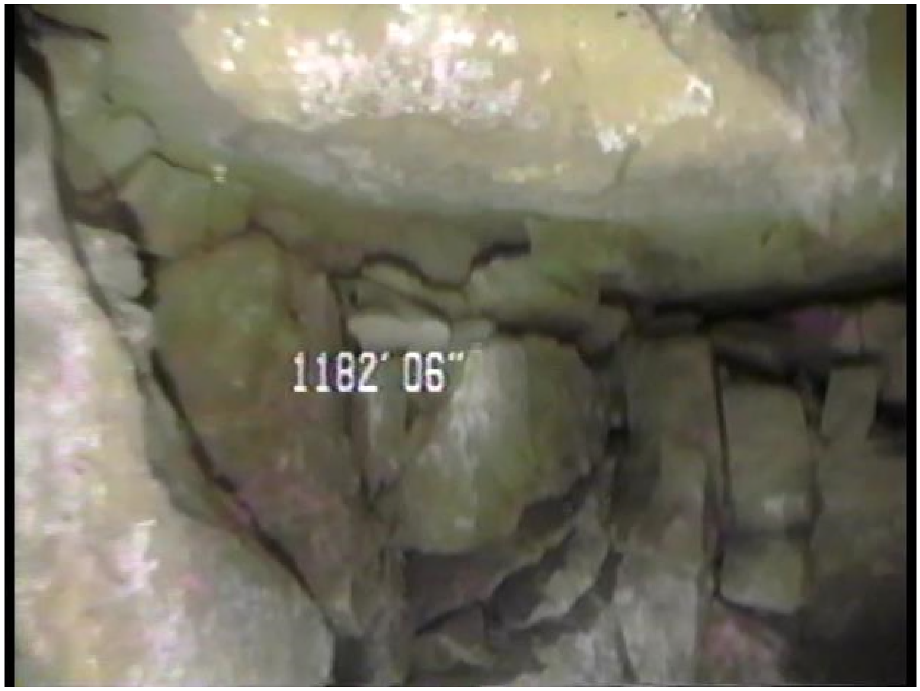


Figure 4-6. BHV view of large cavity in OSF-105 (1,182 ft bls).

In addition to the data summarized above, the APPZ is considered to have high permeability and potential productive capacity based on the following hydraulic and water quality characteristics:

- Bennett (2008) identified three discrete flow zones in well OSF-104 (1,060, 1,140, and 1,230 ft bls) that were the primary sources of production from the APPZ interval and diffuse flow from 1,105 to 1,174 ft bls. Production logging from well OSF-109 (see **Appendix C**) showed a similar pattern, but at different depths. Moderate influxes of water entered the borehole through diffuse flow across the intervals from 1,010 to 1,040 ft bls, 1,175 to 1,197 ft bls, and 1,222 through 1,245 ft bls, while the primary production came from relatively discrete fractured zones centered at 1,112 and 1,230 ft bls.

- An APT conducted in 2007 (Bennett, 2008) utilized the interval from 930 to 1,202 ft bls in OSF-105 as the production zone. Water level response in the monitoring well (OSF-104M) was not sufficient to distinguish from background fluctuations. Based on a specific capacity calculation (Driscoll, 1986), a transmissivity of 78,877 ft^2/day was derived for the APPZ.

- APT#1 of this study utilized the interval from 920 through 1,250 ft bls in OSF-109 (temporary open interval) as the production zone well and 930 through 1,150 ft bls in OSF-104M as monitoring intervals. Results of this test indicated that the transmissivity was in excess of 400,000 ft^2/day, which is much greater than previously calculated (see **Section 5.3.1**).

4.3.2. Middle Confining Unit (MCU)

The top of the middle Floridan confining unit (MCU) at Site C was identified at 1,254 ft bls based on reduced fractures and large-scale solution features evident in BHV and OBI/FMI logs, limited water production evident on the flow and/or temperature logs, and a clear increasing trend in formation salinity below this depth. The MCU (OSF-109) consists predominantly of microcrystalline to fine-grained sucrosic, moderately to well-indurated dolomitic limestone, and dolostone with low to moderate pinpoint and vuggy porosity. This zone occurs entirely within the middle of the Avon Park Formation. Relatively thin intervals with fractures and cavity development and minor flow were identified in OSF-109 from approximately 1,303 through 1,312 ft bls, 1,329 through 1,341 ft bls, and 1,403 through 1,413 ft bls. These intervals are included in the MCU based on lack of significant flow observed in flow logs at OSF-109 and OSF-105, their relative infrequency, and significant difference in water quality.

Confining properties of the MCU are inferred based on the lithology and borehole characteristics described above and the following hydraulic and water quality characteristics:

- A water quality transition observed in groundwater sample results from between OSF-104M and OSF-109 (APPZ) that yielded 248 and 302 mg/L of total dissolved solids (TDS), respectively, and samples from OSF-109U and OSF-109PT4 (LF1) that yielded 2,722 and 2,904 mg/L TDS, respectively. Groundwater samples from the APPZ have Frazee (1982) classifications of TW-I (seawater begins to dominate source water) and TW-I/TCW (connate water dominates source water), as compared to the Frazee classifications of the underlying Lower Floridan permeable zone 1 (LF1) as purely connate water (see **Section 5.2.2**).

- A water quality transition evidenced by a significant increase from fresh to brackish water based on borehole fluid logs and specific-conductance of drill-stem test (DST) samples from OSF-109 and OSF-104 at depths of approximately 1,260 and 1,380 ft bls, respectively (see **Section 5.2**).

- The median measured head drop between the APPZ (OSF-104M) and the underlying LF1 (OSF-109U) in the completed wells was -1.81 feet (October 21, 2013, through November 7, 2013) (see **Section 5.5).**

4.3.3. Lower Floridan Aquifer (LFA)

The LFA is a thick sequence of carbonate rocks that contains several permeable zones separated by thick semi-confining units (Miller, 1986). For central and southern Florida, the LFA permeable zones above the Boulder Zone are described by Reese and Richardson (2007) and labeled sequentially (LF1, LF2, etc.) from highest to lowest. This report uses the same nomenclature system. It is important to note, however, that this labeling convention is specific to an individual site. These flow zones have not been correlated regionally and further work will be required to make these kinds of interpolations from a regional perspective. The top of the LFA occurs at a depth of approximately 1,480 ft bls at Site C. The base was not encountered in the boreholes advanced. Bennett (2008) divided the LFA into LFA1, from 1,490 to 1,635 ft bls, and LFA2, from 1,949 ft bls to total depth (TD) of 2,531 ft bls.

This report identifies three permeable zones, LF1, LF2, and LF3 (shown on **Figure 4-3**), based on direct or inferred evidence of productivity demonstrated from flow logs, packer tests, APTs, and/or water quality changes, supplemented with aquifer characteristics observed on geophysical, BHV, OBI, and/or FMI logs. Zones that appear to have significant permeability based on aquifer characteristics, but without direct evidence of flow, are discussed as potential permeable zones.

4.3.3.1. LF1

The first permeable zone in the Lower Floridan aquifer, LF1, occurs from approximately 1,480 to 1,600 ft bls. The SFWMD selected the depth intervals of 1,489 to 1,573 ft bls in OSF-109 (OSF-109U) for long-term monitoring and hydraulic testing because this interval includes the significant productive intervals of LF1.

The upper portion of LF1 consists of a moderately indurated dolomitic limestone with very fine-grained sucrosic and moldic texture and low visual porosity, and the lower portion consists of moderately to well-indurated dolostone with fine-grained sucrosic texture and moderately to highly visible fracture, pinpoint, and vuggy porosity. Throughout this section, the BHCS logs indicate highly irregular, spikey transit times with numerous porosity zones of over 50 percent and up to 8 ft thick, which correspond to large cavity-rich (see **Figure 4-7**) and fractured zones on the video and OBI logs and are correlative to similar zones observed in OSF-104 and OSF-105. LF1 is considered to have low to moderate permeability and potential productive capacity based on interval test 1, the dynamic flow log, packer tests, and DST results, as summarized below:

- The dynamic flow log of OSF-109 indicates diffuse flow from approximately 1,520 through 1,560 ft bls.
- Reduced static fluid temperature and static fluid conductivity in OSF-109 from approximately 1,508 through 1,575 ft bls infers flow into the borehole.
- A freshening of discharge water at OSF-104 and OSF-109 was observed during DST testing between approximately 1,570 and 1,630 ft bls (see **Section 5.2.1**). This water quality transition may be the result of higher flow through that part of the aquifer.
- Interval test 1 stressed the interval from 1,489 through 1,635 ft bls during construction of OSF-109, yielding a specific capacity of 14.85 gallons per minute per foot (gpm/ft). A transmissivity of 3,970 ft^2/day was derived for this interval, which encompassed LF1 (see **Section 5.3.2**).
- Packer test OSF-109PT4, from 1,545 through 1,575 ft bls, yielded an estimated transmissivity of 2,686 ft^2/day based on specific capacity (see **Section 5.4**).

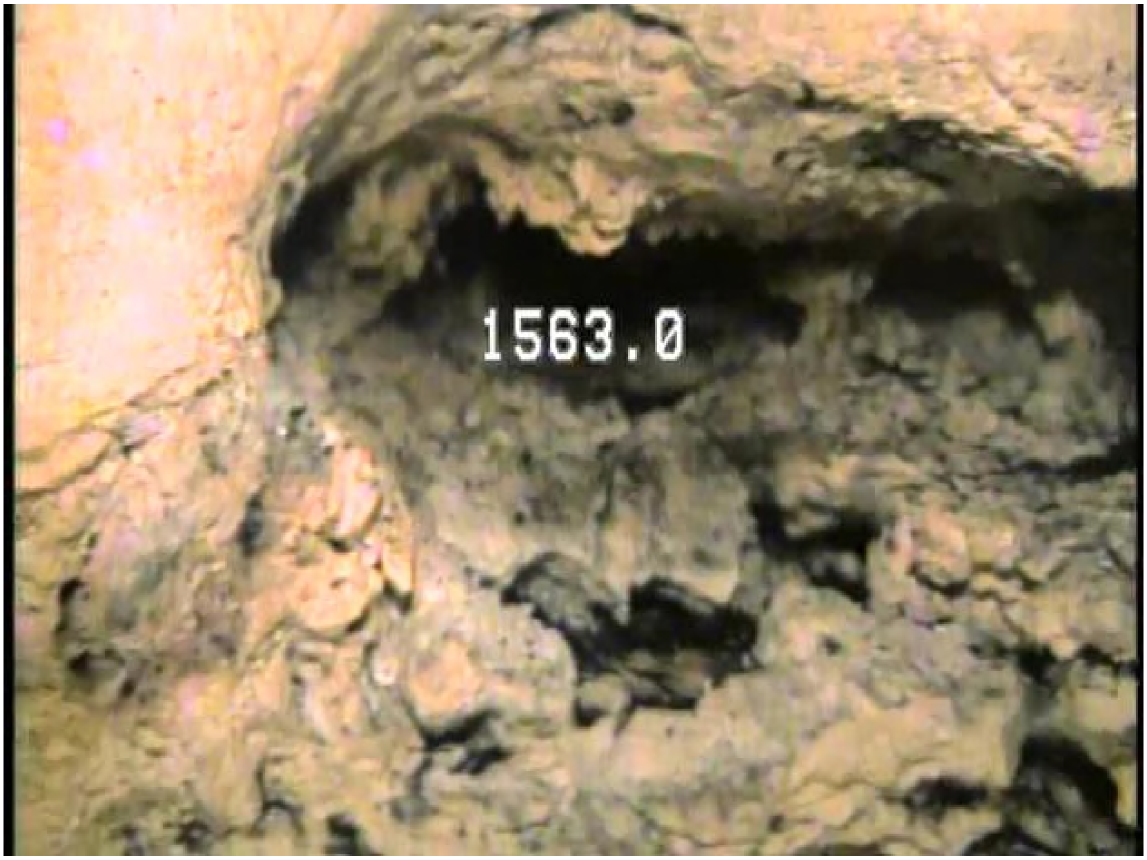


Figure 4-7. Image of cavity from BHV logging of OSF-109.

A relatively thin semi-confining interval exists between LF1 and LF2 and is characterized by a lack of flow observed on the flow logs, slight reduction in and more consistent (less spiky) sonic transit times, and fewer fractures and large-scale solution features seen on the video and OBI/FMI logs. The lithology of drill cuttings is little changed from LF1 and consists of well-indurated, sucrosic dolostone with moderate to high pinpoint and vuggy porosity. Confining properties between LF1 and the underlying LF2 are inferred based on the following hydraulic and water quality characteristics:

- There was a measured head difference of 4 ft between packer test 4 (LF1) and packer test 3 (LF2). The median measured head drop between LF1 (OSF-109U) and the underlying LF2 (OSF-109L) in the completed wells (see **Section 5.5**) was 5.36 ft (October 21, 2013 through November 7, 2013).

- A water quality transition from groundwater samples OSF-109U and OSF-109PT4, within LF1, which yielded 2,722 and 2,904 mg/L TDS, respectively, and sample OSF-109PT3, within LF2, which yielded 6,933 mg/L TDS (see **Section 5.2**). The groundwater samples from LF1 are classified as CW (connate water), compared to the TRSW (transitional seawater) groundwater classification of the sample from the LF2.

- Results from APT#2 yielded estimated leakance of 0.06–0.008 per day across this interval under stressed conditions (see **Section 5.3.3**).

4.3.3.2. LF2

The second permeable and potential productive interval in the Lower Floridan aquifer (LF2) occurs from approximately 1,640 to 1,754 ft bls (OSF-109). The SFWMD selected the depth intervals of 1,684 to 1,745 ft bls in OSF-109 (OSF-109L) for long-term monitoring and hydraulic testing because this interval includes the significant productive intervals of LF2.

The lithology of LF2 consists of a moderate to well-indurated sucrosic dolostone with moderately to highly pinpoint, vuggy, and/or fracture porosity. The BHCS logs indicate spikey transit time with intervals up to 30 ft thick with greater than 50 percent porosity that correspond to cavity-rich, fractured, and cavernous zones visible on the BHV and/or OBI/FMI logs. Two prominent zones with cavernous and cavity-rich porosity from 1,696 to 1,708 ft bls and 1,726 to 1,740 ft bls were evident on the BHCS and BHV logs of OSF-109. These zones were correlative to similar sections of OSF-104 and OSF-105. Flow into the borehole was observed in the BHV log in the uppermost zone in OSF-109 (**Figure 4-8**).

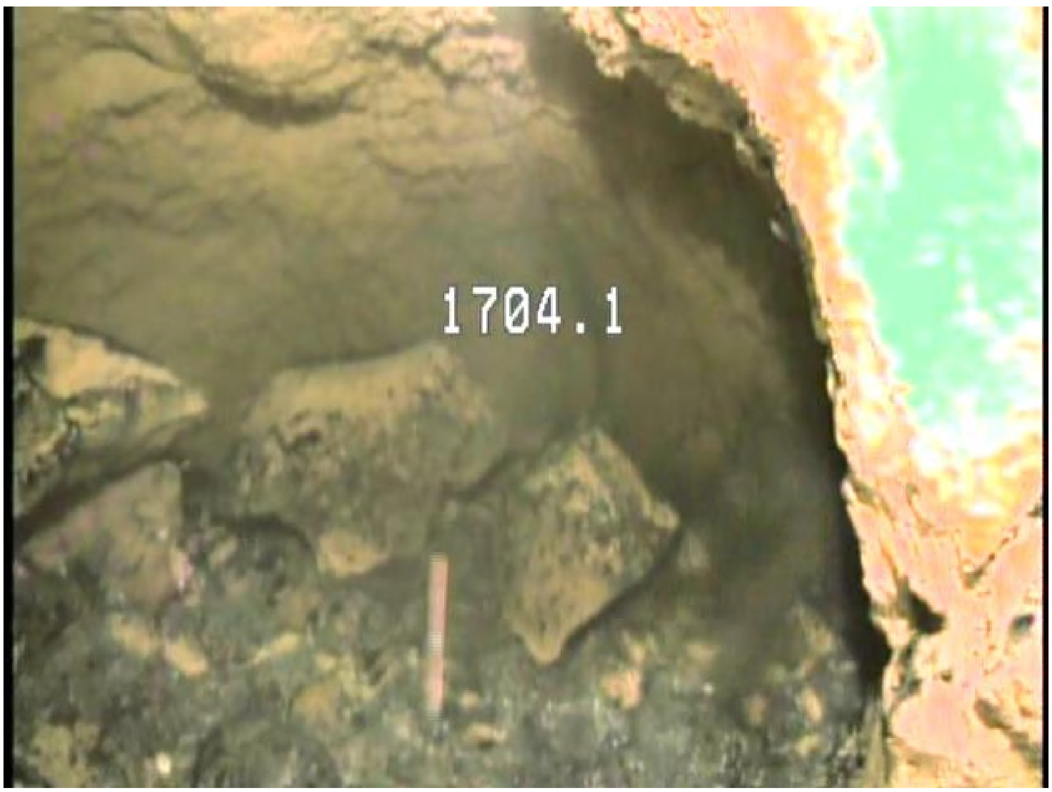


Figure 4-8. BHV view of cavity in OSF-109 with flow into borehole (cloudiness in center of photo)

LF2 is considered to have moderate to high permeability and potential productive capacity based on interval tests 1 and 2, the dynamic flow log, and the results of packer tests and DSTs as summarized below:

- The dynamic flow log of OSF-109 indicates diffuse flow entering the borehole from approximately 1,640 to 1,700 ft bls and 1,725 through 1,755 ft bls. These intervals correspond to the top of two relatively thick, high-porosity intervals evidenced on the sonic and BHV logs.

- Freshening of discharge water at OSF-104 was observed during DST testing between 1,630 and 1,690 ft bls and between 1,750 and 1,780 ft bls, but was not observed at OSF-109. As discussed in **Section 5.2**, this freshening is believed to be the result of dilution of formation waters via downward flow of water from the APPZ into permeable zones during drilling.

- Packer test OSF-109PT3, from 1,689 through 1,719 ft bls, yielded an estimated transmissivity of 2,742 ft^2/day (discussed in more detail in **Section 5.4**).

- Interval test 2 stressed the interval from 1,489 to 1,762 ft bls, encompassing LF2, LF1, and the intervening semi-confining unit (**Section 5.3.2**). After accounting for the contribution from LF1 (interval test 1), a specific capacity of 36.6 gpm/ft and estimated transmissivity of 9,780 ft^2/day were calculated for LF2.

A semi-confining zone is present below LF2 at the project site, characterized by reduced porosity and permeability inferred from a decrease in sonic porosity and few large-scale solution features such as caverns and solution-enhanced fractures as observed on the BHV and OBI/FMI logs of OSF-109 and OSF-104. A single zone of limited flow appears evident on the dynamic flow log of OSF-109, which indicates a zone of point source flow from 1,780 to 1,790 ft bls. The lithology of drill cuttings from the reverse air returns was very similar to LF2, but confining properties are inferred based on the rock textural changes described above and the following hydraulic and water quality characteristics:

- A water quality transition between groundwater samples OSF-109PT3 (LF2), which yielded 6,933 mg/L TDS, and two samples collected from LF3, OSF-109PT2 and OSF-109PT1, which yielded 22,520 and 24,322 mg/L, respectively (**Section 5.2.2**). The groundwater sample from LF2 is classified as TRSW, compared to the RSW (relict seawater) classification of the samples from the LF3.

- During packer testing, an 18-ft head difference was measured between OSF-109PT2 (LF3) and OSF-109PT3 (LF2). Most of this differential can be accounted for by the difference in water density, but if the heads in each zone were converted to freshwater equivalence, there was still a 2-ft head difference between the two zones, indicating the presence of some measure of confinement.

- A median head drop of 30.28 ft (October 21, 2013 through November 7, 2013) was measured between LF2 (OSF-109L) and OSF-104L, completed in the underlying LFA from 2,000 to 2,300 ft bls. The top of this interval is approximately 50 ft below the base of LF3. The water quality from OSF-104L was 34,121 mg/L TDS and the groundwater classification was RSW, similar to that of LF3.

4.3.3.3. LF3

The third potential production interval encountered in the Lower Floridan aquifer during construction of OSF-109 occurs from approximately 1,840 to 1,954 ft bls (OSF-109), and includes the lower part of the Avon Park Formation and the upper few feet of the Oldsmar Formation.

LF3 consists predominantly of a moderately to well-indurated, sucrosic dolostone with moderately to highly visible pinpoint and vuggy porosity in drill cuttings. The lower approximately 10 ft, within the Oldsmar Formation, consists of moderately indurated dolomitic limestone with moderate pinpoint and vuggy porosity. The BHCS and BHV logs (OSF-109) indicate several relatively thick sequences with greater than 50 percent secondary porosity consisting of cavernous, cavity-rich and fractured intervals from 1,840 through 1,864 ft bls, 1,899 through 1,916 ft bls, 1,936 through 1,946 ft bls, and 1950 through 1,954 ft bls (shown in **Figure 4-9**). The BHCS and FMI logs of OSF-104 exhibit correlative porosity development associated with large cavities and fractured intervals.

Figure 4-9. BHV view of cavity in OSF-109 at a depth of 1,912.9 ft bls in LF3.

LF3 is considered to have moderate permeability and potential productive capacity based on interval testing, the dynamic flow log, packer tests, and DST results, as follows:

- The dynamic flow log (OSF-109) indicates diffuse flow from 1,845 through 1,879 ft bls and 1,902 through 1,952 ft bls. Flow logs were not available below 2,000 ft bls, which is the total depth of OSF-109.

- Packer tests of OSF-109, from 1,890 through 1,920 ft bls (PT1) and 1,837 and 1,867 ft bls (PT2), yielded estimated transmissivities of 4,110 ft^2/day and 1,888 ft^2/day, respectively (discussed in detail in **Section 5.4**).

- Interval test 3 stressed the interval from 1,489 to 2,000 ft bls, encompassing LF1 through LF3 and all intervening semi-confining units (**Section 5.3.2**). After accounting for contributions from LF1 and LF2 (interval tests 1 and 2), a specific capacity of 28 gpm/ft and estimated transmissivity of 7,500 ft^2/day were calculated for LF3.

4.3.3.4. Lower LFA

Evidence of flow was not detected during production logging from the base of LF3 at 1,954 ft bls to the total depth of OSF-109 of 2,000 ft bls. However, relatively thin (< 5 ft) intervals with fractures and/or cavities were observed on the BHV and FMI logs at OSF-109 and OSF-104, respectively, from approximately 1,960 through 1,994 ft bls. A freshening of discharge water at OSF-104 was observed during drill-stem testing between 1,960 and 1,990 ft bls, possibly the result of dilution of borehole waters with downward flow of water from the APPZ into permeable zones during drilling (discussed in in **Section 5.2**). This interval is within dolostone and dolomitic limestone of the upper part of the Oldsmar Formation, with up to 50 percent chert present from 1,960 through 1,980 ft bls, and up to 5 percent interstitial gypsum/anhydrite present from approximately 1,960 to 1,975 ft bls. Based on lack of flow observed on the flow log, and intervening low permeability strata, this interval is not included in LF3.

OSF-104 penetrated the interval from 2,000 through 2,531 ft bls at the site. The base of the LFA was not encountered. Several zones of potential productive capacity were identified based on geophysical, video, and FMI logs (described below). Neither production logging nor aquifer tests were performed at these depths; therefore, productive capability of these intervals is not confirmed. The monitoring interval at OSF-104L is from 2,020 through 2,304 ft bls.

Bennett (2008) denotes a well-developed secondary porosity zone based on geophysical logging log from 1,998 through 2,028 ft bls at OSF-104. Large-scale secondary porosity features are not evident on the FMI log, however, and the log-estimated permeability indicates that much of this interval has permeability of less than 1 ft/day. Bennett (2008) describes this interval as a moderately indurated dolomitic limestone. The productivity of this interval has not been tested.

The FMI and BHCS logs (OSF-104 pilot-hole) and down-hole video logging (2014) from the completed well (OSF-104L) indicate reduced development of large-scale secondary porosity features from 2,028 through 2,107 ft bls. A distinctive signature on the gamma ray log appears at 2,042 ft bls. Duncan (1994) identified this signature as belonging to a glauconite marker bed, a low permeability unit associated with pyrite, collophane, and clay. Reese and Richardson (2007) mapped this marker across central and most of southern Florida. Bennett (2008) describes this interval in OSF-104 as a moderately indurated mudstone with good primary porosity development based on BHCS and compensated neutron density log analysis. A salinity inversion was also noted across this interval from the log-derived TDS log, and it was speculated that the fresher water was not native but due to migration down the borehole during the drilling process (Bennett, 2008). An identical inversion was seen in this mudstone unit, however, in SFWMD exploratory well OKF-105, which was drilled in 2009 approximately 17 miles south of Site C (Sunderland et al., 2011) and in the logs from numerous other deep wells in the region (Williams, L, USGS, November 2012, personal communication). Fluid density logging in 2014 confirmed a layer of fresher water (TDS < 12 ppt) below the casing to a depth of approximately 2,120 ft bls, overlying denser water (TDS > 35 ppt) from there to the base of the open-hole interval at 2,300 ft bls. It is now believed that this fresher water zone is actually representative of the native water, possibly trapped in situ during deposition. If that is the case, then it follows that this is a substantial confining unit with no mixing of waters across it.

From approximately 2,107 through 2,271 ft bls, a thick interval of well-developed secondary porosity characterized by large solution cavities and vugs with numerous fractures evident on the video and FMI logs and increased BHCS-derived porosity was observed. Bennett (2008) describes the interval from 2,100 through 2,200 ft bls as composed of moderately indurated packstone and grainstone with good primary porosity development, and from 2,200 through 2,240 ft bls becoming progressively more dolomitic, better indurated, and less porous. Several discreet intervals with solution cavities and fractures were observed on the video and FMI logs from approximately 2,118 to 2,130 ft bls and from 2,234 to 2,239 ft bls. A potential flow zone at the base of this interval is evident based on an apparent cavernous zone visible on the video and FMI log from 2,242 through 2,271 ft bls. A substantial confining interval within a dense, low permeability dolostone, from approximately 2,271 through 2,453 ft bls, is inferred based on relatively high formation resistivity and low sonic transit times, few large-scale solution features such as caverns and fractures observed on the FMI log, and minor secondary porosity observed in drill cuttings.

Good secondary porosity development that includes pinpoint vugs and moldic, fractured, and cavernous porosity types based on the FMI log analysis and drill cuttings is present within a well-indurated dolostone unit from approximately 2,456 through 2,508 ft bls. The BHCS log indicates good porosity development within several intervals up to approximately 10 ft thick. Bennett (2008) notes that the interval from 2,420 to 2,530 had lithology and log signatures similar to those found in the 'Boulder Zone', a highly permeable section of the lower Floridan used for wastewater disposal throughout south Florida. Hydraulic data to support this designation was not available, however, so the Boulder Zone could not be definitively identified at Site C.

5

HYDROGEOLOGIC TESTING

5.1. Geophysical Logging

Geophysical logging was conducted in the pilot hole of each well after each stage of drilling and following reaming of the borehole prior to casing installations. The logs provide a continuous record of physical properties of the subsurface formations and the fluids they contain. The log data were used to assist with casing seat selection and lithologic determination, to identify potential production and confining zones, and to assist in correlation among the wells. All log depth intervals are recorded as feet below land surface.

Table 5-1 summarizes the geophysical logging program conducted at Site C in 2012. A complete dataset of the logs collected at this site is provided in **Appendix C**. A description of the logging program conducted during the previous FAS investigation in 2005 through 2007 is provided in Bennett (2008). Brief descriptions of the information provided by each type of log in the current investigation are as follows:

- **XY Caliper** – A mechanical measure of the dimensions of the borehole in two planes at 90 degrees from each other. It is required for correction of borehole flowmeter logs and also indicates the presence of secondary permeability (vugs, caverns, or fractures). The caliper curve's shape and degree of deviation from the nominal bit size also provide an indicator of the relative induration of the rock and is important for selection of casing setting depths.

- **Natural Gamma** – Measures the presence of natural gamma radiation produced by the decay of potassium (^{40}K) and uranium (^{238}U) and its daughter product thorium (^{232}Th) in the rock formation. Clay and phosphatic rocks are generally rich in these elements. This tool was used to confirm lithologic determination, identify bed boundaries, correlate among wells, and provide depth control for different logging instruments.

- **Resistivity Logs** – Measure the combined electrical properties of the rock matrix and the fluids contained within it. In a formation of uniform water quality, the resistivity will be a good indicator of the porosity of the rock with resistivity decreasing as the water content (porosity) increases. The instrument is also affected by water quality, providing an excellent indication of changes in salinity within the formation.

- **Normal Resistivity** – Measures resistivity at two extents within the formation (16 and 64 inches) and is best applied in freshwater environments.

- **Dual Induction (DI)** – Measures the resistivity at three extents, the shallowest within and immediately adjacent to the borehole, and the deepest being the best representation of native rock and water resistivity. This tool gives important information on water quality and extent of drilling fluid invasion into the formation, and is a qualitative indicator of possible confining and producing zones and permeability.

- **Spontaneous Potential (SP) –** Measures naturally occurring electrochemical voltage differential between drilling fluids and formation fluids, providing an indication of the permeability of a formational unit. It works best in saltwater environments.

- **Borehole Compensated Sonic (BHCS) and Variable Density Log (VDL)** – Measures the velocity of sound waves through the rock adjacent to the borehole and is directly correlated to the porosity of the rock. The more porous a formation, the slower the travel time. The sonic log measures only matrix porosity; therefore, sonic derived porosity can be underestimated in vuggy or fractured formations. The VDL provides a visual representation of the borehole wall, indicating the presence of fractures and solution features.

- **Temperature** and **Fluid Resistivity** – Measures the temperature and resistivity of the fluids filling the borehole. These are generally run under both static and dynamic (pumped) conditions. They provide information on the points of influx into the borehole, confinement and production horizons, and salinity variation with depth.

- **Flow Meter Log** – Measures the vertical velocity of fluids in the borehole. This log is run under both static and dynamic conditions. Under static conditions, the log indicates cross-flow, which is water moving vertically between different aquifers intersecting the borehole due to the head difference between the units. Under dynamic conditions, the log indicates the primary production zones within the borehole.

- **Borehole Video (BHV)** – Where possible, a digital video of the complete borehole is taken under pumping conditions: downhole view from land surface to total depth and side view from total depth to the base of the casing. The video provides qualitative information on lithologic bedding and secondary permeability (solution features and fractures) that is not always obvious from the cuttings and formation logs. The BHV is also used to inspect the integrity of the casing joints.

- **Optical Borehole Image (OBI)** – Produces an oriented, continuous, 360-degree digital image of the borehole wall. From these, the character and orientation of lithologic and structural planar features can be quantitatively analyzed. Like standing before a rock outcrop, the optical imagery allows for direct viewing of the character and relationship between lithology, bedding, and secondary permeability of the formation. The OBI logs were used extensively to assist in the interpretation of lithology and formation boundaries, as well as to support the interpretation of hydrogeologic units.

Table 5-1. Summary of the geophysical logging program at Site C (2012).

Well	Date	Logging Company	Logged Interval (ft bls)	Caliper	Natural Gamma	Borehole Deviation	Normal Resistivity	DI/ SP	BHCS and VDL	Flow Meter	Temp	Fluid Res.	Flow Meter	BHV	OBI
OSF-109	10-Apr-12	AWE	0–300	✓	✓		✓	✓	✓						
OSF-109	16-Apr-12	AWE	0–300	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
OSF-105	3-May-12	USGS	930–1,200												✓
OSF-109	26-Apr-12	AWE	300–922	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
OSF-109	7-May-12	AWE	300–910	✓	✓	✓									
OSF-109	20-Jun-12	AWE	915–1,491	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
OSF-109	4-Aug-12	AWE	1,490–2,000	✓	✓	✓	✓	✓	✓	✓					
OSF-109	18-Aug-12	AWE	1,490–2,000	✓	✓	✓		✓	✓		✓	✓	✓		
OSF-109	20-Aug-12	AWE	1,490–2,000											✓	
OSF-105	10-Sep-12	AWE	920–1,102	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	
OSF-105	3-Oct-12	AWE	1,220–1,750	✓	✓	✓	✓	✓	✓	✓	**Static**	**Static**	**Static**		
OSF-109	4-Oct-12	USGS	1,490–1,745	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
OSF-105	4-Oct-12	USGS	1,226–1,750					✓					✓		✓

5.2. Water Quality and Inorganic Chemistry

Various sampling methods were used to assess the chemistry of the formation water at Site C. Drill-stem sampling and fluid resistivity logging provided a continuous vertical profile of the water within the borehole. Straddle packers at four select intervals gave a more extensive and accurate assessment of those discrete zones. Composite samples were also collected during aquifer performance testing and on the final completed intervals from each well.

5.2.1. Drill Stem Water Quality Sampling

Groundwater samples were collected at 30-ft intervals during open-circulation reverse-air drilling on wells OSF-104 and OSF-109. The site geologist analyzed the samples in the field for pH, temperature, and specific conductance using a calibrated YSI 600XL multiprobe., Laboratory analyses of samples from 1,513 ft bls to the base of OSF-109 were also performed for TDS, chloride, and sulfate. These data were compared and combined with data from 430 ft bls to 2,500 ft bls from the previously drilled well, OSF-104, to construct a more complete picture of changes in water-quality with depth at this location.

Figure 5-1 presents composite views of change in drill-stem water quality with depth at the two wells. Above a depth of 1,300 ft bls, the specific conductance data from both wells indicates very fresh water that is within drinking water standards. Below this depth, there is some deviation in the data from the two wells. Specific conductance in OSF-109 begins to rise fairly rapidly from 600 μS/cm at 1,300 ft bls to greater than 3,000 μS/cm at 1,363 ft bls. In OSF-104, this increase occurs 100 ft deeper. The patterns in the two wells continue similarly from there until a depth of approximately 1,640 ft bls where OSF-104 shows a freshening trend, while salinity in OSF-109 continues to increase. The discrepancies in the data despite the short distance between the wells (they are less than 400 ft apart) are believed to result from the hydrology of the system, the inherent imprecision of drill-stem sampling, and the state of construction of the two wells at the times the samples were collected.

When drilling deep wells, the size and position of intermediate casing strings has a significant impact on the type and quality of testing results with depth. This is particularly true with fluid logs and drill-stem water quality samples. **Table 5-2** illustrates the state of construction in each well at the times when drill-stem samples were collected and pilot-hole logs were run.

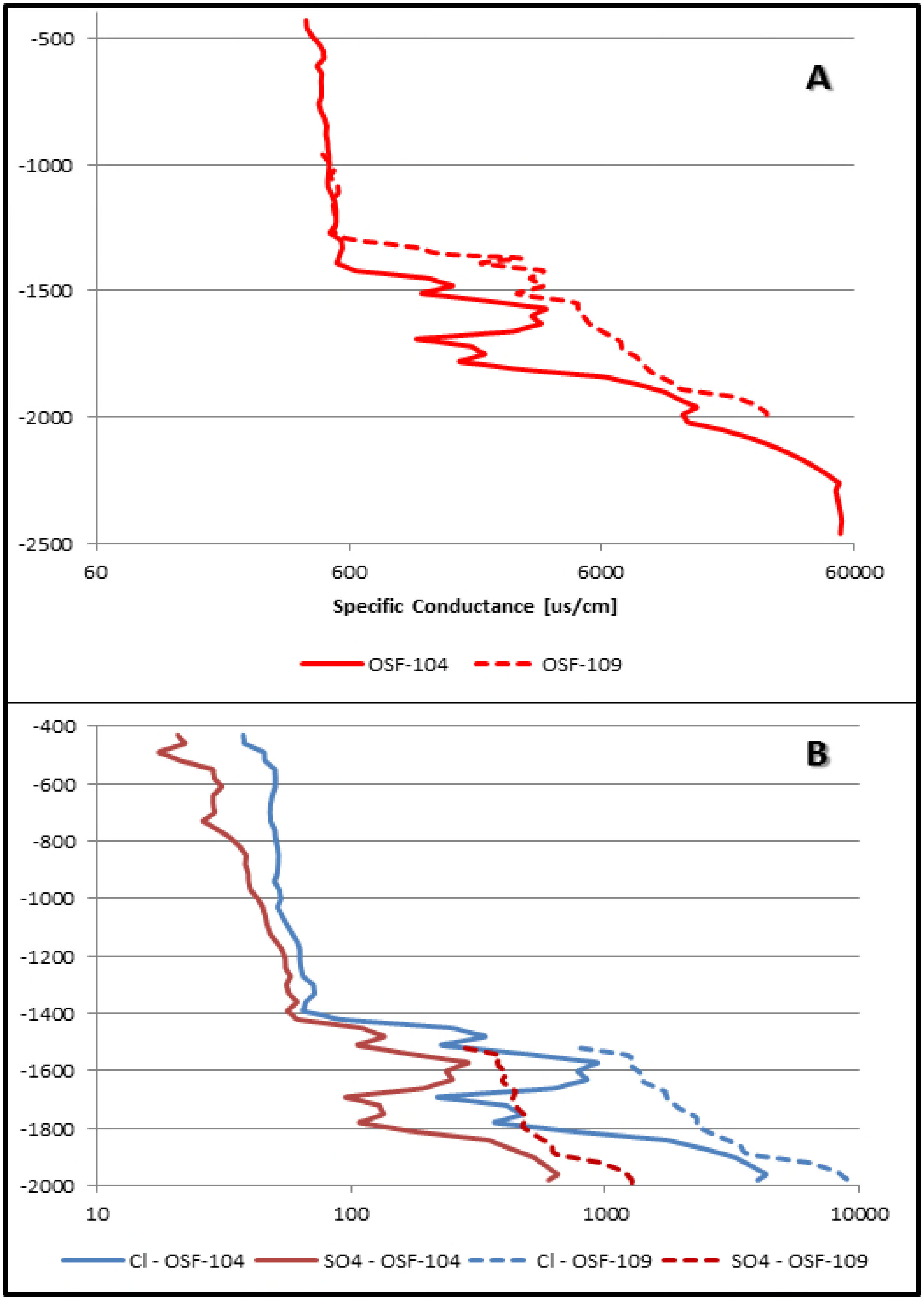


Figure 5-1. Drill-stem water quality variation with depth (ft bls). **A:** Field specific conductance; **B:** Laboratory chlorides and sulfates (mg/L).

Table 5-2. State of well construction.

Well	Casing Depth (ft bls)	Drill-Stem Sampling Depths (ft bls)
OSF-104	333	333–2,000
OSF-104	937	2,000–2,500
OSF-109	915	915–1,490
OSF-109	1489	1,513–2,000

The larger the open-hole interval, the greater the potential for vertical mixing of waters between aquifers. There is a significant downward head gradient across the FAS at this location (see **Section 5.5**). In OSF-104, that gradient induced downward migration of fresh water from the UPZ and highly productive APPZ into permeable sections of the LFA. The intermediate casing in OSF-109 prevented vertical mixing through the pilot hole past a depth of 1,489 ft bls during drill-stem sampling, but the drill-stem data from both wells, to a depth of 1,490 ft bls, represent a mix of formation water with fresher water from the shallower aquifers, with greater mixing occurring in OSF-104. This likely resulted in the apparent lowering of the fresh/brackish water interface in OSF-104 relative to OSF-109 (**Figure 5-1A**), and the well appearing generally fresher than it actually is.

Below 1,490 ft bls, only OSF-104 is affected by mixing with the UFA. Note that the maximum chloride measurement from the first 2,000 ft of OSF-104 was 4,289 mg/L, while in OSF-109 it was over 9,000 mg/L. Salinity inversions in the OSF-104 data set, between 1,630 to 1,690 ft bls and 1,750 to 1,780 ft bls, at the same depths where salinity is increasing in OSF-109, indicate invasion of UFA water into permeable intervals of the LFA at OSF-104.

5.2.2. Discrete Water Quality Sampling

Numerous water quality samples were collected and analyzed by the SFWMD during construction and testing of Site C (**Table 5-3**). A summary of the results is provided here. Complete results from the testing program are available for public download from the SFWMD's DBHYDRO database[2]. The data from individual samples are summarized in Table 5-4. The discrete samples include previously collected data from the surficial aquifer system and intermediate confining unit, and are organized from shallowest to deepest to allow differences between the aquifers to be more easily distinguished.

[2] www.sfwmd.gov/dbhydro

Table 5-3. Summary of samples collected and analyzed at Site C.

Station Test ID	Sample ID	Sample Date	Hydro-geologic Unit	Sample Depth (ft bls)	Notes
POS-2	P37821-1	28-Dec-07	SAS	20–30	Completed Interval
POS-3	P34974-2	4-Jun-07	SAS	75–90	Completed Interval
POH-1	P34974-1	4-Jun-07	ICU	180–200	Completed Interval
OSF-104U	P58662-1	5-Nov-12	UFA	330–550	Completed Interval
OSF-104M	P58662-2	5-Nov-12	APPZ	930–1,150	Completed Interval
OSF-109	P56805-1	8-Jun-12	APPZ	920–1,250	APT#1
OSF-109U	P58726-1	1-Nov-12	LF1	1,489–1,573	APT#2, Completed Interval
OSF-109PT4	P55959-1	24-Aug-12	LF1	1,545–1,575	Packer Test #4
OSF-109PT3	P57331-2	23-Aug-12	LF2	1,689–1,719	Packer Test #3
OSF-109PT2	P57332-3	22-Aug-12	LF3	1,837–1,867	Packer Test #2
OSF-109PT1	P57332-2	22-Aug-12	LF3	1,890–1,920	Packer Test #1
OSF-104L	P58662-3	5-Nov-12	LFA	2,000–2,300	Completed Interval

From 430 to 2,400 ft bls, specific conductance, a surrogate for total ionic strength, was relatively constant at depths less than 1,300 ft bls. The discrete samples show that, although the total ionic strengths are similar, the distribution of individual ions implies several disparate waters distinguishable by their predominant cation and anion groups. **Figure 5-2** is a Langelier plot showing the correlation between the relative ratios of the major cations (Na, Mg, Ca) and anions (HCO_3, Cl, SO_4) from all of the sample data. This plot implies three major groupings of similar waters that represent the surficial aquifer system and intermediate confining unit (Group A), the upper Floridan aquifer (group B), and the lower Floridan aquifer (Group C). Within each of these groups, there is geochemical variety that provides guidance as to the presence of confinement, recharge, source rock, and usefulness for water supply purposes.

Table 5-4. Summary of Site C major ion water chemistry from shallowest to deepest sample.

Station Test ID	Field Parameters			Sample Ion Balance			Total Dissolved Solids [mg/L]	TDS - Specific Cond. Ratio
	pH	Temp. (°C)	Specific Cond. (µS/cm)	Sum of Anions (meq/L)	Sum of Cations (meq/L)	Balance %		
POS-2	6.4	24.6	792	7.244	8.385	7.3	493	0.62
POS-3	7.6	23.3	525	4.455	4.867	4.4	330	0.63
POH-1	7.5	24.5	423	3.692	3.993	3.9	310	0.73
OSF-104U	8.1	24.5	461	4.098	4.472	4.4	212	*0.46*
OSF-104M	8.8	25.1	434	3.774	4.086	4.0	248	0.57
OSF-109	7.8	27.3	589	5.104	5.488	3.6	302	*0.51*
OSF-109U	7.8	28.1	4,624	42.645	45.074	2.8	2,722	0.59
OSF-109PT4	7.4	27.9	4,985	46.995	47.185	0.2	2,904	0.58
OSF-109PT3	7.3	28.1	11,484	113.297	114.396	0.5	6,933	0.60
OSF-109PT2	7.5	27.9	35,936	384.929	382.967	-0.3	22,520	0.63
OSF-109PT1	7.5	28.3	39,867	445.695	438.404	-0.8	25,322	0.64
OSF-104L	7.2	28.9	51,923	602.539	609.588	0.6	34,121	0.66

	Station Test ID	Chloride (mg/L)	Sulfate (mg/L)	Alkalinity (as CaCO3)	Bromide (mg/L)	Fluoride (mg/L)
Anions	POS-2	24.8	BDL	398	--	0.34
	POS-3	41	1	200	--	--
	POH-1	32	BDL	170	--	--
	OSF-104U	52.8	39.1	108	0.23	0.41
	OSF-104M	70.8	12.9	91	0.27	0.26
	OSF-109	77.1	59.6	103	BDL	BDL
	OSF-109U	1192	366	82	4.3	BDL
	OSF-109PT4	1334	378	86	5.37	0.3
	OSF-109PT3	3490	624	104	12.1	BDL
	OSF-109PT2	12362	1638	92	43	1.3
	OSF-109PT1	14291	1939	93	48	1.4
	OSF-104L	19253	2725	108	66	2.1
	Station Test ID	**Sodium (mg/L)**	**Potassium (mg/L)**	**Calcium (mg/L)**	**Magnesium (mg/L)**	**Strontium (mg/L)**
Cations	POS-2	19.4	2.1	133.4	9.7	1.41
	POS-3	32	1.8	58	6.5	--
	POH-1	24	1.5	42	9.9	--
	OSF-104U	28	1.7	34.2	16.8	5.32
	OSF-104M	39.1	3	14.2	17.3	7.7
	OSF-109	40.2	2.3	38.1	19.2	8.72
	OSF-109U	582.5	11.6	235.5	88.6	17.4
	OSF-109PT4	633.2	16.8	223.6	93.4	16.1
	OSF-109PT3	1739	39.4	361.8	232	26.2
	OSF-109PT2	6582	203	546.3	773	26.3
	OSF-109PT1	7575	258	583.9	883	22.3
	OSF-104L	10890	376	576.2	1181	15.2

BDL: below detection limit

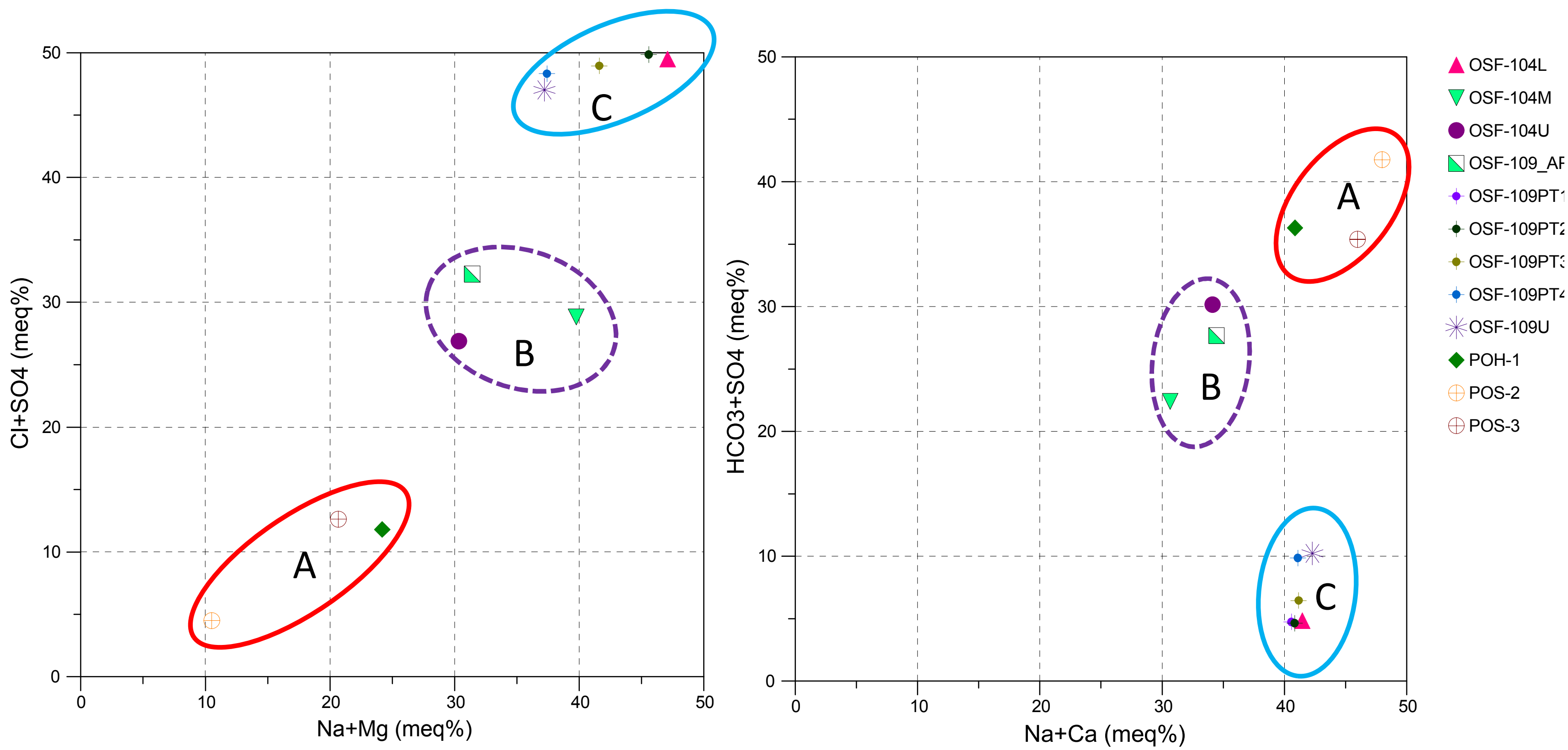


Figure 5-2. Langelier plots of major cation/anion correlations from the Site C samples showing three distinct groupings of waters: A: Surficial/Intermediate, B: Upper Floridan, C: Lower Floridan.

The samples were also examined using the geochemical pattern analysis method developed for the Floridan aquifer system by Frazee (1982) to relate the chemical signature to recharge source, residence time, and saltwater intrusion. The Frazee water types are defined in **Table 5-5**. **Figure 5-3** shows how the water samples from Site C conform to the water types on Frazee's pattern overlay, and this data is summarized in **Table 5-6**.

Table 5-5. Description of Frazee (1982) water types.

Abbreviation	Description	Characteristics
FW-I	Fresh Recharge Water Type I	Rapid infiltration through sands, high calcium bicarbonate ($CaHCO_3$).
FW-II	Fresh Recharge Water Type II	Infiltration through sands and clay lenses, $CaHCO_3$ with sodium (Na), sulfate (SO_4), and chloride (Cl). Marginal type II waters are beginning to transition toward FW IV.
FW-III	Fresh Recharge Water Type III	Infiltration through clay-silt estuarine depositional environment, high sodium bicarbonate ($NaHCO_3$).
FW-IV	Fresh Recharge Water Type IV	Fresh water, low calcium (Ca), magnesium (Mg), sulfate (SO_4), and chloride (Cl). Vertical infiltration insignificant. Older form of FW-II or FW-III.
TW-I	Transitional Water Type I	Seawater begins to dominate source water; chloride (Cl) begins to dominate bicarbonate (HCO_3) with increasing NaCl percentage.
TW-II	Transitional Water Type II	Transitional water with source water still dominant, HCO_4 – SO_4 mixing zone with increasing chloride (Cl).
TCW	Transitional Connate Water	Connate water dominates source water, sulfate (SO_4) begins to dominate HCO_3 with increasing chloride (Cl).
TRSW	Transitional Seawater	Transitional water with seawater dominating source water.
CW	Connate Water	Highly mineralized fresh water with high TDS and $CaSO_4$ dominance. Presence of highly soluble minerals; H_2S gas prevalent.
*RSW	Relict Seawater	Unflushed seawater with NaCl.

*Note: Strongly Na-Cl dominant waters may plot in this category even if the overall salinity is significantly less than seawater.

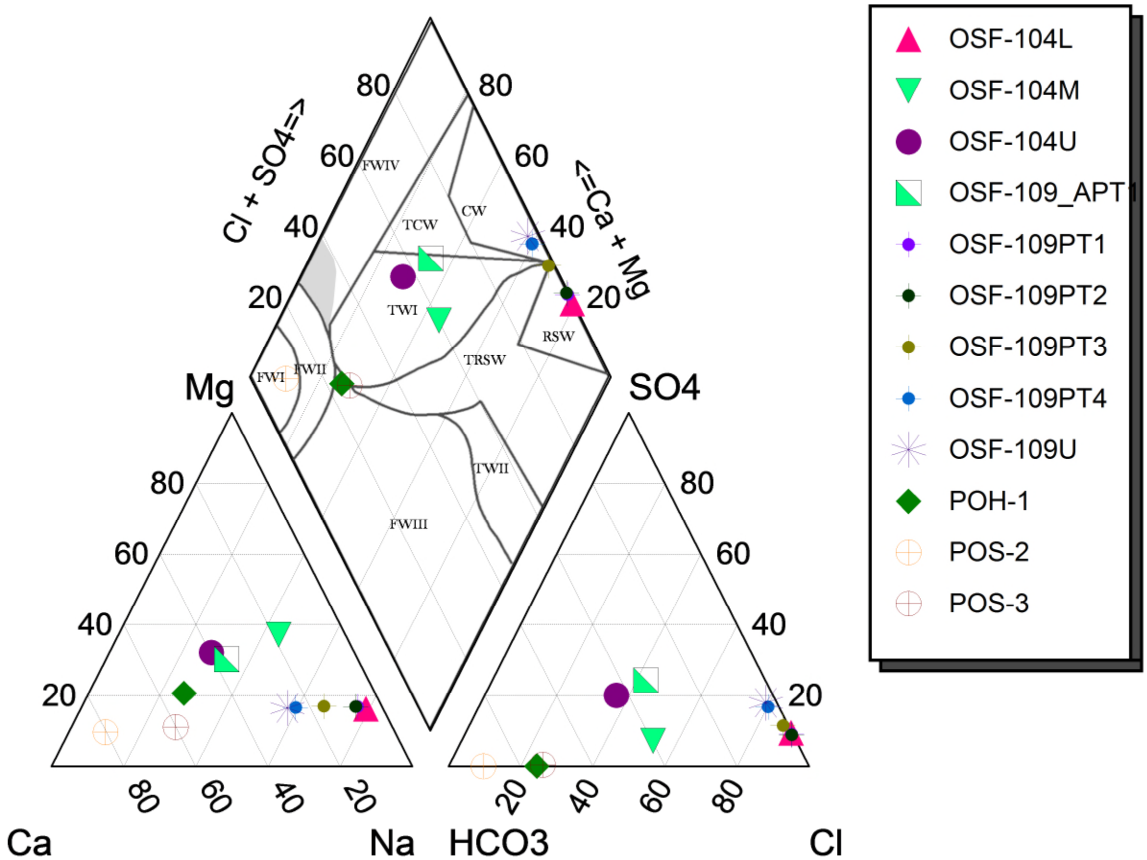


Figure 5-3. Water type classification of Site C sample data (after Frazee 1982).

Table 5-6. Water classification summary for the site C samples.

Station Test ID	Hydro-geologic Unit	Sample Depth (ft bls)	Dominant Ion Pairs	Frazee Water Type
POS-2	SAS	20–30	Ca-HCO3	FWI
POS-3	SAS/ICU	75–90	Ca-Na-HCO3-Cl	FWIII
POH-1	ICU	180–200	Ca-Na-Mg-HCO3-Cl	FWIII
OSF-104U	UFA	330–550	Ca-Mg-Na-HCO3-Cl	TWI
OSF-104M	APPZ	930–1,150	Na-Mg-Cl-HCO3	TWI
OSF-109	APPZ	920–1,250	Ca-Na-Mg-Cl-HCO3-SO4	TWI/TCW
OSF-109U	LF1	1,489–1,573	Na-Ca-Cl	CW
OSF-109PT4	LF1	1,545–1,575	Na-Ca-Cl	CW
OSF-109PT3	LF2	1,689–1,719	Na-Cl	TRSW
OSF-109PT2	LF3	1,837–1,867	Na-Cl	RSW
OSF-109PT1	LF3	1,890–1,920	Na-Cl	RSW
OSF-104L	LFA	2,000–2,300	Na-Cl	RSW

Both the group A and group B samples meet the most common criteria for 'freshwater', with TDS less than 500 mg/L, but only the group A wells qualify as 'freshwater' by Frazee's classification scheme. Each of those samples has calcium and bicarbonate as its dominant ion pair. Only the shallowest well, POS-2, is purely Ca-HCO_3 water. That is also the only well with a pH less than 7, indicating good communication with naturally acidic waters from the adjacent wetlands. The ion balance is out of the desired range (< 5 percent) (Hounslow, 1995), but a previous sample collected by the USGS in 2006 affirms the very high alkalinity and calcium ion dominance in that well. The ion chemistry of POS-3, at just 90 ft bls, is more closely akin to the intermediate confining unit monitor well, POH-1. Frazee characterizes both of those wells as having recharged through a clay-silt estuarine depositional environment high in high sodium bicarbonate ($NaHCO_3$). These results imply some degree of vertical confinement between POS-2 and POS-3.

All of the Upper Floridan wells, group B, are classified as transitional waters under Frazee's scheme. Seawater has begun to dominate source water in these samples, illustrated by the increasing ratio of chloride (Cl) to bicarbonate (HCO_3). Within this group, the APPZ samples are distinguishable from the UPZ as well. The APPZ at Site C is composed of very well-indurated but fractured dolostone, and the Mg/(Ca+Mg) ratio from OSF-104M (930–1,150 ft bls) is characteristic of dolomite dissolution (Hounslow, 1995). The result from APT#1 (920–1,250) is more ambiguous. It indicates that a significant source of calcium and sulfate is present in the interval not common to both samples, between 1,150 and 1,250 ft bls. As this depth is approaching the estimated top of the middle-confining unit, anhydrite/gypsum ($CaSO_4$) would be a logical source of these ions, but the Ca:SO_4 ratios are incompatible with anhydrite/gypsum alone. Sulfate increased by almost twice as much as calcium and the silica content tripled as well. If anhydrite is one source rock, then an additional source of SO_4 and SiO_2 is required as well.

The group C samples, representing the Lower Floridan aquifer, range from brackish to saline. The shallowest (1,489–1,575 ft bls) samples, OSF-109U and OSF-109PT4, characterize the waters of LF1, the uppermost permeable zone of the LFA. Frazee classifies these as connate water. This portion of the Lower Floridan aquifer, with TDS less than 3,000 mg/L, is the most attractive from a water supply perspective. Below this depth, salinity increases significantly. The sample from packer test 3 (OSF-109PT3), which tested the LF2 from 1,689 to 1,719 ft bls, has a TDS of 6,700 mg/L and is classified as transitional seawater. A component of source water still exists, but seawater is dominant. The base of the USDW (waters having a TDS concentration less than 10,000 mg/L), occurs between packer test 3 and packer test 2 (1,837–1,867 ft bls) within LF3, at an estimated depth of approximately 1,760 ft bls. Below this depth, all samples fall into the Frazee classification of relict seawater. The composition of the deepest sample, OSF-104L (composite 2,000–2,300 ft bls), is barely distinguishable from a typical modern seawater composition (**Table 5-7**).

Table 5-7. Range of ionic composition from Site C groundwater in comparison to surface water from the adjacent Kissimmee River and the typical range of modern seawater. Ions are arranged from most to least abundant.

[1]Kissimmee River		POS-2		Typical Seawater		OSF-104L	
HCO3	32.09%	HCO3	67.45%	Cl	55.06%	Cl	54.66%
Cl	18.38%	Ca	18.55%	Na	30.62%	Na	30.92%
SO4	17.23%	SiO2	5.63%	SO4	7.68%	SO4	7.74%
Na	12.85%	Cl	3.45%	Mg	3.66%	Mg	3.35%
Ca	11.09%	Na	2.70%	Ca	1.16%	Ca	1.64%
Mg	3.62%	Mg	1.35%	K	1.10%	K	1.07%
SiO2	2.05%	K	0.29%	HCO3	0.41%	HCO3	0.37%
K	2.01%	Fe	0.20%	Br	0.19%	Br	<.1%
Fe	0.55%	Sr	0.20%	Sr	<.1%	Sr	<.1%
Sr	0.12%	SO4	0.14%	F	<.1%	SIO2	<.1%
F	0.01%	F	<.1%	SiO2	<.1%	F	<.1%

[1]Average of 10 samples collected in 1978 from the river between structures S65 and S65A. DBHYDRO station C38A0100.

Although samples from OSF-104L exhibit a chemical composition equivalent to seawater, calculated formation TDS from the drilling of this well indicated a possible zone of fresher water at the top of the open-hole interval, from 2,020–2,100 ft bls (Bennett, 2008). A borehole conductivity, temperature, and pressure log was conducted on the open interval of the borehole in April 2014, confirming the presence of significantly fresher water (~ 12 ppt TDS) overlying much saltier water (> 35 ppt TDS) below a depth of 2,120 ft bls. Samples from this well are solely representative of the deeper, more productive section of the borehole.

The formation water samples were also compared to primary and secondary drinking water standards for the parameters tested. No primary drinking water standards were exceeded; however, six of the twelve samples were outside one or more secondary drinking water standards (**Table 5-8**).

Table 5-8. Site C samples exceeding secondary drinking water standards.

			Secondary Drinking Water Standards (mg/L)				
			250	2	0.3	0.05	250
Sample ID	Station Test ID	Sample Depth (ft bls)	Chloride (mg/L)	Fluoride (mg/L)	Iron (mg/L)	Manganese (mg/L)	Sulfate (mg/L)
P58726-1	OSF-109U	1,489–1,573	1,192				366
P55959-1	OSF-109PT4	1,545–1,575	1,334		1.389		378
P57331-2	OSF-109PT3	1,689–1,719	3,490		2.221	0.057	624
P57332-3	OSF-109PT2	1,837–1,867	12,362		2.621	0.1	1,638
P57332-2	OSF-109PT1	1,890–1,920	14,291		2.502		1,939
P58662-3	OSF-104L	2,000–2,300	19,253	2.1			2,725

5.3. Aquifer Performance Testing

5.3.1. APT#1 (Avon Park Permeable Zone: 920–1,250 ft bls)

5.3.1.1. Test Description

The APPZ at Site C was first tested in 2007, prior to the construction of OSF-109. That test, described by Bennett (2008), yielded mixed results. The production well, OSF-105, was pumped at a maximum achievable rate of 2,795 gpm for 95 hours without any measurable drawdown being observed in the production zone observation well, OSF-104M, 550 ft away. Strong oscillatory response in the production well drawdown, and near instantaneous recovery, prevented successful application of analytical solutions to the production well data. An approximate transmissivity of 79,000 ft^2/day was estimated from specific capacity data. Given the limited nature of the 2007 results, arrangements were made to allow for a second test of the APPZ during the construction of well OSF-109. **Figure 5-4** shows the site configuration for this test. Data collected during this test can be found in **Appendix D**.

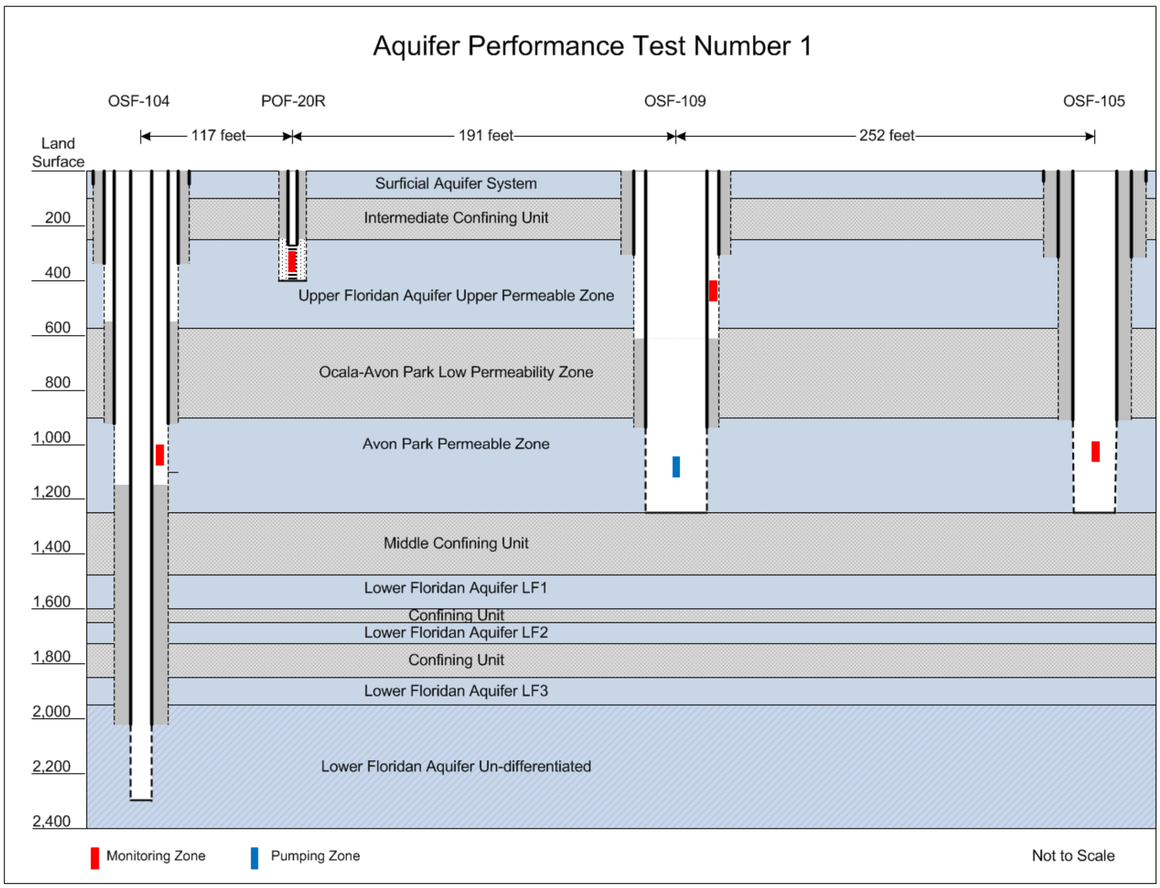


Figure 5-4. Configuration of wells for APT#1, Site C

On June 7, 2012, a step-drawdown test was performed on well OSF-109, which was open to the APPZ from 920 to 1,250 ft bls. The test consisted of four steps at 2,500, 3,000, 3,450, and 4,000 gpm, which was the maximum rate achievable with the available pump. Each step lasted approximately 70 minutes. The fourth step was followed by a recovery period of approximately 70 minutes while water levels in the well recovered to static levels. This preliminary step-drawdown test was run to assess expected well losses and select an appropriate pumping rate for the constant rate discharge test (CRDT).

Transmissivity for each step was estimated using the following equation for confined aquifers (Driscoll, 1986):

$$T = \frac{Q}{s} * 2000 \qquad \textbf{Equation 5-1}$$

where T = transmissivity (gpd/ft)
Q = pumping rate (gpm)
s = drawdown (ft)

Results of the calculations are shown in **Table 5-9**.

Table 5-9. Transmissivity estimations from calculated specific capacity

Step	Pumping Rate (gpm)	Drawdown (feet)	Specific Capacity (gpm/ft at 70 min)	Transmissivity (gpd/ft)	Transmissivity (ft^2/day)
1	2,500	1.9	1,316	2,631,579	355,263
2	3,000	2.9	1,034	2,068,966	279,310
3	3,450	3.7	932	1,864,865	251,757
4	4,000	5.0	800	1,600,000	216,000
			Average	**2,041,352**	**275,583**

There are both linear (laminar) and non-linear (turbulent) components of flow that contribute to the total head loss in a production well. Driscoll's empirical solution for estimating transmissivity from specific capacity, and most analytical solutions for aquifer performance test analysis, are based on the assumption that flow during the test is laminar, meaning drawdown is directly proportional to pumping rate. This assumption breaks down if turbulent conditions occur, so step-drawdown tests were run prior to constant rate discharge tests to evaluate the laminar (BQ) "aquifer loss" and turbulent (CQ^p) "well loss" components of drawdown in OSF-109.

The step-drawdown test results were analyzed using a simple graphical method developed by Bierschenk (1964) (**Figure 5-5**), to yield an estimate of 3E-7 ft/gpm^2 for the turbulent well-loss coefficient C, and laminar head loss coefficient, B, of -2E-5 ft/gpm. These results are problematic because they imply that effectively all of the drawdown during the step-drawdown test was due to turbulent flow. That can only be the case if a large component of turbulent flow occurs in the undisturbed portions of the formation. Given the large open fractures that characterize the APPZ at this location, the occurrence of turbulent flow within the formation is not unreasonable. While it would be imprudent to put too much weight on this single analysis, it is certain that a significant portion of the head-loss in the production well is due to turbulent flow. There are several implications to this. First, it makes this test difficult to interpret with standard analytical methods that rely on the assumption of laminar flow. That problem is generally worked around by using analytical solutions for step-drawdown test data to calculate the well-loss component of drawdown and adjusting for this during the subsequent constant-rate APT. In this case, because a component of the 'aquifer-loss' must also be due to turbulent flow, the step-drawdown solutions are poorly constrained, increasing the uncertainty of predictions. One final implication that might be drawn from the recognition that a large component of the production well drawdown is due to turbulent flow is that the specific capacity-based estimates for transmissivity provided by Bennett (2008) and presented in **Table 5-9** are almost certainly too low.

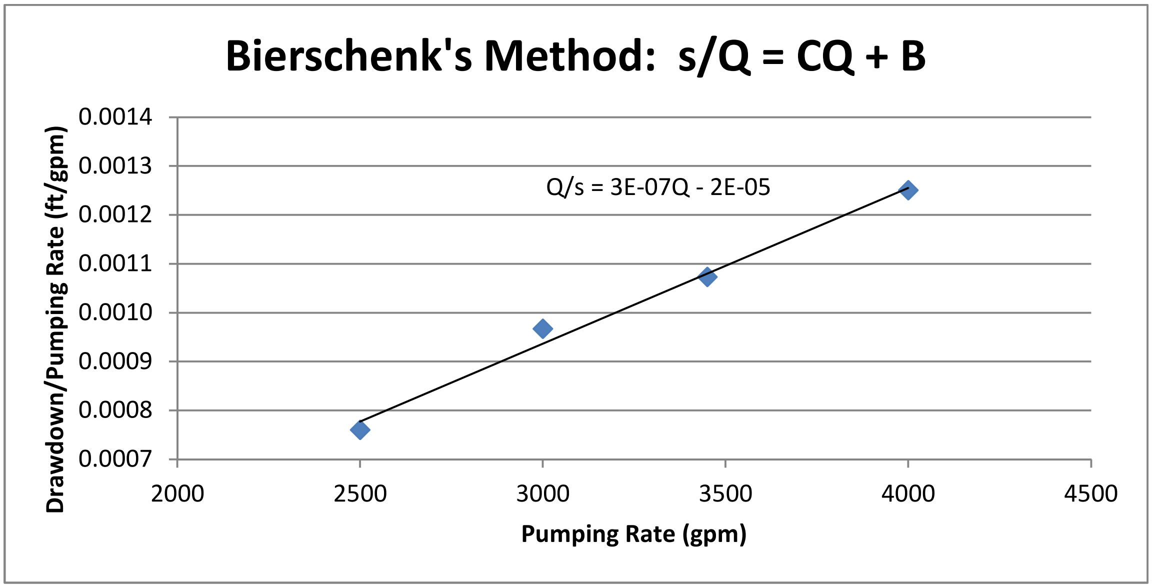


Figure 5-5. Bierschenk's graphical solution for laminar and turbulent well loss terms.

The time-series step-drawdown data (**Figure 5-6**) was also examined. At each change in stress, drawdowns exhibit an oscillatory, underdamped system response. Shapiro (1989) notes that oscillatory water levels are often observed, even in monitor wells, at the beginning of aquifer performance tests in highly transmissive fractured formations. Shapiro's analysis found that if the early-time oscillatory behavior was ignored, the water levels responded analogously to an equivalent porous medium and that the estimated transmissivity was relatively unaffected but storativity could be significantly overestimated.

Storativity cannot be estimated from a single-well step-drawdown test, but if the transmissivity is known, it can be calculated from diffusivity. Streltzova, (1988) derived the following method of calculating the diffusivity (T/S) in a heterogeneous aquifer based on the travel-time of the pressure wave through the aquifer:

$$\eta = \frac{1}{t}\left(\frac{r}{C}\right)^2$$ **Equation 5-2**

where r = radial distance between the production and observation wells
C = constant, generally from 1.89 to 2.0
η= diffusivity (T/S)
t = travel time

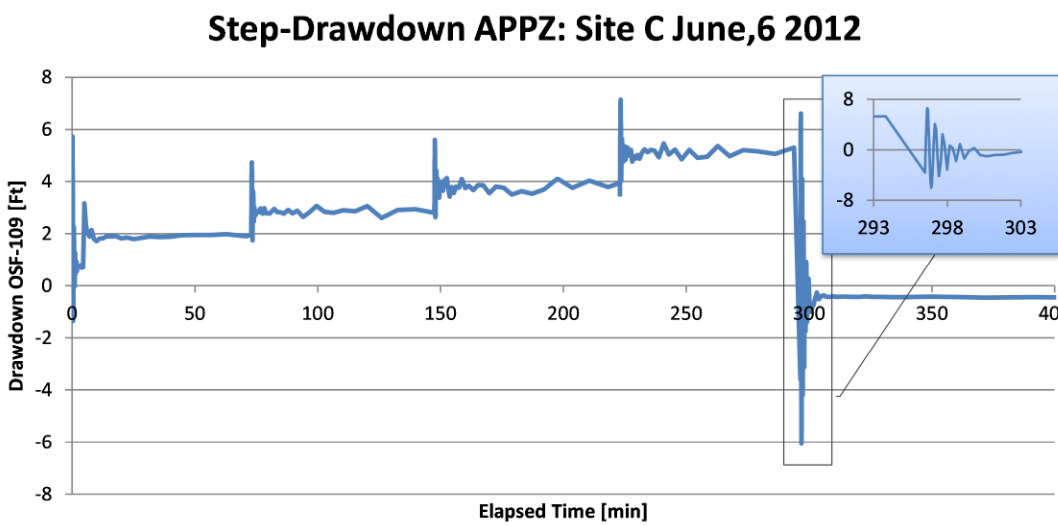


Figure 5-6. Time-series drawdown data from the step-drawdown test on OSF-109. Inset shows large oscillatory response to cessation of pumping stress.

Estimates of diffusivity from the pressure wave travel time (**Figure 5-7**) through the aquifer are provided in **Table 5-10**. Although well OSF-105 is closer than OSF-104M, the peak pressure wave arrival reached there later, indicating anisotropy in this aquifer in keeping with **Figure 4-2** These independent estimates were used to help constrain calculated values of T and S within the APPZ.

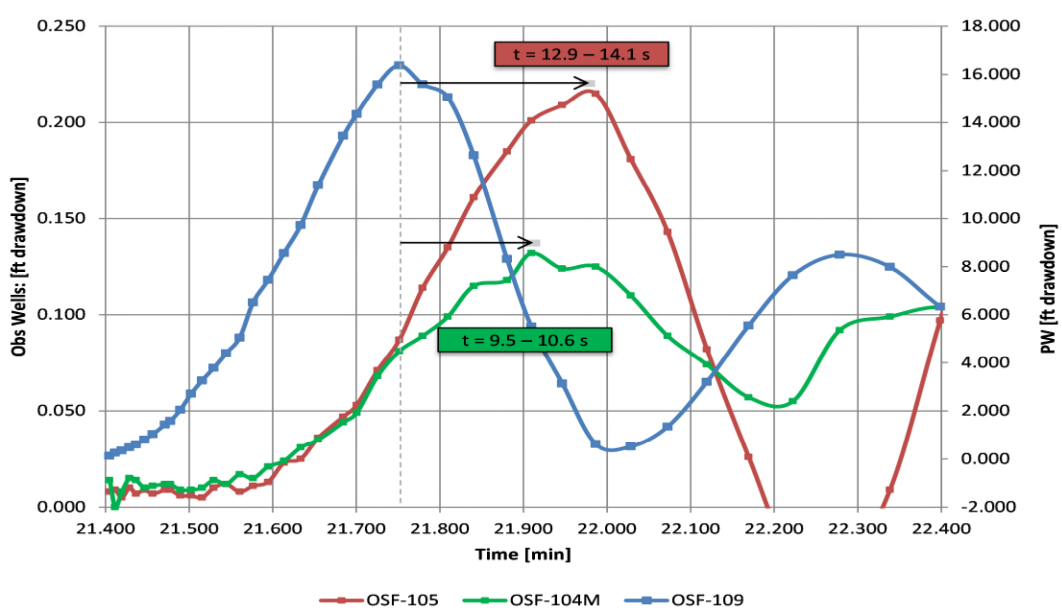


Figure 5-7. Time for the peak of the first pressure wave to travel from OSF-109 to OSF-105 and OSF-104M.

Table 5-10. Diffusivity estimated from pressure wave travel time, Site C

Observation Well	Radial Distance (ft)	Travel Time (s)	Diffusivity (T/S) (ft^2/s)
OSF-105	252	12.9–14.1	1,378–1,261
OSF-104M	308	9.5–10.6	2,795–2,505

On June 7, 2012, AWE initiated constant rate discharge testing on the APPZ of OSF-109. A discharge rate of 4,000 gpm was selected based on the step-drawdown testing. The duration of the constant rate test covered 96 hours, 48 hours of pumping followed by a 48-hour recovery period. The pumping rate was tracked at hourly intervals using an in-line totalizing flow-meter. The production well and monitor wells were instrumented with down-hole pressure transducers to record changes in water levels. The instrumentation was programmed to read on a log cycle time-step, short time increments at the start of pumping, then gradually increasing to regular 1-minute interval readings. During pumping, manual water level readings were also collected hourly to back up the instrumentation. Field data collected as part of this test are provided in **Appendix D**.

5.3.1.2. Analyses

Data from the CRDT were analyzed to evaluate transmissivity, storativity, and leakance properties of the APPZ. As previously discussed, the results of the step-drawdown testing implied initial specific capacity-based transmissivity estimates of 79,000 ft^2/day (Bennett, 2008) to 275,000 ft^2/day (**Table 5-9**) were too low. The turbulent nature of flow and anisotropy in the APPZ at this site make it poorly suited to analytical solution of the CRDT data, so a numerical modeling-based approach was used to estimate hydraulic properties for this test.

The results of the test were analyzed using a modified MODFLOW optimization program. The program attempts to determine a best fit from the parameters provided to solve the observed drawdown data. The test model has 150 lateral columns of variable width stretching outwards approximately 400,000 ft from the production well to minimize boundary affects. The model is also 13 rows deep with the ICU, UFA, and APPZ simulated with three layers each and the SAS, Ocala-Avon Park low permeability zone (OCAPLPZ), MC2, and LF1 simulated with a single layer each. The model layers were configured using the following hydrostratigraphic unit boundaries:

- 0–70 ft bls – Surficial aquifer system (SAS)
- 70–300 ft bls – Intermediate confining unit (ICU)
- 300–580 ft bls – Upper Floridan aquifer (UFA-UPZ)
- 580–925 ft bls – Ocala-Avon Park low permeability zone (OCAPLPZ)
- 925–1,270 ft bls – Avon Park permeable zone (APPZ)
- 1,270–1,490 ft bls – Middle confining unit (MC2)
- 1,490–1,635 ft bls – Lower Floridan aquifer zone 1 (LF1)

The program requires that the data from each well be solved independently to obtain initial aquifer parameters (hydraulic conductivity (K) and storativity (S)) that are then used to solve all observed data simultaneously.

Solving solely for the production well drawdown yielded a value at the production well of approximately KAPPZ = 300.0 ft/day. The model solves for the production well separately from the aquifer. The hydraulic conductivity for the APPZ away from the production well yielded values in excess of 20,000 ft/day, suggesting a significant head loss may be occurring in the production well at the pumped rate of 4,000 gpm.

Using the parameters determined from the analysis of the production well, a second model simulation was conducted that attempted to solve for the drawdown at APPZ monitoring well OSF-105M. Results from this simulation yielded a KAPPZ of 21,000.0 ft/day and SAPPZ of 0.107E-07. The observed data at the APPZ monitoring well OSF-104M did not exhibit the degree of oscillation experienced in both the production well (OSF-109) and OSF-105M. Consequently, the model was not focusing on reducing the sum-of-squares during the swings and yielded a tighter fit. Aquifer parameters calculated for this monitoring well yielded a KAPPZ of 16,313.0 ft/day.

Monitoring well POF-20R in the overlying UFA was used to estimate the k of OCAPLPZ and potentially the k of the LFA or UFA. For this simulation a KAPPZ of 16,313.0 ft/day, as determined from OSF-104M, was fixed and the model was used to estimate the k of OCAPLPZ and/or MC2 and potentially the k of the LFA or UFA-UPZ. The results from this analysis yielded a KOCAPLPZ of 0.4 ft/day and 0.001 ft/day for KMC2. This analysis also suggests a relatively low specific storage of 0.4E-9 for OCAPLPZ, however, which may be unrealistic.

The final simulation for the APPZ APT at OSF-109 solved for all monitoring wells simultaneously but restricted the aquifer property bounds within the degree suggested by the individual model simulation for each well's sensitive parameters. The results of the final simulated parameters for the OSF-109 APT for Site C are show in **Table 5-11**.

Table 5-11. Optimized model results for hydraulic properties of Site C based on data from the June 2012 test.

Unit	Unit Thickness b (ft)	Storativity	Hydraulic Conductivity (ft/d)	Transmissivity (ft^2/d)
SAS	70	0.16 *[Sy]	34	2,380
ICU	230	5.52E-06	0.48	110
UFA	280	3.08E-06	14	3,920
OCAPLPZ	345	1.21E-06	0.42	145
APPZ	345	1.10E-06	18,962	6,541,890
MC2	220	7.26E-04	0.0001	0.02
LF1	145	4.79E-04	18	2610

*Specific Yield

Transmissivity in excess of 6 million ft^2/day is beyond the range previously reported for the APPZ. The Southwest Florida Water Management District reported a transmissivity of 1.6 million ft^2/day from its Prairie Creek test site in Desoto county (Clayton, 1999), but generally, permeability of this magnitude is found only in the vicinity of springs. The resultant diffusivity from the model predicted transmissivity and storage coefficient is orders of magnitude greater than that calculated for the test (**Table 5-10**), leading to the conclusion that the modeled values for transmissivity and storativity are overestimated and underestimated, respectively.

A couple of factors could lead to overestimation of transmissivity from this test. First, the model produced an optimized result based on the observed data. Given that 48 hours of pumping at 4,000 gpm yielded less than 2 inches of drawdown at two observation wells over 250 ft away, only a very high permeability aquifer could yield a favorable match to the data. There is no doubt that the APPZ at this site is extremely permeable, but there is a strong possibility that the level of drawdown observed at the two APPZ wells was mitigated by the degree of storage within the monitor wells themselves, in which case the measured drawdown is not a true reflection of the permeability of the formation. A second factor that could account for unrealistically high estimated transmissivity is the heterogeneity of the production zone. The production well encompassed 330 ft of open-hole, basically the full thickness of the APPZ at this site. However, this entire thickness is not uniformly productive. Based on production logging of the pilot hole, there are multiple discrete flow zones within the open interval. Over 73 percent of the production, however, derived from two discrete fractured intervals with a combined thickness of just 30 ft. Assuming that the model-derived hydraulic conductivity is equivalently distributed, that would result in a transmissivity of approximately 415,000 ft^2/day, a value more commiserate with other reported values for the aquifer.

5.3.2. Interval Testing (Lower Floridan Aquifer: 1,489 –2,000 ft bls)

Interval testing on OSF-109 was performed at three specific depth ranges as drilling of the 10-inch diameter pilot hole progressed through the Lower Floridan aquifer. These were short-term specific capacity tests that provided preliminary estimates of variation in water quality and productivity within the LFA strata and guided the final testing and design of the well. Results from the interval tests are summarized in **Table 5-12**.

Table 5-12. Summary of interval test results at Site C.

Tested Interval (ft bls)	Temp (°C)	TDS (mg/L)	Specific Weight (lb/ft^3)	Max. Drawdown (PSI)	Friction Head Loss (PSI)	Max. Corrected Drawdown (ft)	Q (gpm)	Specific Capacity (gpm/ft)	T (ft^2/d)
1,489–1,635	28.05	3,473	62.33	31.39	0.73	70.84	1,052	14.85	3,970
1,489–1,762	28.42	5,200	62.40	9.474	0.71	20.22	1,040	51.42	13,750
1,489–2,000	28.66	11,181	62.68	6.24	0.71	12.71	1,010	79.49	21,255

Approximate estimates of transmissivity for these intervals were calculated from specific capacity (Q/s) using Equation 5-3. Prior to estimating transmissivity, however, measured drawdown data were corrected for density variations resulting from differences in water-quality with depth and head losses due to friction of the casing. Water density was estimated as a function of temperature and solids concentration using the following empirical formula (Maidment., 1993) and the results were used to determine an appropriate pounds per square inch to feet of water conversion for all packer test data:

$$\rho_s \text{ (kg m}^{-3}\text{)} = \rho_o + AS + BS^{3/2} + CS^2 \qquad \textbf{Equation 5-3}$$

Where: ρ_o = density calculated as a function of temperature (g kg^{-1}).

$$\rho_o = 1000 \times \frac{1 - (T + 288.9414)}{(508929.2 \times (T + 68.12963)) \times (T - 3.9863)^2}$$

T = temperature (°C)

$A = (8.24493\text{x}10^{-1}) - (4.0899\text{X}10^{-3}\,T) + (7.6438\text{X}10^{-5}\,T^2) - (8.2467\text{x}10^{-7}\,T^3) + (5.3675\text{X}10^{-9}T^4)$

$B = (-5.724\text{x}10^{-3}) + (1.0227\text{x}10^{-4}\,T) - (1.6546\text{X}10^{-6}\,T^2)$

$C = 4.8314\text{x}10^{-4}$

S = salinity (g kg^{-1})

The drawdown data were corrected for head loss due to friction in the pipe using the Hazen-Williams equation (Finnemore and Franzini, 2002):

$$P_d = L\,\frac{4.52Q^{1.85}}{C^{1.85}\,d^{4.865}} \qquad \textbf{Equation 5-4}$$

Where:

P_d = pressure drop due to friction loss over the length of pipe in psig

L = length of pipe (feet)

Q = discharge rate (gpm)

C = pipe roughness coefficient

d = inside pipe diameter (inches)

The first interval test was conducted from 1,489 to 1,635 ft bls on July 17, 2012. Water levels were recorded while the well was stressed at a rate of 1,051 gpm for 3 hours, and then allowed to recover to background conditions. A pressure drop of 31.39 psi was recorded during the pumping portion of the test. A friction head loss of 0.73 psi and pressure to feet conversion of 2.310 were estimated, yielding a corrected drawdown of 70.79 ft and specific capacity of 14.86 gpm/ft. Using Equation 5-1, the transmissivity was estimated to be 29,272 gpd/ft or 3,970 ft^2/day.

The borehole was advanced to a depth of 1,762 ft bls and a second interval test was conducted. Water levels were recorded while the well was stressed at a rate of 1,040 gpm for 3 hours, then allowed to recover to background conditions. A pressure drop of 9.474 psi was recorded during the pumping portion of the test. A friction head loss of 0.71 psi and pressure to feet conversion of 2.308 were estimated, yielding a corrected drawdown of 20.22 ft and specific capacity of 51.42 gpm/ft. Using Equation 5-1, the transmissivity was estimated to be 102,840 gpd/ft or approximately 13,750 ft^2/day.

The borehole was advanced to the total depth of the well, 2,000 ft bls, and a final interval test was run over this interval on July 21, 2012. Water levels were recorded while the well was stressed at a rate of 1,010 gpm for 3 hours, then allowed to recover to background conditions. A pressure drop of 6.24 psi was recorded during the pumping portion of the test. A friction head loss of 0.71 psi and pressure to feet conversion of 2.298 were estimated, yielding a corrected drawdown of 12.71 ft and specific capacity of 79.49 gpm/ft. Using Equation 5-1, the transmissivity was estimated to be 158,980 gpd/ft or approximately 21,255 ft^2/day.

Since specific capacity and transmissivity are essentially additive properties, this information can be extrapolated to indicate the relative productivity of each section of the borehole. Assuming a simple mixing model, the dissolved solids contribution can be estimated also. Results from these approximations are provided in **Table 5-13**.

Table 5-13. Approximate estimates of productivity and salinity from discrete sections of the borehole within the lower Floridan aquifer, derived from the interval test results, Site C.

Interval (ft bls)	Specific Capacity (gpm/ft)	Transmissivity (ft^2/d)	Total Dissolved Solids (mg/L)
1,489–1,635	14.85	3,970	3,473
1,635–1,762	36.57	9,780	5,900
1,762–2,000	28.07	7,500	22,140

5.3.3. APT 2 (Lower Floridan Aquifer from: 1,489–1,573 ft bls)

Original plans for Site C called for construction of well OSF-109 as a single-zone well to serve as the production well for aquifer performance testing of the Lower Floridan aquifer with OSF-105R as the production zone monitor well for the test. The drilling problems at OSF-105 prevented completion of a production zone monitor well for the test and prompted redesign of OSF-109 as a dual-zone Lower Floridan aquifer monitor well. Consequently, this test was conducted using the upper annular zone of OSF-109 as the production well, with monitoring only in the over- and underlying units, which limited the interpretation of the test results. **Figure 5-8** provides a schematic drawing for the test set-up. Data collected during this test can be found in **Appendix D**.

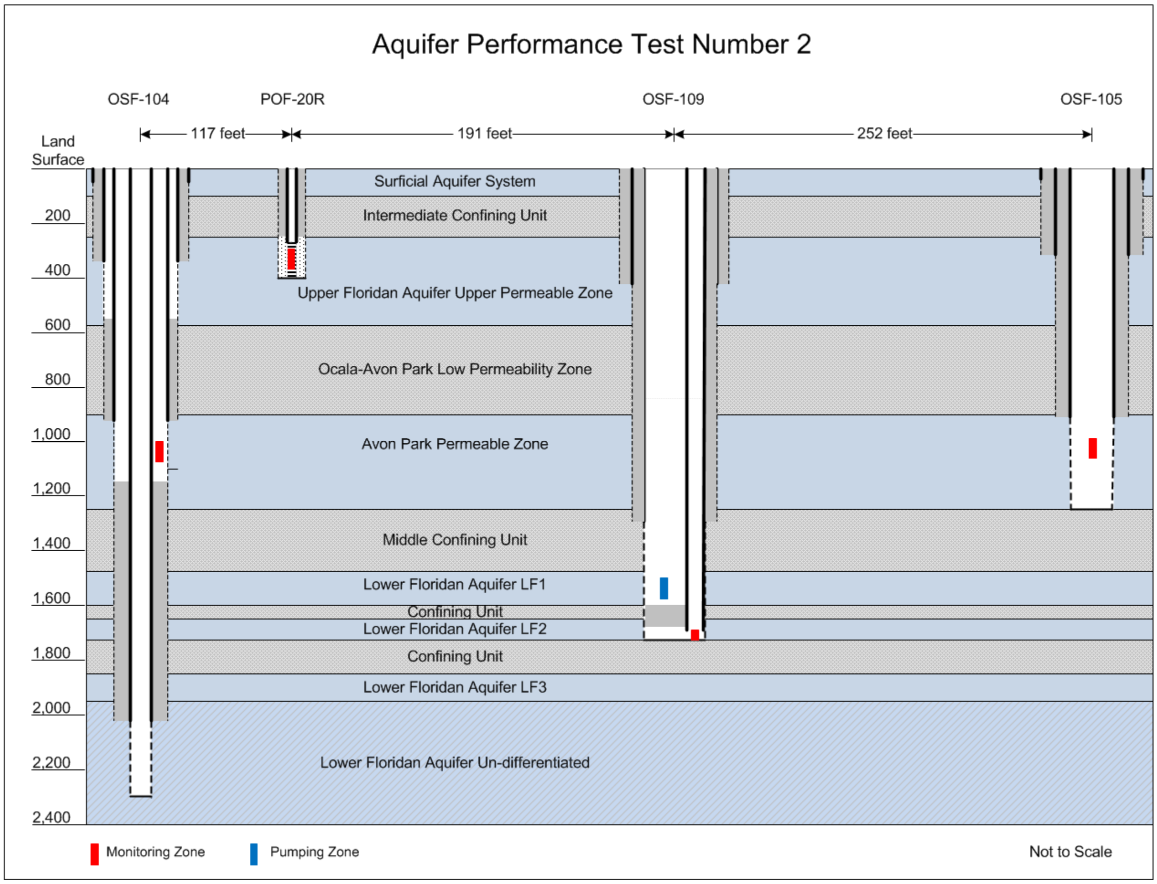


Figure 5-8. Configuration of wells for APT 2, Site C.

On October 29, 2012, AWE initiated aquifer performance testing on the uppermost permeable zone of the Lower Floridan aquifer at Site C. A preliminary step-drawdown test was conducted to evaluate discharge rates for the CRDT and to ensure that monitoring equipment was configured and reading correctly. Following the preliminary test, water levels were allowed to return to background conditions. The step-drawdown results indicated that a rate of less than 500 gpm was necessary to ensure that drawdown did not fall to the pump set depth (165 ft bls). This was lower than anticipated based on the results of interval test 1, indicating that there was more productivity in the interval from 1,573 to 1,635 ft bls than anticipated from the geophysical logging and packer test results, or some damage may have been done to formation permeability in the annular zone during cementing operations.

The CRDT began at 18:00 on October 29, at a constant pumping rate of 430 gpm. At 18:00 on November 2, 2012, the pump was shut down and the test went into recovery. **Figure 5-9** illustrates the time-drawdown relationship at the production well. Drawdown in the well increased to a maximum of 138.3 ft approximately 464 minutes (7.8 hours) into the test. After that, drawdowns began to decrease, dropping 3.7 ft by the time the test went into recovery, implying the presence of a recharge boundary.

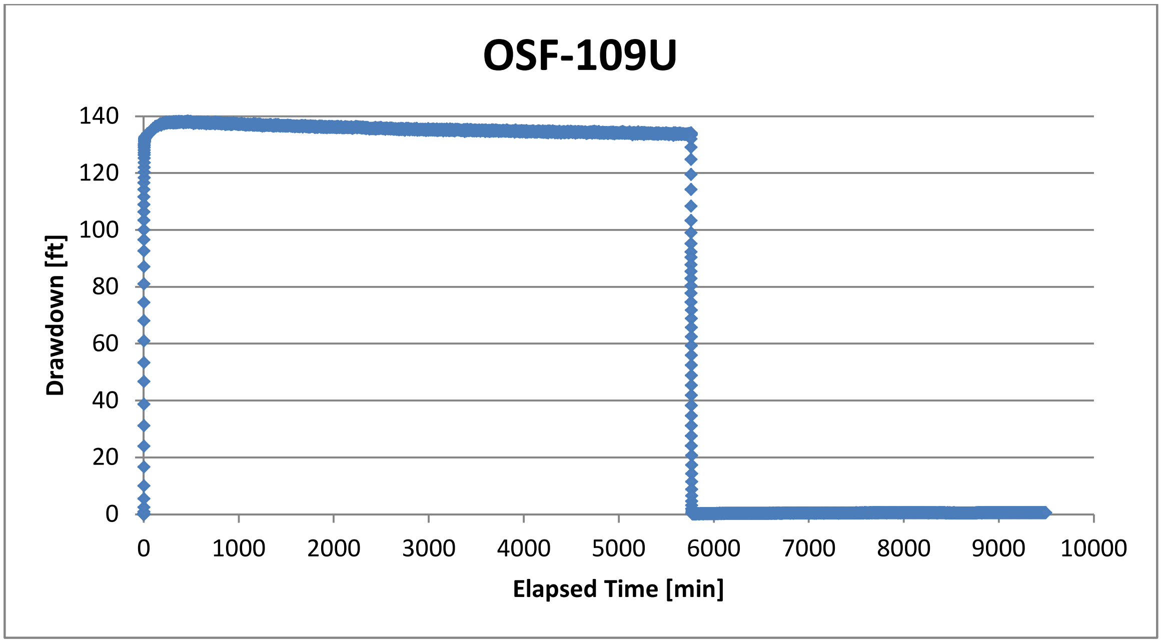


Figure 5-9. Time drawdown in production well OSF-109U.

AQTESOLV software (Duffield, 2007) was used to evaluate analytical solutions to this test data. Utilizing only the early hours of the test, prior to hitting the recharge boundary, application of the Cooper-Jacob (1946) solution yielded a transmissivity estimate of 2,400 ft^2/day for LF1 (**Figure 5-10**). The lack of a producing zone monitor well and presence of significant wellbore storage effects make it impossible to estimate the storage coefficient, but the estimated transmissivity is commensurate with the results of the earlier interval testing (**Section 5.2**) and modeling exercise (see **Table 5-11**).

The most likely source of this recharge is the underlying LF2 unit. OSF-109L, which monitors LF2, was the only monitor well to show a response to the pumping in OSF-109U, and there is only 40 ft of confinement between these two producing zones. However, several factors make a reliable leakance across this unit difficult to determine from this test.

Figure 5-11 shows the APT transducer and manual drawdown data from OSF-109L. During the drawdown portion of the test, the transducer data from OSF-109L was rendered useless by vibrations from the pump. It is clear from the manually sampled data that there was a steady-state drawdown of about 0.3 ft due to the pumping in the overlying annular zone, but the early time data was unavailable.

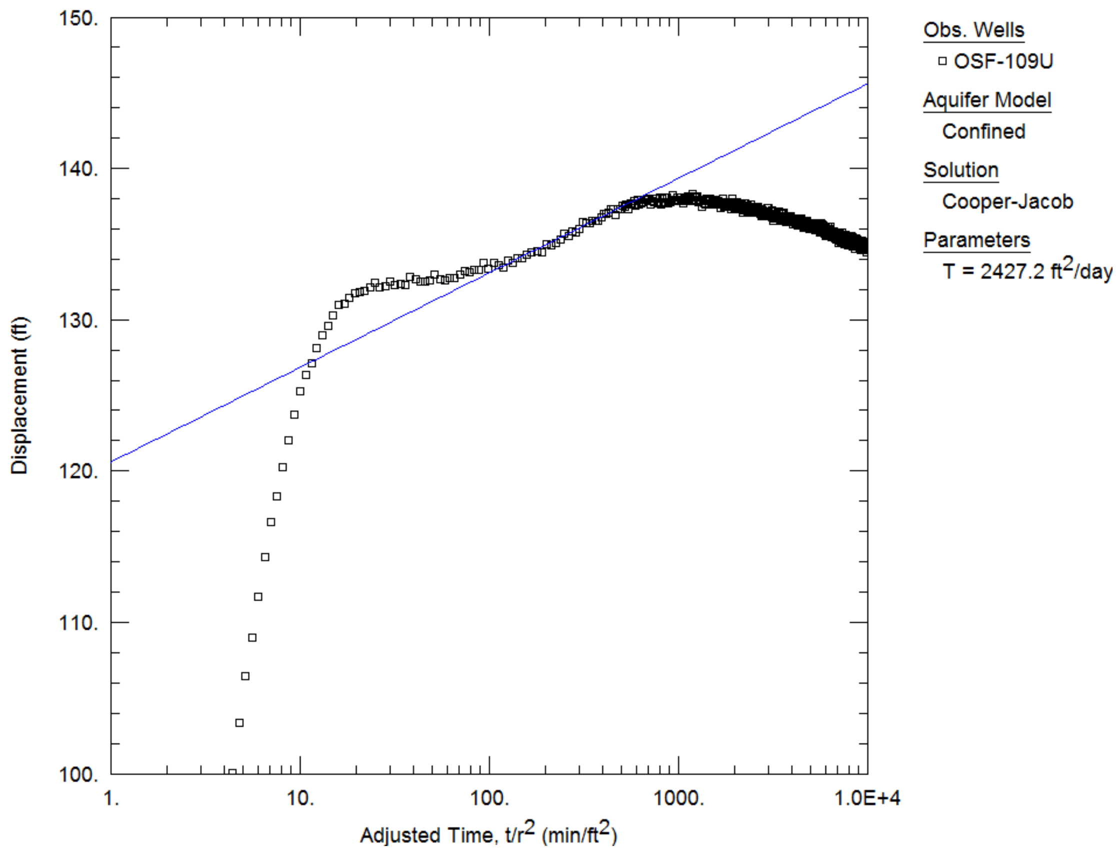


Figure 5-10. Cooper-Jacob analysis of drawdown data for the linear portion of the test (OSF-109U).

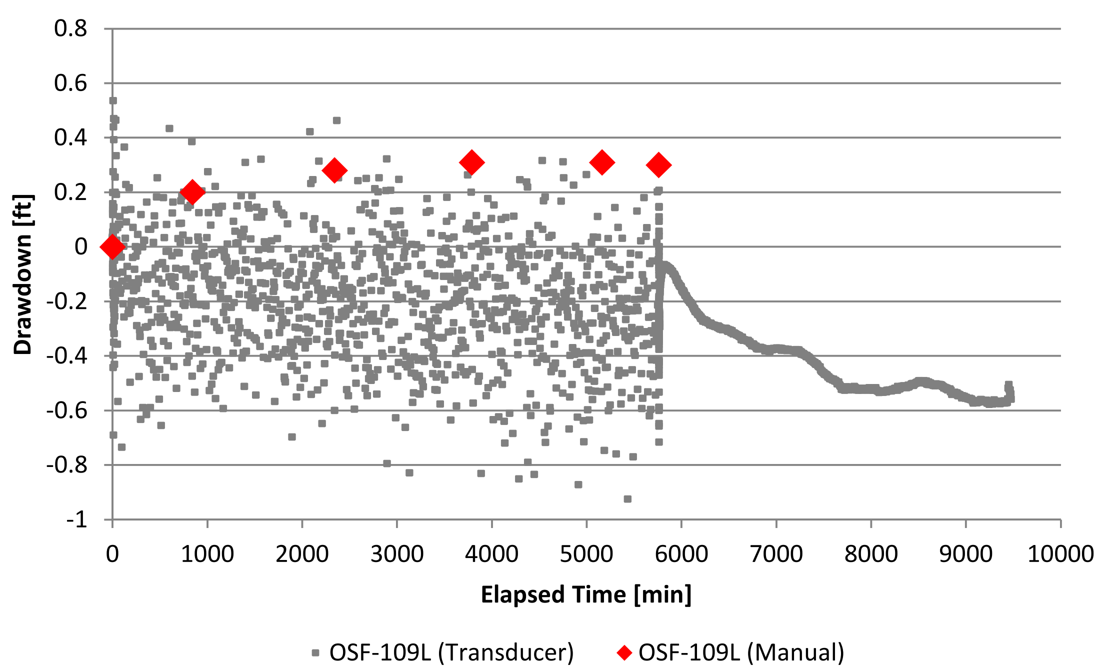


Figure 5-11. Time-series drawdown from OSF-109L during APT#2.

The lack of a pumping zone monitor well also prevents finding an analytical solution for a storage coefficient. Consequently, this parameter must be estimated and fixed as a constant for any leakance calculation. Failure of the annular zone to produce at the same rate as it did prior to construction implies damage to the formation requiring a positive skin factor, another variable that must be estimated to acquire an analytic solution for leakance. Finally, although no drawdown response was observable in the overlying APPZ monitor wells, it must be remembered that both of those wells are much farther from the production well than OSF-109L. The APPZ has been shown to be so productive that a withdrawal of this nominal magnitude would scarcely be detectable even if an immediately adjacent monitor well were available. Acknowledging these difficulties, a modeling approach was used to provide rough estimates of leakance for the confining unit between LF1 and LF2.

A simple three-layer, two-dimensional model was configured as shown in **Figure 5-12**. Hydraulic parameters for LF2 were fixed based on estimated transmissivity (T) from the interval testing results and a reasonable value for storativity (S) in the FAS. Given initial heads equivalent to observed unstressed conditions (see table 5-16) and the maximum observed drawdown in LF2 under the LF1 pumping rate of 430 gpm, the model was run to solve for the leakance (L) across the confining unit given the expected range of transmissivity and storativity for LF1. It was assumed for these simulations that all leakance was derived from LF2. The model results are summarized in **Table 5-14**.

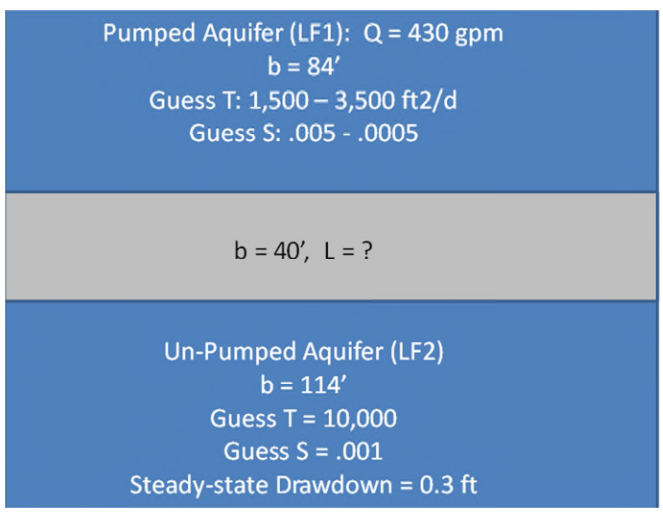


Figure 5-12. Model configuration for estimation of leakance from APT#2.

Table 5-14. Leakance results from the model.

Transmissivity (ft^2/day)	Storativity	Vertical Permeability (confining unit) (ft/day)	Leakance (per day]
1,500	5.00E-04	0.25	0.00625
1,500	5.00E-03	2.8	0.07
2,500	5.00E-04	0.3	0.0075
2,500	5.00E-03	2.4	0.06
3,500	5.00E-04	0.36	0.009
3,500	5.00E-03	2.4	0.06

Given a probable range of hydraulic parameters for LF1, the vertical permeability of the lower confinement ranges an order of magnitude, from 0.25 to 2.5 ft/day.

5.4. Packer Testing

Four straddle-packer tests were conducted during exploratory drilling of OSF-109 at Site C to determine productive capacities and collect representative formation water samples below the APPZ. Packer set depths and test duration are shown in **Table 5-15**.

Table 5-15. OSF-109 packer test depth summary, Site C.

Test No.	Test Date	Depth (ft bls)	Pumping Duration (Minutes)	Recovery Duration (Minutes)
1	22-Aug-2012	1,890–1,920	125	56
2	22-Aug-2012	1,837–1,867	153	26
3	23-Aug-2012	1,689–1,719	171	42
4	24-Aug-2012	1,545–1,575	195	35

As part of the set-up for the testing, a submersible pump and pressure transducer were installed inside the drill pipe. A transducer was also set outside of the drill pipe to monitor changes in pressure (head) that might indicate leakage around the packer. Manual measurements in the test interval and annular space were taken before, during, and after the test to confirm transducer readings. The caliper log from the pilot hole was reviewed to determine the optimal depth to set the packers. Based on this review, a target test interval of 30 ft was selected. AWE connected two inflatable packers to the drill pipe to effectively isolate the test zone. Initial water quality samples were recorded for specific conductance, temperature, and pH. Each test consisted of a drawdown and recovery phase, during which heads in the packed-off interval were continuously recorded**.** Check valves were installed in the pumps to prevent recharge of water above the pump when turned off.

During the pumping phase of testing, water level responses were erratic. Drill-stems were not developed prior to conducting the drawdown tests and this in combination with a permeable formation and stratified water quality, may have resulted in discharge from the formation of variable-density water during pumping, resulting in the erratic water levels. Therefore, only the data from the recovery portion of each test was used to estimate hydraulic properties. Final depth to water DTW at the end of recovery is assumed to represent the background water level from that depth interval.

During each packer test, the annular transducer recorded changes in water level, which indicates some leakage around the packers. Proper sealing results in minimal changes in water level in the zone above the upper packer. During PT1, PT2, and PT3, water levels changes were minimal in the annular zones. During the recovery phase of PT4, the water level rose in the annular zone by 0.34 ft, compared to a rise of 4.39 ft in the packed interval. Water levels during the drawdown phase dropped in both the annular and packer zones. It is unclear why water levels in the annular zone tracked those in the packed zone, however, this could be due to an incomplete seal that allowed water to be drawn into the annular zone from the test zone. It should be noted that a poor seal would tend to bias transmissivity and hydraulic conductivity values upward. This should be taken into consideration before applying the results.

The Hazen-Williams equation (Finnemore and Franzini 2002) was used to calculate the head loss due to friction in the pipe prior to each packer test analysis. Correcting for head loss is necessary to calculate an accurate specific capacity for each interval, otherwise the specific capacity would be underestimated. After appropriate corrections were made, the following two methods were used to calculate hydraulic properties:

1. Driscoll (1986) presented an empirical formula for estimating transmissivity in a confined aquifer based on the specific capacity as previously shown in Equation 5-1 and by definition:

$$K = \left(\frac{T}{b}\right)$$ **Equation 5-5**

where: K = hydraulic conductivity (gpd/ft²)
b = thickness of the tested interval (feet)

2. Cedergren (1977) presented the following formula for estimating the coefficient of permeability (hydraulic conductivity) from packer test data:

$$K = \frac{q}{2\pi Ls} ln \frac{L}{r}$$ **Equation 5-6**

where consistent units are used, and:
K = hydraulic conductivity (length/time [l/t])
q = constant rate of flow into the borehole (l^3/t)
s = drawdown (l)
L = length of the section of hole being tested (l)
r = radius of the section of hole being tested (l)

The hydraulic data for the packer tests are summarized in **Table 5-15.**

Table 5-15. Summary of packer test hydraulic data from OSF-109, Site C.

Test No.	Depth (ft bls)	Pumping Rate (gpm)	Drawdown (ft)	Drawdown Phase		
				[1] Transmissivity (ft^2/day)	[1] Hydraulic Conductivity (ft/day)	[2] Hydraulic Conductivity (ft/day)
1	1,890 – 1,920	85	4.83	4,705	156.9	84.3
2	1,837 – 1,867	73	10.34	1,888	62.9	33.8
3	1,689 – 1,719	40	3.90	2,742	91.4	49.1
4	1,545 – 1,575	45	4.23	2,686	89.6	48.1

[1] from Driscoll (1986)
[2] from Cedergren (1977)

At the end of the drawdown phase, water quality samples were collected for screening in the field for pH, temperature, specific conductance, and alkalinity, as well as laboratory analyses for pH, hardness, alkalinity, major anions and cations, nutrients, total dissolved organic compounds, TDS, fluoride, and bromide. Each sample sent for laboratory analysis was collected in the appropriate container, field filtered and preserved (if necessary), and placed in a cooler on ice for shipping to a certified facility for analysis. The field measurements were recorded using a YSI 6920 multiparameter probe that was calibrated for pH and specific conductance before and after sample collection. The water quality results are provided in **Section 5.2.2**. The following sections provide a summary of the individual packer test set-up and hydraulic properties calculations.

5.4.1. OSF-109 Packer Test 1 (1,890 to 1,920 ft bls)

This testing interval was selected because it was in a high porosity section of the upper portion of LF3 based on geophysical logs. During this test, AWE pumped the interval for 125 minutes at a discharge rate of 85 gpm. The recovery period was 56 minutes with an increase in water level of 5.53 ft. The specific capacity of this interval during recovery was 15.4 gpm/ft. The transmissivity was 30,674 gpd/ft, or 4,110 ft^2/day, calculated using Equation 5-1 (Driscoll, 1986). Water quality data collected from this packer test interval is discussed in Section 5.2. Depth to water of 34.99 ft bls was recorded at the end of recovery.

5.4.2. OSF-109 Packer Test 2 (1,837 to 1,867 ft bls)

This interval has relatively high porosity within the upper portion of LF3 based on geophysical logs and is just below the base of the USDW. The purposes of this test were to bracket the USDW, collect water quality data, and test the production capacity and specific capacity for this discrete interval. During this test, AWE pumped the interval for 153 minutes at a discharge rate of 73 gpm. The recovery period was 26 minutes with an increase in water level of 10.86 ft. The specific capacity of this interval during recovery was 6.72 gpm/ft. The transmissivity for this zone was 13,412 gpd/ft, or 1,797 ft^2/day, calculated using Equation 5-1 (Driscoll, 1986). Water quality data collected from this packer test interval is discussed in Section 5.2. Depth to water of 29.32 ft bls was recorded at the end of recovery.

5.4.3. OSF-109 Packer Test 3 (1,689 to 1,719 ft bls)

This interval has relatively high porosity within LF2 based on geophysical logs, and is just above the USDW. The purposes of this test were to bracket the USDW, collect water quality data, and test the production capacity and specific capacity for this discrete interval. During this test, AWE pumped the interval for 171 minutes at a discharge rate of 40 gpm. The recovery period was 42 minutes with an increase in water level of 4.07 ft. The specific capacity of this interval during recovery was 9.83 gpm/ft. The transmissivity for this zone was 19,614 gpd/ft, or 2,628 ft^2/day, calculated using Equation 5-1 (Driscoll, 1986). Water quality data collected from this packer test interval is discussed in Section 5.2. Depth to water of 10.84 ft bls was recorded at the end of recovery.

5.4.4. OSF-109 Packer Test 4 (1,545 to 1,575 feet bls)

This interval was selected because it was in a moderate porosity interval within the upper portion of LF1 based on geophysical logs and drill-stem test data indicated a freshening of water quality across this zone (discussed in more detail in Section 4.3), indicating a possible transition into a productive zone. Water quality data were collected and specific capacity and production capacity were computed for this zone. During this test, AWE pumped the interval for 195 minutes at a discharge rate of 45 gpm. The recovery period was 35 minutes with an increase in water level of 4.39 ft. The specific capacity of this interval during recovery was 9.68 gpm/ft at 35 minutes. The transmissivity for this zone was 19,323 gpd/ft or 2,589 ft^2/day, calculated using Equation 1 (Driscoll, 1986). Water quality data collected from this packer test interval is discussed in Section 5.2. Depth to water of 6.89 ft bls was recorded at the end of recovery.

5.5. Hydraulic Heads

As a component of the LFAKB Project, the new dual-zone well OSF-109 was instrumented for long-term monitoring of water levels. The final instrumentation was completed in October 2013. **Figure 5-13** depicts the first month of recorded water levels from the well, along with those of the previously constructed OSF-104, providing a synoptic view of change in head with depth in the FAS at this location.

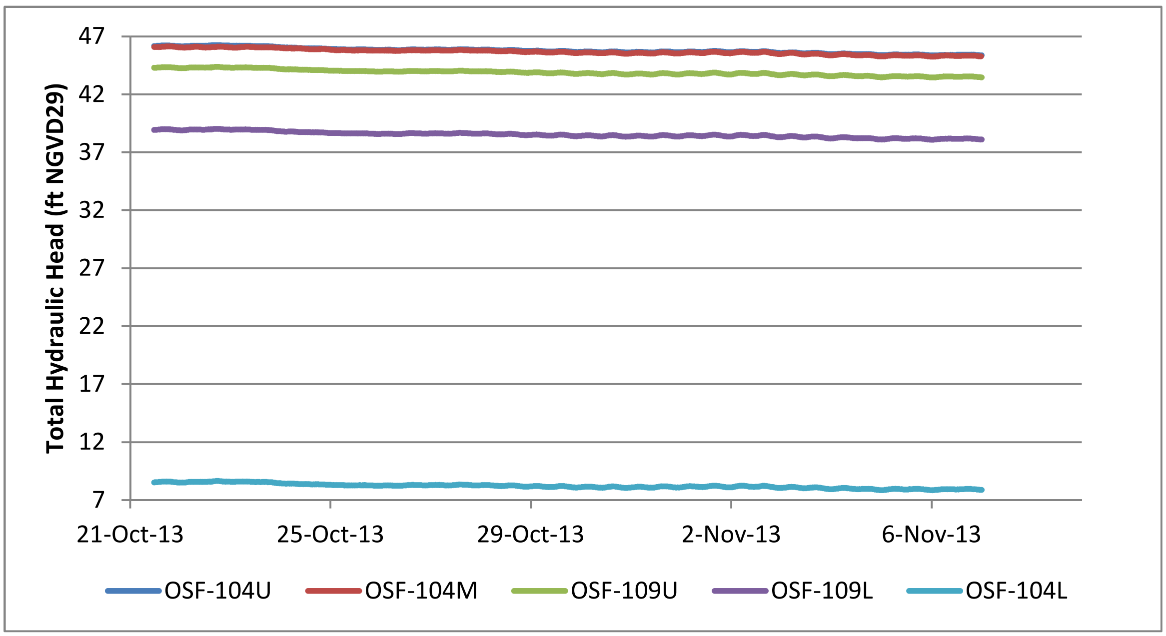


Figure 5-13. Variation in total hydraulic head with depth in the FAS at Site C. (Note: OSF-104U tracks behind OSF-104M at this vertical scale)

Table 5-16 summarizes referenced water level data from this first month of OSF-109 data collection for all instrumented wells at the site. Information on vertical head gradients may be gleaned from this data. During this period, the highest heads were recorded in the intermediate confining unit, with heads declining above and below. This implies that the ICU is effectively isolating the FAS from the SAS with little exchange of water at this location. A review of the previous four years of data from POS-3, POH-1, and OSF-104U (**Figure 5-14**), confirms this is more than a short-term trend. During extreme rainfall events, heads in the SAS can temporarily exceed those in the ICU, offering potential for downward recharge to the FAS, but the most likely direction for those unsustainably high levels to move is laterally, to local surface drainage. At several points in the period of record, heads in the SAS fall below those in the Upper Floridan as well, but heads in the ICU never fall below those in the Upper Floridan, precluding the possibility of upward recharge.

Table 5-16. Summary of vertical distribution in total hydraulic head at Site C (October 21, 2013–November 7, 2013).

Aquifer	Depth (ft bls)	Source	Median (ft NGVD29)	Min. (ft NGVD29)	Max (ft NGVD29)	Std. Dev. (ft NGVD29)
SAS	20–30	POS-2	43.58	43.26	43.87	0.19
SAS	75–90	POS-3	45.82	45.53	46.04	0.16
ICU	180–200	POH-1	47.84	47.56	48.13	0.17
UF-UPZ	330–550	OSF-104U	45.71	45.36	46.25	0.24
UF-APPZ	930–1,150	OSF-104M	45.65	45.25	46.13	0.24
LF1	1,489–1,573	OSF-109U	43.84	43.45	44.37	0.25
LF2	1,694–1,745	OSF-109L	38.48	38.08	39.02	0.25
LF3	1,890–1,920	OSF-109	17.15[a]	--	--	--
Undif. LF	2,000–2,300	OSF-104L	8.20	7.86	8.65	0.20

[a] Single measurement from DTW at end of recovery during packer test 1.

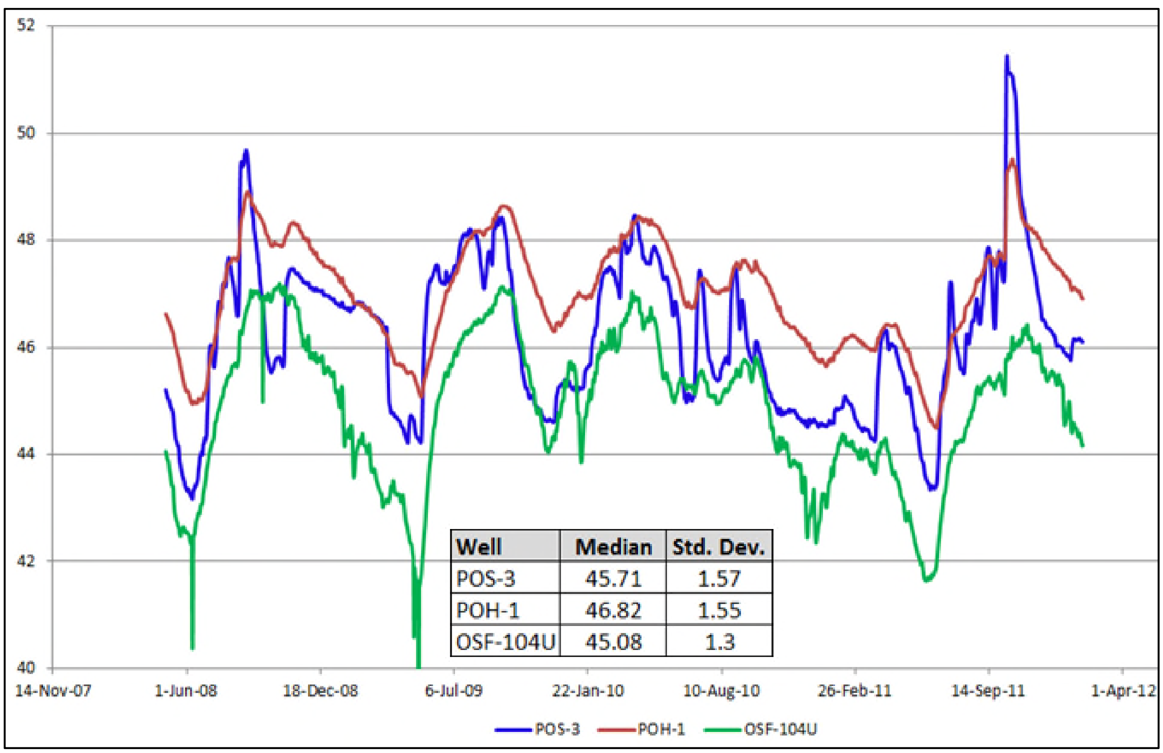


Figure 5-14. Long-term water level (ft NGVD29) relationship between the SAS, ICU, and Upper Floridan at Site C.

Between the UPZ and APPZ there is, on average, less than 0.1 ft of difference in head, but there is almost 2 ft of head drop between the APPZ and LF1. Between LF1 and LF2 there is an additional 5 ft head drop, and over 30 ft of downward gradient between LF2 and the Lower Florida aquifer beneath LF3, represented by monitor well OSF-104L.

Despite these significant differences in total head, there is a strong correlation between the water levels in the FAS wells (**Figure 5-15**). This site is relatively isolated. The primary stressor is the natural fluctuation in barometric pressure. The high degree of correlation observed here is due to the response to that same forcing function.

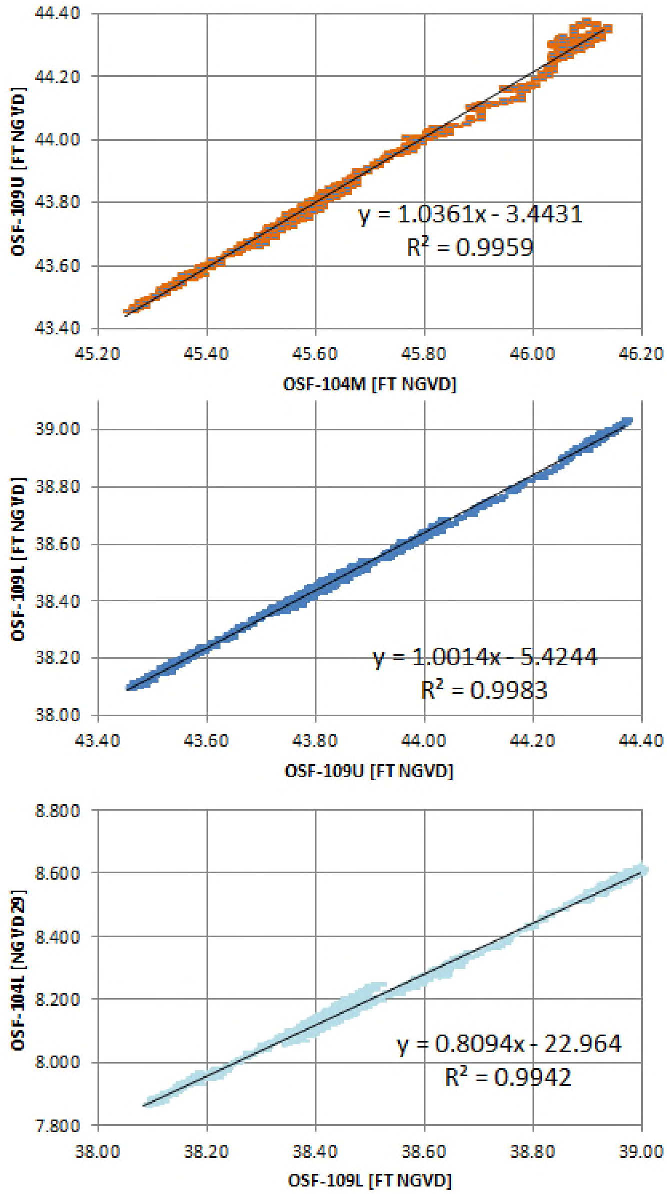


Figure 5-15. Correlation between FAS wells (October 21, 2013–November 6, 2013).

6
SUMMARY

The Site C testing program included:

- Construction and testing of an LFA exploratory well (OSF-109), completed as a dual-zone monitor well in the uppermost two producing zones of the Floridan aquifer.
- Modification and testing of an existing Floridan aquifer system well (OSF-105) for aquifer performance testing.
- Determination of water quality with depth, and sampling for field and laboratory analysis of formation waters during:
    - Drilling (drill-stem and interval test sampling)
    - Straddle-packer testing from four select zones
    - Aquifer performance testing
    - Development of completed monitor zones
- Implementation and analysis of aquifer performance tests, discretely evaluating the APPZ and a portion of the LFA.

Drilling at Site C penetrated to a maximum depth of 2,000 ft bls. Major findings from the drilling and testing program include:

- The following boundaries of the major hydrogeologic units at this location based on lithology, geophysical logs, and water quality, water level and hydraulic data:
    - Top of the intermediate confining unit: 85 ft bls
    - Top of the Floridan aquifer system: 258 ft bls
    - Top of the OCAPLPZ confining unit between the UPZ and the APPZ: 560 ft bls
    - Top of the APPZ: 916 ft bls
    - Top of the MC2 confining unit between the APPZ and the LFA: 1,254 ft bls
    - Top of the LFA: 1,480 ft bls
    - The base of the Floridan aquifer system/top of the sub-Floridan confining unit is below the maximum explored depth at this site (more than 2,500 ft bls from a previous study)
- Three discrete productive intervals, or flow zones, with varying degrees of confinement between them were identified within the LFA at Site C. These zones are numbered sequentially, from shallowest to deepest (LF1–LF3) as follows:

Flow Zone	Top Depth (ft bls)	Base Depth (ft bls)	Relative Productivity Estimate
LF1	1,480	1,600	Low - Moderate
LF2	1,640	1,754	Moderate
LF3	1,890	1,954	Low - Moderate

- Analysis of formation water samples yielded the following distribution of dominant ions and TDS for the hydrogeologic units sampled:

Station Test ID	Hydrogeologic Unit	Sample Depth (ft bls)	Total Dissolved Solids (mg/L)	Dominant Ion Pairs
POS-2	SAS	20–30	493	Ca-HCO3
POS-3	SAS/ICU	75–90	330	Ca-Na-HCO3-Cl
POH-1	ICU	180–200	310	Ca-Na-Mg-HCO3-Cl
OSF-104U	UFA-UPZ	330–550	212	Ca-Mg-Na-HCO3-Cl
OSF-104M	APPZ	930–1,150	248	Na-Mg-Cl-HCO3
OSF-109	APPZ	920–1,250	302	Ca-Na-Mg-Cl-HCO3-SO4
OSF-109U	LF1	1,489–1,573	2,722	Na-Ca-Cl
OSF-109PT4	LF1	1,545–1,575	2,904	Na-Ca-Cl
OSF-109PT3	LF2	1,689–1,719	6,933	Na-Cl
OSF-109PT2	LF3	1,837–1,867	22,520	Na-Cl
OSF-109PT1	LF3	1,890–1,920	25,322	Na-Cl
OSF-104L	LFA	2,000–2,300	34,121	Na-Cl

Discrete, referenced water level measurements within the hydrogeologic units identified at Site C were taken at different points during construction and testing. With completion of this project, a very comprehensive vertical transect of the aquifers above and within the Floridan aquifer system is available. From these data, it appears that the highest heads are in the UFA, decreasing both above and below that unit. There is an approximate 2-ft head drop between the APPZ and LFA at this site, and an additional 35-ft drop within the LFA between the shallowest and deepest measurements.

Aquifer	Depth (ft bls)	Source	Median
SAS	20–30	POS-2	43.58
SAS	75–90	POS-3	45.82
ICU	180–200	POH-1	47.84
UFA-UPZ	330–550	OSF-104U	45.71
APPZ	930–1,150	OSF-104M	45.65
LF1	1,489–1,573	OSF-109U	43.84
LF2	1,694–1,745	OSF-109L	38.48
LF3	1,890–1,920	OSF-109	17.15[a]
Undifferentiated LFA	2,000–2,300	OSF-104L	8.20

Hydraulic testing yielded the following results:

- A 48-hour aquifer performance test (APT) of the APPZ using wells open from (920–1,250 ft bls) indicated a highly productive APPZ at this location, with transmissivity in excess of 400,000 ft^2/day and a storage coefficient of 1×10^{-6}
- Interval testing within the Lower Floridan aquifer yielded the following transmissivity estimates from calculated specific-capacity for LF1, LF2, and LF3:

Hydrogeologic Unit	Specific Capacity (gpm/ft)	Transmissivity (ft^2/day)
LF1	14.85	3,970
LF2	36.57	9,780
LF3	28.07	7,500

- An extended APT of LF1 resulted in a slightly lower transmissivity estimate of 2,470 ft^2/day and an estimated leakance between the LF1 and LF2 producing zones of 0.06–0.008 per day. Drilling problems at the site, which prevented the use of a production zone monitor well, precluded a more precise leakance estimate.

The results of drilling and testing at Site C confirm the presence of several productive intervals within the LFA. The two uppermost intervals, LF1 and LF2, are above the base of the underground source of drinking water (USDW; defined as an aquifer with less than 10,000 mg/l TDS), and can be considered as a potential alternative water supply source. Their suitability for that purpose is most easily assessed by comparison to other lower Floridan sites.

Testing results at site C show a continuation of the trend of decreasing permeability in the lower Floridan aquifer from north to south within the CFWI region. The combined productive capacity of LF1 and LF2 at site C is about a quarter of that at site B, 25 miles to the north. Site C capacity is commensurate with, but slightly less than that of the recently permitted southeast Polk wellfield, which lies approximately 19 miles west and north of Site C. Although southeast Polk appears to be withdrawing from the equivalent hydrogeologic units, there is a major increase in salinity over that distance (TDS increase from a maximum of 1,100 mg/l at the southeast Polk to over 5,000 mg/l at site C). Given that the position of the USDW is less than 10 feet below the base of LF2, it is reasonable to expect that, even with careful wellfield design, that salinity will increase even more under prolonged pumping stress. It is possible that the less brackish LF1 could be targeted independently, but its productivity alone is not really sufficient justify the expense, and the confining unit which separates it from LF2 is sufficiently leaky that it too would see increased salinity over time. Comparatively poor productivity and water-quality make the lower Floridan around site C a poor candidate for alternative water supply development at this time.

REFERENCES

Bennett, M.W. 2008. *Hydrogeologic Investigation of the Floridan Aquifer System S-65A Site, Osceola County Florida (OSF-104 & OSF-105)*. Prepared for SFWMD by AECOM Water.

Bierschenk, W.H. 1964. *Determining Well Efficiency by Multiple Step Drawdown Tests*. Publication 64, International Association of Scientific Hydrology.

Bryan, J.R., R.C. Green and G.H. Means. 2011. *An Illustrated Guide to the Identification of Hydrogeologically Important Formations in the South Florida Water Management District.* Unpublished Contract Deliverable to SFWMD.

Cedergren, H.R. 1977. *Seepage, Drainage & Flow Nets*. Wiley & Sons., 64 p.

Clayton, J.M. 1999. *ROMP 12 Prairie Creek: Final Report – Drilling and Testing Program Southern District Water Resource Assessment Project DeSoto County, FL*. Southwest Florida Water Management District.

Cooper, H.H. and C.E. Jacob. 1946. *A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History*. Transactions of the American Geophysical Union, 27:526–534.

Davis, J.D. and D. Boniol. 2011. *Grids Representing the Altitude of Top and/or Bottom of Hydrostratigraphic Units for the ECFT 2012 Groundwater Model Area*. St. Johns River Water Management District, Bureau of Engineering and Hydrologic Sciences.

Driscoll, F.G. (ed.). 1986. *Groundwater and Wells* (Second edition). Johnson Division, St. Paul, MN.

Duffield, G.M. 2007. *AQTESOLV for Windows, Version 4.5, Professional*. HydroSOLVE Inc., Reston, VA.

Duncan, J.C., W.L. Evan, III and K.L. Taylor. 1994. *Geologic Framework of the Lower Floridan Aquifer System in Brevard County, Florida*. Florida Geological Survey, Bulletin 64.

Embry, A.F., and J.E. Klovan. 1971. A Late Devonian reef tract on Northeastern Banks Island, NWT*. Canadian Petroleum Geology Bulletin*, 19(4):730-781.

Finnemore, E.J. and J.B. Franzini. 2002. *Fluid Mechanics with Engineering Applications*. McGraw Hill Higher Education, 790p.

Frazee, Jr., J.M. 1982. *Geochemical Pattern Analysis: Method of Describing the Southeastern Limestone Regional Aquifer System*. Studies of Hydrogeology of the Southeastern United States, Special Publications: Number 1, Georgia Southwestern College, Americus, GA.

Horstman, T. 2011. *Hydrogeology, Water Quality, and Well Construction at ROMP 45.5 – Progress Energy Well Site in Polk County, Florida.* Southwest Florida Water Management District. Brooksville, FL, 40p.

Hounslow, A.W. 1995. *Water Quality Data Analysis and Interpretation*. Lewis Publishers. 397 p.

King, K.C. 1979. *Tampa Formation of Peninsular Florida, a Formal Definition.* Master's Thesis, Florida State University, Tallahassee, FL 83 p.

Miller, J.A. 1986. *Hydrogeologic Framework of the Floridan Aquifer System in Florida and Parts of Georgia, Alabama and South Carolina.* USGS Professional Paper 1403-B. U.S. Geological Survey, Washington, DC, 91 p.

Maidment, D.R. (ed.). 1993. *Handbook of Hydrology*, McGraw-Hill Inc.

Reese, R.S. and E. Richardson. 2007. *Synthesis of the Hydrogeologic Framework of the Floridan Aquifer System, Delineation of a Major Avon Park Permeable Zone in Central and Southern Florida.* U.S. Geological Survey Scientific Investigations Report 2007-5207, U.S. Geological Survey, Reston, VA.

Scott, T.M. 1988. *The Lithostratigraphy of the Hawthorn Group (Miocene) of Florida*. Florida Geological Survey, Bulletin No.59.

Sepulveda, N., C.R. Tiedeman, A.M. O'Reilly, J.B. Davis and P. Burger. 2012. *Groundwater Flow and Water Budget in the Surficial and Floridan Aquifer Systems in East-Central Florida.* U.S. Geological Survey Open-File Report 2012-1132, U. S. Geological Survey, Reston, VA.

Shapiro, A.M. 1989. *Interpretation of Oscillatory Water Levels in Observation Wells During Aquifer Tests in Fractured Rock*. Water Resources Research, 25(10):2129-2137.

Spechler, R.M., and S.E. Kroening. 2007. *Hydrology of Polk County, Florida*. U.S. Geological Survey Scientific Investigations Report 2006-5320, U. S. Geological Survey, Reston, VA.

Streltsova, T.D. 1988. *Well Testing in Heterogeneous Formations*. John Wiley & Sons: New York, NY, 413p.

Sunderland, R.S.A etal., 2011. *Hydrogeologic Investigation of the Floridan Aquifer System at the S-65C Site (Well OKF-105), Okeechobee County, Florida.* SFWMD Technical Publication WS-32

Tucker, M.E., and V.P. Wright. 1990. *Carbonate Sedimentology*. Blackwell Science, Oxford, 482.