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905-3D and 905-136D Performance and Flow Testing

K. L. Dixon

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EXECUTIVE SUMMARY

A treatability study is currently being planned to address the acidic pH conditions in the groundwater beneath the 484-17D Coal Storage Area (DCSA) and 489-D Coal Pile Runoff Basin (CPRB) and the discharge to surface water in the D-Area Discharge Canal (SRNS 2019). The treatability study proposes using the artesian flow from production wells 905-3D and 905-136D to supply water to a field of shallow injection wells to be installed near the DCSA. Hydrologic testing was conducted to provide input to support the final design of the treatability study for groundwater injection at the D-Area Groundwater Operable Unit (DAG OU).

Testing was conducted to establish performance curves for both production wells. These curves were used to illustrate the impact that piping network design will have on system performance. Based on the results of the short duration testing, a minimum diameter of 6-inches is recommended for the piping network connecting the production wells to the injection well field. The piping network design should minimize the equivalent length of the system to preserve as much of the available artesian head as possible.

Three flow tests were conducted with the primary goal being to monitor the flow from the production wells to identify potential issues with supply to the proposed injection field. These tests included: 1) a 7-day flow test at 905-3D with aquifer response measured at 905-136D, 2) a 3-day flow test at 905-136D with aquifer response measured at 905-3D, and 3) a 30-day flow test using both 905-3D and 905-136D with aquifer response measured at the P-26 well cluster.

Water was withdrawn from 905-3D for 7 days. The initial flow from the well was 327 gpm. Over the course of the test, flow decreased to 308 gpm with about half of the decline occurring in the first 24 hours. The aquifer was then allowed to recover before testing was conducted at 905-136D. Water was withdrawn from 905-136D for about 3 days and during that time flow declined from 319 to 303 gpm. For the 30-day test, water was withdrawn from 905-3D and 905-136D simultaneously. Flow from 905-3D declined from 315 to 287 gpm over the 30-day period. Likewise, flow from 905-136D declined from 312 gpm to 277 gpm over the 30-day period. For both wells, about half of the flow decrease occurred during the first 24 hours.

Data collected during the flow tests were analyzed to determine the hydraulic properties of the McQueen Branch aquifer and to qualitatively assess the suitability of the aquifer to supply the proposed injection field. The average aquifer transmissivity was determined to be 11.97 ft^2/min with a standard deviation of 0.82 ft^2/min. The average storativity of the aquifer was determined to be 0.0002 with a standard deviation of 0.0001. Using an average transmissive thickness of 178 ft, the hydraulic conductivity of the McQueen Branch aquifer was determined to be 97 ft/day. The average leakance of the McQueen Branch confining unit was estimated to be 9.1E-06 ft/day/ft.

Two injection well fields are proposed, and each well field is estimated to require about 60 gpm (~5 gpm per well). Based on the flow testing, the production wells should be able to meet this requirement. However, the actual flow the production wells can provide will be a function of the piping network used to supply the injection field. As such, the following recommendations are provided.

- A minimum 6-inch diameter smooth walled pipe (i.e. PVC) is recommended for the distribution network connecting the production wells to the injection well fields. Head loss due to friction in the piping network will have a significant impact on system performance. To the extent possible, friction losses should be minimized.
- Results from the flow testing show that flow will decrease with time as head is lowered in the aquifer. The design of the network should consider future loss of available head and flow at the wellhead. The head in the aquifer has decreased 4 to 6-feet over the past 26 years. This application and future water withdrawals in the surrounding aquifer will contribute to additional declines of head in the aquifer. The design of the distribution network should consider a head loss device that can be periodically adjusted to account for future reductions in supply head. For typical piping applications some form of throttling valve would be considered.

Based on the results of this project, the production wells will be able to supply the injection well fields if the delivery piping network is designed appropriately to minimize head loss. The highly transmissive McQueen Branch aquifer can supply several hundred gallons per minute of artesian flow under the current hydrologic conditions. It is important to note that there may be other users of the aquifer besides SRS (both industrial and agricultural). Continuous, long term withdrawals from the aquifer will lower the artesian head and reduce the availability of water for the injection well network.

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~	approximate, approximately
bgs	below ground surface
DAG OU	D-Area Groundwater Operable Unit
EC&ACP	Environmental Compliance and Area Completion Projects
CBCU	Crouch Branch Confining Unit
CPRB	Coal Pile Runoff Basin
ft	feet
GCCU	Green Clay Confining Unit
GDMS	Geological Data Management System
gpm	gallons per minute
HWMF	Hazardous Waste Management Facility
K	Hydraulic conductivity
msl	mean sea level
PVC	Polyvinyl Chloride
S	Storativity
SCDHEC	South Carolina Department of Health and Environmental Control
SRNL	Savannah River National Laboratory
SRNS	Savannah River Nuclear Solutions
SRS	Savannah River Site
T	Transmissivity
UIC	Underground Injection Control Permit
UTRA	Upper Three Runs Aquifer

1.0 Introduction

A treatability study is currently being planned to address the acidic pH conditions in the groundwater beneath the 484-17D Coal Storage Area (DCSA) and 489-D Coal Pile Runoff Basin (CPRB) and the discharge to surface water in the D-Area Discharge Canal (SRNS 2019). Exposure of the coal to rainwater has allowed the degradation of iron sulfide (pyrite; a mineral commonly found in coal) to sulfuric acid. As a result, the soils underneath the 484-17D Coal Storage Area, associated storm water runoff, and groundwater underlying the area have been acidified. The acidification led to leaching of metals from both the coal and the natural minerals in the underlying soils in the vadose zone and aquifer, resulting in a sulfate and metals groundwater plume in the Upper Three Runs Aquifer (UTRA). Currently, acidic groundwater is discharging downgradient into the D-Area Discharge Canal at pH levels generally below 4.

The presence of the low-pH plume in the groundwater is expected to last for decades under natural groundwater conditions. The treatability study proposes to test the viability of using the artesian flow from production wells 905-3D and 905-136D to supply water to a field of shallow injection wells to be installed into the aquifer upgradient of the low-pH, metals, and sulfate plume to flush the aquifer. The approach to remediating the low pH is to simply flush the aquifer with groundwater injections of a more neutral pH potable water. Production wells 905-3D and 905-136D are screened in a deep artesian aquifer (McQueen Branch aquifer) and are expected to supply enough flow and pressure to deliver large volumes of water to the proposed injection fields. The artesian groundwater will be piped to the 484-17D Coal Storage Area and 489-D CPRB and injected into the UTRA water table with a series of injection wells. Based on aqueous chemical equilibrium modeling software, a total of 10 pore space volumes of injected potable groundwater could significantly flush and raise the pH levels in the upper water table within a three-year study period (SRNS, 2019). The artesian conditions of the production wells are expected to support the groundwater injection strategy in addition to future remedial activities if needed.

To support the D-Area Groundwater Operable Unit (DAG OU) Treatability Study and provide data for the final engineering design of the injection field and system, testing of the production wells was needed to determine performance characteristics of the wells and aquifer. The testing conducted as part of this task included short duration step testing of the artesian wells to establish performance curves to be used in the design of the injection system piping network. Flow testing was also conducted to determine the hydraulic properties of the McQueen Branch aquifer and, to evaluate the artesian flow from both wells over a longer period than the short duration flow tests.

This report discusses the hydrologic tests conducted on production wells 905-3D and 905-136D. The information and recommendations provided in this report may serve as input to the final design of the injection field and system.

2.0 Hydrologic Test Methods and Objectives

The objectives of this testing were to determine the performance characteristics of the artesian production wells 905-3D and 905-136D and to determine the hydraulic properties of the McQueen Branch aquifer.

2.1 Hydrogeologic Conceptual Model

D Area is located on an alluvial terrace in the southwest quadrant of the SRS approximately 3,050 ft east of the Savannah River at an elevation approximately 130 ft above mean sea level (msl). Production wells 905-3D and 905-136D are located within D-Area (Figure 1) and are screened in the McQueen Branch aquifer (Figure 2). The P-26 well cluster is located approximately 6100 ft northwest of the production wells and contains two wells screened in the McQueen Branch aquifer, P-26TA and P-26TB (Figure 2 and Figure 3). P-26TC is screened above the McQueen Branch confining unit in the Crouch Branch aquifer (Figure 2 and Figure 3).

Figure 4 provides a generalized hydrostratigraphic cross section for SRS and shows the McQueen Branch aquifer bounded on the top by the McQueen Branch confining unit. Geophysical logs for wells 905-136D, P-26, and PW96G are compared in Figure 5. Records include natural gamma logs for 905-136D, P-26, and PW-96G and resistivity logs (16 and 64ohm-m) for 905-136D. Figure 6 shows the resistivity log (64 ohm-m) and stratigraphic picks for 905-136D from the site Geological Data Management System (GDMS). These geophysical logs combined with the hydrogeologic data presented by Aadland et al. (1995) were used to create the semi-confined hydrogeologic conceptual model for this analysis.

The McQueen Branch confining unit consists of interbedded silty, often sandy clay beds and sand beds. The clay beds thin along a line parallel to the Pen Branch Fault which is south of the study area (Figure 7). The unit thickness at P-26 is 72 feet with a total confining thickness of 43 feet (Figure 7). Confining thickness is the sum of the clay and clayey-sand thickness and represents the non-transmissive sediments in the confining unit. The unit thickness at 905-136D is estimated to be 82 feet. Specific information about the clay fraction of the confining unit is not available at 905-136D. However, based on P-26, the total confining thickness at 905-136D is estimated to be 49 feet. The lithology for 905-3D is comparable to 905-136D. However, the logs did not extend to the bottom of the borehole and are not presented.

The McQueen Branch aquifer consists primarily of medium to very coarse grained, angular, slightly silty sand and clayey, poorly to moderately well-sorted, fine to medium sand and silty clay. The aquifer typically contains clay beds that may locally divide the aquifer into two zones. At P-26, the thickness of the aquifer is estimated to be about 199 feet and the thickness of transmissive sediments is estimated to be 179 ft. At 905-136D, the aquifer is estimated to be about 196 ft thick (Figure 5 and Figure 6). Based on the thickness of transmissive sediments at P-26, the transmissive thickness at 905-136D is estimated to be 176 feet. Figure 8 shows the transmissive thickness of the McQueen Branch aquifer in the study area.

The McQueen Branch aquifer is underlain by the Appleton confining system which is the lowermost confining system in the Southeastern Coastal Plain. The thickness of the Appleton confining system is about 150 feet in the study area (Figure 9).

Most of the water in the McQueen branch aquifer comes from leakage through overlying sediments and, groundwater flow in the study area is generally to the southeast towards the Savannah River (Aadland et al. 1995). Figure 10 shows the potentiometric surface for the McQueen Branch aquifer. In the study area, the potentiometric surface is above ground elevation resulting in artesian flowing conditions at the production wells (905-3D and 905-136D) and at the P-26 well cluster. The curvature of the potentiometric surface near the study area suggests that flow converges towards a high permeability zone that may be related to the Pen Branch Fault which runs south of the area (Figure 10). Both production wells and well cluster P-26 appear to be in this zone of high permeability.

Hydrostratigraphic data for the production wells and P-26 are summarized in Table 2. These dimensions formed the basis for the subsequent analysis of pumping test data.

2.2 Review of Previous Investigations of the McQueen Branch Aquifer

There are no historical measurements of hydraulic properties for the McQueen Branch aquifer near the production wells in D-Area. However, pumping tests in other areas of SRS have been conducted on the McQueen Branch aquifer. Siple (1967) reported results from nine pumping tests of the McQueen Branch aquifer conducted in 1951 and 1952. The average transmissivity of these tests was 19.3 ft^2/min. Siple (1967) conducted one test in A/M area and determined a transmissivity of 13.7 ft^2/min and a storage coefficient of 0.0003. The remaining tests were conducted in F- and H-Area where transmissivity ranged from 9.7 ft^2/min to 34.8 ft^2/min. Storage coefficients were determined from two tests and were found to be 0.0007 and 0.0008.

A 60-day pumping test was conducted at the Barnwell Nuclear Fuel Plant on a well screened in the lower part of the Crouch Branch aquifer and the upper part of the McQueen Branch aquifer (Aadland et al. 1995). Based on results from the pumping well and two observation wells, transmissivity was estimated to be 13 ft^2/min. Pumping tests were conducted on two wells in F-Area and one well in L-Area in 1988 (Aadland et al, 1995). Transmissivity ranged from 8.3 to 16.7 ft^2/min with an average of 11.1 ft^2/min.

A 24-hour pumping test was conducted on 905-120P (Bledsoe, 1990). The aquifer was pumped at an average flow rate of 755 gpm. Aquifer response was measured in P-24TA, P-24TB, P-24TC, and P-24TD. Wells P-24TC and P24-TD did not respond to pumping. Data collected from P24-TA were used to estimate a transmissivity of 8.04 ft^2/min and a storativity of 0.0002. Aquifer thickness was assumed to be 100 ft yielding a hydraulic conductivity of 114 ft/day.

2.3 Performance Tests

During the spring and summer of 2019, performance testing was conducted on both 905-3D and 905-136D to determine the artesian flow from the wells at various operating pressures. Work was done in accordance with groundwater withdrawal permit #06IN055 issued by SCDHEC. Each well was configured with a manifold consisting of an impeller driven flow meter, direct reading pressure gauge, and throttle valve (Figure 11 and Figure 12). Initial testing was conducted to determine the maximum artesian flow from each well by fully opening the throttle valve. Following adjustment, flow and pressure parameters were allowed to stabilize and then recorded.

After allowing the aquifer to recover, a step test was conducted on each well to determine the performance characteristics of the aquifer as a function of head loss. This information was used to predict the expected flow rate for each well field once the final piping design is complete. The step-drawdown tests were conducted in approximately 1.0 psig increments with each increment approximately 10 to 20 minutes in duration. The tests were conducted by slowly opening the throttle valve from the fully closed position. At each pressure increment, the corresponding flow rate was manually recorded in the field notebook. Testing proceeded until reaching the fully open valve position.

2.4 Flow Tests

Three flow tests were conducted with the primary goal being to monitor the flow from the production wells to identify potential issues with supply to the proposed injection field. These tests included: 1) a 7-day flow test at 905-3D with aquifer response measured at 905-136D, 2) a 3-day flow test at 905-136D with aquifer response measured at 905-3D, and 3) a 30-day flow test using both 905-3D and 905-136D with aquifer response measured at the P-26 well cluster.

Prior to the start of testing, the direct reading pressure gauge on each manifold was replaced with a data logging pressure transducer (In-Situ, Inc., Level TROLL 700). This allowed pressure response to be monitored in the flowing production well while simultaneously monitoring aquifer response in the other production well which was closed to flow. To conduct a test, the valve of the flowing well was fully opened as quickly as possible. Flow readings were recorded manually on a frequent basis initially and later reduced to once daily when flow parameters stabilized

For the 30-day test, the data logging pressure transducers were moved to wells P-26TA and P-26TB to monitor aquifer response due to withdrawal at the production wells. Since both P-26TA and P-26TB are flowing artesian wells, the transducers were attached to the existing above ground plumbing. The transducers were programmed to record data on a one-minute interval. Direct reading pressure gauges were reinstalled on the production well manifolds.

After a period of pretest monitoring, the throttle valves on both production wells were fully opened simultaneously to initiate the test. Flow and pressure readings on the production wells were manually recorded on a field data sheet. Drawdown in P-26TA and P-26TB was periodically downloaded to monitor aquifer response. Barometric pressure was monitored continuously at the P-26 well cluster using a data logging barometer (In-Situ, Inc., Barotroll).

2.5 Analysis of Flow Test Data

The McQueen Branch aquifer is considered a leaky confined aquifer being overlain by the McQueen Branch Confining Unit at the top and the Appleton Confining System at the bottom (Aadland et al., 1995). Therefore, the method chosen for analyzing the bulk of data from the aquifer pumping tests considers leakage from an overlying semi-confining layer. Initial estimates of aquifer properties were made using the Theis solution for confined aquifers (Theis, 1935).

The Theis equation is given as:

$$\boldsymbol{s = \frac{Q}{4\pi T}\int_{u}^{\infty}\frac{e^{-y}}{y}dy} \qquad (2\text{-}1)$$

where s is drawdown in the aquifer, Q is the pumping rate (Fetter, 1994). The parameter u is given as:

$$\boldsymbol{u = \frac{r^2 S}{4Tt}} \qquad (2\text{-}2)$$

where r is the radial distance from the pumping well, S is the storativity of the aquifer, T is the transmissivity of the aquifer, and t is the time since pumping started.

Equation 2-1 is typically abbreviated as:

$$\boldsymbol{s = \frac{Q}{4\pi T}W(u)} \qquad (2\text{-}3)$$

where W(u) is referred to as the Theis well function (Chow, 1964).

The Theis well function W(u) is given as:

$$\boldsymbol{W(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2*2!} + \frac{u^3}{3*3!} - \frac{u^4}{4*4!} + \cdots} \tag{2-4}$$

Assumptions associated with the Theis method include:

- The aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- the pumping well is fully or partially penetrating (Hantush, 1961a)
- flow to the pumping well is horizontal when the pumping well is fully penetrating
- aquifer is nonleaky confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of a pumping well is very small so that storage in the well can be neglected

Hantush and Jacob (1955, 1961a and b) developed a well function that accounts for confining layer leakage and it is one of the most common solutions used to analyze leaky aquifers. Walton (1991) gives the equation for drawdown in a leaky confined aquifer as:

$$\boldsymbol{s = \frac{Q}{4\pi T} W\left(u, \ \frac{r}{B}\right)} \tag{2-5}$$

where Q is the extraction flow rate, T is the transmissivity. W(u, r/B) is the Hantush-Jacob leaky well function defined by:

$$\boldsymbol{W\left(u, \ \frac{r}{B}\right) = \int_u^\infty \frac{1}{y} e^{\left\{-y - \frac{\left(\frac{r}{B}\right)^2}{4y}\right\}} dy} \tag{2-6}$$

where u is defined by Equation 2-2 and:

$$\frac{r}{B} = \frac{r}{\sqrt{\left(\frac{Tb'}{k'}\right)}} \tag{2-7}$$

where r is the radial distance from the pumping well, S is the storativity, t is time, b' is the confining layer thickness, and k' is the permeability of the confining layer. The assumptions of the Hantush-Jacob solution are the same as those for the Theis solution except for leakage from the confining layer.

Transmissivity is converted to hydraulic conductivity with following equation:

$$K = \frac{T}{b} \tag{2-8}$$

where K is hydraulic conductivity, T is transmissivity, and b is aquifer thickness.

The Hantush-Jacob method was implemented using the computer code AQTESOLV (Duffield, 2007). Parameters used in the Hantush-Jacob model for leaky aquifers include the saturated thickness of the aquifer, the thickness of the overlying confining layer, and the zone of penetration of the pumping and observation wells. The hydrogeologic conceptual model described in Section 2.1 was used to establish the layer thicknesses used in AQTESOLV.

Derivative analysis was used to aide in interpretation of the pumping test data. Derivative analysis is useful for identifying flow regimes, wellbore storage effects, identifying barriers, and selecting appropriate aquifer models. AQTESOLV was used to conduct the derivative analysis of the drawdown data. Derivative plots were created by plotting the derivative of the drawdown type curve as a function of time on a log axis. These plots were compared to standard plots in the AQTESOLV library to identify flow regime and aquifer type.

2.6 Barometric Effects

Fluctuations in barometric pressure can impact water level measurements in a confined aquifer even when vented pressure transducers are used because the well serves as a direct connection to the atmosphere for the aquifer. Any change in atmospheric pressure is immediately transmitted to the aquifer through the opening provided by the well screen. For wells near the pumping well, barometric effects may be minimal in comparison to the head change induced by pumping. However, for wells further away where the head change in the aquifer is smaller, barometric effects can be significant. Data collected during aquifer testing at the production wells were corrected for barometric effects.

Corrections to water level data were made using the following equations (Gonthier, 2007).

$$\Delta \boldsymbol{w_{cor}} = \boldsymbol{w_{obs}} - \boldsymbol{B_{eff}} * \Delta \boldsymbol{BP} \tag{2-9}$$

where w_{cor} = corrected water level, ft H_2O
w_{obs} = observed water level, ft H_2O
B_{eff} = Barometric efficiency
ΔBP = change in barometric pressure, ft H_2O

$$\boldsymbol{B_{eff}} = \frac{\Delta \boldsymbol{wl}}{\Delta \boldsymbol{BP}} \tag{2-10}$$

where B_{eff} = Barometric efficiency
Δwl = change in water level, ft H_2O
ΔBP = change in barometric pressure, ft H_2O

Water level measurements were made in the observation wells for several days prior to testing to establish baseline hydraulic conditions. These data were used to calculate barometric efficiency which was then used to correct the water level measurements collected during the test.

3.0 Results

Testing was conducted at production wells 905-3D and 905-136D to evaluate the use of these wells to supply a proposed injection well field. The test methods employed are described in Section 2.0. Performance testing of the production wells occurred on 5/21/2019. Well 905-3D was tested in the morning and well 905-136D was tested in the afternoon. A 7-day flow test was conducted on well 905-3D from 6/17/2019 through 6/24/2019. A 3-day flow test was conducted on well 905-136D from 7/8/2019 through 7/10/2019. A 30-day flow test using both wells 905-3D and 905-136D was conducted from 7/15/2019 through 8/14/2019. The following sections provide a discussion and analysis of the results obtained from the hydrologic testing.

3.1 Performance Testing

Prior to the start of flow testing, the static artesian head in both production wells was recorded. The static head in 905 3D was found to be 30.6 ft H_2O whereas the static head in 905-136D was found to be 29.4 ft H_2O. At the time of installation (1993), the static head in 905-3D was 36.7 ft H_2O whereas the static head in 905-136D was 33.7 ft H_2O. This indicates a decline in artesian head on the order of about 5-feet since the time of installation (~ 26 years).

Testing was conducted by incrementally opening the throttle valve on the test manifold and monitoring the flow rate observed on the flow meter. Pressure and flow data were recorded for each increment (Table 3). These data were used to generate the equivalent of a "pump curve" for each of the supply wells. These curves are presented in Figure 13 and are indicative of how each well will perform with regards to pressure head and flow.

In Figure 14 through Figure 19 the "pump curve" for each of the supply wells is combined with system curves for hypothetical piping systems. In combination, these performance curves can be used to match the necessary piping system characteristics with the capability of the pump. In this case, the aquifer is the pump and the piping system is the piping network from the well head to the injection manifold. The curve for the hypothetical piping system is presented in terms of equivalent distance for various piping diameters, a process and nomenclature used in the design of piping networks. The point of intersection of the "pump curve" and the network curve identify the system operating point. For the application at hand, this determines the total flowrate of water available. Data from the performance testing were used to generate the "pump curve" which is presented in the figures as the aquifer curve. Piping system head loss was calculated for 2, 4, and 6-inch diameter PVC for piping network lengths ranging from 1000 to 5000 ft. The intersection of the aquifer performance curve and a piping network curve provides an estimate of where the system will operate. For example, from Figure 14, a 6-inch diameter PVC piping network 5000 ft in length would be expected to operate at approximately 210 gpm and 17 ft of head (~ 7.8 psig).

The performance curves presented for both wells illustrates the benefits of using larger diameter pipe for the proposed injection well network. In the case of 905-3D, reducing the pipe diameter from 6 inch to 4-inch reduces the flow from 210 to 80 gpm for a network length of 5000 ft. For 2-inch diameter pipe, head loss is nearly equal to the available head from the aquifer and therefore minimal flow would be expected for a piping network length of 5000 ft.

As illustrated in Figure 14 through Figure 19, the design of the piping network will have a long-term impact of the effectiveness of the proposed remedy. The design of this network should also consider future loss of available head at the wellhead. As previously identified, the head in the aquifer has decreased 4 to 6-feet over the past 26 years. This application and future water withdrawals in the surrounding aquifer will likely contribute to additional declines of head in the aquifer. The design of the distribution network should consider a head loss device that can be periodically adjusted to account for future reductions in supply head. For typical piping applications some form of throttling valve would be considered. It should be noted that both 905-3D and 905-136D are currently configured with a pump and associated piping. The pump and piping will serve to create head loss and reduce artesian flow. Removal of in-well equipment will increase artesian head and flow under operating conditions.

3.2 Flow Testing

As described in Section 2.4, flow testing was conducted on both production wells to identify potential issues with supply to the proposed injection field. The natural artesian flow from the production wells was used to stress the aquifer. Although both wells have pumps installed, the pumps were not used in the testing. Three flow tests were conducted under artesian conditions: 1) a 7-day flow test at 905-3D with aquifer response measured at 905-136D, 2) a 3-day flow test at 905-136D with aquifer response measured at 905-3D, and 3) a 30-day flow test using both 905-3D and 905-136D with aquifer response measured at the P-26 well cluster.

Drawdown data from the various tests were used to determine the hydraulic properties of the McQueen Branch aquifer. Data collected from the observation wells were corrected for barometric effects as described in Section 2.6. Initial estimates of aquifer properties were obtained using the Theis method (1935) for confined aquifers. After obtaining initial estimates, the Hantush-Jacob method (1955, 1961a and b) for leaky, confined aquifers was used to refine the analyses. All simulations were conducted using the computer code AQTESOLV (Duffield, 2007) as described in 2.5. This method provides large volume estimates of average aquifer properties including transmissivity and storativity. Dimensions used in the AQTESOLV analyses are presented in Table 4.

3.2.1 905-3D Aquifer Test

A 7-day (174.1 hours) aquifer test using well 905-3D began on 6/17/2019 and continued through 6/24/2019 (Figure 20). At the start of testing, the throttle valve was fully opened, and it remained in this position for the duration of the test. The initial flow rate was 327 gpm. As head declined in the aquifer due to water withdrawal, the flow rate decreased to 308 gpm (Figure 20). A total of 3.26 million gallons of water were removed from the aquifer during the test. Aquifer response was measured in well 905-136D where the maximum drawdown observed was 2.2 ft. Drawdown data were recorded with a data logging pressure transducer. A transducer malfunction at the end of the stress period prevented the collection of recovery data. The drawdown data were analyzed to determine aquifer hydraulic properties and the results are presented in Table 5 and Figure 21. Data were analyzed in AQTESOLV using the Hantush-Jacob Leaky aquifer model described in Section 2.5. Transmissivity was estimated to be 11.68 ft^2/min and aquifer storativity was estimated to be 0.0001. Using an average transmissive thickness of 178 ft (Table 2), hydraulic conductivity was estimated to be 94.7 ft/day. The leakage factor (r/B) was estimated to be 0.0143. The hydraulic conductivity of the McQueen Branch confining layer, K', was estimated to be 2.7E-04 ft/day. Using an average confining thickness of 46 ft yields a leakance value of 5.8E-06 ft/day/ft. The estimated property values are comparable to those from previous studies of the McQueen Branch aquifer (Section 2.2).

Derivative analysis was used to identify the flow regime and aquifer type based on the results of the aquifer test. The derivative of the drawdown type curve the observation well is presented in Figure 21. The shape of the derivative curve is consistent with a leaky, confined aquifer with infinitely acting radial flow (Duffield, 2007).

3.2.2 905-136D Aquifer Test

A two-day (50.3 hours) aquifer test using well 905-136D began on 7/8/2019 and continued through 7/10/2019. Upon conclusion, recovery data were collected with this test (Figure 22). At the start of testing, the throttle valve was fully opened, and it remained in this position for the duration of the test. The initial flow rate from the well was 319 gpm. As the head in the aquifer decreased in response to water withdrawal, flow decreased to 303 gpm (Figure 22). A total of 0.93 million gallons of water were removed from the aquifer during the test. Aquifer response was measured in well 905-3D where the maximum drawdown observed was 1.8 ft. Drawdown and recovery data were analyzed to determine aquifer hydraulic properties and the results are presented in Table 5 and Figure 23 Data were analyzed in AQTESOLV using the Hantush-Jacob Leaky aquifer model described in Section 2.5. Transmissivity was estimated to be 11.61 ft^2/min and aquifer storativity was estimated to be 0.0001. Using an average transmissive thickness of 178 ft (Table 2) yields a hydraulic conductivity of 94.1 ft/day. The leakage factor (r/B) was estimated to be 0.0320. The hydraulic conductivity of the McQueen Branch confining layer, K', was estimated to be 1.3E-03 ft/day. Using an average confining thickness of 46 ft yields a leakance value of 2.9E-05 ft/day/ft. Although the leakance value is somewhat higher than estimated from the 905-3D testing, good agreement is noted with the estimates for transmissivity and storativity. Likewise, the results are comparable to those from previous investigations of the McQueen Branch aquifer

Derivative analysis was used to identify the flow regime and aquifer type based on the results of the aquifer test. The derivative of the drawdown type curve the observation well is presented in Figure 23. The shape of the derivative curve is consistent with a leaky, confined aquifer with infinitely acting radial flow (Duffield, 2007).

Recovery data from 905-3D were analyzed separately to provide confirmation of the calculated hydraulic properties (Figure 24). The Theis recovery method was used for the analysis (Theis, 1935). Recovery data is collected after pumping has stopped and represents the water level rise in the well as a function of time. The transmissivity estimated from the recovery data was 11.64 ft^2/min. This compares favorably to the other estimates of transmissivity (11.68 and 11.61 ft^2/min).

3.2.3 905-3D and 905-136D 30-Day Aquifer Test

A 30-day (720.5 hours) test was conducted using both 905-3D and 905-136D. Testing began on 7/15/2019 and continued through 8/14/2019 and recovery data were collected through 9/9/2019. To initiate the test, the throttle valves on both wells were fully opened simultaneously. The valves remained fully opened for the duration of the test. At the conclusion of the test, the valves were closed, and aquifer recovery was monitored in the observation wells. The maximum artesian flow from 905-3D was 315 gpm and flow decreased to 287 gpm by the end of the 30-day test. Likewise, the maximum flow from 905-136D was 319 gpm declining to 277 gpm at the end of the test. For both wells, about half of the decrease in flow occurred during the first 24 hours (Figure 25). The static artesian head in both production wells was about 30 ft prior to the start of the 30-day test. The maximum drawdown observed in both wells was about 22 ft. A total of 28.9 million gallons of water were removed from the aquifer during the test.

Aquifer response was monitored at the P-26 well cluster which is located about 6100 ft from the production wells. The P-26 well cluster consists of several wells with two screened in the McQueen Branch aquifer (Figure 3). P-26TA and P-26TB are both screened in the McQueen Branch aquifer with P-26TA in the lower portion and P-26TB in the upper portion of the aquifer. Both wells are flowing artesian wells. The pre-test hydraulic head at P26-TA was 158.2 ft msl which is approximately 6 ft above the ground surface. Head measured at P26-TB was slightly lower at 158.0 ft msl. The head measured at P26-TC, which is screened in the Crouch Branch aquifer, was 153.6 ft msl. This placed the water level at P-26TC about 6 inches below the top of casing and above the ground surface (~152 ft msl) prior to the start of the test.

Water levels in wells P-26TA and P-26TB were monitored with data logging pressure transducers connected to the above ground pluming. Initially, the water level in P-26TC was monitored manually using an electric water level tape. Once it became apparent that P-26TC was being influenced by the test, a data logging transducer was also placed in P-26TC.

Aquifer response was observed at P-26TA, P-26TB, and P-26TC. The maximum drawdown observed at P-26TA and P-26TB was 2.9 and 2.6 ft, respectively (Figure 25). Drawdown at P-26TC was about 1.7 ft (Figure 26). P-26TC is screened in the Crouch Branch aquifer which is separated from the McQueen Branch aquifer by the McQueen Branch confining unit (Figure 5). The lithologic logs for P-26 show the confining unit consists of interbedded layers of sands and clays. Aadland (1995) notes that the clay beds of the McQueen Branch confining unit thin dramatically near the Pen Branch Fault which runs south of the study area (Figure 7). The response measured in P-26TC suggest that there is good communication between the McQueen Branch aquifer and the overlying Crouch Branch which indicates that the McQueen Branch confining unit may be more permeable in this area.

PW96G is located 1237 ft from P-26TC and is screened in the Crouch Branch aquifer (Figure 5). PW96G is occasionally pumped to support other site missions and the response in P-26TC due to this pumping is evident in Figure 26. Records for PW96G listed short pumping periods on 7/18/2019 and 8/14/2019. Figure 26 also shows a response in P-26TC due to pumping from an unidentified well on 8/4/2019. P-26TA and P-26TB did not respond to the short intervals of pumping at PW96G.

Drawdown and recovery data collected from P-26TA and P-26TB were analyzed using AQTESOLV to determine aquifer hydraulic properties. Initially, a poor fit to the observed data was obtained for both wells P-26TA and P-26TB (Figure 27 and Figure 28). Analysis of the derivative data for both wells revealed multiple inflection points that may be indicative of influence from unidentified pumping wells not included in the initial conceptual model. A review of SRS wells screened in the McQueen Branch aquifer did not identify any nearby wells that would be expected to influence P-26TA and P-26TB. However, a review of satellite imagery identified at least two possible irrigation areas located across the Savannah River (Figure 29). Center-pivot irrigation systems require large volumes of water and are usually supplied by deep wells screened in highly transmissive aquifers. Therefore, it was assumed these irrigation areas are supplied by wells that may influence P-26TA and P-26TB. To investigate this assumption, two hypothetical wells were included in the AQTESOLV model at distances corresponding to the irrigation areas. Pumping rates and timing were adjusted to obtain the best fit to the observed data.

Figure 30 and Figure 31 show the improved fit to the observed data for both P-26TA and P-26TB. For both wells, the derivative type curves provide a good fit to the derivative data. The improved fit to both observation data and derivative data adds confidence in the assumption that the observation wells are influenced by unknown pumping wells. Predicted hydraulic properties are comparable to those obtained from the single well testing (Section 3.2.1 and 3.2.2). Analysis of the drawdown data form P-26TA produced a transmissivity of 13.18 ft^2/min with a storativity of 0.0002 (Table 5). Using an average transmissive thickness of 178 ft (Table 2) yields a hydraulic conductivity of 106.9 ft/day. The leakage factor (r/B) was estimated to be 0.0189. The hydraulic conductivity of the McQueen Branch confining layer, K’, was estimated to be 8.4E-06 ft/day. Using an average confining thickness of 46 ft yields a leakance value of 1.8E-07 ft/day/ft.

For P-26TB, transmissivity was estimated to be 11.39 ft^2/min with a storativity of 0.0004 (Table 5). Using an average transmissive thickness of 178 ft (Table 2) yields a hydraulic conductivity of 92.4 ft/day. The leakage factor (r/B) was estimated to be 0.0604. The hydraulic conductivity of the McQueen Branch confining layer, K', was estimated to be 7.4E-05 ft/day. Using an average confining thickness of 46 ft yields a leakance value of 1.6E-06 ft/day/ft.

3.2.4 McQueen Branch Aquifer Hydraulic Properties

Results from the hydraulic testing are presented in Table 5. The average transmissivity of the McQueen Branch aquifer was estimated to be 11.97 ft^2/min with a median value of 11.65 ft^2/min. The average and median storativity were estimated to be 0.0002. The average and median hydraulic conductivity were estimated to be 97.0 and 95.2 ft/day, respectively. The hydraulic conductivity of the McQueen Branch aquifer falls in the range of a clean sand (Freeze and Cherry, 1979). Leakance for the McQueen Branch Confining unit averaged 9.1E-06 ft/day/ft with a median of 3.7E-06 ft/day/ft. These values are comparable to those from other testing of the McQueen Branch aquifer in other areas of SRS (Section 2.2).

4.0 Conclusions

A treatability study is currently being planned to address the acidic pH conditions in the groundwater beneath the 484-17D Coal Storage Area (DCSA) and 489-D Coal Pile Runoff Basin (CPRB) and the discharge to surface water in the D-Area Discharge Canal (SRNS 2019). The treatability study proposes using the artesian flow from production wells 905-3D and 905-136D to supply water to a field of shallow injection wells to be installed near the DCSA. Hydrologic testing was conducted to provide input to support the final design of the treatability study for groundwater injection at the D-Area Groundwater Operable Unit (DAG OU).

Testing was conducted to establish performance curves for both production wells. These curves were used to illustrate the impact that piping network design will have on system performance. Based on the results of the short duration testing, a minimum diameter of 6-inches is recommended for the piping network connecting the production wells to the injection well field. The piping network design should minimize the equivalent length of the system to preserve as much as possible the available artesian head.

Three flow tests were conducted with the primary goal being to monitor the flow from the production wells to identify potential issues with supply to the proposed injection field. These tests included: 1) a 7-day flow test at 905-3D with aquifer response measured at 905-136D, 2) a 3-day flow test at 905-136D with aquifer response measured at 905-3D, and 3) a 30-day flow test using both 905-3D and 905-136D with aquifer response measured at the P-26 well cluster.

Water was withdrawn from 905-3D for 7 days. The initial flow from the well was 327 gpm. Over the course of the test, flow decreased to 308 gpm with about half of the decline occurring in the first 24 hours. The aquifer was then allowed to recover before testing was conducted at 905-136D. Water was withdrawn from 905-136D for about 3 days and during that time flow declined from 319 to 303 gpm. For the 30-day test, water was withdrawn from 905-3D and 905-136D simultaneously. Flow from 905-3D declined from 315 to 287 gpm over the 30-day period. Likewise, flow from 905-136D declined from 312 gpm to 277 gpm over the 30-day period. For both wells, about half of the flow decrease occurred during the first 24 hours.

Data collected during the flow tests were analyzed to determine the hydraulic properties of the McQueen Branch aquifer and to qualitatively assess the suitability of the aquifer to supply the proposed injection field. The average aquifer transmissivity was determined to be 11.97 ft^2/min with a standard deviation of 0.82 ft^2/min. The average storativity of the aquifer was determined to be 0.0002 with a standard deviation of 0.0054. Using an average transmissive thickness of 178 ft, the hydraulic conductivity of the McQueen Branch aquifer was determined to be 97 ft/day. The average leakance of the McQueen Branch confining unit was estimated to be 9.1E-06 ft/day/ft.

Based on the results of this project, the production wells will be able to supply the injection well fields if the delivery piping network is designed appropriately to minimize head loss. The highly transmissive McQueen Branch aquifer can supply several hundred gallons per minute of artesian flow under the current hydrologic conditions. It is important to note that there may be other users of the aquifer besides SRS (both industrial and agricultural). Continuous, long term withdrawals from the aquifer will lower the artesian head and reduce the availability of water for the injection well network.

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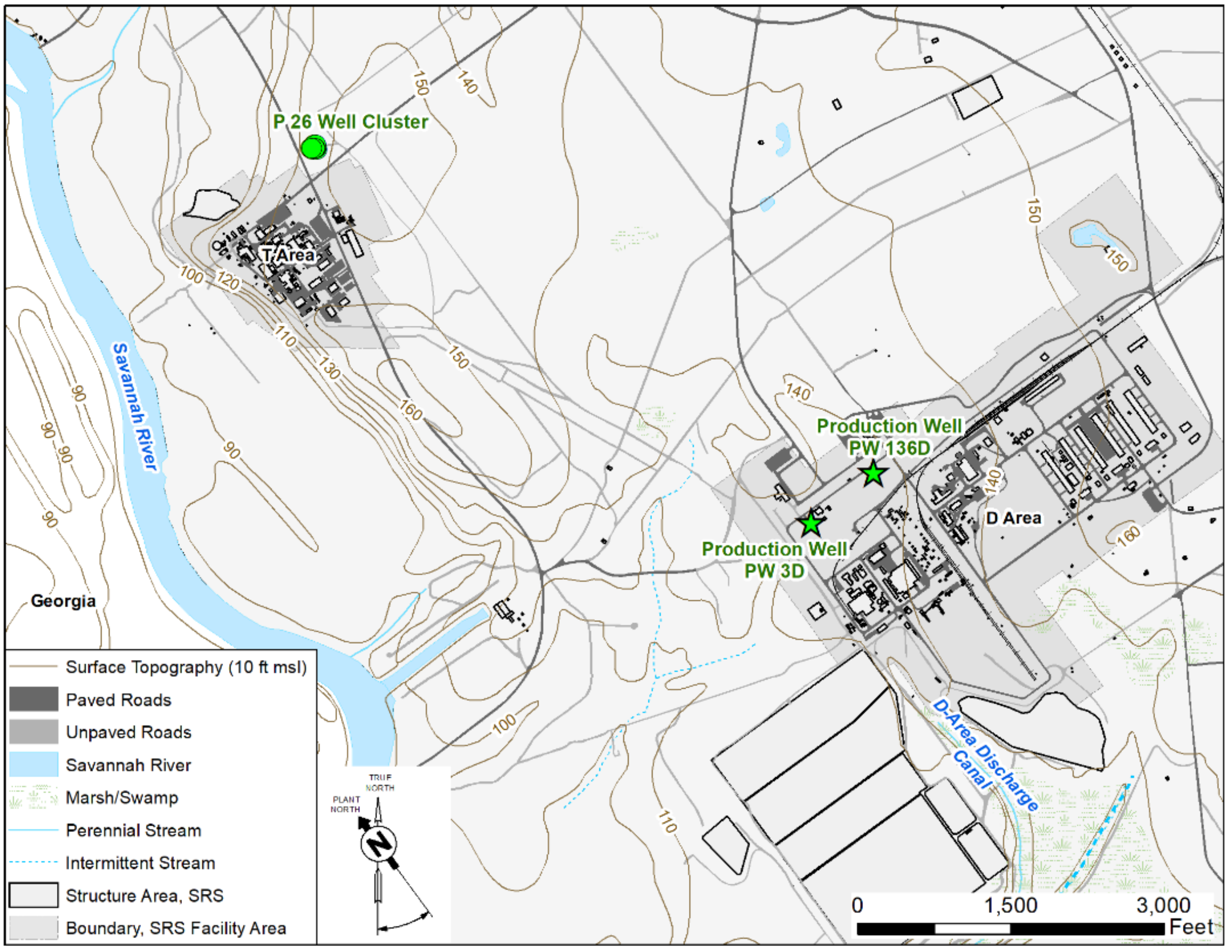

Figure 1. Location of Production Wells and P26 Well Cluster.

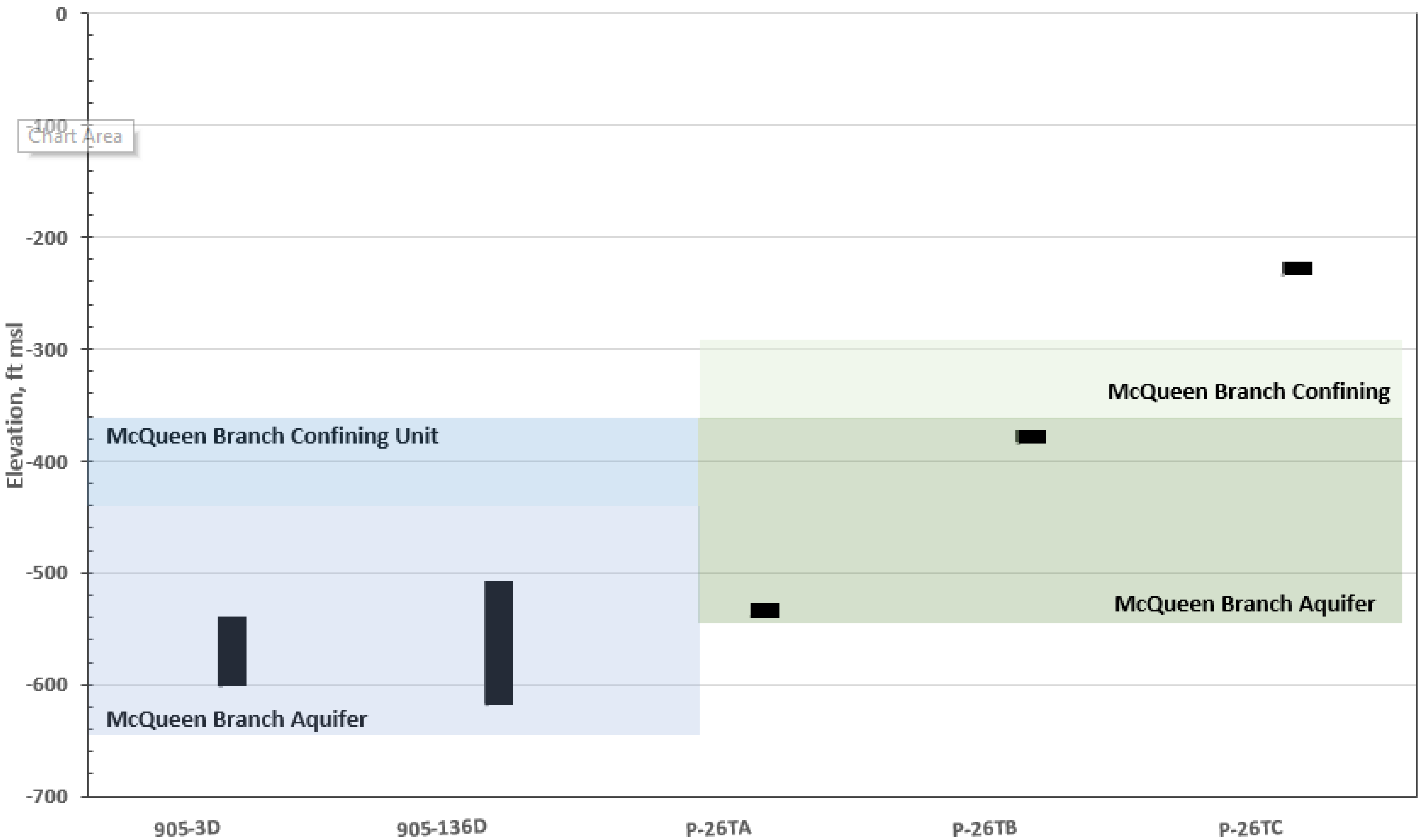

Figure 2. Screen Elevations for McQueen Branch Aquifer Test Wells

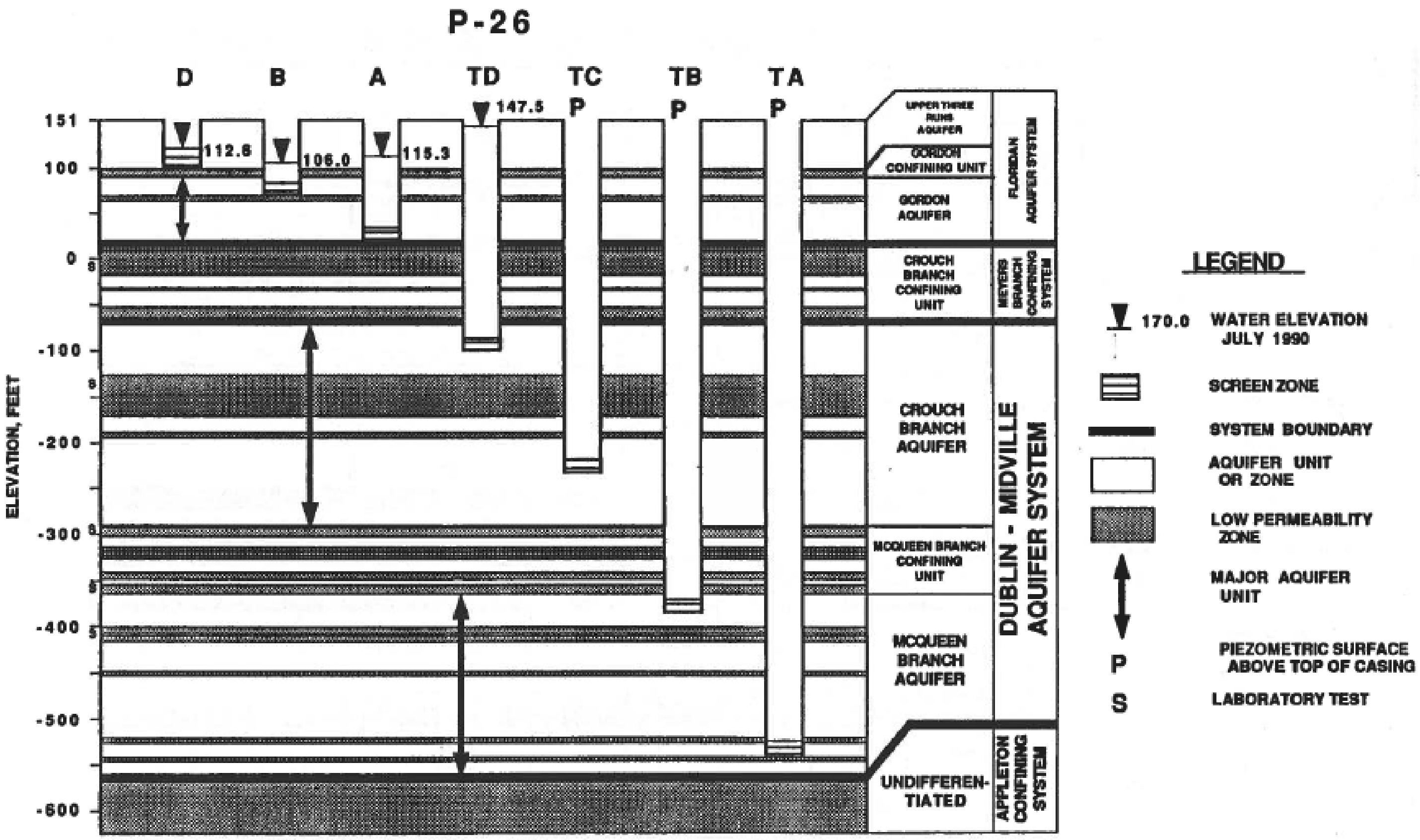

Figure 3. Screen Placements for P-26 Well Cluster

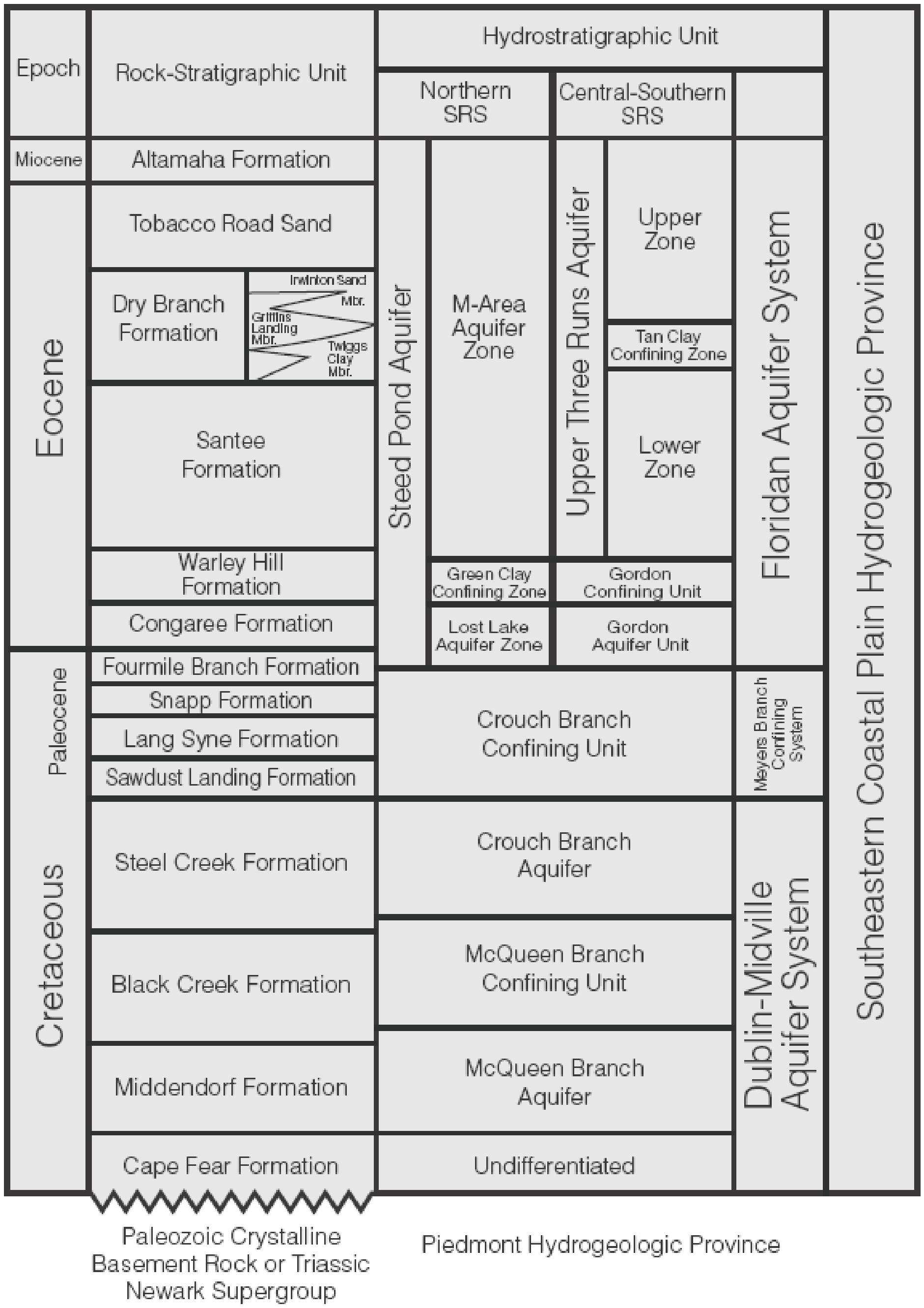

Figure 4. Hydrostratigraphic Units at SRS (Aadland et al., 1995).

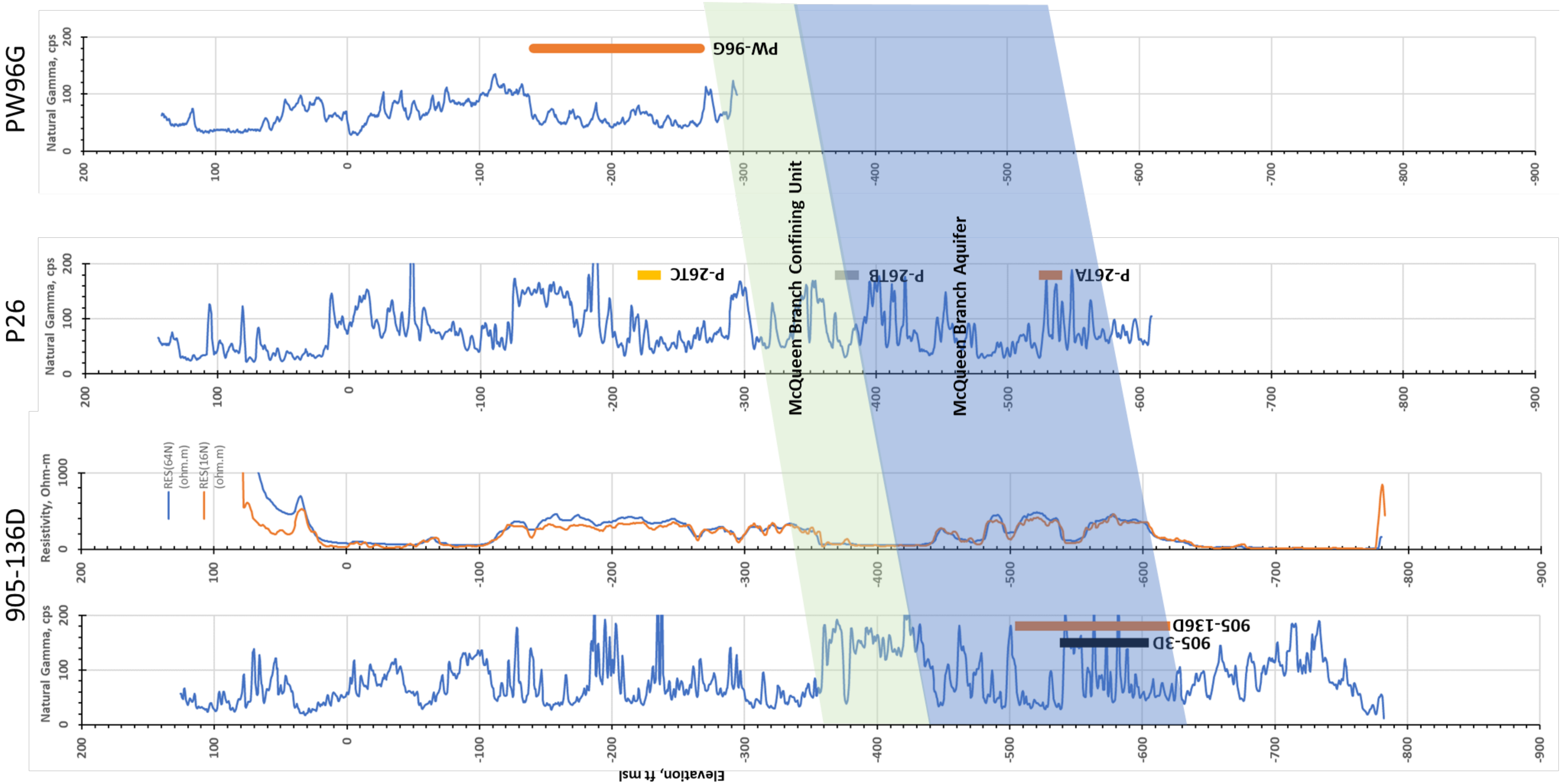

Figure 5: Generalized Lithologic Cross Sections for McQueen Branch Aquifer Test

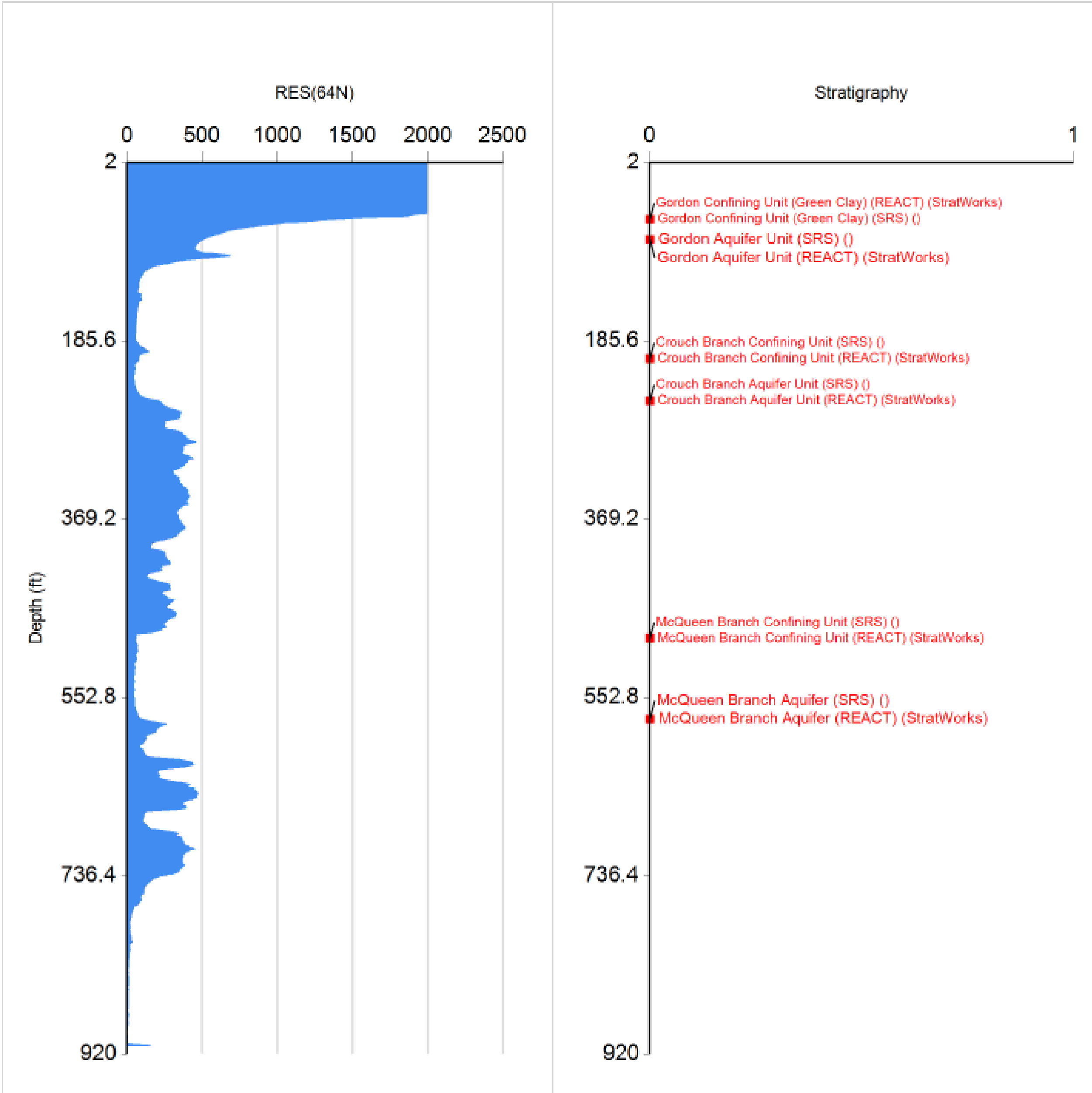

Figure 6: Resistivity Log for 905-136D Showing Hydrostratigraphic Picks for the McQueen Branch Confining Unit and Aquifer (SRS Geological Data Management System).

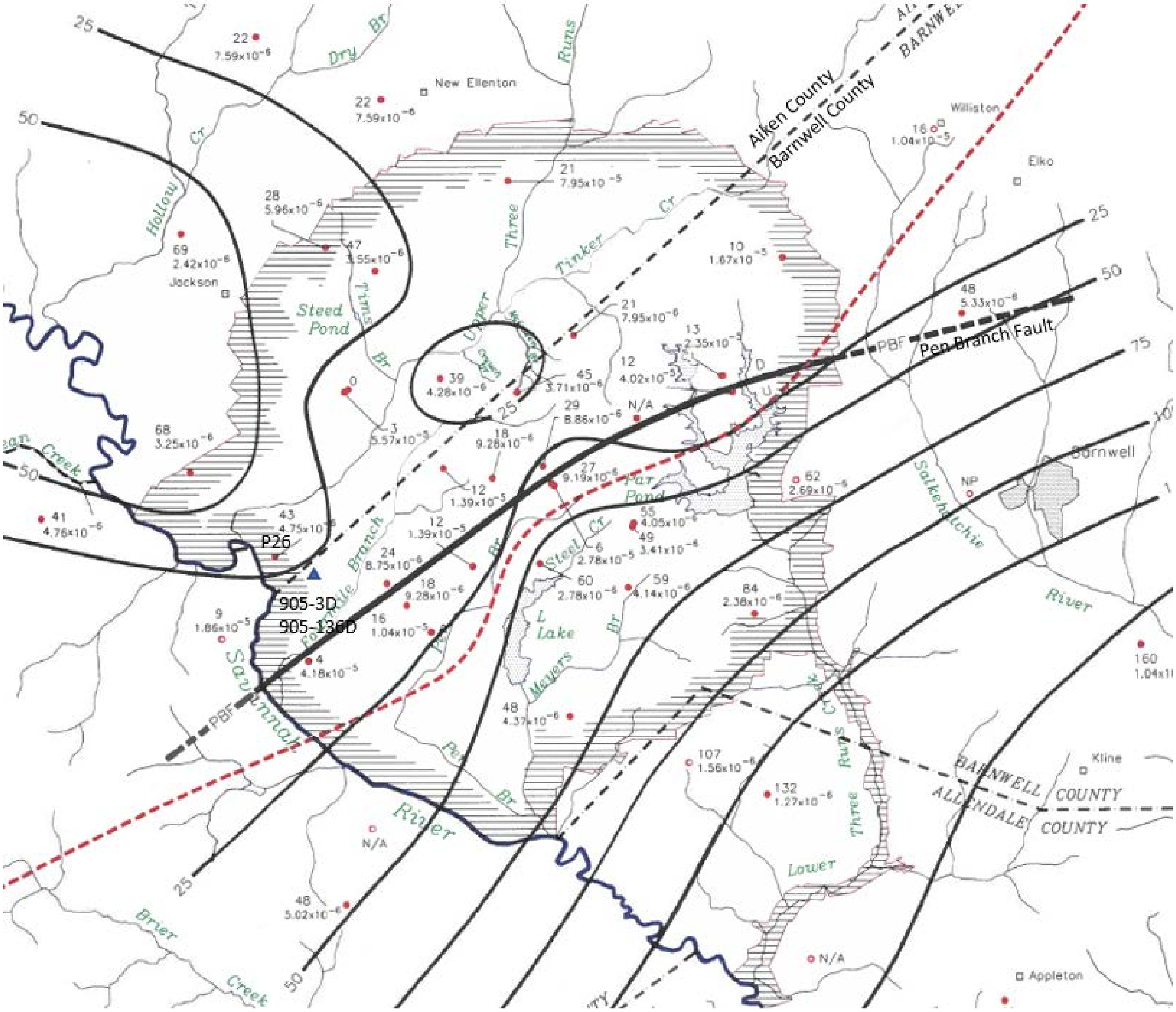

Figure 7: Thickness of Non-Transmissive Beds of the McQueen Branch Confining Unit (modified from Aadland et al., 1995).

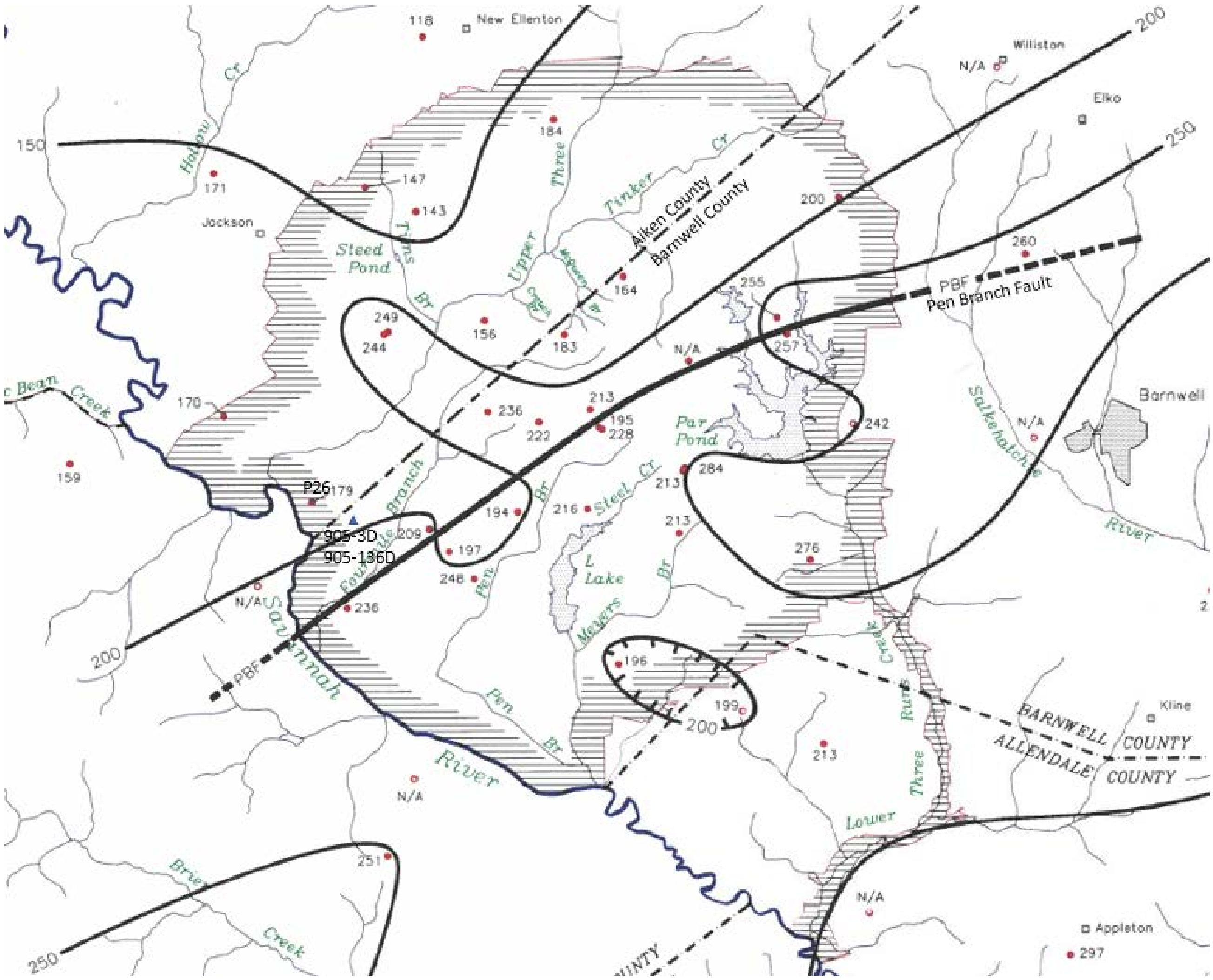

Figure 8: Thickness of Transmissive Sediments of the McQueen Branch Aquifer Near Production Wells 905-3D and 905-136D (modified from Aadland et al., 1995).

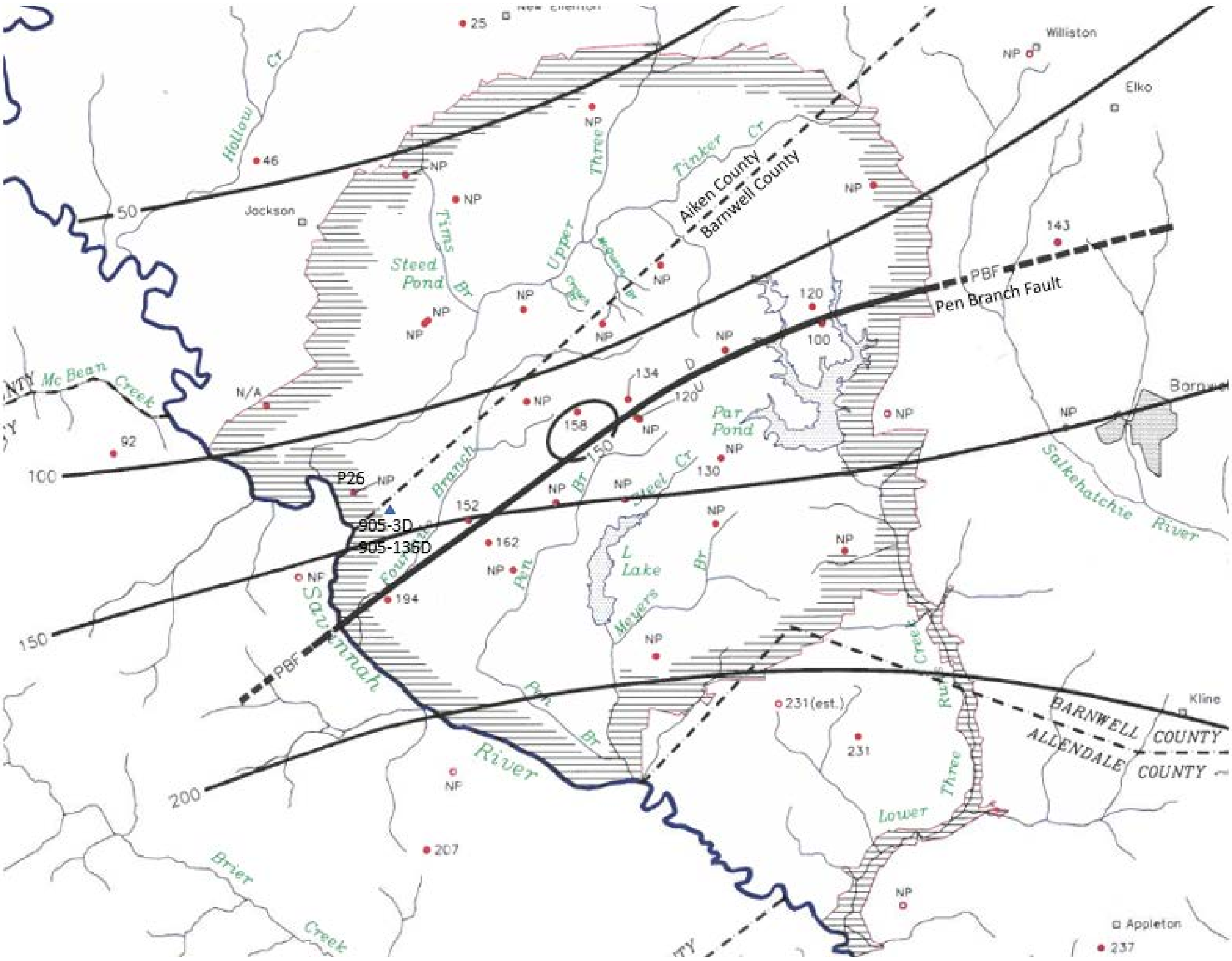

Figure 9: Thickness of the Appleton Confining System Near Production Wells 905-3D and 905-136D (modified from Aadland et al., 1995).

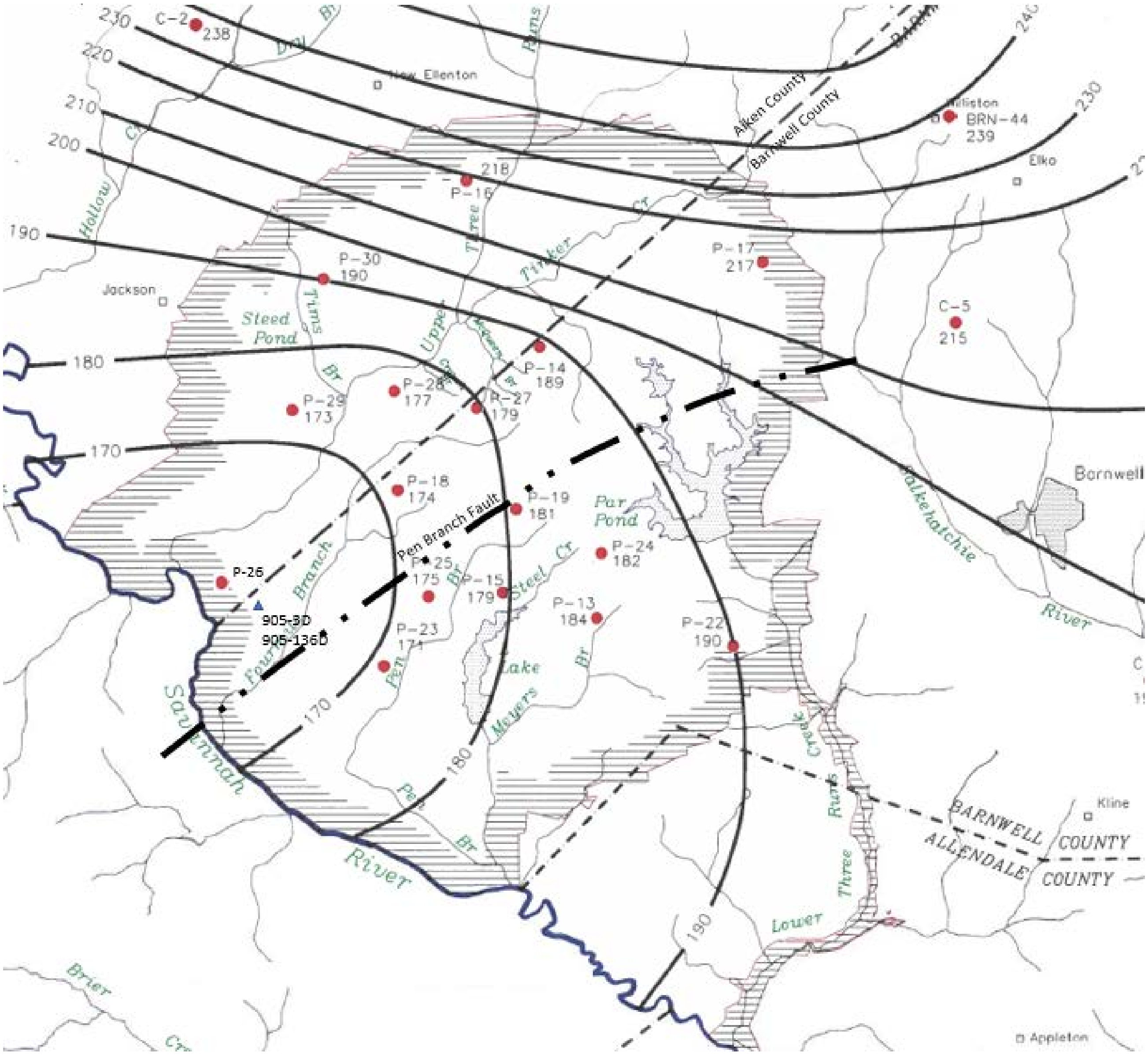

Figure 10: Potentiometric Surface of the McQueen Branch Aquifer Near Production Wells 905-3D and 905-136D (modified from Aadland et al., 1995).

Figure 11: Test Manifold Used for 905-3D.

Figure 12: Test Manifold Used for 905-136D.

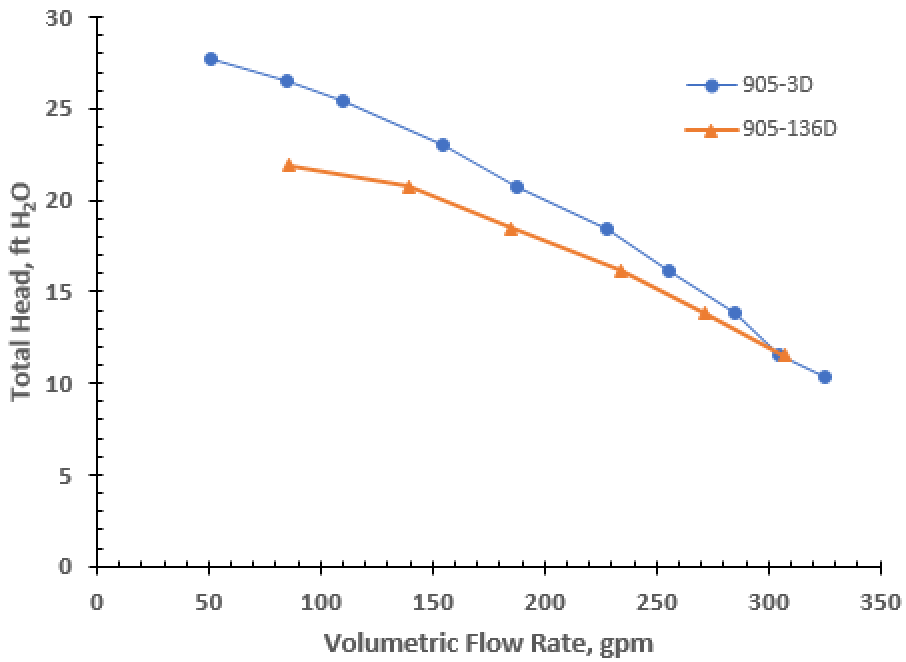

Figure 13: Equivalent "*pump curves*" for supply wells 905-3D and 905-136D.

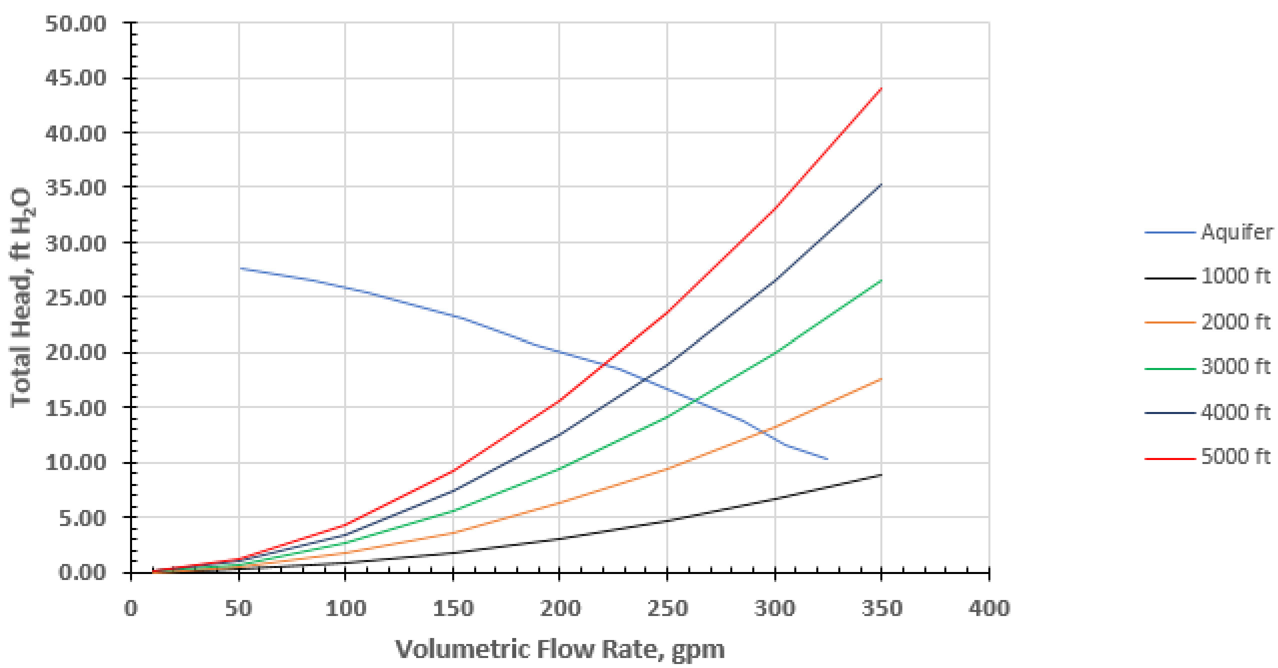

Figure 14. Performance Curve for 905-3D using 6-inch Diameter PVC Pipe.

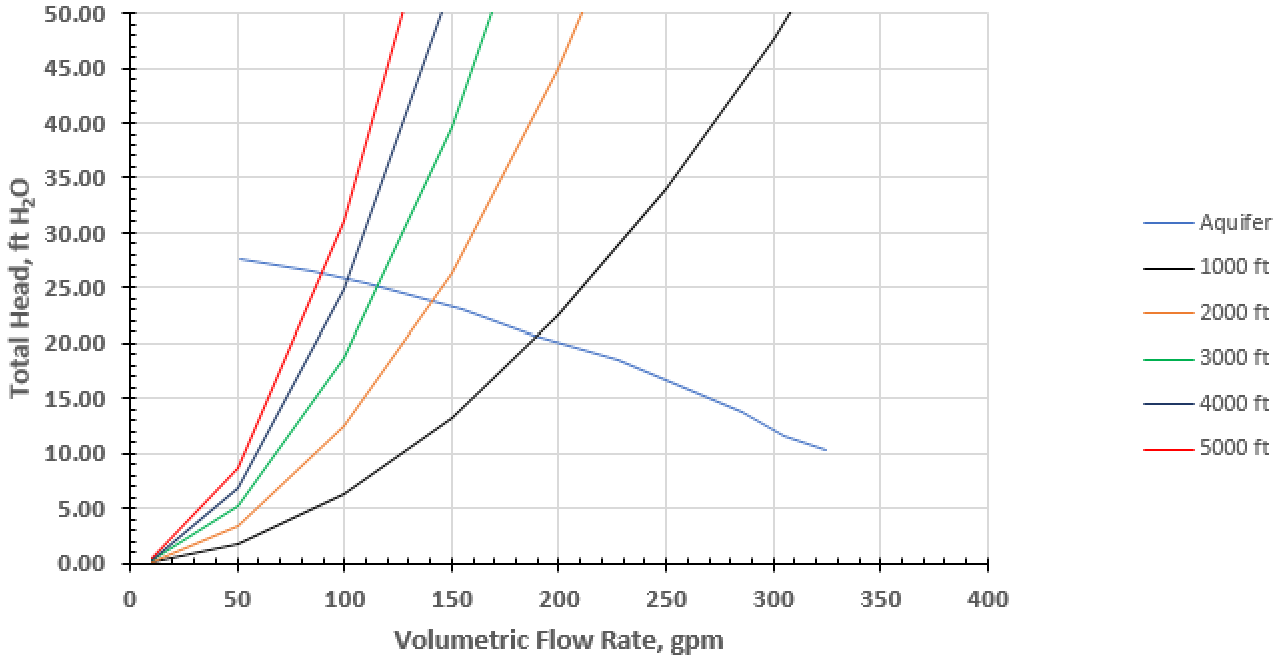

Figure 15. Performance Curve for 905-3D using 4-inch Diameter PVC Pipe.

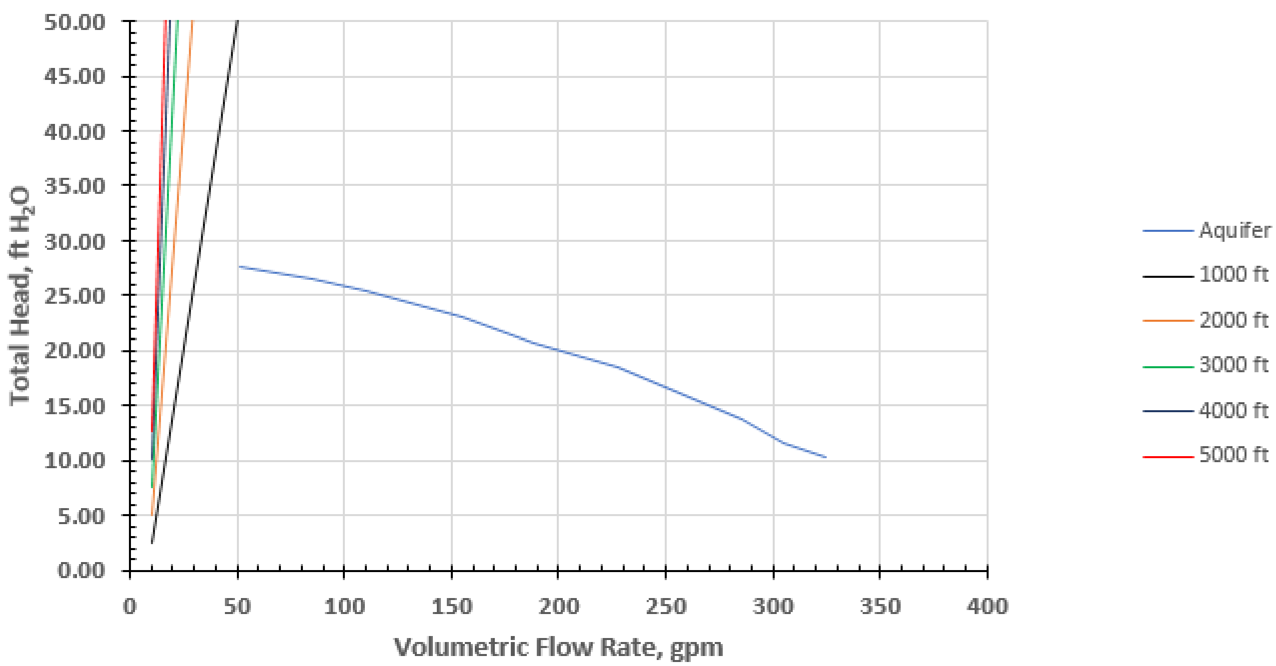

Figure 16. Performance Curve for 905-3D using 2-inch Diameter PVC Pipe.

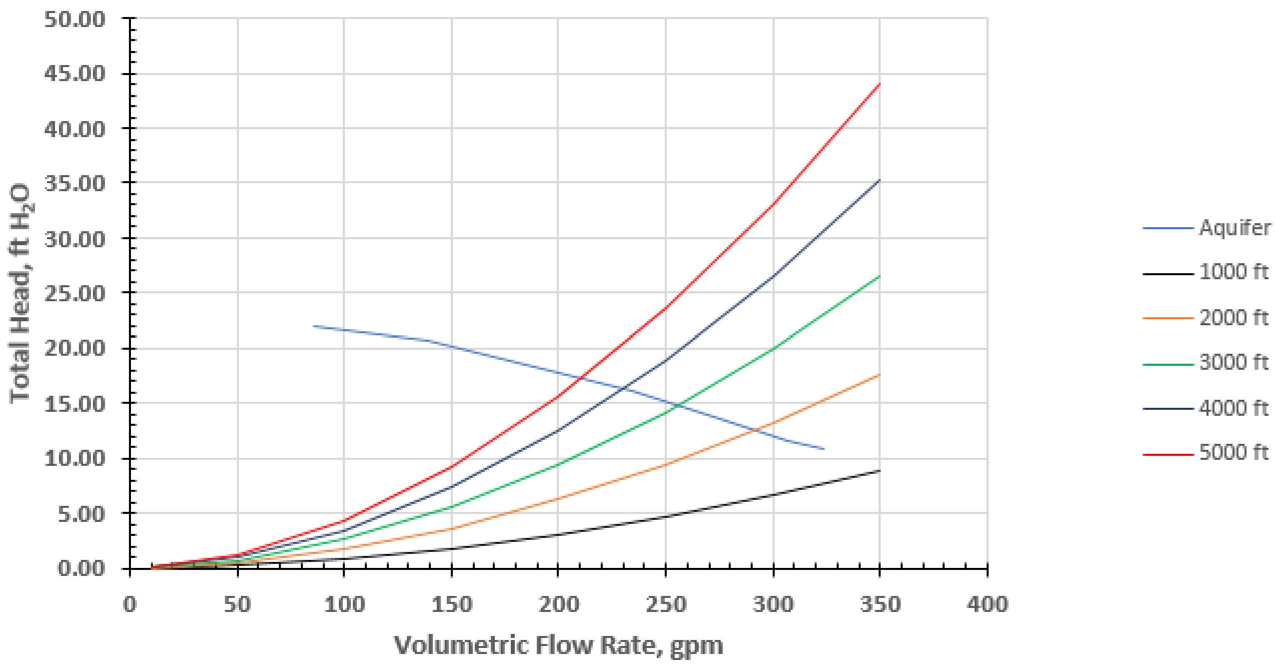

Figure 17. Performance Curve for 905-136D using 6-inch Diameter PVC Pipe.

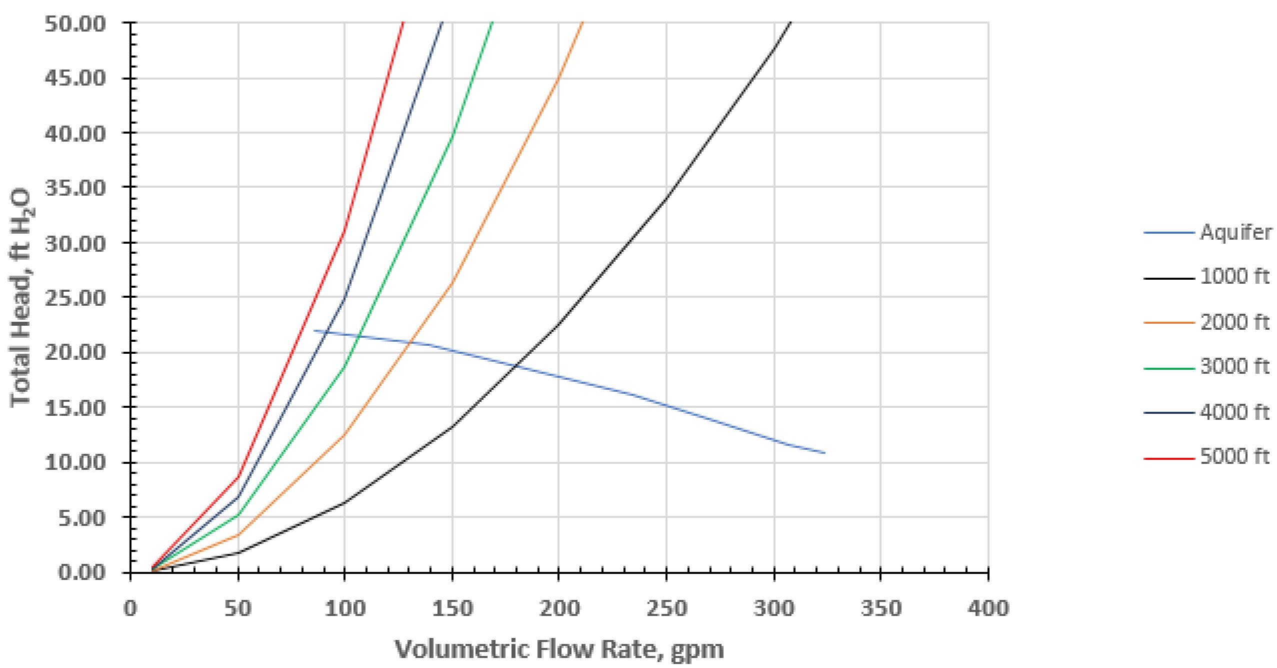

Figure 18. Performance Curve for 905-136D using 4-inch Diameter PVC Pipe.

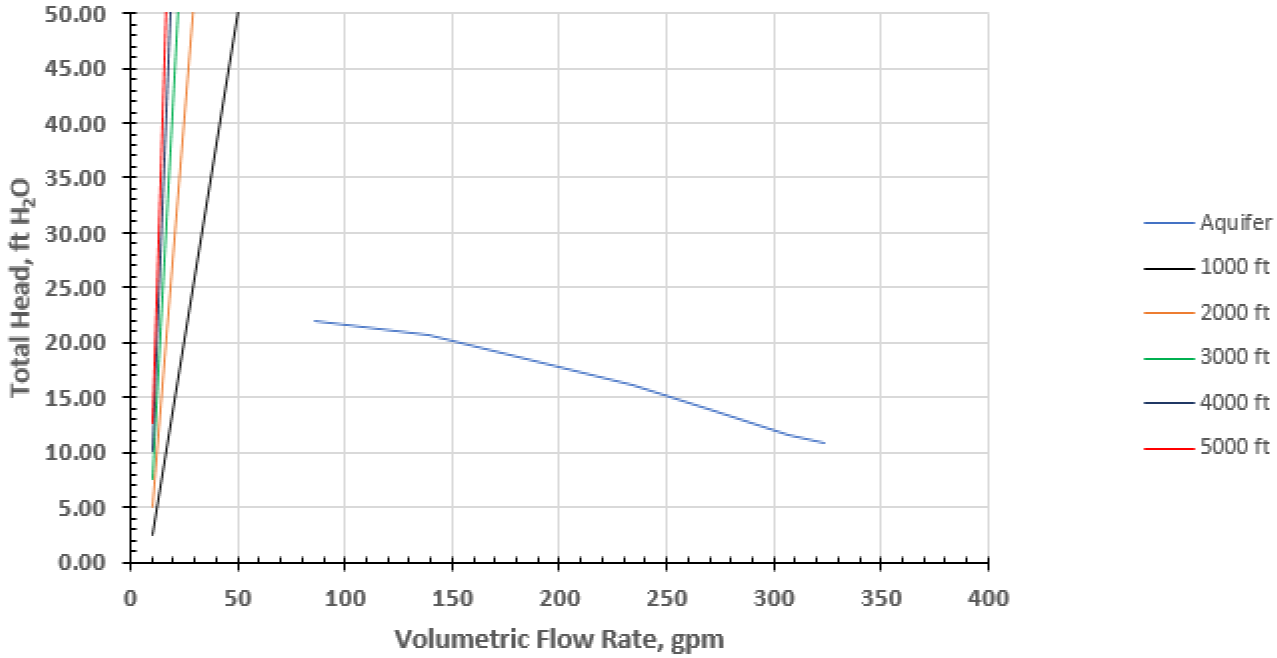

Figure 19. Performance Curve for 905-136D using 2-inch Diameter PVC Pipe.

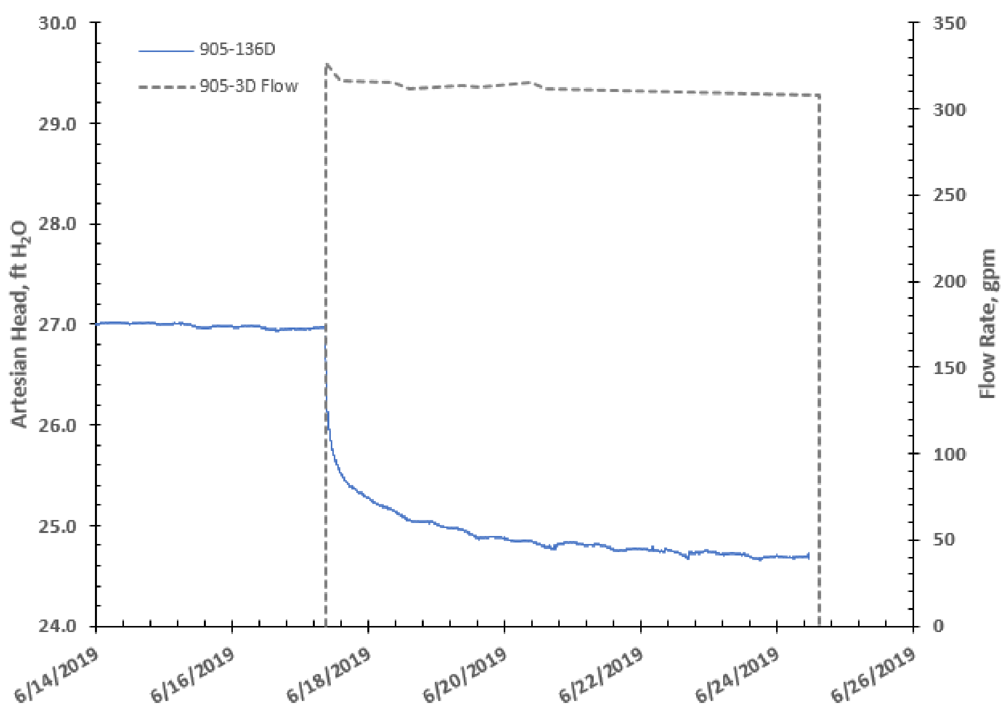

Figure 20. Aquifer Response at 905-136D Due to Withdrawal at 905-3D.

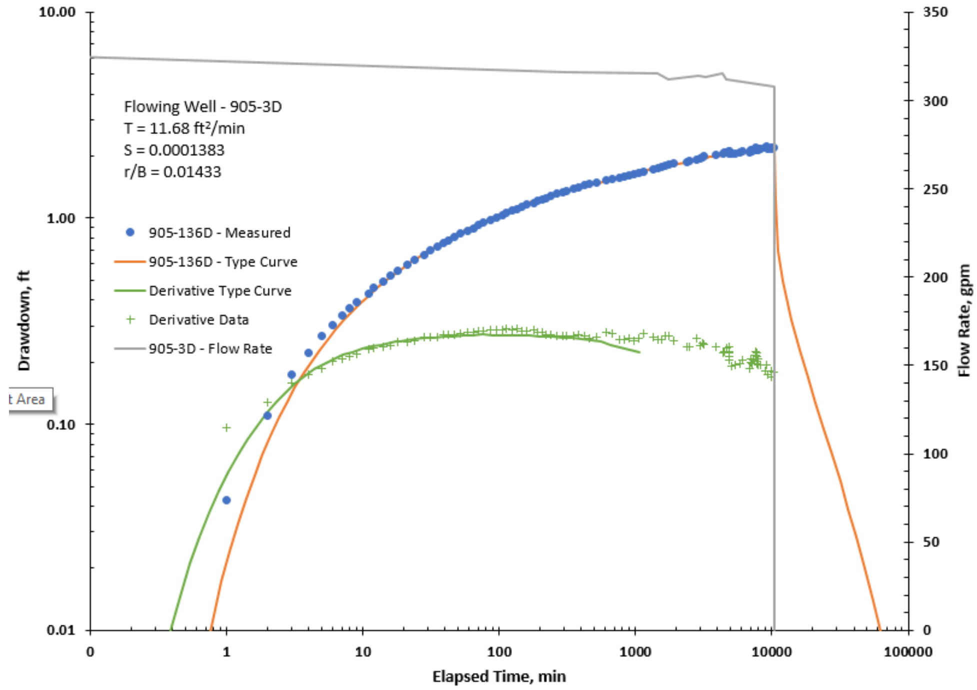

Figure 21. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for 905-136D with 905-3D Flowing.

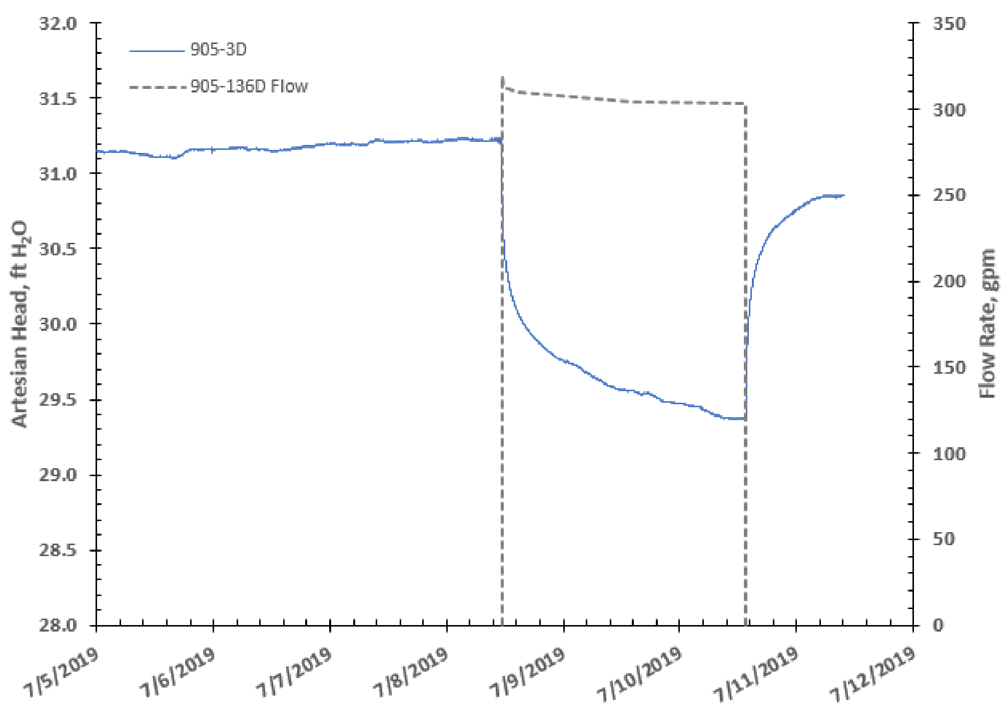

Figure 22. Aquifer Response at 905-3D Due to Withdrawal at 905-136D.

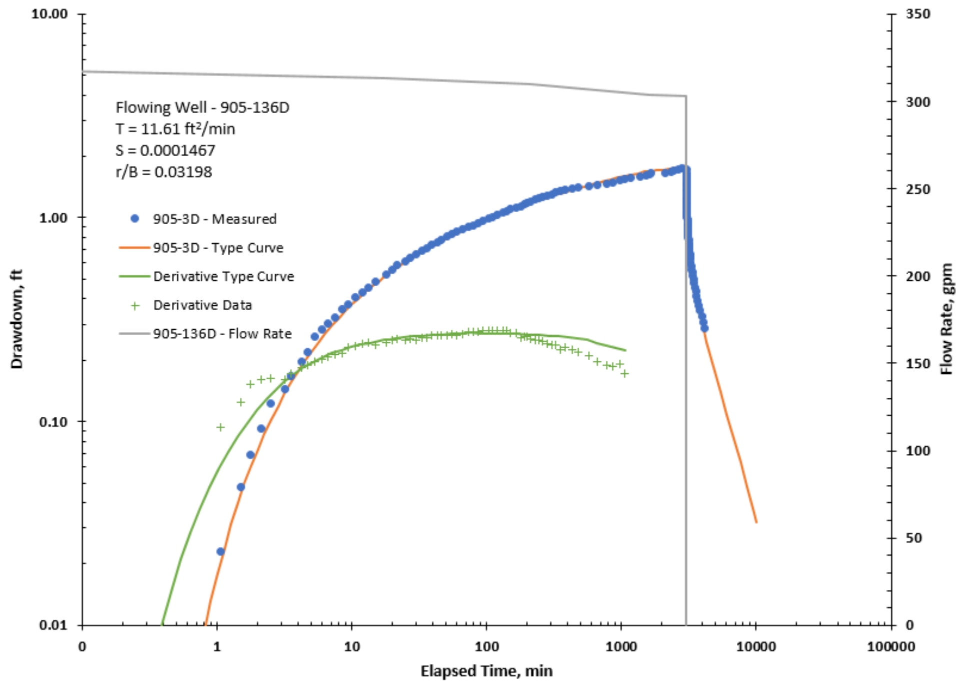

Figure 23. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for 905-3D with 905-136D Flowing.

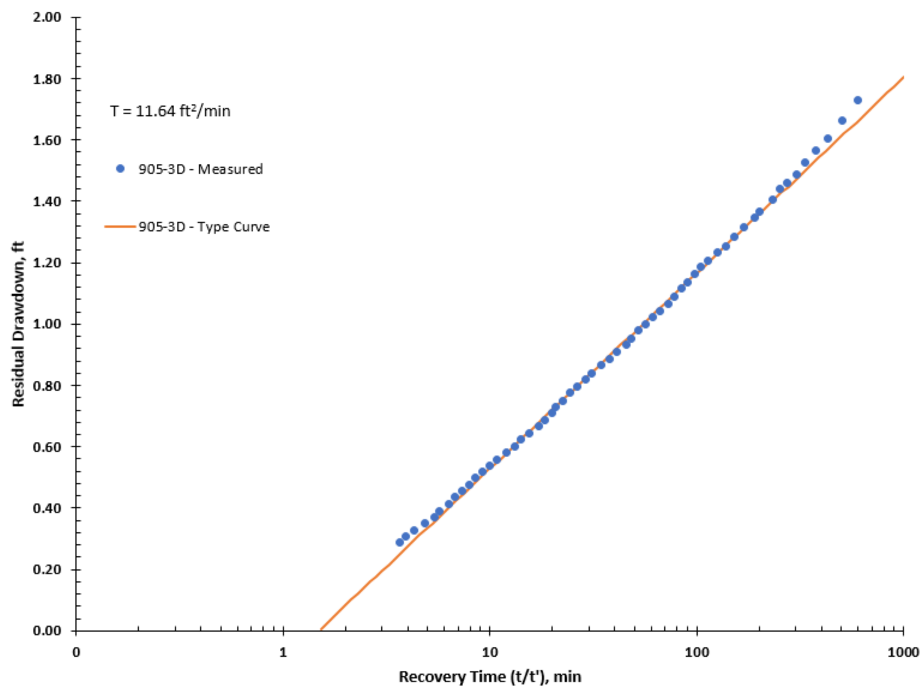

Figure 24. Recovery Data and Theis Recovery Type Curve for 905-3D after Cessation of Pumping at 905-136D Flowing.

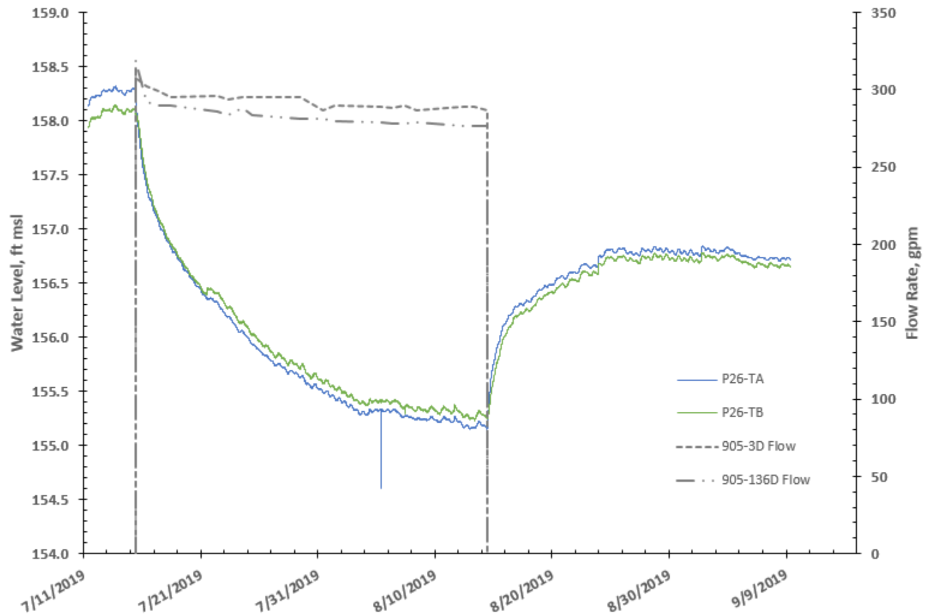

Figure 25. Aquifer Response at P-26TA and P-26TB Due to Withdrawal at 905-3D and 905-136D.

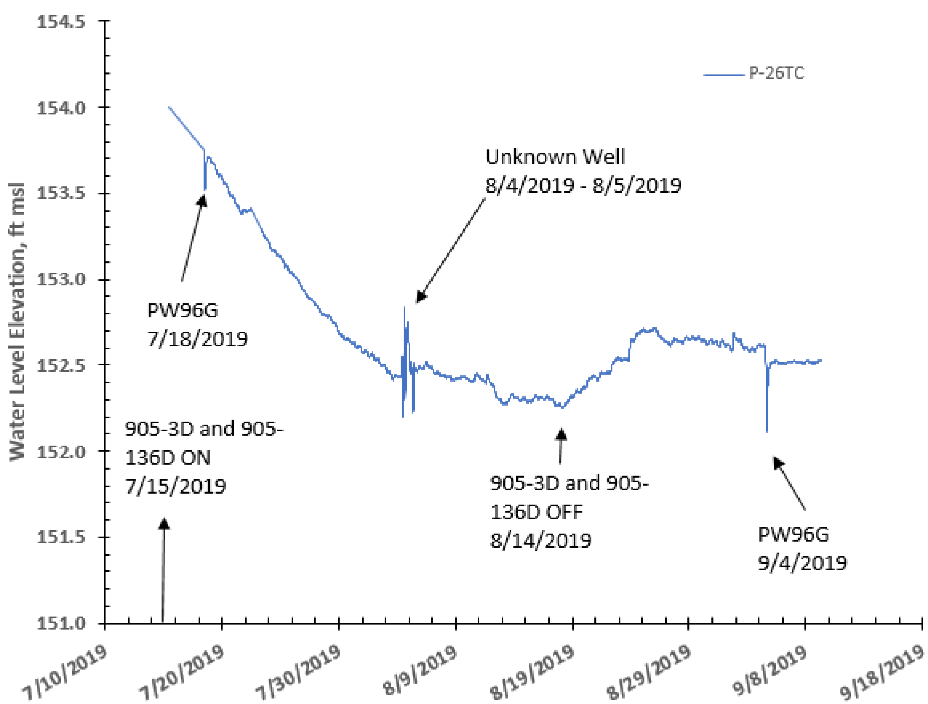

Figure 26. Aquifer Response at P-26TC Due to Withdrawal at 905-3D and 905-136D.

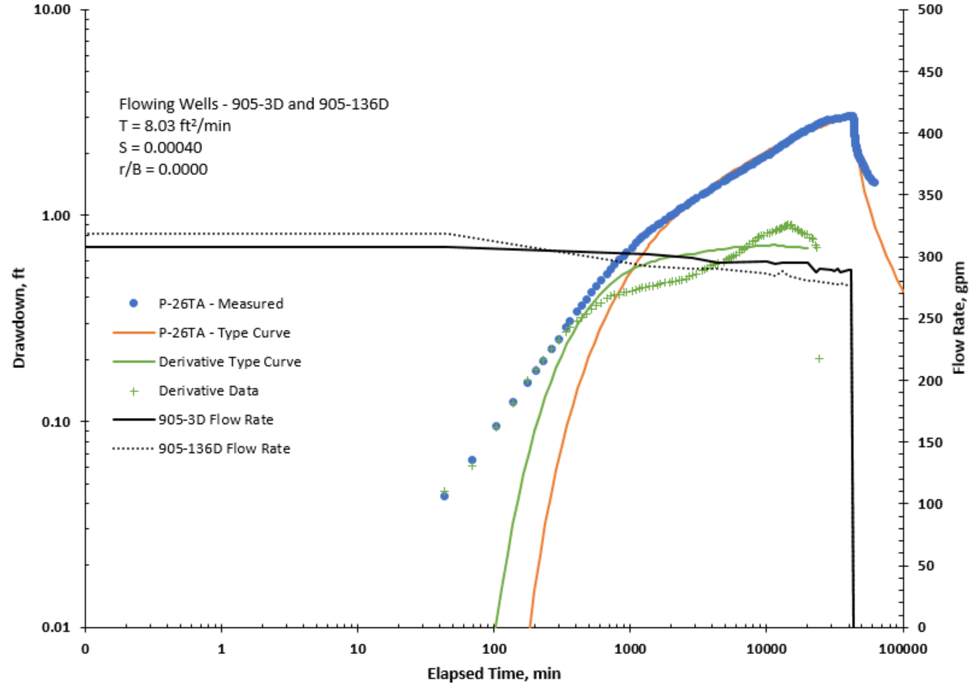

Figure 27. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for P-26TA with 905-3D and 905-136D Flowing.

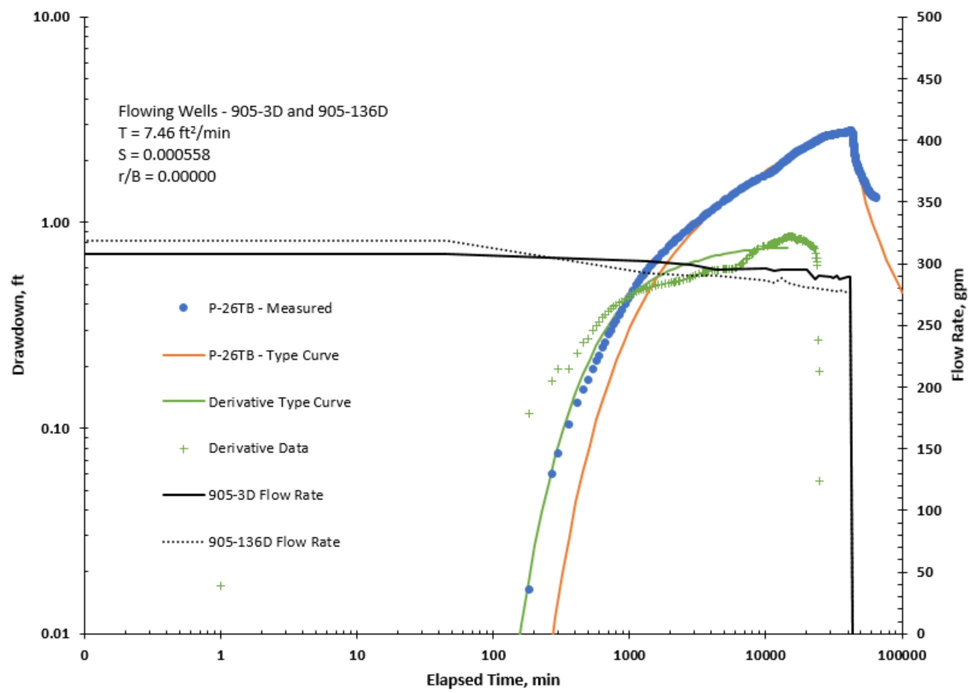

Figure 28. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for P-26TB with 905-3D and 905-136D Flowing.

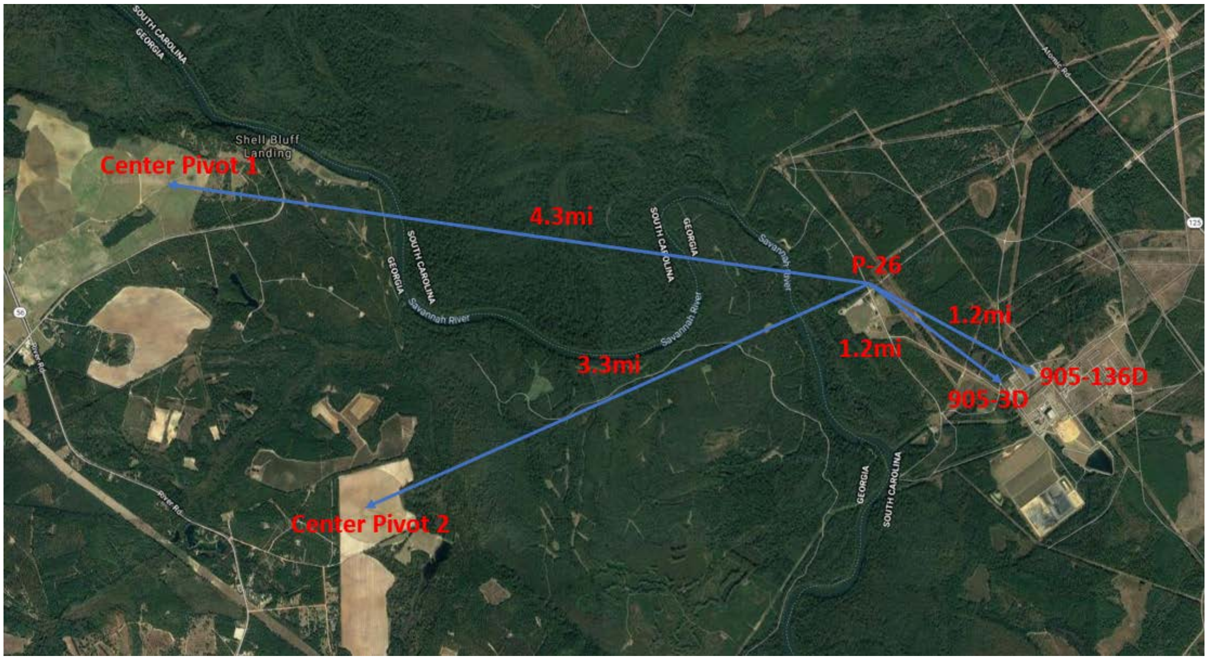

Figure 29. Location of Potential Irrigation Wells.

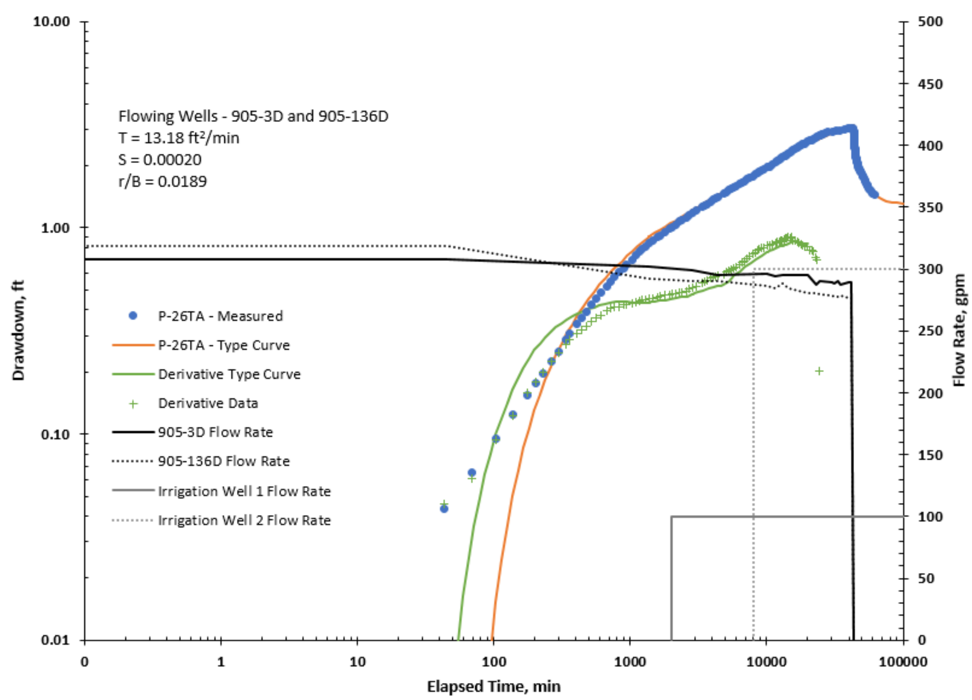

Figure 30. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for P-26TA with 905-3D, 905-136D, and Two Hypothetical Irrigation Wells Flowing.

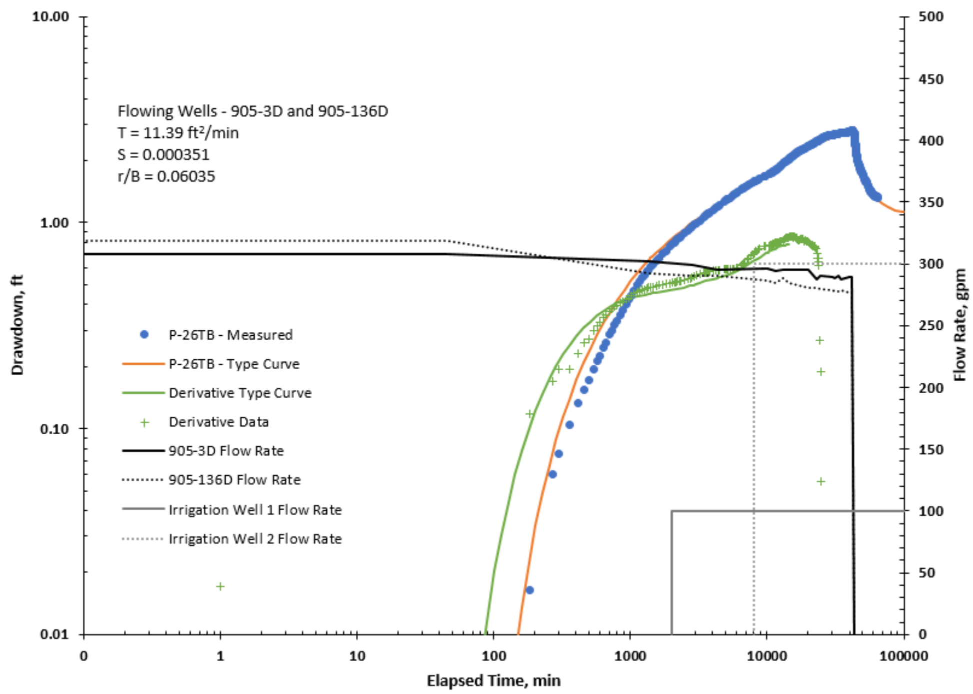

Figure 31. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for P-26TB with 905-3D, 905-136D, and Two Hypothetical Irrigation Wells Flowing.

Table 1 Construction Details for Wells Used in Aquifer Test.

Well Name	Distance from 905-3D (ft)	Diameter (in)	SRS East (ft)	SRS North (ft)	Top of Screen (ft msl)	Bottom of Screen (ft msl)	Top of Screen (ft bgs)	Bottom of Screen (ft bgs)	Total Depth (ft)	Screen Length (ft)
905--3D	0.00	6	19820.0	66150.0	-541.10	-601.10	670.00	730.00	736.00	60
905-136D	769	6	20588.0	66180.0	-507.50	-617.50	640.00	750.00	760.00	110
P-26TA	6072	4	18051.5	71958.6	-527.20	-537.80	679.40	690.00	695.00	11
P-26TB	6084	4	18057.0	71973.4	-372.30	-383.10	524.20	535.00	540.00	11
P-26TC	6092	4	18056.5	71981.6	-222.50	-233.10	374.30	384.90	389.90	11

Table 2: Hydrostratigraphic Data for Wells 905-3D, 905-136D, and P26.

Location	Unit	Unit Thickness (ft)	Transmissive Thickness (ft)	Non-Transmissive Thickness (ft)
905-3D and 136D[1]	McQueen Branch Confining Unit	82	33	49
	McQueen Branch Aquifer	196	176	20
	Appleton Confining System	150	-	-
P-26	McQueen Branch Confining Unit	72	29	43
	McQueen Branch Aquifer	199	179	20
	Appleton Confining System	150	-	-
Average	McQueen Branch Confining Unit	77	31	46
	McQueen Branch Aquifer	198	178	20
	Appleton Confining System	150	-	-

[1]Also referred to as PW-3D and PW-136D

Table 3 Data from flow testing of 905-3D and 905-136D

905-3D		905-136D	
Pressure (ft H_2O)	Flow (gpm)	Pressure (ft H_2O)	Flow (gpm)
27.7	51	21.9	86
26.5	85	20.8	139
25.4	110	18.5	185
23.1	155	16.2	234
20.8	188	13.8	272
18.5	228	11.5	307
16.2	256	11.0	324
13.8	285		
11.5	305		
10.4	325		

Table 4: Relative Well Dimensions Used in AQTESOLV Analysis of Pumping Test Data.

	Distance from 905-3D (ft)	Depth Below MBCU (ft)	Screen Length[1] (ft)	Well Casing Radius (ft)	Effective Radius (ft)
905-3D	0	103.3	60.0	0.25	0.70
905-136D	769	69.7	110.0	0.25	0.71
P-26TA	6072	89.4	10.6	0.17	0.33
P-26TB	6092	0	11.0	0.17	0.33

[1]As determined from BEIDMS well construction information.

Table 5. Hydraulic Properties of the McQueen Branch Aquifer Near Production Wells 905-3D and 905-136D.

Pumping Well	Observation Well	Transmissivity (ft^2/min)	Hydraulic Conductivity (ft/day)[a]	Storativity	r/B	McQueen Branch Confining Unit Hydraulic Conductivity (ft/day)[b]	Leakance (ft/day/ft)
905-3D	905-136D	11.68	94.7	0.00014	0.0143	2.7E-04	5.8E-06
905-136D	905-3D	11.61	94.1	0.00015	0.0320	1.3E-03	2.9E-05
905-3D 905-136D	P-26TA	13.18	106.9	0.00019	0.0189	8.4E-06	1.8E-07
905-3D 905-136D	P-26TB	11.39	92.4	0.00035	0.0604	7.4E-05	1.6E-06
Average		11.97	97.0	0.0002	0.0314	4.2E-04	9.1E-06
Median		11.65	94.4	0.0002	0.0254	3.7E-04	3.7E-06
Standard Deviation		0.82	6.6	0.0001	0.0207	1.3E-04	1.3E-05

[a]Average transmissive thickness = 178 ft
[b]Average non-transmissive thickness = 46 ft

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