Upper Floridan Aquifer Testing Project St. Cloud and River Ranch

SOUTH FLORIDA WATER MANAGEMENT DISTRICT

Sites Osceola and Polk Counties, Florida

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1
INTRODUCTION

The South Florida Water Management District (SFWMD) Hydrogeology section is working to provide a hydrogeologic characterization of the Upper Floridan aquifer in Osceola and Polk counties, Florida. The primary goal of this project is to expand the information obtained during an ongoing study of the upper portion of the Floridan aquifer. This project will provide hydrostratigraphic information for the upper portion of the Floridan aquifer, along with hydraulic parameters necessary for the subregional modeling efforts presently underway. This project required the modification of two existing long-term monitoring sites to allow testing to be performed. Two aquifer performance tests (APTs) were performed at two different sites within the Kissimmee Basin. Each site was modified to allow a two-well APT to be performed on the Upper Floridan aquifer.

1.1 SITE LOCATIONS

The first site was located in St. Cloud, Florida, where production well OSF-70 was modified by backfilling the existing borehole from 470 feet below land surface (bls) to 246 feet bls using gravel and neat cement. This was done in order to isolate the Upper Floridan aquifer and seal off the underlying Avon Park permeable zone. Once completed, a new monitor well (OSF-107) was drilled with the same configuration as the production well 50 feet away. The St. Cloud site is located and constructed along the SFWMD-owned right-of-way on the south side of the C-31 Canal, just outside of the St. Cloud city limits. This site is located in the southeast quadrant of Section 5 of Township 26 South, Range 30 East. The site consists of two surficial monitor wells (OSS-70S and OSS-70D), an Upper Floridan monitor well (OSF-107), an Upper Floridan production well (OSF-70), an Avon Park producing zone well (OSF-82U), and a Lower Floridan aquifer monitor well (OSF-82L). Final well construction details are provided in **Appendix A**.

The second site was River Ranch, where a new production well (POF-26) was drilled 50 feet away from the existing Upper Floridan aquifer monitor well (POF-23). The River Ranch site is located on SFWMD-owned property along the western access road to the Kissimmee River, in the southwest quadrant of Section 25 of Township 31 South, Range 31 East. The site consists of two shallow surficial aquifer monitor wells (POS-4 and POS-5), an Upper Floridan monitor well (POF-23), and an Upper Floridan production well (POF-26). Both the St. Cloud and River Ranch sites are shown in **Figure 1**.

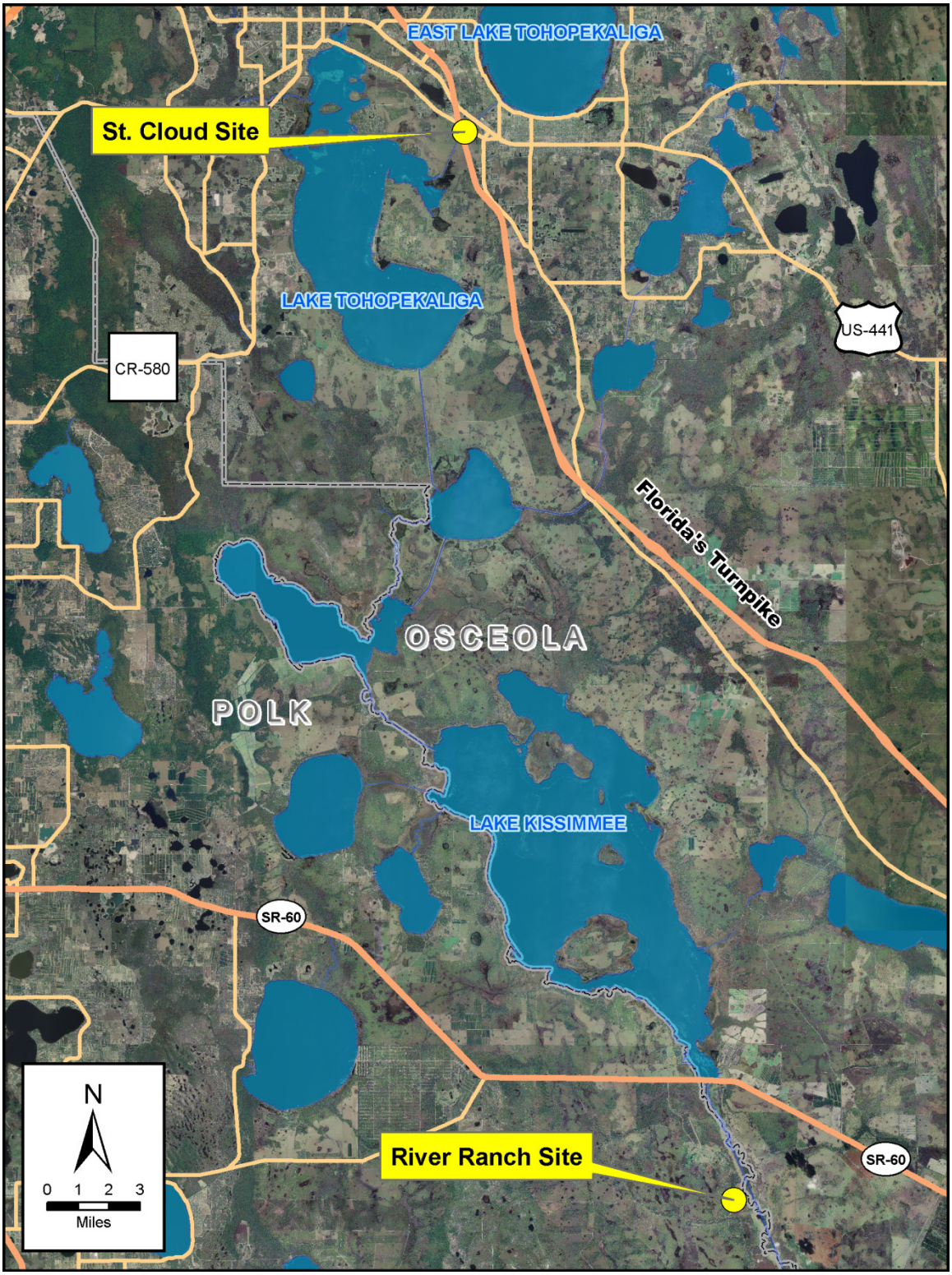

Figure 1. Kissimmee Basin site map.

2
WELL CONSTRUCTION

2.1 DRILLING OF ST. CLOUD SITE, OSF-70/OSF-107

The SFWMD hired Advanced Well Drilling, Inc. (AWD) to conduct the work at the St. Cloud site (OSF-70/OSF-107). AWD was contracted to complete three mains tasks: backfill an existing well (OSF-70), drill a new monitoring well (OSF-107), and complete two aquifer performance tests (APT), as discussed in **Section 4**.

The first task was to backfill an existing 8-inch diameter borehole (OSF-70) at the St. Cloud site, from a total depth of 470 feet below land surface (bls) to a depth of 246 feet bls (**Figure 2**). A caliper log was scheduled to be run on the existing borehole in order to verify the actual borehole diameter and to calculate the amount of cement and materials needed to complete this task. However, the SCADA system installed on the existing site could not be removed, and the well was backfilled using the gravel and tag method until the desired depth was reached. Gravel was used to bring the borehole up to approximately 300 feet bls, and neat cement was used to complete the interval to 246 feet bls. Confirmation of each stage of this operation was required and recorded with a hard tag. This was considered the well rehabilitation phase of this project, which was completed on June 3, 2008.

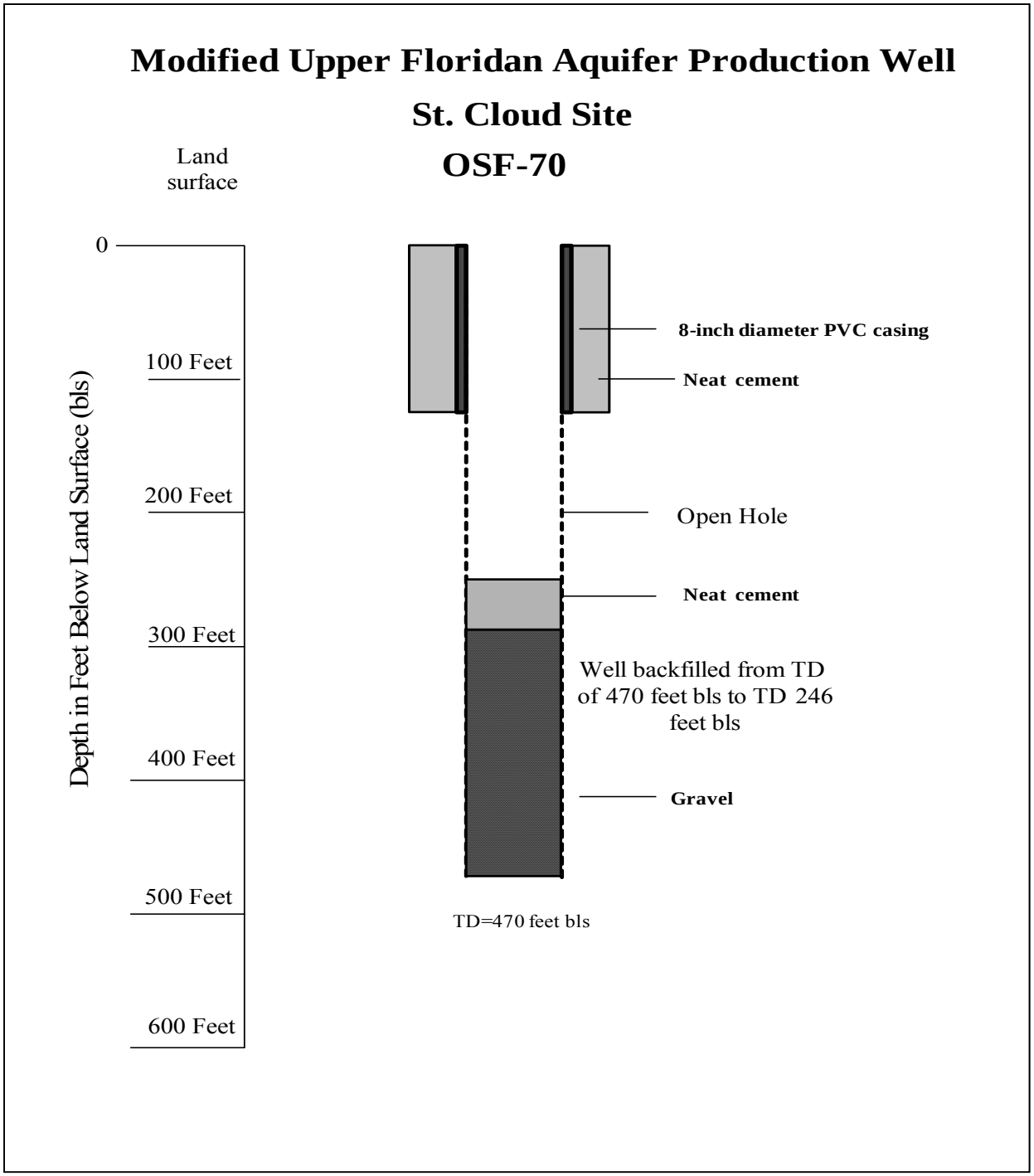

Figure 2. Modified Upper Floridan aquifer production well, OSF-70.

The second task was to drill and complete a single-zone monitor well (OSF-107) in the upper portion of the Floridan aquifer, as shown in **Figure 3**. On June 4, 2008, the AWD rig was set up on the drill site, approximately 50 feet from OSF-70. On June 5, 2008, an 8-inch borehole was drilled to 125 feet bls, where extremely hard rock was encountered. The bit used was a 7⅞-inch diameter rock bit with a stabilizer.

A white, dense limestone with visible calcite crystals was determined to be lower Hawthorn and provide a good casing seat. Once the casing depth was determined by a SFWMD geologist, the borehole was cleaned out and the mud was conditioned for casing installation. Four-inch diameter steel casing was run to 125 feet bls and cemented in place by pressure grouting, using 25 sacks of neat cement with a 75-gallon water displacement behind the cement. The grout was left to cure over the weekend. The following Monday, June 8, 2008, the borehole was entered and mud was conditioned in anticipation of loss of circulation conditions, which occurred at 129 feet bls. The rig was then switched over to reverse-air rotary drilling due to lost circulation conditions. A 3⅞-inch diameter bit was used inside the 4-inch diameter steel casing. Poor cuttings return was an issue when trying to collect drill cuttings from the remaining portion of the borehole. Cuttings were collected every ten feet, marked accordingly, and bagged using SFWMD-approved cuttings bags supplied by the driller. The borehole was advanced to a total depth of 250 feet bls with reverse-air rotary drilling. Once the borehole was completed, the well was developed until clear of any visible solids. The OSF-107 well construction is shown in **Figure 4**.

Figure 3. Drilling activities at the St. Cloud site.

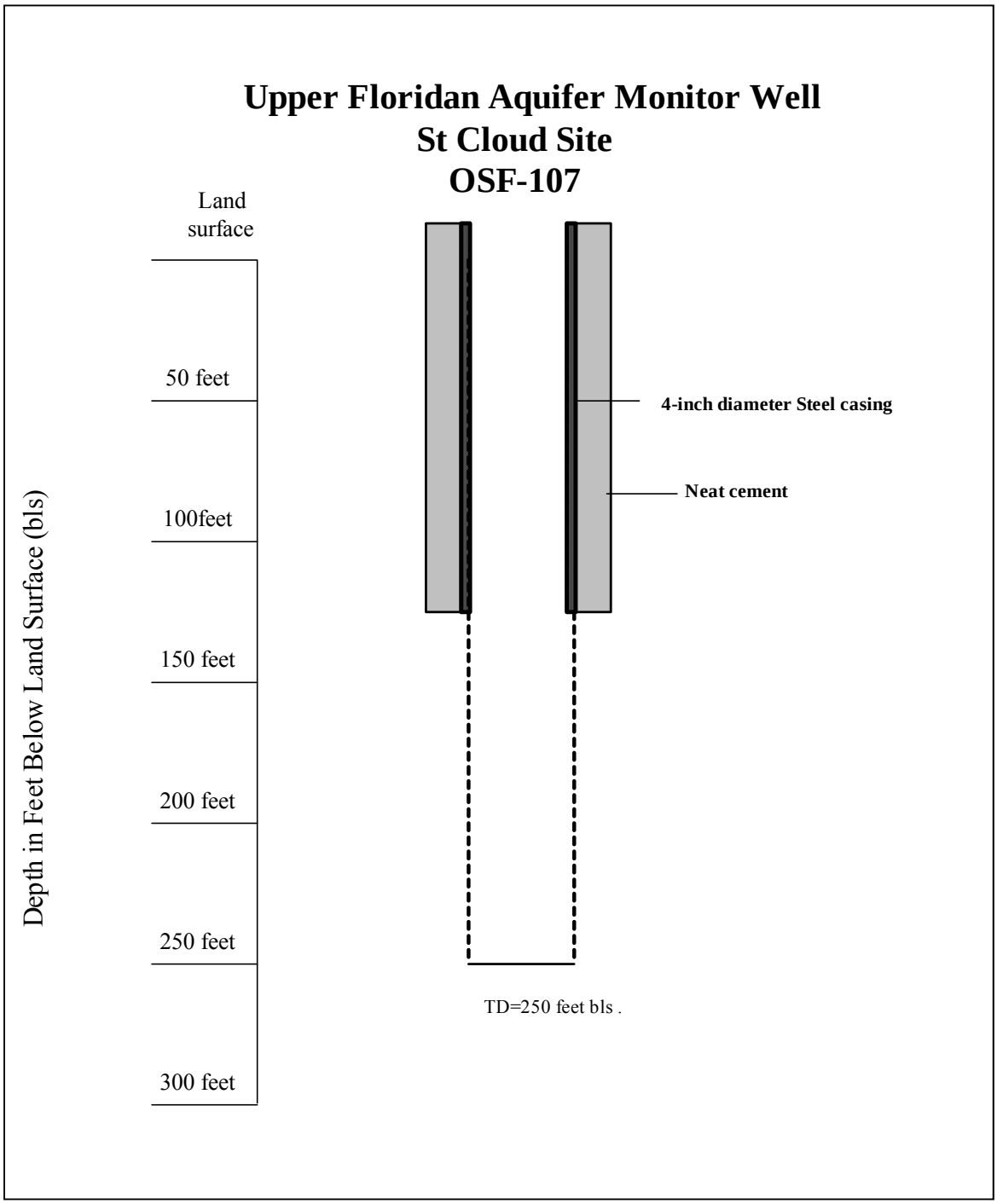

Figure 4. Upper Floridan aquifer monitor well, OSF-107.

2.2 DRILLING OF RIVER RANCH SITE, POF-23/POF-26

A second task was also issued to AWD, which required drilling a new 8-inch diameter borehole to a total depth of 400 feet bls at the River Ranch site. The work entailed the drilling and completion of a production well in the upper portion of the Floridan aquifer. The well construction included drilling a pilot hole and reaming a 14-inch diameter mud-rotary borehole to approximately 250 feet bls.

The drilling for the production well POF-26 started on June 6, 2008, with the field staking of the location, approximately 50 feet from monitor well POF-23. The surface casing was installed and cemented on June 11, 2008, with 56 feet of Schedule 80, 12-inch diameter PVC. The surface casing cement cured overnight and was topped off on June 12, 2008, with 25 sacks of neat cement. Mud-rotary drilling began at 12:00 p.m. on June 12, 2008, using a nominal 12-inch diameter drill bit, and continued through the afternoon of June 13, 2008, to a total depth of 248 feet bls. Eight-inch diameter steel casing, in 21-foot sections, was installed to 248 feet bls and cemented in place via the pressure grout method, using 80 sacks of neat cement (**Figure 5**). The cement was allowed to set and cure overnight.

On the following day, June 14, 2008, an additional 5 sacks of neat cement were used to top the outside annulus to land surface. Drill mud was mixed, and AWD tripped back into the hole with a 7⅞-inch diameter drill bit. Drilling was difficult from 248 feet bls to 250 feet bls. At 250 feet, AWD broke through the cap rock of the Floridan aquifer and lost circulation. The rig was converted to reverse-air, and drilling continued to a depth of 319 feet bls until the drill rod became stuck with a loose, biogenic-type limestone. AWD worked to free the rod and drill bit but was unsuccessful. The contractor then used the air compressor on the rig to clean out part of the hole to get the rod and bit turning. AWD and the SFWMD decided to trip out of the hole and determine if the well could yield enough water to run an APT. The well was developed with air, and enough clear water was produced to run the required APT with the production well depth of 319 feet bls (**Figure 6**).

Figure 5. Setting casing at River Ranch site.

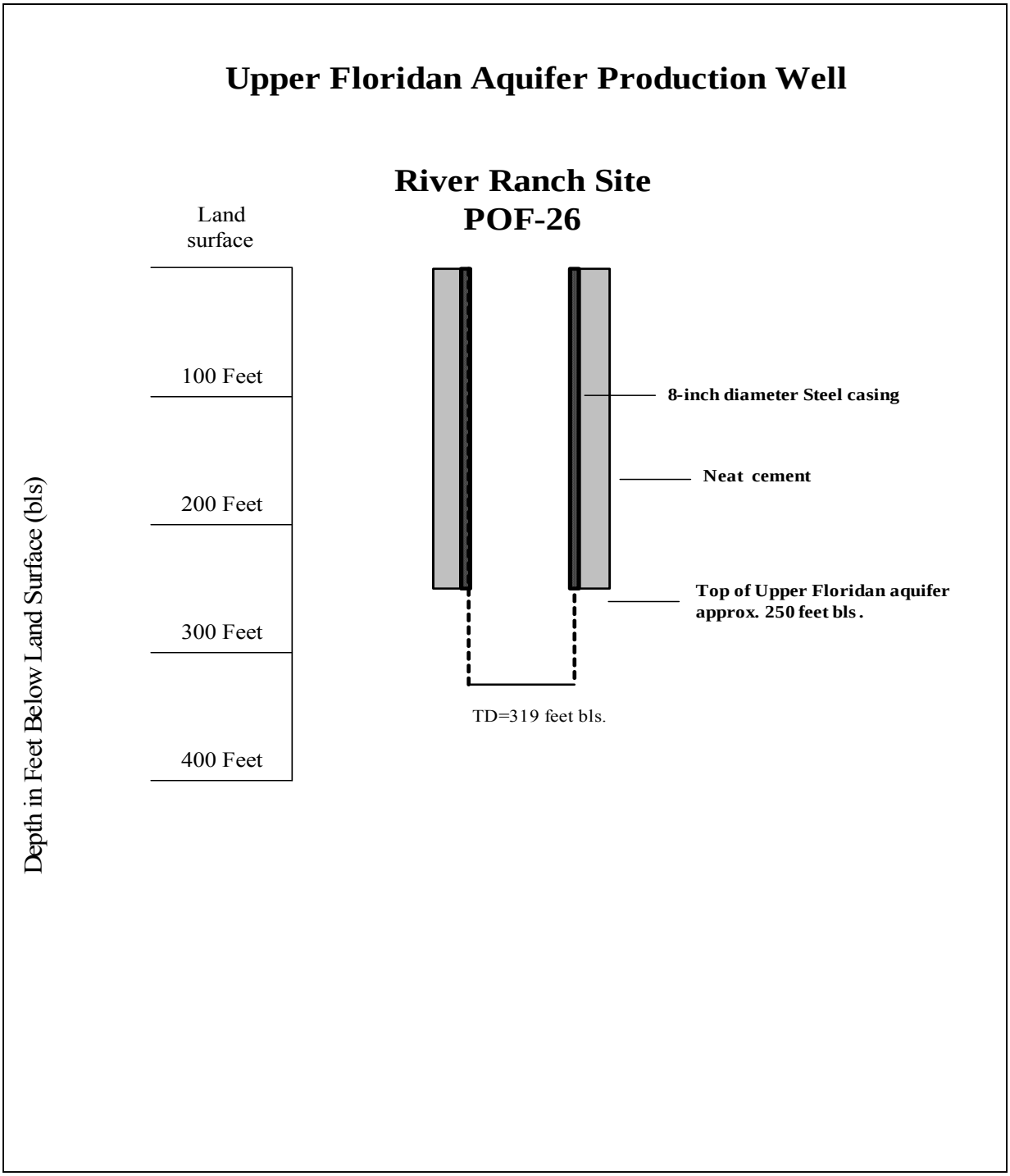

Figure 6. Upper Floridan aquifer production well, POF-26.

The Floridan aquifer monitoring well (**Figure 7**) was drilled at an earlier date (February 2007) to establish a pair of surficial aquifer monitoring wells and a Floridan aquifer monitoring well. **Appendix B** presents the detailed lithologic descriptions of drill cuttings analyzed by the Florida Geologic Survey (FGS) for the St. Cloud site (OSF-70) and the on-site field descriptions from a SFWMD hydrogeologist on the other three wells.

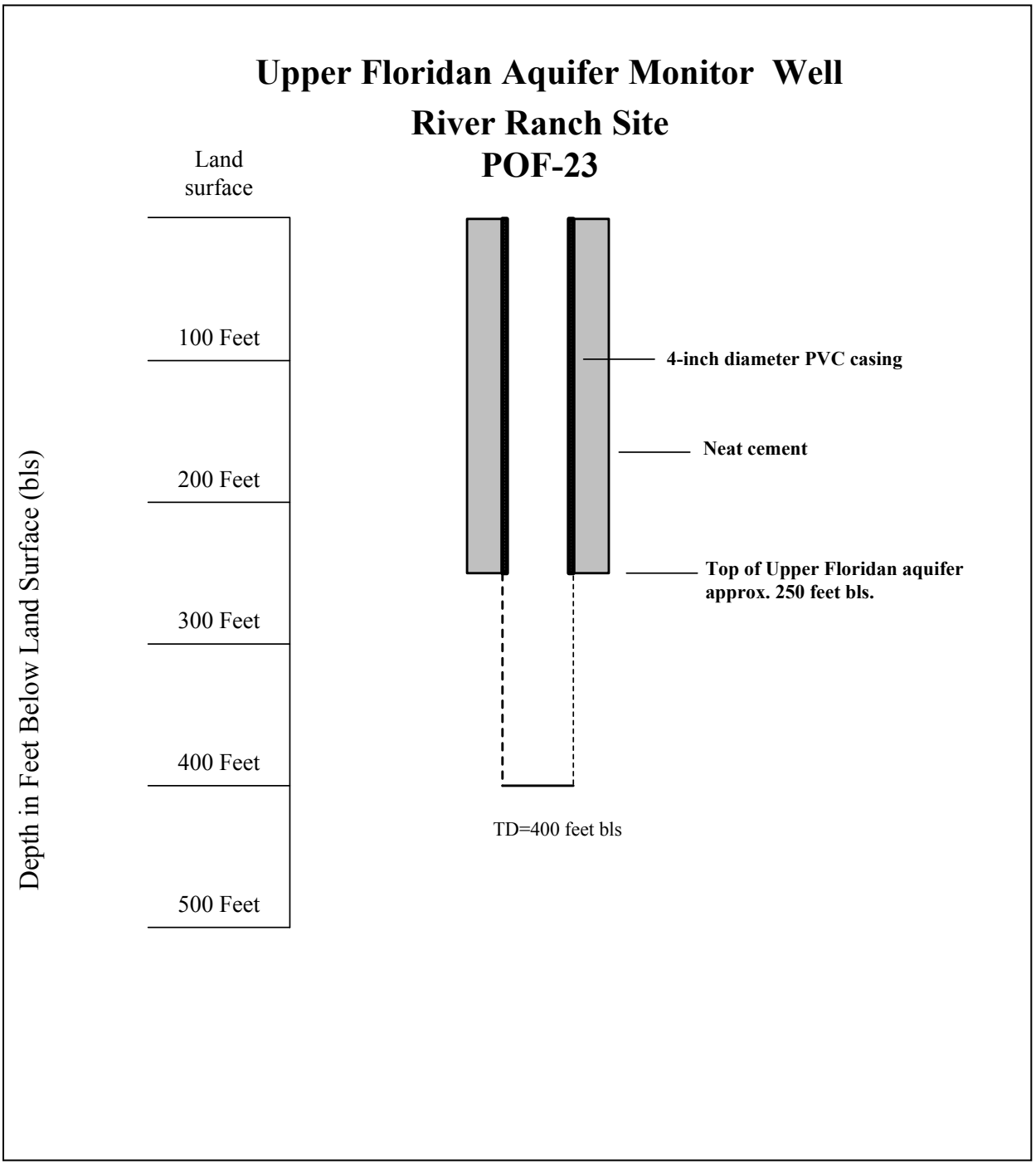

Figure 7. Upper Floridan aquifer monitor well, POF-23.

2.3 GEOPHYSICAL LOGGING AT POF-26

Geophysical logging took place at the POF-26 site on August 18, 2008. A series of logs, including caliper, natural gamma ray, lateral 16 and 64 resistivity, spontaneous potential (SP), temperature, fluid resistivity, and flow logs were run. The well was pumped at 250 gallons per minute during the dynamic flow log in order to develop a flow zone profile. The resulting logs provide a continuous record of the geometry of the borehole and physical properties of the subsurface formations and their respective fluids. Composites of the geophysical log traces for well POF-26 are presented in **Appendix C**.

The caliper log, coupled with the natural gamma log, indicated that a casing seat was located at the lowermost portion of the Hawthorn Group and the upper portion of the Ocala Limestone. The natural gamma log generally shows a significant vacillation of natural gamma activity due to the presence of phosphatic sands generally associated with the Hawthorn Group. Once through the Hawthorn Group, the resistivity logs indicate a higher resistivity in the upper portion of the Floridan aquifer due to increased formation resistivity shown by both the 16-inch resistivity log and the lateral log associated with the Ocala Limestone. In fact, the Hawthorn Group/Ocala Limestone contact is the flow zone at this site, determined by flow log and resistivity logs. A large cavity at the top portion of this zone yielded the only flow zone within this borehole, as demonstrated by the flow logs in **Appendix C**.

3
HYDROGEOLOGY

3.1 HYDROGEOLOGIC SETTING

3.1.1 Surficial Aquifer System (SAS)

The surficial aquifer system (SAS) in the Kissimmee Basin area is predominantly unconsolidated quartz sand and varying amounts of shell, limestone, and clay of late Holocene and Pliocene-Pleistocene age. The surficial aquifer system is unconfined, and the upper boundary is defined by the water table. The thickness of the aquifer system varies from 30 to 225 feet. The SAS was interpreted to be 90 feet deep by the Florida Geological Survey at the St. Cloud test site. Olive green clay was encountered at 50 to 55 feet bls, indicating the top of the Intermediate Confining Unit at the River Ranch site.

3.1.2 Intermediate Confining Unit (ICU)

The Hawthorn Group of Miocene age occurs below the SAS and extends from 50 to 250 feet within the two sites under investigation in the upper Kissimmee Basin. The top was encountered at approximately 90 feet bls at the St. Cloud site, and at approximately 55 feet bls at the River Ranch site. The Hawthorn Group sediments consist of unconsolidated shell beds, soft non-indurated clay, silt, and quartz phosphatic sand units. The lower portion of the Hawthorn Group contained sandy clay with a hard beige limestone member. Once penetrated, this dense limestone caused loss of drilling fluid circulation.

3.1.3 Floridan Aquifer System (FAS)

The Floridan aquifer system is divided into two aquifers of relatively high permeability. The Upper Floridan aquifer contains fresh water, and the Lower Floridan aquifer contains more mineralized water. The two aquifers are separated by less permeable units, also known as middle confining units. This study focused only on the Upper Floridan aquifer.

The top of the FAS, as defined by the Southern Geological Society AdHoc Committee on Florida Hydrostratigraphic Unit Definition (1986), coincides with the top of a vertically continuous permeable carbonate sequence. Generally, the Upper Floridan

aquifer consists of thin water-bearing horizons with high permeability interspersed within thick units of late to middle-Eocene age sediments with low permeability, including the basal Arcadia Formation, Ocala Limestone, and the Avon Park Formation.

The formation contact between the Miocene-aged Arcadia Formation (Hawthorn Group) and the underlying Eocene-aged Ocala Limestone was encountered at 130 feet bls, just below a hard, dense, moderately to well-indurated layer of limestone with phosphatic sands at the St. Cloud site, and at 249 feet bls at the River Ranch site. This discontinuity is evidenced by allochems consisting of diagnostic benthic foraminifera (*Lepidocyclina* sp.) at the St. Cloud site (**Appendix B**), and is located below a significant attenuation of the natural gamma activity and marked by an increase in the formation resistivity from the geophysical logs at the River Ranch site (**Appendix C**). Once penetrated, all circulation materials for mud-rotary drilling were lost at both sites. Drilling operations had to be converted to the reverse-air rotary drilling method. The upper portion of the FAS consists of limestone, with both intergranular and intragranular porosities, and as drilling continued, the limestone became a friable, very light orange calcarenite with fossil fragments.

Table 1. Generalized stratigraphic and hydrogeologic units of Polk and Osceola counties, Florida.

Geology and Lithology	Series	Stratigraphic Unit	Hydrogeologic Units	Approximate Thickness (ft)
Undifferentiated sands and shell – surficial deposits	Pleistocene Pliocene	Undifferentiated surficial deposits	Surficial Aquifer System	30-225
Sandy clay with shell fragements	Miocene	Hawthorn Group	Intermediate Confining unit	50-250
Limestone	Eocene	Ocala Limestone	Upper Floridan aquifer	0-115
Limestone	Eocene	Avon Park Formation	Upper Floridan aquifer	300-400

(Modified from Barr, 1992; O'Reilly and others, 2002; Spechler and Kroening, 2006)

4
AQUIFER TESTING

The third task of this project was to conduct two long-term APTs on the upper portion of the Floridan aquifer at the St. Cloud (OSF-70/OSF-107) and River Ranch (POF-23/POF-26) sites. The total estimated length of each APT was 96 hours, consisting of a 72-hour constant-rate drawdown phase and a 24-hour recovery period.

4.1 OSF-70/OSF-107 APT, ST. CLOUD SITE

The contractor installed a submersible pump capable of continuously pumping 1,000 gallons per minute from the OSF-107 production well, as shown in **Figure 8**. Background data and step-drawdown tests were run to determine the full range of pumping rates and equipment functionality.

Figure 8. Pump installation at St. Cloud site.

The aquifer performance testing at the St. Cloud site involved six wells: one Upper Floridan aquifer production well, one Upper Floridan aquifer monitoring well, one Avon Park producing zone monitoring well, one Lower Floridan aquifer monitoring

well, and two SAS (surficial aquifer system) monitoring wells. The well names and construction information used in this APT are presented in **Table 2**. **Figure 9** is a plan view showing the layout of the wells used during the aquifer test.

Table 2. St. Cloud site APT well information.

Well Name	Well Type	Cased Depth (feet, bls)	Total Depth (feet, bls)	Well Diameter (inches)	Aquifer	Distance from Production Well (feet)
OSS-70S	Monitor	16.5	26.5	2	SAS	9
OSS-70D	Monitor	45	55	2	SAS	70
OSF-107	Monitor	125	250	4	Upper Floridan	50
OSF-82U	Monitor	350	583	14	Avon Park Producing Zone	164
OSF-82L	Monitor	1,230	1,503	4	Lower Floridan	164
OSF-70	Production	130	246	8	Upper Floridan	0

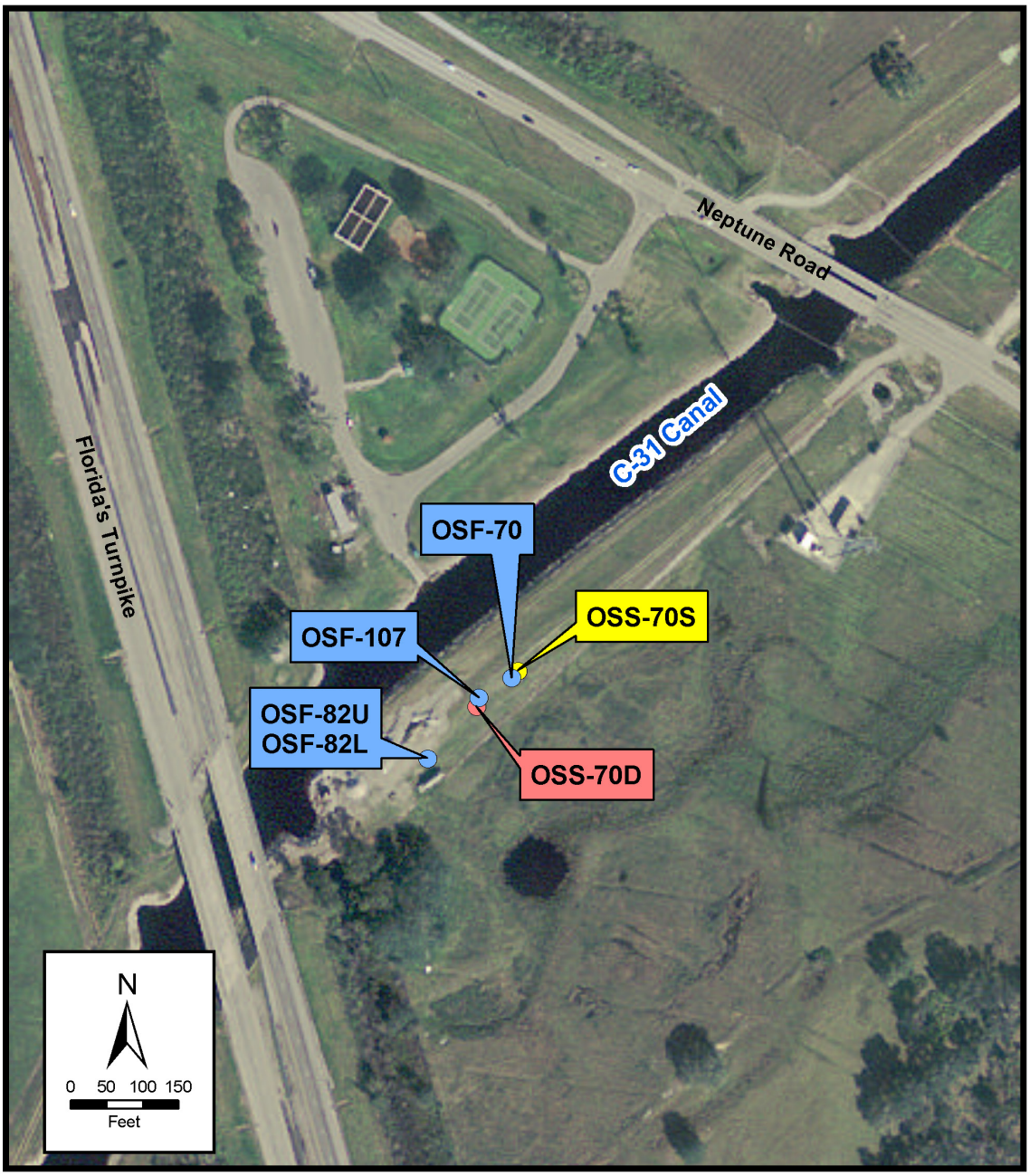

Figure 9. Locations of the St. Cloud wells used for the APT.

4.1.1 Background Water Level Data

The SFWMD collected background data from all of the Floridan aquifer monitor wells at the St. Cloud site every ten minutes, for four days. The water level data for this background monitoring were based on an arbitrary value of zero feet when the Hermit® 3000 data logger started recording. The unit recorded the change in water level from this starting value over a four-day period, between June 23 and 27, 2008. **Figure 10** shows the barometric pressure and water level fluctuations from the Floridan aquifer monitoring wells during the background monitoring period.

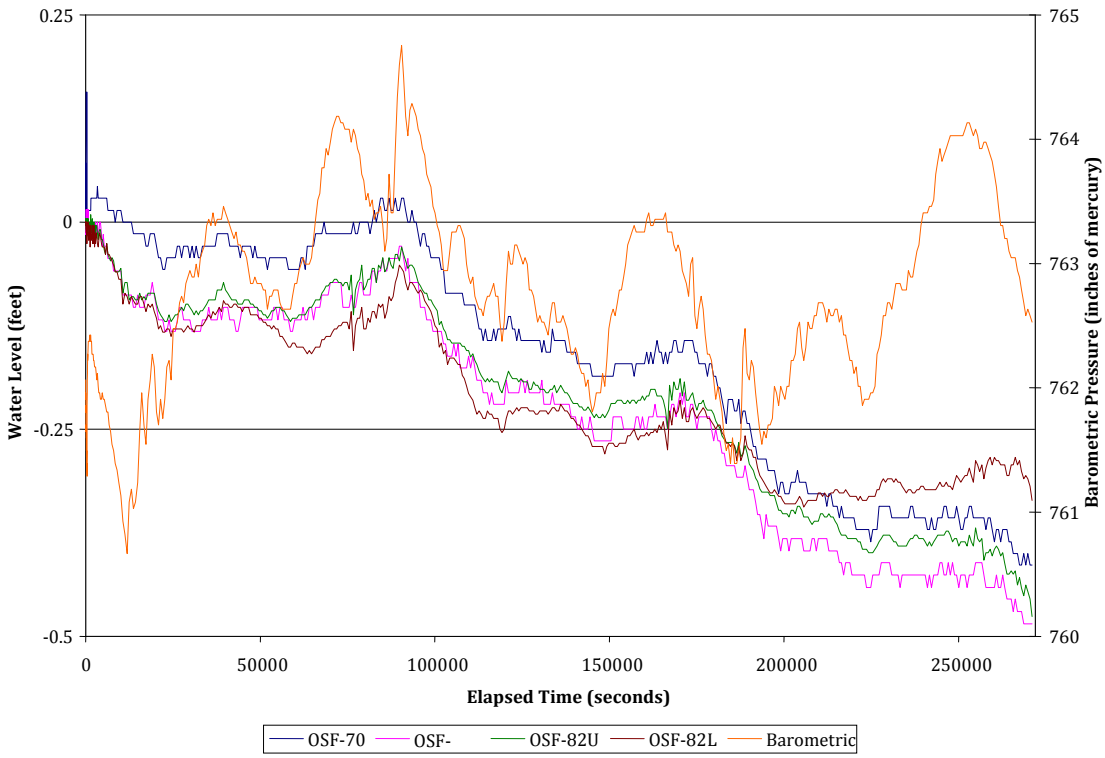

Figure 10. Background water level fluctuations in Floridan aquifer monitoring wells.

The data does not seem to show any relationship between water levels in the Floridan aquifer and barometric pressure. As barometric pressure varied over the course of the monitoring, the water level in the Floridan aquifer decreased. This could be due to the relatively thin confinement layer between the surficial aquifer and underlying Floridan aquifer. The intermediate confining unit at this site, which is the layer that separates the two aquifers, is only 40-feet thick and consists of poorly indurated limestone.

4.1.2 Step-Drawdown Test

The step-drawdown test began by setting the pump to achieve three pumping steps, with a final recovery period to determine the optimum pumping rate for the

72-hour APT. The gate valve on the discharge pipe was continuously closed to determine how low of a flow rate could be obtained, which resulted in the discharge pipe separating from the 90-degree elbow at the wellhead. After reattaching the discharge pipe and setting screws into the PVC, the system held the back-pressure. The drawdown test eventually started at 1:20 p.m. on Friday, June 27, 2008, with three steps: the first at 650 gallons per minute (gpm), the second at 760 gpm, and the third at 900 gpm; each step lasted 45 minutes.

The SFWMD used the step-drawdown test primarily to determine the maximum sustainable pumping rate for the 72-hour APT. The SFWMD ran three steps for this test, each at 45 minutes. In a step-drawdown test, a well is pumped at a low constant-discharge rate until drawdown in the well stabilizes. The pumping rate is then increased to a higher constant discharge rate and again, drawdown in the well is allowed to stabilize. **Figure 11** presents the drawdown data collected during the step-drawdown test.

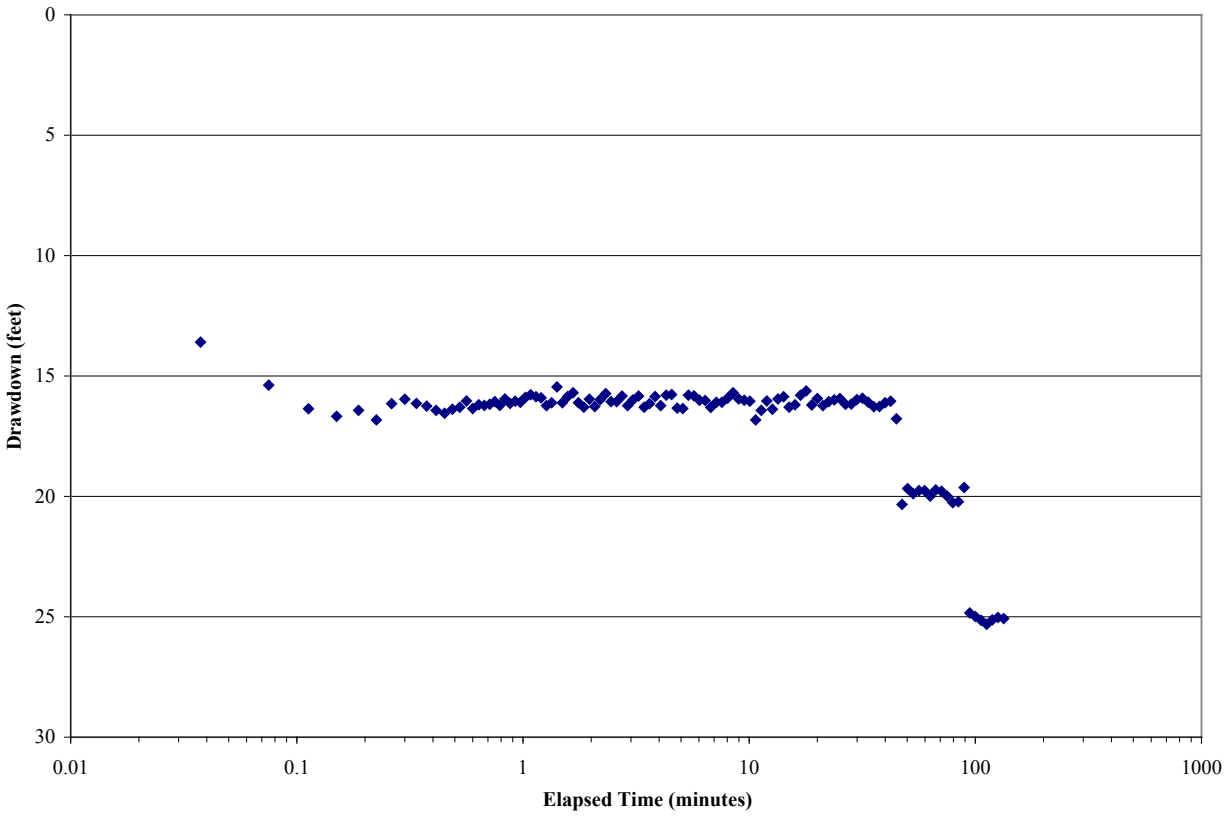

Figure 11. St. Cloud site step-drawdown test data.

This step-drawdown test allowed the SFWMD to calculate well and aquifer losses, as well as the specific capacity of the well at different discharge rates. Drawdown in a well is determined by the use of **Equation 1** (Jacob 1947), as shown below.

(**Equation 1**) $S_w = BQ + CQ^2$

Where:

S_w = drawdown (feet)

Q = discharge rate (gallons per minute [gpm])

B = aquifer loss coefficient (feet/gpm)

C = well loss coefficient (feet/gpm^2)

BQ = well loss due to laminar flow (feet)

CQ = well loss due to turbulent flow (feet)

Well losses occur due to damage and compaction to the aquifer from drilling, turbulent flow in the well bore, and head losses in the aquifer adjacent to the well, caused by turbulent flow. In general, this term covers head losses due to turbulent groundwater flow. These well losses are responsible for the drawdown in the well being greater than on theoretical grounds (Kruseman and deRidder 1990). Aquifer losses are head losses that occur due to laminar flow of water in the aquifer. These aquifer losses vary linearly with the well discharge rate. Based on Walton (1960), the well loss coefficient, C, shows that OSF-70 is properly designed and developed. The Hantush-Bierschenk method (Hantush 1964, and Bierschenk 1964) was used to determine the well and aquifer losses.

The SFWMD determined, from the step-drawdown test, that a pumping rate of 900 gpm was optimal for the 72-hour APT. At this rate, the calculated specific capacity is approximately 36 gallons per minute per foot of drawdown (gpm/ft) at 45 minutes.

Table 3. Results from step-drawdown test at the St. Cloud site.

Step	Discharge Rate (gpm)	Drawdown (feet)	Specific Capacity (gpm/ft)	Aquifer Losses (feet)	Well Losses (feet)
1	650	16.1	40.4	10.8	5.3
2	760	20.2	37.6	12.8	7.4
3	900	25.1	35.9	15.0	10.1

Notes:
gpm gallons per minute
gpm/ft gallons per minute per foot

4.1.3 Aquifer Performance Test

Part of the third task to be completed by AWD was to provide and run a pump for the aquifer testing of OSF-70 and POF-26 (**Section 4.2**). AWD provided a 6-inch diameter, 30-horsepower Goulds submersible pump (Model 6M304) and set it 80 feet deep in the OSF-70 well. A 6-inch diameter polyvinyl chloride (PVC) pipe ran from the pump to land surface, where a 90-degree PVC elbow directed the discharge water through a gate valve and into the 6-inch diameter PVC pipe, which carried the water away from the well to the discharge point. The discharge point for all hydraulic testing was 27 feet north of OSF-70, where the water discharged into a drainage swale and subsequently into the C-31 Canal by natural seepage. The SFWMD's staff were on-site at 8:00 a.m. on Monday, June 30, 2008, to collect initial water level readings on all monitoring and pumped wells (**Figure 12**). The test began at 10:00 a.m. on June 30, 2008. In addition to the data logger readings, manual readings were recorded for the first ten minutes (on minute intervals), then to one-hour readings. The total drawdown after 72 hours of pumping was 29.62 feet in the production well, and 1.54 feet in the Upper Floridan monitoring well located 50 feet away.

Figure 12. Running of APT at the St. Cloud site.

The SFWMD used an In-Situ Inc. Hermit® 3000 data logger and several In-Situ Inc. PXD-261 pressure transducers to collect water level data during all phases of the aquifer performance testing. The SFWMD also set up a second In-Situ Inc. Hermit®

3000 data logger and several In-Situ Inc. PXD-261 pressure transducers as backup units in case there were problems with the first set of equipment. The SFWMD's hydrogeologists also manually recorded water levels with an electronic water level tape. Hand measuring is an option used to verify the electronic data and can be used as a backup in case both data loggers fail. These data were recorded in a field book and later typed into a spreadsheet on a laptop computer. The SFWMD programmed each Hermit® 3000 data logger to record water level data on a logarithmic scale during the drawdown and recovery phases of the APT. A logarithmic scale allows the instrument to rapidly collect numerous data points for the first ten minutes of the test when drawdown occurs quickly. After ten minutes, the Hermit® 3000 data logger collects data on a linear time scale. In both the St. Cloud and River Ranch site APTs, the time interval was one minute. A circular orifice weir consisting of a 6-inch by 5-inch orifice plate and a manometer allowed for discharge measurements. The height of the water (in inches) in the manometer tube is used with a table for specific orifice weir/discharge pipe combinations in order to determine the discharge rate.

The SFWMD conducted a 72-hour APT between June 30, 2008, and July 3, 2008, to determine the hydraulic properties of the upper portion of the Floridan aquifer. The SFWMD set pressure transducers in the production well (OSF-70), the Upper Floridan monitor well (OSF-107), a monitoring well completed in two deeper zones in the Floridan aquifer (OSF-82U and OSF-82L), and the two shallow monitoring wells in the overlying surficial aquifer (OSS-70S and OSS-70D). The purpose of the latter two pressure transducers was to determine if there were any hydraulic connections between these zones. AWD used the same pump for the 72-hour APT that was used during the step-drawdown test. **Figure 13** shows the configuration of the monitoring and test-production wells used in the APT. The drawdown phase of this APT consisted of pumping the well at a constant rate of 900 gpm for 72 hours. A 24-hour recovery period followed the drawdown phase, where pumping stopped and water levels were allowed to return to static conditions.

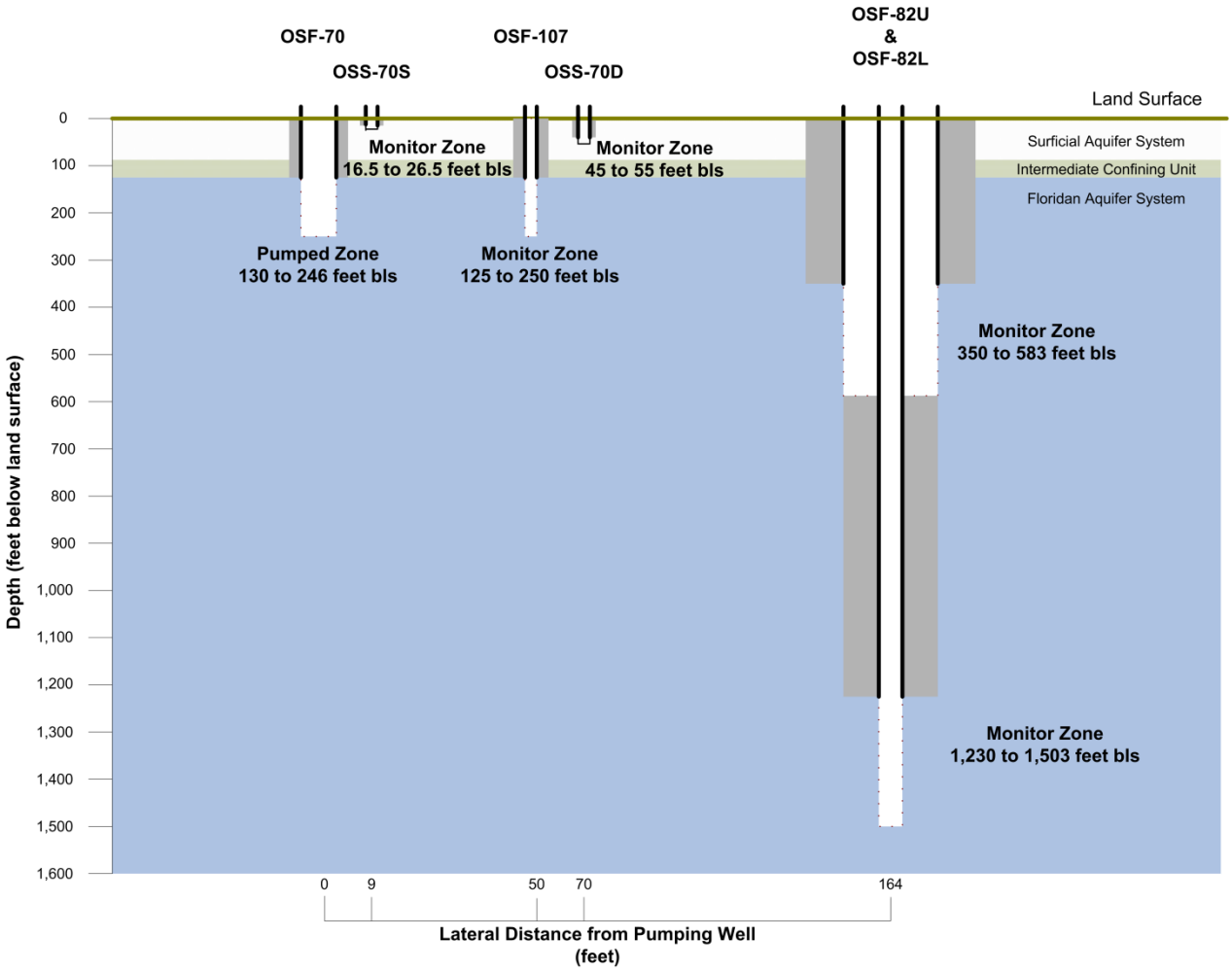

Figure 13. Cross-section of wells used at the St. Cloud APT.

At the time of the APT, heavy rainfall fell around the St. Cloud site on July 2, 2008, causing the water level in the C-31 Canal to rise. The increase occurred as excess water flowed over the S-59 spillway, from East Lake Tohopekaliga to Lake Tohopekaliga. The water level in the C-31 Canal adjacent to the site rose approximately 0.7 feet from July 2, 2008, through the end of the test on July 3, 2008. The elevated water level in the canal only impacted the shallowest groundwater monitor well (OSS-70S), and the water level in this well responded by increasing approximately 0.3 feet. Before the rainfall event, this monitoring well was not responding to the pumping of OSF-70, indicating that there was moderate hydraulic confinement between the Floridan aquifer system (FAS) and the upper portion of the surficial aquifer system (SAS).

Before stopping the pump, the SFWMD reconfigured the various Hermit® 3000 data loggers to record the recovery data in both the test production well and the monitoring wells. The recovery phase of the APT continued for 24 hours, ending on July 7, 2008. Electronic copies of the original drawdown, recovery, and orifice weir

(flow rate) data for the APT are archived and available for review at the SFWMD's headquarters in West Palm Beach, Florida.

The SFWMD's hydrogeologists applied various analytical models to the drawdown and recovery data collected during the APT to determine the hydraulic properties of the aquifer and aquitard(s) at this site. The analytical methods included both confined and semi-confined "leaky" solutions. The shape of semi-log plots with the drawdown data indicated that the aquifer is leaky, semi-confined. The confined transient analytical solutions include the Theis (1935) non-equilibrium method, and the semi-confined "leaky" analytical models include the Hantush-Jacob (1955), Hantush (1960), Neuman-Witherspoon (1969), and Moench (1985); see **Appendix D**. The methods referenced are based on various assumptions, and interested readers should refer to the original articles for further details. In general, drawdown data from a single observation well (for recovery data) only provides an estimate of aquifer and confining unit properties because many of the type curves are similar in shape to one another and do not necessarily provide a unique match to a given data set.

Figure 14 is a log/log plot of drawdown versus time for OSF-107. The shape of the drawdown curve of OSF-107 indicates that the Upper Floridan aquifer is a leaky-type aquifer. This determination comes from the fact that the drawdown curve for this well does not follow the Theis curve (see red line in **Figure 14**), but drops below it. A leaky (semi-confined) aquifer is one that loses or gains water (depending on the pressure gradients) through a semi-confining unit. If a semi-confining unit is composed of a thick layer of unconsolidated or poorly indurated high porosity sediments, it may provide water to the pumped interval. Both the deeper monitoring well in the overlying SAS and the well intersecting a lower permeable section of the FAS responded to the pumping of OSF-70 in the Upper Floridan aquifer, indicating leakage from both above and below the Upper Floridan aquifer.

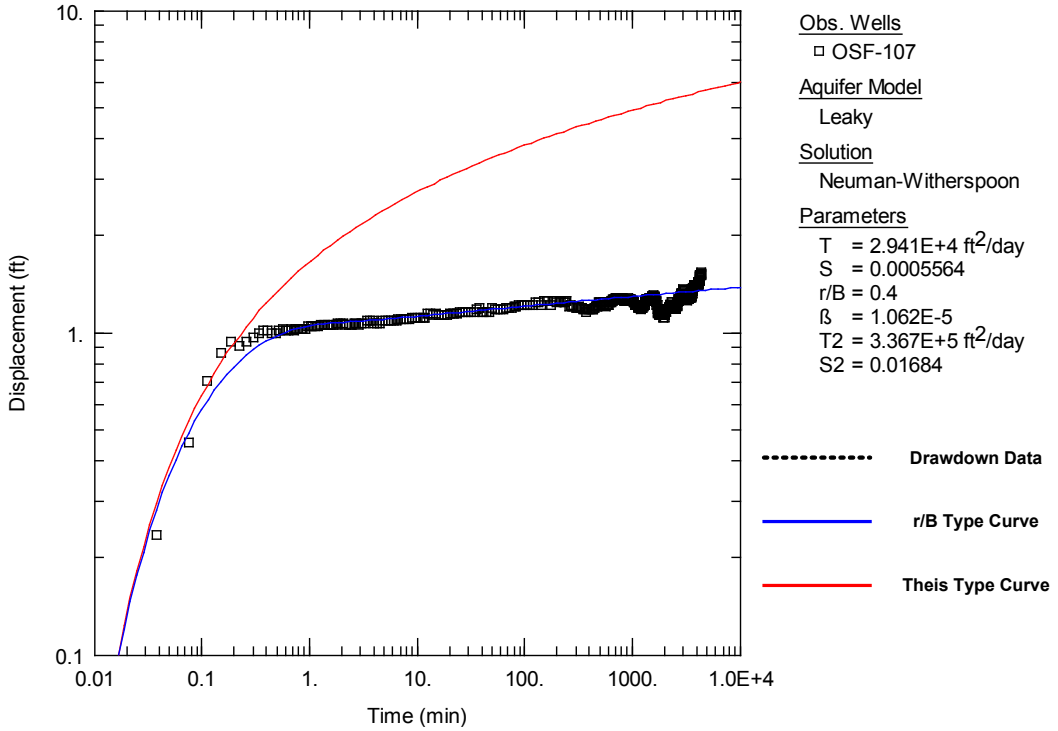

Figure 14. Log-log plot of drawdown data for OSF-107, Neuman-Witherspoon (1969).

Table 4 shows the aquifer's characteristics from the OSF-70 and OSF-107 wells, which were calculated using the various analytical models previously mentioned. Since monitoring wells in both the overlying SAS and in deeper sections of the FAS responded to the pumping of OSF-70, it was determined that leakance is occurring through the overlying and underlying aquitards. Based on these analytical considerations and the site-specific hydrogeologic data collected during aquifer testing, the Neuman-Witherspoon analytical model (1969) appears to best represent the conditions present at this time. The results of this solution yielded a transmissivity value of 29,410 ft^2/day, and a storage coefficient of 5.56 x 10^{-4}. The vertical hydraulic conductivities, and subsequently leakance, were calculated using an r/B value of 0.4, derived from the Neuman-Witherspoon (1969) analysis. The dimensionless parameter r/B represents the leakage across the aquitard(s) to the pumped aquifer; from this value, a leakance value of 1.88 gpd/ft^3 was calculated by dividing the hydraulic conductivity of the overlying aquitard by the thickness of the aquitard. **Table 3** shows a variation in the storativity depending on the various solutions used, and the hydraulic conductivities for the underlying aquitard appear higher than expected since the solutions used treated the underlying aquitard as a confining unit, and flow is vertical. In fact, the underlying aquitard is highly fractured, as indicated from a caliper log run on an adjacent well (OSF-82), and has been considered part of the Upper Floridan aquifer in past studies. This is confirmed by the drawdown in the underlying unit that was over 0.5 feet in the adjacent monitor well (OSF-82) approximately 165 feet away.

Table 4. Aquifer characteristics calculated using the various analytical models from wells OSF-70 and OSF-107.

Method	T (ft^2/day)	S	K (ft/day)	b (feet)	K′ (ft/day)	b′ (feet)	K″ (ft/day)	b″ (ft/day)	L (gpd/ft^3)
Drawdown Results									
Moench (1985)	27,150	4.56×10^{-4}	226	120	70	40	177	100	1.75
Hantush (1960)	26,610	5.85×10^{-4}	222	120	68	40	170	100	1.70
Neuman-Witherspoon (1969)	29,410	5.56×10^{-4}	245	120	75	40	186	100	1.88
Hantush-Jacob (1955)	26,660	5.35×10^{-4}	222	120	68	40	171	100	1.70
Recovery Results									
Moench (1985)	27,690	4.61×10^{-4}	231	120	71	40	1.77	100	1.78
Hantush (1960)	26,710	1.13×10^{-5}	223	120	86	40	221	100	2.15
Neuman-Witherspoon (1969)	29,860	7.51×10^{-4}	249	120	76	40	191	100	1.90
Hantush-Jacob (1955)	28,610	7.19×10^{-4}	238	120	73	40	183	100	1.83

Legend:

T Transmissivity in square feet per day
S Storativity (dimensionless)
K Hydraulic conductivity in feet per day
b Aquifer thickness in feet
K′ Hydraulic conductivity of the overlying aquitard for vertical flow in feet per day
b′ Overlying aquitard thickness in feet
K″ Hydraulic conductivity of the underlying aquitard for vertical flow in feet per day
b″ Underlying aquitard thickness in feet
L Leakage factor

4.1.4 Field Water Quality Testing

Field water quality data was collected on 2-hour intervals during the first 24 hours of the 72-hour aquifer test. After baseline data was established, water quality data was collected every 4 hours. The field data was collected from the discharge orifice pipe used for the APT. A composite sample was collected using a bucket, and a YSI probe was submerged in the sample to measure parameters, including specific conductance, temperature, and pH. These field data are displayed in **Figure 15**. Since the field samples from the Upper Floridan aquifer were not analyzed for dissolved-solids concentrations, these values were estimated by multiplying specific

conductance by 0.55 to 0.65, yielding a reasonable approximation of the dissolved-solids concentration (Spechler and Kroening 2006). The field data indicate that the water quality in the Upper Floridan aquifer at this site in Osceola County meets the U.S. Environmental Protection Agency's (2000) secondary drinking water standards of 500 mg/L for dissolved-solid concentrations.

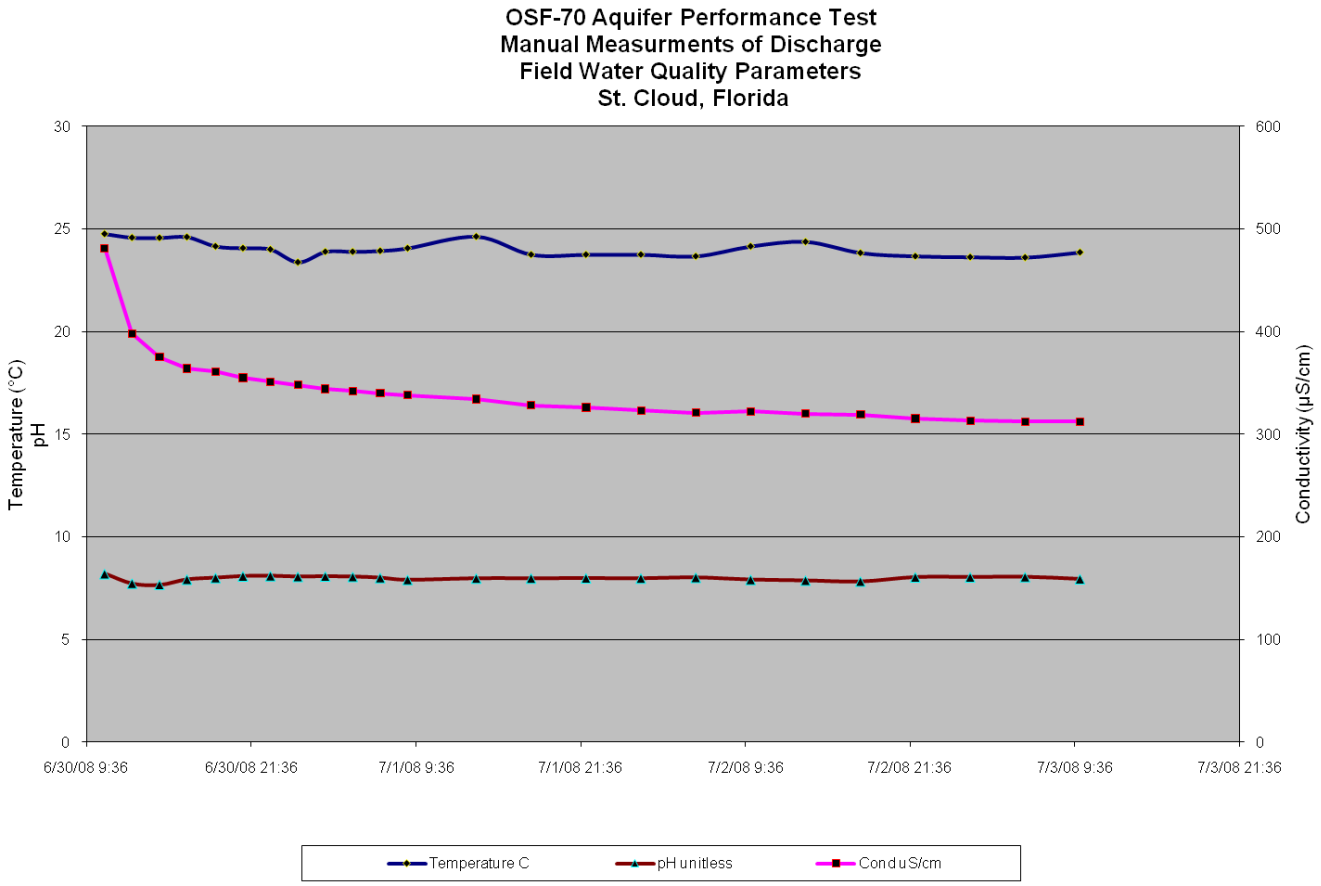

Figure 15. Field water quality data plot of St. Cloud APT.

4.2 POF-23/POF-26 APT, RIVER RANCH SITE

The SFWMD also hired AWD to run the pump for the hydraulic testing of the River Ranch site. AWD provided a 6-inch diameter, 30-horsepower Goulds submersible pump (Model 6M304) and set it 100 feet deep in the POF-26 production well. A 6-inch diameter PVC pipe ran from the pump to land surface, where a 90-degree PVC elbow directed the discharge water away from the well, through a gate valve, and into a 10-foot section of a 6-inch diameter PVC pipe. The discharge point for all hydraulic testing and the orifice weir and manometer was located 177 feet east of POF-26. A 6-inch diameter lay-flat hose linked the 6-inch diameter PVC from the pump in POF-26 to the manometer and orifice weir.

The SFWMD used an In-Situ Inc. Hermit® 3000 data logger and In-Situ Inc. PXD-261 pressure transducers to collect water level data during the step-drawdown, background, and drawdown/recovery phases of the aquifer tests. The SFWMD also set up a second In-Situ Inc. Hermit® 3000 data logger with several In-Situ Inc. PXD-261 pressure transducers as a backup unit in case of equipment failure. The SFWMD's hydrogeologists recorded water levels manually with an electronic water level tape (for backup purposes), and these data were recorded in the field book. The SFWMD programmed the data logger to record water level data on a logarithmic scale during the drawdown and recovery phases of the APT and the step-drawdown test. A logarithmic scale allows the instrument to collect numerous data points rapidly for the first ten minutes of the test, when drawdown occurs quickly. After ten minutes, the data logger collects data on a linear time scale, and in both APTs, the time interval was one minute.

The aquifer test at the River Ranch site involved four wells: one FAS production well, one FAS monitoring well, and two SAS monitoring wells. The well names and construction information used in this APT are presented in **Table 5**. **Figure 16** is a plan view showing the layout of the wells used during the aquifer test.

Table 5. River Ranch APT well information.

Well Name	Well Type	Cased Depth (feet bls)	Total Depth (feet bls)	Well Diameter (inches)	Aquifer	Distance from Production Well (feet)
POS-4	Monitor	9	19	2	SAS	40
POS-5	Monitor	97	117	2	SAS	40
POF-23	Monitor	252	400	4	FAS	50
POF-26	Production	248	319	8	FAS	0

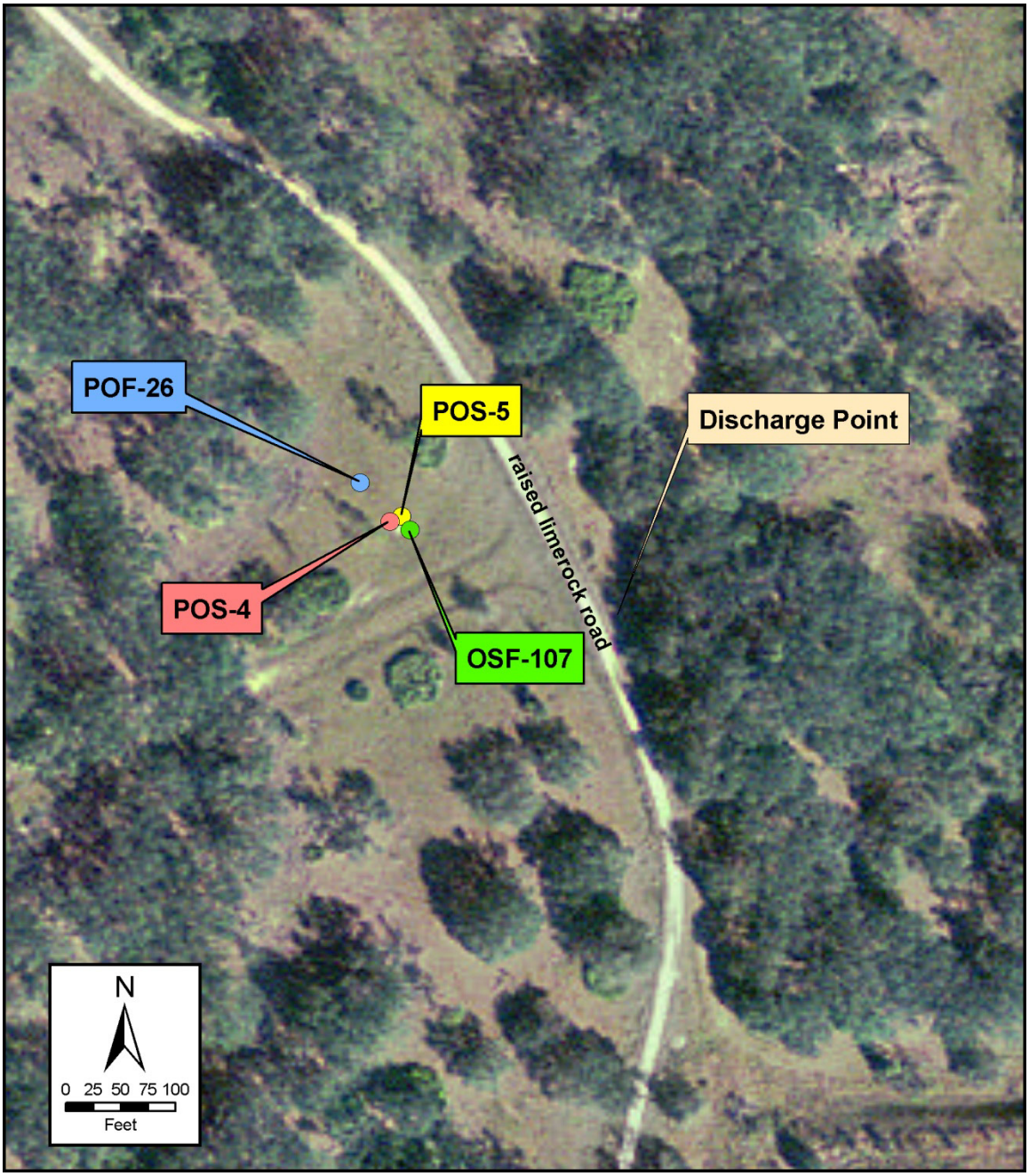

Figure 16. Locations of the monitoring wells used for the River Ranch site APT.

Aquifer testing began at the River Ranch site on July 17, 2008. The SFWMD ran a step-drawdown test to determine the maximum sustainable discharge rate for the 72-hour APT. After water levels in each of the wells returned to their static level, the SFWMD collected background water levels before the drawdown phase of the APT. The background water level data show barometric and other fluctuations in the water level data. Background water level data collection started on July 17, 2008 and ended on July 21, 2008. The drawdown phase of the 72-hour APT began at noon

on July 21, 2008, and ended at noon on July 24, 2008. The SFWMD stopped the recovery phase of the APT at noon on July 28, 2008.

4.2.1 Step-Drawdown Test

The SFWMD used the step-drawdown test primarily to determine the maximum sustainable pumping rate for the 72-hour APT. The SFWMD ran three steps for this test, each at two hours long. In a step-drawdown test, a well is pumped at a low constant-discharge rate until drawdown in the well stabilizes. The pumping rate is then increased to a higher constant discharge rate, and again, drawdown in the well is allowed to stabilize. Shutting the flow control valve at the top of the well causes extreme back pressure, so the initial step of the test was run with the valve $^{1}/_{3}$ open. This resulted in a discharge rate of 737 gpm. After two hours, the SFWMD moved the control valve to $^{2}/_{3}$ open, and the discharge rate increased to 770 gpm.

The final step of the test was run with the control valve completely open. However, the flow rate did not increase and remained at 770 gpm. The stagnation in the flow rate was probably due to the frictional losses in the 177 feet of piping from the pump to the discharge point, where the manometer was located. This length of discharge pipe, including use of the lay-flat hose, was necessary to channel the discharge water across the access road to an appropriate discharge point. At 770 gpm, there was 5.8 feet of drawdown in POF-26 (the pumped well). The SFWMD determined that a pumping rate of 770 gpm was suitable for the 72-hour APT. At this pumping rate, the calculated specific capacity was approximately 133 gpm/ft. Once the step-drawdown test was completed, the water level in POF-26 recovered to static conditions and the SFWMD collected background water level data for the next four days. It should be noted that the site was inundated with approximately six inches of water during the step-drawdown test (**Figure 18**).

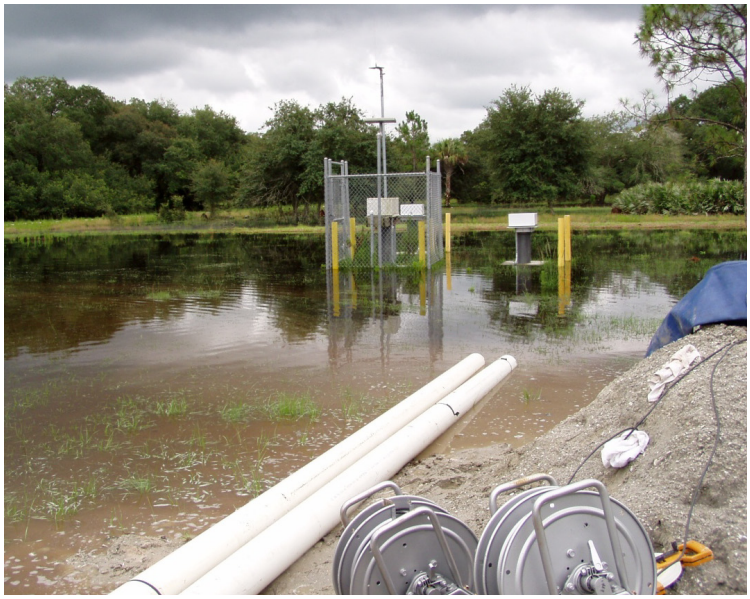

Figure 17. Wet site conditions during step-drawdown testing.

4.2.2 Background Water Level Data

The SFMWD collected background data in monitor well POF-23 every ten minutes for approximately four days before the APT. The water level data for this background monitoring were based on an arbitrary value of zero feet when the Hermit® 3000 data logger began recording. The unit recorded the change in water level from this starting value over the four-day period. **Figure 18** shows the water level fluctuations during the background monitoring period.

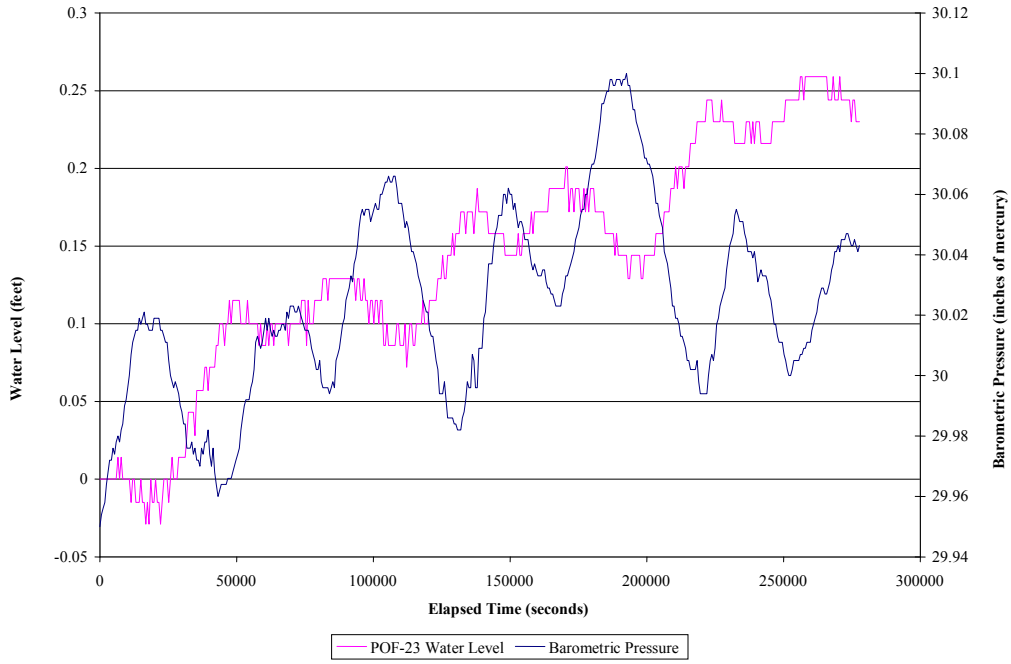

Figure 18. Natural water level changes in POF-23 before APT.

The data shows an inverse relationship between water levels in the Floridan aquifer and barometric pressure. As barometric pressure increases, the water level in the Floridan aquifer decreases and vice versa. During the background data collection period, the land surface dried (due to infiltration and evapotranspiration), causing the water level in all of the monitoring wells at the River Ranch site to rise. As a result, recharge to the surficial aquifer and the Upper Floridan aquifer indicated the presence of a hydraulic connection between the two units.

4.2.3 Aquifer Performance Test

The SFWMD conducted a 72-hour APT between July 21 and 24, 2008, to determine the hydraulic properties of the Upper Floridan aquifer. The SFWMD set pressure transducers in both the production well (POF-26) and the Upper Floridan monitor well (POF-23), as well as the two monitoring wells in the overlying surficial aquifer system. The purpose of the latter two pressure transducers was to determine if

there was a hydraulic connection between these zones. AWD used the same pump for the 72-hour APT that was used during the step-drawdown test. **Figure 20** shows the configuration of the monitoring and test-production wells used in the APT. The drawdown phase of this APT consisted of pumping the well at a constant rate of 795 gpm for 72 hours, which is higher than expected from the step-drawdown test, with a total drawdown of 5.4 feet in the production well and 3.95 feet in the monitoring well located 50 feet from the production well. A 24-hour recovery period followed the drawdown phase, where pumping stopped and water levels were allowed to return to static conditions.

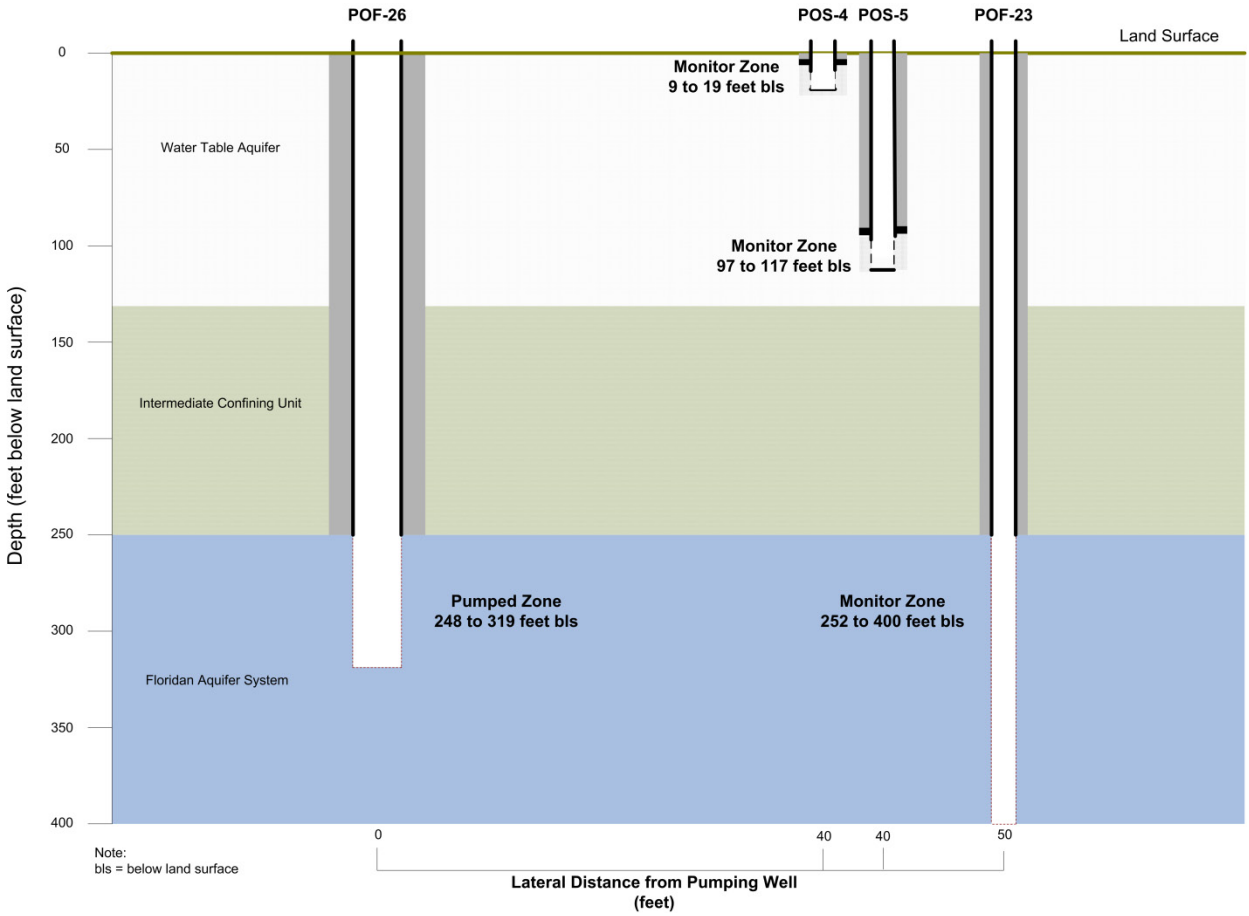

Figure 19. Cross-section of wells used at the River Ranch APT.

At the beginning of the drawdown phase, the surface water present during the step-drawdown test was gone and the site was dry. Fifty-five hours into the test, a thunderstorm deposited approximately 2.25 inches of rain (on-site rain gauge) and the site flooded with approximately 6 inches of water, returning the site to the condition seen during the step-drawdown test. The rainfall started at 7:00 p.m. on July 23, 2008, and stopped around 11:20 p.m. the same night. The effects of the rainfall were noticeable as the water level in each monitoring well rose. **Table 6** shows the rise in water levels in each well after the thunderstorm.

Table 6. Influence of precipitation on water levels in the monitoring wells.

Well	Water Level Before Rainfall (feet NGVD)	Water Level 40 Minutes After Rainfall Stopped (feet NGVD)	Water Level 8 Hours After Rainfall Stopped (feet NGVD)	Water Level 12 Hours After Rainfall Stopped (feet NGVD)	Total Water Level Rise at APT Stop Time (feet)
POF-23	40.24	40.33	40.32	40.30	0.06
POS-4	55.17	55.79	55.84	55.87	0.70
POS-5	52.40	52.46	52.50	52.53	0.13

After reviewing the water level data from the drawdown phase of the aquifer performance test and the log/log plot of the drawdown versus time, the author considered the rainfall effects to be negligible in this leaky aquifer since the curve match considered the initial drawdown data before the rainfall event. The shape of the curve from a leaky-type aquifer becomes relatively flat with the latter drawdown data.

Before stopping the pump, the SFWMD reconfigured the various Hermit® 3000 data loggers to record the recovery data in both the test production well and the monitoring wells. The recovery phase of the APT continued for 72 hours through the weekend, ending on July 28, 2008. Electronic copies of the original drawdown, recovery, and orifice weir (flow rate) data for the APT are archived and available for review at the SFWMD's headquarters in West Palm Beach, Florida.

As with the St. Cloud site, the SFWMD's hydrogeologists applied various analytical models to the drawdown data collected during the River Ranch site APT to determine the hydraulic properties of the aquifer and aquitard(s) at this site. The analytical methods included both confined and semi-confined "leaky" solutions. The shape of the semi-log plot with the drawdown data indicated that the aquifer is leaky, semi-confined. The confined transient analytical solutions include the Theis (1935) non-equilibrium method, and the semi-confined "leaky" analytical models include the Hantush-Jacob (1955), Hantush (1960), Neuman-Witherspoon (1969), and Moench (1985); see **Appendix D**. The methods referenced are based on various assumptions, and interested readers should refer to the original articles for further details. Analyses of the water level recovery data produced similar hydraulic results. In general, drawdown data from a single observation well (for recovery data) only provides an estimate of aquifer and confining unit properties because many of the type curves are similar in shape to one another and do not necessarily provide a unique match to a given data set.

Figure 20 is a log/log plot of drawdown versus time for POF-23. The shape of the drawdown curve of POF-23 indicates that the Upper Floridan aquifer is a leaky-type aquifer. This determination comes from the fact that the drawdown curve for this

well does not follow the Theis curve (red line in **Figure 20**) but drops below it. A leaky (semi-confined) aquifer is one that loses or gains water (depending on the pressure gradients) through a semi-confining unit. If a semi-confining unit is composed of a thick layer of unconsolidated or poorly indurated high porosity sediments, it may provide water to the pumped interval. Both monitoring wells in the surficial aquifer responded to the pumping of POF-26 in the Upper Floridan aquifer.

Table 7 presents the aquifer characteristics calculated using the various analytical models previously mentioned for both drawdown and recovery data. The plots for all analytical models run are presented in **Appendix D**. Based on these analytical considerations and the site-specific hydrogeologic data collected during aquifer testing, the Hantush (1960) analytical model appears to best represent the conditions present at this time. The results of this solution yielded a transmissivity value of 12,170 ft^2/day, and a storage coefficient of 5.05 x 10^{-5}. The vertical hydraulic conductivities, and subsequently leakance, were calculated using an r/B value of 0.1 derived from Hantush (1960) analysis. The dimensionless parameter r/B represents the leakage across the aquitard(s) to the pumped aquifer; as a result of this value, a leakance value of 0.05 gpd/ft^3 was calculated by dividing the hydraulic conductivity of the overlying aquitard by the thickness of the aquitard.

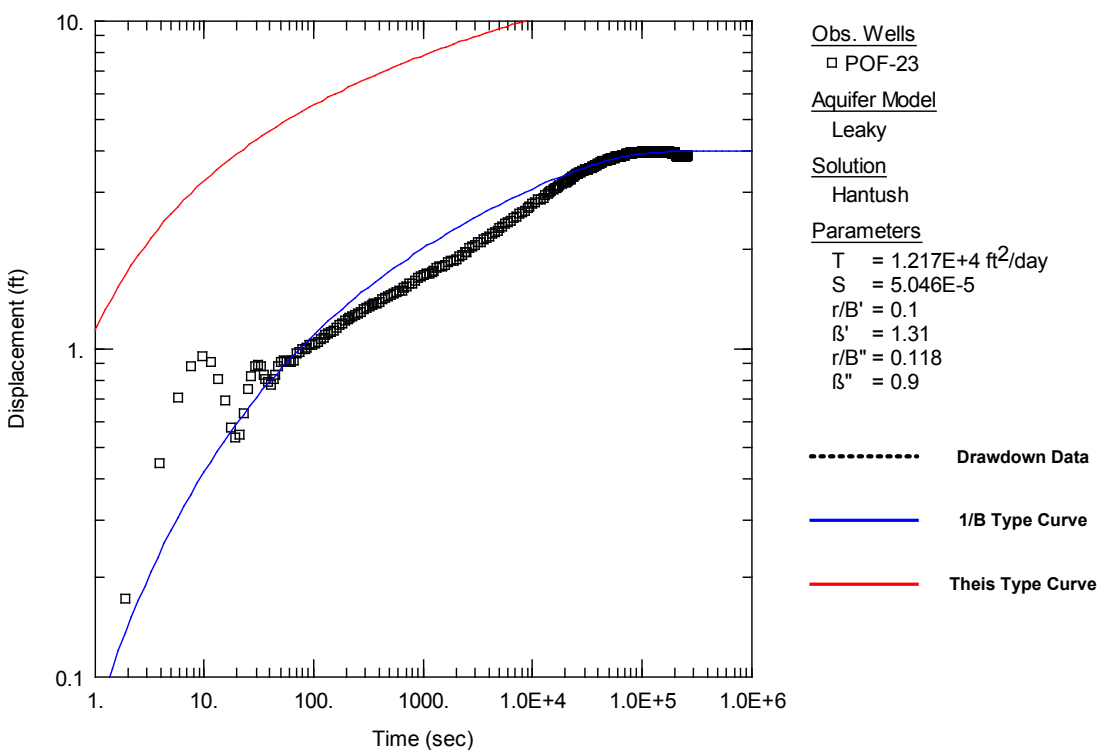

Figure 20. Log-log plot of drawdown data for POF-23, Hantush (1960) solution.

Table 7. Aquifer characteristics using various analytical models from wells POF-23 and POF-26.

Method	T (ft^2/day)	S	K (ft/day)	b (feet)	K′ (ft/day)	b′ (feet)	L (gpd/ft^3)
Drawdown Results							
Moench (1985)	12,460	4.74×10^{-5}	83	150	9.67	194	0.05
Hantush (1960)	12,170	5.05×10^{-5}	81	150	9.44	194	0.05
Neuman-Witherspoon (1969)	12,440	1.30×10^{-5}	101	150	9.65	194	0.05
Hantush-Jacob (1955)	15,040	5.14×10^{-4}	100	150	11.67	194	0.06
Recovery Results							
Moench (1985)	12,060	8.74×10^{-3}	80	150	9.36	194	0.05
Hantush (1960)	12,240	5.34×10^{-3}	82	150	9.50	194	0.05
Neuman-Witherspoon (1969)	13,580	5.50×10^{-3}	91	150	10.54	194	0.05
Hantush-Jacob (1955)	13,420	4.21×10^{-2}	89	150	10.41	194	0.05

Legend:
T Transmissivity in square feet per day
S Storativity (dimensionless)
K Hydraulic conductivity in feet per day
b Aquifer thickness in feet
K' Hydraulic conductivity of the aquitard for vertical flow in feet per day
b' Aquitard thickness in feet
L Leakage factor

4.2.4 Field Water Quality Testing

Field water quality data was collected during 2-hour intervals in the first 24 hours of the 72-hour aquifer test. After baseline data was established, water quality data was collected every 4 hours. The field data was collected from the discharge orifice pipe used for the APT. A composite sample was collected using a bucket, and the YSI probe was submerged in the sample. These field data are displayed in **Figure 21**. Since the field samples from the Upper Floridan aquifer were not analyzed for dissolved-solids concentrations, these values were estimated by multiplying specific conductance by 0.55 to 0.65, yielding a reasonable approximation of the dissolved-solids concentration (Spechler and Kroening 2006). The field data indicate that the water quality in the Upper Floridan aquifer at this site in Polk County meets U.S.

Environmental Protection Agency (2000) established secondary drinking water standards of 500 mg/L for dissolved-solids concentrations.

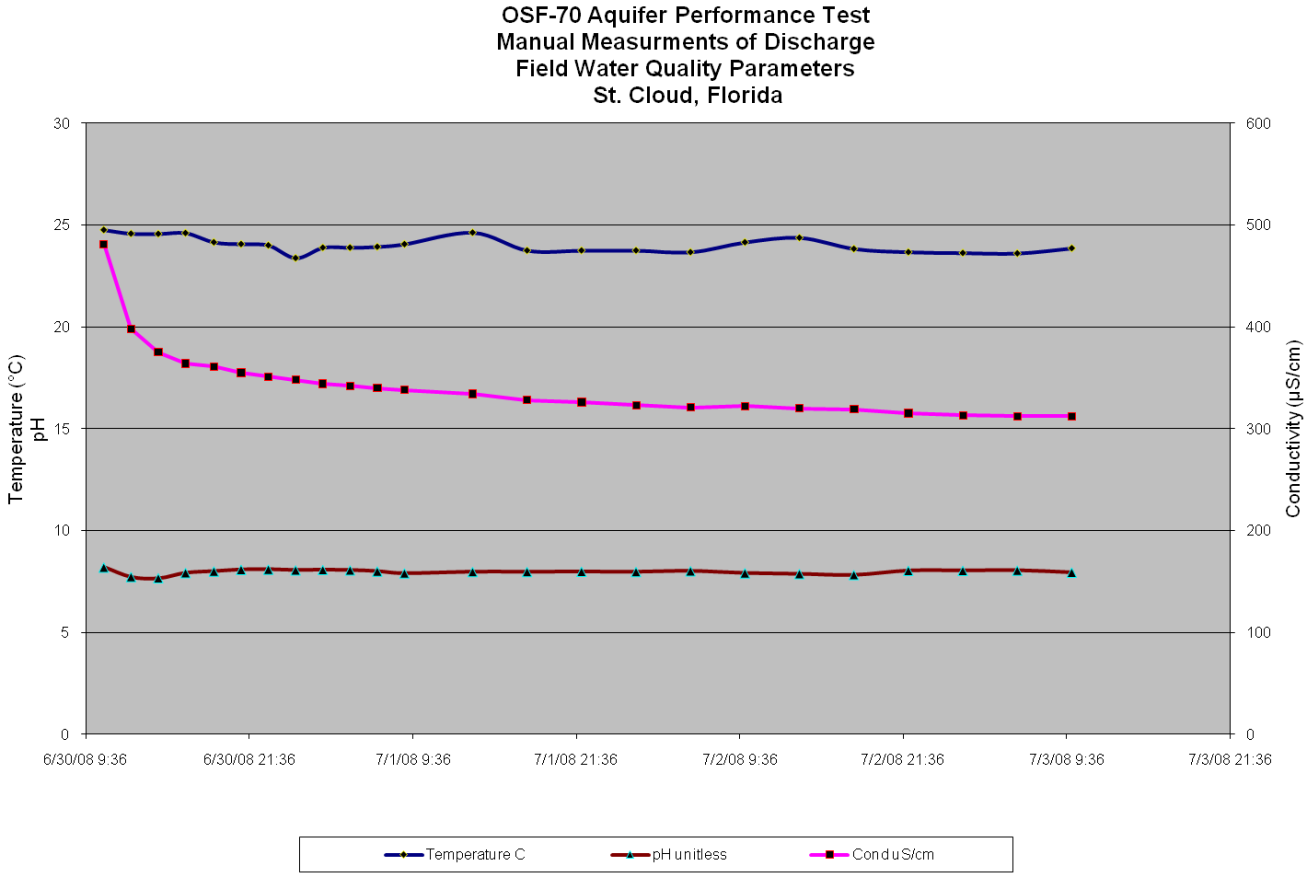

Figure 21. Field water quality data plot of River Ranch APT.

5

SUMMARY AND CONCLUSIONS

1. The top of the Upper Floridan aquifer occurs at a depth of 125 feet bls and 248 feet bls, with the first occurrence of the contiguous semi-permeable limestone unit at the St. Cloud and River Ranch sites, respectively. This first occurrence of limestone was encountered and marked by the characteristic cavernous dense unit, followed by large cavities.
2. The specific capacity and aquifer performance test (APT) results indicate a production capacity of at least 1,000 gallons per minute from the Upper Floridan aquifer at both sites.
3. The Upper Floridan production zone (125-250 feet bls) at the St. Cloud site yielded a transmissivity value of 29,410 feet squared per day, a storage coefficient of 5.56×10^{-4} based on the best fit curve of the Neuman-Witherspoon method, a (r/B) value of 0.4, and a leakance value of 1.88 gpd/ft^3.
4. The Upper Floridan production zone (248-320 feet bls) at the River Ranch test wells yielded a transmissivity value of 12,170 feet squared per day, a storage coefficient of 5.05×10^{-5} based on the best fit curve of the Hantush method, an (r/B) value of 0.1, and a leakance value of 0.05 gpd/ft^3.
5. The aquifer testing at the St. Cloud site indicates that leakance is occurring through the overlying and underlying aquitards due to water level fluctuations within the SAS and Lower Floridan aquifer monitoring wells.
6. Aquifer testing at the River Ranch site indicates that leakance is occurring through the overlying aquitards due to water level fluctuations in the SAS, which is a result of pumpage and rainfall.
7. The field data indicate that the water quality in the Upper Floridan aquifer meets U.S. Environmental Protection Agency (2000) established secondary drinking water standards of 500 mg/L for dissolved-solids concentrations at both the St. Cloud and River Ranch sites.

6
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APPENDIX A

WELL CONSTRUCTION DETAILS

St. Cloud Site	Top of Casing Elevation NGVD 29	Total Depth (feet bls)	Screen Interval (feet bls)	Screen Type
OSF-70	64.36	246	130-246	Open hole
OSF-107	64.76	250	125-250	Open Hole
OSS-70S	65.08	26.5	16.5-26.5	Screen, slot 10 (0.10 inches)
OSS-70D	64.76	55	45-55	Screen, slot 10 (0.10 inches)
OSF-82U	66.14	583	350-583	Annular space
OSF-82L	64.43	1,503	1,230-1,503	Open Hole

River Ranch Site	Top of Casing Elevation NGVD 29	Total Depth (feet bls)	Screen Interval (feet bls)	Screen Type
POF-23	59.25	400	252-400	Open Hole
POF-26	56.86	319	248-319	Open Hole
POS-4	59.45	19	9-19	Screen, slot 10 (0.10 inches)
POS-5	58.64	117	97-117	Screen, Slot 10 (0.10 inches)

APPENDIX B

FLORIDA GEOLOGICAL SURVEY (FGS) LITHOLOGIC DESCRIPTIONS: OSF-70

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LITHOLOGIC WELL LOG PRINTOUT     SOURCE - FGS
WELL NUMBER: W-16954             COUNTY - OSCEOLA
TOTAL DEPTH:  460 FT.            LOCATION: T.26S R.30E S.05
47 SAMPLES FROM 0 TO 460 FT.     LATITUDE = 28D 15M 08S
COMPLETION DATE: 10/29/91        LONGITUDE = 81D 19M 41S
                                 ELEVATION: 60 FT.

OTHER TYPES OF LOGS AVAILABLE - NONE
OWNER/DRILLER: SOUTH FLORIDA WATER MANAGEMENT DISTRICT

WORKED BY:  A. HOWELL (10/92)
WELL IS REPRESENTED BY CUTTINGS FROM 0-460'
THE SFWMD ID# FOR THE CORE IS: 097-19 (HOLE#: OSF-70)
SFWMD GEOPHYSICAL LOG # 097-0000029 IS AVAILABLE FOR THIS WELL
THIS WELL IS LOCATED IN THE ST. CLOUD NORTH QUADRANGLE (14).
THE PLIO-PLEISTOCENE UNIT WILL BE NAMED THE OKEECHOBEE FORMATION IN THE
NEAR FUTURE


FEET         DESCRIPTION

0.   -  30.  090UDSC UNDIFFERENTIATED SAND AND CLAY
30.  -  90.  121PCPC PLIOCENE-PLEISTOCENE
90.  -  130. 122HTRN HAWTHORN GROUP
130. -  170. 124OCAL OCALA GROUP
170. -     . 124AVPK AVON PARK FORMATION

0 - 20       SAND; VERY LIGHT ORANGE TO PINKISH GRAY
             35% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
             GRAIN SIZE: FINE; RANGE: FINE TO VERY FINE
             ROUNDNESS: SUB-ANGULAR TO SUB-ROUNDED; MEDIUM SPHERICITY
             UNCONSOLIDATED
             ACCESSORY  MINERALS:  PHOSPHATIC  SAND,  PLANT  REMAINS,  HEAVY
             MINERALS
             VERY CLEAN SAND; ONLY TRACES OF PHOSPHATE, ORGANICS, AND HEAVY
             MINERALS
             SLIGHT COLOR VARIATION

20 - 30      SAND; DARK YELLOWISH BROWN
             25% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
             GRAIN  SIZE:  FINE;  RANGE:  VERY  FINE  TO  COARSE  ROUNDNESS:  SUB-
             ANGULAR TO SUB-ROUNDED; MEDIUM SPHERICITY
             POOR INDURATION
```

FGS LITHOLOGIC DESCRIPTIONS: OSF-70

CEMENT TYPE(S): ORGANIC MATRIX, CLAY MATRIX
ACCESSORY MINERALS: ORGANICS - 07%, CLAY - 05%, SILT - 05%, PHOSPHATIC SAND
CONTAINS FRAGMENTS OF PURE CLAY, WHICH ARE PROBABLY FROM INTERVAL BELOW. COARSE QUARTZ SAND GRAINS ARE FROSTED

30 - 40 CLAY; YELLOWISH GRAY
POROSITY: INTERGRANULAR, INTRAGRANULAR; POOR INDURATION
CEMENT TYPE(S): CLAY MATRIX, PHOSPHATE CEMENT
ACCESSORY MINERALS: CALCARENITE - 10%, CALCILUTITE, AND QUARTZ SAND
FOSSILS: FOSSIL FRAGMENTS, MOLLUSKS
CONTAINS SHELL FRAGMENTS, PHOSPHATE CLAYS, A TRACE OF CALCILUTE AND FEW QUARTZ SAND GRAINS.

40 - 50 CLAY; YELLOWISH GRAY
POROSITY: INTERGRANULAR, INTRAGRANULAR; POOR INDURATION
CEMENT TYPE(S): CLAY MATRIX, PHOSPHATE CEMENT
ACCESSORY MINERALS: CALCARENITE - 15%, QUARTZ SAND - 05%
PHOSPHATIC SAND - 01%, CALCILUTITE
OTHER FEATURES: COQUINA
FOSSILS: FOSSIL FRAGMENTS, MOLLUSKS, ECHINOID
TRANSITION LAYER BETWEEN CLAY ABOVE AND SANDY LAYER BELOW

50 - 90 SAND; LIGHT OLIVE GRAY
POROSITY: INTERGRANULAR, INTRAGRANULAR
GRAIN SIZE: FINE; RANGE: VERY FINE TO COARSE
ROUNDNESS: SUB-ANGULAR TO SUB-ROUNDED; MEDIUM SPHERICITY
POOR INDURATION
CEMENT TYPE(S): CLAY MATRIX, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCARENITE - 15%, PHOSPHATIC SAND - 02%
CLAY, CALCILUTITE
OTHER FEATURES: COQUINA
FOSSILS: FOSSIL FRAGMENTS, MOLLUSKS
HIGH CLAY/SILT AND CALCILUTITE CONTENT; PHOSPHATE PEBBLES PRESENT.

90 - 130 CALCILUTITE; YELLOWISH GRAY
POROSITY: INTERGRANULAR, INTRAGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
10% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: GRANULE TO MEDIUM
POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: DOLOMITE - 10%, QUARTZ SAND - 10%

FGS LITHOLOGIC DESCRIPTIONS: OSF-70

PHOSPHATIC GRAVEL - 07%, CALCARENITE - 07%
FOSSILS: FOSSIL FRAGMENTS, MOLLUSKS
CALCILUTITE MATRIX WITH DOLOSILT, FRAGMENTS OF
WELL-INDURATED DOLOSTONE, SHELL FRAGMENTS, PHOSPHATE
GRAVELS, PHOSPHATE SAND, LIMESTONE, QUARTZ SAND, AND A TRACE OF
HEAVY MINERALS.

130 - 150 LIMESTONE; PINKISH GRAY
15% POROSITY: INTERGRANULAR, INTRAGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC,
GRAIN SIZE: GRANULE; POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCARENITE - 30%, DOLOMITE
OTHER FEATURES: LOW RECRYSTALLIZATION
FOSSILS: ECHINOID, FOSSIL FRAGMENTS, MOLLUSKS
BIODEBRIS IS POORLY PRESERVED AND CONSISTS OF ECHINOID SHELLS,
SPINES, AND MOLLUSK FRAGMENTS.
DOLOMITE CAVINGS ARE PRESENT. ECHINOID SHELLS ARE RECRYSTALLIZED.

150 - 170 CALCARENITE; VERY LIGHT ORANGE
15% POROSITY: INTERGRANULAR, INTRAGRANULAR
GRAIN TYPE: BIOGENIC, CALCILUTITE
50% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY COARSE; RANGE: GRAVEL TO MEDIUM
POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE - 50%
OTHER FEATURES: MEDIUM RECRYSTALLIZATION
FOSSILS: ECHINOID, BENTHIC FORAMINIFERA, FOSSIL FRAGMENTS
MOLLUSKS
SUBEQUAL PARTS OF SKELETAL DEBRIS AND CALCILUTITE.
FOSSILS INCLUDE ECHINOIDS, NUMULITES, CONES (D. COOKIE), MOLLUSK
FRAGS, AND TEXTULARID FORAMS.

170 - 200 CALCARENITE; VERY LIGHT ORANGE
15% POROSITY: INTERGRANULAR, INTRAGRANULAR
GRAIN TYPE: BIOGENIC, CALCILUTITE
50% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY COARSE; RANGE: GRAVEL TO MEDIUM
POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE - 50%
OTHER FEATURES: MEDIUM RECRYSTALLIZATION
FOSSILS: ECHINOID, BENTHIC FORAMINIFERA, FOSSIL F FRAGMENTS
MOLLUSKS
GOOD PRESERVATION WITH CONES BECOMING DOMINANT FOSSIL TYPE.

FGS LITHOLOGIC DESCRIPTIONS: OSF-70

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200 - 210    CALCILUTITE; VERY LIGHT ORANGE
             20% POROSITY: INTERGRANULAR, INTRAGRANULAR
             GRAIN TYPE: CALCILUTITE, BIOGENIC
             30% ALLOCHEMICAL CONSTITUENTS
             GRAIN SIZE: VERY COARSE; RANGE: GRAVEL TO MEDIUM
             POOR INDURATION
             CEMENT TYPE(S): CALCILUTITE MATRIX
             ACCESSORY MINERALS: CALCARENITE - 30%
             OTHER FEATURES: CHALKY
             FOSSILS: CONES, FOSSIL FRAGMENTS, BENTHIC FORAMINIFERA
             ECHINOID
             POOR PRESERVATION OF FOSSILS

210 - 240    CALCILUTITE; VERY LIGHT ORANGE
             15% POROSITY: INTERGRANULAR, INTRAGRANULAR
             GRAIN TYPE: CALCILUTITE, BIOGENIC
             30% ALLOCHEMICAL CONSTITUENTS
             RANGE: VERY COARSE TO GRAVEL; MODERATE INDURATION
             CEMENT TYPE(S): CALCILUTITE MATRIX
             ACCESSORY MINERALS: CALCARENITE - 30%
             OTHER FEATURES: MEDIUM RECRYSTALLIZATION
             FOSSILS: ECHINOID, CONES, FOSSIL FRAGMENTS, FOSSIL MOLDS
             SAME COMPOSITION AS INTERVAL ABOVE AND BELOW BUT WITH HIGHER
             INDURATION AND LOWER POROSITY.

240 - 300    CALCILUTITE; VERY LIGHT ORANGE
             20% POROSITY: INTERGRANULAR, INTRAGRANULAR
             GRAIN TYPE: CALCILUTITE, BIOGENIC
             30% ALLOCHEMICAL CONSTITUENTS
             GRAIN SIZE: VERY COARSE; RANGE: GRAVEL TO MEDIUM
             POOR INDURATION
             CEMENT TYPE(S): CALCILUTITE MATRIX
             ACCESSORY MINERALS: CALCARENITE - 30%
             OTHER FEATURES: CHALKY
             FOSSILS: ECHINOID, CONES, FOSSIL FRAGMENTS, FOSSIL MOLDS
             RECRYSTALIZATION OF ECHINOIDS; PHOSPHATE CAVINGS.

300 - 320    DOLOSTONE; GRAYISH ORANGE TO VERY LIGHT ORANGE
             12% POROSITY: INTERGRANULAR, PIN POINT VUGS
             50-90% ALTERED; SUBHEDRAL
             GRAIN SIZE: VERY FINE; RANGE: MICROCRYSTALLINE TO FINE
             GOOD INDURATION
             CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
             ACCESSORY MINERALS: CALCILUTITE
             OTHER FEATURES: CHALKY
```

FGS LITHOLOGIC DESCRIPTIONS: OSF-70

320 - 330 CALCILUTITE; VERY LIGHT ORANGE
15% POROSITY: INTERGRANULAR, INTRAGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: MEDIUM TO GRANULE
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCARENITE-05%, PYRITE
OTHER FEATURES: LOW RECRYSTALLIZATION
FOSSILS: ECHINOID, FOSSIL FRAGMENTS, MOLLUSKS
DOLOMITE CAVINGS

330 - 380 CALCILUTITE; VERY LIGHT ORANGE
20% POROSITY: INTERGRANULAR, INTRAGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC
05% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: COARSE; RANGE: GRANULE TO MEDIUM
POOR INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCARENITE - 05%
OTHER FEATURES: MEDIUM RECRYSTALLIZATION
FOSSILS: ECHINOID, FOSSIL FRAGMENTS, MOLLUSKS

380 - 400 DOLOSTONE; VERY LIGHT ORANGE TO GRAYISH BROWN
POROSITY: INTERGRANULAR, LOW PERMEABILITY; 50-90% ALTERED
SUBHEDRAL
GRAIN SIZE: MICROCRYSTALLINE
RANGE: MICROCRYSTALLINE TO CRYPTOCRYSTALLINE
GOOD INDURATION
CEMENT TYPE(S): DOLOMITE CEMENT, CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCILUTITE, PYRITE, AND CALCARENITE
OTHER FEATURES: COQUINA
FOSSILS: FOSSIL FRAGMENTS

400 - 420 LIMESTONE; VERY LIGHT ORANGE
15% POROSITY: INTERGRANULAR
GRAIN TYPE: CALCILUTITE, BIOGENIC, CRYSTALS
30% ALLOCHEMICAL CONSTITUENTS
GRAIN SIZE: VERY COARSE; RANGE: GRANULE TO MEDIUM
MODERATE INDURATION
CEMENT TYPE(S): CALCILUTITE MATRIX
ACCESSORY MINERALS: CALCARENITE - 30%
OTHER FEATURES: MEDIUM RECRYSTALLIZATION, DOLOMITIC
HIGH DOLOMITE CONTENT IN SAMPLE INDICATES THAT THE TRANSITION FROM DOLOMITE TO LIMESTONE OCCURRED TOWARD THE TOP OF THE INTERVAL.
SAMPLE ALSO CONTAINS SOME CHALKY BIO-FREE LIMESTONE, WHICH APPEARS TO BE FROM THE TRANSITION AT THE BASE OF THE INTERVAL.
SAMPLE ALSO CONTAINS SOME CAVINGS OF FOSSIL FRAG AGGREGATES.

FGS LITHOLOGIC DESCRIPTIONS: OSF-70

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420 - 440    LIMESTONE; VERY LIGHT ORANGE
             POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
             PIN POINT VUGS
             GRAIN TYPE: CALCILUTITE, BIOGENIC
             03% ALLOCHEMICAL CONSTITUENTS
             GRAIN SIZE: COARSE; RANGE: GRANULE TO MEDIUM
             MODERATE INDURATION
             CEMENT TYPE(S): CALCILUTITE MATRIX
             ACCESSORY MINERALS: CALCARENITE - 03%
             OTHER FEATURES: MEDIUM RECRYSTALLIZATION, CHALKY
             FOSSILS:  ECHINOID,  BENTHIC  FORAMINIFERA,  FOSSIL  FRAGMENTS,
             MOLLUSKS
             CHALKY LIMESTONE WITH LITTLE FOSSILS
             DOLOMITE CONTENT CONSIDERED CAVINGS

 440 - 460   LIMESTONE; POOR QUANTITY OF SAMPLE; ALL APPEAR TO BE CAVINGS
             FORAMINIFERAL GRAINSTONES, DOLOMITE, ECHINOID FRAGMENTS
             MOLLUSK FRAGMENTS, LIMESTONE FRAGMENTS AND BIOCALCARENITE

 460         TOTAL DEPTH
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FGS LITHOLOGIC DESCRIPTIONS: OSF-107

FEET	FIELD DESCRIPTION
0-10	DARK BROWN SAND CONTAINING MAJOR ORGANICS
10-19	LIGHT GRAY FINE TO MEDIUM GRAIN SAND WITH MINOR SHELL FRAGMENTS
19-20	LIGHT OLIVE GREEN/GRAY CLAY WITH MINOR SAND
20-30	MEDIUM OLIVE GREEN CLAY-SOLID PLASTIC-LIKE
30-40	SAME WITH MINOR SAND
40-50	LIGHT GRAY/WHITE SHELL AND CLAY 43-FOOT SHELL BED
50-53	LIGHT GRAY/WHITE SHELL AND CLAY
53-60	LIGHT GRAY/WHITE CLAY AND LIMESTONE, EASY DRILL
60-70	LIGHT GRAY /WHITE CLAY, SHELL AND LIMESTONE
70-78	SAME AS ABOVE
78-80	WHITE SHELL, HARDER DRILL
80-85	CLAY MEDIUM GRAY/LIGHT OLIVE GREEN
85-90	WHITE TO BEIGE LIMESTONE, HARD DRILL WITH DRILL RIG CHATTER
90-97	SAME AS ABOVE, SOFTER DRILL
97-100	WHITE LIMESTONE, HARD DRILL
100-101	WHITE LIMESTONE WITH FIRST OCCURRENCE OF PHOSPHATE, HARD DRILL, A LOT OF PHOSPHATE WHILE CIRCULATING
100-108	LAYERS OF LIGHT AND DARK GRAY CLAY
108-114	OFF-WHITE LIMESTONE WITH PHOSPHATE, HARD DRILL, STRINGERS
114-116	SOFTER WHITE TO OFF-WHITE LIMESTONE
116-120	WHITE LIMESTONE WITH CALCITE AND WITH MINOR PHOSPHATE
120-125	OFF-WHITE LIMESTONE, EXTREME HARD DRILL, CALCITE WITH MINOR PHOSPHATE, SLOW DRILL, RIG CHATTER, AT 125 FEET BLS, PLATE-LIKE, LAYERED BEIGE LIMESTONE
125-130	BEIGE LIMESTONE, HARD DRILL, LOSS CIRCULATION
130-140	NO CUTTINGS, DRILL ROD DROP TO 140 FEET BLS
140-150	BEIGE TO WHITE LIMESTONE, VERY SOFT DRILL
150-160	MEDIUM BEIGE LIMESTONE, SOFT DRILL
160-170	LIGHT BEIGE LIMESTONE, SOFT DRILL
170-180	LIGHT BEIGE LIMESTONE, SOFT DRILL
180-190	DARKER BEIGE LIMESTONE, CHALKY HARDER DRILL
190-200	LIGHTER BEIGE LIMESTONE, SMALL FRAGMENTS, HARD DRILL
200-210	LIGHT BEIGE LIMESTONE, SOFTER DRILL
210-220	SAME AS ABOVE
220-230	LIGHT BEIGE LIMESTONE, SOFT DRILL
230-240	SAME AS ABOVE
240-250	SAME AS ABOVE, TD

FGS LITHOLOGIC DESCRIPTIONS: POF-26

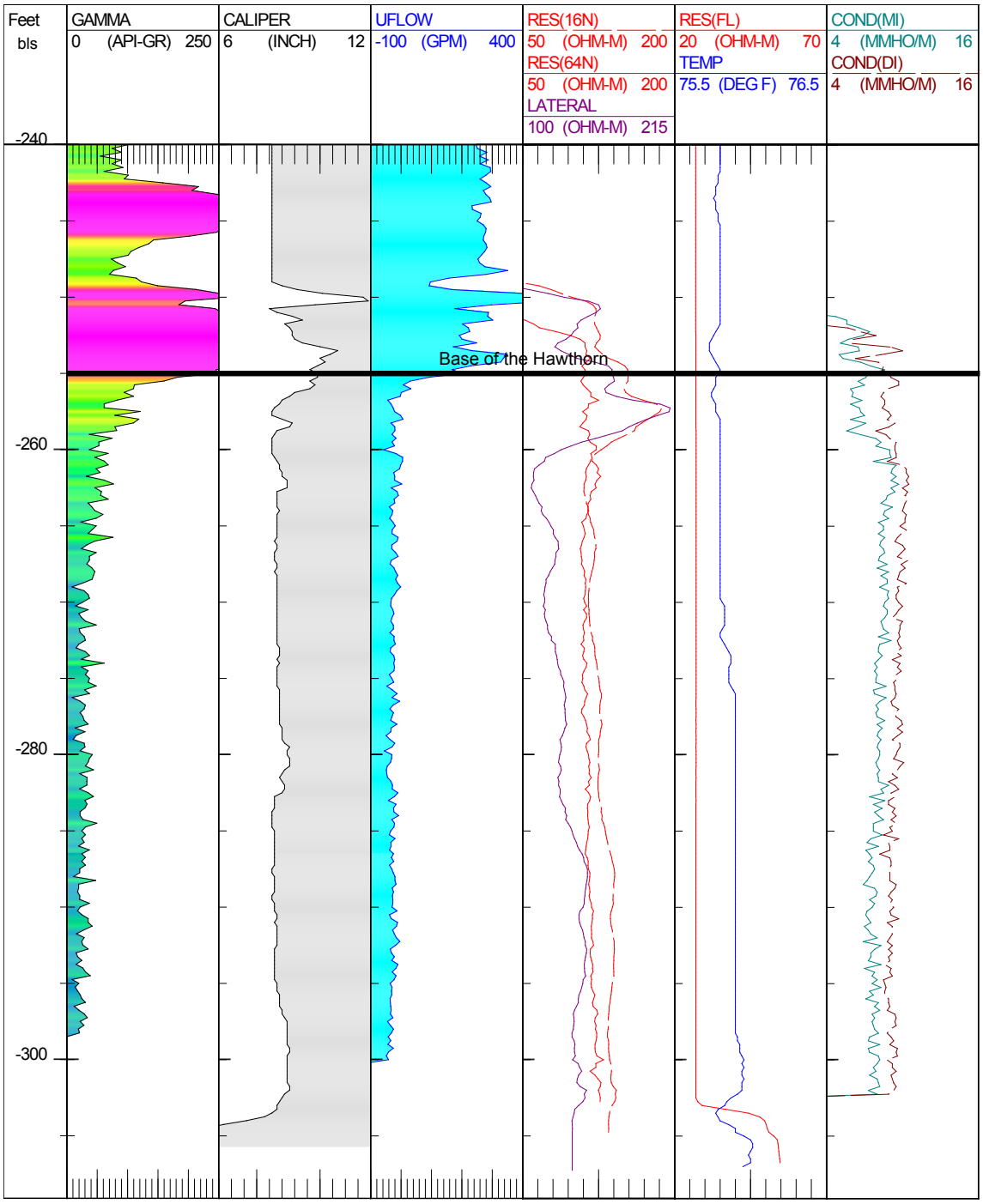
FEET	FIELD DESCRIPTION
0-9	SOFT SAND, DARK BROWN
9-20	HARD, DENSE, DARK BROWN CEMENTED SANDSTONE MIXED WITH MEDIUM/FINE LIGHT TAN SAND
20-32	HARD ROCK LIMESTONE MIXED WITH MEDIUM TAN SAND, STRINGERS OF HARD DRILL
32-35	CLAY, OLIVE GREEN WITH TAN LIMESTONE PIECES, SOFT DRILL
35-40	SANDY CLAY WITH SHELL
40-50	LIGHT OLIVE GREEN CLAY AND WHITE SHELL FRAGMENTS, SHARK TOOTH
50-55	OLIVE GREEN CLAY AND SHELL
55-56	DARK GREEN CLAY
60-70	DARK OLIVE GREEN CLAY WITH MINOR SHELL
70-80	DARK OLIVE GREEN CLAY WITH INCREASE AMOUNT OF SHELL
80-90	DARK OLIVE GREEN CLAY WITH ABUNDANT PHOSPHATE
90-100	DARK GRAY/GREEN CLAY WITH ABUNDANT SHELL AND PHOSPHATE, SHARK TOOTH
100-110	LIGHT TO DARK GRAY CEMENTED SHELL BED, A LOT OF RIG CHATTER
110-120	DARK GRAY CEMENTED SHELL BED WITH ABUNDANT PHOSPHATE
120-130	MAJOR WHITE TO LIGHT GRAY SHELL BED SLIGHTLY CEMENTED
130-140	SAME AS ABOVE
140-150	MEDIUM OLIVE GREEN CLAY WITH MODERATE SHELL
150-160	MEDIUM OLIVE GREEN CLAY WITH MINOR SHELL
160-172	DARKER OLIVE GREEN CLAY
172	LIMESTONE LEDGE/STRINGER
172-180	MEDIUM TO LIGHT GRAY/WHITE CLAY
180-190	LIGHT GRAY CLAY EASY DRILL
190-200	LIGHT GRAY CLAY EASY DRILL
200-210	LAYERS OF LIGHT GRAY CLAY AND LIMESTONE
210-220	SAME AS ABOVE WITH BEIGE LIMESTONE
220-225	HARD DRILL, WHITE LIMESTONE WITH MODERATE PHOSPHATE
225-230	DARK GRAY LIMESTONE/RUBBLE WITH ABUNDANT PHOSPHATE AND CLAY EASY DRILL
230-235	DARK GREEN/GRAY CLAY WITH ABUNDANT PHOSPHATE SLOW DRILL DUE TO PLASTIC CLAY
235-240	SAME AS ABOVE
240-249	WHITE TO LIGHT GRAY LIMESTONE WITH ABUNDANT PHOSPHATE HARD DRILL STRINGERS
250-258	VOID, LOST CIRCULATION, DROP TO 258 FEET BLS
258-270	LIGHT TO MEDIUM BEIGE LIMESTONE, ABUNDANT MOLLUSKS
270-280	LIGHT TO MEDIUM BEIGE LIMESTONE, HARDER DRILL
280-290	SAME AS ABOVE
290-300	LIGHT TO MEDIUM BEIGE LIMESTONE, EASIER DRILL
300-310	SAME AS ABOVE, POOR CUTTING RETURN
310-320	LIGHT BEIGE LIMESTONE, FINE MATERIAL, EASY DRILL
321	DRILL ROD STOCK IN HOLE, WORKED TO GET OUT, TD

FGS LITHOLOGIC DESCRIPTIONS: POF-23

FEET	FIELD DESCRIPTION
0-15	SAND DARK BROWN, MEDIUM TO FINE
15-37	LIGHT TAN TO WHITE SAND MIXED THE MODERATE SHELL
37-50	SAND AND SHELL MIX, LIGHT GRAY
50-60	SAME AS ABOVE, TURNING TO CLAY AND SHELL
60-70	LIGHT GRAY/OLIVE GREEN CLAY WITH MODERATE SHELL
70-80	LIGHT OLIVE GREEN CLAY AND WHITE SHELL
80-90	GRAY SHELL AND CLAY
90-100	LIGHT GRAY MIX OF SHELL, SAND, AND CLAY
100-120	MODERATELY SORTED SAND AND SHELL, GOOD PRODUCTION ZONE
120-150	LIGHT GRAY CLAY, SAND, AND SHELL MIX
150-180	LIGHT GRAY SANDY CLAY
180-190	SAME AS ABOVE
190-220	CLAY WITH MODERATE SHELL
220-248	LIGHT GRAY CLAY WITH SHELL
248-252	HARD, DENSE LIMESTONE WITH SHELL
252-257	VOID
256-260	MINOR CUTTINGS, BEIGE LIMESTONE
260-400	NO CUTTING RETURN

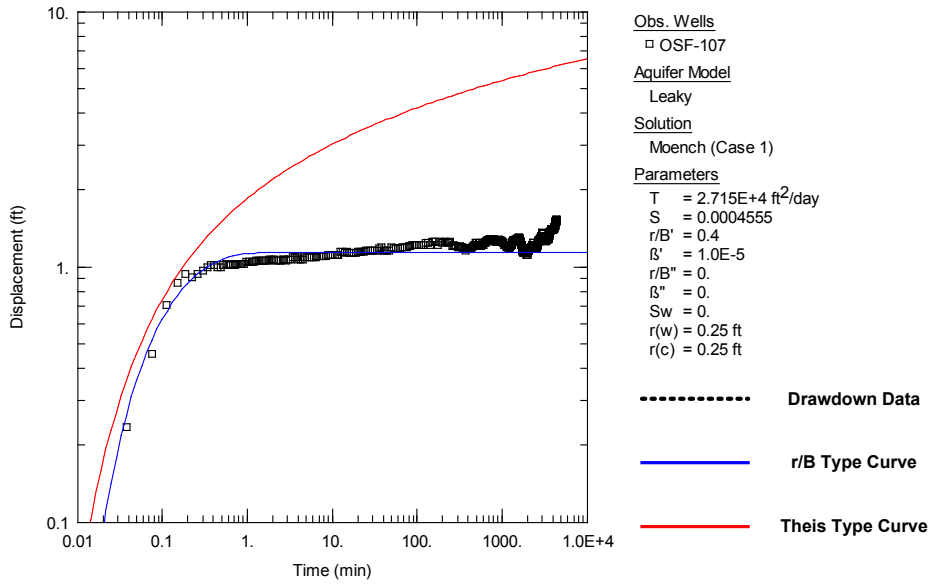
APPENDIX C

GEOPHYSICAL LOGS: POF-26

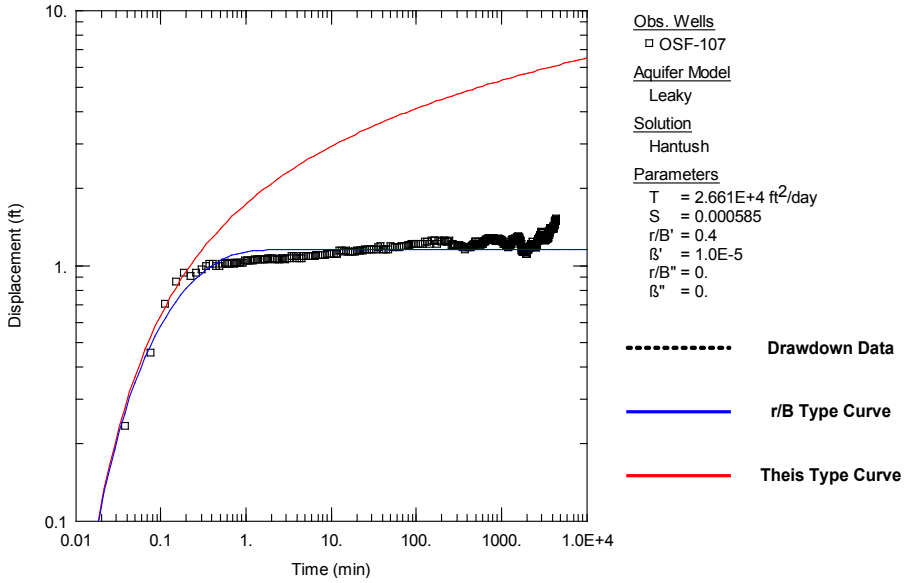


APPENDIX D

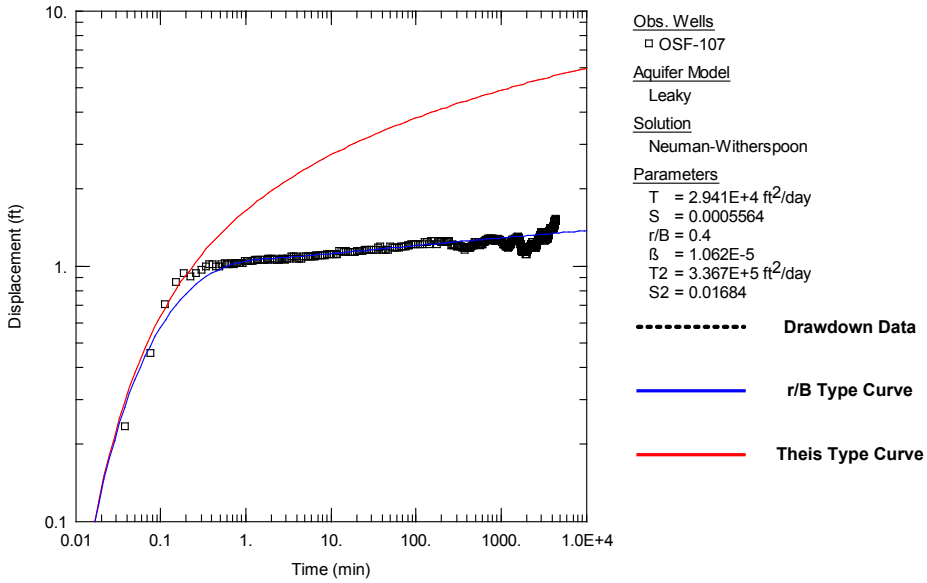
ANALYTICAL SOLUTIONS: ST. CLOUD SITE



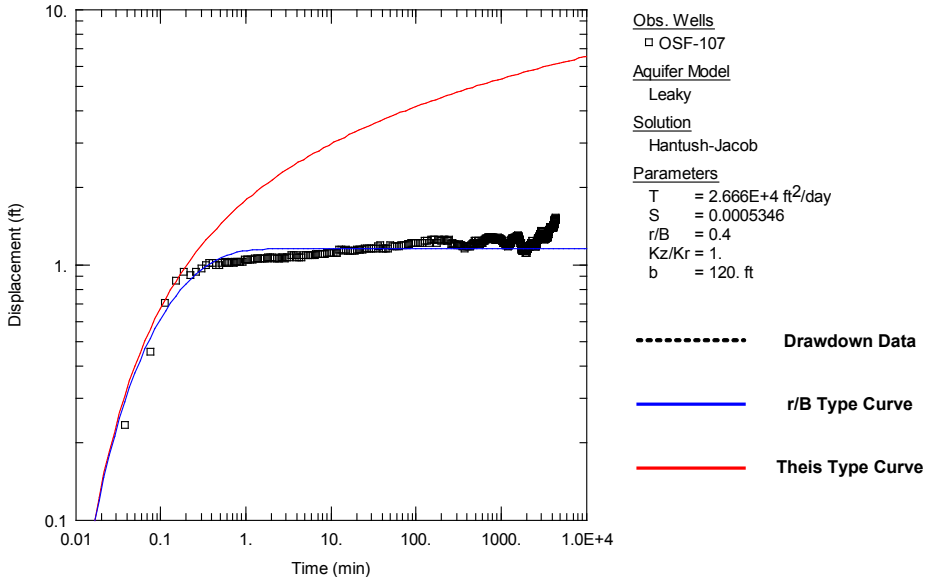
Log-log plot of drawdown for OSF-107, Moench (Case 1)



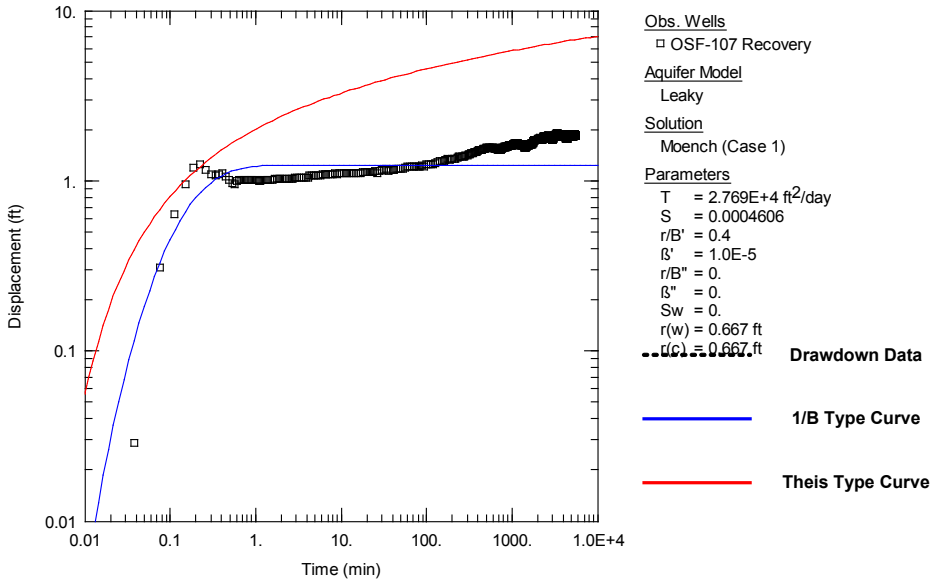
Log-log plot of drawdown for OSF-107, Hantush



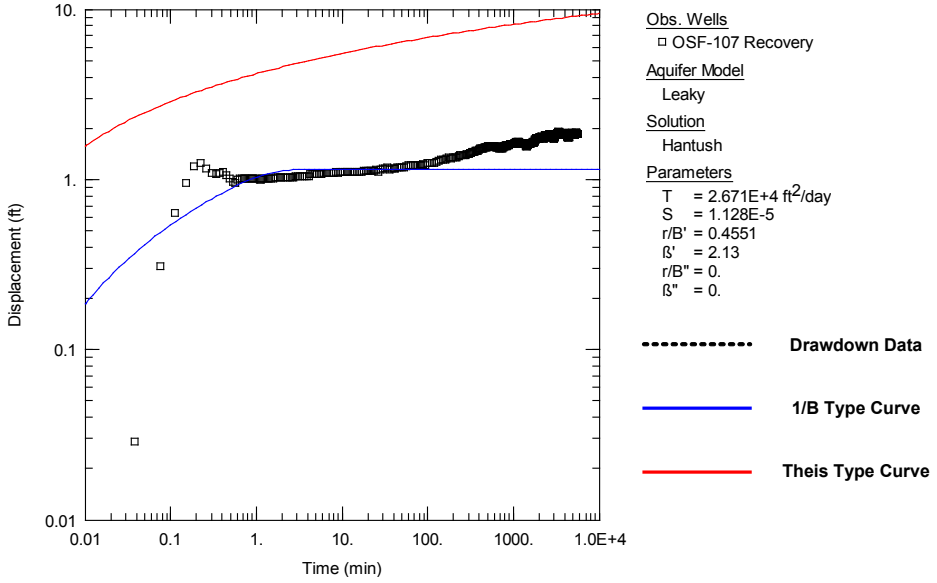
Log-log plot of drawdown for OSF-107, Neuman-Witherspoon



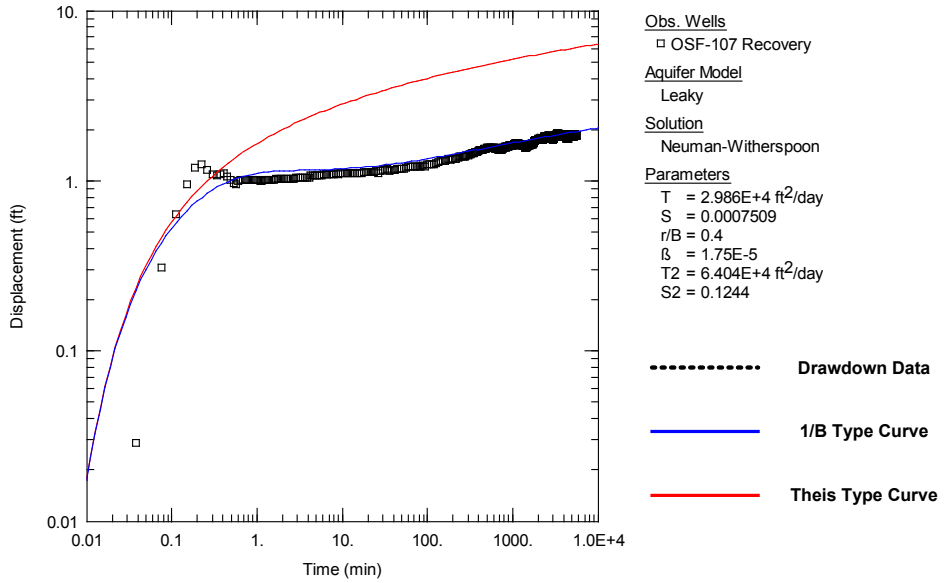
Log-log plot of drawdown for OSF-107, Hantush-Jacob



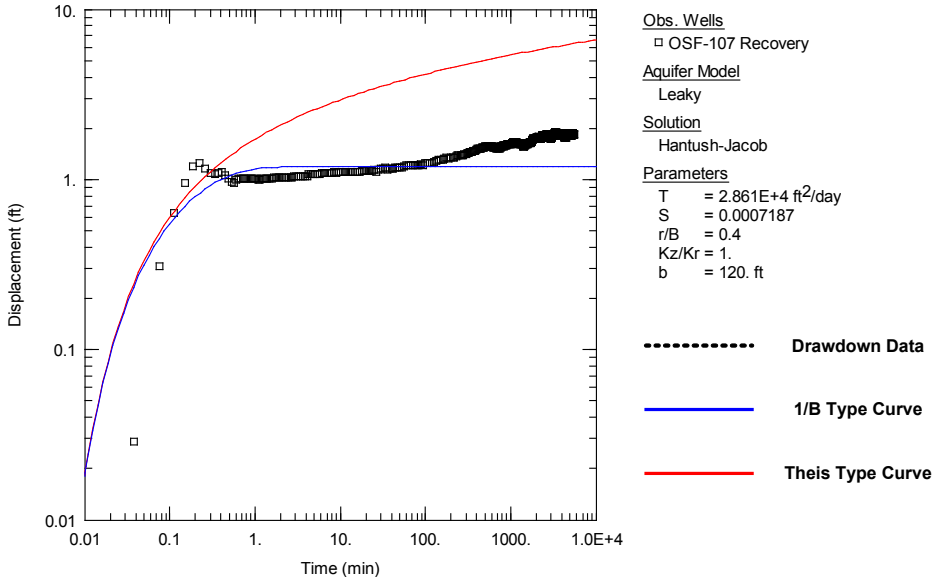
Log-log plot of recovery data for OSF-107, Moench (Case 1)



Log-log plot of recovery data for OSF-107, Hantush

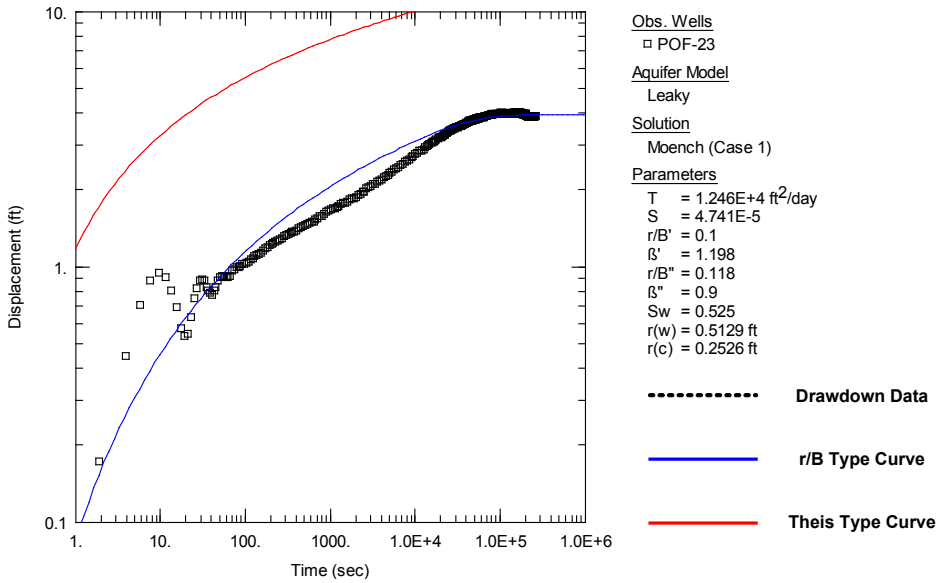


Log-log plot of recovery data for OSF-107, Neuman-Witherspoon

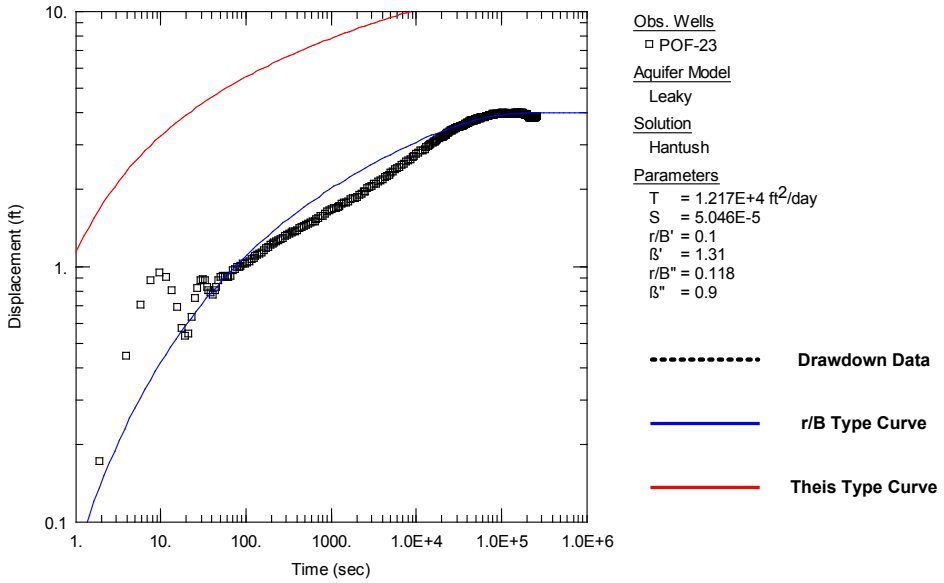


Log-log plot of recovery data for OSF-107, Hantush-Jacob

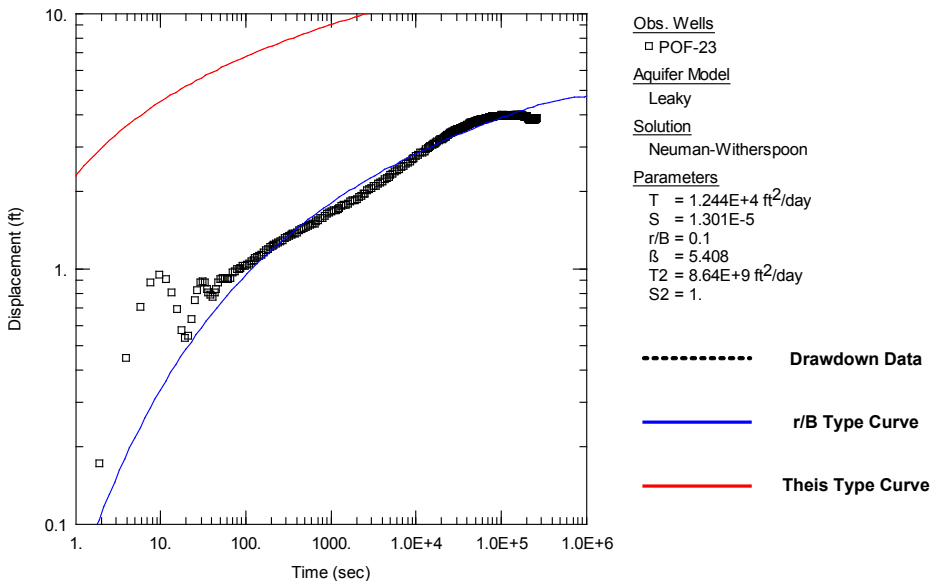
ANALYTICAL SOLUTIONS: RIVER RANCH SITE



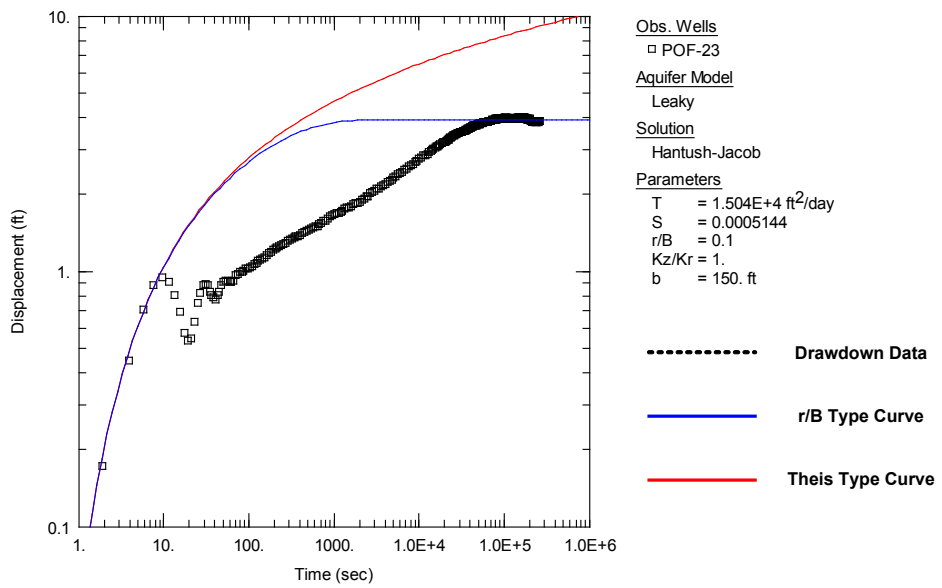
Log-log plot of drawdown for POF-23, Moench (Case 1)



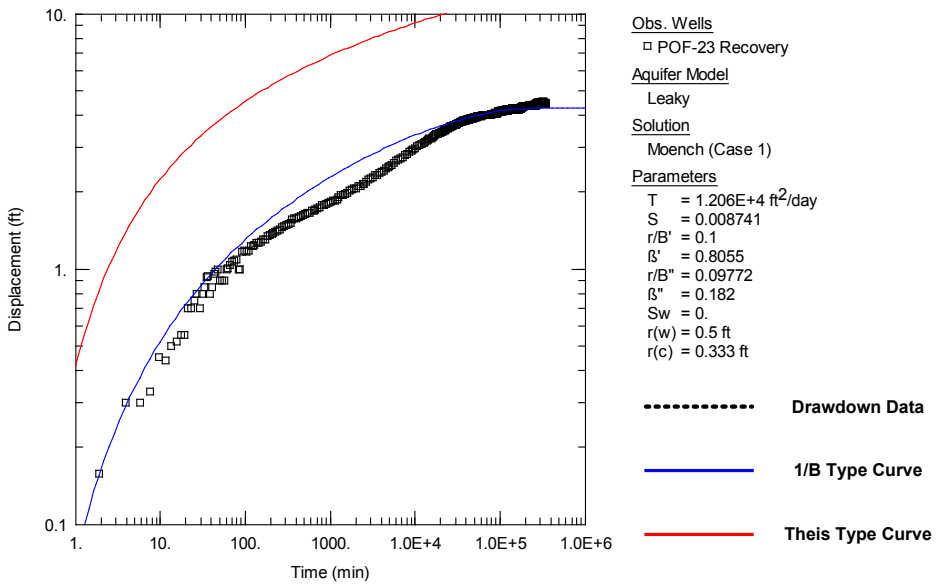
Log-log plot of drawdown for POF-23, Hantush



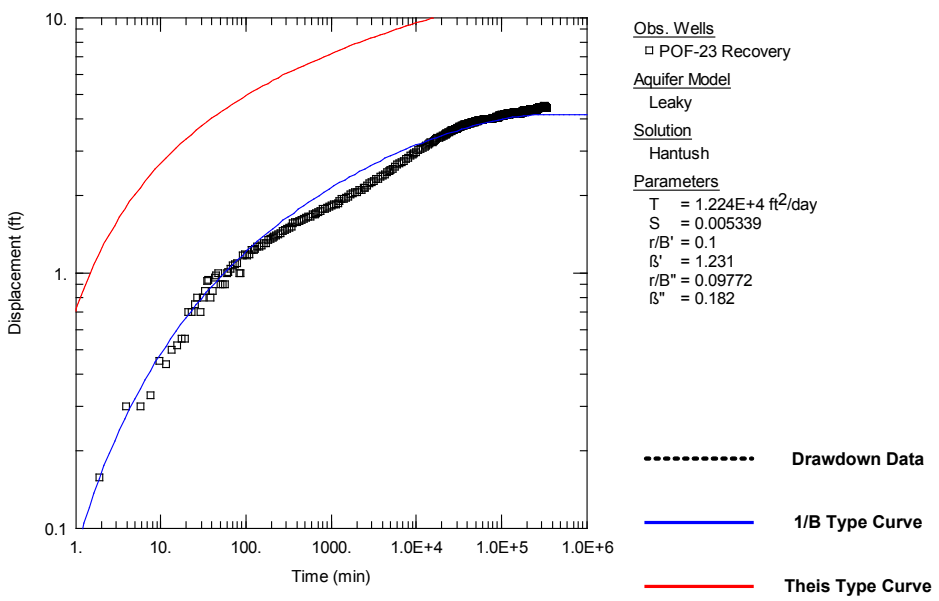
Log-log plot of drawdown for POF-23, Neuman-Witherspoon



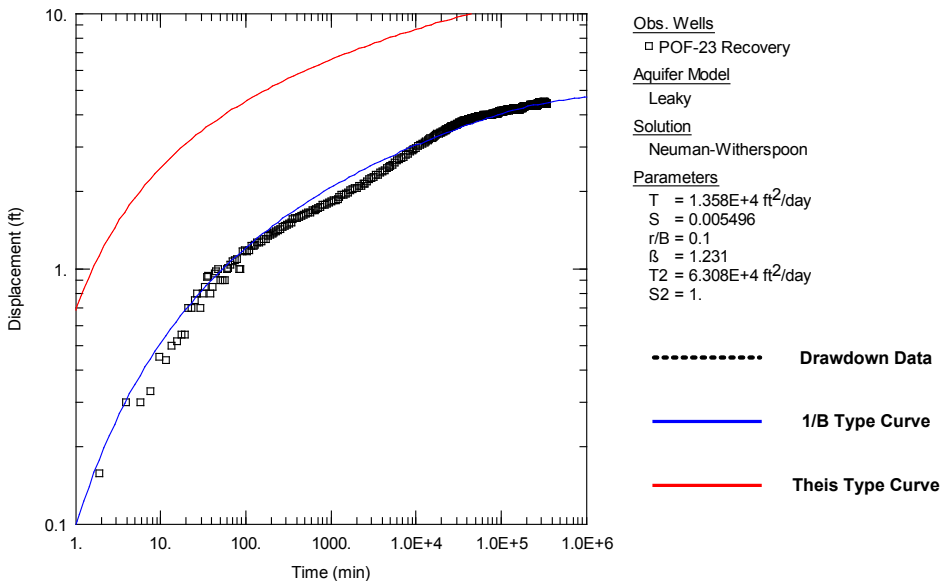
Log-log plot of drawdown for POF-23, Hantush-Jacob



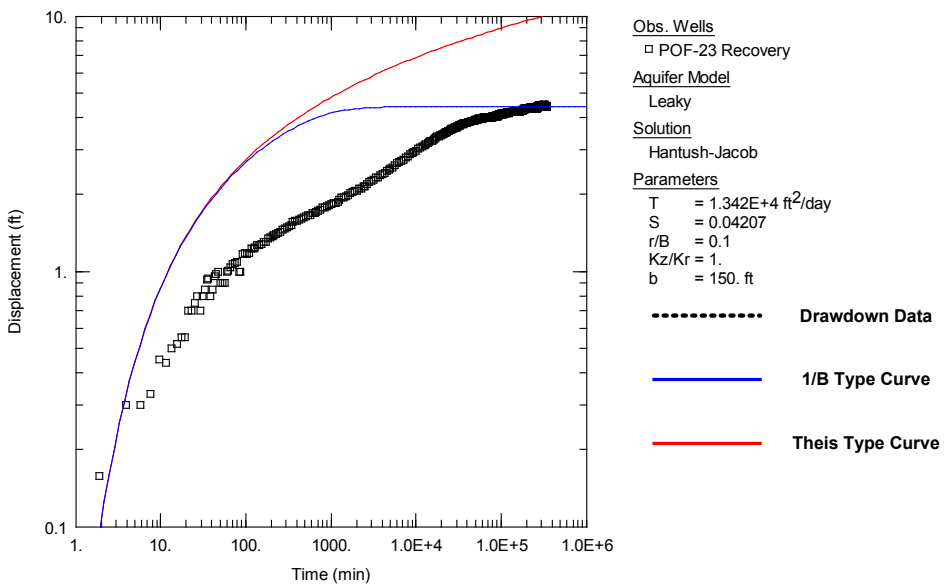
Log-log plot of recovery data for POF-23, Moench (Case 1)



Log-log plot of recovery data for POF-23, Hantush



Log-log plot of recovery data for POF-23, Neuman-Witherspoon



Log-log plot of recovery data for POF-23, Hantush-Jacob