Remedial Options for Saltwater Encroachment in the 1,500-Foot Sand

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Prepared by
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Bloomington, Indiana

REMEDIAL OPTIONS FOR SALTWATER ENCROACHMENT IN THE 1,500-FOOT SAND

FINAL PROJECT REPORT

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About the Authors

Rhett Moore is a professional hydrologist with expertise in hydrologic investigations for resource assessments, water-supply development and planning, and wellfield design and optimization. Rhett applies analytical and numerical models with his field expertise to solve groundwater and surface-water problems. He has used groundwater flow models for projects involving water-supply management and development and surface water models for TMDL development. He has also performed aquifer tests, supervised well installations, and collected and evaluated hydrologic data from operating well fields to assess system performance.

After obtaining his Bachelor's degree from the University of Tennessee in Engineering and his Master's degree at Indiana University in Environmental Science, Rhett worked for 8 years with the U. S. Geological Survey on basin-scale water-quality assessments as part of the National Water Quality Assessment Program (NAWQA). Rhett has planned and managed large and small-scale hydrologic field monitoring investigations, installed monitoring networks, and collected thousands of water-quality samples. He has validated and managed large water-quality datasets for RCRA programs and assessed the quality of receiving waters for NPDES purposes. Rhett is also a licensed water-well driller and has used that expertise in groundwater resource assessments.

Dr. Victor Kelson is a certified groundwater professional and one of the leading developers of hydrological modeling tools and codes in the United States. He has written groundwater modeling code for the USEPA, tools for pre and postprocessing South Florida Water Management District's regional simulation model (RSM) and he has developed other tools that are now embedded in the commercial Groundwater Management System (GMS) developed by Environmental Modeling Systems, Incorporated. Dr. Kelson, along with his colleague Dr. Mark Bakker, is a co-inventor of a new technique for modeling the effects of radial collector wells on groundwater flow.

Prior to becoming a Chief Modeler at Layne Hydro, Vic worked for two years as a Senior Engineer in the Hydrologic Systems Modeling Division at the South Florida Water Management District. While in Florida, Vic was primarily responsible for groundwater model code development including methods for integrating the results of surface water and groundwater flow models. At Layne Hydro, Vic is responsible for managing the development of modeling and data management tools for application to water resources planning. Over the past decade Dr. Kelson has been involved in some of the largest hydrologic analysis arguments in the country, including the restoration of the Everglades ecosystem, the Crandon Mine (in Wisconsin).

Dr. Erik Anderson is a professional engineer with BS and MS degrees in Civil and Environmental Engineering from the University of Wisconsin-Madison, and a Ph.D. in Civil Engineering from the University of Minnesota. He has worked as a design engineer/consultant in Wisconsin and Minnesota, and as an assistant professor of Civil Engineering at the University of South Carolina.

As a consulting engineer, he has worked for 19 years on numerous water resources projects. His work has included dam design and rehabilitation, surface water modeling including dam-failure analyses and flood studies, regional groundwater flow modeling for water supply and availability studies and wellhead protection studies, seepage studies, and large scale dewatering design.

At the University of South Carolina, Erik conducted research in groundwater hydraulics and developed and taught courses in dynamics, fluid mechanics, numerical methods for engineers, groundwater mechanics, and hydrodynamics. His research has focused on analytical modeling of groundwater-surface water interaction, and developing tools to incorporate three-dimensional effects in two-dimensional, numerical models of groundwater flow. He has developed analytical tools for addressing groundwater flow problems with leaky boundaries and internal boundaries. The methods have been applied to solve problems of flow to clogged streambeds, pumping wells near partially-penetrating streams, and flow in faulted, single and multiple aquifer systems.

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1 Introduction

The Baton Rouge Water Company (BRWC) relies on wells that pump water from the 1,500-Foot sand aquifer (1,500-Foot sand) beneath Baton Rouge, which is a major source of fresh groundwater for the Baton Rouge area. Historic pumping from the aquifer has caused leakage of saline water across the Baton Rouge Fault and into the aquifer. Saline water was first detected in the 1,500-Foot sand north of the fault in 1965. Since then, a saltwater plume has migrated into the aquifer between the fault and three BRWC pumping stations with wells screened in the 1,500-Foot sand: the Government Street Station, the North 45$^{\text{th}}$ Street Station, and the Lula Avenue Station.

Recent increases in the background chloride concentration observed at the Lula Station are of particular concern. Chloride concentrations in Lula wells have increased from a background concentration of approximately 3 milligrams per liter (mg/L) to as high as 180 mg/L. The Lula Station is an integral source of supply for the utility, pumping an average of 10.9 million gallons per day (mgd) between 2000 and 2009 from five wells screened in the 1,500-Foot sand. During this period, an additional 3.6 mgd was pumped from wells screened in the 1,500-Foot sand at the Government Station (two wells) and the North 45$^{\text{th}}$ Station (one well).

This report presents results from an investigation of options for controlling saltwater encroachment in the 1,500-Foot sand between the fault and the BRWC pumping stations.

2 Objectives

Given the current understanding of saltwater encroachment in the 1,500-Foot sand, it is anticipated that chloride levels in the Lula wells will continue to rise and could soon be approaching the USEPA drinking-water standard of 250 mg/L. The primary objective of BRWC is to control and mitigate saltwater encroachment in the 1,500-Foot sand between the fault and BRWC wells so that drinking-water standards can be met into the foreseeable future. The objectives of this investigation were to collect new field data for characterizing the aquifer and the saltwater plume and to investigate engineering approaches for extending the life of BRWC stations. Specific objectives of this investigation were:

- define the vertical distribution of chlorides in the 1,500-Foot sand near the Lula Station by observing Lula Well 19 during active pumping,
- characterize the stratigraphy of the 1,500-Foot sand between the Lula Station and the fault,
- define the vertical extent and distribution of chlorides in the 1,500-Foot sand between the Lula Station and the fault,

- evaluate engineering options for controlling and mitigating saltwater encroachment in the 1,500-Foot sand, and
- recommend a course of action for extending the life of BRWC stations pumping from the 1,500-Foot sand.

3 Approach

To meet the study objectives, we took the following steps in evaluating remedial alternatives:

- Collected, reviewed, and assessed the existing data for the 1,500-Foot sand. Results from this step included the development of a conceptual model for groundwater flow and saltwater encroachment in the 1,500-Foot sand.
- Conducted field testing at Lula Well 19 to provide new information and refine the conceptual model.
- Installed and tested an observation well in Progress Park to provide new information and refine the conceptual model.
- Developed a regional groundwater flow model to include available hydrologic data within a single framework and calibrated the model to existing data.
- Used the groundwater flow model as a predictive tool for initial assessment of remedial options and to aid in design of field testing.
- Conducted final predictive modeling using the groundwater flow model as a design tool for the hydraulic design of a remedial system.

The results of these steps are presented in the following sections of this report.

4 Assessment of Existing Data

Our understanding of the 1,500-Foot sand and the occurrence of saltwater in the aquifer as it relates to the BRWC supply wells is based on review and analysis of existing information. Figure 1 shows the area of interest, including portions of five parishes (East Baton Rouge, West Baton Rouge, East Feliciana, West Feliciana, and Pointe Coupee). Features of interest are shown for reference, including the Baton Rouge Fault, wells that are in the USGS Chloride Monitoring Network, and the BRWC pumping stations.

4.1 Geologic Setting

Underlying the Baton Rouge area is a complex system of interconnected sand layers that are part of the Coastal Lowlands Aquifer System. The aquifer system is formed by a wedge of sediment that thickens towards the coast and consists of alternating beds of sand, gravel, silt, and clay (Weiss, 1992) (Figure 2). The sediments, deposited under fluvial, deltaic, and marine conditions, are very heterogenous. Changes in lithology occur over short distances laterally and vertically (Martin and Whiteman, 1999). Generally, the aquifer system consists of massive sand beds separated by clay layers.

The sand layers were historically named as aquifers by Meyer and Turcan (1955) according to their depth below ground surface in the industrial area, with the 1,500-Foot sand being the aquifer of interest in this study (Figure 2). In Mississippi, the aquifers subcrop beneath unconsolidated sediments and dip toward the Baton Rouge Fault in the south at an average of 50 ft per mile (Huntzinger et al., 1985). Aquifer sands north of the fault provide the principal supply of freshwater for the Baton Rouge area. South of the fault, most of the sand layers are contaminated with saltwater.

4.2 Baton Rouge Fault

The Baton Rouge Fault is an active east-west striking fault which lies approximately 2.5 miles south of the Lula Station (Figure 1). The fault is a listric normal fault that dips toward the Gulf Coast Basin to the south and shows little change in displacement over large depth intervals (5,000-10,000 ft) (McCulloh, 1991). Vertical displacement of 300 ft or more has occurred below a depth of about 1,000 ft. The fault is known to be active, but does not produce earthquakes. The geometry and interconnectedness of the individual sand layers in the system is difficult to interpret from boring logs or pumping tests. As illustrated on Figure 2, the Baton Rouge Fault has juxtaposed aquifer layers to the north with either clay layers or other sand layers to the south. At the fault, there is at least 40 ft of overlap between the 1,500-Foot sand north of the fault and the 1,200-Foot sand south of the fault (Whiteman, 1979).

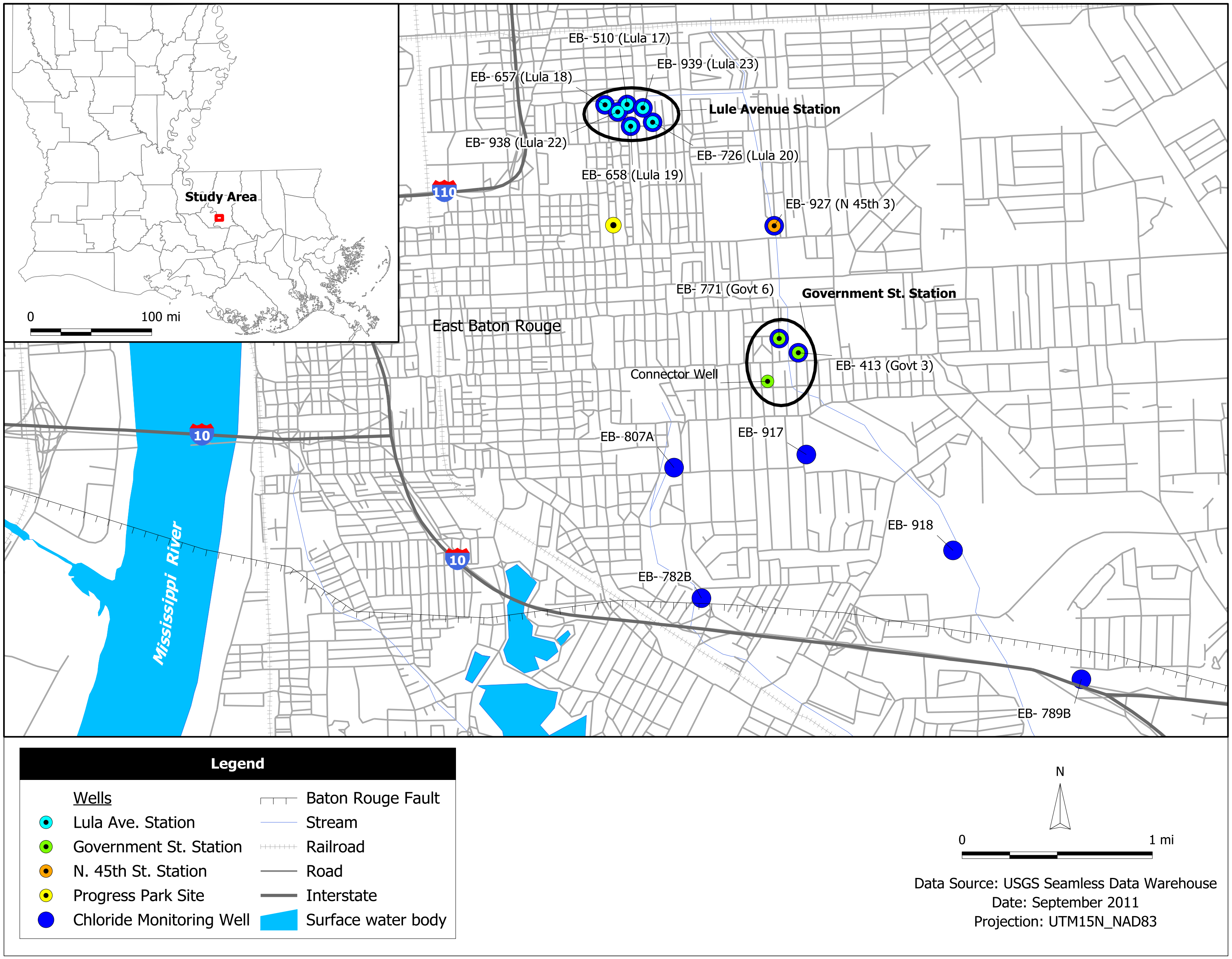


Figure 1: Location map showing the area of interest.

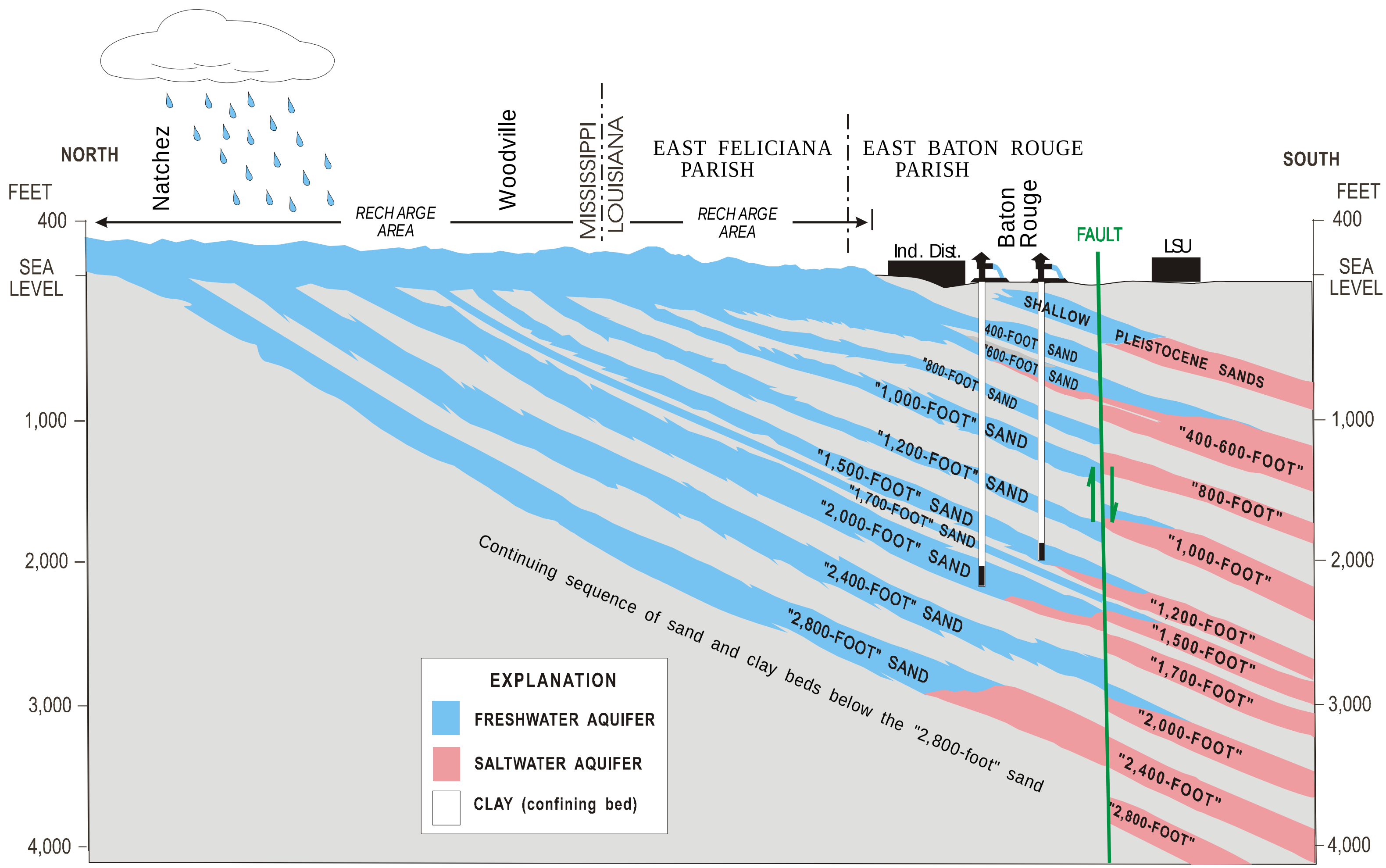


Figure 2: Conceptual sketch of the aquifer system in a north-south cross section (Tomaszewski, 1996).

Little is known about the hydraulic properties of the Baton Rouge Fault, but based on water levels and the observed distribution of chlorides in the various sand layers, the fault is assumed to be a leaky barrier to horizontal flow of groundwater across the fault, and therefore, a barrier to the transport of chlorides from the south to the north. Groundwater flowing from one layer to another through a leaky barrier is restricted with the leakage rate through the barrier being proportional to the head gradient between the two layers. Due to the nature of fault mechanics, the hydraulic properties of the Baton Rouge Fault are certainly highly heterogeneous and anisotropic and cannot be quantified without detailed field testing.

4.3 The Denham Springs–Scotlandville Fault

The Denham Springs–Scotlandville Fault lies approximately 3.5 miles north of the Lula Station. Like the Baton Rouge Fault, the Denham Springs–Scotlandville Fault is east-west striking and known to be active based on damage to structures that has occurred due to subsidence at the fault. Unlike the Baton Rouge Fault, the vertical offset between the downthrown and upthrown sides of the Denham Springs–Scotlandville Fault is small. Observed displacement is a consistent 40-50 ft to a depth of 10,000 ft (McCulloh, 1991).

Existing evidence suggests that impacts from the Denham Springs–Scotlandville Fault on the hydraulics of groundwater flow in the 1,500-Foot sand are minor in comparison to the pronounced effects of the Baton Rouge Fault. The potential offset does not appear to be significant enough to juxtapose aquifer layers against clay layers, which would impede flow in some aquifers. USGS mapping of the regional piezometric contours in the 1,200-Foot, 1,500-Foot, and 1,700-Foot sands shows no hydraulic effects due to the presence of the Denham Springs–Scotlandville Fault (Griffith and Lovelace, 2003b,a; Prakken, 2004). There is also no evidence of the fault acting as a conduit for flow along the fault plane, although this is difficult to detect based on observed heads on either side of the fault. Because the hydraulic effects of the Denham Springs–Scotlandville Fault are minor, we have not included it in our analysis of flow in the 1,500-Foot sand.

4.4 1,500-Foot sand

The 1,500-Foot sand is part of the Evangeline Equivalent Aquifer System, which is a regionally extensive aquifer system of Pliocene and Miocene age (Weiss, 1992). The Evangeline Equivalent Aquifer System is part of the Southern Hills Regional Aquifer System of Southeastern Louisiana (Griffith, 2003). The 1,500-Foot sand consists of braided channels of porous materials with variable base and top elevations and is known to be divided by clay layers in some locations, joined with the underlying 1,700-Foot sand in some locations, and nonexistent in other locations (Griffith, 2003).

Regionally, we know little about the geometry of the 1,500-Foot sand, particularly between the Lula Station and EB-807A and west of EB-807A (Figure 1).

Additionally, there has been little field testing of the physical properties of the 1,500-Foot sand, including the hydraulic conductivity and the vertical anisotropy, which have great bearing on the feasibility and potential success of any mitigation system. Aquifer properties cited in the literature (Whiteman, 1979; Tomaszewski, 1996; Huntzinger et al., 1985; Williamson et al., 1990; Griffith, 2003; Rollo, 1969) typically refer to a few pumping tests conducted over 50 years ago (Meyer and Turcan, 1955; Morgan, 1961), and the original test data is not available for review.

4.4.1 Pumping trends in the 1,500-Foot sand

Annual withdrawals from the 1,500-Foot sand were summarized by Griffith and Lovelace (2003b) for the period of record (Figure 3). For the Baton Rouge area, including the parishes of East and West Baton Rouge, East and West Feliciana, and Pointe Coupee, average withdrawals increased dramatically from 5 mgd in 1952 to 16 mgd in 1975. Pumping rates were maintained near the 1975 levels until 1988 when production increased to 18.5 mgd, continuing at high levels from 18 to 19.5 mgd until 1995, and then decreasing to 17.8 mgd in 2001.

Since 1975, the Capital Area Ground Water Conservation Commission (CAGWCC) has maintained records of withdrawals from the 1,500-Foot sand from both industrial and public water supply users. Recent CAGWCC records indicate near-record pumping rates of 19.1 mgd in 2009, with most of the pumping occurring in East Baton Rouge Parish (15.5 mgd) (CAGWCC, 2011). The increasing trend in pumping rates has resulted in decreasing water levels in the 1,500-Foot sand near the pumping centers, as illustrated in Figure 3 for well EB-168, which lies approximately 2 miles north of the Lula Station. The growing cone of depression centered around the Lula Station has exacerbated the problem of saline water crossing the Baton Rouge Fault and entering the 1,500-Foot sand and increased the speed of northward encroachment.

4.4.2 Pumping withdrawals by industry

Total withdrawal from the 1,500-Foot sand fluctuated between approximately 14 and 19.5 mgd from 1975 to 2001 (Figure 3). During this period, industrial pumping was responsible for 17 to 26 percent of the total withdrawals from the aquifer. Most of the total withdrawal from the 1,500-Foot sand occurs in East Baton Rouge Parish. Recent data from East Baton Rouge Parish shows that industrial pumpage from the 1,500-Foot sand in 2009 and 2010 was approximately 16-19% (Table 1) (CAGWCC, 2011).

The 1,700-Foot sand is joined with the underlying 1,700-Foot sand in some locations and is considered to be hydraulically connected to the 1,500-Foot sand in the industrial area north of the

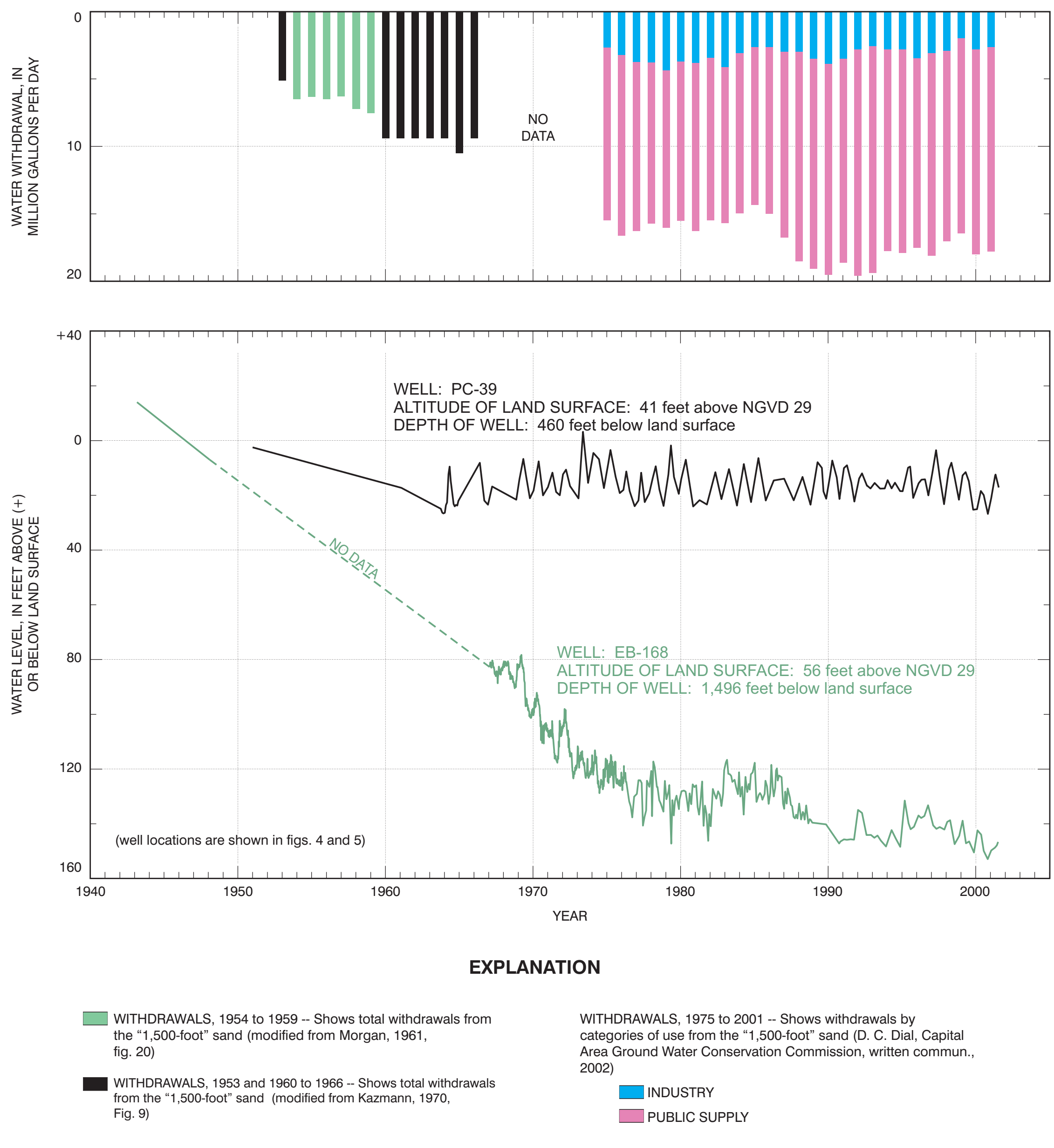


Figure 3: Pumping trends and water-level trends in the 1,500-Foot sand, 1973-2001 (Griffith and Lovelace, 2003b).

Table 1: Pumpage by use from the 1,500-Foot and 1,700-foot sands in East Baton Rouge Parish, 2009 and 2010 (CAGWCC, 2011).

	2009				2010			
Aquifer	Industrial (mgd)	Public Supply (mgd)	Total (mgd)	Industrial Fraction ($\%$)	Industrial (mgd)	Public Supply (mgd)	Total (mgd)	Industrial Fraction ($\%$)
1,500-Foot sand	2.958	12.517	15.475	19.1	2.129	11.388	13.517	15.8
1,500/1,700-Foot sand	8.327	0	8.776	100	8.776	0	8.776	100
1,700-Foot sand	1.545	4.753	6.298	24.5	1.936	4.728	6.664	29.1
Total	12.830	17.270	30.546	42.0	12.841	16.116	28.957	44.3

Note. mgd=million gallons per day

Lula Station (discussed in more detail in Sections 6.2.5 and 7.5). The CAGWCC reports substantial pumping from the 1,500/1,700-Foot sand and the 1,700-Foot sand in East Baton Rouge Parish (Table 1). The wells classified as pumping from the 1,500/1,700-Foot sand are classified as such because the specific screened interval is unknown or because the well is known to be screened in both sand layers. The CAGWCC reports substantial industrial pumping (>8 mgd) from the 1,500/1,700-Foot sand in East Baton Rouge Parish in 2009 and 2010 (Table 1). This pumpage is concentrated in the industrial area. The CAGWCC also reports approximately 1.5 to 2 mgd being pumped from the 1,700-Foot sand in the industrial area in 2009 and 2010 (CAGWCC, 2011). The total industrial pumpage from the 1,500-Foot and 1,700-Foot sands in East Baton Rouge Parish in 2009 and 2010 was greater than 40% of the total pumpage of approximately 30 mgd (Table 1).

4.4.3 Saltwater encroachment in the 1,500-Foot sand

Rollo (1969) first detected saline water in the 1,500-Foot sand north of the fault in 1965. Based on the geometry of the fault, observed hydraulic gradients, and geochemical signatures of the groundwater, Whiteman (1979) concluded that the source of saline water in the 1,500-Foot sand north of the fault is the 1,200-Foot sand south of the fault. There is at least 40 ft of overlap between the section of the 1,500-Foot sand where encroachment has been observed and the downthrown 1,200-Foot sand south of the fault is known to contain saltwater. The two sand zones are hydraulically connected; water levels in the 1,200-Foot sand south of the fault respond to water-level changes in the 1,500-Foot sand north of the fault (Whiteman, 1979). However, the magnitude and timing of the response in the 1,200-Foot sand and differences in static water levels between the two zones suggest that the fault acts as a leaky barrier to movement of saltwater across it. Similarities in water-quality characteristics between the two aquifers adjacent to the fault suggest that saltwater observed in the 1,500-Foot sand originated in the 1,200-Foot sand (Whiteman, 1979).

The fault has been described as a potential conduit for the vertical flow of groundwater and transport of chlorides within it (Bense and Person, 2006). With this conceptual model, the source of saltwater encroachment in the 1,500-Foot sand could be sands layers south of the fault other than the 1,200-Foot sand. Based on isotope ratios, Stoessell and Prochaska (2005) hypothesize that saltwater in the aquifers north of fault has migrated up fault planes from deeper, older halite formations. Windeborn and Hanor (2009) agree that the source may be older halite formations, but believe that the brine has migrated upward through fractures associated with salt domes south of the Baton Rouge Fault and migrated along the shallower Miocene sand layers to the fault. This conceptual model is supported by the spatial variability of salinity (calculated from logs) across the fault and the fact that highest chloride concentrations occur at mid-depth in the aquifer system (1,500-2,000-Foot sands) rather than at the base (Windeborn and Hanor, 2009).

When dense saline water moves through an aquifer, it does not simply migrate as a "plug" that saturates the entire aquifer thickness. If the saltwater is sufficiently concentrated, freshwater that is moving within the aquifer floats on top of the salt, with the thickness of salt increasing near the source of saltwater. In the 1,500-Foot sand, the "tongue" of saltwater that moves along the aquifer bottom arrives at wells much sooner than the bulk of the saline water that is encroaching from the south. In addition, the conditions along the interface between saltwater and freshwater may lead to a transition zone between salt and freshwater. As a result, a well that is becoming saline will exhibit a gradual increase in salt concentration.

The Chloride Monitoring Network provides little information regarding the thickness of or the concentrations in the saltwater tongue. However, the monitoring program has been helpful in tracking the general movement of the saltwater front in the 1,500-Foot sand through time. Figure 4 shows the observed chloride concentrations in select wells with time. The results from observation wells and production wells are separated because the different well types provide samples at different locations within the aquifer. The monitoring wells were constructed with short screens located at either the bottom of the aquifer where the denser saline water is observed or at the saltwater-freshwater interface that was present at the time of installation (Lovelace, 2010). The production well samples are a composite of aquifer water, integrated from a screen that is open to most of the vertical section of the aquifer.

Because of the sparsity of data points and the different types of wells in the network, the areal extent of the saltwater tongue and the vertical distribution of saline water in the aquifer are poorly understood. Figure 5 shows the inferred shape of the saltwater tongue through time along with the location of observation wells and supply wells used to assess saltwater encroachment in the 1,500-Foot sand. There are no observation points west of EB-807A and no observation points between EB-807A and the Lula Station. Further, the period of record for EB-807A ends in 1996 due to well failure, leaving a 15 year gap in the record. EB-807A is screened at the bottom of the aquifer, and the chloride concentration in it has steadily increased from a background concentration in 1970 to about 3,000 mg/L in 1990 to about 4,000 mg/L in 1996 when the period of record for this well terminates. It is unknown if the concentration in this well has increased since 1996. We also don't know if the front remains this concentrated or if it disperses as it travels toward the Lula Station. However, we can conclude that saline water with chloride concentration of at least 3,000 mg/L was moving past EB-807A at least 20 years ago.

4.5 Connector Well

The connector well, installed in 1998 by CAGWCC to test the concept of a recharge barrier to mitigate saltwater encroachment in the 1,500-Foot sand, reportedly moves about 500 gpm from the 800-Foot sand to the 1,500-Foot sand. Water-quality results show that chloride concentrations in Well 3 at the Government Station have not increased as much or as quickly as observed at the Lula

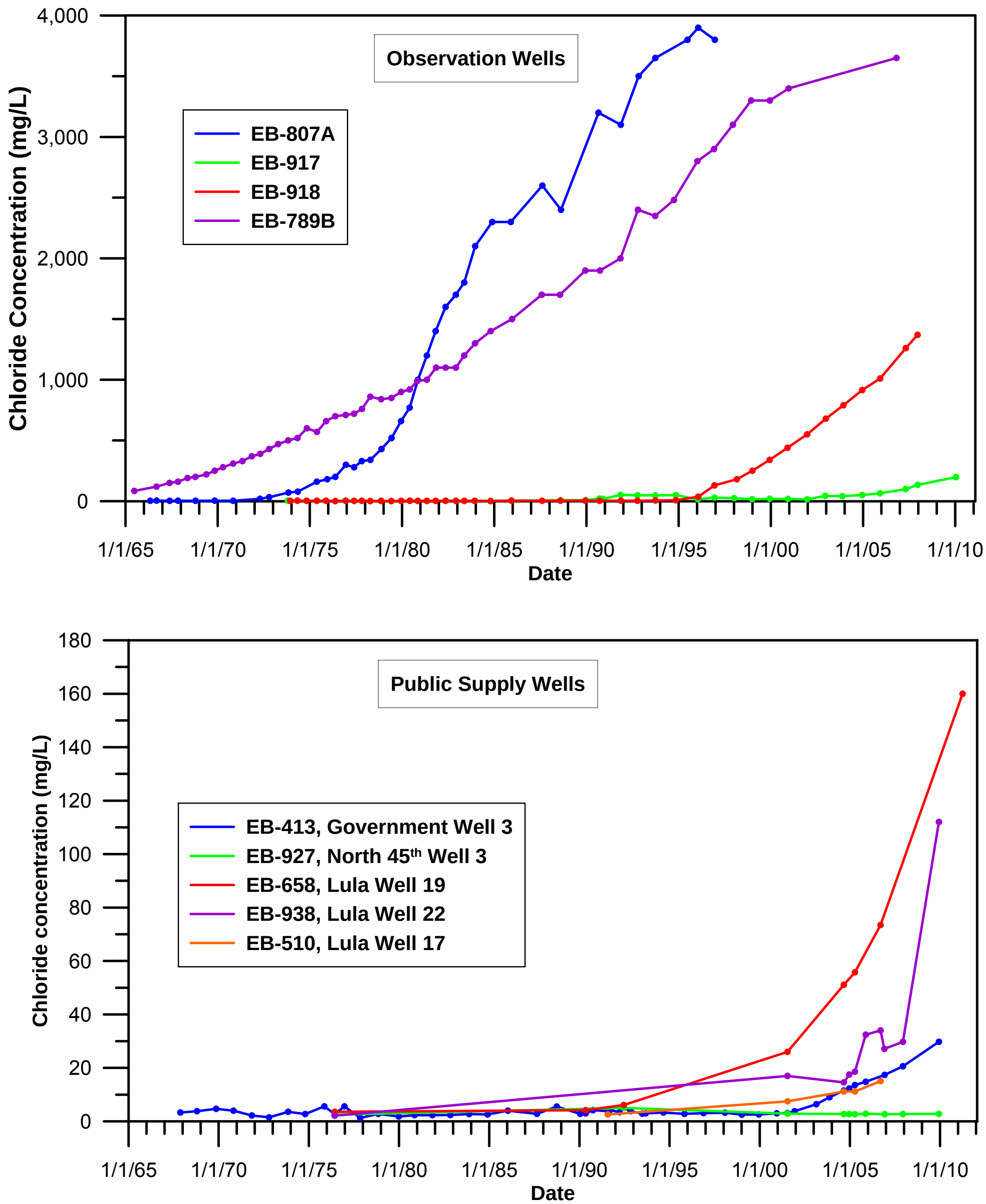


Figure 4: Chloride observations through time in select wells in the USGS Chloride Monitoring Network (Lovelace, 2010).

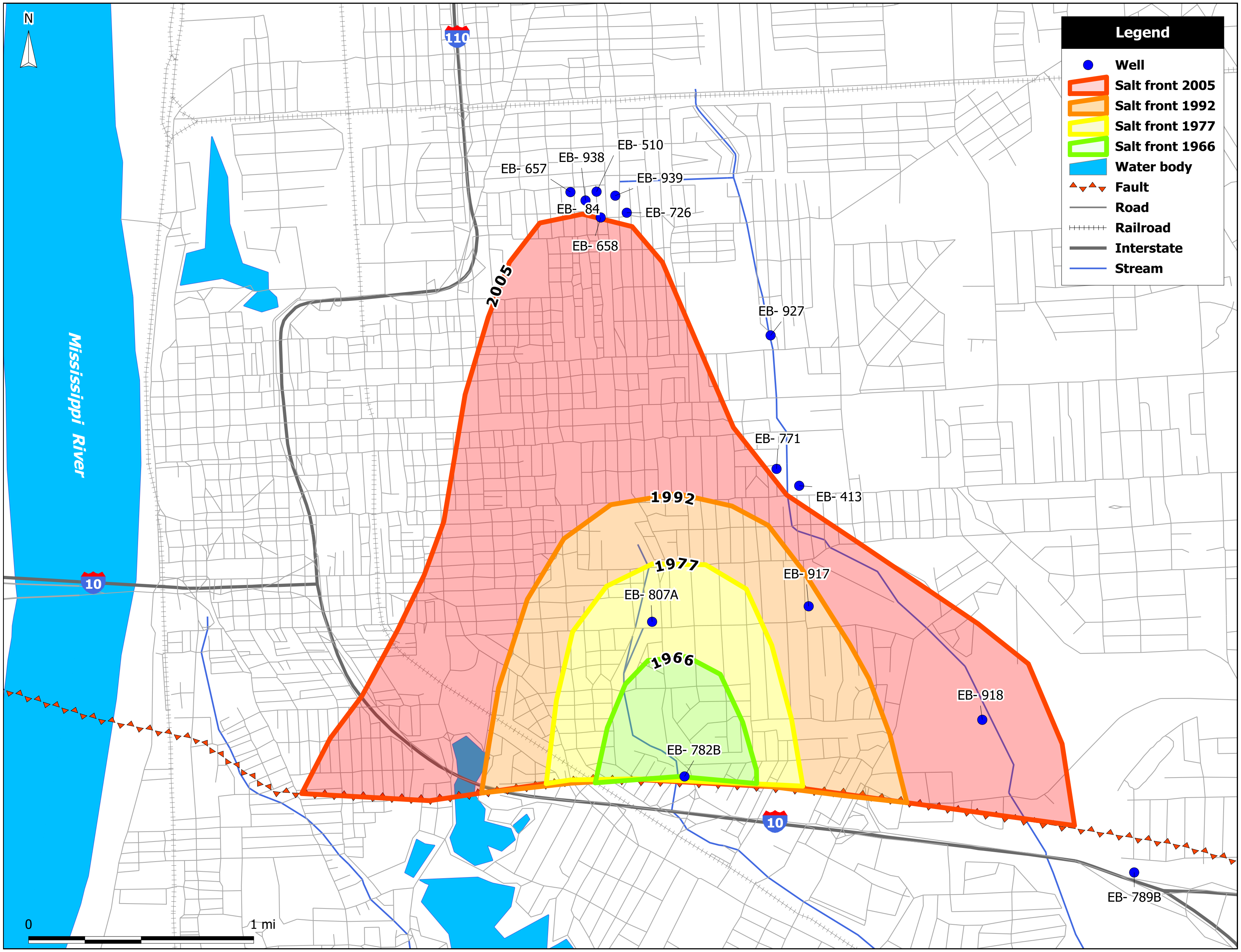


Figure 5: Chloride Monitoring Network and estimated location of the saltwater front through time (Whiteman, 1979; Tomaszewski, 1996; Prakken, 2004).

Station, despite being located much closer to the fault. The effectiveness of the connector well is likely helped by extensive pumping at the Lula Station. Water-level measurements show that the hydraulic gradients that control movement of water from the fault are dominated by the cone of depression created by the Lula Station (Griffith and Lovelace, 2003b; Prakken, 2004).

4.6 Conclusions

Based on our review and analysis of existing information, we conclude:

- Over-pumping in the 1,500-Foot sand has resulted in a saltwater tongue moving northwards from the Baton Rouge Fault toward the Lula Station.
- The areal extent and vertical distribution of the saltwater front in the 1,500-Foot sand is poorly understood because data are sparse. Current chloride conditions in the aquifer are only documented by composite samples collected from BRWC wells. Based on observations at EB-807A, saline water with a chloride concentration of at least 3,000 mg/L was moving past EB-807A at least 20 years ago.
- Based on the geometry of the fault, observed hydraulic gradients, and limited water-quality data, the USGS has concluded that encroachment of saline water in the 1,500-Foot sand in East Baton Rouge is due to leakage of saltwater from the downthrown 1,200-Foot sand south of the fault. The source of saltwater south of the fault is likely from deeper halite formations.
- Regionally, little is known about the hydrogeologic characteristics of the 1,500-Foot sand, such as aquifer interaction, leakage, and interactions across the Baton Rouge Fault. The complex setting makes interpreting existing data difficult and collecting new pertinent data costly.

5 Field Investigation

Field tests were conducted to estimate the hydraulic properties of the 1,500-Foot sand and to better understand the distribution of saltwater in the aquifer. The field testing included:

- Testing at Lula Well 19 with the objective of defining the vertical distribution of chlorides over the depth of the aquifer. This testing included a spinner flow test, conductivity logging, and discrete water-quality sampling. The Well 19 test results were inconclusive because the conditions that cause the elevated chloride concentration in the well were not present during the test. This analysis included correlating chloride levels in individual wells with the operation of Well 19.
- Drilling and testing a new observation well at Progress Park, south of the Lula Station. This included geophysical logging, hydrophysical logging, a spinner flowmeter tests to evaluate the vertical distribution of flow in the aquifer, and multiple water-quality tests to evaluate the vertical distribution of chlorides in the aquifer.
- Collection and correlation of water-level data at the Progress Park observation well during controlled pumping at the Lula and North 45th Stations. The results confirm that the observation well is screened in a formation in direct connection with the Lula and North 45thStations, which allowed for evaluating the hydraulic properties of the aquifer.

5.1 Lula Well 19 testing

Spinner flowmeter testing and fluid electrical conductivity (FEC) logging were conducted by Layne's logging division (COLOG) at Well 19 on May 12 and 13, 2010. The objective of the logging was to define the vertical distribution of freshwater and saline water entering the screen during both ambient and pumping conditions. The well was pumped with a temporary submersible pump at approximately 725 gpm for approximately 30 hours, beginning at 0943 hours on May 12, 2010. A complete description of the test and results are in Appendix A.

Prior to pumping, ambient measurements showed no vertical difference in FEC. Measurements recorded during active pumping showed little water entering the bottom of the screen where we would expect the heavier saline water to be located. For the active test, Well 19 was pumped for approximately 30 hours, beginning May 12, while the conductivity and the flow rate were recorded. Based on the logs, conductivity generally increased during the test, with some stratification developing late in the test. This stratification was apparent in the conductivity of groundwater entering the well directly above the non-producing portion of the screen (about 10 ft above the bottom of the screen).

The results from Well 19 showed that during the test, chloride was entering the well as a vertically diffuse front. Subsequent water-quality results indicated that, at the end of the test, the stratification evident in the conductivity log was not significant with regard to chloride. Results from discrete water-quality samples collected at the top of the casing and at the lowest productive area of the screen where the highest conductivity was recorded were not significantly different. At the end of the test, water with a chloride concentration of approximately 15 mg/L was entering the well throughout the vertical length of the screen.

The Well 19 test results were inconclusive regarding the vertical distribution of freshwater and saline water because the conditions that cause elevated chloride in the well to rise were not present during the test. This is very likely due to the fact that Well 19 was used sparingly in the eight weeks prior to testing on May 12. During this time, the well was pumped for only four days, between April 30 and May 3. During the test, Well 19 was not pumped long enough for the elevated chloride to be observed entering the screen. As noted by BRWC's monthly chloride sampling, the occurrence of elevated chloride in the Lula wells is related to pumping stress. When Well 19 is off, the chloride concentration increases in other wells, particularly at Well 22.

Another factor that may have contributed to the inconclusive test was that Well 19 was not tested at the normal production rate as planned. Because of space issues in the casing, the pumping rate for the test was constrained to 725 gpm, which is about 60% of the well's normal production rate.

The chloride response to changes in pumping at the Lula Station described in Section 5.2 is consistent with the modeled capture zones of the wells. When all of the wells are pumping, Well 19 captures a large portion of the water moving toward the station from the south (Figure 6). When Well 19 is off, Well 22 and Well 17 capture more water moving toward the Lula Station between North 32nd St. and North 30th St.

Despite the ambiguous results, we can draw some conclusions from the test. When low chloride concentration (<20 mg/L) is observed in Well 19, chloride is entering the well as a diffuse front. While we did not observe elevated chloride (>20 mg/L) conditions in Well 19 during the test, the FEC logs suggest that a stratified front with a higher chloride concentration was developing at the bottom of the screen. These results imply that the saltwater front is broad and diffuse (chloride <20 mg/L) at the edges and more narrow and concentrated between Well 19 and Well 22.

5.2 Saltwater encroachment at Lula Station

Chloride concentration at the Lula Station wells changes in response to pumping stress. The results from BRWC monitoring suggests that a broad and diffuse saltwater edge (chloride <20 mg/L) is present at all of the wells, depending on pumping, and a more narrow and concentrated front is present between Well 19 and Well 22.

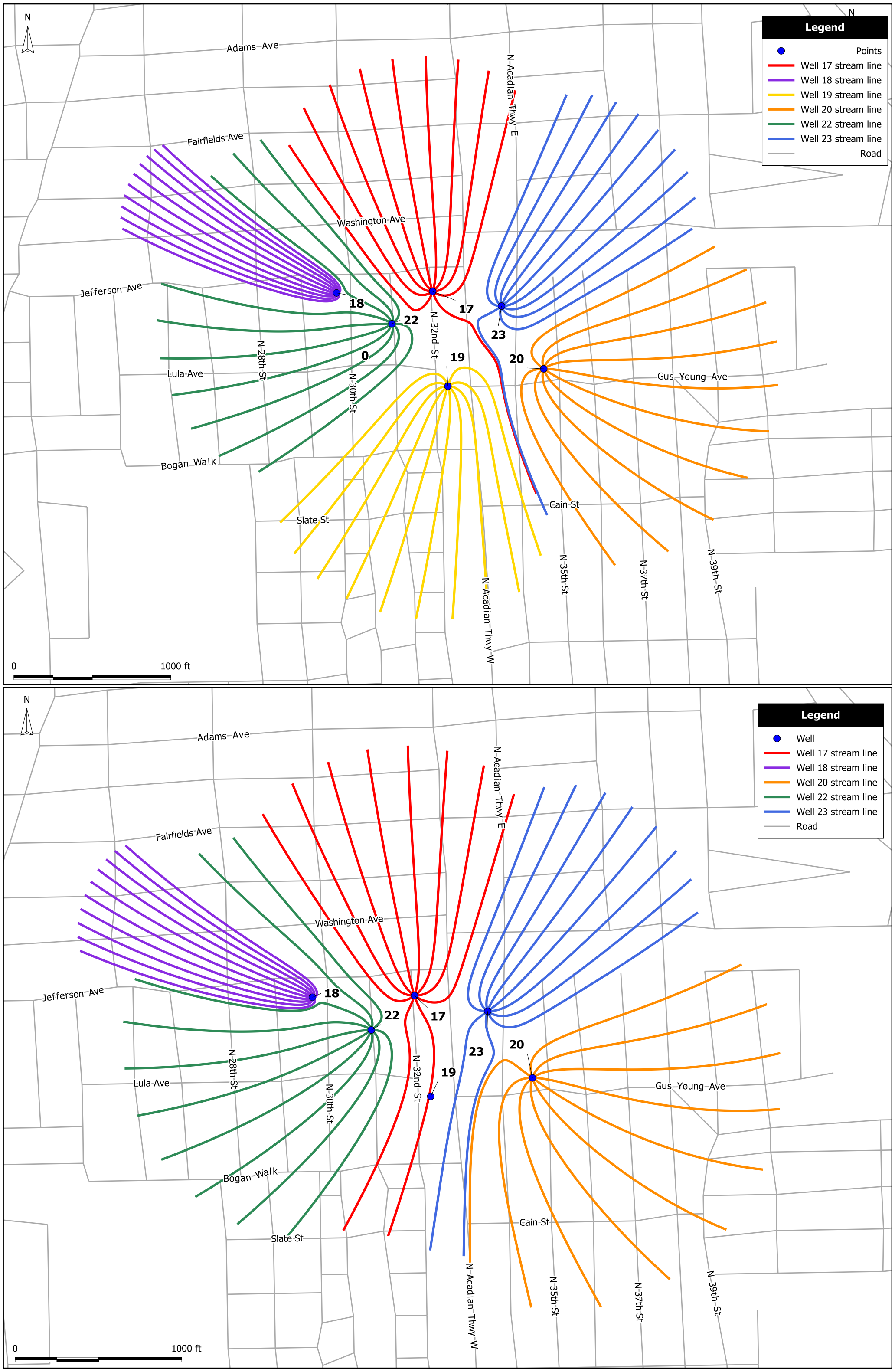


Figure 6: Capture zones of Lula wells with all wells pumping (A) and all wells pumping except Well 19 (B).

Chloride concentrations in the Lula wells have increased from a background concentration of approximately 3 mg/L since approximately 2001 (Lovelace, 2010). Monthly sampling of the Lula wells by BRWC since the Fall of 2009 shows that chloride concentrations at the Lula Station are affected by pumping stress (Figure 7). Specifically, when all the wells are pumping consistently, the raw water from Well 19, Well 22, and Well 17 are elevated above background concentrations. Of the three wells, Well 19 pumps the highest concentration of chloride (120-180 mg/L). When Well 19 is off for more than two weeks the chloride concentration drops below 20 mg/L in Well 19 and increases in Well 22. When Well 19 is returned to service, the chloride concentration increases in Well 19 and decreases in Well 22. This is consistent with the conclusion that the saltwater front is broad and diffuse (chloride <20 mg/L) at the edges and more narrow and concentrated between Well 19 and Well 22.

5.3 Progress Park observation well

A new observation well was installed in the southwest corner of Progress Park to investigate the occurrence of the 1,500-Foot sand, investigate the distribution of saltwater in the aquifer, and estimate the hydraulic properties of the aquifer between Progress Park and the Lula and North 45th Stations. The observation well is located approximately 2,800 ft south of Lula Well 19 and 10,400 ft north of the fault (Figure 8). Information regarding drilling and construction of the well, including a construction log, the registration form submitted to the state, the driller's formation log, sieve analysis results, and the complete geophysical log is included in Appendix B.

The geophysical log indicates the presence of aquifer material in two distinct zones, between depths of 1,495 ft and 1,530 ft and between depths of 1,555 ft and 1,670 ft (Figure 9). The observation well was constructed with 60 ft of screen placed at the base of the sand unit. The screen length and location were chosen based on the geophysical log. The gamma log indicates aquifer material with discontinuities from a depth of approximately 1,555 ft to 1,670 ft. The decrease in the resistivity log beginning at a depth of 1,620 ft over this interval indicates that the formation water is increasing in electrical conductivity, which is interpreted as an increase in salt content. The screen was placed at a depth of 1,605 ft to 1,665 ft to provide access to formation water from the base of the sand, where chloride is expected to be the highest, to above the perceived saltwater/freshwater interface.

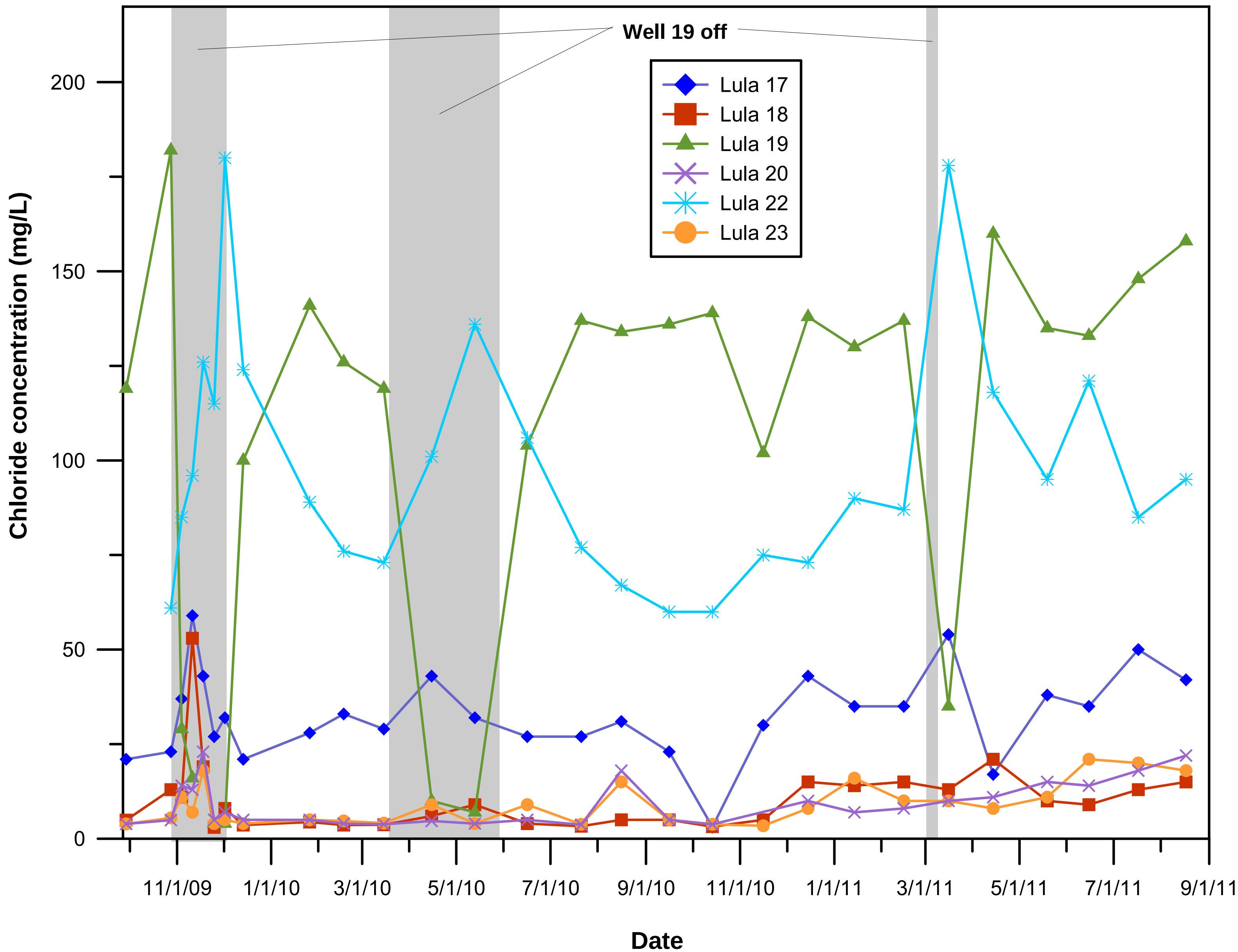


Figure 7: Monthly chloride concentrations in Lula Station wells [BRWC]. Shaded area shows periods when Well 19 was off.

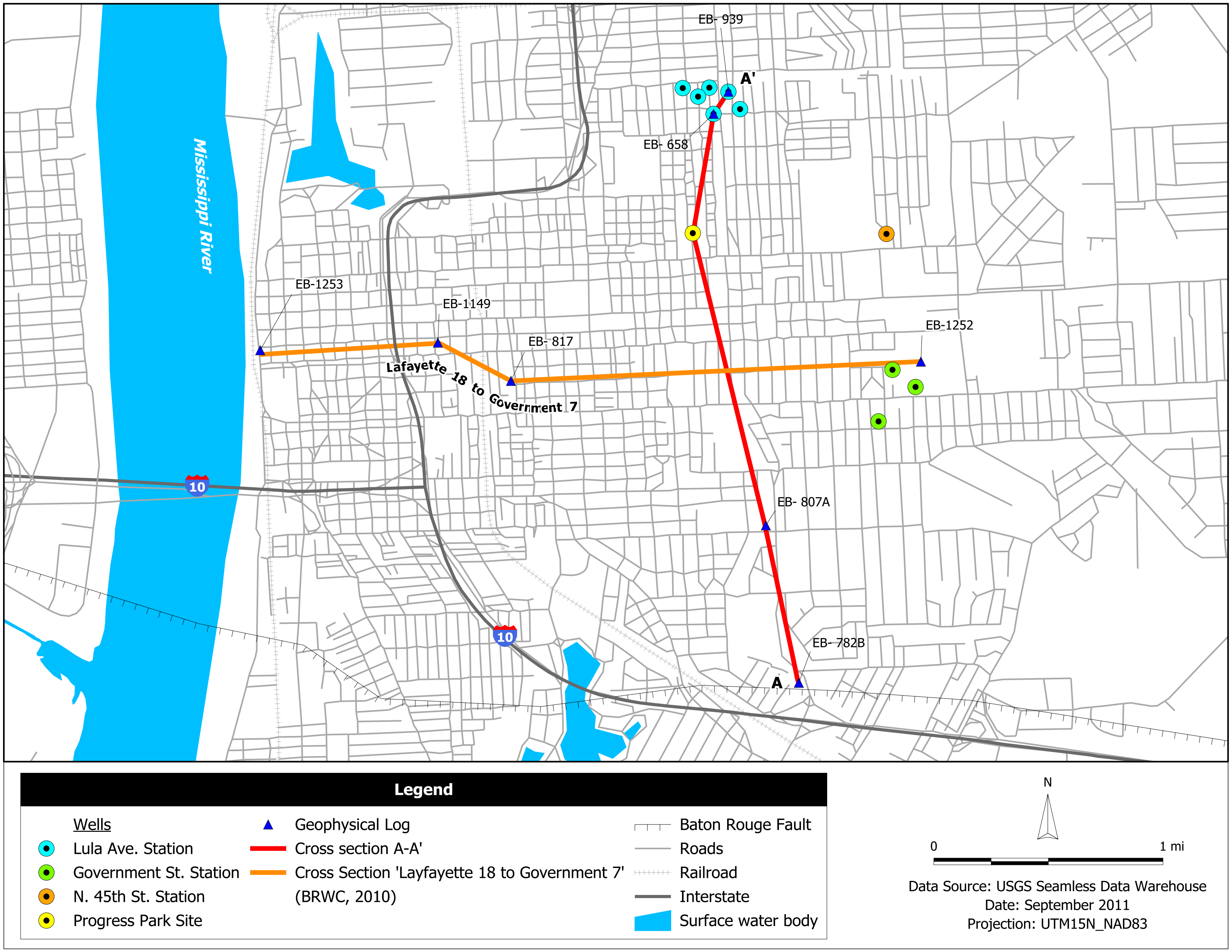


Figure 8: Location of new observation well in Progress Park and transect for Cross section A-A'.

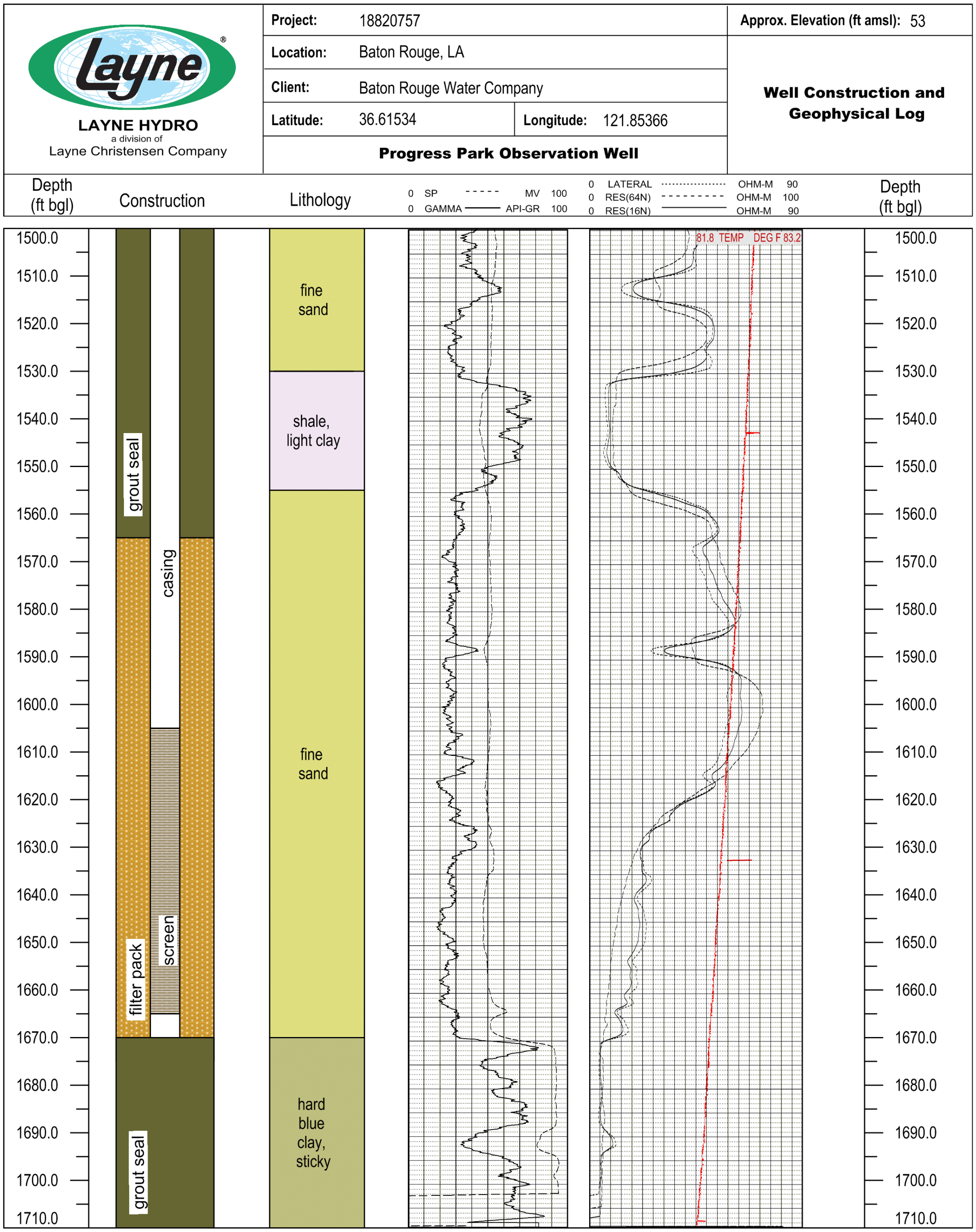


Figure 9: Comparison of lithology and geophysical log to the screened interval at the Progress Park observation well.

5.3.1 Geologic cross section

We integrated the new geologic information from the Progress Park well with existing information to create an updated cross section of the 1,500-Foot sand (Cross section A-A') in the area between the Lula Station and the fault (Figure 8). Cross section A-A' shows our interpretation of the location of the 1200-Foot sand, the 1500-Foot sand, and the 1,500/1,700-Foot sand layers (Figure 10). In addition to the lithologic information from the Progress Park well, the new cross section was based on geophysical logs from existing wells (EB-781, EB-807-A, EB-972, Lula Well 19, and Lula Well 23). We also used existing regional cross sections (Griffith, 2003) as well as local cross sections created by BRWC (BRWC, 2010). The projection of local east-west cross section Lafayette 18 – Government 7 as shown on Figure 8 was used to create Cross section A-A'. This and other local cross sections guided our interpretation of the geophysical logs and the differentiation and connectivity between the different sand layers.

Cross section A-A' suggests continuity between the saltwater zone at Progress Park and the Lula and North 45th Stations. This conclusion is confirmed by the water-level response in the Progress Park well due to pumping changes at the Lula Station (Section 5.4). The cross section is based on sparse data between the fault and the Lula wells, but the lower section of aquifer material observed at the Progress Park observation well appears to be a continuation of what others have identified as the 1500/1700-Foot sand (BRWC, 2010; Griffith, 2003).

5.3.2 Hydrophysical logging

Hydrophysical logging was conducted at the Progress Park observation well on April 23, 2010, to understand flow in the screen under pumping conditions and observe the distribution of chlorides in the aquifer. Results of the the flow results, conducted while pumping a net 75 gpm, are summarized in Figure 11 and detailed results are included in Appendix C. Results of the test show three distinct zones of productivity in the screen, with most of the water entering in the top 20 ft of the screen and little water entering the middle of the screen and the bottom 14 ft of screen.

Based on the flow results from hydrophysical logging, water-quality samples were collected while pumping at 75 gpm; a composite sample was collected at the wellhead and discrete samples were collected in the screen at depths of 1613 ft and 1631 ft. The chloride concentration at the wellhead was 449 mg/L. Because the samples were collected during pumping, each observed concentration represents an average chloride value in the underlying water column. The flow results were used to infer by mass balance the chloride concentrations entering the middle section of the screen. Results of the testing show inferred chloride concentrations of 75 mg/L at a depth of 1,610 ft and 722 mg/L at a depth of 1,622 ft and an observed concentration of 1,955 mg/L at a depth of 1,648 ft (Figure 12). Complete water-quality results are in Appendix D.

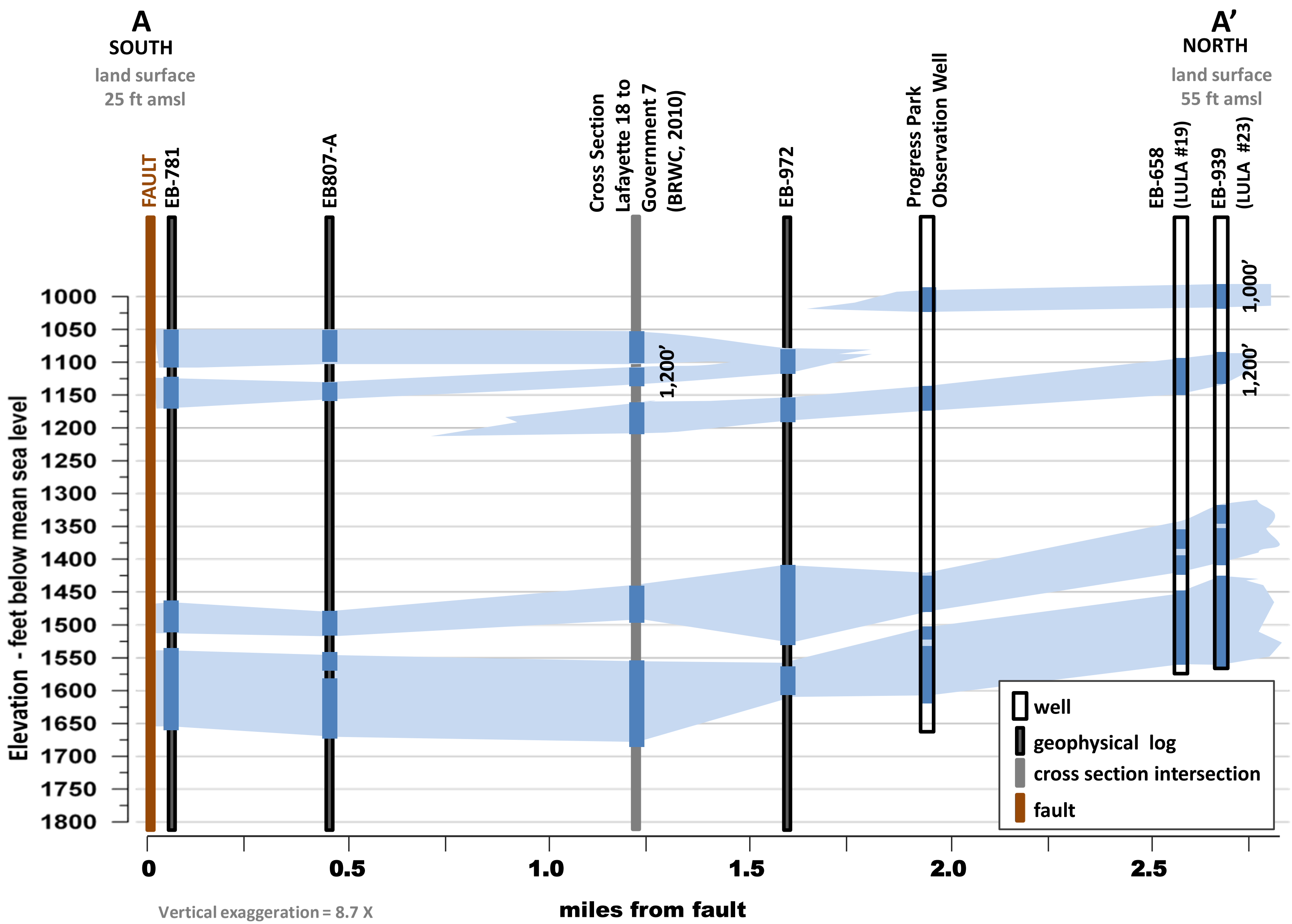


Figure 10: Cross section A-A' showing the 1,200-Foot and the 1,500-Foot sand between the Baton Rouge Fault and the Lula Station.

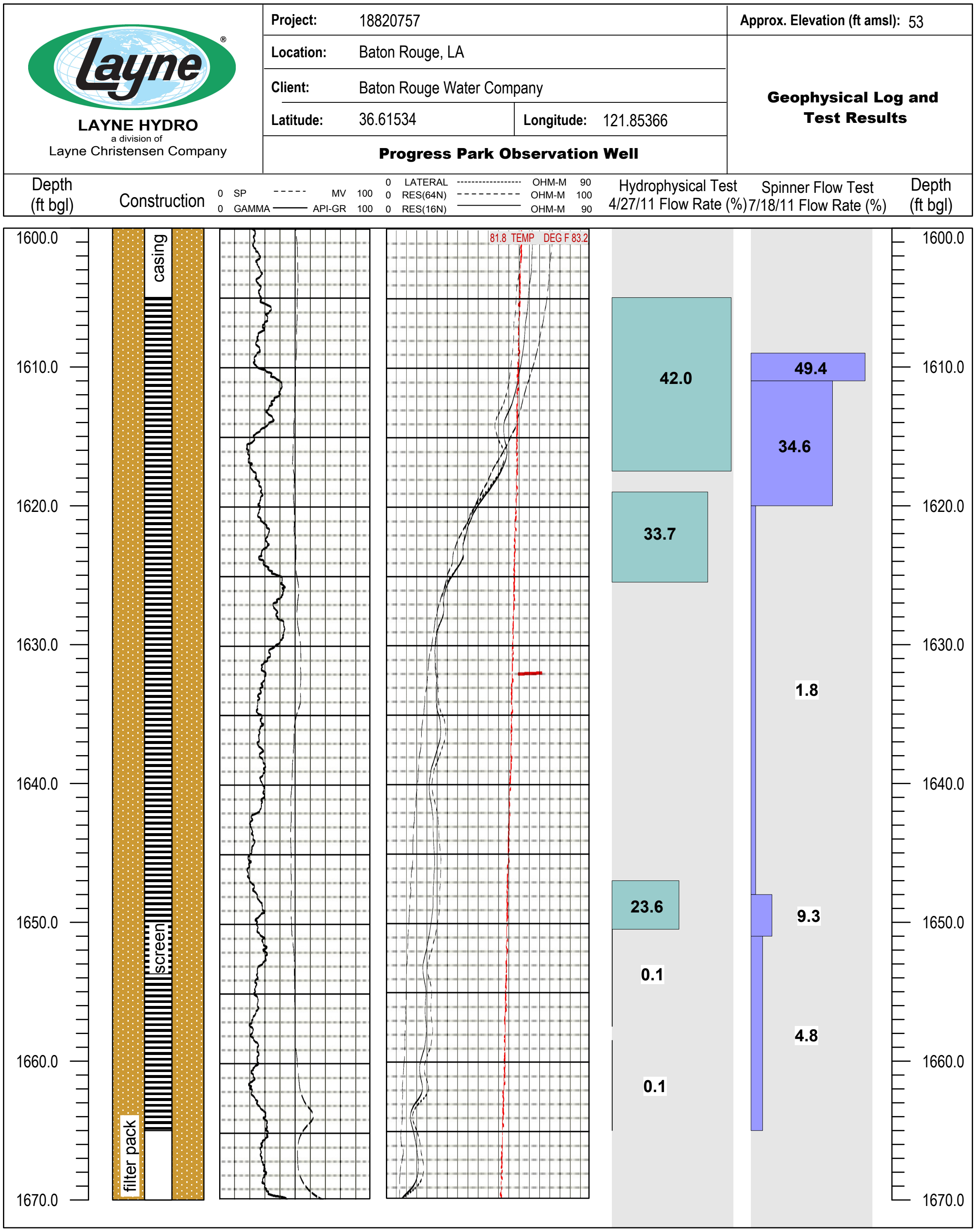


Figure 11: Results from flow testing the Progress Park observation well, including a hydrophysical logging test conducted on 4/27/11 while pumping 75 gpm and a spinner flowmeter test conducted on 7/18/11 while pumping 221 gpm.

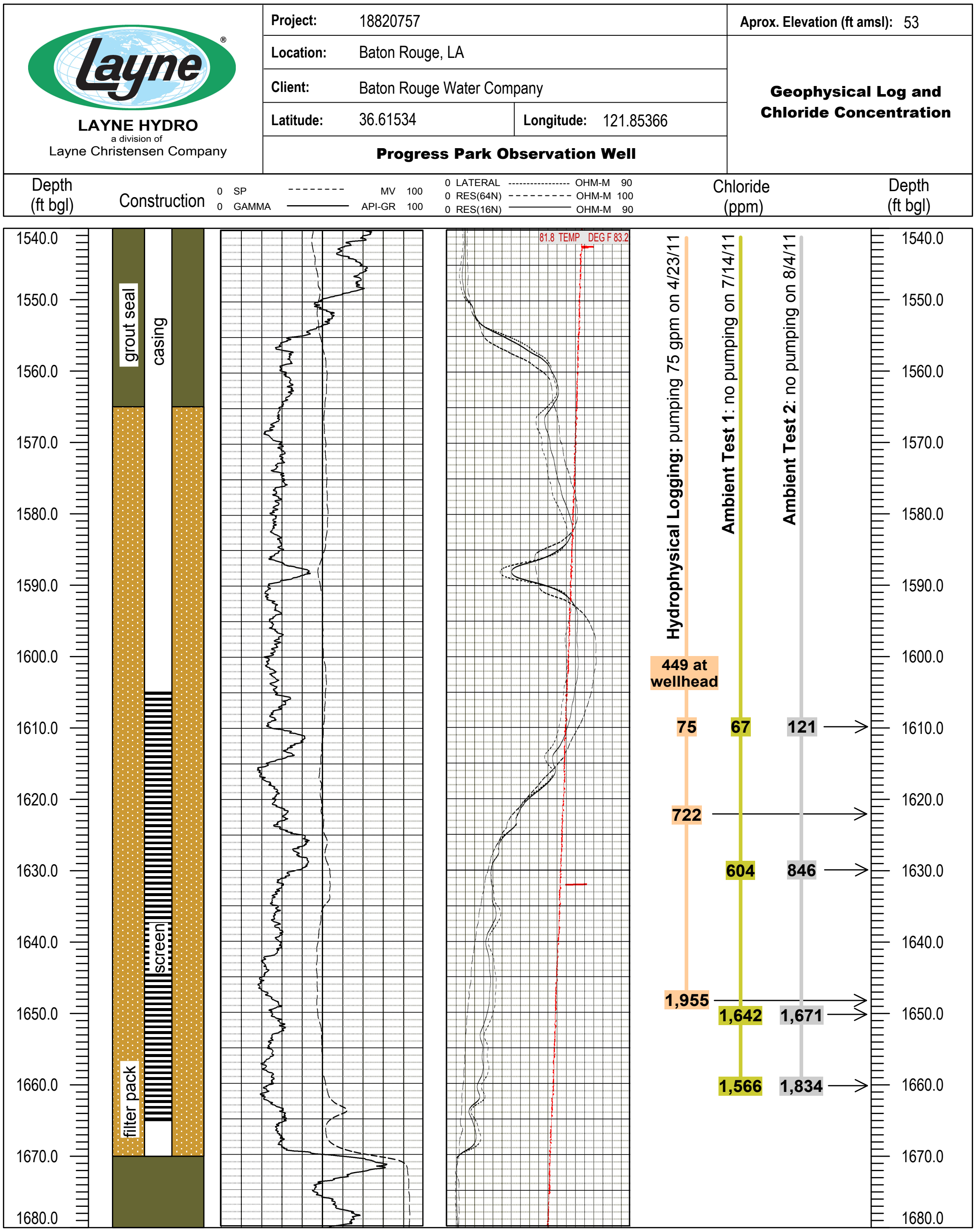


Figure 12: Chloride concentrations in the Progress Park observation well at discrete depths during active pumping and non-pumping conditions.

5.3.3 Additional development and testing

Additional well development, including chemical and mechanical treatment, was conducted between June and August, 2011 to ensure that remnants of the drilling mud were removed and the screen was sufficiently open to the aquifer to characterize the chloride profile. A spinner flowmeter test was conducted on July 13, 2011 to re-assess flow conditions in the screen. Results of the the flow test, conducted while pumping a rate of 221 gpm, are summarized in Figure 11. Results of the spinner flowmeter test were similar to those from the hydrophysical logging test on April 23, 2011, and showed that most of the pumped water was from a zone near the top of the screen. However, the spinner flowmeter test also showed low, but measurable flow in the middle and lower parts of the screen that were previously unproductive.

Discrete samples were collected from four locations in the screen on July 14, 2011 under ambient conditions (Figure 12). The ambient testing showed similar stratification as observed during the hydrophysical logging, with 67 mg/L of chloride at a depth of 1,610 ft, 604 mg/L at a depth of 1,630 ft, 1,642 mg/L at a depth of 1,650 ft, and 1,566 mg/L at the bottom of the screen. On August 4, 2011, after more development that focused on the middle part of the screen, discrete samples were again collected under ambient conditions from the same locations in the screen. The second ambient test showed similar stratification as observed during the hydrophysical logging and the first ambient test, with 121 mg/L at a depth of 1,610 ft, 846 mg/L at a depth of 1,630 ft, 1,671 mg/L at a depth of 1,650 ft, and 1,834 mg/L at the bottom of the screen. Results of the spinner flowmeter testing are in Appendix E. Complete water-quality results, including samples collected at various times from the wellhead to assess development efforts, are in Appendix D.

5.3.4 Source of saline water

The composition of saline water at Progress Park suggests that the source of saline water observed near the base of the sand layer at Progress Park is from leakage at the fault. To confirm the source of saline water observed at Progress Park, Layne collected two samples from EB-918, which is screened in the 1,500-Foot sand north of the fault and has exhibited elevated chloride levels. Water-quality characteristics of saline water at EB-918 are similar to saline water observed Progress Park: water from both sites is dominated by sodium and chloride and have similar concentrations of iron and manganese (Table 2). Natural water from the 1,500-Foot sand north of the fault is soft, sodium-bicarbonate water that contains small amounts of magnesium and sulfate (Meyer and Turcan, 1955). Figure 13 compares water-quality characteristics of saline water at Progress Park with EB-918, freshwater from the 1,500-Foot sand, and results from observation wells south of the fault screened in saline portions of the 1,200-Foot and 1,500-Foot sands. The figure shows that the general ionic composition of water at Progress Park is similar to EB-918 and potential sources south of the fault, and is distinctly different than natural freshwater from the 1,500-Foot sand. The freshwater samples are dominated by sodium bicarbonate and the saline samples are dominated by sodium and chloride.

Table 2: Comparison of select water-quality results from EB-918 and Progress Park.

Constituent	EB-918 9/2/11 900 gal purge	EB-918 9/2/11 1880 gal purge	Progress Park 4/23/11 1613 ft	Progress Park 4/23/11 1631 ft
pH	8.28	8.06	7.79	7.67
Conductivity–ms/cm	7.79	7.43	4.03	6.09
Sodium Chloride–mg/L	3,498	3,358	2,192	3,092
Magnesium Chloride–mg/L	89.9	83.4	35.2	40.7
Manganese–mg/L	1.05	0.99	0.93	1.81
Iron–mg/L	0.48	0.34	0.14	0.68
Potassium–mg/L	5.07	4.88	3.07	3.87
Magnesium	23.0	21.3	9.0	10.3
Sodium–mg/L	1,372	1,320	779	1,216
Bicarbonate–mg/L	53.7	58.6	127	80.0
Chloride–mg/L	2,596	2,477	1,233	1,955
Sulfate–mg/L	1	1	<1	<1

Note. mg/L=milligrams per liter, ms/cm=millisiemen per centimeter, gal=gallons

5.4 Water-level monitoring at Progress Park

A transducer was placed in the Progress Park observation well from May 3 through May 19, 2011. The transducer recorded water-level fluctuations in the aquifer, which were correlated to the transient operation of wells at the Lula and North 45th Stations (Figure 14).

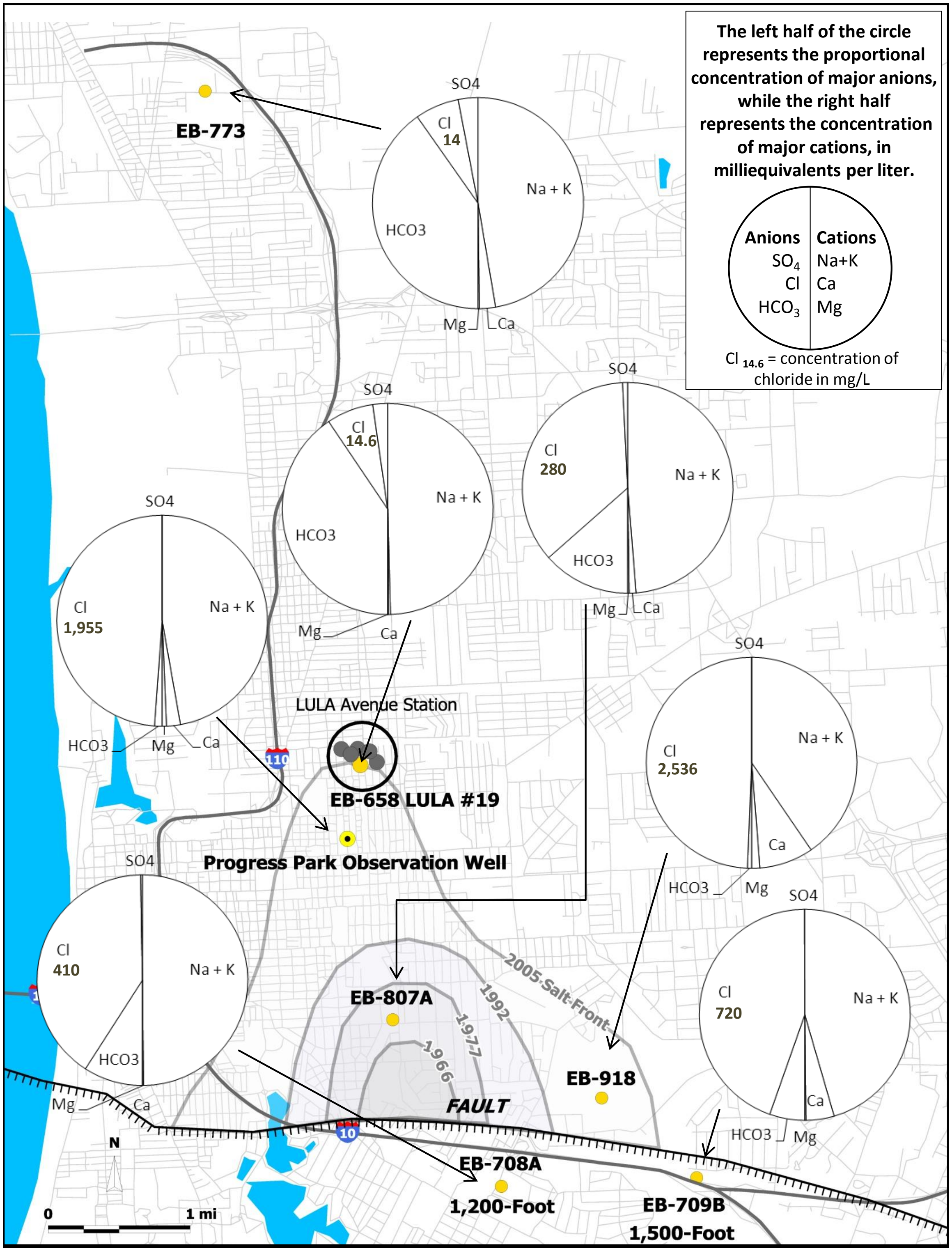


Figure 13: Comparison of general water-quality characteristics of saline water at Progress Park with new results from EB-918 and existing data from the 1,500-Foot and 1,200-Foot sands.

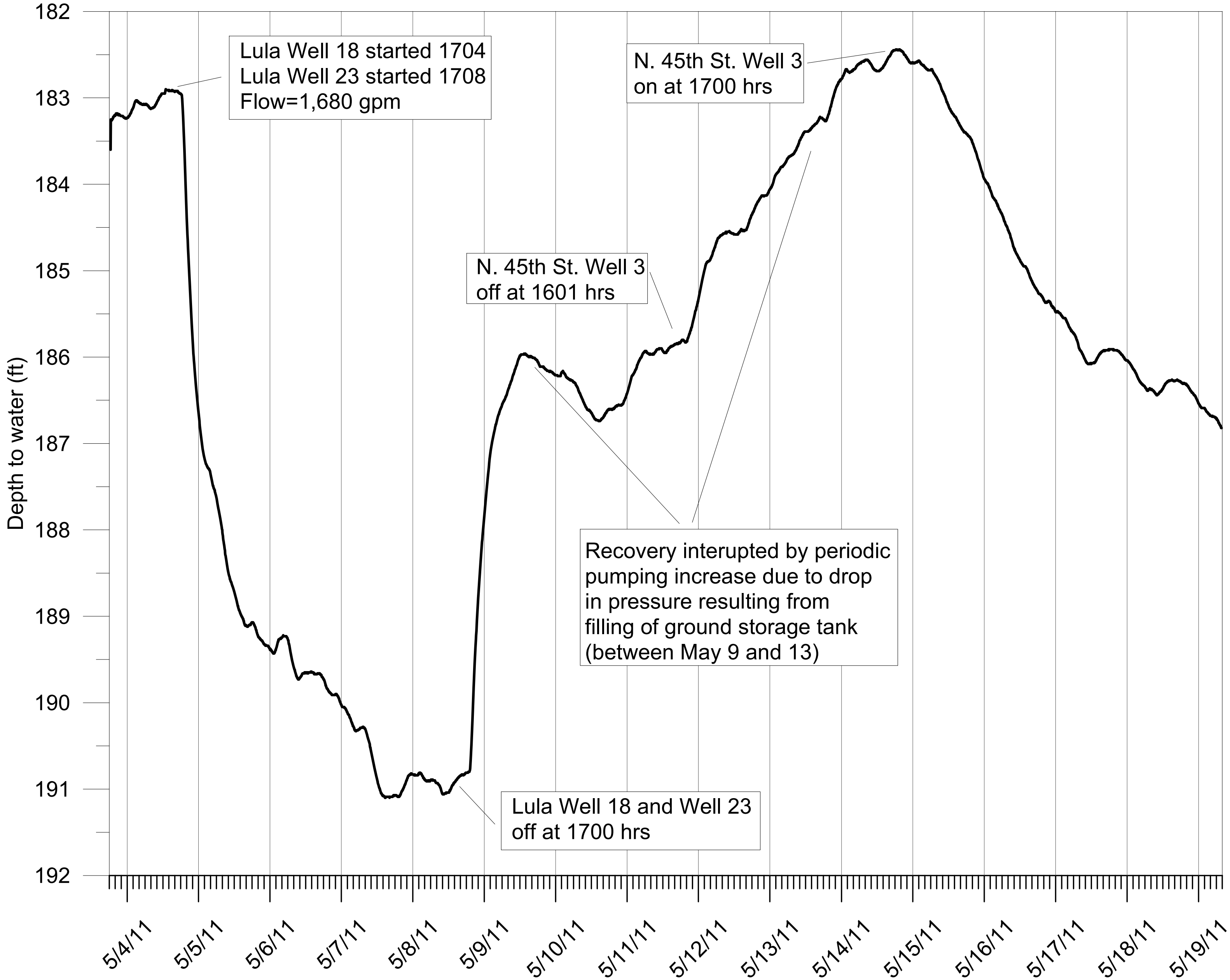


Figure 14: Water-level monitoring at the Progress Park observation well, May 3–May19, 2011.

The water-level data was split into two samples. The first sample (May 4–May 9) represents the drawdown at Progress Park caused by turning on Lula Wells 18 and 23 at a combined pumping rate of 1,680 gpm and subsequently shutting them down; the second sample (May 14–May19) represents the drawdown caused by operation of the well at the North 45$^{\text{th}}$ Station. Each data set was analyzed separately using AQTESOLV software (Duffield, 2002) to evaluate the hydraulic properties of the 1,500-Foot sand (Figure 15). The results are summarized in Table 3. As noted in the table, a standard Theis analysis for a confined aquifer (Theis, 1935) was performed on the first data set, and a Cooper-Jacob analysis (Cooper and Jacob, 1946) performed on the second data set. The transmissivity values obtained from the two analyses are similar (12,810–13,560 ft^2/day) and comparable to published values for the 1,500-Foot sand. The storage coefficients are large for a confined system (0.00771–0.01978). This is likely due to confining layer storage and possibly due to some degree of inter-aquifer leakage occurring, although the leakage could not be quantified from the pumping test data and does not appear to be significant.

Table 3: Results of pumping test analysis.

Data set	Transmissivity (ft^2/day)	Storage coefficient (–)	Analysis
Lula wells pumping	13,560	0.00771	Theis
North 45$^{\text{th}}$ wells pumping	12,810	0.01978	Cooper-Jacob

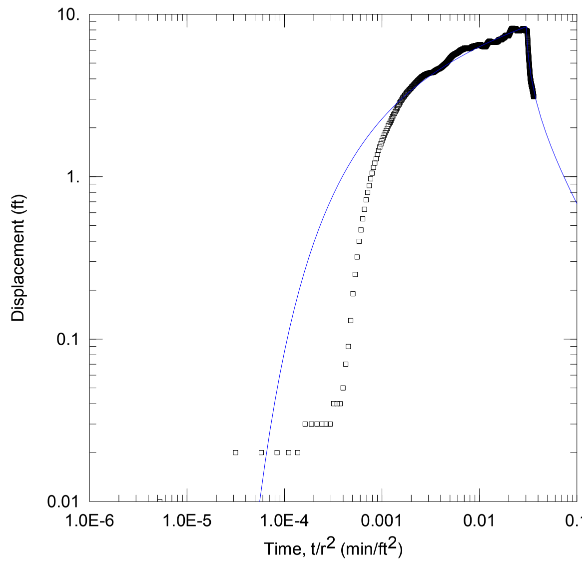
Note. ft^2/day=feet squared per day

5.5 Conclusions

Field tests were conducted to investigate the hydrogeologic characteristics of the 1,500-Foot sand and to characterize the occurrence of saltwater encroachment south of the Lula Station. Results of the field testing were used to evaluate potential methods for controlling the encroachment of saltwater in the 1,500-Foot sand. Based on the results of field testing, we conclude:

- Currently, operation of Lula Well 19 helps mitigate the chloride levels at the remaining Lula wells. Shutting down Well 19 results in increased chloride concentrations at the other wells, with the largest impact on Well 22 and Well 17. The observed chloride levels in the wells and the modeled capture zones suggests that Well 19 shields the other wells from portions of the saline plume with the highest chloride concentrations, which appears to lie between Wells 19 and 22.
- The saltwater plume is vertically stratified at Progress Park, with a general chloride concentration between:

A



LULA

Data Set: Z:\...\Lula-test-Theis.aqt
Date: 05/24/11 Time: 15:00:18

PROJECT INFORMATION

Company: Layne Hydro
Client: BRWC
Project: bato
Location: Baton Rouge
Test Well: Lula #18 and #23
Test Date: 5/4/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
Lula 18	0	0
Lula 23	1040	82

Observation Wells

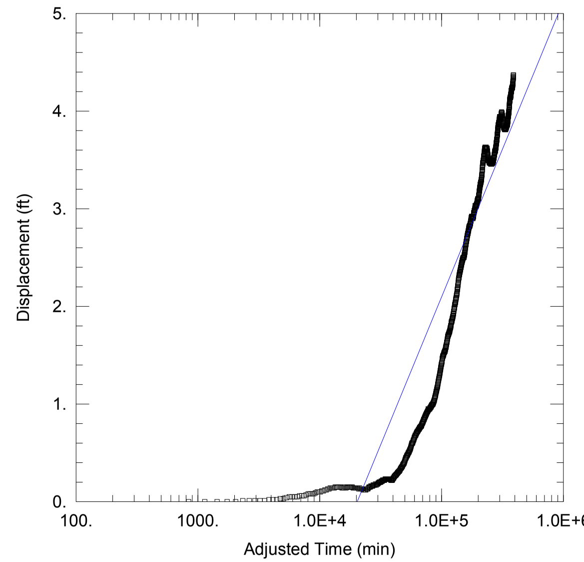
Well Name	X (ft)	Y (ft)
▫ Progress Park Well	125	3376

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 1.356E+4 ft^2/day
Kz/Kr = 0.1
S = 0.007709
b = 50. ft

B



WELL TEST ANALYSIS

Data Set: Z:\...\N45-Cooper-Jacob-AUTO.aqt
Date: 06/01/11 Time: 15:33:33

PROJECT INFORMATION

Company: Layne Hydro
Client: BRWC
Project: bato
Location: Baton Rouge
Test Well: N. 45th
Test Date: 5/14/11

AQUIFER DATA

Saturated Thickness: 50. ft
Anisotropy Ratio (Kz/Kr): 0.2

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
New Well	4531	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ Progress Park	0	0

SOLUTION

Aquifer Model: Confined
Solution Method: Cooper-Jacob

T = 1.281E+4 ft^2/day
S = 0.01978

Figure 15: Pumping test analysis results: A) Lula Wells 18 and 23 and B) North 45th Well 3.

- 65 mg/L and 120 mg/L at the top of the screened interval (1,605 ft–1,615 ft deep)
- 600 mg/L and 850 mg/L in the middle of the screened interval (1,615–1,640 ft deep)
- 1,500 mg/L and 2,000 mg/L at the bottom of the screened interval (1,640–1,665 ft deep).

- Water-quality results suggest that the source of saline water observed at Progress Park is from leakage at the fault. The general water-quality characteristics of saline water at Progress Park is similar to EB-918 and potential sources south of the fault.

- The water-level response to pumping changes at the Progress Park observation well indicates that the screened interval of the Progress Park well is hydraulically connected to the screened intervals of the Lula and North 45th wells.

- In the context of existing information, the new lithologic data from the Progress Park well suggests that there is continuity between the saltwater zone at Progress Park and the Lula Station. This conclusion is confirmed by the water-level response in the Progress Park well to pumping changes at the Lula Station.

- The transmissivity of the 1,500-Foot sand is about 13,000 ft^2/day in the region between the Lula Station and Progress Park. The results are in agreement with published estimates of the local transmissivity of the aquifer in East Baton Rouge Parish. Locally, leakage between aquifers does not appear to be significant.

6 Groundwater Flow Model

A steady-state, regional, single-density groundwater flow model of the 1,500-Foot sand was constructed using TimML software (Bakker, 2004). TimML is an open-source, analytic element modeling code. TimML was chosen because of its flexibility for modeling extensive regions, complex multi-aquifer systems, and three-dimensional flow to partially penetrating features such as scavenger wells. A single density model was chosen since the density variations in the regional groundwater are not the primary feature driving the flow system. The features driving the flow system are the pumping centers north of the Baton Rouge Fault that create a large cone of depression drawing saline water across the fault.

6.1 Conceptual model of regional groundwater flow in the 1,500-Foot sand

A conceptual model of groundwater flow in the 1,500-Foot sand is illustrated in Figure 16. The 1,500-Foot sand is one aquifer in a system of several sand aquifers that are separated by thick, clay confining units. As shown in the figure, the aquifer is recharged with precipitation far to the north of the Baton Rouge area, where the aquifer subcrops beneath unconsolidated material. Vertical leakage from over- and under-lying aquifers occurs throughout the system through the clay confining units and where the clay is thin or absent.

The primary regional flow direction in the aquifer is from the recharge area in the north to the Baton Rouge Fault in the south. However, pumping centers in the East Baton Rouge area create a large cone of depression locally producing radial flow, and capturing water originating from both the north recharge area and groundwater from south of the Baton Rouge Fault. The Baton Rouge Fault is a leaky barrier to horizontal groundwater flow, which limits the northward flow of groundwater across the fault. The fault juxtaposes aquifer layers; it is believed that flow from south to north across the fault into the 1,500-Foot sand originates in the 1,200-Foot sand (Whiteman, 1979). Groundwater that crosses the fault and flows north toward the pumping center has high salt concentrations.

6.2 Features and parameters of the regional model

The regional model of groundwater flow in the 1,500-Foot sand is conceptually simple with few parameters. The model reflects a confined aquifer that dips to the south from the recharge area in Mississippi where the aquifer intersects the ground surface, to the Baton Rouge Fault where the depth of the aquifer is approximately 1,500 ft to 1,600 ft below the ground surface. The total area represented by the regional model is extensive, and is much larger than the region of interest between the fault and the BRWC well fields. The purpose for the large regional extent of the model is to explicitly include the recharge area where the aquifer subcrops under unconsolidated materials

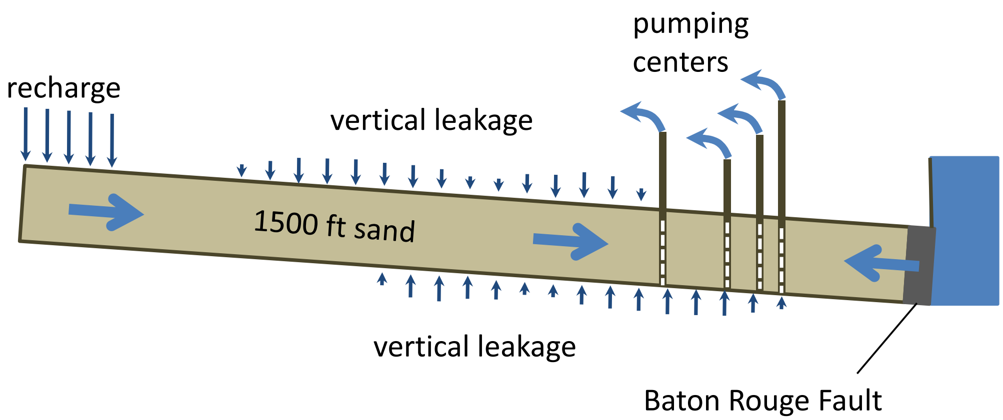


Figure 16: Conceptual sketch of flow in the 1,500-Foot sand. North-to-south section through the aquifer (*not to scale*).

far to the north, and to limit the effects of artificial boundaries on model results in the East Baton Rouge area (Figure 17) As shown in Figure 17, the groundwater flow model includes the following features:

- impermeable boundaries defining the model domain
- recharge area represented by a trapezoidal area element
- resistance line sinks representing the Baton Rouge Fault
- zones of varying aquifer transmissivity, represented by model inhomogeneities
- pumping center represented by a circular area element
- pumping wells

Each of these features are discussed in more detail in the following report sections.

6.2.1 Impermeable boundaries

As indicated in Figure 17, impermeable boundaries were placed around the entire model, defining the model domain. To the north, the impermeable boundary represents the real limit of the aquifer. To the east and west, the impermeable boundaries were chosen to roughly follow path lines based on USGS mapping of the regional potentiometric surfaces (Prakken, 2004). To the south, an artificial impermeable boundary is placed adjacent to the Baton Rouge Fault to facilitate modeling the fault as a leaky boundary.

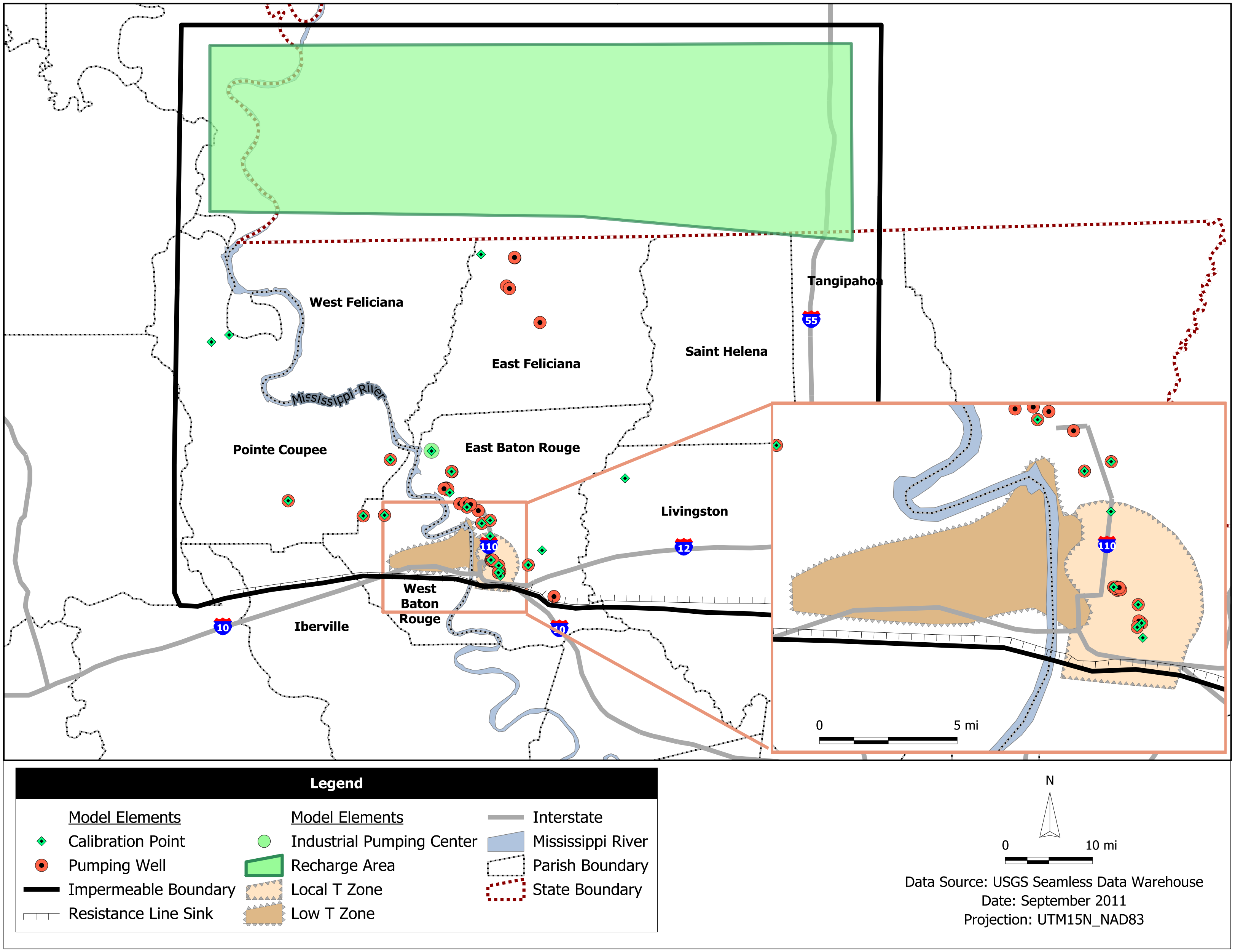


Figure 17: Extent and features of the groundwater flow model.

Table 4: Properties of the areal recharge applied to the regional groundwater flow model.

	Rate (*in/yr*)	Area (mi^2)	Total input (*mgd*)	Published values of rate (*in/yr*)	Source
Recharge	0.307	1,491	21.8	0.17–0.66	Williamson et al. (1990)

Note. in/yr=inches per year, mi^2=miles squared, mgd=million gallons per day

6.2.2 Areal recharge

Recharge to the 1,500-Foot sand occurs through infiltration from precipitation far to the north of Baton Rouge where the aquifer subcrops below unconsolidated material at the surface. This area is delineated in Figure 17, and was included in the model as an area element for which a constant infiltration rate was specified. The area over which recharge from infiltration occurs and the average recharge rate were estimated from hydrologic data provided by Williamson et al. (1990). Calibrated recharge values are presented in Table 4.

In addition to recharge from precipitation, recharge from aquifer interaction is likely to occur throughout the 1,500-Foot sand. Aquifer interaction occurs by vertical leakage from overlying and underlying aquifers through the low permeability clay confining layers and where the confining layers are absent. Vertical leakage between the 1,500-Foot sand and the over- and under-lying 1,200-Foot sand and 1,700-Foot sand is likely occurring throughout the model domain. However, the field data necessary to confirm this interaction and estimate the parameters necessary to model the aquifer interaction are not available. Locally, in the East Baton Rouge area, boring logs and geologic section data indicate that the 1,500-Foot sand is separated from the overlying 1,200-Foot sand by 100 ft to 250 ft of clay, and it is separated from the underlying 1,700-Foot sand by 50 ft of clay. This degree of separation from the adjacent aquifers suggests that leakage between aquifers is small in the East Baton Rouge area. Therefore, aquifer interaction is not included explicitly in the groundwater flow model.

6.2.3 Baton Rouge Fault

The geometry of the Baton Rouge Fault, illustrated in Figure 17, was based on USGS reports (Prakken, 2004; Griffith and Lovelace, 2003b,a). The hydraulic properties of the fault were assumed to be highly spatially variable and anisotropic. There are no direct field measurements of the hydraulic properties of the fault. Available estimates of the resistance of the fault to groundwater flow normal to the fault are based on calibrations of models to observed head data (Tsai and Li, 2008a,b), and are reported in Table 5, along with the calibrated value from the current study.

The Baton Rouge Fault is modeled as a vertical, leaky wall with a combination of an impermeable boundary to the south, and a string of resistance line sinks. The heads applied to the resistance line sinks are varied to mimic the observed head in the 1,200-Foot sand south of the fault, which is believed to be the source of the saltwater crossing the fault.

6.2.4 Variations in transmissivity

Three inhomogeneities representing zones of constant transmissivity were modeled (Figure 17). Inhomogeneity properties are summarized in Table 6. The regional transmissivity, representative of large-scale conditions in the aquifer, includes most of the model domain. A local zone of low transmissivity was included where the 1,500-Foot sand is observed to be thin or absent (Griffith and Lovelace, 2003b). A local high transmissivity zone was included to the east of the zone of low transmissivity, including the East Baton Rouge area. This high transmissivity zone allows for model calibration to the local data sets while maintaining regional calibration of the model; the boundaries of the inhomogeneity were assumed. A porosity of 25% was used for the entire model domain. This assumed value is reasonable for sand is the same value assumed by the USGS (Tomaszewski, 1996).

6.2.5 Pumping wells and pumping centers

Withdrawals from the aquifer were represented in the model primarily by individual pumping wells. Two pumping well data sets obtained from the CAGWCC were used in modeling (CAGWCC, 2011): average 2001 pumping rates and average 2009 pumping rates for the 1,500-Foot sand (Table 7).

In addition, a large pumping center was modeled as a circular area element in the industrial area to the north of the Lula Station. The pumping center, identified by the USGS to be in the 1,700-

Table 5: Properties of the Baton Rouge Fault represented in the groundwater flow model.

	Calibrated model head variation (1200-Foot sand) (*ft msl*)	Calibrated model resistance (*days*)	Published values of resistance (*days*)	Source
Fault properties	0.0 to -20.0	2,000	1,927	Tsai and Li (2008b)
			6,452	Tsai and Li (2008a)

Note. ft msl=feet, man sea level

Table 6: Variations in transmissivity within the regional groundwater flow model.

Parameter	Regional value	Local value	Low T zone	Published values	Source
Transmissivity (ft^2/day)	8,000	12,000	800	10,230–12,090	Morgan (1961); Griffith (2003)
				4,300–12,000	Tomaszewski (1996)
				1,296–34,560	Huntzinger et al. (1985)

Note. ft^2/day=feet squared per day

Foot sand, was included in the model of the 1,500-Foot sand because the 1,500-Foot sand and the 1,700-Foot sand are considered to be hydraulically connected in this region (Prakken, 2004). During model calibration, we inferred a strong interaction between the aquifers in the industrial area; the large withdrawals in the 1,700-Foot sand are reflected in the potentiometric surface of the 1,500-Foot sand. The combined withdrawal of the 1,500-Foot and 1,700-Foot sands in the industrial area was documented as 11.28 mgd in 2001 by Prakken (2004). In 2009 and 2010, the total pumped by industry from the 1,500-Foot and 1,700-Foot sands was approximately 13 mgd, most of which was pumped from the industrial area (CAGWCC, 2011). The total withdrawal at the industrial pumping center specified in the model was 10.0 mgd. Additional industrial wells were specified individually in the model. These withdrawals include all wells listed in Table 7 with a USGS identifier of "EB-" and without a "BRWC-" identifier. Total industrial pumping in the model was approximately 13 mgd.

Well EB-1293, commonly referred to as the connector well, is modeled as a recharge-specified well in the 1,500-Foot sand. The connector well is a passive well connecting the 1,500-Foot sand and the 800-Foot sand. The head difference in the two aquifers produces a net flow from the 800-Foot sand to the 1,500-Foot sand. The flow rate has been measured by the BRWC to be approximately 475 gpm. The connector well acts to protect the Government Station from high salinity groundwater being drawn north across the Baton Rouge Fault.

6.3 Model calibration

Much discharge and head data is available for the 1,500-Foot sand, including annual pumpage collected by CAGWCC, periodic observations of water levels and chloride concentrations made by the USGS (Griffith and Lovelace, 2003b; Prakken, 2004), and measurements made during annual testing of the well fields operated by BRWC. However, interpretation of the existing data is difficult due to the transient conditions in the aquifer. Transient effects in the aquifer include seasonal variations in areal recharge and transient pumping at major pumping centers, combined with de-

Table 7: Pumping wells and average pumping rates in 2001 and 2009 in the Baton Rouge area. Note: wells WBR-112, -113, -132, and -173 are excluded as they lie to the south of the Baton Rouge Fault (CAGWCC, 2011).

BRWC	USGS			2001 rate		2009 rate	
Well ID	Well ID	Latitude	Longitude	*(mgd)*	*(gpm)*	*(mgd)*	*(gpm)*
Govt 3	EB- 413	30.44500	-91.14222	1.04	723	1.45	1010
	EB- 491	30.54686	-91.18177	0.14	100	0.00	1
Lula 17	EB- 510	30.46417	-91.15694	1.66	1156	1.50	1040
	EB- 561	30.55306	-91.20361	0.03	20	0.03	20
	EB- 655	30.55889	-91.21722	0.02	11	0.02	11
Lula 18	EB- 657	30.46417	-91.15889	0.22	155	0.34	233
Lula 19	EB- 658	30.46250	-91.15667	1.47	1024	1.18	816
Lula 20	EB- 726	30.46278	-91.15472	1.33	921	1.61	1119
	EB- 748	30.58547	-91.24289	0.00	0	0.00	0
Govt 6	EB- 771	30.44611	-91.14389	0.76	529	1.19	826
Robin 1	EB- 773	30.52556	-91.17556	0.83	575	0.68	470
N45th 3	EB- 927	30.45472	-91.14417	0.74	514	1.65	1145
Lula 22	EB- 938	30.46361	-91.15778	1.58	1100	1.33	923
Lula 23	EB- 939	30.46389	-91.15556	1.31	907	1.14	795
Cortana 5	EB- 961	30.45472	-91.08722	0.59	409	0.20	140
	EB- 963	30.64750	-91.27028	1.55	1073	1.32	917
	EB- 969	30.61250	-91.23139	0.04	29	0.04	29
	EB- 970	30.61278	-91.23222	0.01	10	0.00	0
	EB- 977	30.55972	-91.20611	0.18	122	1.00	695
	EB- 984	30.55722	-91.19667	0.39	268	0.20	139
	EB-1048	30.58241	-91.24122	0.14	97	0.16	109
	EB-1155	30.58408	-91.24011	0.14	97	0.21	144
	EB-1260	30.58435	-91.24733	0.02	12	0.00	1
Stumberg 2	EB-1295C	30.40139	-91.03861	0.28	197	0.23	163
	EF- 225	30.96768	-91.10316	0.05	33	0.04	30
	EF- 252	30.85907	-91.05649	0.08	57	0.00	0
	EF- 296	30.91667	-91.11444	0.06	41	0.05	36
	PC- 268	30.63408	-91.35011	0.13	88	0.09	65
	PC- 276	30.56797	-91.54845	0.16	109	0.12	82
	WBR- 103	30.42297	-91.20761	0.03	18	0.00	0
	WBR- 176	30.54158	-91.36289	0.21	146	0.26	178
	WBR- 177	30.54102	-91.40400	0.21	146	0.26	178

Note. mgd=million gallons per day, gpm=gallons per minute creasing water level trends in the aquifer due to increases in annual pumping. While the storage coefficient for the aquifer is estimated to be very small, the distance to aquifer boundaries is very large making observed fluctuations difficult to interpret. Water level observations in the 1,500-Foot sand show yearly and seasonal fluctuations of heads up to 20 ft, presumably due to to a combination of seasonal variations in recharge and pumping rates.

Many of the observation wells monitored by the USGS are also production wells. Griffith and Lovelace (2003b) state that USGS measurements of water levels in production wells were taken after shutting the wells down. Water levels were recorded after an appropriate recovery period, but the period of time is not provided. An aquifer may take many days to equilibration when pumping wells are shut off. Further, measurements made in resting production wells often occur near other operating wells in pumping centers; the water levels monitored in the resting wells are sensitive to the pumping rate of the well field at the time the measurements were taken.

Despite the difficulties in interpreting the data, the groundwater flow model was calibrated to several sets of the available data. First, the regional model was calibrated to a USGS data set of observed heads collected in 2001. Second calibrations of the local model in the area of the BRWC well fields was conducted using well performance data collected by the BRWC. Finally, the local value of transmissivity calibrated with the model was verified by a pumping test performed at the new Progress Park observation well (Section 5.4).

6.3.1 Regional calibration

A data set collected by the USGS and consisting of 21 observations made between April and June 2001 (Griffith and Lovelace, 2003b) was used to calibrate the regional model parameters. The model was tested first by calculating head residuals at observation wells with all wells pumping at the average 2001 rate. The 2001 pumping rates were obtained from the CAGWCC, and are presented in Table 7. Results showing head residuals (modeled head minus observed head) are presented in column seven of Table 8. When observations were made at significant pumping centers, the steady-state model was run after shutting off one pumping well at a time and recording the model head value at that well, to mimic the data collection process documented by Griffith and Lovelace (2003b). Those observation wells are identified in columns eight and nine of Table 8. The composite residuals at observation wells, shown in the last column of Table 8, are obtained by combining the residuals at non-pumping centers (column seven) with the residuals calculated at the pumping centers (column nine). A similar procedure was followed for a data set of three head observations made in April, 2009 (Table 9).

The composite residuals provided in Table 8 and residuals provided in Table 9 are presented graphically in Figure 18. The figure is a comparison of observed and modeled head values; a perfect fit

Table 8: Composite model residuals using the 2001 USGS regional data set (Griffith and Lovelace, 2003b). Values in red indicate approximate well locations.

BRWC Well ID	USGS Well ID	Latitude	Longitude	Observed head *(ft msl)*	Model head, wells on *(ft msl)*	Residual *(ft)*	Model head, wells off *(ft msl)*	Residual *(ft)*	Composite residual *(ft)*
	EB- 392	30.47889	-91.06000	-56.0	-54.3	1.7			1.7
Govt 3	EB- 413	30.44500	-91.14222	-102.7	-125.7	-23.0	-97.0	5.7	5.7
	EB- 561	30.55306	-91.20361	-64.2	-61.0	3.2			3.2
Lula 18	EB- 657	30.46417	-91.15889	-135.2	-143.7	-8.5	-137.5	-2.3	-2.3
Robin 1	EB- 773	30.52556	-91.17556	-88.3	-94.5	-6.2	-66.2	22.1	22.1
	EB- 917	30.43722	-91.14167	-99.2	-106.0	-6.7			-6.7
N45th 3	EB- 927	30.45472	-91.14417	-99.2	-126.7	-27.5	-106.6	-7.4	-7.4
Cortana 5	EB- 961	30.45472	-91.08722	-67.0	-88.2	-21.2	-68.1	-1.1	-1.1
	EB- 963	30.64750	-91.27028	-61.4	-124.4	-63.0	-74.8	-13.4	-13.4
	EB- 970	30.61278	-91.23222	-48.8	-54.8	-6.0			-6.0
	EB- 996	30.53028	-91.15917	-73.9	-72.2	1.6			1.6
	EB-168	30.50397	-91.15982	-92.8	-89.7	3.1			3.1
	EB-1152	30.57778	-91.23656	-56.5	-54.1	2.4			2.4
	EF-210	30.97440	-91.16841	123.5	123.5	0.0			0.0
	Li-195	30.59657	-90.89743	47.0	24.9	-22.1			-22.1
	PC-39	30.83457	-91.69316	28.1	81.8	53.7			53.7
	PC-268	30.63408	-91.35011	-40.0	-26.8	13.1			13.1
	PC-276	30.56797	-91.54845	-55.7	12.6	68.3			68.3
	PC-280	30.84591	-91.65874	24.7	84.2	59.4			59.4
	WBR-176	30.54158	-91.36289	-36.9	-29.3	7.6			7.6
	WBR-177	30.54102	-91.40400	-34.0	-19.2	14.8			14.8

Note. ft msl= feet, mean seal level

Table 9: Model residuals for the 2009 data set in East Baton Rouge.

BRWC Well ID	USGS Well ID	Latitude	Longitude	Observed head *(ft msl)*	Model head *(ft msl)*	Residual *(ft)*
	EB-392	30.47889	-91.06000	-69.0	-60.1	8.9
Robin 1	EB-773	30.52556	-91.17556	-91.5	-98.0	-6.5
	EB-917	30.43722	-91.14167	-123.4	-119.9	3.5

Note. ft msl= feet, mean seal level

Table 10: Combined calibration statistics (2001 and 2009 data).

Statistic	Regional data	East Baton Rouge data
Number of observations	24	16
Head change over model *(ft)*	258.7	86.5
Maximum residual *(ft)*	68.3	22.1
Minimum residual *(ft)*	-22.1	-13.4
Mean absolute error *(ft)*	13.9	6.0
MAE, % of head change	5.3	6.9
Root mean square error *(ft)*	23.3	7.9
RMSE, % of head change	9.0	9.1

Note. ft=feet

of modeled to observed values would be indicated by all data points lying on the line of slope 1. The location of each of the observation wells is identified in Figure 18 by the parish in which it resides. Calibration statistics are presented in Table 10; the data is presented for both the regional data set and the subset of that data that lies within the East Baton Rouge Parish. Regionally, the head residuals vary from -22.1 ft to +68.3 ft, with a Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of 5.3% and 9.0% of the total head change, respectively. In East Baton Rouge, the residuals vary from -13.4 ft to +22.1 ft, with the MAE and RMSE being 6.9% and 9.1% of the total head change, respectively.

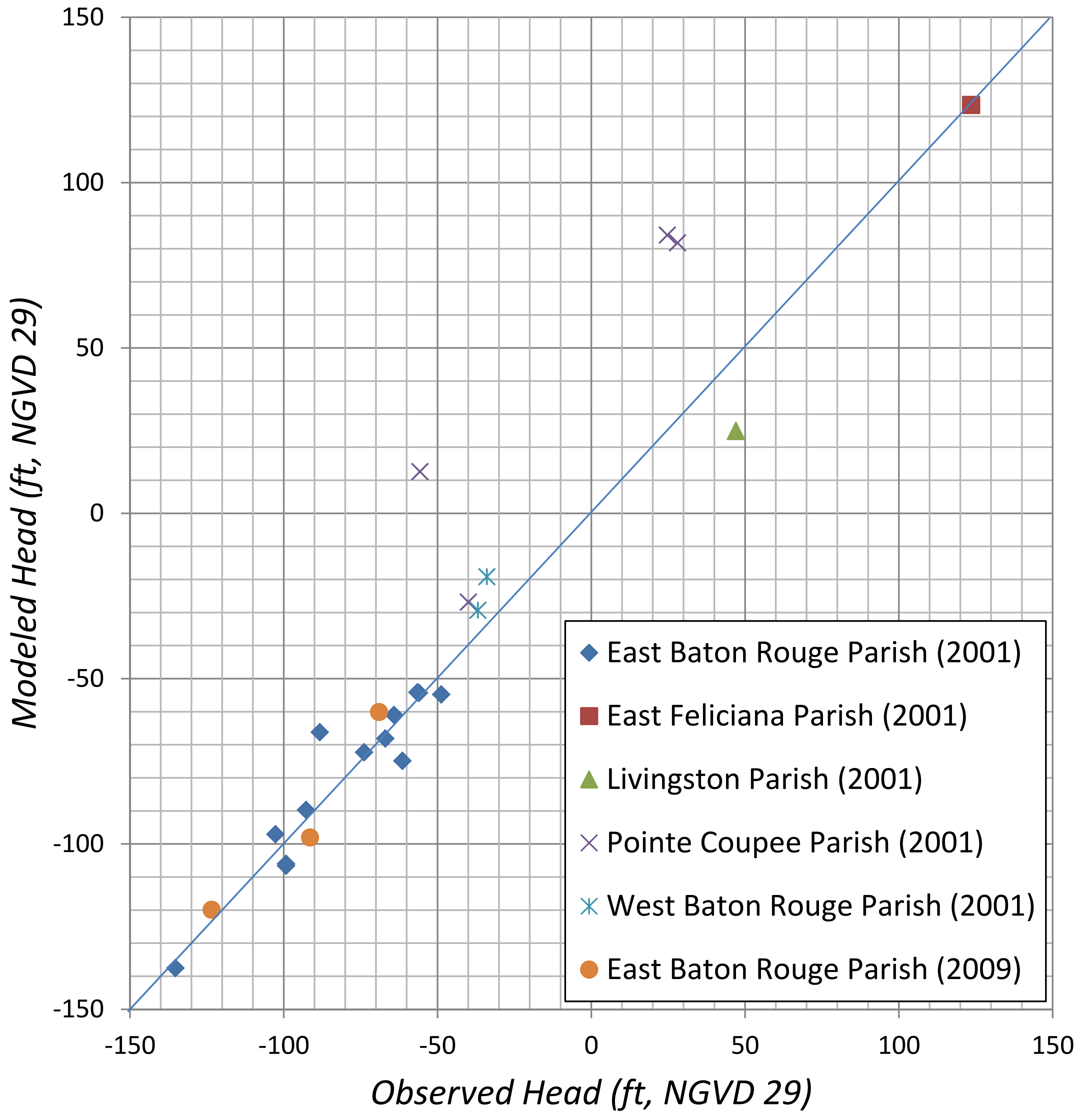


Figure 18: Model residuals for the USGS 2001 data set.

As illustrated in Figure 18, larger residuals occur outside of East Baton Rouge Parish, particularly in Point Coupee Parish. This indicates that there are hydrologic features in that parish not represented in the model. However, the observation wells with large residuals are far from the area of interest (the East Baton Rouge area) and are separated from it by significant hydrologic boundaries including a large pumping center to the north and a zone of low transmissivity to the east.

6.3.2 Local calibration

Model calibration was tested and refined locally in the East Baton Rouge area using data from BRWC annual well testing, performed in the fall and spring of each year. Testing procedures include shutting down all wells in a well field for four hours before measuring the static water level in the well and conducting a step-drawdown test. During the test, the discharge is increased in steps, allowing time for stabilization of water levels at each step. Measurements of drawdown are made for each pumping rate. Records for each well extend back to 1991, providing an extensive history of static water levels and well field drawdowns.

This well field testing data was used in two ways. First, the history of static water levels at each well was compared to steady-state heads predicted with the groundwater flow model. Average pumping rates for 2009 were specified in the model; a separate model run was made for each of the BRWC wells, individually setting the pumping rate to zero and computing the static water level at the well. This approach avoids dealing with well efficiencies as the wells are not pumping when measurements are made. Figure 19 illustrates the comparison of observed static heads at BRWC pumping wells with the model results. The figure clearly shows the difficulties in calibrating the steady-state groundwater flow model. The blue bars indicate the range of observed statics over the record, which for most wells extends from 1991 to 2009. The range of observed values is large, greater than 40 ft in all wells and nearly 80 ft at Lula Well 20. The large range is due to a combination of seasonal effects, short term transient effects due to wells turning on and off, and a trend of decreasing water levels in the aquifer over the past 20 years. In addition, the figure displays the average static heads for both the fall and spring well-testing records. In all cases, the spring observations are higher than the fall observations, and the range at each well indicates the average seasonal effect on static water levels. In all cases, the model results lie within the observed range of static water levels, with most results lying between the average fall and spring observations. The exceptions include Lula Well 18 where the model results are lower than the spring and fall averages, and Lula Well 20 where the model results are higher than the spring and fall averages.

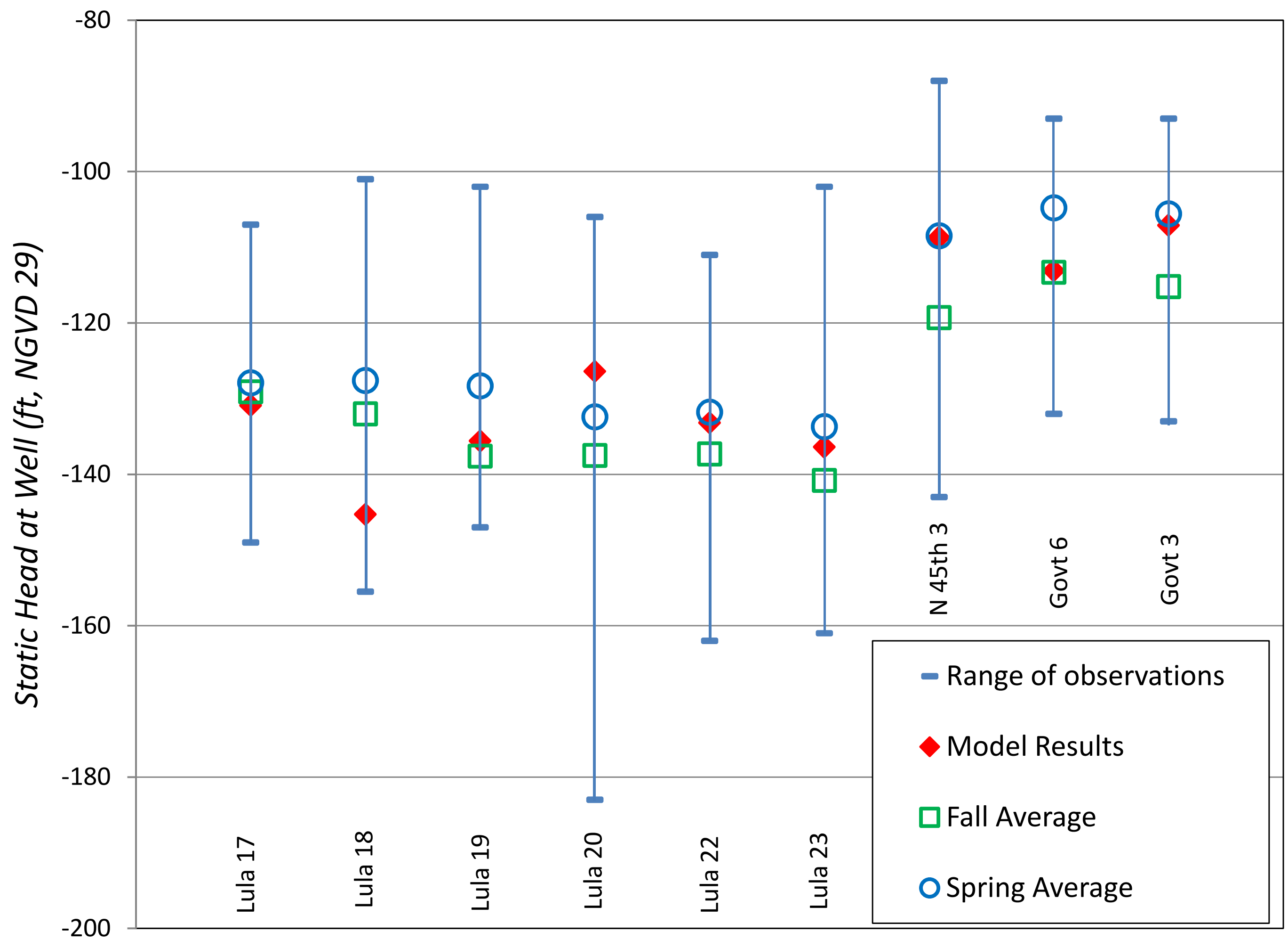


Figure 19: Comparison of modeled and observed static levels at BRWC wells. Observed values span the years 1991-2009, and the observed range is shown as the blue line. Fall and Spring average values are shown with the model results.

In addition, the most recent well-testing records were used for Lula Wells 19, 22, and 23 to investigate the rating curves for the wells. Records from Fall 2009 and Spring 2010 testing were compared with model results of drawdown for increasing pumping rates. Drawdown was evaluated at the radius of the well in the model. Figure 20 shows the observed rating curves for the fall (green) and spring (blue) testing compared to those obtained from the groundwater flow model (red). In general, the model rating curves follow the shape of the observed rating curves, indicating that the model behavior is similar to observations. This confirms that the transmissivity specified in the model is accurate. Further comparison or calibration based on the testing data is difficult as the model results do not include head losses due to the screen (well efficiency), and it is unlikely that the field testing procedures used would result in steady state conditions. If we assume high-efficiency wells and neglect screen losses, the model results should over-predict the drawdown due to non-steady conditions during observations. This behavior is displayed for Wells 19 and 23. Model results for Well 22 lie between the fall and spring rating curves. Evidence that steady state conditions are not achieved during well testing is provided by the COLOG testing performed by Layne in June 2010 (Section 5). During that testing, Lula Well 19 was shut off for up to 2 weeks prior to testing, and then pumped for 30 hours at 725 gpm. Both the resting and pumping periods were significantly longer than those during the annual well-testing. The drawdown observed during the COLOG test at the end of the pumping period was 28.9 ft; results from the groundwater flow model for a pumping rate of 725 gpm indicate a drawdown of 30.0 ft at Lula Well 19. These values compare much better than those shown in Figure 20 for Lula Well 19, suggesting that Lula Well 19 has a high efficiency, and steady state conditions are not achieved during the annual well testing.

6.4 Current conditions in the 1,500-Foot sand

Model results showing conditions in the 1,500-Foot sand representative of 2009 pumping rates are presented in Figure 21 and Figure 22 for the area between the Baton Rouge Fault and the Lula Station. In both figures, the contours represent the average potentiometric head in the region. It is also apparent that the cone of depression in the potentiometric surface is centered at the Lula Station, with heads less than -155 ft (NGVD 29). At the fault the lowest head is approximately -117 ft. The blue arrow in Figure 21 represents the total leakage through the fault in this region induced by 2009 pumping rates (910 gpm or 1.3 mgd). The modeled leakage rates vary along the length of the fault in proportion to the head change across the fault.

In both figures, the estimated position of the salt front in 2005 (Lovelace, 2007) is shown as the pink shaded area. Path lines representative of the groundwater flow in the region are presented on Figure 22. In general, the path lines generated with the groundwater flow model are consistent with the estimated shape of the area of saltwater encroachment. The freshwater cell flowing from the connector well to the Government Station wells is also illustrated on Figure 22 with light blue

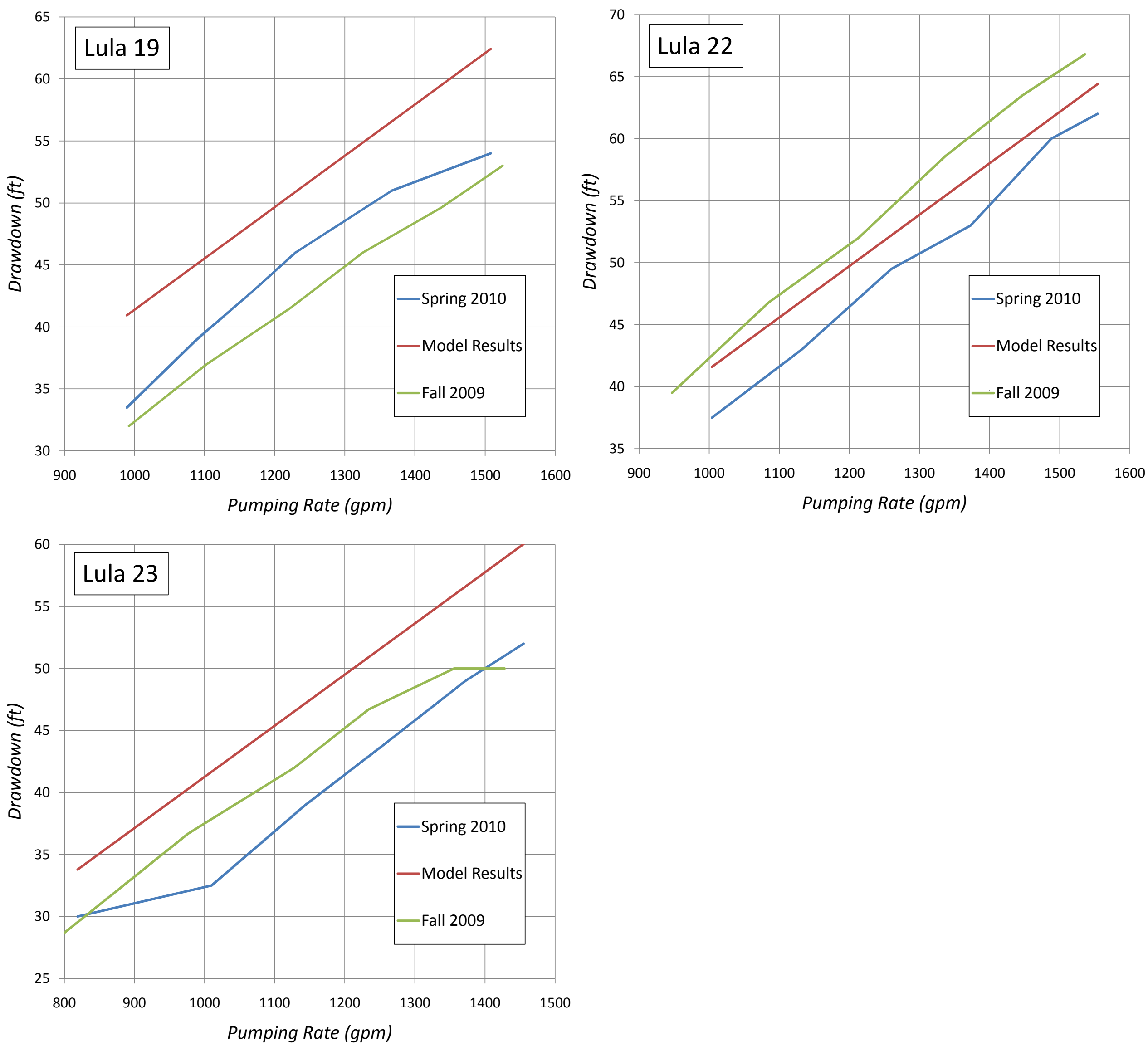


Figure 20: Comparison of drawdown from annual spring and fall well-testing with model results for BRWC wells.

shading. The path lines overlain on the estimated region of encroachment show some saltwater reaching the Government Station, and no saline water reaching the North 45thStation. These results are consistent with chloride monitoring results at the two stations. Historically, the connector well has protected the Government wells from encroaching saltwater; this behavior is reflected by the model.

Figure 23 shows path lines traced backward from Lula Well 19; the region contained within the bounding path lines is the capture zone of the well. The path lines are color coded to represent the travel time to the well. The light blue path lines end at 2.5 year travel time to the well. The dark blue lines end at a 5 year travel time to the well. From the figure it is seen that, under current pumping conditions in the aquifer, the travel time from the Progress Park observation well to Lula Well 19 is 2.5 years. This estimate is based purely on advection of the high chloride groundwater. We note that the capture zone for Well 19 contains much of the chloride plume. As the plume approaches the Lula Station, Well 19 will act as an interceptor well, partially shielding the other Lula Station wells.

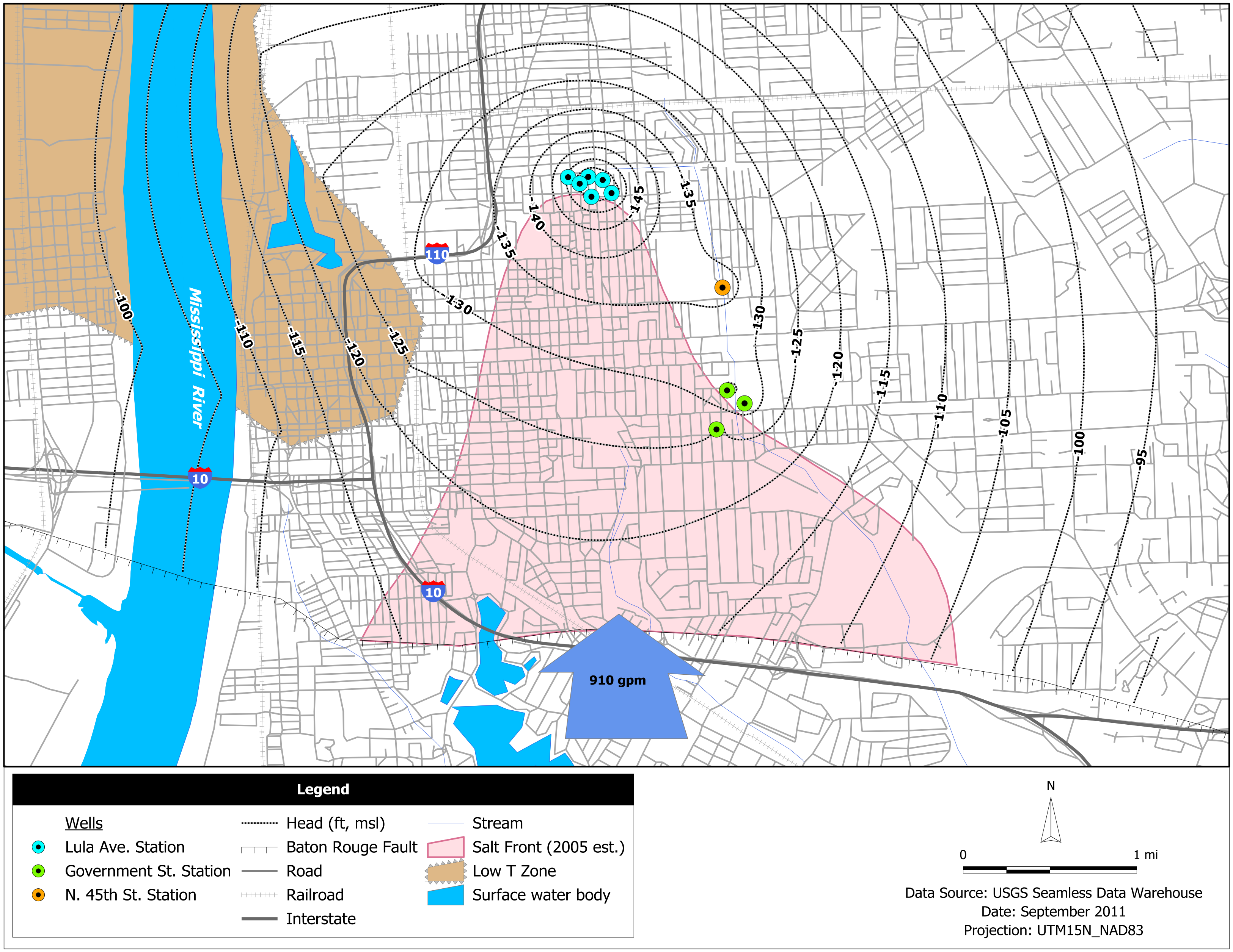


Figure 21: Model results: contours of head in the 1,500-Foot sand in and around East Baton Rouge Parish, 2009 pumping rates.

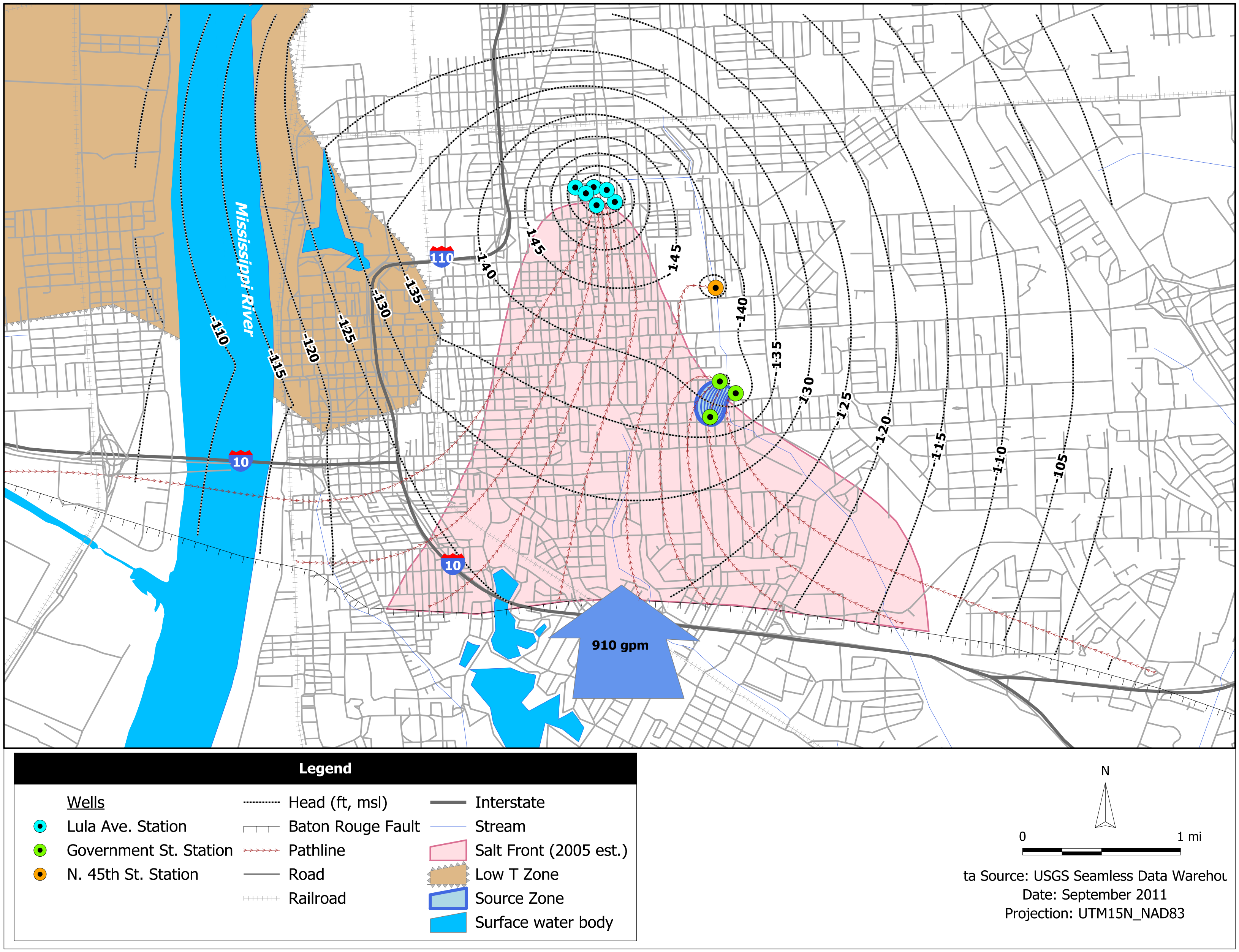


Figure 22: Model results showing: path lines and contours of head in the 1,500-Foot sand in and around East Baton Rouge Parish, 2009 pumping rates. The zone of circulated water from the connector well to the Government Street Station is indicated by the light blue area. The location of the connector well is estimated.

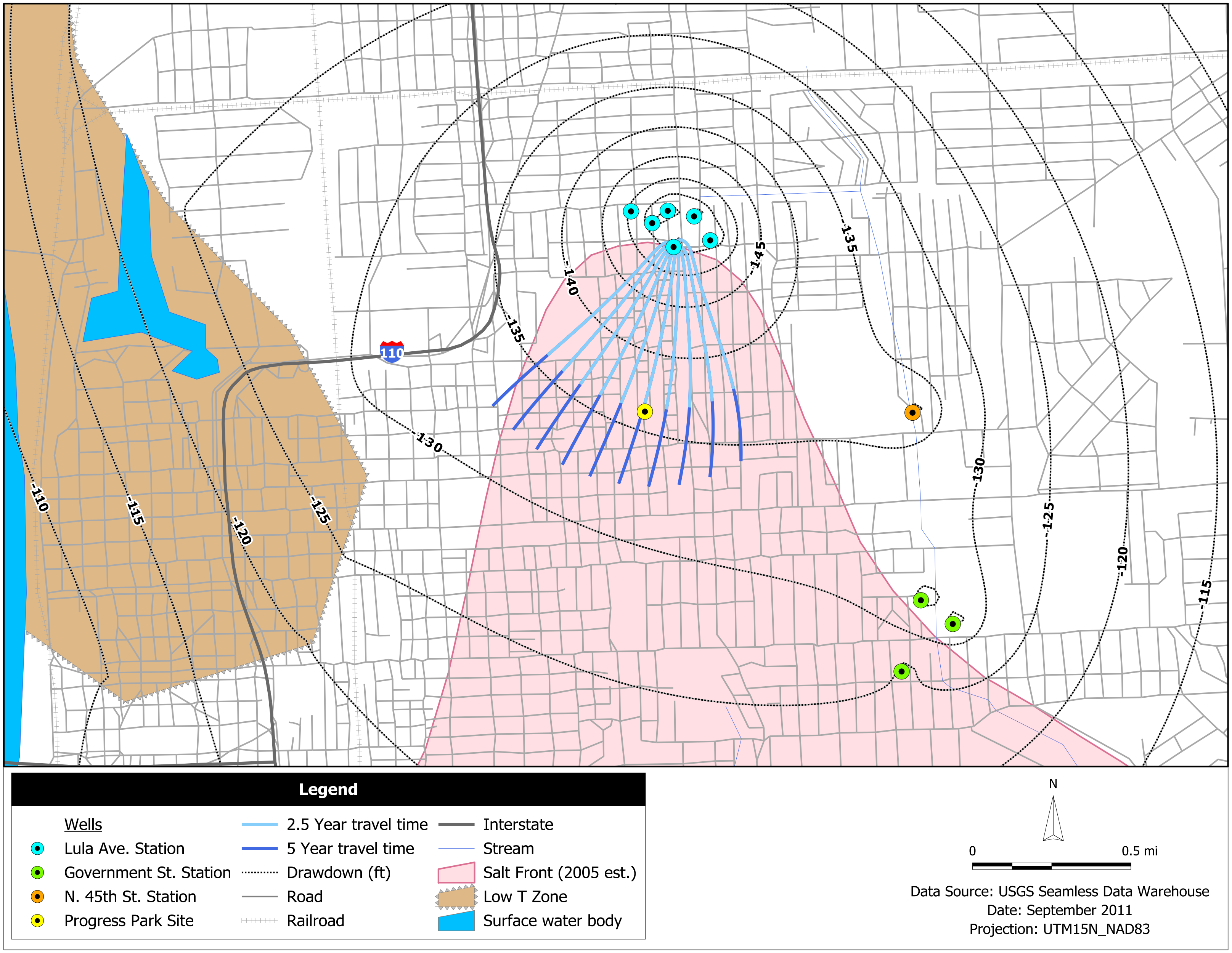


Figure 23: Model results showing the 2.5 year and 5 year capture zones for Well 19.

7 Remedial Options

Potential methods for controlling the encroachment of saltwater from the Baton Rouge Fault have been discussed for over 40 years (Rollo, 1969; Whiteman, 1979; Tomaszewski, 1996). The proposed methods generally include recharge or discharge barrier wells. Recharge wells could be used to inject water into the 1,500-Foot sand with the objective of creating a hydraulic barrier between the Lula Station and the saline water approaching from the south. Similarly, discharge wells could be used to form a hydraulic barrier by creating a low-head trough intended to intercept saline water before it reaches the Lula Station. For the purpose of this report, we will refer to recharge and discharge barrier wells as recharge and interceptor wells, respectively. More recently, scavenger wells have been proposed as a way to control saltwater encroachment (Tomaszewski, 1996). Assuming that the aquifer is stratified with the denser saline water at the bottom, scavenger wells could be used to capture only the saline water from the bottom of the aquifer.

Three general approaches for extending the life of the Lula Station were considered:

A. Recharge wells

B. Interceptor wells

C. Scavenger wells

The tradeoffs for the three approaches include considerations of effectiveness, capital costs, operating cost, saltwater disposal (approaches B and C), and freshwater source (approach A). Each option is described below and assessed through predictive modeling. We also discuss the expected future trends in chloride concentrations at Progress Park; we provide estimates of the time over which the chloride concentrations are expected to double.

Finally, we investigate the effects of shutting off all industrial wells in East Baton Rouge Parish pumping from the 1,500-Foot sand. We quantify the resulting increase in head in the aquifer, the decrease in leakage rates across the fault, and the decrease in groundwater velocities between the fault and the Lula Station, using the groundwater flow model.

7.1 Recharge Wells

Recharge wells have been used successfully to control saltwater intrusion in coastal areas all over the world. This approach would involve injecting freshwater into the aquifer, thereby creating and maintaining a hydraulic barrier between the Lula Station and the fault. This approach is currently helping to mitigate salt levels in the Government Street supply wells, as described in Section 4.5.

The primary advantages of the recharge well approach for protecting the Lula Station is that:

- Saltwater encroachment can potentially be controlled without having to dispose of saline water.
- There are no potential negative impacts on production.
- There are only positive impacts on the leakage rate across the fault.

The disadvantages of this approach include:

- high capital costs
- the need for a consistent supply of high-quality freshwater
- the possibility of saline groundwater traveling around the freshwater ridge and after several years of operation, high chloride levels reappearing at the Lula Station
- the possibility of saline groundwater being redirected by the freshwater ridge toward the North 45th and Government Stations, resulting in increased chlorides at those wells

Figure 24 illustrates results from the groundwater flow model after placing three recharge wells approximately 2,500 feet south of the Lula Station. The injection rate of each of the wells was 500 gpm, and was based on the flow rate obtained by EB-1293, the connector well near the Government Station. The choice of spacing, location, and injection rates of the wells was for demonstration only, and was based on the width of the saline plume as estimated by Lovelace (2007). Figure 25 shows model results representing current conditions in the aquifer, for comparison with Figure 24. Contours shown on the figures represent the potentiometric head in the aquifer. By comparison with Figure 25, heads at the Lula Station are increased up to 30 ft by the presence of the recharge wells. Leakage through the fault was decreased from 910 gpm without the recharge wells to 710 gpm with the recharge wells.

Path lines indicating the direction of groundwater flow are also shown in Figures 24 and 25. Groundwater flow originating at the recharge wells is indicated by the purple pathlines in Figure 24, with arrows indicating the direction of flow; all water injected is captured at the Lula Station, primarily by Lula Wells 19, 20, and 22. Red path lines are shown in Figures 24 and 25 south of the Lula Station, beginning at regular intervals across the estimated region of saline water. By comparison of the figures we see that much of the saline plume is diverted by the recharge wells to the east, increasing the saline water captured by the North 45th and Government Stations. Some of the saline water flows between the recharge wells, with some bypassing the recharge wells to the east and west and eventually reaching the Lula Station. The heavy blue arrows in Figure 24 indicate travel

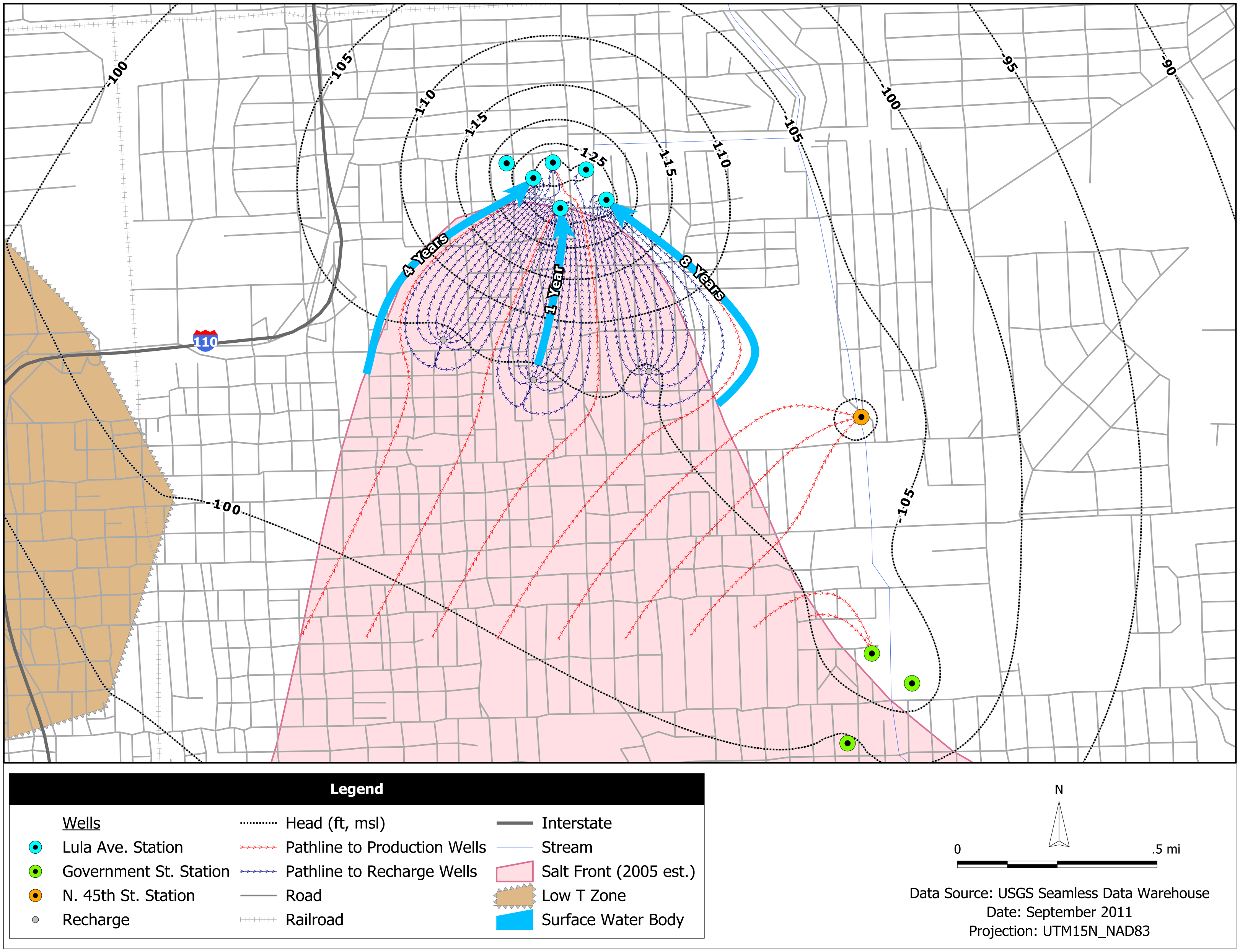


Figure 24: Recharge wells south of the Lula Station: pathlines and contours of potentiometric head.

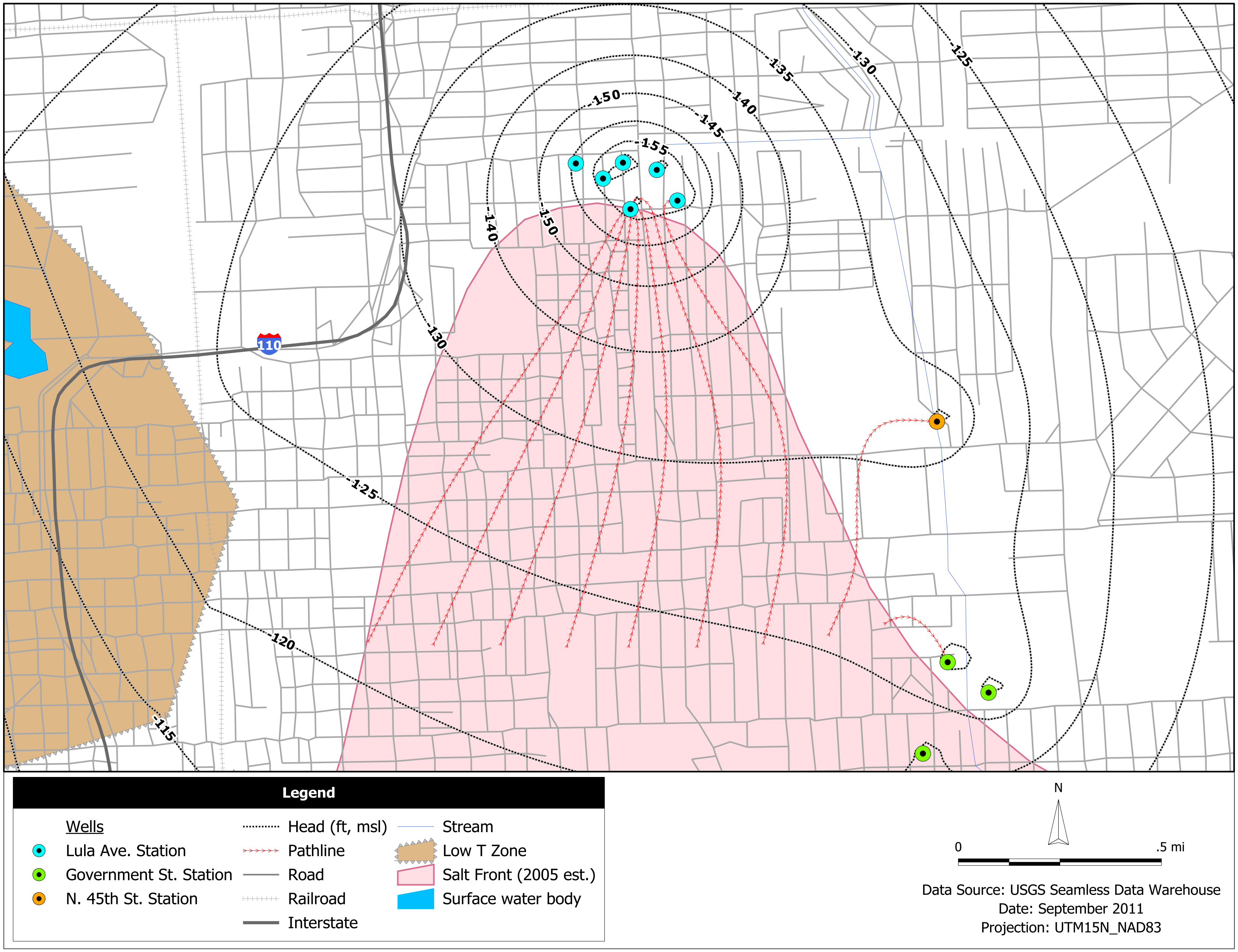


Figure 25: Current conditions with 2009 pumping rates: pathlines and contours of potentiometric head.

times in the aquifer. Travel time from the center recharge well to Well 19 is approximately 1 year, indicating that much of the saline water currently within 2,500 feet of the Lula Station would be flushed out relatively quickly. Saline water is shown bypassing the recharge wells to the west with a travel time of approximately 4 years, and to the east the travel time is approximately 8 years.

The recharge wells divert the saline plume to the west and the east of the Lula Station. Based on the model results, we anticipate that installation of the recharge wells will result in a flushing of the saline water lying between the recharge wells and the Lula Station out of the aquifer within one to two years, thereafter reducing the chloride concentration at Well 19. However, within a period of four to eight years, increasing chloride levels will be observed at the other Lula wells as the chloride plume is diverted around the recharge wells. In that same period of time, the chloride levels would be expected to rise at the Government and North 45th Stations, with the most significant increases occurring at the North 45th Station.

7.2 Interceptor wells

Interceptor wells or capture wells have been used successfully in various applications and settings to prevent the movement of contaminated groundwater. This approach would involve placing new wells to intercept saline water traveling north toward the Lula Station.

The advantage of this approach is that it could have positive effects on BRWC wells at the Government and North 45th Stations as well as the Lula Station. However, there are several disadvantages associated with this approach. In order to achieve capture zones that extend the width of the saltwater tongue, the capture system would require high-capacity wells that pump water from the entire vertical section of the aquifer. In addition, a system of high-capacity wells will lower water levels in the area. This will increase drawdown in existing BRWC wells and increase the hydraulic gradient across the fault, likely causing a higher leakage rate.

Potential locations for effective interceptor wells were identified based on preliminary modeling results and the presence of undeveloped land identified on aerial photos. The undeveloped area within and surrounding Kernan Avenue Park was identified as a suitable location for capture of the plume.

7.2.1 A single interceptor well near Kernan Avenue Park

The capture zone envelope for a 1 mgd (694 gpm) interceptor well placed at Kernan Avenue Park is shown in Figure 26. The capture zone extends from the well to the south, increasing in width as it approaches the fault. A single well pumping at 1 mgd is shown to be effective at capturing much of the estimated saltwater tongue. Contours of drawdown in the aquifer caused by the well are also shown on the figure.

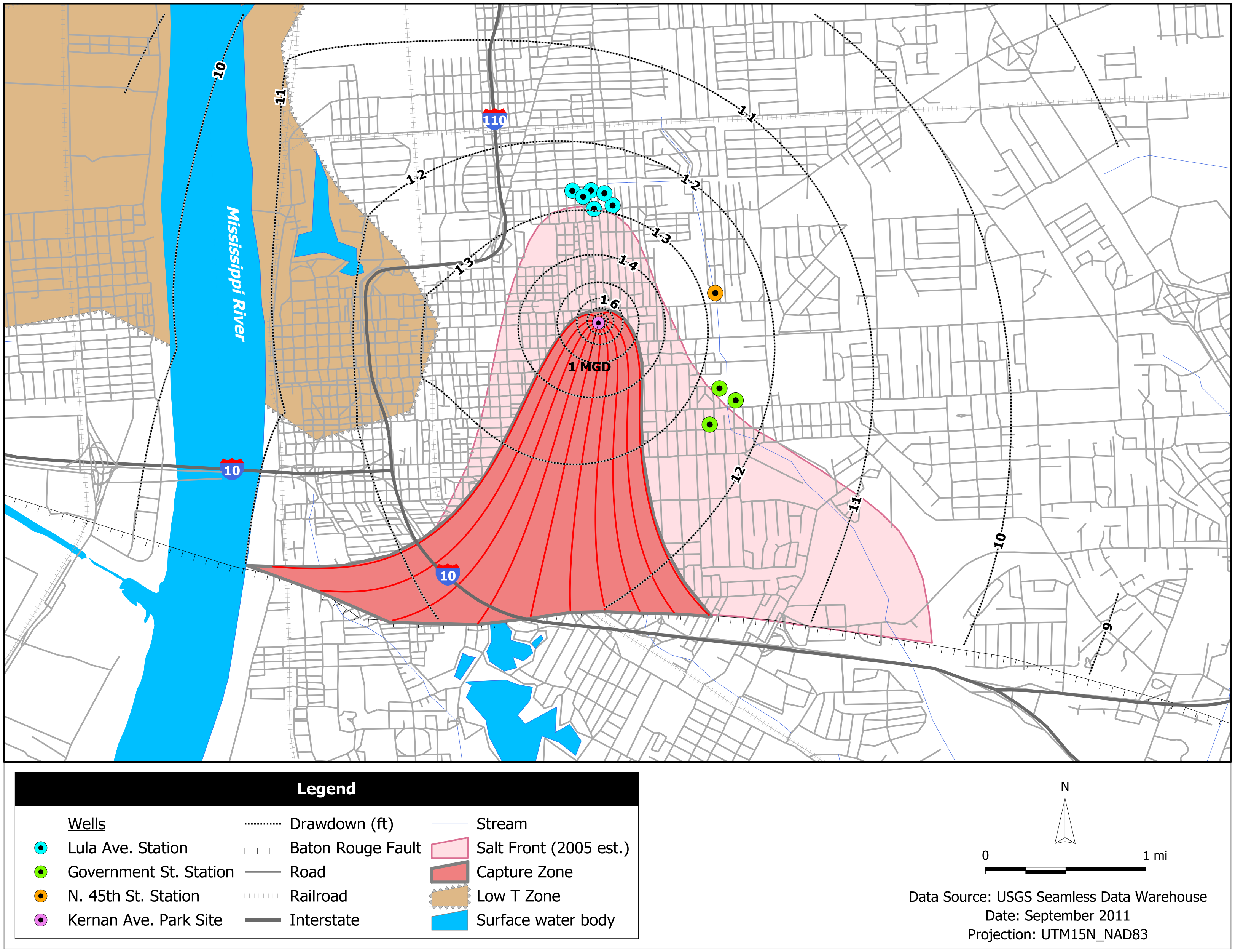


Figure 26: A single interceptor well pumping 1 mgd (694 gpm) at Kernan Park.

7.2.2 Potential effects on the Lula, Government, and North 45th Stations

An interceptor well placed at Kernan Avenue Park and pumping at a rate of 1 mgd will have impacts on the hydraulic conditions at the other BRWC pumping stations. First, as illustrated in Figure 26, the additional drawdown due to the interceptor well at the Lula, Government, and North 45th Stations is 12.5 ft to 13.0 ft: the operating head at the pumping stations will decrease. The rate of leakage across the Baton Rouge Fault is increased by the new pumping well. In the region extending from the east bank of the Mississippi River to the east edge of the saline plume, the leakage across the fault is estimated to be 1000 gpm, a 90 gpm (10%) increase over current conditions.

The effects of the interceptor well on chloride concentrations at the Lula Station will be to reduce the long-term chloride concentrations, as much of the chloride plume will be extracted before reaching the Station. Figure 27 shows path lines to Lula Well 19 after installation of the interceptor well; the path lines are color coded based on the groundwater travel time to the well. The effect of the interceptor well on the capture zone of Well 19 is to shift the capture zone to the east and west of the interceptor well capture zone (compare with Figure 23). We expect that chloride concentrations at the eastern and western edges of the plume are lower than at the center of the plume which is captured by the extraction well, although direct field evidence of this is not available. Based on model results shown in Figure 27, we anticipate that chloride concentrations at Well 19 may continue to rise over a five year period following installation of the interceptor well. This is the time frame required to capture the portion of the chloride tongue lying between the interceptor well and the Lula Station. Following that 5 year period, we expect the chloride concentrations at Well 19 to decrease as the lower chloride groundwater from the east and west edges of the plume reach the well.

As further illustrated on Figure 27, the combined effect of the capture zones of the interceptor well and Well 19 is to shield all other production wells at the Lula Station from drawing high chloride water from the plume. The capture zones for the remaining Lula Station wells are shifted further to the east and west, capturing water not originating from the fault. Although we expect the chloride concentrations at Well 19 to decrease over time, regardless of what happens at Well 19, the well must not be shut off. The well acts as the last defense of the well field against chloride contamination of the remaining wells. Shutting down Well 19 due to high chloride levels will quickly result in chloride contamination of the other Lula wells. In addition, the capture zone for Well 19 as shown in Figure 27 acts to shield the Government and North 45th Stations from increases in chloride. We anticipate that chloride concentrations at the Government and North 45th Stations would stabilize at low levels after construction of the interceptor well.

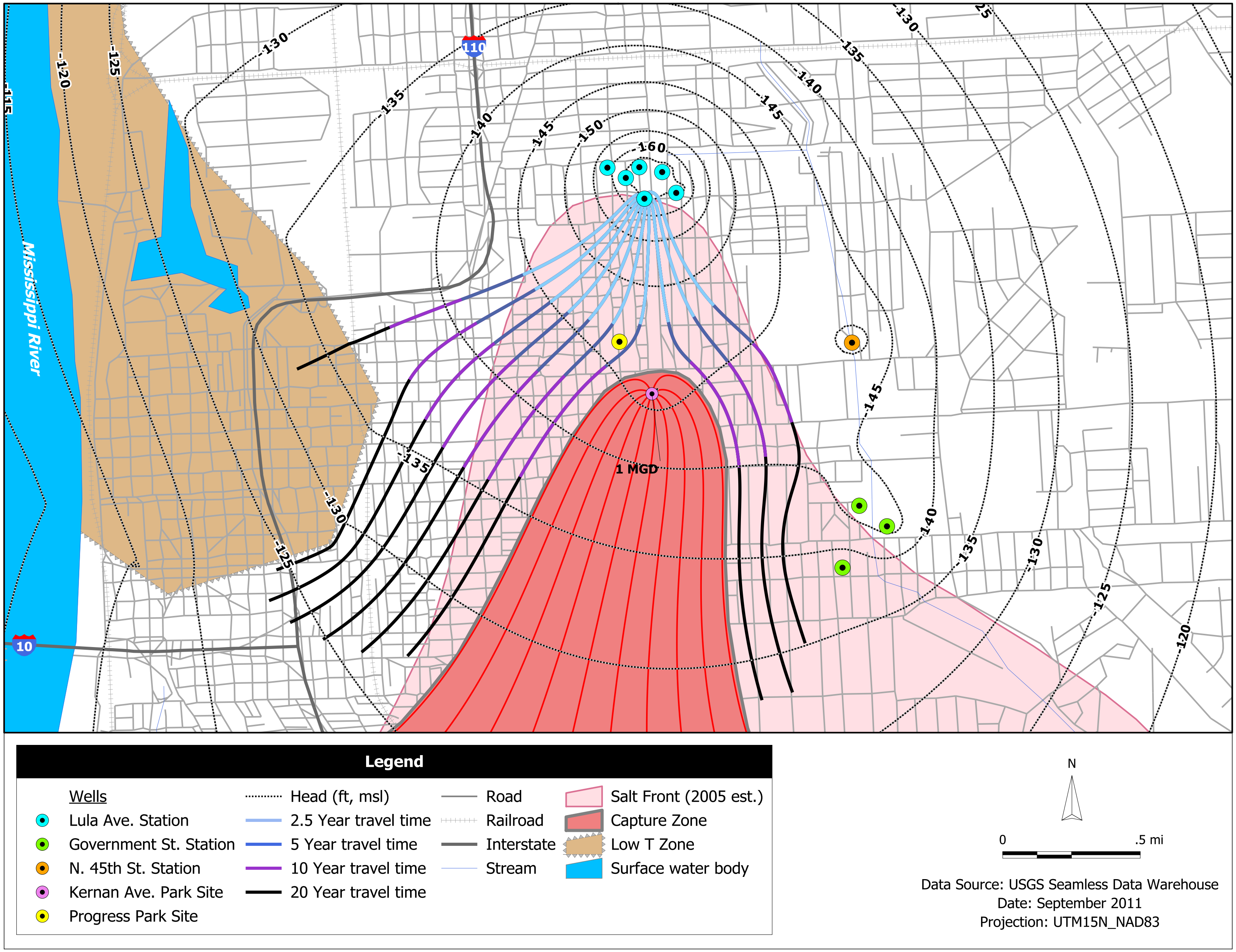


Figure 27: Behavior of the capture zone for Lula Well 19 after placement of a single interceptor well at the Kernan Avenue Park location.

7.2.3 Multiple interceptor wells

Our current understanding of the 1,500-Foot sand, which was implemented in the groundwater flow model, suggests that a single well placed at Kernan Avenue Park and pumping at 1 mgd is adequate to capture a significant portion of the saline plume. If, after installation, it is found that it is not possible to pump 1 mgd from a single interceptor well placed at that location, additional interceptor wells may need to be constructed. Predictive simulations were made for the cases of one and two additional interceptor wells. The second interceptor well is placed in the model to the southwest of Kernan Park at the corner of North Boulevard and South Eugene Street.; the third well is placed to the southeast of Kernan Park at the corner of Convention Street and South Acadian Thruway. These sites were chosen based on the presence of undeveloped space identified on aerial photos.

Figure 28 shows the combined capture zone for two interceptor wells each pumping at 0.5 mgd (347 gpm); Figure 29 shows the combined capture zones for three interceptor wells each pumping at 0.33 mgd (231 gpm). In both figures, contours of potentiometric head in the aquifer are shown. By comparing Figures 26, 28, and 29, we see that the size and shape of the combined capture zones for one, two and three wells are very similar. Also, by comparing Figure 27 to Figure 28 and 29, we see that the potentiometric heads in the aquifer are very similar for the three cases. The effects of the two and three well systems on aquifer drawdown and flow conditions at the Lula, Government, and North 45th Stations and at the Baton Rouge Fault are nearly identical to the effects of the one well system.

7.2.4 Use of the Progress Park well as an interceptor well

The Progress Park well could be used as an interceptor well in combination with other wells. Using the Progress Park well alone as an interceptor well is not a viable long-term solution because the pumping rate of this well is limited. From field testing, we know that pumping rates of 200 gpm may be achieved with moderate drawdown at the well; pumping rates up to 400 gpm may be possible if lower pumping levels at the well are allowed. Figure 30 shows capture zones for the Progress Park well pumping at rates of 200 gpm and 400 gpm, for comparison. The capture zone for the Progress Park well extends south and west of Progress Park. Based on these results, using the Progress Park well as an interceptor well would provide control of the western portion of the saltwater plume that is south of Progress Park, but would not provide any control for saltwater moving north that is east of Progress Park. In addition, using the Progress Park well as an interceptor well alone does not appreciably decrease the travel time between Progress Park and the Lula wells. In other words, it does not slow the migration of saltwater that has already moved north of Progress Park. Use of the Progress Park well in combination with a scavenger well couple at Kernan Park is discussed in Section 7.3.3.

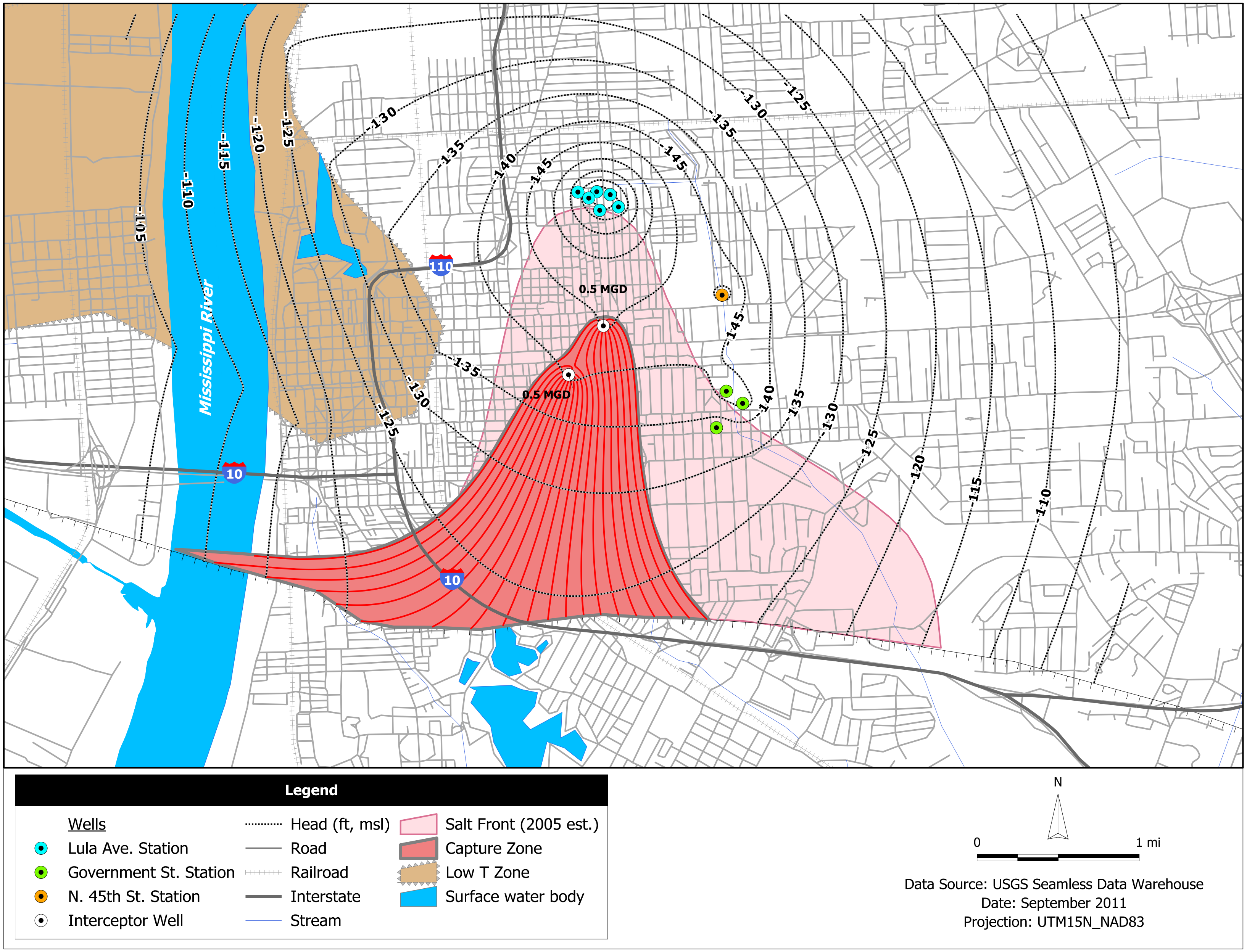


Figure 28: The combined capture zones for two interceptor wells pumping at 0.5 mgd (347 gpm) each. Contours of potentiometric head are shown.

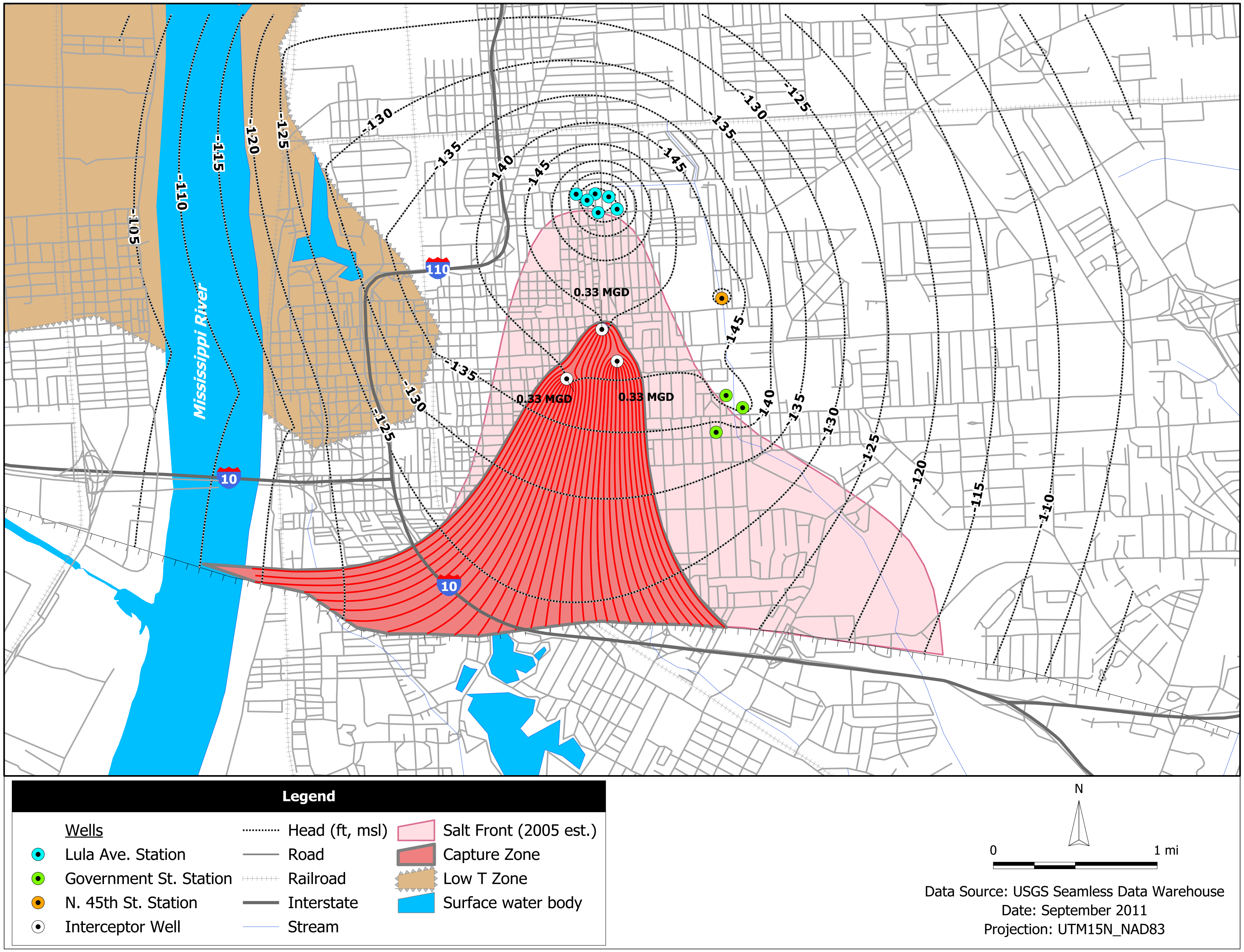


Figure 29: The combined capture zones for three interceptor wells pumping at 0.33 mgd (231 gpm) each. Contours of potentiometric head are shown.

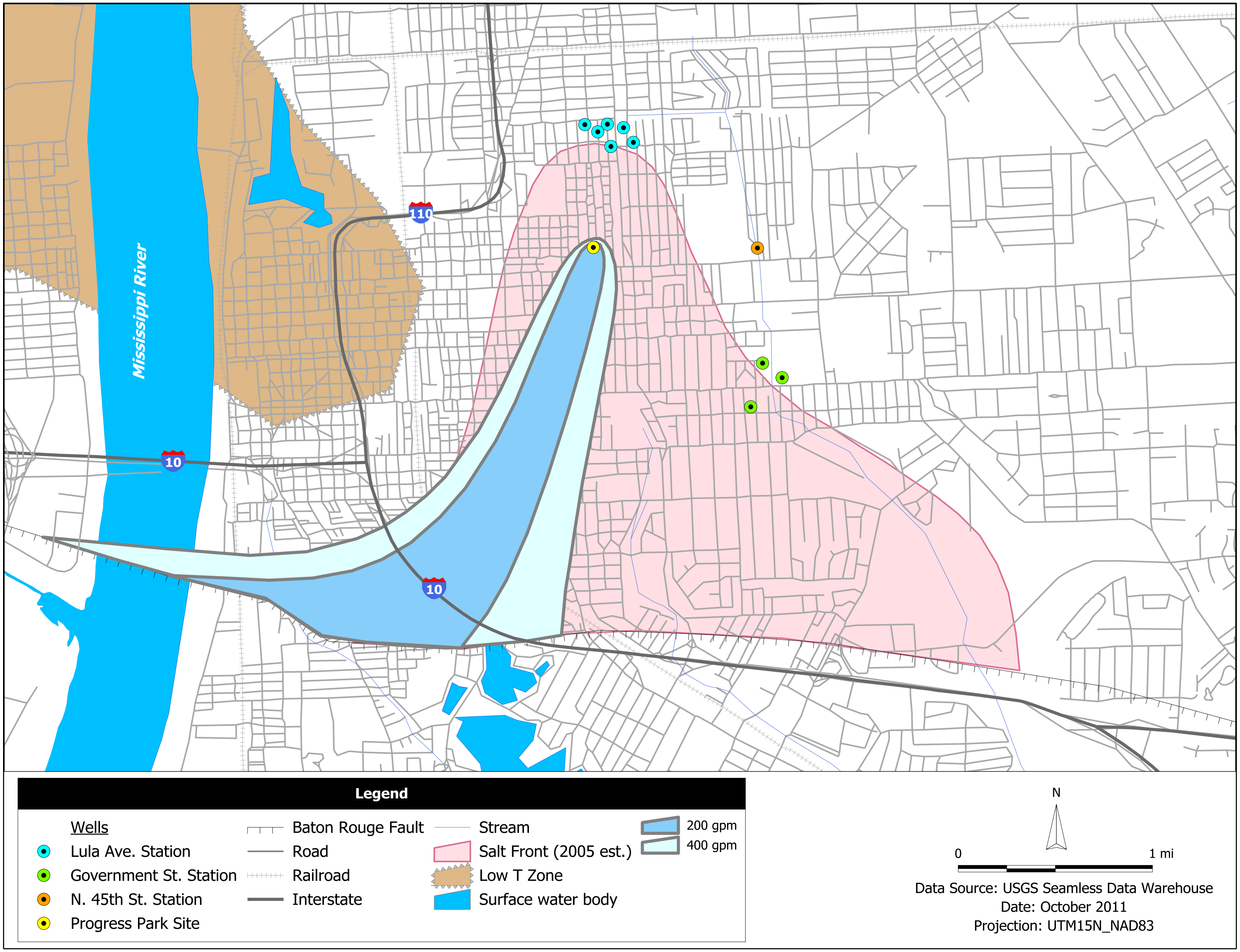


Figure 30: Comparison of capture zones for the Progress Park well pumping at 200 gpm and 400 gpm.

7.3 Scavenger wells

Scavenger wells have been employed successfully at select locations around the world as an inexpensive, practical solution for the long-term development of fresh groundwater. In a stratified aquifer, scavenger wells work by pumping saline water from the bottom of the aquifer without mixing with the overlying freshwater. The saltwater is pumped to waste. There are many advantages to the scavenger well approach, the most important of which are low capital costs, rapid improvement in water quality, and optimal capture of freshwater and saline water. A disadvantage is that scavenger wells require routine management of pumping rates to optimize the capture of saline water and freshwater. In addition, the pumping rates of freshwater supply wells may need to be decreased to optimize the system.

The most effective design for scavenging saline groundwater combines both a freshwater pumping well and a saltwater pumping well in a scavenger couple. Two conceptual sketches of typical scavenger well couples are shown in Figure 31A and Figure 31B. The scavenger couple design works by extracting groundwater both from above and below the saltwater-freshwater interface. Flow lines with arrows show the direction of groundwater flow in the figure, and the thick blue line represents the edge of the capture zone for the system. The designs shown in Figure 31A and 31B are very effective when the proportion of saltwater pumping to fresh water pumping is properly tuned after construction to avoid capturing a significant quantity of freshwater by the saltwater well. In this case, the combined pumping rate of the system, $Q_{total} = Q_{fresh} + Q_{salt}$, is limited only by the hydraulics of the pumping system and well construction. Increasing the total discharge of the couple does not cause increased mixing of fresh and saltwater as long as the tuned ratio of Q_{salt} to Q_{fresh} is maintained.

The scavenger well couple concept has been demonstrated to be effective in southern Louisiana. Long (1965) investigated this approach in Ascension Parish by modifying a production well in the town of Gonzalez previously abandoned due to saltwater contamination. At the site, the Gonzales Aquifer contained water with a chloride concentration of approximately 14 mg/L near the top and 2,000 mg/L near the base. Long modified the well by creating two sections of screen, a lower screen and an upper screen that could be pumped independently. Before modification, the supply well produced raw water with a chloride concentration of 400 mg/L. By tuning the pumping rates of the well couple, Long was able to produce freshwater with a chloride concentration near the background concentration. Long concluded that the scavenger well couple was an effective approach for extending the life of a supply well.

A less effective scavenger well system is illustrated in Figure 31C and 31D; only a saltwater pumping well is included in the design. If the saltwater pumping rate, Q_{salt} , used in a scavenger couple system is maintained in a scavenger well without a freshwater couple, the scavenger well will pump both fresh water from the top of the aquifer and saltwater from the bottom of the aquifer, as illus-

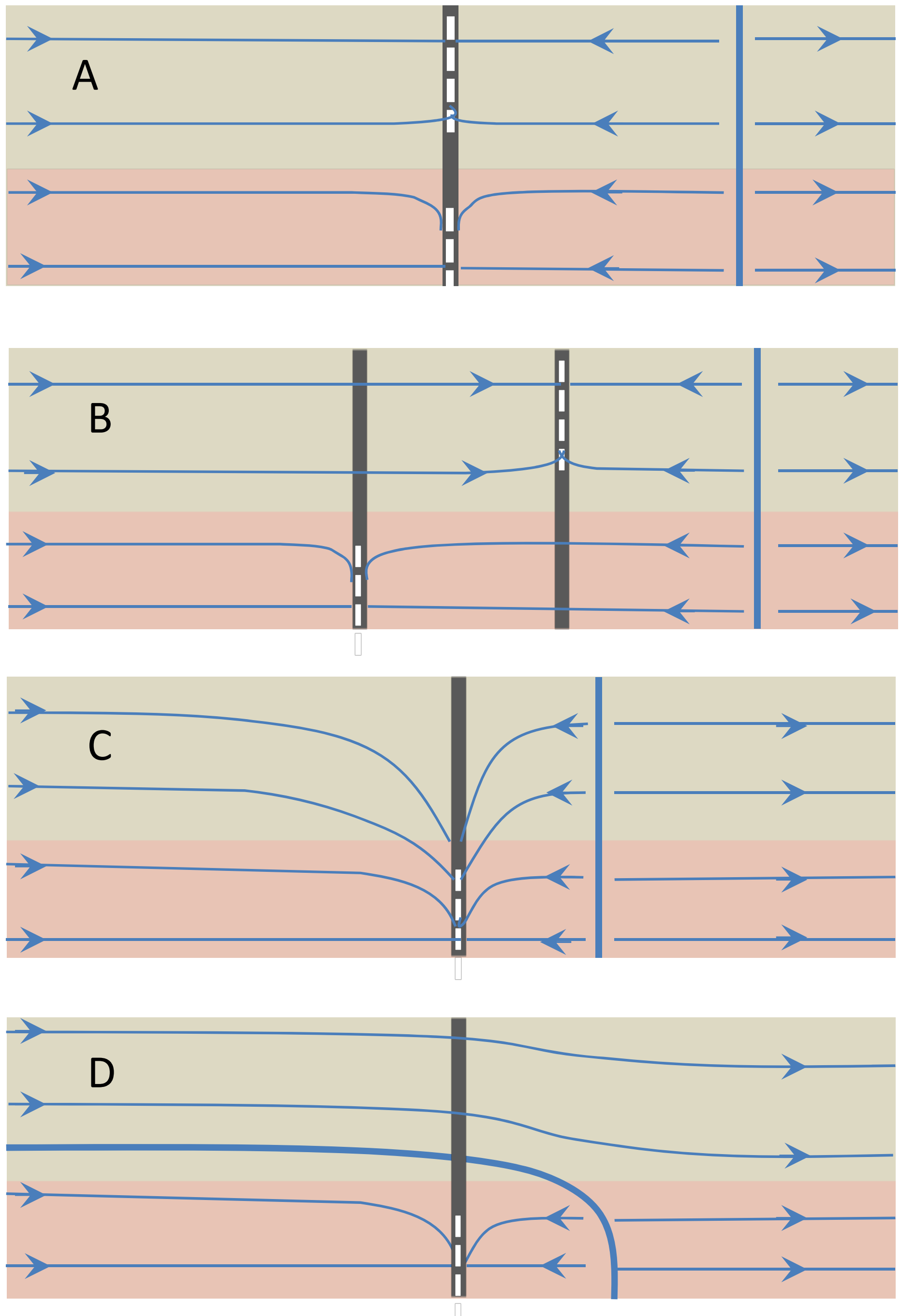


Figure 31: Conceptual sketches showing abstraction of saline groundwater with a scavenger well. (A) A saltwater–freshwater couple in the same well bore, (B) a saltwater–freshwater couple in separate well bores, (C), a saltwater pumping scavenger well with high pumping rate, and (D) a saltwater pumping scavenger well with low pumping rate. The pink shading represents the portion of the aquifer with high chlorides. Flow lines with arrows indicate the direction of flow and flow patterns near the wells, and the thick blue line represents the edge of the capture zone.

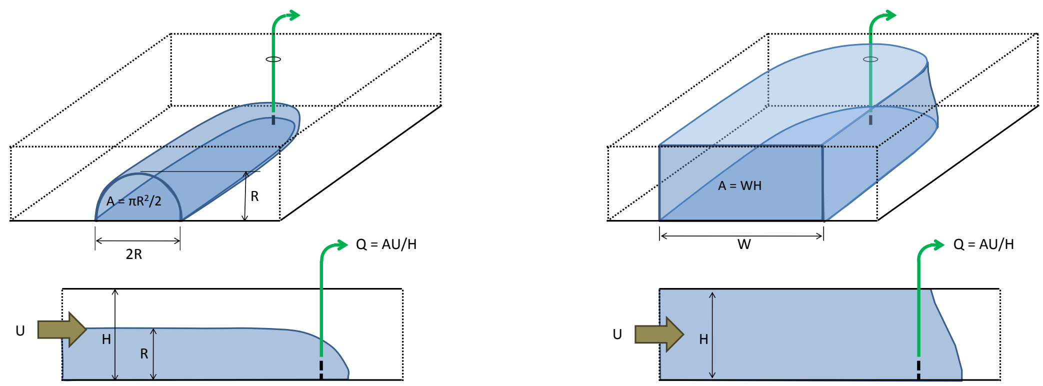
trated by the flow lines in Figure 31C. The capture zone of the well will be smaller in areal extent in comparison to Figure 31A and Figure 31B as the total discharge is reduced by the amount Q_{fresh}, but it will fully penetrate the aquifer as shown in Figure 31C. A significant reduction in the saltwater pumping rate is required to pump only the saltwater from the bottom of the aquifer. This is illustrated in Figure 31D, where the pumping rate of the well is reduced until the capture zone only extends over the bottom portion of the aquifer. Typically, the withdrawal rate of the scavenger well must be reduced drastically compared to the freshwater well couple. In this case, multiple scavenger wells with small pumping rates may be needed to capture a given width of the saline plume.

Ultimately, the feasibility of a scavenger well system depends on the vertical distribution of chlorides in the aquifer; stratification of the chlorides is necessary for the approach to be successful. Also, in order for a scavenger well with a partially-penetrating well screen to capture a significant width of a saline plume, the groundwater flow rate must be high. This means that the scavenger well system will likely be only be effective if the salt extracting well or wells are placed at or very near the Lula pumping center, or a new production well is installed that would act as the freshwater well in the couple. The further away from the Lula pumping center the scavenger wells are placed, the lower the groundwater flow rate, and the more saltwater-pumping scavenger wells will be needed to capture a significant width of the saline plume.

Field data collected at the Progress Park observation well indicates that chloride concentrations are stratified, but scavenger wells may still be effective in controlling the saltwater plume at that location when combined with an interceptor well. Two scavenger well options located at Progress Park are discussed below: a gallery of saltwater pumping scavenger wells, and a scavenger well couple. The first option is not feasible, as discussed below. The second option may be helpful in mitigating the effects of the saltwater plume as an alternative to treatment.

7.3.1 Saltwater pumping scavenger wells at Progress Park

Here we demonstrate the limitations of the saltwater pumping scavenger well option at Progress Park with model results and simple analytical equations for estimating the geometric properties of a partially-penetrating capture zone. The explanation is based on equations valid for constant density groundwater flow. This is an approximation, but is appropriate for the Progress Park setting. Based on the water-quality data collected at the Progress Park observation well, we expect only a 0.1% to 0.2% density difference in groundwater over the depth of the screen, and therefore, may neglect the effects of variable density on the groundwater flow field without large errors. As chloride concentrations increase over time, the following results are still approximately valid, as long as the flow of high chloride water is stable. That is, as long as the chloride concentrations increase with depth. For unstable conditions with high chloride water overlying fresh water, the simple analytical expressions that follow are not valid.



A **B**

Figure 32: Conceptual sketches of the capture zones for a partially penetrating well of small discharge (A) and large discharge (B).

Figure 32 shows conceptual sketches of the capture zone for a scavenger well with a short screen at the bottom of an aquifer in uniform regional flow. For small well discharges, the cross-sectional shape of the capture zone up-gradient from the well is approximately a semicircle, as shown in Figure 32A. In this case groundwater at the top of the aquifer (the fresh water) is flowing over the capture zone and bypassing the well. For a homogeneous, isotropic aquifer, the radius of the semicircle may be evaluated as

$$R = \sqrt{\frac{2QH}{U\pi}} \tag{1}$$

where Q [L^3/T] is the pumping rate of the well, H [L] is the thickness of the aquifer, and U [L^2/T] is the regional groundwater discharge. The regional discharge is evaluated as

$$U = k_h H i \tag{2}$$

where k_h [L/T] is the horizontal hydraulic conductivity, and i [–] is the regional head gradient. As the pumping rate of the well is increased, the radius of the capture zone increases until it touches the top of the aquifer, and the capture zone penetrates the full thickness of the aquifer. With further increases in discharge, the capture zone spreads laterally, as shown in Figure 32B, until it is similar in appearance to the capture zone of a well screened over the full thickness of the aquifer. When the capture zone of the scavenger well becomes fully penetrating, the fresh water at the top of the aquifer can no longer bypass the well and is captured.

When the aquifer is anisotropic, the cross-sectional shape of the capture zone for small pumping rates is elliptical rather than semicircular, as illustrated in Figure 33. When vertical anisotropy is

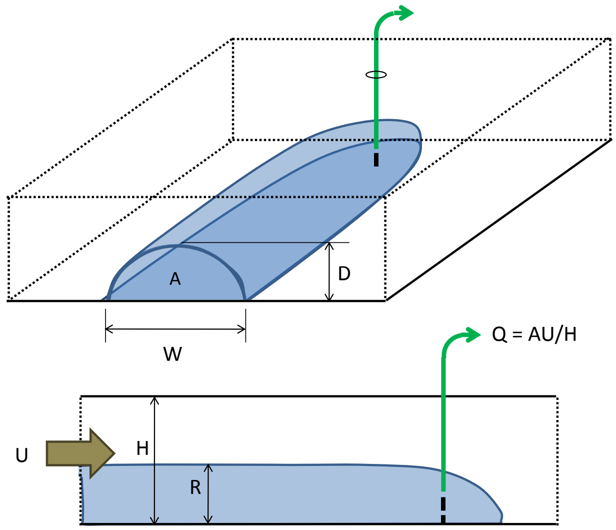


Figure 33: Capture zone for a partially penetrating well with small discharge in an anisotropic aquifer.

present, the height, D, of the capture zone and the width, W, as illustrated in Figure 33, are calculated from R (1) as follows:

$$D = R(k_v/k_h)^{1/4} \tag{3}$$

$$W = 2D(k_h/k_v)^{1/2} \tag{4}$$

where k_v [L/T] is the vertical hydraulic conductivity of the aquifer. As the anisotropy ratio k_h/k_v increases, the width of the capture zone also increases while the height decreases.

We tested the effects of partial penetration at the Progress Park observation well and developed a preliminary design for a scavenger well system. The groundwater flow model with 2009 pumping conditions was used to estimate U, the regional groundwater flow rate near Progress Park; the flow rate was calculated to be 42 ft^2/day at Progress Park. Using this value for U, we evaluate the maximum pumping rate and geometry of the capture zone for a scavenger well located at the bottom of an anisotropic aquifer. We combine equations (1) and (3), and solve for the pumping rate, Q,

$$Q = \frac{D^2 U \pi}{2H}\sqrt{\frac{k_h}{k_v}} \tag{5}$$

Based on water-quality data at the Progress Park observation well, approximately half the thickness

Table 11: Pumping rates and capture zone widths for a scavenger well capturing half the depth of the aquifer.

Anisotropy ratio (k_h/k_v)	Pumping rate *(gpm)*	Width of capture zone *(ft)*	Minimum no. wells to capture 3,000 ft wide plume
1.0	9	100	30
3.0	15	173	18
10.0	27	316	10
100.0	86	1000	3

Note. ft=feet, gpm= gallons per minute

of the aquifer would have to be captured to allow only fresh water to pass the scavenger well. For D =50 ft, H =100 ft, U =42 ft^2/day, and the anisotropy ratio k_h/k_v ranging from 1.0 to 100, we obtain the pumping rates and capture zone widths shown in Table 11. Based on the estimated plume width near the Progress Park of 3,000 ft, the minimum number of scavenger wells required to capture the full width of the plume while only capturing water from the bottom half of the aquifer can be estimated. The estimated number of wells depends strongly on the anisotropy ratio, decreasing one order of magnitude for a two order of magnitude increase in the anisotropy (Table 11). Vertical anisotropy is difficult to measure in this setting and the geologic origins of the aquifer suggest that the anisotropy ratio will be highly heterogeneous, varying throughout the aquifer. Typical values for this setting would range from 1.0 to 10.0, and thus the minimum number of scavenger wells needed would range from 10 to 30 closely spaced wells (100 ft to 300 ft apart).

This analysis was incorporated into the groundwater flow model to test the preliminary conclusions. The model simulation included 20 scavenger wells spaced 150 ft apart lying in a east-west line, beginning at the Progress Park well (Figure 34). The wells were screened over the bottom 20% of the aquifer and each pumps at 15 gpm. The anisotropy ratio for the aquifer is specified as 3.0 in the model. Model results indicate that the vertical thickness of the capture zone ranges from 20% of the aquifer thickness at the edges to 60% of the aquifer thickness in the middle of the line of wells, and an average depth of capture of approximately 50% of the aquifer thickness. Drawdown due to the scavenger wells ranges from 5 ft to 6 ft (Figure 34). The total discharge of the scavenger wells is 300 gpm. The model results compare favorably with the preliminary analysis. Both clearly show that the scavenger well alone approach is not practical in this setting because of the large number of wells required. The savings resulting from small pumping rates and thus small volumes of high chloride waste water are offset by the costs for installation of multiple, closely spaced wells.

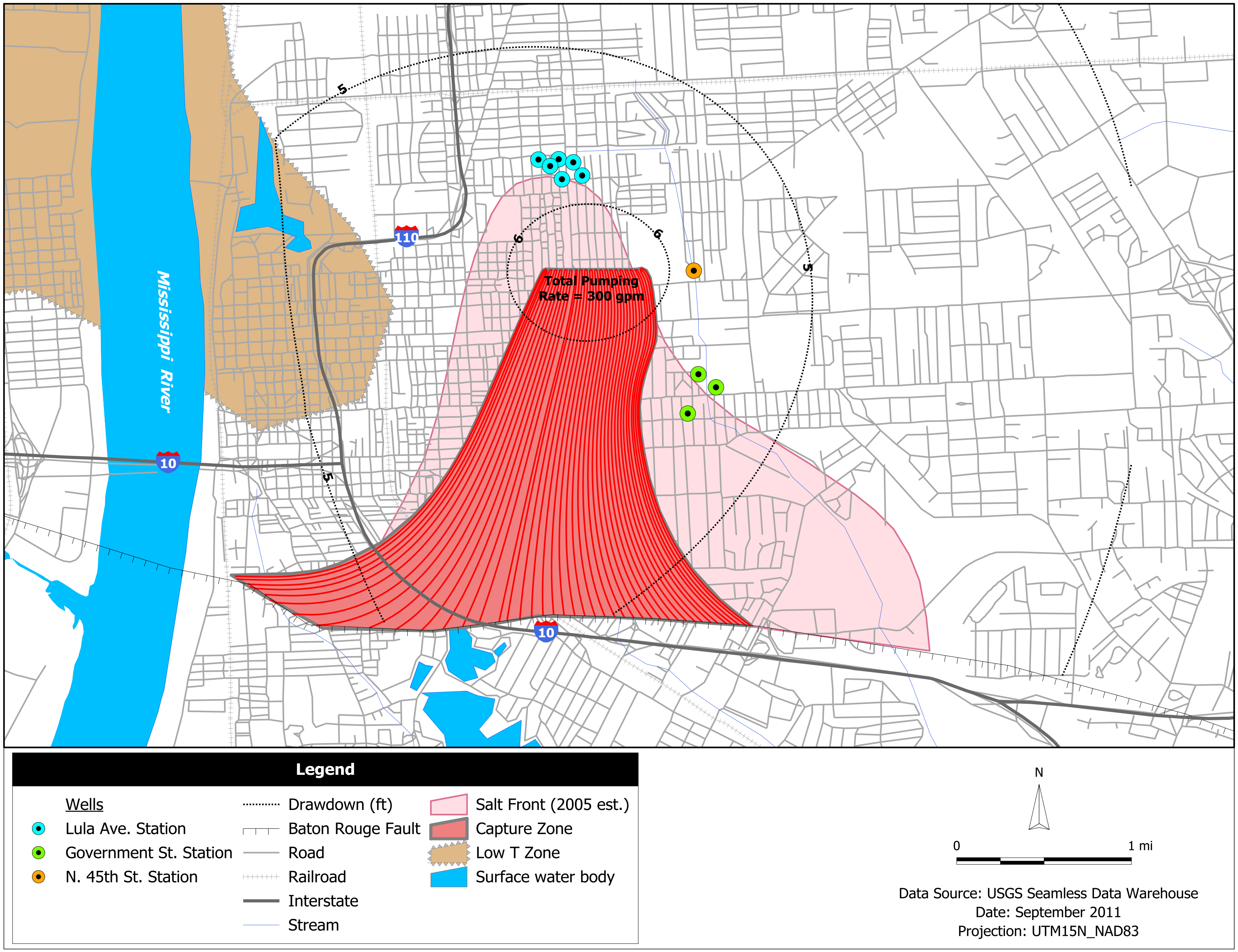


Figure 34: The combined capture zone and drawdown contours for a system of 20 scavenger wells each pumping at 15 gpm for a total rate of 300 gpm.

Table 12: Estimate of the vertical variation in horizontal hydraulic conductivity at the Progress Park observation well.

Aquifer interval *(ft bgs)*	Hydraulic conductivity *(ft/day)*	Transmissivity *(ft^2/day)*
1550–1615	153	9,960
1615–1625	24	240
1625–1655	40	1,200
1655-1665	60	600

Note. ft bgs=feet below ground surface, ft/day=feet per day
ft^2/day=feet squared per day

7.3.2 Scavenger well couple at Progress Park or Kernan Park

We evaluated the option of installing a scavenger well couple at Progress Park or Kernan Park. One option would be to modify the Progress Park well to act as the saltwater pumping well and installation of a new production well nearby to the north. A second option is to construct a scavenger well couple south of the observation well, possibly at Kernan Park. The second option would allow the observation well to be used as a sentinel well for chloride monitoring, which would provide useful information for the operation of the scavenger well couple. In either case, the results are similar.

Effective design of a scavenger well couple requires knowledge of the vertical variations in the aquifer's horizontal hydraulic conductivity to estimate the ratio of saltwater to freshwater that will be pumped by the couple. We have estimated this distribution at the Progress Park location based on the spinner logging performed on the observation well on July 13, 2011 (Table 12). Based on these results, a scavenger well at Progress Park would need to pump at a rate of 29% of the total well couple pumping rate to capture the saline water at the bottom 60 ft of the aquifer. If the observation well were used as the scavenger well and operated at a pumping rate of 200 gpm, the freshwater production well would need to pump from the top portion of the aquifer at a rate of 490 gpm, with a combined pumping rate of 1 mgd. The design of a scavenger well couple at Kernan Park would be based on site-specific data. The flows presented here for Progress Park are estimates only; once constructed, tuning of the well couple would be necessary to determine the actual ratio of saltwater and freshwater pumping rates. The combined capture zone is similar to a single interceptor well pumping 1 mgd (Figure 35).

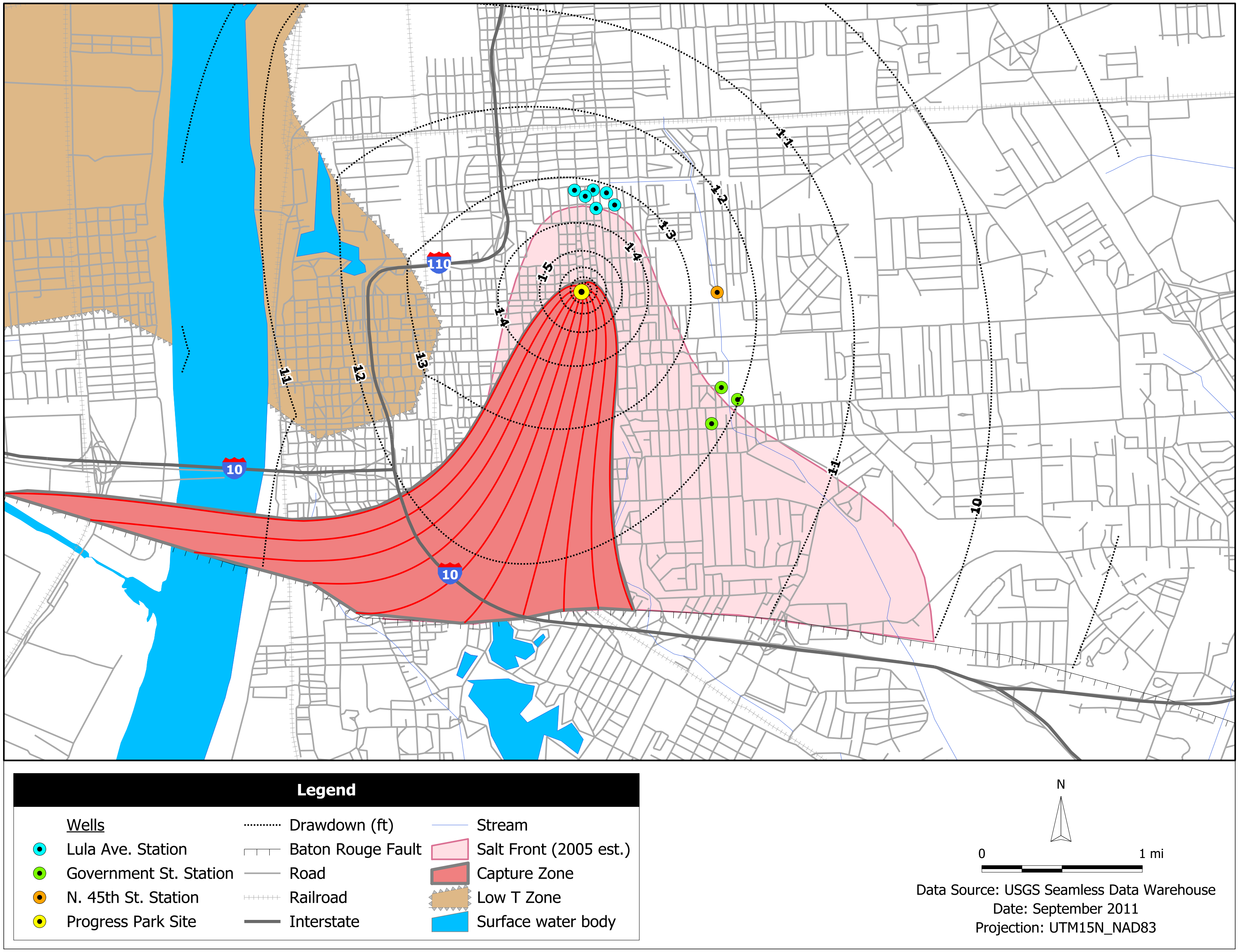


Figure 35: Combined capture zone for a scavenger well couple at Progress Park with a total pumping rate of 1 mgd (694 gpm). Pumping rate of the saltwater scavenger well is estimated to be 200 gpm. Drawdown contours due to the couple are shown.

7.3.3 Use of the Progress Park well as an interceptor well combined with a scavenger well couple at Kernan Park

We evaluated the option of using the Progress Park well as an interceptor well in combination with a scavenger well couple at Kernan Park. Figure 36 shows the combined capture zone for the Progress Park well pumping at a rate of 400 gpm combined with a scavenger well couple at Kernan Park pumping a total of 1 mgd. The results show that the Progress Park well captures water flowing around each side of the Kernan Park scavenger well couple. The additional pumping at Progress Park extends the width of the capture zone at the fault compared to the scavenger well couple pumping alone (shown in Figure 30).

The addition of the Progress Park well to a scavenger well couple at Kernan Park does not appreciably decrease the travel time between Progress Park and the Lula wells. However, the addition of the Progress Park well does extend the capture zone at the fault farther to the east and west, roughly doubling its width. Using this combination of wells would add a level of protection to BRWC wells by increasing the system's capacity to intercept saltwater moving north from the fault. This setup also increases the width of the capture zone for Lula 19, making it more effective as a last line of defense interceptor well.

7.4 Estimated chloride trend at Progress Park

We used three methods to develop a rough estimate of the rate of increase in chloride concentration in the Progress Park area. We first used the groundwater flow model to estimate the travel time between well EB-807A and Progress Park under two possible scenarios. This calculation was made to estimate the time period over which the chloride concentration at the bottom of the Progress Park well will increase from the current observed range of 1,500 mg/L to 2,000 mg/L to the last concentration observed at EB-807A in 1997 (approximately 4,000 mg/L). The first scenario assumes that the transmissisivity of the aquifer is 12,000 ft^2/day with a constant horizontal hydraulic conductivity over the depth of the aquifer of 120 ft/day, and an aquifer porosity of 0.25. Model results based on 2009 pumping rates indicate that advection moves the chlorides at EB-807A to the Progress Park area in 17 years. Fourteen years have passed since the last chloride measurement was taken at EB-807A. Given this, it is possible that the chloride concentration at the bottom of the aquifer in the Progress Park area could rise rapidly in the next 3 years.

The second scenario also assumes an aquifer transmissivity of 12,000 ft^2/day, and an aquifer porosity of 0.25. In this case, however, the hydraulic conductivity is allowed to vary over the depth of the aquifer, as indicated in Table 12, with high values in the top half of the aquifer and low values in the bottom half. This scenario assumes that the vertical variation in the aquifer hydraulic conductivity is the same throughout the aquifer, and not a local feature representative only of the Progress

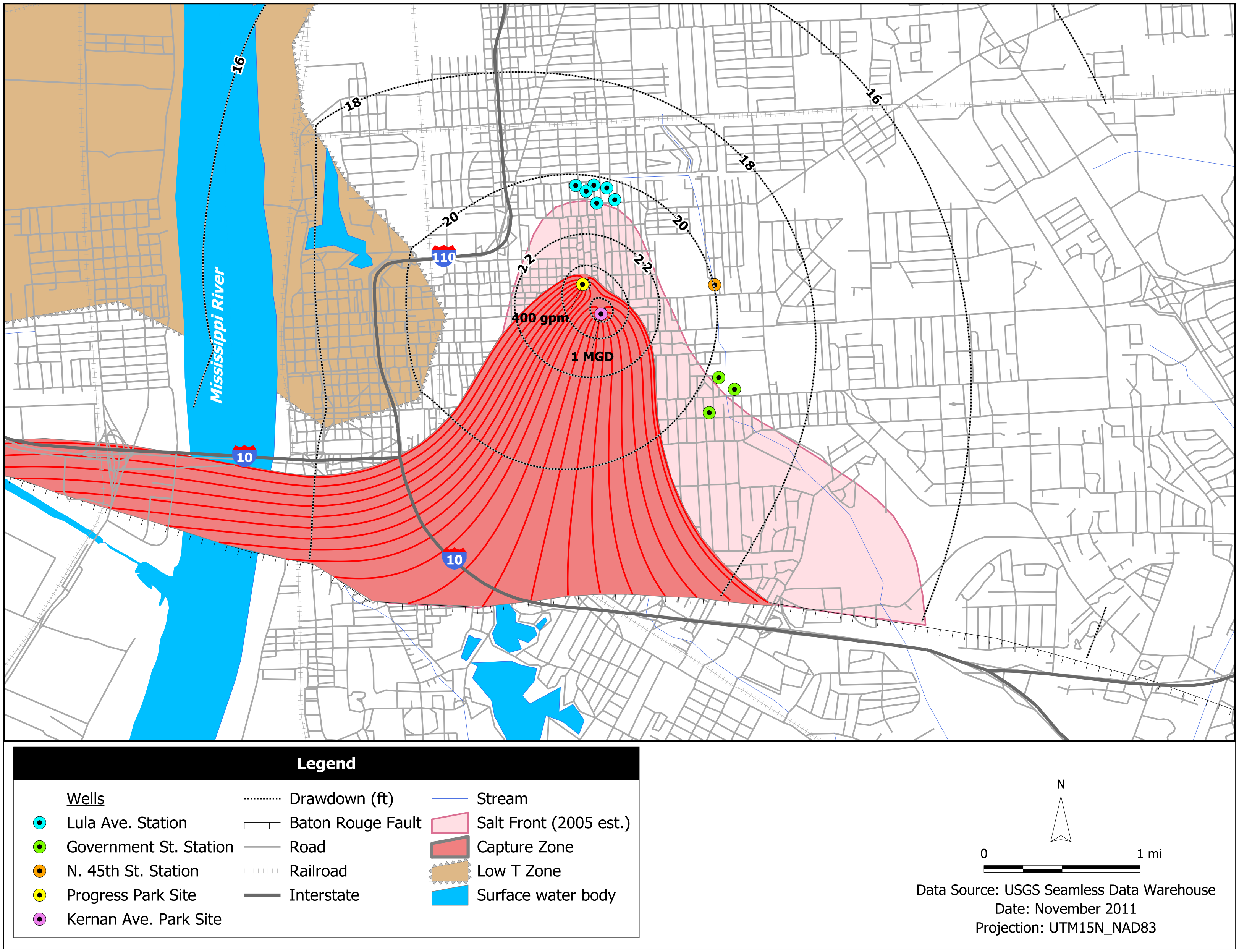


Figure 36: Combined capture zone for a scavenger well couple at Kernan Park and interceptor well at Progress Park. The total scavenger well couple pumping rate is 1 mgd (694 gpm) with the pumping rate of the saltwater scavenger well at 200 gpm. The pumping rate of the interceptor well is 400 gpm. Drawdown contours are shown.

Park area. Based on Table 12, the largest hydraulic conductivity in the bottom half of the aquifer is 60 ft/day–one-half the value from scenario one. This suggests that the saline water in the bottom half of the aquifer moves at a rate 2 times slower on average than the speeds predicted in scenario one. Based on this model, the high chloride water observed at EB-807 may take as much as 34 years to travel to the Progress Park area. As 14 years have passed since the last observation at EB-807, the second scenario suggests that chloride levels at Progress Park will rise to 4,000 mg/L over the next 20 years, which is significantly longer than the 3 years estimated in the first scenario.

The third estimate is based on observed rates of increase in chloride concentration at observation wells north of the fault (Section 4.4.3) Using existing data to estimate the rate of chloride increase at Progress Park suggests that chloride concentration at the bottom of the aquifer in Progress Park may double in less than 10 years.

Using both the model and existing data to estimate the rate of chloride increase, we are left with a wide range from 3 to 20 years. As the assumption on which model scenario two is based–a constant low hydraulic conductivity at the bottom of the aquifer–is not supported with other field data, we present that result as a best case scenario only. Based on the remaining two estimates, we anticipate that over the next 3-10 years chloride concentrations at the bottom of the aquifer in Progress Park will increase rapidly to 4,000 mg/L. With 4,000 mg/L of chloride at the bottom of the aquifer, we estimate that the depth-averaged concentration will be approximately 900 mg/L.

7.5 Effects of eliminating industrial pumping in the 1,500-Foot sand

As discussed in Section 4.4.2, significant pumping occurs in the industrial area where the 1,500-Foot and the 1,700-Foot sands are considered to be hydraulicly connected. To test the effects of reduced industrial pumping on conditions in the 1,500-Foot sand, all groundwater withdrawals from the aquifer in East Baton Rouge Parish not related to pumping by the BRWC were removed from the groundwater flow model. These withdrawals include all wells listed in Table 7 of Section 6.2.5 with a USGS identifier of “EB-” and without a “BRWC-” identifier. The withdrawals also include the industrial pumping center identified on Figure 17 and discussed in Section 6.2.5. As discussed in Section 6.2.5, the pumping center in the model represents large withdrawals reported in the 1,500/1,700-Foot and the 1,700-Foot sands. The total reduction of pumpage from the modeled 2009 conditions is 13 mgd, of which 10 mgd is due to removal of the industrial pumping center.

The results of removing industrial pumping suggests that industrial pumping is an important factor for regional groundwater flow and saltwater encroachment. The effects of eliminating industrial withdrawals include an increase in heads of 35 to 45 ft at the Lula Station and along the fault and a decrease in the simulated inflow of saline water across the fault by 270 gpm (30% reduction) (Table 13). These results are based on the assumption of a direct hydraulic connection between the 1,500-

Table 13: Changes in conditions in the 1,500-Foot sand due to eliminating industrial pumping.

1.	Increase in heads near Lula Station	40 ft
2.	Increase in heads along the Baton Rouge Fault	35 to 45 ft
3.	Reduction in leakage rate through the Baton Rouge Fault	270 gpm
4.	Percent reduction in leakage through the Baton Rouge Fault	30%

Foot sand and the 1,700-Foot sand in the industrial area. The degree of connectivity between the sand layers should be verified with site-specific testing before drawing final conclusions about the effects of eliminating industrial pumping from the 1,500-Foot and 1,700-foot sands.

8 Conclusions

Based on our review and analysis of existing information, field testing, and groundwater flow modeling, we conclude:

1. Field data collected and groundwater flow modeling performed for the current study confirms and reinforces the previous understanding of flow and chloride conditions in the 1,500-Foot sand aquifer.

2. The saline plume at the new Progress Park observation well is stratified, with concentrations of approximately 1,500 mg/L to 2,000 mg/L at the bottom of the well, 600 mg/L to 850 mg/L 35 ft above the bottom of the well and 65 mg/L to 120 mg/L at top of the well screen (60 ft above the bottom of the well). The depth averaged chloride concentration measured during pumping of the well is around 400 mg/L.

3. Groundwater modeling of plume advection indicates that the high chloride groundwater observed at the Progress Park observation well will reach Lula Well 19 in 2.5-5 years, under current pumping conditions in the aquifer. The chloride concentrations at Lula Well 19 are expected to rise to the levels currently observed at Progress Park.

4. Groundwater modeling of plume advection indicates that the high chloride groundwater at concentrations observed in 1997 at the bottom of well EB-807A will reach Progress Park within the next three years. Observed trends in existing wells suggest that it could take 10 years for the chloride concentration at the bottom of the aquifer in the Progress Park area to double. We anticipate that over the next 3-10 years chloride concentrations at the bottom of the aquifer in Progress Park will increase rapidly to 4,000 mg/L, with an estimated increase of depth averaged concentration from approximately 400 mg/L to 900 mg/L.

5. Published values of the transmissivity of the 1,500-Foot sand have been verified by pumping test analysis and calibration of the groundwater flow model. Results indicate that the local transmissivity of the aquifer is 12,000 -13,500 ft^2/day.

6. Lula Well 19 shields the other Lula wells from chloride contamination. This was demonstrated during field testing of Well 19 and verified by capture zone analysis with the groundwater flow model. Well 19 acts as a last defense of the pumping station against chloride contamination.

7. Recharge wells would provide a short-term fix to high chlorides at the Lula Station, but the chloride plume will bypass the barrier wells in a period of four to eight years, contaminating the other Lula wells screened in the 1,500-Foot sand as well as the Government and North 45th Stations.

8. The interceptor well option in combination with maintained pumping at Lula Well 19 is feasible to protect the Lula, Government, and North 45th wells. The interceptor well or wells should operate at a total pumping rate of 1 mgd to have a significant, long-term impact on the saltwater plume.

9. Scavenger wells located at or near Progress Park are practical only if installed in combination with freshwater pumping wells as scavenger well couples. The scavenger well couple may also be feasible at the Kernan Park area, depending on conditions at the site. Based on the stratification of chloride and the variation in hydraulic conductivity at Progress Park, we estimate that pumping a total of 1 mgd from a scavenger well couple will result in 200 gpm of high chloride water and 490 gpm of freshwater. The true ratio of salt to freshwater pumping rates must be evaluated by trial and error after installation of the wells. Over time, we expect the rate of freshwater pumping to decrease and the scavenger system would need to be converted to an interceptor well system as the saltwater plume advances.

10. Using the Progress Park well as an interceptor well in combination with a scavenger well couple at Kernan Park increases the width of the capture zone compared to a scavenger well couple pumping alone. The combined capture zone of these two wells extends farther to the east and west. Using this combination of wells would add a level of protection to BRWC wells by increasing the system's capacity to intercept saltwater moving north from the fault. This setup also increases the width of the capture zone for Lula 19, making it more effective as a last line of defense interceptor well.

11. Removing all industrial pumping from the 1,500-Foot sand results in a 40 ft increase in the simulated heads near Lula and substantially reduces the simulated inflow of saline water across the fault by 30%. These results suggest that industrial pumping is an important factor for regional groundwater flow and saltwater encroachment.

9 Recommendations

We recommend the installation of a scavenger well couple to control saltwater encroachment in the 1,500-Foot sand. A scavenger well couple could be constructed at Progress Park by using the existing observation well as the scavenger well and constructing a new well screened higher in the aquifer to pump freshwater. However, given space limitations at Progress Park, we recommend constructing a scavenger well couple in the Kernan Park area if warranted by site conditions. The saltwater plume could also be controlled with one or more interceptor wells. This approach, however, would eventually require expensive membrane treatment when the chloride concentration becomes too high to blend with other wells. Given the stratification observed at Progress Park, the scavenger well approach would allow optimal extraction of saltwater and freshwater without the need for treatment. This tradeoff, however, will require ongoing management to maximize the production of freshwater. Further, we recommend a phased approach for developing the remedial system, with timely assessment of new data at the conclusion of each step. As the data currently available to evaluate the extent and behavior of the saltwater plume is limited, each step will produce new data which must be critically evaluated to ensure that the remedial system will operate as planned. We recommend the following steps be taken:

1. Drill a test boring at Kernan Park. If the preliminary sampling and testing indicates that the vertical stratification of chlorides is adequate for a scavenger well couple, design and install a scavenger well couple. We recommend a dual completion well with two separate screens. Based on current conditions at Progress Park, the ideal pumping rate for the scavenger portion of the well is 200 gpm and for the freshwater portion of the well is 490 gpm, with a combined pumping rate of approximately 1 mgd. When chloride levels rise too high to produce blendable freshwater, convert the well to an interceptor well and pump it to waste or treat it using a desalination membrane process. Monitor the chloride concentrations and water levels at the well continuously, prior to, and after the well is online.

2. Employ the new Progress Park well as an interceptor well in combination with a scavenger well couple at Kernan Park if it is feasible to pump the well at a rate comparable to 400 gpm and if it is economically feasible to dispose of or blend the high chloride water with other source water that is low in chloride. If it not feasible to use the Progress Park well as an interceptor well, then use the well as a dedicated observation well. An observation well south of the Lula Station would serve as a sentinel for saltwater migration and is essential for decision-making. Regardless of how this well is deployed, we recommend proceeding with a regular schedule of water testing and water-level measurements or installing continuous monitoring equipment. The time-series of chloride concentrations at the Progress Park well will help BRWC to anticipate changes in chlorides at the Lula Station and adjust operations

accordingly.

3. Maintain pumping at Lula Well 19. Regardless of the remedial option chosen, Well 19 is the last defense against chloride contamination of the entire Lula Station. The capture zone for Well 19 extends south over the area of the chloride plume and shields the other wells, whose capture zones extend primarily to the the west and east. Shutting down Well 19 will rapidly result in increased chlorides in the other Lula wells. This was demonstrated during the testing of Well 19 conducted for this study. As the saltwater plume approaches the Lula Station, it becomes even more important to maintain pumping at Well 19. If the time comes that the chlorides in Well 19 are too high to blend, the well must continue pumping to protect the remaining wells at the pumping station. When the chlorides are too high to blend, the water must be pumped to waste or treated. Depending on the distribution of chlorides in the aquifer at that time, a scavenger well could be installed in or near Well 19 (within 50 ft) to capture saltwater, allowing Well 19 to operate as the freshwater component of the well couple.

4. Continue frequent chloride monitoring at the Lula, Government, and North 45th Stations or install continuous monitoring equipment. Maintain pumping records including rates and when wells are turned on and off.

5. Evaluate the system. After the Kernan Park Well has operated long enough for trends in the chloride levels to develop, analyze the time series of chloride and head measurements at the Progress Park observation well, the Kernan Park scavenger well couple, and the BRWC production wells. Assess chloride removal rates and verify aquifer transmissivity. Re-evaluate the operation of the system.

6. If the system is operating as planned, continue monitoring chloride levels, pumping rates, and water levels. If the system is not operating as planned and additional mitigation is necessary, install one new scavenger well couple to the west of the Kernan Park Well. Well installation on the west side of the plume will provide new chloride data in a region where there currently is no data and will maximize the value of the new information.

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Appendix A - Well 19 Test Results

SPINNER FLOW METER AND FLUID CONDUCTIVITY LOGGING RESULTS FOR WITTMAN HYDRO GROUP BATON ROUGE WATER COMPANY WELL #19

Executive Summary

The spinner flow meter and fluid electrical conductivity (FEC) logging performed in Well #19 for Wittman Hydro in support of the Baton Rouge Water Company project in Baton Rouge, Louisiana identified six primary water bearing intervals at a pumping rate of approximately 725 gpm. Additionally, the FEC logging identified an interval of increased FEC at a depth of approximately 1580 to 1593 feet. A downhole water sample was procured using a discrete-point fluid sampler at 1589.9 feet for TDS and chloride analysis. The results of which are not available for this report. Of particular note is the fluctuating interval-specific FEC over the entire length of the screened interval – most pronounced at the interval of 1580 to 1593 feet. The interval at 1580 to 1593 feet (interval #5) decreased in FEC the moment Well #22 was shut in, then after approximately 17 hours of pumping interval #5 began to increase in FEC as did the other flow zones in the well screen, but none as much as the zone at 1580 to 1593 feet. Interval #5 produced 147 gpm during pumping at 725 gpm, contributing 20.3% of the total inflow during testing. Maximum drawdown of 28.89 feet was observed at 1630 hours on May 12th, 2010, thirty minutes prior to shutting off of Well #22. This equates to a Specific Discharge of 25.1 gpm/ft drawdown while the well field is actively pumping. The results of testing are:

Interval No.	Depth of Interval (feet)	Interval Specific Flowrate (gpm)	Percent of Total Flow (%)	Interval-Specific FEC (uS/cm)
1	1509 – 1535	101	13.9	360
2	1535 – 1545	163	22.5	365
3	1549 – 1567	184	25.4	357
4	1570 – 1574	90	12.4	354
5	1580 – 1593	147	20.3	372
6	1593 – 1599	40	5.5	360

1.0 Introduction

On May 12th and May 13th, 2010, COLOG logged Well #19 utilizing a spinner flow meter and a fluid electrical conductivity (FEC) and temperature probe. The objective of the logging was to identify and quantify the inflow of formation waters to the wellbore under pumping conditions and estimate relative water quality with respect to FEC using the FEC probe and/or downhole samples. The well is screened from approximately 1507 to 1599 feet, where sediment precludes any further logging. The probes were unable to log past a depth of 1599 feet due to accumulated material at the bottom of the well. A tool access tube was installed from ground surface to 335 feet. All depths reported herein are referenced to the top of the cement well pad (stickup from ground surface approximately 1.84 feet). Prior to testing, the ambient depth to water was recorded at 217.30 feet from the top of the cement pad. Prior to initiating pumping an ambient FEC/temperature profile was acquired and is presented in Figure Well 19:1

2.0 Fluid Electrical Conductivity Profiling During Pumping at 725 GPM

Fluid electrical conductivity and temperature data were logged from 1450 to 1599 feet in Well #19 under two different conditions: one log prior to pumping (ambient) and numerous consecutive logs during pumping. Of particular note is the fluctuating FEC observed in the well during pumping. At the start of pumping at 0943 hours on May 12th, 2010, the observed FEC downhole was a uniform 315 µS/cm with a minor increase in FEC below 1580 feet. Continuous FEC profiling over time indicated little change in FEC over the course of approximately 11 hours. Please see Figure Well 19:2 for a summary of the FEC profiles acquired during pumping at 725 gpm. At approximately 2045 hours, the FEC in the well was observed to decrease to approximately 292 µS/cm (FEC2052 in Figure Well 19:2). A subsequent log at 0938 hours the following morning after pumping was maintained at approximately 725 gpm indicated a further decrease in FEC to approximately 280 µS/cm. This is the lowest FEC observed during testing. Subsequent FEC profiles after FEC0938 indicated a slow, erratic increase in FEC over the length of the screened interval until the conclusion of FEC profiling at 1621 hours on May 13th, 2010. The highest FEC during testing, observed on the final log FEC1621, was observed at 1589 feet at 374 µS/cm. The interval at 1580 to 1593 feet continuously showed an elevated FEC with respect to the remainder of the screened interval, suggesting this flow interval contains the highest levels of chloride and TDS.

3.0 Spinner Flow Meter Log

Spinner log data were collected at three line speeds (30, 60 and 90 feet/minute) from 1450 feet to 1599 feet. An additional two logs at 30 feet/minute were acquired to demonstrate repeatability.

The 30 feet/minute logs were utilized in the interval-specific flow estimations. All three line speeds have the same general shape to the data curve with a constant offset. The 90 ft/min log has a constant offset of approximately 523 counts per second (cps) more than the 60 ft/min run as expected for faster line speeds (impeller buoyancy force). The 60 ft/min log has a constant offset of approximately 512 cps more than the 30 ft/min run. The constant offset between the three logs illustrates repeatability and a relatively constant, or non-changing, condition downhole. The 30 ft/min runs are discussed in the following paragraph.

In summary, the 30 ft/min spinner log identifies six different intervals (Table Well 19:1) producing significant quantities of water during pumping. In general, the depths of the producing intervals identified by the spinner flow meter data do not correspond to anomalies observed in the FEC profiling with the exception of the interval at 1580 to 1593 feet due to the lack of anomalies observed in the FEC profiles during pumping. The spinner flow meter data indicates a relatively uniform vertical distribution of flow during pumping and, with the possible absence of a confining layer in the screened interval, the FEC profiles are expected to lack character or anomalies. In general, the two dominant producing interval are identified at 1535 to 1545 feet and 1549 to 1567 feet, producing 163 and 184 gpm, respectively, or a combined 47.9% of the total inflow during pumping.

The maximum average cps from the spinner flow meter inside blank casing are estimated to be 2392.2 cps. At 1593 feet the spinner flow meter cps are observed to stall, then continue to fall to near zero. The stall at 1593 feet, combined with stationary readings obtained during pumping at 1592 feet (zero cps) indicate the flow at this depth has decreased to a point such the the spinner flow meter can no longer register flow. In a 12” casing the lowest measureable flow for the spinner flow meter is approximately 40 gpm. There is evidence of flow beneath 1593 feet however, based on the FEC profiles. The FEC profiles indicate a still-elevated FEC at this depth, down to approximately 1595 feet. As such, for the interval 1593 to 1599 feet, the lowest measureable flow rate for the spinner flow meter of 40 gpm is assigned.

Interval specific flow rates are estimated by assuming the observed cps at 1593 feet equate to 40 gpm (continued cps due to line speed) and the observed maximum cps at the top of the test interval to equate to 100 percent of the observed flow (725 gpm). A percentage of flow can then be calculated for each zone in the well showing a net decrease in cps. The percentage of flow can then be converted to actual interval specific flow rates assuming 725 gpm total flow. Please refer to Table Well 19:1 and the Spinner flow Meter Summary Plots for a summary of inflow locations and flow rates.

FIGURE Well 19:1. Ambient Temperature and Fluid Electrical Conductivity;Wittman Hydro; BRWC; Baton Rouge, Louisiana; Wellbore: #19

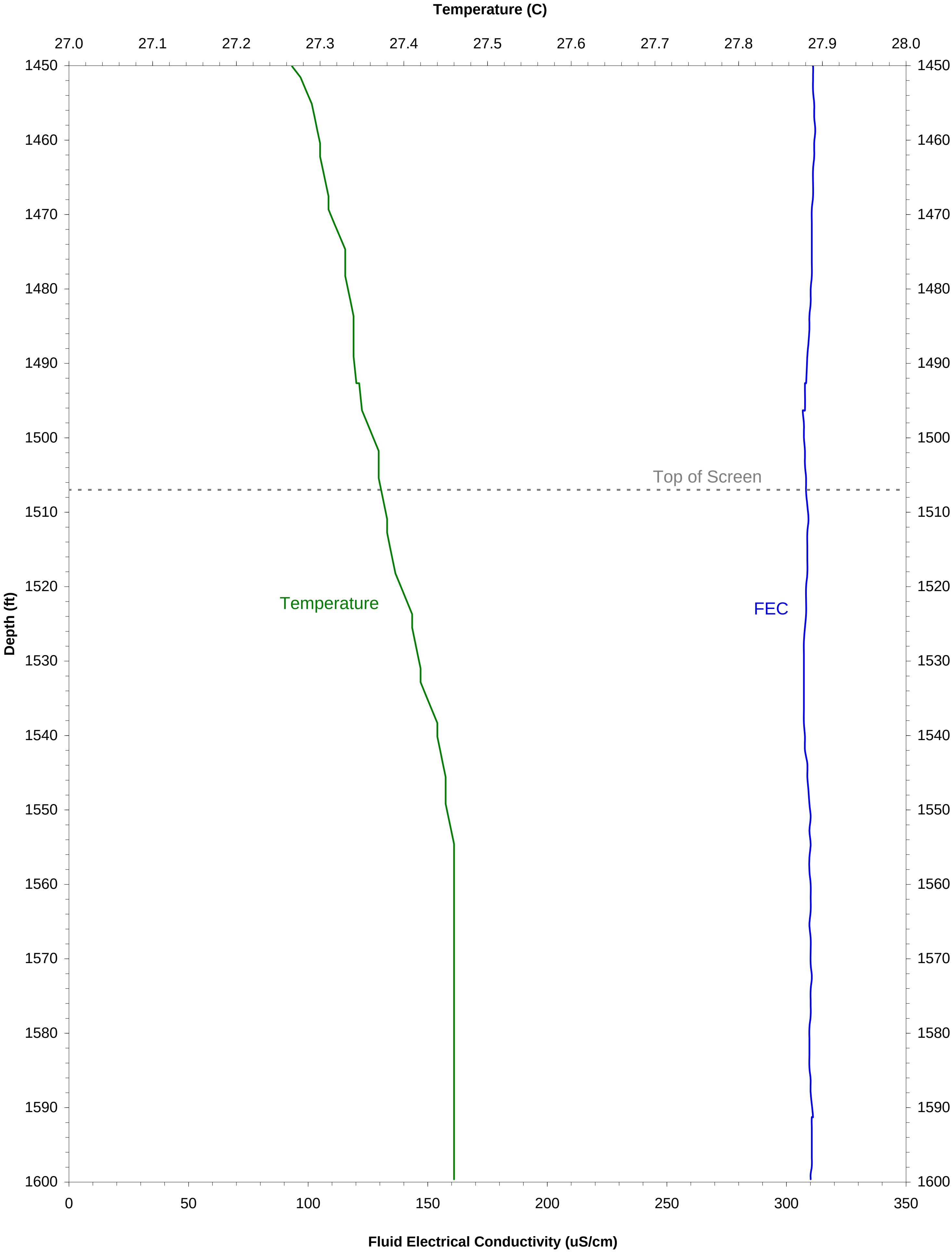
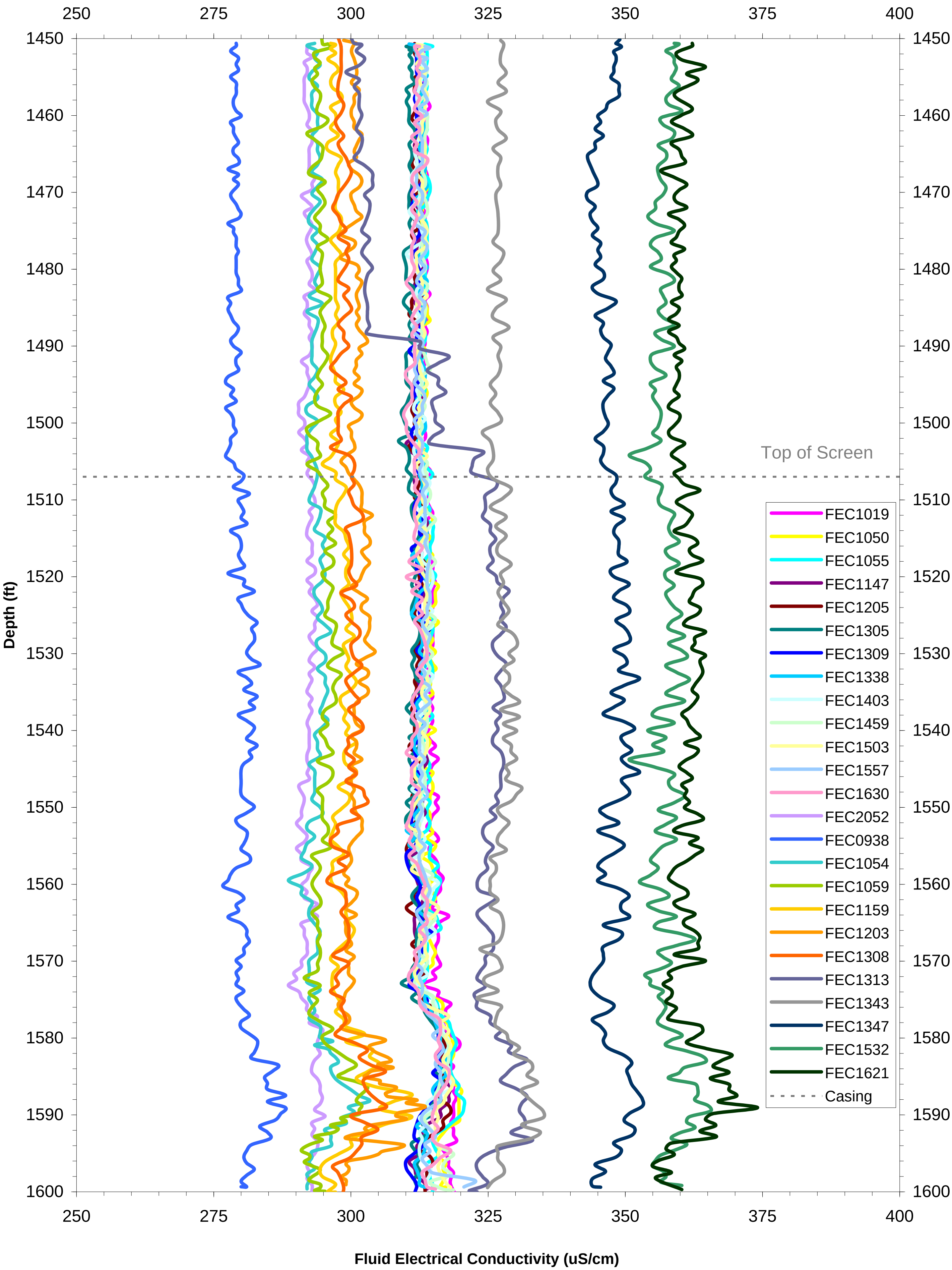


FIGURE Well 19:2. Summary of Fluid electrical Conductivity Logs During Pumping at 725 GPM;Wittman Hydro; BRWC; Baton Rouge, Louisiana; Wellbore: #19



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Spinner Flow Meter
Fluid Temperature
Fluid Conductivity

Company Wittman Hydro
Well Well #19
Field Baton Rouge Water Co.
County
State Louisiana

COMPANY Wittman Hydro
WELL #19
FIELD Baton Rouge Water Company
COUNTY **STATE** Louisiana

LOCATION
Baton Rouge, LA

QTR **SEC** **TWP** **RGE**

OTHER SERVICES
Fluid Conductivity

PERMANENT DATUM Top of Cement Pad **ELEVATION** NA

LOG MEAS. FROM Top of Cement 1.84 ft **ABOVE PERMINANT DATUM**

DRILLING MEAS. FROM GROUND LEVEL

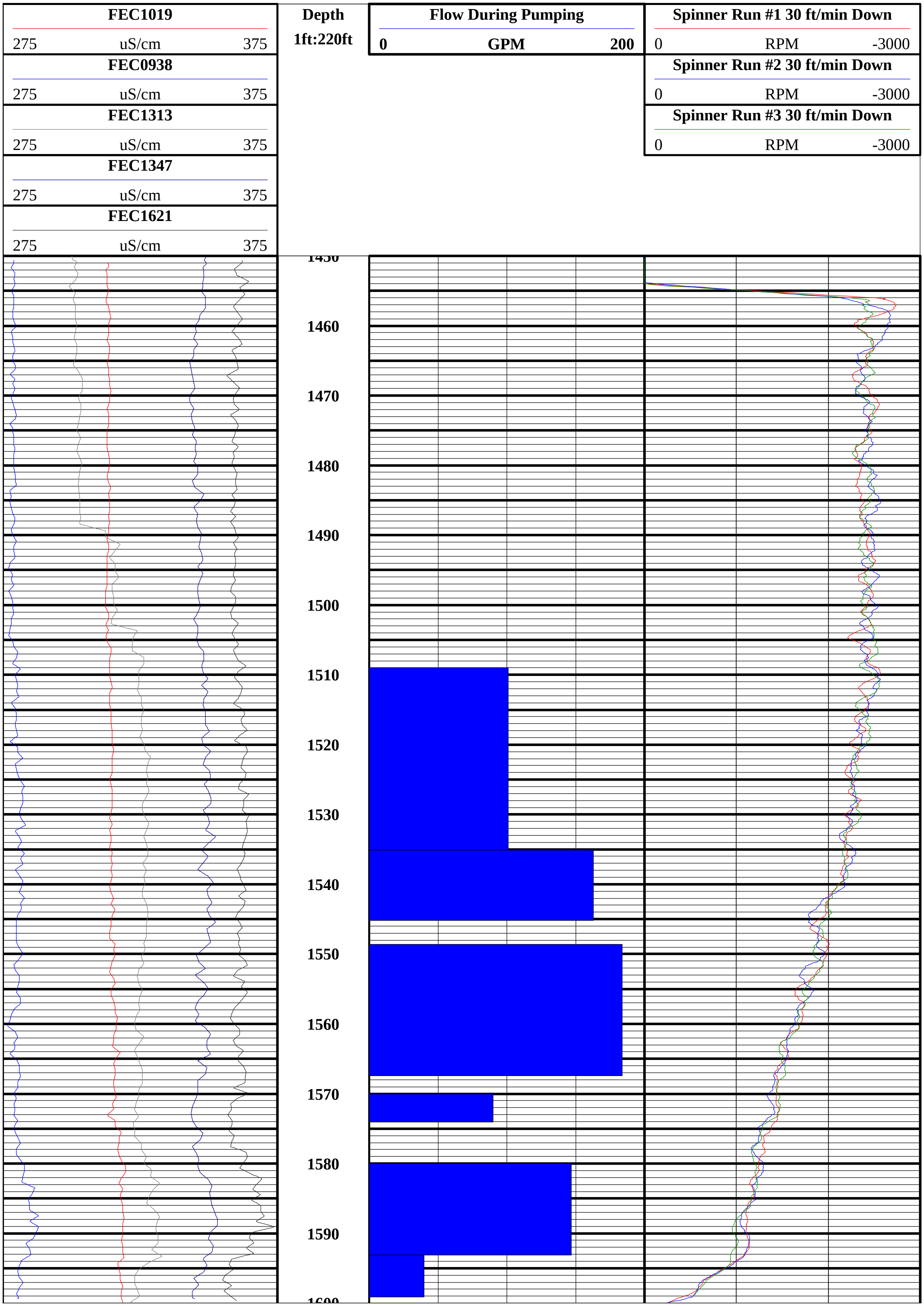
DATE ACQUIRED	12 May 2010	13 May 2010		
RUN NUMBER	1	2		
LOG TYPE	Temp/FEC	Spinner Flow Meter		
DEPTH-DRILLER	1610'	1610'		
DEPTH-LOGGER	1599'	1599'		
BTM LOG INTERVAL	1599'	1599'		
TOP LOG INTERVAL	1509'	1509'		
RECORDED BY	Greg Bauer	Greg Bauer		
WITNESSED BY	Bruce	Bruce		
PROBE TYPE, S/N	HpL #1	HRFM 4211		
LOGGING SPEED	30 ft/min	30/60/90 ft/min		
A.S.D.E.	0.4'	0.5'		
SAMPLE INTERVAL	0.5'	0.1'		

BOREHOLE RECORD				**CASING RECORD**			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**

COMMENTS

NA - Not Available, N/A - Not Applicable

Pumping was being conducted at 725 gpm at the time of logging.


FEC1019
275 uS/cm 375
FEC0938
275 uS/cm 375
FEC1313
275 uS/cm 375
FEC1347
275 uS/cm 375
FEC1621
275 uS/cm 375
Depth
1ft:220ft
Flow During Pumping
0 GPM 200
Spinner Run #1 30 ft/min Down
0 RPM -3000
Spinner Run #2 30 ft/min Down
0 RPM -3000
Spinner Run #3 30 ft/min Down
0 RPM -3000
1460
1470
1480
1490
1500
1510
1520
1530
1540
1550
1560
1570
1580
1590

Company	Wittman Hydro
Well	Well #19
Field	Baton Rouge Water Co.
County	
State	Louisiana

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Spinner Flow Meter
Fluid Temperature
Fluid Conductivity

COMPANY	Wittman Hydro		
WELL	#19		
FIELD	Baton Rouge Water Company		
COUNTY		**STATE**	Louisiana
LOCATION	Baton Rouge, LA	**OTHER SERVICES**	Fluid Conductivity
QTR	**SEC**	**TWP**	**RGE**

PERMANENT DATUM Top of Cement Pad **ELEVATION** NA
LOG MEAS. FROM Top of Cement 1.84 ft **ABOVE PERMINANT DATUM**
DRILLING MEAS. FROM GROUND LEVEL

DATE ACQUIRED	12 May 2010	13 May 2010	
RUN NUMBER	1	2	
LOG TYPE	Temp/FEC	Spinner Flow Meter	
DEPTH-DRILLER	1610'	1610'	
DEPTH-LOGGER	1599'	1599'	
BTM LOG INTERVAL	1599'	1599'	
TOP LOG INTERVAL	1509'	1509'	
RECORDED BY	Greg Bauer	Greg Bauer	
WITNESSED BY	Bruce	Bruce	
PROBE TYPE, S/N	HpL #1	HRFM 4211	
LOGGING SPEED	30 ft/min	30/60/90 ft/min	
A.S.D.E.	0.4'	0.5'	
SAMPLE INTERVAL	0.5'	0.1'	

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**

COMMENTS

NA - Not Available, N/A - Not Applicable

Pumping was being conducted at 725 gpm at the time of logging.

Notice the character of the logs acquired at 60 ft/min and 90 ft/min match the character of the repeatable logs acquired at 30 ft/min

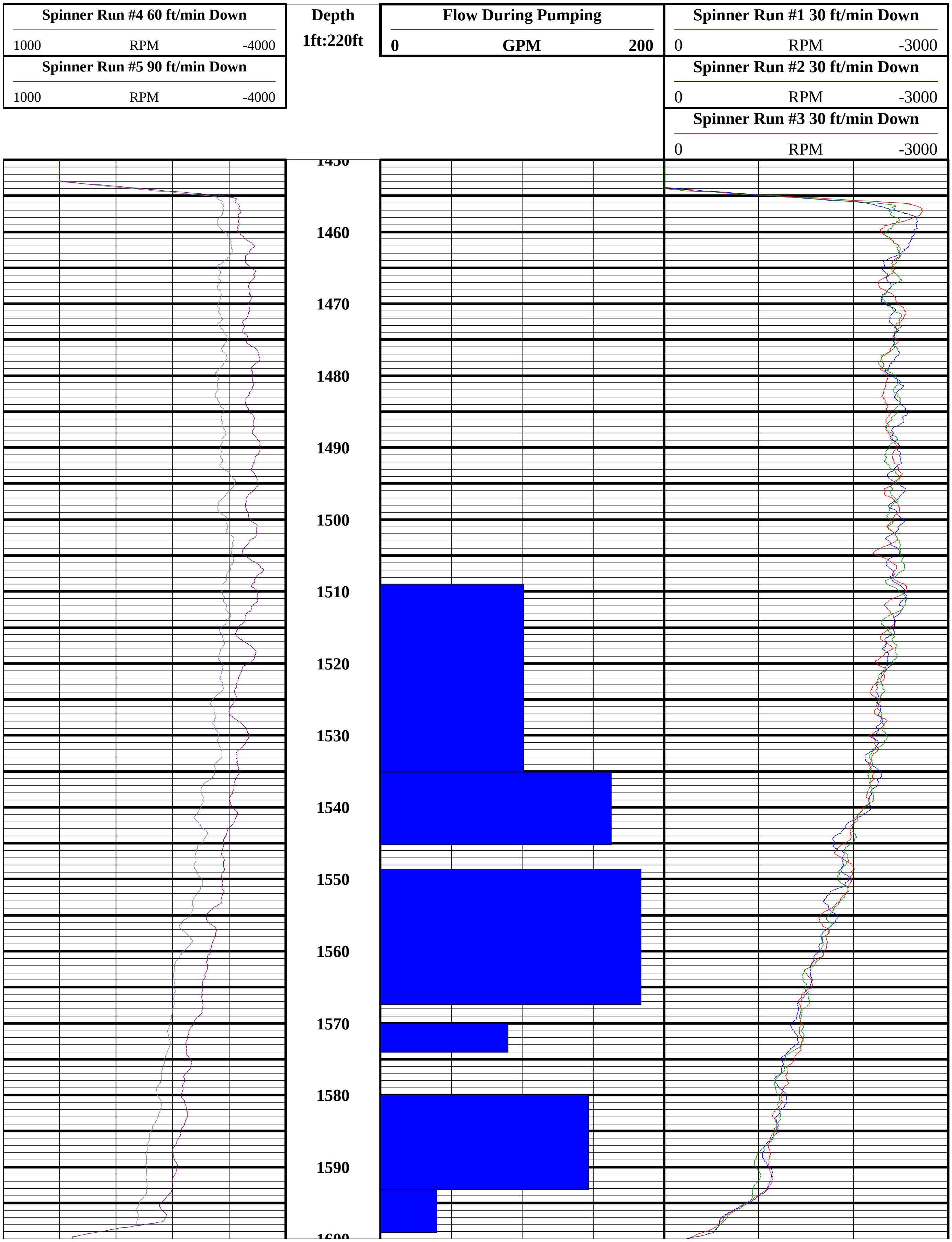
Spinner Run #4 60 ft/min Down
1000 RPM -4000
Spinner Run #5 90 ft/min Down
1000 RPM -4000
Depth
1ft:220ft
Flow During Pumping
0 GPM 200
Spinner Run #1 30 ft/min Down
0 RPM -3000
Spinner Run #2 30 ft/min Down
0 RPM -3000
Spinner Run #3 30 ft/min Down
0 RPM -3000
1460
1470
1480
1490
1500
1510
1520
1530
1540
1550
1560
1570
1580
1590

Table Well 19:1. Summary of Spinner Flow Meter Logging Results; Wittman Hydro; BRWC; Baton Rouge, LA; Wellbore: #19

Well Name	19
Ambient Depth to Water (fbgs)	215.46
Maximum Drawdown (ft)	28.89

Interval No.	Top of Interval (ft)	Bottom of Interval (ft)	Length of Interval (ft)	Interval Specific Flow Rate During Pumping (gpm)
1	1509	1535	26.1	101
2	1535	1545	10.0	163
3	1549	1567	18.7	184
4	1570	1574	4.0	90
5	1580	1593	13.0	147
6	1593	1599	6.0	40

Appendix B - Progress Park Well Logs

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
WATER RESOURCES SECTION
WATER LL REGISTRATION LONG FORM (DOTD-GW-1)

COPY

PLEASE PRINT IN INK OR TYPE WHEN COMPLETNG THIS FORM

1. Well Owner: BATON ROUGE WATER COMPANY Phone (225 231-0307
Address: P.O. BOX 96016
BATON ROUGE, LA 70896-9016
Owner's Well Number or Name (If Any) PROGRESS PARK OBSERVATION WELL #1

LAYNE (BR) CHRISTENSEN CO.
Name of Water Well Contractor
LICENSE NUMBER WWC- 010
Bucelh Duhe 5/16/11
Authorized Signature (Date)

2. LOCATION OF WELL: Parish EAST BATON ROUGE, Well is Near, PROGRESS PARK (Town, City)
Approximately SW CORNER ~~XXX~~ from NORTH 30TH AT PROGRESS ST. Crossroads, Railroad, Any Landmark, etc.
(Please draw sketch on back of Original Form)

MAIL ORIGINAL TO:
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
ATTN: CHIEF - WATER RESOURCES SECTION
P.O. BOX 94245
BATON ROUGE, LA 70804-9245
(225) 274-4172

2. WELL INFORMATION: Ground elevation 50' ft. M.S.L. Depth of Hole: 1710 ft.
Diameter of Hole 15 in. Depth of Completed Well: 1665 ft.
Is well gravel-packed? Yes ☒ No ☐ Date Completed: 04/15/11
NAME OF THE PERSON WHO DRILLED THE WELL: BUDDY LOWERY & BARRY CROOK

4. CASING AND SCREEN INFORMATION:
CASING: TYPE STEEL SCREEN TYPE 304 SS PIPE-BASE
6 in. from +3 ft. to 600 ft. 4 in. from 1605 ft. to 1665 ft.
4 in. from 600 ft. to 1605 ft. __ in. from __ ft. to __ ft.
__ in. from __ ft. to __ ft. __ in. from __ ft. to __ ft.
Extension Pipe N/A in. from __ ft. to __ ft.
Cemented from 1565 ft. to ground surface.
Pumpdown cementing method used: ☐ Inside casing ☒ Outside casing

5. WATER LEVEL AND YIELD INFORMATION: On 04/20/11 (Date) the static water level in well was 186 ft.
☒ below ☐ above ground surface. How determined? ELECTRIC TAPE The pumping water level was 229 feet below ground surface. The well yielded 166 gpm with a drawdown of 43 ft. after 9 hours of continuous pumping on (date) 04/20/11. Describe how yield was measured FLOW METER. It is planned to pump the well at a rate of 0 gpm for 0 hours per day for 0 days per year. Proposed average daily pumping rate: N/A gallons. Motor HP N/A Pump setting N/A ft.

6. USE OF WELL (Check Appropriate Box)
☐ Irrigation/Agricultural ☐ Industrial ☐ Community Public Supply ☐ Power Generation
☐ Dewatering ☒ Observation ☐ Non-community Public Supply ☐ Test Hole
☐ OTHER (Please Specify)
(If industrial or public supply is checked please see bottom of this form)

7. AVAILABLE INFORMATION (Check Appropriate Boxes)

	YES	NO	
Is an electrical log or other borehole geophysical log available?	☒	☐	(if yes, please attach a copy of log)
Is a mechanical analysis of the drill cutting available?	☒	☐	(if yes, please attach a copy)
Is a chemical analysis of water available?	☒	☐	(if yes, please attach a copy)
Is a bacteriological analysis available?	☐	☒	(if yes, please attach a copy)
Are aquifer test results available?	☒	☐	(if yes, please attach a copy)

FOR OFFICE USE ONLY
STATE 2 2 PARISH WELL NO. -
IDENTIFICATION NUMBER 0
REVISED COORDINATES
Geologic Unit
Use of Well
SECTION TOWNSHIP RANGE
ELEV. QUAD NO. 1 6 3 A
INPUT BY: DATE:
INSPECTED BY:
INSPECTION DATE:
REMARKS:

8. ABANDONMENT INFORMATION: (Check Appropriate Boxes)
If well is new does it replace an existing well? YES ☐ NO ☒
If yes, has owner been informed of state regulations requiring plugging of abandoned wells? YES ☐ NO ☐

9. REMARKS (Such as engineer, pump information, acreage irrigated, water well subcontractor and license no., etc.)
PLUGGED BOTTOM OF TEST HOLE FROM 1710' TO 1685' WITH PORTLAND CEMENT

10. DRILLER'S LOG (Description and color of cuttings, such as, shale, sand, etc. in feet below ground level).

FROM	TO	DESCRIPTION	FROM	TO	DESCRIPTION	FROM	TO	DESCRIPTION
		ATTACHED						

(If necessary, continue log on back of original form.)

PUBLIC SUPPLY: (If well is for public-supply purpose please check one of the following to indicate principal category of public-supply use.)
☐ Municipal ☐ Therapeutic
☐ Rural ☐ Institutional/Government
☐ Commerical ☐ Other __ Please Specify

INDUSTRIAL: (If wellis for industrial purpose please check one of the following to indicate the standard industrial category representing the prinipal industrial use).
☐ Food and Kindred Products ☐ Paper and Allied Products
☐ Textile Mill Products ☐ Chemicals and Allied Products
☐ Lumber & Wood Products (Except Furniture). ☐ Petroleum Refining & Related Industries
☐ Other __ Please Specify ☐ Primary Metal Products

(REV. 04/05)

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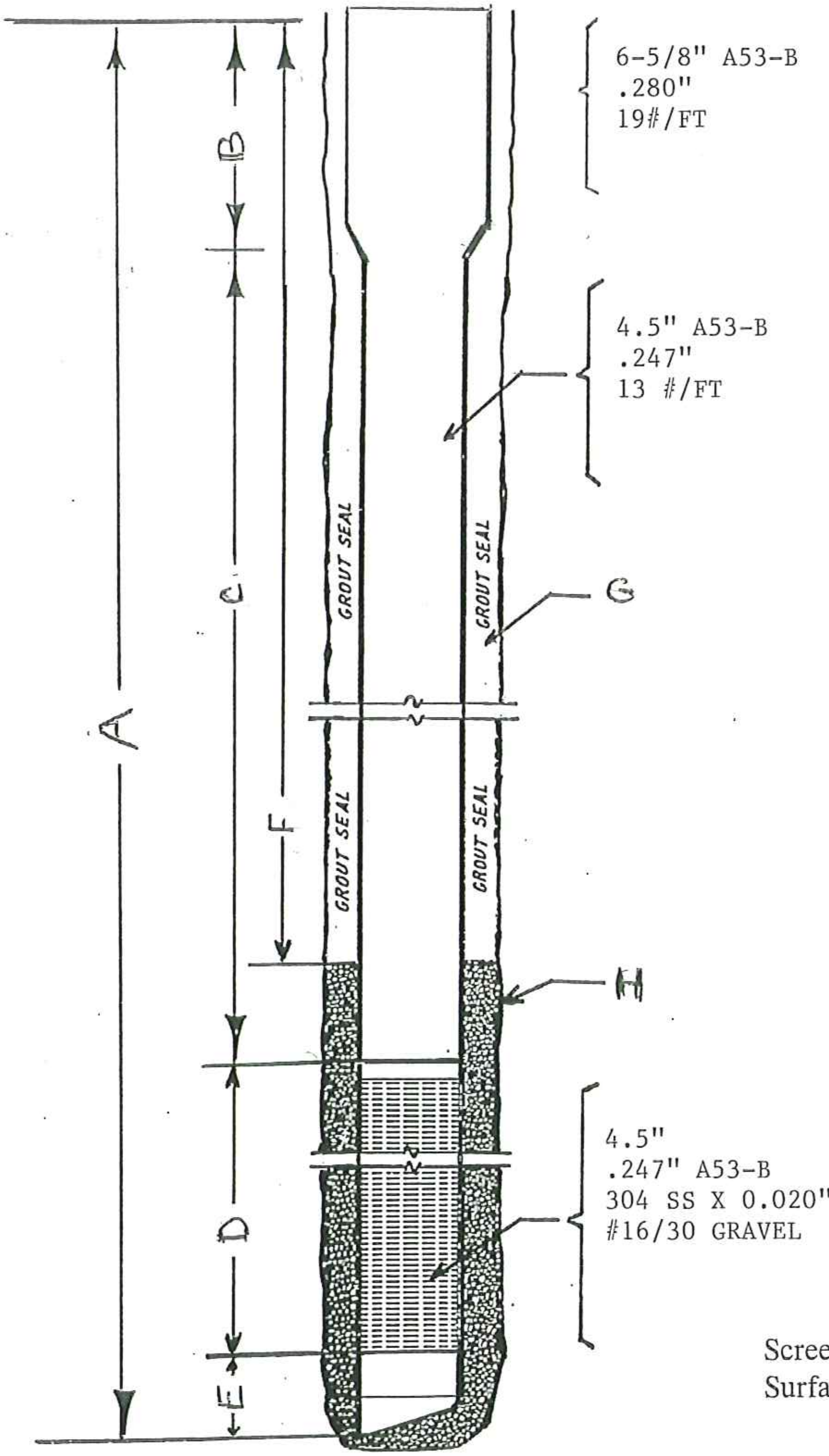
Layne Christensen Company

P.O. Box 1652 • Prairieville, Louisiana 70769 • (225) 744-4899 • Fax: (225) 744-4858 • LA Wats: 1-800-225-7495



Project: OBSERVATION WELL

Client: BATON ROUGE WATER CO.

Location: PROGRESS PARK

Target Stratum: "1500 FT" SAND

Date: 05/11/11

Well Construction

A. 1665'

B. 600'

C. 1005'

D. 60'

E. N/A

F. 1565'

G. 15" DIA.

H. 15" DIA.

Screen Setting: 1605' TO 1665'

Surface/Pit Casing: 80' OF 18" X .375"

Formation Log

Client: Baton Rouge Water Company
Location: Progress Park; Baton Rouge
Well: Observation Well
Job # 18820757
Driller: Buddy Lowrey; Barry Crook
Date: 03.12.11

From	To	Formation
0	76	Tan & Brown Clay
76	127	Blue Clay
127	162	Gray Clay (light)
162	266	Blue Clays/Shale sand streaks
266	508	Gray clay; shale & sand streaks
508	521	Gray clay; sand
521	527	Hard Clay; sandy streak
527	547	Blue clay; sand streak
547	689	Five Sand & Clay streaks
689	742	Sandy clay
742	775	Sandy Clay
775	779	Hard Clay
779	897	Sandy Clay
897	1043	Clay; sand shale streaks
1043	1117	Sand and clay
1117	1172	Hard clay
1172	1218	Sand and clay
1218	1295	Hard clay; sand streak
1295	1296	Rock/hard sand
1296	1454	Hard clay; sand & shale streak
1454	1603	Fine sand; shale; light clay
1603	1655	Fine sand
1655	1701	Hard blue clay; sticky

Johnson screens

SAND ANALYSIS

Weatherford

From: Layne Christensen

DATE: 05/11/11

Location: Baton Rouge- Observation Well

DEPTH	1439	1449	1459	1470	1480	1490	1502	1512	1522	1533	1543	1553
FEET	1449	1459	1470	1480	1490	1502	1512	1522	1533	1543	1553	1563
GAUGE												
0.0331	0	0	0	0	0	0	0	0	0	0	0	0
0.0234	0	0	0	0	0	0	0	0	0	0	0	0
0.0165	0	1	0	1	0	0	1	3	8	11	14	10
0.0117	7	10	6	8	5	6	14	22	31	39	46	38
0.0098	18	22	16	21	17	18	29	38	44	58	65	61
0.0083	32	38	31	36	35	37	46	55	62	73	79	74
0.0070	50	55	48	55	54	58	65	70	77	88	90	87
0.0059	69	74	67	75	73	80	83	84	89	93	96	94
0.0029	100	100	100	100	100	100	100	100	100	100	100	100
PAN	100	100	100	100	100	100	100	100	100	100	100	100

*** Note : There is no charge for sand analysis when an order is pending . ***

*** If no order is pending a $ 50.00 per sample charge will occur. ***

Johnson screens

SAND ANALYSIS

Weatherford

From: Layne Christensen **DATE: 05/11/11**

Location: Baton Rouge- Observation Well

DEPTH	1563	1573	1583	1592	1602	1612	1622	1632	1642	1653	1663	1673	1685
FEET	1573	1583	1592	1602	1612	1622	1632	1642	1653	1663	1673	1685	1701
GAUGE										Clayish	Clayish	Clayish	Clayish
0.0331	0	0	0	0	0	0	0	0	0	13	9	3	0
0.0234	1	0	0	1	0	1	1	1	1	24	18	11	4
0.0165	13	12	10	14	11	16	17	15	16	40	33	24	16
0.0117	42	40	39	47	41	55	57	54	60	59	51	45	39
0.0098	63	57	58	67	63	76	78	75	82	68	60	56	53
0.0083	78	71	73	82	76	89	91	88	94	75	71	68	66
0.0070	87	84	85	91	88	96	97	94	99	81	79	77	77
0.0059	93	92	94	97	95	99	100	99	100	86	85	86	87
0.0029	100	100	100	100	100	100	100	100	100	96	95	97	99
PAN	100	100	100	100	100	100	100	100	100	100	100	100	100

*** Note : There is no charge for sand analysis when an order is pending . ***
*** If no order is pending a $ 50.00 per sample charge will occur. ***

JOHNSON SCREENS
11939 Aldine-Westfield Rd.
Houston, Texas 77093
800-237-7593
FAX 281-442-0503

Weatherford

SAND ANALYSIS PLOT

DATE SAMPLE ANALYZED 03/12/2011

JOB NAME Baton Rouge- Observation Well

CITY ______ STATE ______

CONTRACTOR Layne Christensen Co.

SAMPLE NO. 1563" - 1701' Composite Sample

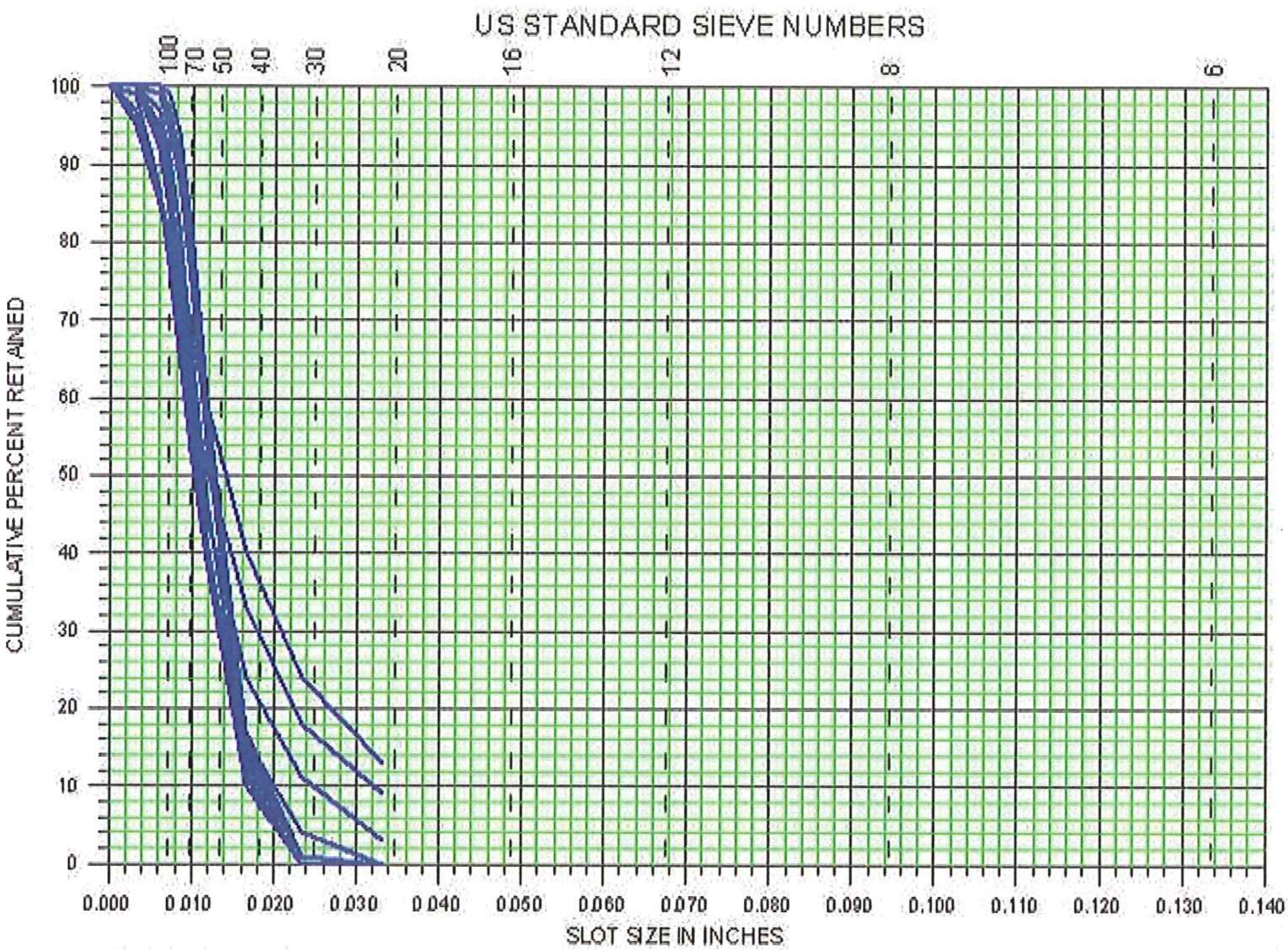
SCREEN SLOT SIZE IF GRAVEL PACKED ______

SCREEN SLOT SIZE IF NATURAL DEV. ______

GRAVEL PACK RECOMMENDED ______

US SIEVE NUMBER	SLOT SIZE IN INCHES	CUMULATIVE PERCENT RETAINED
#20	0.0331	Composite
#30	0.0234	Graph
#40	0.0165	
#50	0.0117	
#60	0.0098	
#70	0.0083	
#80	0.0070	
#100	0.0059	
#200	0.0029	
Pan	0.0001	

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SUBMITTED SAND SAMPLES ARE CORRECT, WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF ANY WELL



JOHNSON SCREENS
11939 Aldine-Westfield Rd.
Houston, Texas 77093
800-237-7593
FAX 281-442-0503

Weatherford

SAND ANALYSIS PLOT

DATE SAMPLE ANALYZED 03/12/2011

JOB NAME Baton Rouge- Observation Well

CITY ____ STATE ____

CONTRACTOR Layne Christensen Co.

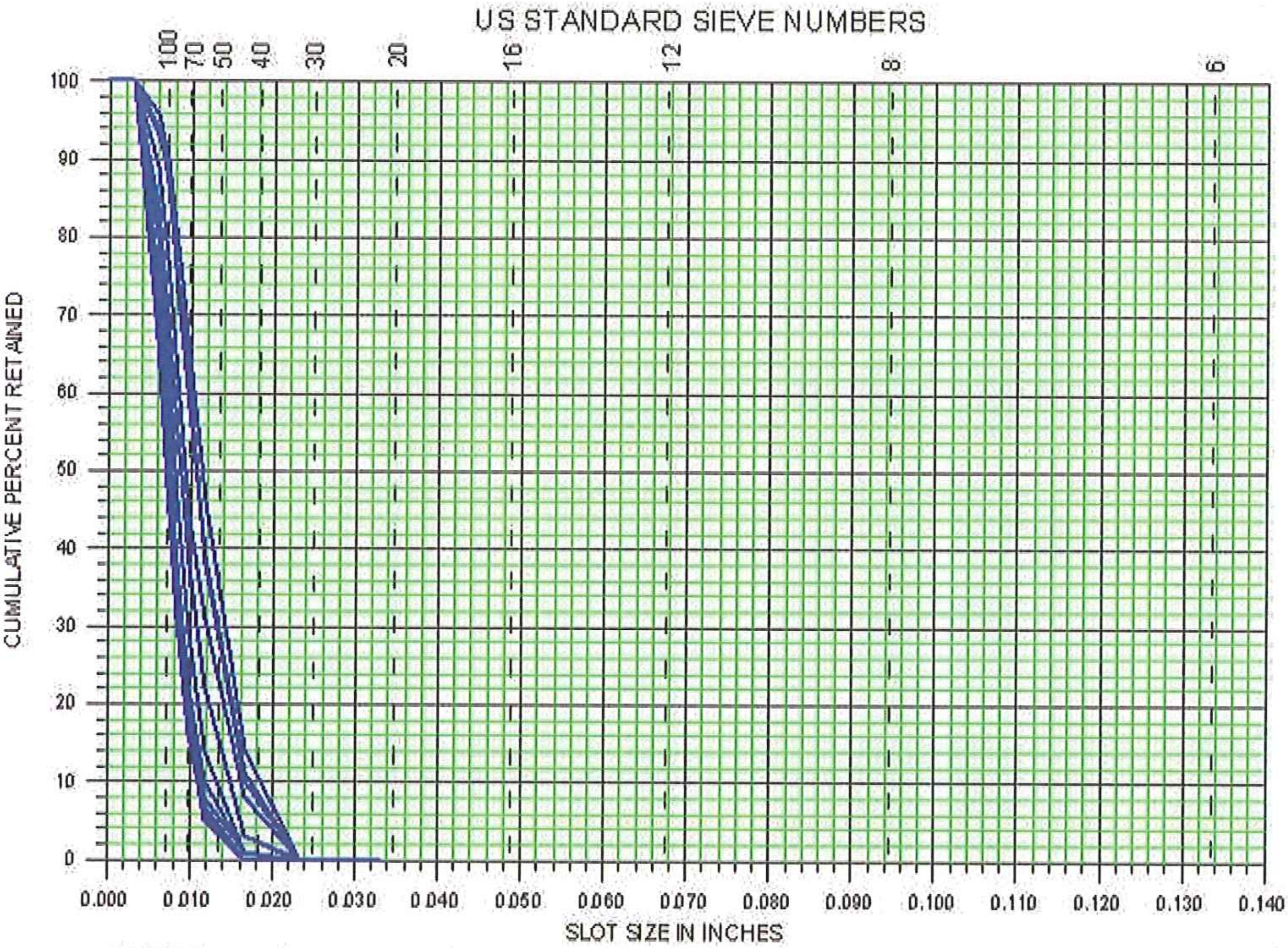
SAMPLE NO. 1439" - 1563' Composite Sample

SCREEN SLOT SIZE IF GRAVEL PACKED ____

SCREEN SLOT SIZE IF NATURAL DEV. ____

GRAVEL PACK RECOMMENDED ____

US SIEVE NUMBER	SLOT SIZE IN INCHES	CUMULATIVE PERCENT RETAINED
#20	0.0331	Composite
#30	0.0234	Graph
#40	0.0165	
#50	0.0117	
#60	0.0098	
#70	0.0083	
#80	0.0070	
#100	0.0059	
#200	0.0029	
Pan	0.0001	



RECORD OF TEST

LAYNE CHRISTENSEN COMPANY
P.O. BOX 1652, PRAIRIEVILLE, LA 70769

No. OB Well #1	Pump No. 20 Hp Test	Date: April 20, 2011
For: Baton Rouge Water Company		
City: Baton Rouge	State: La	
Location: Progress Park		
Air Lift Test	Guaranteed GPM at psi	Feet/Pounds
	Static Level 186.30	Feet
Running Pressure Pounds	Actual length of water level drawdown	
9-Hour Flow Test. Test Performed with 50 KW Generator.	Measuring Airline	Inches

	Pump						AMPS			
Time 8:30 AM	Start Test	Pressure LBS-Ft	Pumping Water Level	Draw-down	Inches on 4x3" weir or orifice	GPM				
8:35			223.25	36.95	15	153				
8:40			223.40	37.1	15	153				
8:45			223.45	37.15	15	153				
9:00			223.35	37.05	15	153				
9:15			223.50	37.2	15	153				
9:30			223.65	37.35	15	153				
10:00			223.40	37.1	15	153				
10:30			223.55	37.25	15	153				
11:00			223.90	37.6	15	153				
11:30			223.85	37.55	15	153				
12:00	PM		224.05	37.75	15	153				
12:30			223.95	37.65	15	153				
1:00			224.0	37.7	15	153				
1:30			223.30	37	14.5	151				
2:00			218.90	32.6	11.5	134				
2:30			216.15	29.85	10	125				
3:00			223.95	37.65	15	153				
3:30			229.75	43.45	17.5	166				
4:00			229.50	43.2	17.5	166				
4:30			229.45	43.15	17.5	166				
5:00			229.70	43.4	17.5	166				
5:30	END		229.30	43	17.5	166				

Comments: At two o'clock had problems with generator performing at 60 Hz made some adjustments continued test.

______________________ Damien Anastasio

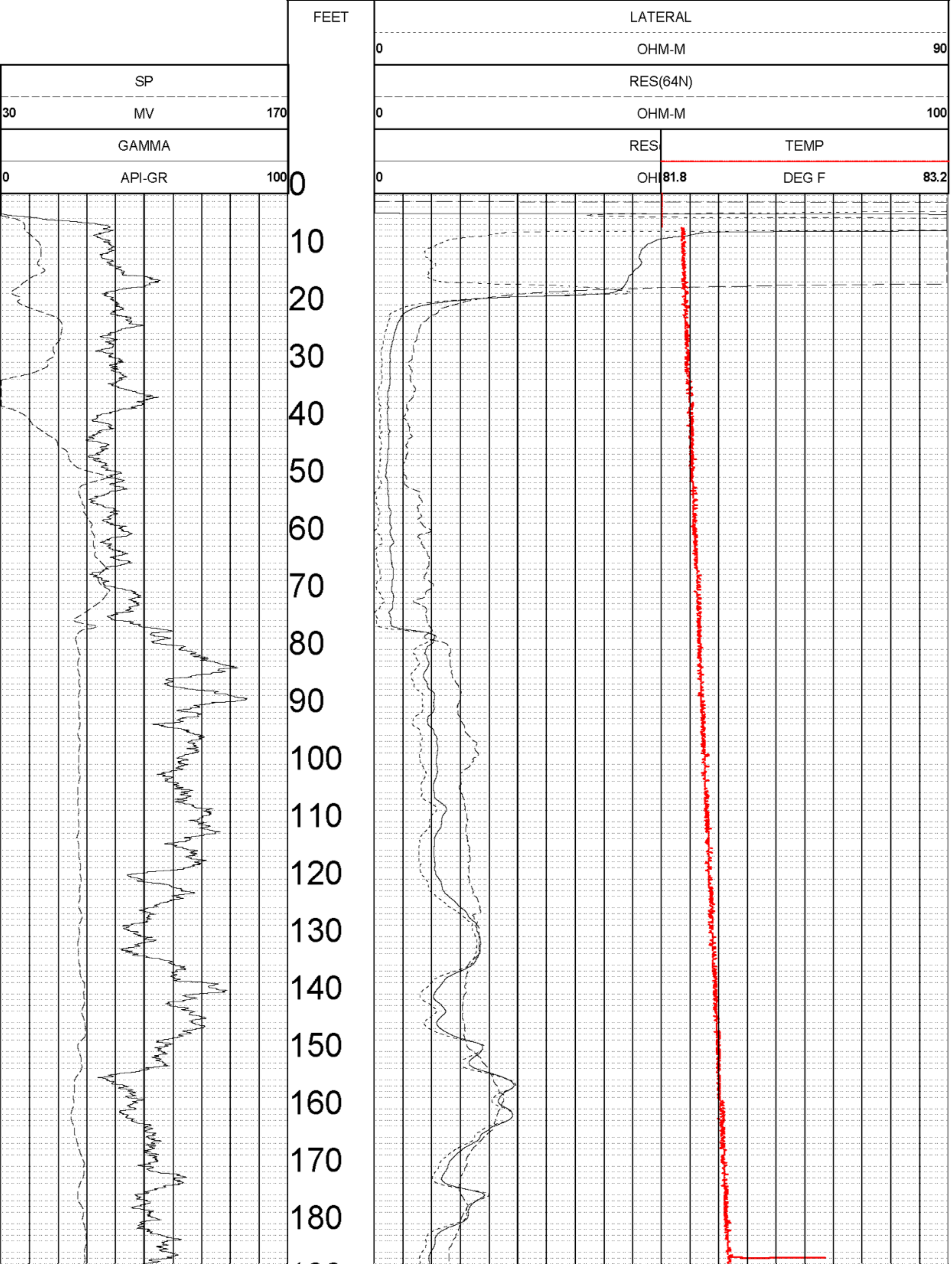
Representative For Owner Representative for Layne Christensen

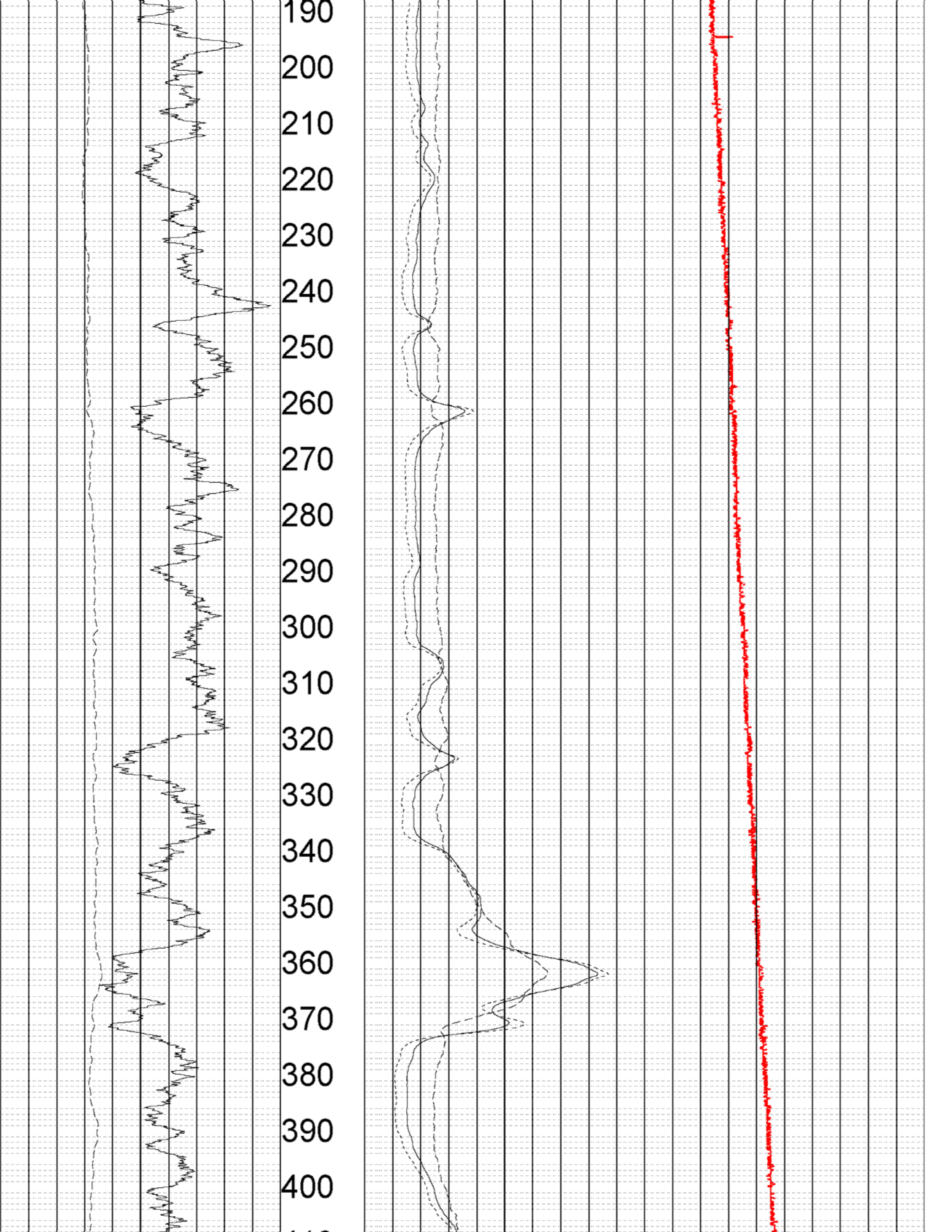
WELL#1882-0757 PROGRESS PARK

COMPANY	: BATON ROUGE WATER	OTHER SERVICES:			
WELL	: WELL#1882-0757 PROGRESS PARK				
LOCATION/FIELD	: NORTH 30TH STREET				
COUNTY	: E. BATON ROUGE				
LOCATION	: GONZALES				
SECTION	:	TOWNSHIP	:	RANGE	:
DATE	: 03/12/11	PERMANENT DATUM	:		
DEPTH DRILLER	: 1701'			KB	:
LOG BOTTOM	: 1709.15	LOG MEASURED FROM	: GL.	DF	:
LOG TOP	: 1.63	DRL MEASURED FROM	: GL.	GL	:
CASING DIAMETER	: 16"	LOGGING UNIT	: 2643		
CASING TYPE	: STEEL	FIELD OFFICE	: GONZALES		
CASING THICKNESS	: 16"	RECORDED BY	: COLWART		
BIT SIZE	: 15.000	BOREHOLE FLUID	:	FILE	: ORIGINAL
MAGNETIC DECL.	: 3.9	RM	: 9.6	TYPE	: 8144A
MATRIX DENSITY	: 2.85	RM TEMPERATURE	: 80.0	LGDATE	: 03/12/11
NEUTRON MATRIX	: DOLOMITE	MATRIX DELTA T	: 44		
				THRESH	: 99999

GPS COORDINATES: N 30' 27.285 W 91' 09.50

MUD WT. 9.2 SLICK 1/32" RMHRMC 9.6 RMF 6.


FEET
LATERAL
0
OHM-M
90
SP
30
MV
170
RES(64N)
0
OHM-M
100
GAMMA
0
API-GR
100
TEMP
81.8
DEG F
83.2
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180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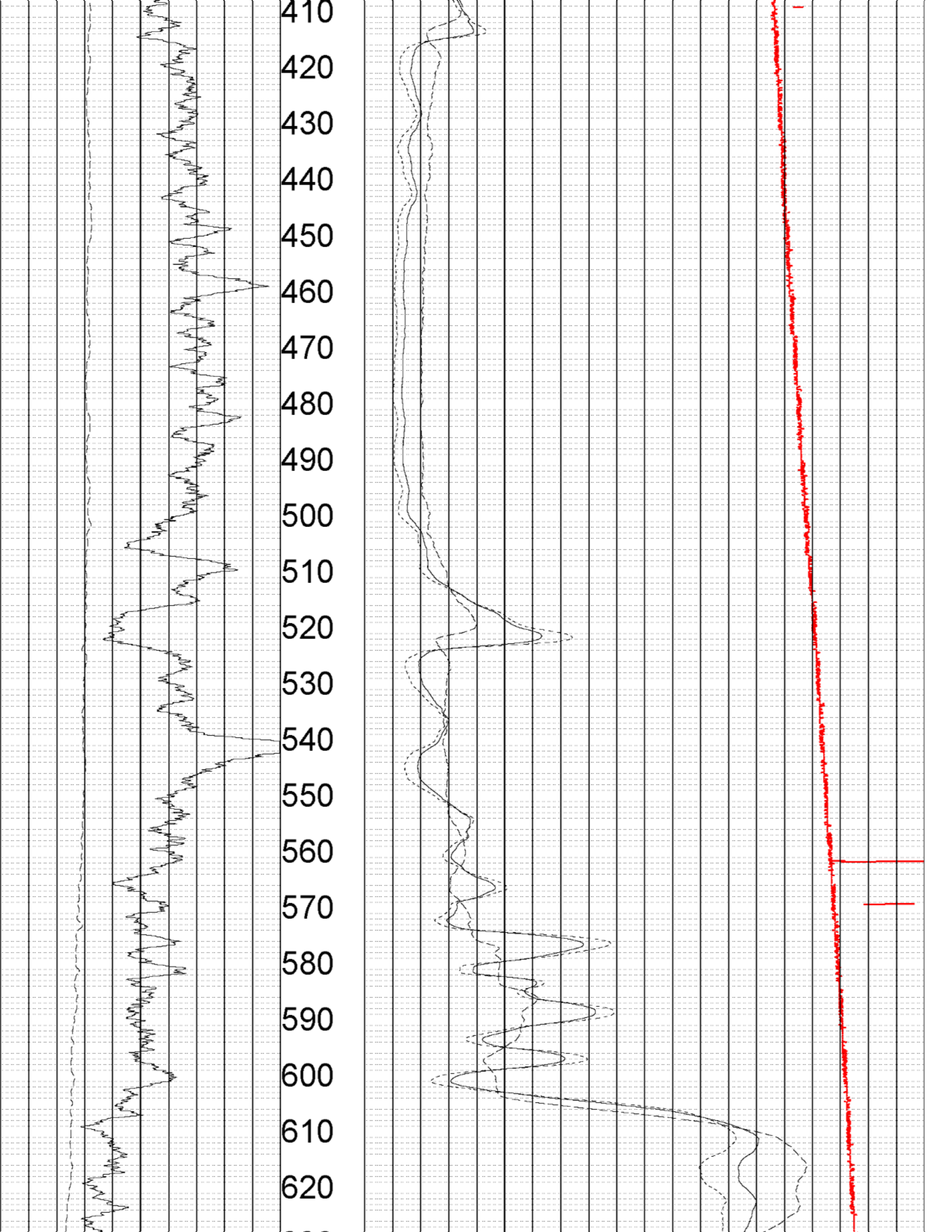
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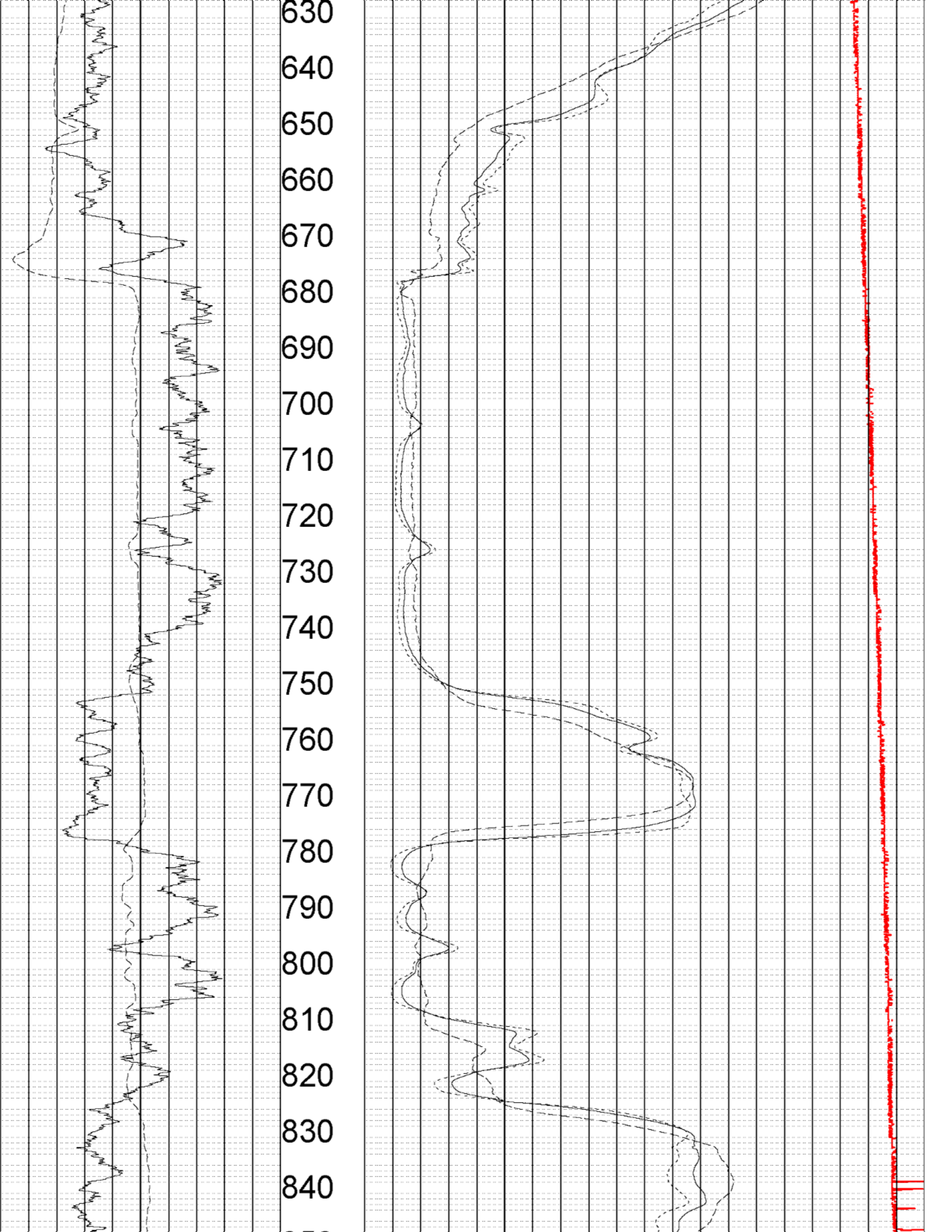
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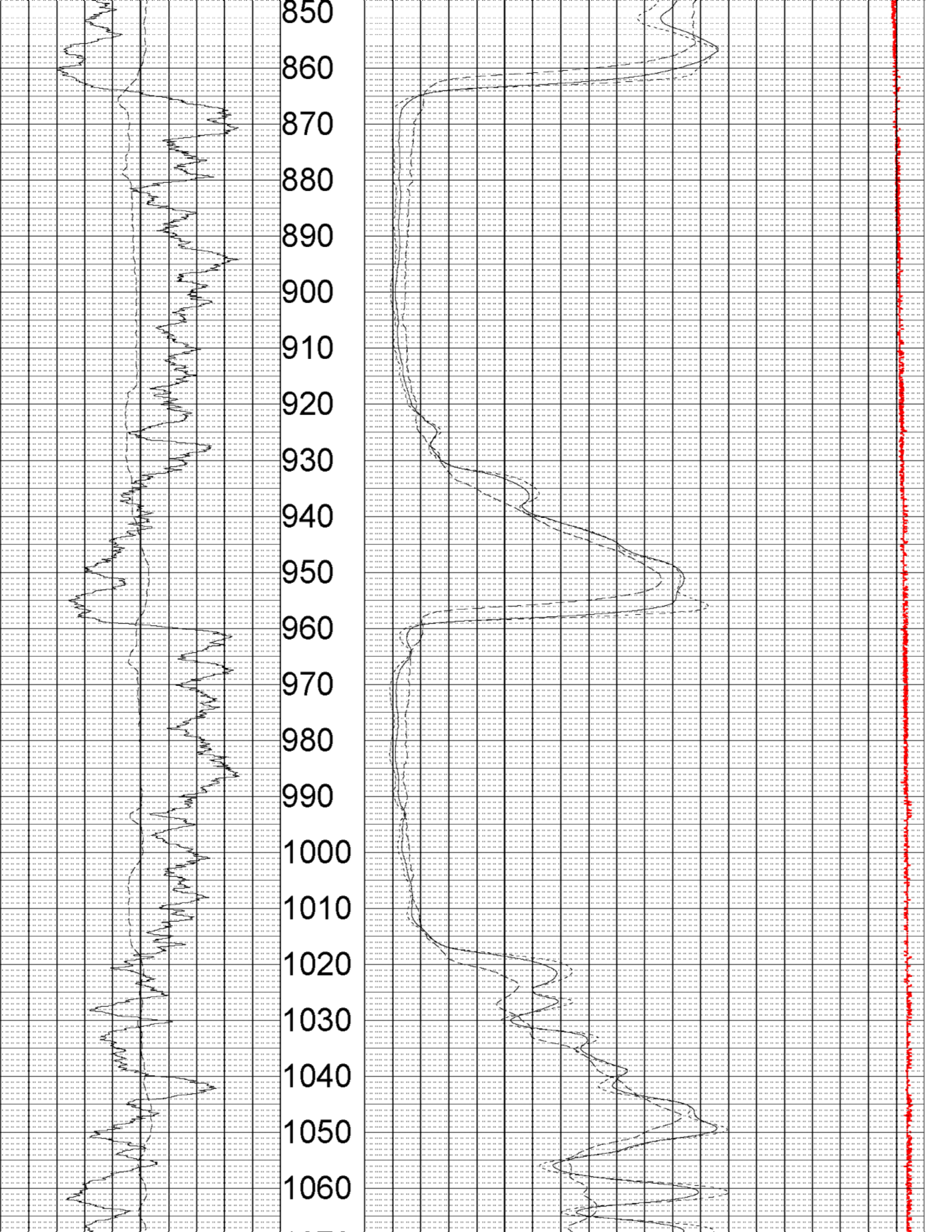
830
840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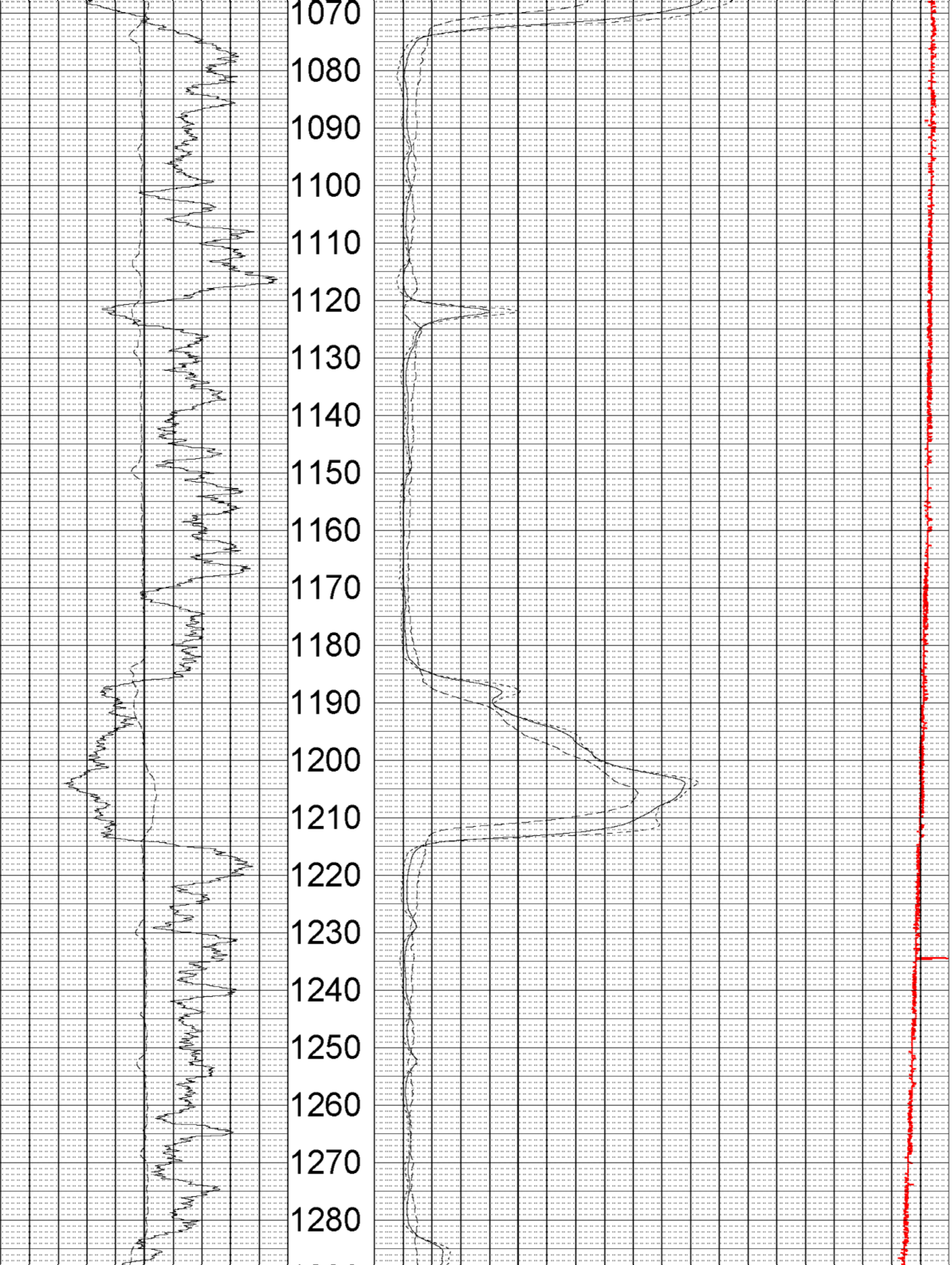
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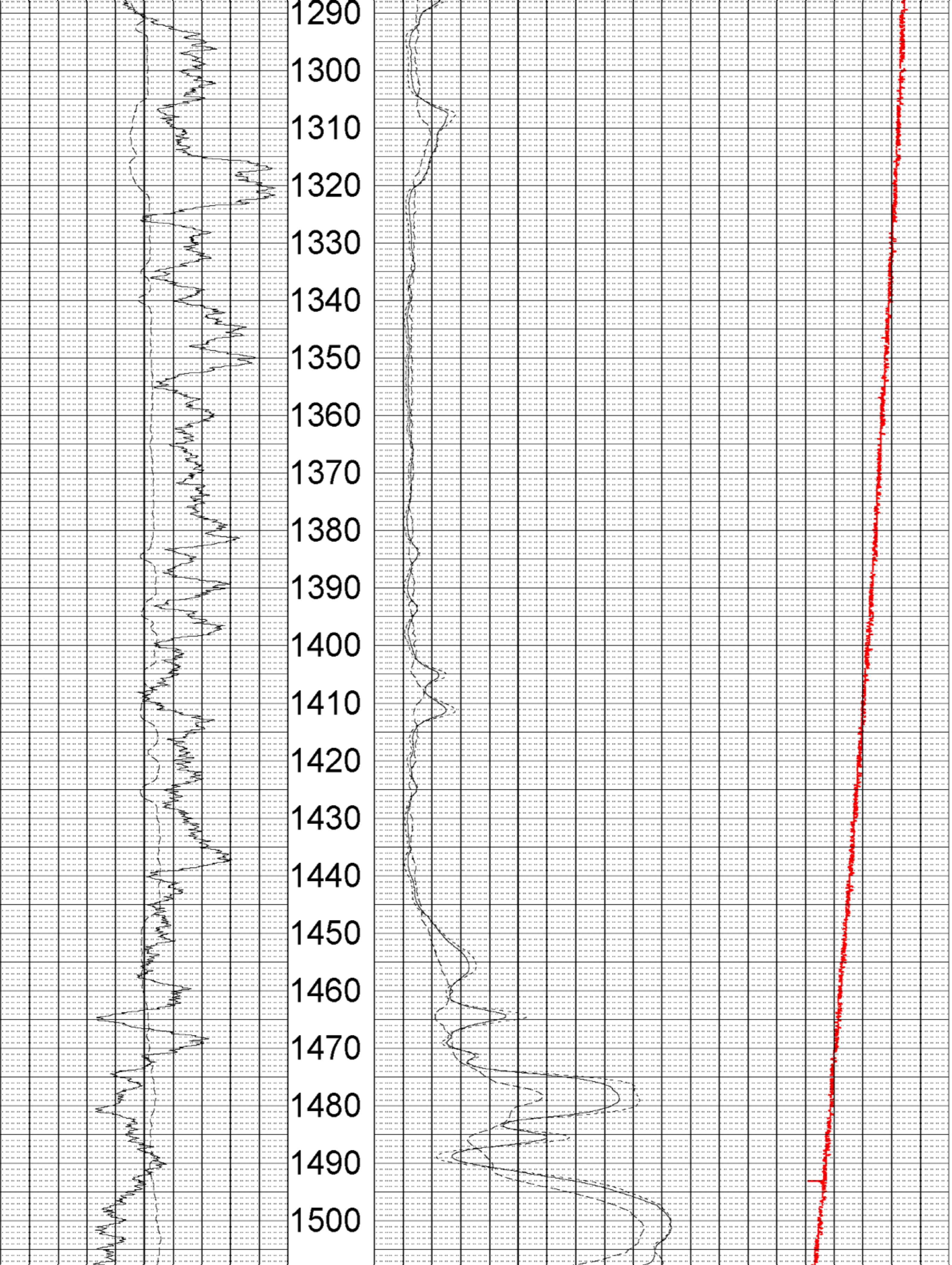
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1490
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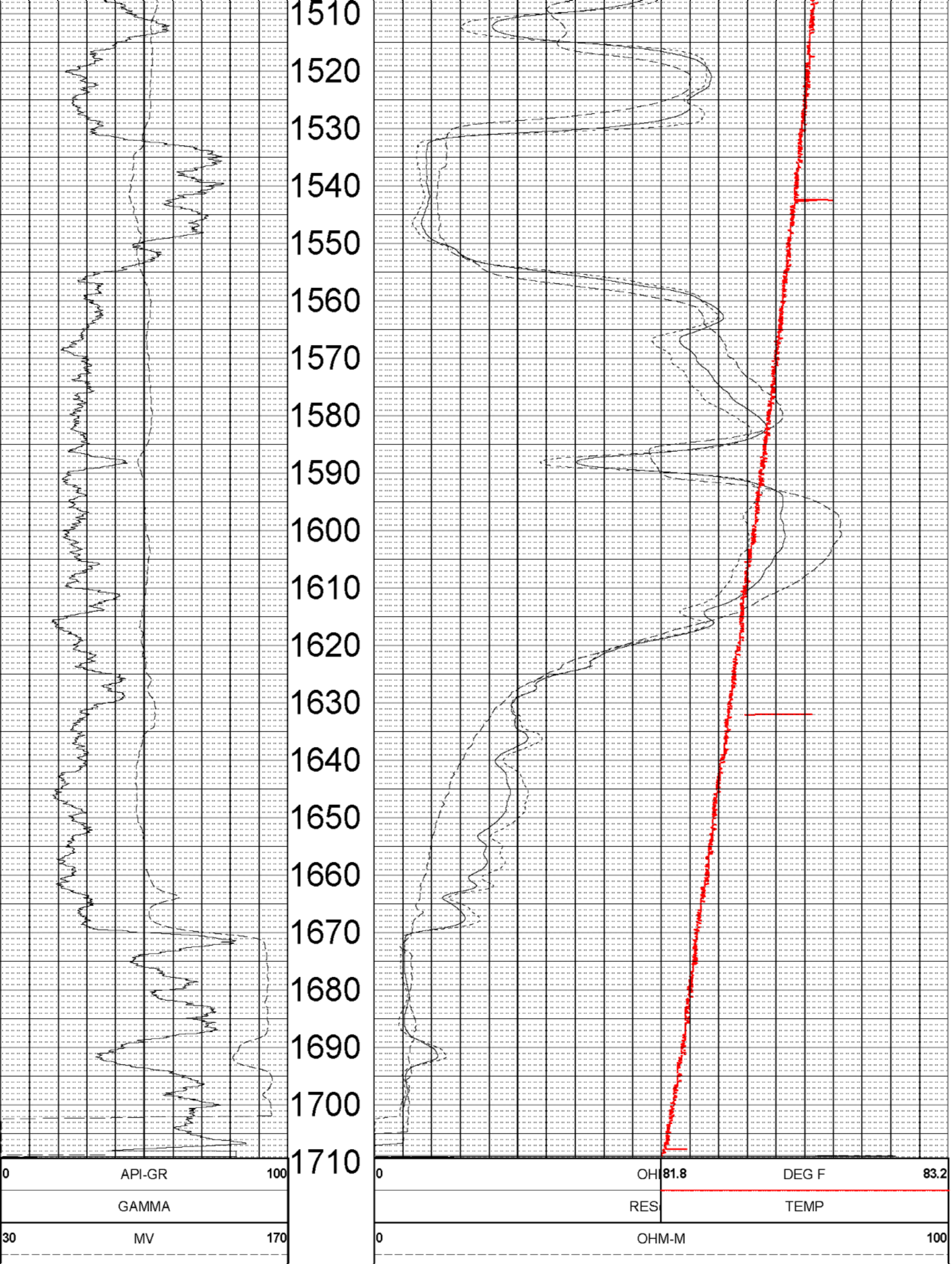
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1550
1560
1570
1580
1590
1600
1610
1620
1630
1640
1650
1660
1670
1680
1690
1700
1710
0
API-GR
100
GAMMA
30
MV
170
0
OHI
RES
81.8
DEG F
83.2
TEMP
0
OHM-M
100

SP		RES(64N)	
	FEET	0 OHM-M	90
		LATERAL	

Appendix C - Hydrophysical Logging Results

Hydrophysical Logging Results
Layne Hydro
Progress Park South Scavenger Well
Baton Rouge, Louisiana

Prepared for
Layne Hydro
October 10, 2011

Prepared by
COLOG Division of Layne Christensen Company
810 Quail Street Suite E, Lakewood, CO, 80215
Phone: (303) 279-0171 Fax: (303) 278-0135

Prepared By:	Reviewed By:
______________________________	______________________________
Greg D. Bauer	Michael J. Culig
Asst. Gen. Manager/Senior Hydrogeologist	Division Manager

Table of Contents

Hydrophysical Logging Results,
Progress Park South Scavenger Well; Baton Rouge, Louisiana

List of Acronyms

gpm – gallons per minute
FEC – Fluid Electrical Conductivity
ft – feet
ftbtoc – feet below top of casing
ftbgs – feet below ground surface
min. – minute
cm – centimeters
s – second
μS – micro Siemons
HpL - Hydrophysical Logging
DI – De-ionized, e.g., DI water
GS – Ground Surface

Hydrophysical Logging Results,
Progress Park South Scavenger Well; Baton Rouge, Louisiana

1. Executive Summary

The results of the Hydrophysical logging performed in the Scavenger well in Progress Park South in Baton Rouge, Louisiana identified water-bearing intervals throughout the screened interval ranging in flow rates of 0.11 to 32.7 gpm during production testing. Downhole sampling was conducted at two locations and one sample was procured at the well head to evaluate the vertical distribution of aqueous-phase constituents. In summary, intervals below 1642 feet, producing 19.9 gpm, or 23.6 percent of the total inflow during production testing, contributed the highest concentrations of: chloride, calcium, sodium and potassium. Moreover, the analyzed aqueous-phase constituents showed a general increase in concentration with increasing depth. The exception to the analyzed constituents is, bicarbonate, which showed a decrease in concentration with depth. The interval near the top of the screened interval, producing 32.7 gpm, or 43.1 percent of the total inflow during production testing, registered no detect (ND) for four of the five analyzed aqueous-phase constituents (chloride, calcium, sodium and potassium).

Special Circumstances

A second pump test at 45 gpm was performed in order to obtain flow data under two different pressure conditions. In order to estimate interval-specific permeability, interval-specific flow should be estimated under two or more different pressure conditions. Unfortunately, due to software acquisition problems, the 45 gpm production test data is not useable for interpretation, along with the ambient FEC/temperature log acquired prior to the installation of the downhole plumbing. To estimate interval-specific permeabilities, the assumption therefore is made of zero ambient flow, thus providing the second pressure condition. Using this assumption, estimated interval-specific transmissivities range from 1.54 to 478 ft^2/day with the interval of 1,600.0 to 1,612.8 feet registering the highest transmissivity.

Please refer to Table Summary:1 for a complete summary of the hydrophysical logging results. All depths reported herein are referenced to ground surface.

Table Summary:1. Summary of Hydrophysical Logging Results.

Interval No.	Top of Interval (ft)	Bottom of Interval (ft)	Interval-Specific Flow Rate: 75 GPM Test (gpm)	Interval-Specific Hydraulic Conductivity (ft/day)	Interval-Specific Transmissivity (ft2/day)	Specific Capacity (gpm/foot-drawdown)	Interval-Specific Chloride Concentration (mg/L)
1	1600.0	1612.8	32.7	3.74E+01	4.78E+02	1.95	ND
2	1614.0	1620.3	25.3	5.87E+01	3.70E+02	1.51	722
3	1642.0	1645.6	17.7	7.19E+01	2.59E+02	1.05	1955
4	1645.6	1652.3	0.11	2.29E-01	1.54E+00	0.01	
5	1653.8	1659.3	0.11	2.85E-01	1.57E+00	0.01	

2. Introduction

In accordance with COLOG's proposal, COLOG has applied hydrophysical (HpL) and downhole fluid sampling to characterize the formation waters and vertical distribution of aqueous-phase constituents intersecting the Progress Park South Scavenger well in Baton Rouge, Louisiana. The objectives of the investigation were to:

1) Evaluate temperature and fluid electrical conductivity under pre-testing conditions.
2) Characterize and quantify flow in the borehole under two different pumping conditions.
3) Evaluate the vertical distribution of flow and interval-specific permeability for all identified water-producing fractures or intervals.
4) Evaluate the vertical distribution of aqueous-phase constituents in identified water-bearing intervals.

The wellbore hydrophysically logged was the scavenger well in Progress Park South. The well is 4-inch PVC cased to 1,600 feet. Below 1,600 feet the well is screened to 1,660 feet. Ambient water level was measured at 185.35 ftbtoc prior to testing. The hydrophysical logging methods used to achieve the objectives were hydrophysical logging under two different pumping conditions (45 gpm and 75 gpm) and downhole discrete-point fluid sampling.

COLOG's logging of the scavenger well was performed over the period of April 22nd through April 23rd, 2011.

3. Methodology

A. Hydrophysical Logging (HpL)

The hydrophysical logging technique involves pumping the wellbore and then pumping while injecting into the wellbore with deionized water (DI). During this process, profiles of the changes in fluid electrical conductivity of the fluid column are recorded. These changes occur when electrically contrasting formation water is drawn back into the borehole by pumping or by native formation pressures (for ambient flow characterization). A downhole wireline hydrophysical tool, which simultaneously measures fluid electrical conductivity (FEC) and temperature is employed to log the physical/chemical changes of the emplaced fluid.

The computer programs FLOWCALC and/or BOREII (Hale and Tsang, 1988 and (Daughtery and Tsang, 2000) can be utilized to evaluate the inflow quantities of the formation water for each specific inflow location. FLOWCALC is used to estimate the interval-specific flow rates for the production test results based on “hand-picked” values of FEC and depth. The values are determined from the “Pumping” and “Pumping During DI Injection logs”. Numerical modeling of the reported data is performed using code BORE/BOREII. These methods accurately reflect the flow quantities for the identified water bearing intervals.

In addition to conducting hydrophysical logging for identification of the hydraulically conductive intervals and quantification of the interval specific flow rates, additional logging runs are also typically performed. Prior to emplacement of DI, ambient fluid electrical conductivity and temperature (FEC/T) logs are acquired to assess the ambient fluid conditions within the borehole. During these runs, no pumping or DI emplacement is performed, and precautions are taken to preserve the existing ambient geohydrological and geochemical regime. These ambient water quality logs are performed to provide baseline values for the undisturbed borehole fluid conditions prior to testing.

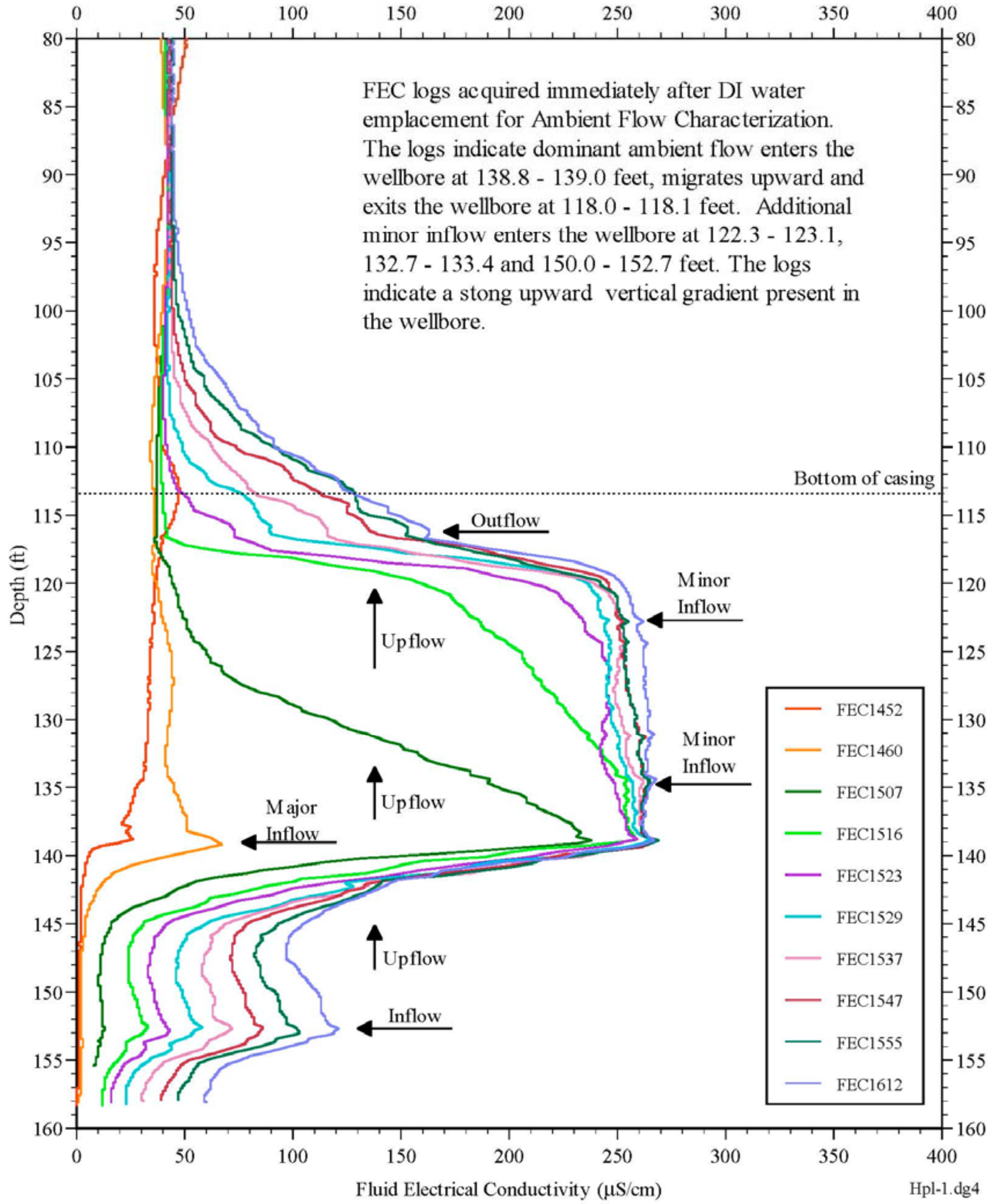
For interval-specific permeability estimations, COLOG utilizes Hvorslev’s 1951 porosity equation in conjunction with the HpL results. Several assumptions are made for estimating the permeability of secondary porosity. First, the type of production test COLOG performs in the field may significantly affect the accuracy of the transmissivity estimation. The permeability equation is relatively sensitive to overall observed drawdown. For a high yield wellbore, drawdown will usually stabilize and an accurate observed drawdown can be estimated. However, for a low yield wellbore, drawdown usually does not stabilize but instead, water level continues to drop until it reaches the pump inlet and the test is complete. In this case COLOG utilizes the maximum observed drawdown. The inaccuracy arises in the fact that overall observed drawdown does not stabilize and therefore is more an arbitrary value dependent on the placement of the pump downhole. Secondly, in an environment where flow originates from secondary porosity the length of the interval is derived from the either the thickness of the fracture down to 0.1 feet or the thickness of the fracture network producing water. This assumption of a fracture network producing water versus a porous media is not how the permeability equation was designed to be used. In lieu of a more appropriate equation unknown to COLOG at this time, COLOG utilizes Hvorslev’s 1951 porosity equation based on its sensitivity to interval-specific flow which can be measured accurately, drawdown which can be measured accurately in the case of a high yield wellbore and its insensitivity to effective radius. The insensitivity to effective radius is critical when an observation well is not available to measure drawdown at a known distance from the subject wellbore.

How to Interpret Hydrophysical Logs

Ambient Flow Characterization:

Figure HpL:1 below is an example data set acquired under ambient conditions. The data represents HpL™ logs acquired immediately after deionized (DI) water emplacement for ambient flow evaluation. For ambient flow evaluation the wellbore fluids are first replaced with DI water (termed “emplacement”), then a series of fluid electrical conductivity (FEC) logs are acquired over a period of a time to monitor ground water entering the wellbore under natural pressures and migrating either vertically or horizontally through the wellbore. The wellbore fluids are replaced with DI water without disturbing the ambient free-water level by injecting DI water at the bottom of the wellbore and extracting wellbore water at exactly the same rate at the free-water surface. However, at the beginning of the DI water emplacement, a slightly depressed free-water level (approximately one tenth of a foot below ambient free water-level) is achieved and maintained throughout the test. This procedure is implemented to ensure that little to no DI water is able to enter the surrounding formation during DI water emplacement. By acquiring FEC logs during the emplacement of DI water and by continuously measuring water level with a downhole pressure transducer the emplacement can be properly monitored and controlled to minimize the disturbance of the recorded ambient water. After the wellbore fluids are replaced with DI water, the injection and extraction pumps are turned off and in most cases the downhole plumbing is removed from the wellbore. A check valve is installed in the pump standpipe to ensure water in the standpipe does not drain back into the wellbore. While the plumbing is removed from the wellbore DI water is injected from the top of the wellbore to maintain ambient water level. Often a baseline FEC log is acquired during the final stages of the emplacement of DI water to provide baseline conditions just before the ceasing of pumping. Figure HpL:1 illustrates ambient flow entering the wellbore at depths of 150.0 to 152.7, 138.8 to 139.0, 132.7 to 133.4, 122.3 to 123.1 and 118.0 to 118.1 feet. The location of these intervals is illustrated by the sharp increases or “spikes” in FEC. The increase in FEC over time at these four intervals is characteristic of ambient inflow. The upward vertical trend in this inflow is also apparent from the FEC logs. For example, the dominant inflowing zone at 138.8 to 139.0 feet illustrates a major growth in FEC above the inflow “spike”, and little growth below the “spike.” The zone at 118.0 to 118.1 feet is the termination of all inflow into the well. The sum of the four inflow zones make up the outflow of this zone, and this value, along with the value of the four inflow zones is computed using code BOREII.

FIGURE HpL:1. EXAMPLE OF HYDROPHYSICAL LOGS DURING AMBIENT FLOW CHARACTERIZATION WITH EXAMPLE INTERPRETATION.



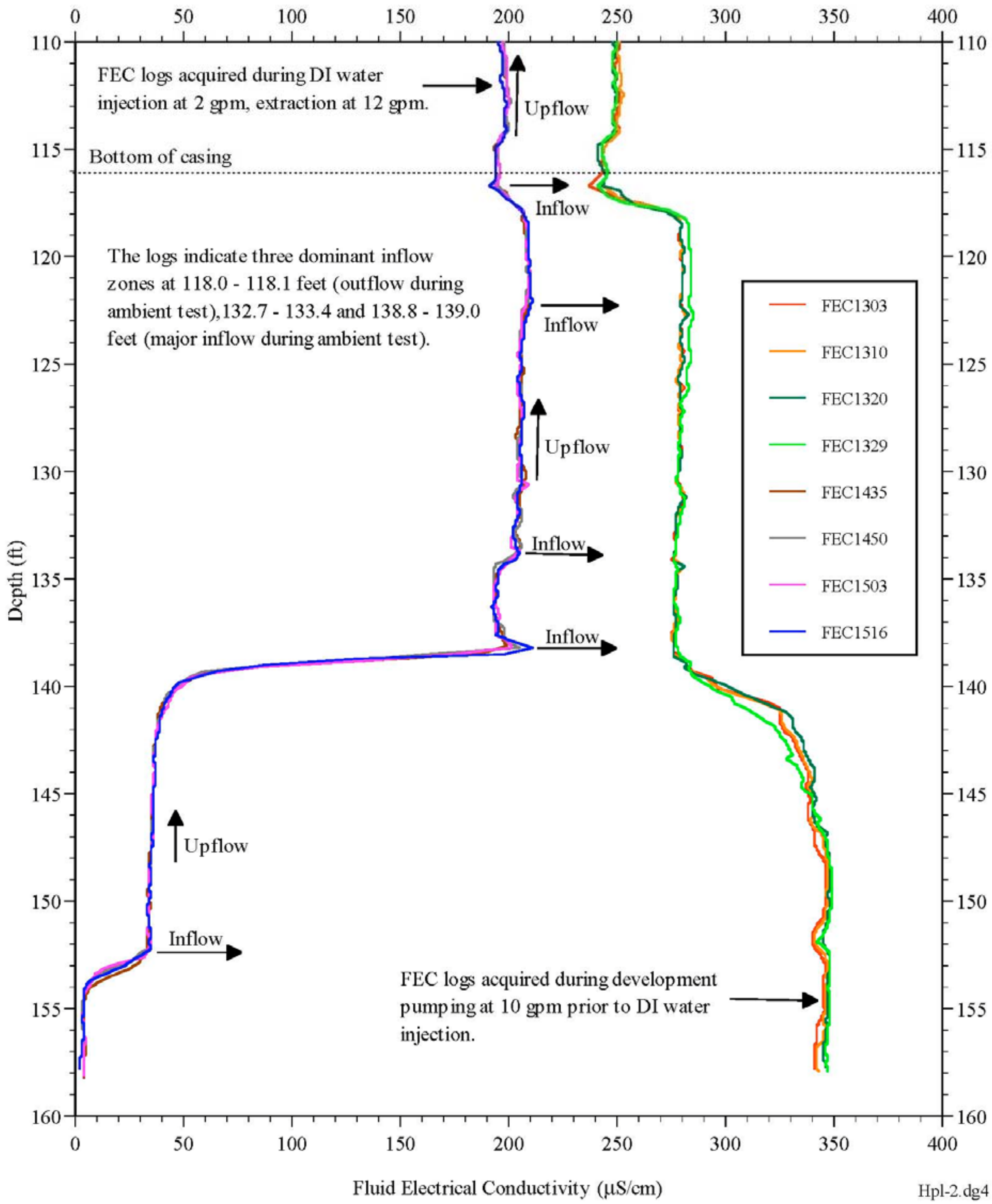
Flow Evaluation Under Stressed Conditions:

COLOG uses three types of tests to identify the water-bearing intervals in a wellbore under stressed conditions. In the lowest yield environment (less than 0.5 gpm) a slug test approach is utilized. In a relatively low-yield wellbore environment a pump after emplacement (PAE) test is conducted, and in a relatively medium to high-yield wellbore environment a pump and inject (PNI) test is conducted. The decision on the type of test to perform on a specific wellbore is made in the field based on the ability of the wellbore to recover to ambient free-water level when a disturbance in water level is introduced into the well, i.e. installation of the plumbing.

In a low-yield wellbore environment a slug or PAE test is utilized to identify the water-bearing intervals under stressed conditions. These tests are similar in protocol and involve first a replacement of wellbore fluids with DI water in a manner identical to that of the emplacement during an ambient flow evaluation. Often a baseline FEC log is acquired during the final stages of the emplacement of DI water to provide baseline conditions just before the ceasing of injection pumping. Following the cessation of injection pumping, the extraction pump is left used to either pull an instantaneous slug (slug test) or is used to pump at a relatively steady low rate of flow in the wellbore (approximately 1-2 gpm). During this time numerous FEC logs are acquired over time. The location of water-bearing intervals is apparent by the sharp increases or "spikes" in FEC over time. The rate at which these intervals inflow is calculated using BOREII and is based on the rate of increase of mass (area under the curve using the FEC log as the curve). Flow direction is easily determined by tracking the center of mass of the area under the curve. In most cases, if pumping is being conducted flow is traveling up the wellbore towards the pump which is situated inside casing.

Figure HpL:2 is an example data set from the same wellbore as Figure HpL:1, acquired under stressed conditions. The data represents HpL™ logs acquired during a PNI test. The set of FEC logs on the right of this figure (FEC1303, FEC1310, FEC1320, and FEC1329) illustrate the condition of the wellbore during development pumping. In the case of this example, the wellbore was stressed at a rate of approximately 10 gpm until a relatively steady-state condition was achieved in the wellbore. A steady-state condition is apparent when the FEC logs begin to repeat as they do in figure HPL:2. Repeatable FEC logs indicate that the hydrochemistry of the water inflowing to the wellbore is not changing over time (steady-state) and that the flow rates of all inflow zones is also not changing over time. Additionally, the drawdown is monitored continuously to observe a "slowing down" in the rate of increase of drawdown. When drawdown (water level) is stable, the inflow rates of the various inflow zones are assumed to be steady. By contrast, if DI water injection is begun in the early stages of pumping when drawdown is still increasing, i.e. water level is dropping rapidly, the inflow rates of the various inflow zones would increase with time as less wellbore storage is used to maintain a particular pumping rate. The remaining FEC logs (FEC1435, FEC1450, FEC1503, and FEC1516) illustrate the conditions in the wellbore during pumping and injection procedures. Fluid was extracted from the wellbore at a rate of approximately twelve gpm while DI water was simultaneously injected at the bottom of the wellbore at a rate of approximately two gpm, until a relatively steady-state condition existed in the well. Water-bearing intervals in the wellbore are identified by changes or "steps" in FEC throughout the FEC logs. The flow rate of these intervals is computed using BOREII and/or Flowcalc software. Every location that the FEC increases in these logs is a zone of inflow. Similarly, where the logs decrease in FEC indicates a zone of inflow with water lower in FEC than the water in the wellbore. A zone exhibiting a decrease in FEC on the injection logs should also decrease at the same depth on the development (pre-DI water injection) logs. Please see Appendix B for a detailed discussion of code BOREII used to numerically model the reported field FEC logs.

FIGURE HpL:2. EXAMPLE OF HYDROPHYSICAL LOGS DURING A 10 GPM PRODUCTION TEST WITH EXAMPLE INTERPRETATION.



Hpl-2.dg4

Sensitivity of Transmissivity to Effective Radius

An estimation of transmissivity (T) has be made for all identified water-bearing intervals using an equation after Hvorslev (1951) assuming steady-state radial flow in an unconfined aquifer:

$$T = KL = \frac{q_i}{2\pi\Delta h_w} \ln\left(\frac{r_e}{r_w}\right)$$

where K is the hydraulic conductivity, q_i is the interval specific inflow rate calculated using HpL results (or "Delta Flow" which equals "Interval-Specific Flow Rate During Pumping Conditions" minus "Ambient Flow Rate" if any), r_w is the borehole radius, r_e is the effective pumping radius, Δh_w is the observed maximum drawdown and L is the thickness of the zone through which flow occurs. For this example the data for wellbore MW-655 is used. The thickness, or length of the interval is calculated using a combination of both the HpL data and any geophysical data available. The length of the interval, L, can usually be estimated with a high degree of confidence. Q_i, or Delta Flow, can also be estimated accurately using code BOREII (see appendix B) for the HpL data sets. Δh_w is estimated with a high degree of confidence using Cologs' downhole pressure transducer and a laptop to record water-level data every 1 second. Additionally, the borehole radius is confirmed quite readily from the caliper data. For this example, r_w equals 0.20 feet, r_e has been assumed to be approximately 100 feet and the observed maximum drawdown was 9.98 feet. By applying L and q_i from the HpL results under the two pressure conditions, the interval specific transmissivity can be calculated for each identified water-producing interval.

Colog utilizes Hvorslevs' 1951 equation when an observation well a known distance away with measurable drawdown is not available. Essentially, Hvorslevs' 1951 equation is similar to the prevalent Theis equation minus the observation well drawdown information. In replace of the observation well drawdown data Hvorslevs' equation uses an assumed "effective radius" divided by the borehole radius. One benefit to using Hvorslevs' 1951 equation when observation well data is unavailable is the insensitivity of the equation to the assumed effective radius as this is the only "unknown" variable in the equation. All other variables are known or calculated with a high degree of confidence. Only the effective radius is unproven, or unsupported, but its value can be estimated with some degree of accuracy.

The following example will illustrate the insensitivity of Hvorslevs' 1951 equation to the assumed effective radius of an aquifer. The greatest magnitude of change in this example between r_e of 50 feet and r_e of 300 feet is 22.0 feet^2/day transmissivity.

Interval (feet)	**Length of Interval (feet)**	**Q_i - Delta Flow (gpm)**	**Borehole Radius (feet)**	**Transmissivity Using r_e of 50 Feet**	**Transmissivity Using r_e of 100 Feet**	**Transmissivity Using r_e of 300 Feet**
118.0 – 118.1	0.1	3.997	0.20	6.78 x E^{01}	7.63 x E^{01}	8.98 x E^{01}
122.3 – 123.1	0.8	0.335	0.20	5.68 x E^{00}	6.39 x E^{00}	7.53 x E^{00}
132.7 – 133.4	0.7	1.217	0.20	2.06 x E^{01}	2.32 x E^{01}	2.73 x E^{01}
138.8 – 139.0	0.2	3.961	0.20	6.72 x E^{01}	7.56 x E^{01}	8.90 x E^{01}
150.0 – 152.7	2.7	0.197	0.20	3.34 x E^{00}	3.76 x E^{00}	4.43 x E^{00}

Progress Park South Scavenger Well Logging Results

4.0 Hydrophysical Logging

4.1 Ambient Fluid Electrical Conductivity and Temperature Log: Scavenger Well

Typically an ambient temperature/fluid electrical conductivity log is acquired prior to the installation of the pumping equipment. However, due to a problem with the acquisition software, the data for this log is compromised and can not be used here.

4.2 Flow Characterization During 45 GPM Production Test: Scavenger Well

On April 22, 2011, a hydrophysical production test at 45 gpm was conducted to provide one of two tested pressure conditions. However, due to a problem with the acquisition software, the data for this test is compromised and can not be used here.

4.3 Flow Characterization During 75 GPM Production Test: Scavenger Well

Pumping of borehole fluids and simultaneous DI injection was conducted at one pumping rate to establish the inflow locations and evaluate the interval specific inflow rates. Pumping at a given rate was conducted until reasonably constant drawdown was observed. When constant drawdown was observed, DI injection was initiated at about 20% of the pumping rate and the extraction pumping rate was increased to maintain a constant total formation production rate (i.e. pumping rate prior to DI injection). These procedures were conducted at a differential rate of 75.9 gpm.

On April 23 15th, 2011, at 08:09 hours (t = 0 minutes elapsed time of testing), development pumping was initiated at approximately 75 gpm. Prior to initiating pumping, the ambient depth to water was recorded at 185.35 ftbgs. All drawdown values are referenced to this ambient water level. Time dependent depth to water, totals and flow rate information were recorded digitally every second and are presented in Figure Scavenger:1. Pumping was maintained at a time-averaged rate of 77.5 gpm until 11:34 hours (t = 205 minutes, elapsed time of testing). DI water injection at the bottom of the wellbore was initiated at 11:34 hours at a time-averaged rate of 11.2 gpm while the total extraction rate was increased to a time-averaged rate of 87.1 gpm, resulting in a total borehole formation time-averaged production rate of 75.9 gpm. These flow conditions were maintained until 12:23 hours (t = 254 minutes) during which time a reasonably constant drawdown of approximately 16.8 feet was observed. During dilution procedures, numerous FEC profiles were acquired. Of these logs, the final three, FEC1203, FEC1208 and FEC1221, are presented in Figure Scavenger:2A, along with the final five FEC traces acquired during re-development pumping for comparison purposes. The logs acquired at the conclusion of the dilution phase illustrate a reasonably stable condition of the fluid column, based on the repeatable logs and stable drawdown, with local inflow locations identified by spikes or incremental step increases or decreases in FEC. The logs acquired during dilution procedures suggest the presence of five inflow zones ranging in flow from 0.11 to 32.7 gpm with the dominant inflow zone at 1,600.0 to 1,612.8 feet, producing 32.7 gpm, or 43.1 percent of the total formation production rate. Please refer to Table Scavenger:1 for a summary of hydrophysical flow results and the depths of individual inflow zones.

At the conclusion of the dilution phases, the DI water injection was ceased and re-development pumping was maintained at a time-average rate of 87.1 gpm. During re-development pumping numerous FEC profiles were acquired. Of these FEC profiles, five are presented in Figure Scavenger:2B. Note the sudden decrease in FEC at 1,600 feet evidenced in FEC traces FEC1453 and FEC1516. This decrease in FEC is most likely the result of regional pumping conditions changing over time, causing the conductivity of this zone to decrease.

4.4 Estimation of Interval Specific Transmissivity: Scavenger Well

An estimation of transmissivity (T) can be made using an equation after Hvorslev (1951) assuming steady-state radial flow in an unconfined aquifer:

$$T = KL = \frac{q_i}{2\pi\Delta h_w} \ln\left(\frac{r_e}{r_w}\right)$$

where K is the hydraulic conductivity, q_i is the interval specific inflow rate calculated using HpL™ results, r_w is the borehole radius (0.167 ft), r_e is the effective pumping radius, Δh_w is the observed maximum drawdown (16.8 feet) and L is the thickness of the zone through which flow occurs. For our calculations, COLOG used r_e of 500 feet (assumed). By applying L and q_i from the HpL™ results under the two pressure conditions, the interval specific transmissivity can be calculated for each identified water-producing interval. These calculations were made at each identified interval and are presented in Table Scavenger:1. In summary, the interval 1,600.0 to 1,612.8 feet exhibited the highest transmissivity of approximately 478 ft^2/day.

4.5 Downhole Sampling: Scavenger Well

On April 23 15th, 2011, at 15:54 hours, downhole sampling was conducted in the Scavenger well. Two downhole samples and one wellhead sample were acquired from the Scavenger wellbore at downhole depths of 1,613 and 1,631 feet. Prior to sampling the wellbore was developed at a time averaged flow rate of 87.1 gpm for approximately 260 minutes. Prior to each downhole sampling event, the downhole sampler was thoroughly cleaned with DI water and alconox solution and a DI water rinse. Using the results from laboratory analysis of each sample procured in the field, the pore water or actual contaminant concentration may be estimated for each sampled inflow point using the mass-balance equation where:

$$C_o = \frac{\sum q_i C_{i\ actual}}{\sum q_i}$$

C_o = Contaminant concentration of procured sample at a given depth as reported by laboratory analysis.

q_i = Interval specific inflow rate for each hydraulically conductive interval beneath the sample location as determined by code BOREII.

$C_{i\ actual}$ = Estimated actual contaminant concentration associated with the sampled interval(s).

Five aqueous-phase constituents, chloride, calcium, sodium, potassium and bicarbonate, were analyzed to estimate the actual, or “pore water’ concentrations for each sampled interval. The results of the downhole sampling and mass-balance calculations are presented in Table Scavenger:2. In summary, the intervals below 1,642.0 feet produced the highest concentrations of for of the five constituents, with the lone exception of bicarbonate. The interval of 1,600.0 to 1,612.8 feet was observed to produce waters of no detectable concentrations of chloride, calcium, sodium and potassium. The notable exception is bicarbonate, which exhibited the highest concentration of 148 mg/L at this interval.

Please see Tables Scavenger:1 and Scavenger:2 for a complete summary of the hydrophysical logging and downhole sampling results which includes the locations, flow rates and transmissivity and hydraulic conductivity estimates assessed by COLOG.

FIGURE Scavenger:1. Pumping And Drawdown Data During 75 GPM Production Test; Layne Hydro; Progress Park South; Baton Rouge, LA; Wellbore: Scavenger

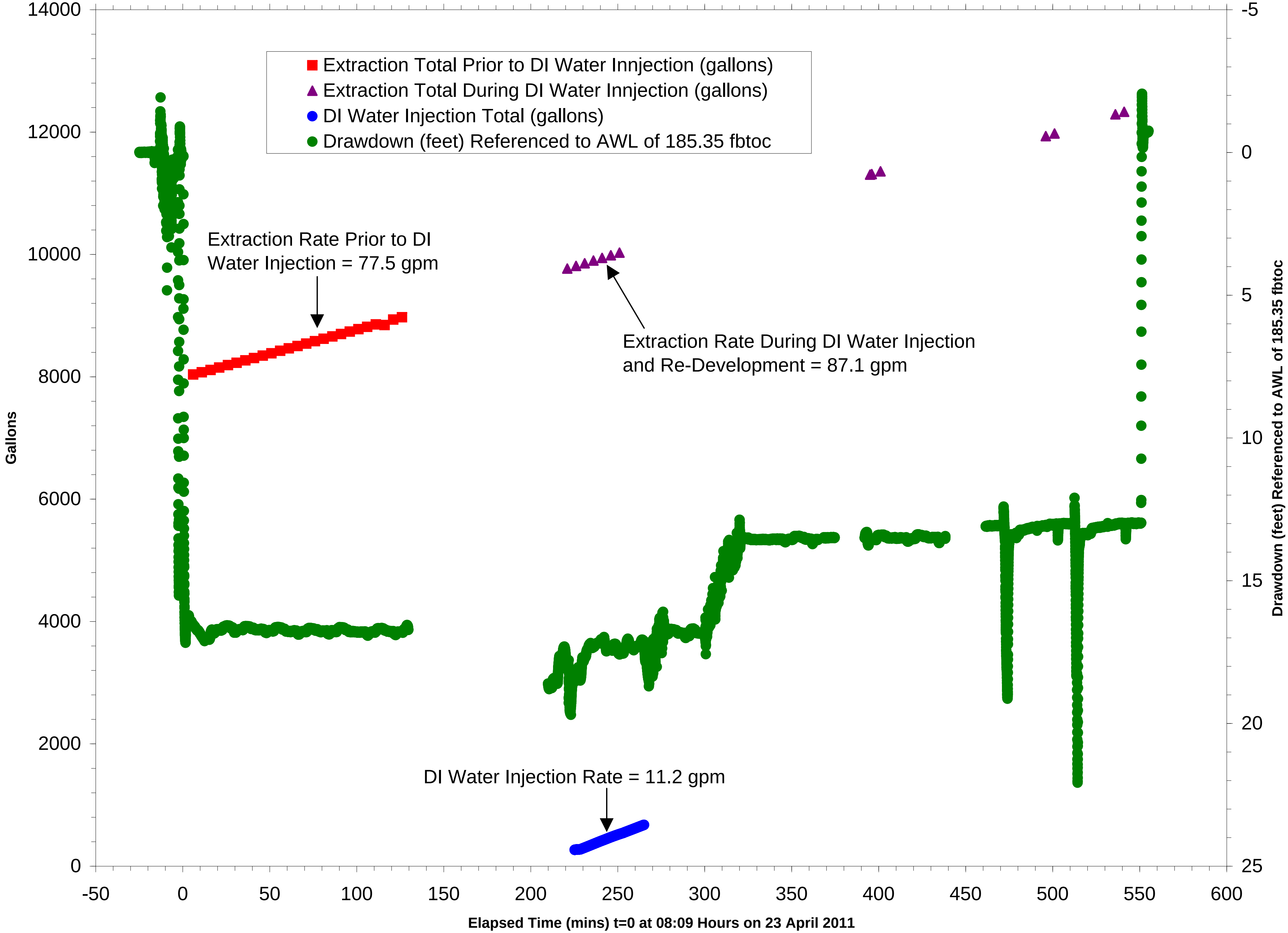


FIGURE Scavenger:2A. Summary of Hydrophysical Logs During 75 GPM Production Test;Layne Hydro; Progress Park South; Baton Rouge, LA; Wellbore: Scavenger.

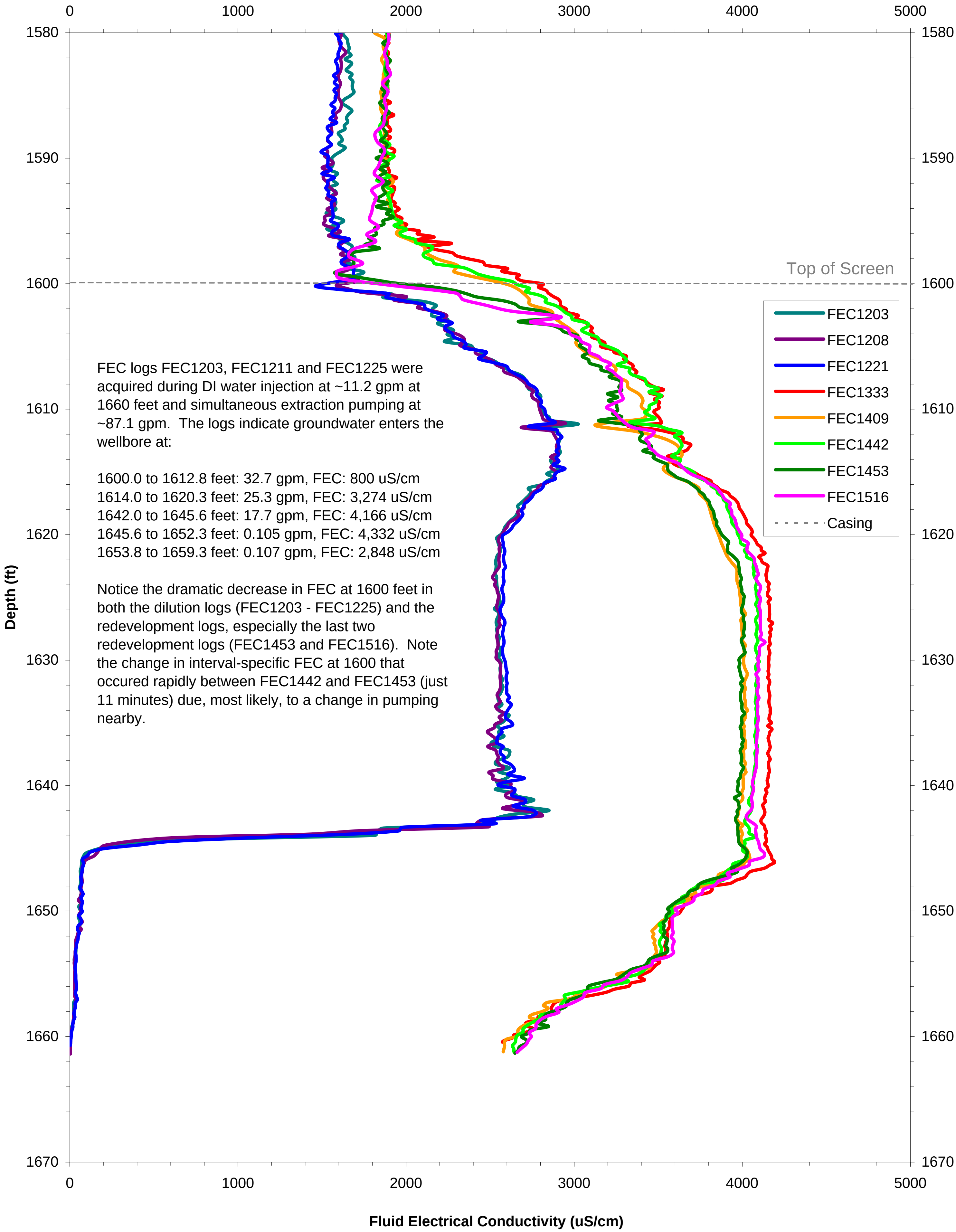


FIGURE Scavenger:2B. Summary of Hydrophysical Logs During Redevelopment Pumping at 85 GPM for Sampling; Layne Hydro; Progress Park South; Baton Rouge, LA; Wellbore: Scavenger.

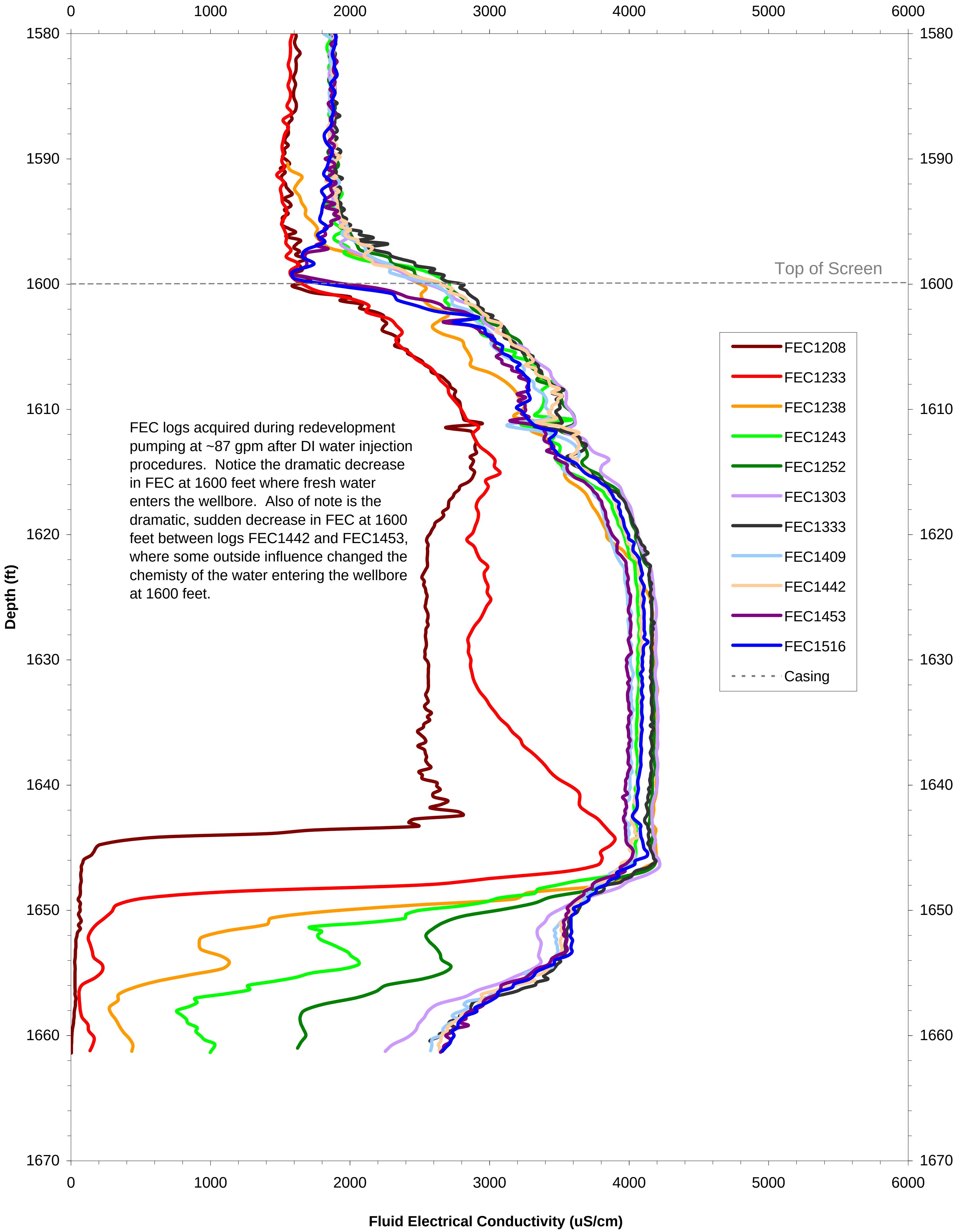


Table Scavenger:1. Summary of Hydrophysical Logging ResultsWith HydraulicConductivity and Transmissivity Estimations; Layne Hydro; Progress Park South; Baton Rouge, LA; Well: Scavenger.

Well Name	Scavenger
Ambient Depth to Water (ftbtoc)	185.35
Diameter of Wellbore (ft)	0.333
Maximum Drawdown (ft)	16.8
Effective Radius (ft)	500

Interval No.	Top of Interval (ft)	Bottom of Interval (ft)	Length of Interval (ft)	Interval-Specific Flow Rate: 45 GPM Test (gpm)	Interval-Specific Flow Rate: 75 GPM Test (gpm)	Interval Specific Hydraulic Conductivity[1] (ft/day)	Transmissivity (ft2/day)	Specific Capacity (gpm/foot-drawdown)	Interval Specific Fluid Electrical Conductivity (microS/cm)
1	1600.0	1612.8	12.8	NA	32.7	3.74E+01	4.78E+02	1.95	800
2	1614.0	1620.3	6.3	NA	25.3	5.87E+01	3.70E+02	1.51	3274
3	1642.0	1645.6	3.6	NA	17.7	7.19E+01	2.59E+02	1.05	4166
4	1645.6	1652.3	6.7	NA	0.11	2.29E-01	1.54E+00	0.01	4332
5	1653.8	1659.3	5.5	NA	0.11	2.85E-01	1.57E+00	0.01	2848

[1] Hydraulic conductivity and transmissivity estimates are based on single well drawdown data, a porus-medium equivilent model and Hvorslev's 1951 porosity equation.

Table Scavenger:2. Calculation of Actual Concentration of Aqueous-Phase Constituents From Hydrophysical Logging Results; Layne Hydro; Progress Park South; Baton Rouge, LA; Well: Scavenger.

INPUT								CALCULATIONS					
			OBSERVED CONCENTRATION (mg/L)					ACTUAL CONCENTRATIONS (µg/L)					
ID #	Sample Depth (ft)	q_i	A	B	C	D	E	q_{ti}	A	B	C	D	E
1	WH	32.7	449	15.6	320.8	1.37	136.2	75.92	ND	ND	ND	ND	148.4
2	1613	25.3	1233	44.3	778.8	3.07	126.9	43.22	722	37.6	469	2.50	160.06
3	1631	17.92	1955	53.8	1216	3.87	80.03	17.92	1955	53.8	1216	3.87	80.03
	Total Flow:	75.9											

CONTAMINANTS

A =	Chloride - mg/L
B =	Calcium - mg/L
C =	Sodium - mg/L
D =	Potassium - mg/L
E =	Bicarbonate - mg/L

q_i=Interval Specific Flow Rate (gpm)
q_{ti}=Intermediate Total Flow Rate (gpm)
Values for q_i are based on the calculation performed by FLOWCALC.

APPENDIX A

STANDARD OPERATING PROCEDURES FOR HYDROPHYSICAL LOGGING

Standard Operating Procedures
HydroPhysical™ Logging for Aquifer Characterization

1. Purpose

Application of the HydroPhysical™ (HpL™) logging method to analyze and determine:

- The location of hydraulically conductive intervals within a wellbore
- The interval specific rate of inflow during well production, in conjunction with the drawdown data, can be used to estimate interval specific hydraulic conductivity or transmissivity
- Ambient (non-pumping) flow conditions (inflow and outflow rates, and locations)
- The hydrochemistry (fluid electrical conductivity (FEC) and temperature) of the associated formation waters

In addition, when downhole, discrete point fluid sampling is coupled with the HydroPhysical™ Logging technique, analysis of the actual contaminant concentrations associated with each identified conductive interval is accomplished for any aqueous phase contaminant.

2. Equipment and Materials

This SOP specifically applies to application of the technique using COLOG's HydroPhysical™ Logging Truck 16, which has been specially configured to handle those field conditions associated with small diameter, low-moderate yield wells The maximum capability of the van is to a total depth of 700 ft and 350 ft total drawdown (maximum depth to water) . In the event of high yield wells, the wireline capability of any COLOG truck can be used to accompany fluid management equipment.

- HydroPhysical™ logging truck field equipment includes:

- Fluid management system
  - Back Pressure Regulator or orifices
  - Rubber hose (0.75-inch i.d.) for injection
  - Submersible Pump
  - Evacuation Line
  - Storage tanks (as required) with inlet/outlet valves
  - Surface Pump
  - Fluid management manifold/Monitoring Panel
  - Data Acquisition System (for recording volumes, flow rates, time)
  - Wireline System
  - Wireline winch unit
  - Depth encoder
  - Water level indicator
  - Computer System

    - HydroPhysical™ Logging tool
    - Downhole Fluid Sampler
- Deionizing Units
- Deionized water (prepared with wellbore fluids or transported on-site)
- Standard Reference Solutions - Electrical conductivity reference solutions (set of 3 solutions).

3. Procedures

1.) Review well construction details and complete general well information sheet. The HydroPhysical™ logging technique involves dilution of the wellbore fluids with DI water and profiling of the wellbore dynamics using a HydroPhysical™ logging tool. Significant aberrations or reductions in the borehole diameter should be identified as the downhole equipment can become lodged in the borehole. Additionally, application of the technique requires certain wellbore conditions:

- In open bedrock boreholes, casing must be installed through the overburden and grouted at the rock/alluvium interface to inhibit water leakage into the borehole from the saturated alluvium. For cased boreholes, the well should be fully cased and gravel packed with single or multiple screened intervals;
- The diameter of the borehole must be approximately 4 inches or greater for application with the slim-tool (1.5-inch o.d.). Two inch i.d. boreholes may be tested using the slug test approach described in Section 5.
- For newly drilled wells, cuttings and drill fluids must be removed from the affected fractures by standard well development procedures.

2.) Review and record additional wellbore construction/site details and fill out the general well information form which includes the following information:

- Ambient depth-to-water
- Depth of casing
- Total depth of well
- Lithology (if available)
- Estimated well yield and any available drawdown data
- Type and concentration of contamination

3.) Prepare the deionized (DI) water. Consult with DI water tank firm for assistance if necessary. If DI water has not been transported to the site, surface or groundwater may be used if it is of suitable quality Generally source water containing less than 1000 micro Siemens per centimeter (µS/cm) and less then 200 ppb VOCs will not significantly affect the deionizing units, but this should be confirmed with DI water firm. If the groundwater from the well under construction cannot be used for DI water generation, then DI water must be transported to the site and containerized at the wellhead.

Depending on the amount of HydroPhysical™ testing to be performed (ambient and/or during production) the typical volume of DI water required for each borehole is approximately three times the volume of the standing column of formation water in the wellbore per type of HydroPhysical™ characterization.

If preparation takes place on site, pump the source water through a pre-filter, to the deionizing units, and into the storage tanks.

Monitor the FEC of the DI water in-line to verify homogeneity; the target value is 5 to 25 μS/cm.

4.) Calibrate the HydroPhysical™ logging tool using standard solutions prepared and certified by a qualified chemical supply manufacturer. Fill out tool calibration form following the steps defined in the software program, "tools" under the directory, calibration. Also use a separate field temperature / FEC / pH meter to support calibration data. Record the results of the tool calibrations, specifically noting any problems on the tool calibration form. Also record the certification number of the standard solutions.

5.) Set datum on the depth encoder with the FEC sensor on the tool as 0 depth at the top of casing. If inadequate space is available at the wellhead, measure 10 feet from the FEC sensor up the cable (using measuring tape) and reference with a wrap of electrical tape. Lower the tool down the hole to the point where the tape equals the elevation at the top of the casing and reference that as 10 feet depth on the depth encoder.

6.) Place the top of the tool approximately 3 feet below the free-water surface to allow it to achieve thermal equilibrium. Monitor the temperature output until thermal stabilization is observed at approximately $\pm$ .02 °C.

7.) After thermal stabilization of the logging tool is observed, log the ambient conditions of the wellbore (temperature and FEC). Fill out the water quality log form. During the logging run, the data are plotted in real time in log format on the computer screen and, the data string is simultaneously recorded on the hard drive.

Log the ambient fluid conditions in both directions (i.e. record down and up). The ideal logging speed is 5 feet per minute (fpm). For deeper wells the logging speed can be adjusted higher, but the fpm should not exceed 20.

At completion of the ambient log, place the tool approximately 10 feet below the free water surface. The tool will remain there during equipment set up as long as borehole conditions permit. Establish and record ambient depth to water using top of protective casing as datum.

8.) Attach back pressure regulator or orifice, if used, and weighted boot, to end of emplacement line and secure. Insure that the injection line is of adequate length to reach the bottom of the wellbore.

9.) Lower the flexible emplacement line to the bottom of the well allowing one foot of clearance from the well bottom to the outlet of the injection line.

10.) Lower tool about 10 feet below the water surface. The tool will be stationed beneath the submersible pump during non-logging times.

11.) Lower submersible pump in the well to a depth just above the logging tool. Record approximate depth of the pump location.

12.) Record all initial readings of gauges at elapsed time 0.0 minutes. Fill out well testing data form.

13.) Mark hoses with a round of electrical tape for reference. In addition, establish datum for tool depth to the nearest foot and mark on wire with wrap of tape. Reset datum on optical encoder for this depth.

14.) When ambient flow characterization is to be conducted, it should be done now, before disturbing the aquifer (i.e. by pumping). Fill out ambient flow characterization (AFC) form. Skip to Section 17 for procedures.

15.) After AFC, if performed, conduct a controlled, short term well production test (pump test) to characterize the overall hydraulics of the wellbore (drawdown at given pumping rate provides total well transmissivity or yield) and to make an initial assessment of formation water hydrochemistry. Begin pumping at a total extraction flow rate appropriate for wellbore under investigation (see Section 4 Special Notes). During this period, record elapsed time of pumping, depth to water, total gallons extracted, and extraction flow rate at approximately one minute intervals.

During extraction, log the fluid column continuously until at least three wellbore volumes have been extracted from the wellbore, or a stabilized water level elevation is obtained.

Review fluid logging results to verify that true formation water is present within the affected borehole interval and that the vertical distribution of water quality parameters within this interval is stable.

16.) Review data obtained during the pumping test to determine DI water emplacement and pumping/logging procedures. Extraction procedures for detection and characterization of hydraulically conductive intervals and the formation water hydrochemistry are determined based on the pumping test information. The emplacement, testing and pumping procedures will differ depending upon well yield and determined lengths of intervals of interest. In wellbore situations where intervals of interest are small (less than 30 feet) and hydraulic characteristics observed during borehole advancement and preliminary hydraulic testing indicate hydraulically conductive intervals with extremely low flow rates (i.e. <0.10 gpm/foot of drawdown), a slug testing procedure can be employed. In wellbore cases where the preliminary hydraulic testing indicates low to moderate total yield (i.e. $0.10 < Q < 4$ gpm/foot of drawdown), constant low flow rate pumping after DI water emplacement procedures can be employed. In wellbore situations where intervals of interest are large, and high total yield (i.e. > 4 gpm/foot of drawdown) is observed, constant pumping during DI water injection procedures will be employed.

17.) When the fluid column is to be replaced with DI water, (vertical flow characterization, slug testing, logging during pumping after DI water emplacement) the following emplacement procedures apply:

Pump the DI water to the bottom of the wellbore using the surface pump and the injection riser. Simultaneously use the submersible pump to maintain a stable, elevated total head by extracting groundwater from near the free-water surface. When groundwater from the subject well is used for DI water generation, generate DI water from the extracted formation water and re-circulated to the well bottom via the solid riser.

Use the water level meter to observe the elevated total head during emplacement. If borehole conditions permit (i.e. the absence of constricted borehole intervals), the logging tool is used to monitor the advancement of the fluid up the borehole as it displaces the standing formation water. Draw the logging tool up the wellbore in successive increments as the DI water is emplaced. Monitor the electrical conductivity of the fluid expelled from the evacuation pump during emplacement procedures. When FEC values are representative of the DI water, or sufficiently diluted formation water, terminate emplacement procedures.

Emplacement is complete when DI water, or sufficiently diluted formation water, is observed from the evacuation pump or when logging tool stationed near the pump indicates DI water or sufficiently diluted formation water.

Upon completion, turn off the evacuation pump. Then turn off the injection line.

18.) Record volumes of extracted and injected fluids on the well testing data form. Calculate the volume of DI water lost to the formation.

19.) Take initial background HydroPhysical™ log, or begin continuous logging depending upon extraction method (i.e. slug vs. continuous).

20.) Pumping and testing procedures vary depending upon wellbore hydraulics and construction detail.

21.) Continuous logging is conducted until stabilized and consistent diluted FEC logs are observed. If inflow characterization at a second pumping rate is desired, increase extraction rate and assure the proper DI water injection rate. Perform continuous logging until stabilized and consistent FEC logs are observed and all diluted formation water is re-saturated with formation water.

22.) After stabilized and consistent FEC traces are observed, terminate DI water injection. Reduce the total extraction flow rate to the net formation rate and conduct continuous logging. Conduct logging until stable and consistent FEC values are observed.

23.) Conduct depth specific sampling at this time.

24.) At the conclusion of the above procedures, assess the wellbore fluid conditions and compare them with those observed during the original pumping (Step 14).

25.) Turn all pumps off. First remove the extraction pump from the borehole. During removal, thoroughly clean the evacuation line (2-inch o.d.) with a brush and alconox and rinse DI water. Also clean the outside of the pump. Place the pump in a drum of DI water and flush DI water through the system.

Remove the tool. Clean the wireline for the tool in a similar manner during its withdrawal from the borehole.

Remove the injection line from the well. Follow the same procedures when cleaning the injection line as for the evacuation line.

Store the pumps and logging tools properly for transport.

Place cover on well and lock (if available).

4. Special Notes

On-site pre-treatment of groundwater using activated carbon, can be conducted prior to DI water generation, if there is a contaminated groundwater source. In addition, on-site treatment can also be considered to handle extracted fluids that would require containerization and treatment prior to disposal.

The rate(s) of pumping are determined by drawdown information previously obtained or at rate(s) appropriate for the wellbore diameter and saturated interval thickness. The appropriate extraction rate is a function of length of saturated interval, borehole diameter, and previous well yield knowledge. The appropriate pumping procedures to be employed are also dictated by the length of the exposed rock interval. In general, the extraction flow rate should be sufficient to induce adequate inflow from the producing intervals. The concern is that the extraction flow rate does not cause extreme drawdown within the well i.e. lowering the free water surface to within the interval of investigation.

5. Discussion

LOW YIELD: Extraction Slug Test After DI water Emplacement

In wells with very low total flow capability (i.e. < 0.10 gpm/foot of drawdown), perform a slug test in accordance with procedures developed by Hvorslev (1951). Rapidly extract a small volume of water from near the free water surface using the extraction riser and pump. A drop in piezometric head of about 2 feet should be adequate for the initial test. Record the rise in the free water surface with time and develop a conventional time-lag plot.

When the free water surface has recovered to a satisfactory elevation, log the wellbore fluid conditions. Repeat the procedures described above with successive increases in the drop of piezometric head (or volume extracted). Let the wellbore recover and record the rise in the free water surface. Repeat logging of the wellbore fluid after the free water surface has recovered to a satisfactory elevation. The number of slug tests performed is determined in the field after review of previous logging results.

MODERATE YIELD: Time Series HydroPhysical™ Logging During Continuous Pumping After DI water Emplacement

In the case of moderate yield wells (i.e. 0.10 < Y < 4 gpm/foot of drawdown), maintain a constant flow rate from the evacuation pump and record the total volume of groundwater evacuated from the wellbore. Employ a continuous reading pressure transducer (or equivalent device) to monitor the depressed total head during pumping, along with the associated pumping rate.

Hold the flow rate from the evacuation pump constant at a rate determined for the specific borehole. Drawdown of the free water surface produced during pumping should not overlap any identified water producing interval. Conduct hydrophysical logging continuously. The time interval is a function of flow rate and is specific to each well. The number of logging runs and the length of time required to conduct all loggings is a function of the particular hydraulic conditions. Logging and pumping is continued until the fluid column is re-saturated with formation water (i.e. all DI water is removed from the borehole).

HIGH YIELD: Time Series Wellbore Fluid Logging During Continuous Pumping and Simultaneous DI Water Injection

When wells exhibit high yield (> 4 gpm/foot of drawdown), as determined by a review of the interval of interest, the borehole diameter and the results obtained from previous information and preliminary hydraulic testing, the appropriateness of time series fluid logging during continuous pumping and simultaneous DI water injection is determined.

In this case, maintain a constant flow rate from the evacuation pump and record this rate and the associated drawdown. During this period, conduct hydrophysical logging until reasonably similar HydroPhysical™ logs are observed and stabilized drawdown is achieved. After reasonably similar downhole fluid conditions are observed and simultaneous with extraction pumping, inject DI water at the bottom of the well at a constant rate of 10 to 20% of that employed for extraction. Increase the total rate of extraction to maintain total formation production reasonably similar to that prior to DI water injection (i.e. increase the total extraction by amount equal to the DI water injection rate).

Periodically record the total volume and flow rate of well fluids evacuated and the total volume and flow rate of DI water injected. Use a continuous reading pressure transducer or similar device to monitor the depressed total head during pumping. Record the depressed total head (piezometric surface) periodically, with the associated pumping and injection data.

The evacuation and DI water injection flow rates are held constant at a rate determined for the specific wellbore. Drawdown of the free water surface during pumping must not overlap any identified water producing intervals. HydroPhysical™ Logging is conducted continuously. The number of logging runs and the length of time required to conduct all loggings is a function of the particular hydraulic conditions exhibited by the well under investigation.

APPENDIX B

BORE II MODELING SOFTWARE

LBNL-46833

BORE II – A Code to Compute Dynamic Wellbore Electrical Conductivity Logs with Multiple Inflow/Outflow Points Including the Effects of Horizontal Flow across the Well

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Abstract

Dynamic wellbore electrical conductivity logs provide a valuable means to determine the flow characteristics of fractures intersecting a wellbore, in order to study the hydrologic behavior of fractured rocks. To expedite the analysis of log data, a computer program called BORE II has been developed that considers multiple inflow or outflow points along the wellbore, including the case of horizontal flow across the wellbore. BORE II calculates the evolution of fluid electrical conductivity (FEC) profiles in a wellbore or wellbore section, which may be pumped at a low rate, and compares model results to log data in a variety of ways. FEC variations may arise from inflow under natural-state conditions or due to tracer injected in a neighboring well (interference tests). BORE II has an interactive, graphical user interface and runs on a personal computer under the Windows operating system. BORE II is a modification and extension of an older code called BORE, which considered inflow points only and did not provide an interactive comparison to field data. In this report, we describe BORE II capabilities, provide a detailed user's guide, and show a series of example applications.

1. Introduction

The variation of formation permeability surrounding a wellbore is useful information not only for identifying hydraulically conducting fractures or other high-conductivity features intercepted by the well, but also for quantifying the heterogeneity of the medium. These are essential data in the evaluation of in-situ flow and transport characteristics at a given site.

Methods to evaluate permeability values along the depth of a well include the packer method, in which constant pressure, constant flow, or pulse tests are conducted in packed-off intervals in a wellbore, and various downhole flow meters. The packer method has the disadvantage that it is very time consuming and costly, and the vertical resolution is limited by the interval between the two packers that can be set in the well. Flow meter methods such as spinners and heat pulse flow meters generally allow better vertical resolution than the packer method, but they are not as accurate in determining permeability, because they mostly measure the wellbore fluid velocity, which is very sensitive to variations in the wellbore radius.

In 1990, Tsang et al. (1990) proposed a method using logs of fluid electric conductivity (FEC) at successive times under constant-pumping conditions to obtain inflow from the formation into the well as a function of depth in the well. In this method, the wellbore is first filled by de-ionized water or water of a constant salinity (i.e., ion concentration) distinct from that of the formation water. This is usually done by passing the de-ionized water down a tube to the bottom of the wellbore at a given rate while simultaneously pumping at the top of the well at the same rate. After this is done, the well is pumped at a constant flow rate, which can be adjusted to optimize wellbore flow conditions. An electric resistivity probe is lowered into the wellbore to scan FEC as a function of depth along the wellbore. This is what is called fluid conductivity logging. A series of five or six such logs are obtained at time intervals over a one- or two-day period. At the depth levels where water enters the wellbore, the conductivity log displays peaks, which grow with time and become skewed in the direction of water flow. By analyzing these logs, it is possible to obtain the permeability and salinity of each hydrologic layer transmitting water. The method has been very successful, being much more accurate than flow meters and much more efficient (much cheaper) than packer tests (Tsang et al. 1990), particularly in low permeability formations. A typical 1000-m section in a deep hole can be tested in two or three days at a spatial resolution of ~0.10 m all along the length of the wellbore section. The method is now being widely used in Europe and the U.S. (Marschall and Vomvoris, 1995; Pedler et al., 1992; Bauer and LoCoco, 1996), both under natural-state flow conditions and while tracer is injected in a neighboring well (i.e., interference tests).

Along with the method, a code was developed called BORE (Hale and Tsang, 1988), which performed the forward calculation to produce wellbore FEC profiles given different inflow positions, rates, and concentrations. The code has been well used over the last decade. However, it appears now that there is a need to revise the code to make it more suitable for current computer environments and to add new capabilities. Thus, the code has been updated to run under current operating systems, provide interactive modification of model parameters, and produce graphical comparisons between model and field data. More importantly, the revised code allows the possible inclusion of both flows into and out of the well at various depths, a feature that has been observed in real field conditions when different layers penetrated by the well have different hydraulic heads. Furthermore, the new code allows the calculation of the case with equal inflow and outflow at the same depth level, which is effectively the special case of horizontal flow across the wellbore. Drost (1968) proposed a measurement of solute dilution in the wellbore to evaluate ambient horizontal flow velocity in the formation and it has become a well-accepted method. The new code provides the opportunity to analyze such cases and to identify the depth interval of horizontal flow to within ~0.1 m as well as to estimate the flow rate. Moreover, one can analyze the combination of horizontal flow across the wellbore and vertical diffusion or dispersion along the length of the wellbore, which is not possible with Drost's solution.

The report is organized as follows. In Section 2, the basic capabilities of the revised code, called BORE II, are described, and the key parameters associated with BORE II are defined. Details of the mathematical background and numerical approach are described in Appendix 1, which is adapted from Hale and Tsang (1988). A user's guide is presented in Section 3, which includes a description of BORE II's interactive user interface, required input items, and options available when running BORE II. Four example applications are given in Section 4 to conclude the report.

We are still open to further improvements of BORE II; any suggestions and comments are invited and should be addressed to the authors.

2. BORE II Capabilities

BORE II calculates FEC as a function of space and time in a wellbore containing multiple feed points given the pumping rate of the well, the inflow or outflow rate of each feed point, its location and starting time, and, for inflow points, its ion concentration. A simple polynomial correlation between ion concentration, C, and FEC is assumed. Ion transport occurs by advection and diffusion along the wellbore, with instantaneous mixing of feed-point fluid throughout the wellbore cross-section. These assumptions allow use of a one-dimensional model. BORE II divides the wellbore section under study into equal height cells and solves the advection/diffusion equation using the finite difference method. Further details of the mathematical and numerical approach are given in Appendix 1.

Inflow and Outflow Feed Points

The original BORE code (Hale and Tsang, 1988) considered inflow points only, so flow through the wellbore was upward at all depths. BORE II allows both inflow and outflow points, so flow in the wellbore can be upward, downward, or horizontal at different depths and flow at either end of the wellbore section being studied can be into or out of the wellbore section or be zero. By convention, upward flow in the wellbore is positive and flow into the wellbore is positive.

Steady and Varying Fluid Flow

The original BORE code considered steady fluid flow, so feed points had constant flow rates. They also had constant concentrations, but delayed starting times for feed-point concentration to enter the wellbore were allowed. BORE II permits both steady and varying fluid flow. For the steady-flow case, the user specifies flow rate, concentration, and concentration start time for each feed point, but for outflow points (those with negative flow rates) the concentration and concentration start time are not used. Variable flow rate or concentration can be specified for feed points by interpolating from a table of time, flow rate, and concentration. If a table includes both positive and negative flow rates (i.e., a feed point alternates between inflow and outflow), the concentration for the positive flow rate is used when interpolating between positive and negative flow rates.

Concentration Boundary Conditions

If the flow at the top of the wellbore section under study is into the wellbore, the initial concentration for the uppermost cell in the wellbore is used as the inflow concentration. Analogously, if flow at the bottom of the wellbore section is a flow up from greater depths, the initial concentration for the lowermost cell in the wellbore is used as the inflow concentration. Furthermore, for inflow points with a concentration start time greater than zero, the initial concentration of the wellbore is used as the inflow concentration for times less than concentration start time.

Horizontal Flow

The special case of horizontal flow through the wellbore, as described by Drost (1968), can also be considered, by locating an inflow point and an outflow point with equal magnitude flow rates at the same depth. The flow rates may be specified as either (1) the Darcy velocity through the aquifer or (2) the volumetric flow rate into/out of the wellbore. BORE II multiplies Darcy velocity by the cross-sectional area of the feed point (wellbore diameter times cell height) and Drost's α_h convergence factor to convert it to a volumetric flow rate. The value of α_h can range from 1 (no convergence) to 4 (maximum possible convergence, which occurs for the case of a thick, highly-permeable well screen). Drost suggested that for a uniform aquifer with no well screen, $\alpha_h = 2$, and that for typical applications, a good choice for α_h is 2.5. Horizontal flow feed points may have time-varying flow rates, but for Darcy-velocity calculations to make sense, the inflow and outflow rates must be equal and opposite at any time. Thus, if a feed point location changes from a horizontal flow point to a non-horizontal flow point with time, volumetric flow rates must be specified rather than Darcy velocities.

BORE II Parameters

The key parameters associated with BORE II are defined below.

Parameter	I/O units*	Description
C	g/L	Ion concentration in the wellbore; converted to FEC using FEC $= \gamma + \beta C + \alpha C^2$, where α, β, and γ are user-specified constants (default values are provided in the code, see Section 3)
C_i	g/L	Ion concentration of *i*th feed point
C_0	g/L	Initial ion concentration in wellbore
D_0	m^2/s	Diffusion coefficient (may include dispersive effects as well molecular diffusion)
d_w	cm	Wellbore diameter (assumed constant)
FEC	μS/cm	Fluid electrical conductivity
q	L/min	Fluid flow rate in wellbore (upward flow is positive)
q_i	L/min	Fluid flow rate of *i*th feed point; positive for inflow and negative for outflow
q_w	L/min	Fluid flow rate in wellbore at $x_{\max}$, specified by the user
q_0	L/min	Fluid flow rate in wellbore at $x_{\min}$ (or any depth of interest), calculated internally
T or TEMP	^{o}C	Temperature (assumed constant)
t	hr	Time
$t_{\max}$	hr	Maximum simulation time
t_{0i}	hr	Concentration start time of *i*th feed point
v_d	m/day	Darcy velocity through aquifer for horizontal flow ($q_i = v_d\, \alpha_h\, \Delta x\, d_w$)
x	m	Depth (positive, increases down the wellbore)
$x_{\min}$, $x_{\max}$	m	Top and bottom, respectively, of wellbore interval being studied
Δx	m	Cell height for wellbore discretization
α_h	–	Drost (1968) convergence factor for horizontal flow

*I/O units are chosen for convenience; all quantities are converted to SI units before BORE II calculations.

3. BORE II User's Guide

Operating System

BORE II may be run under Windows 95, 98, or 2000 by double-clicking the executable icon (BOREII.EXE) in Windows Explorer, by double-clicking on a desktop shortcut key to BOREII.EXE, or by typing BOREII in the Run command in the Start Menu or in a DOS-prompt window. BORE II will not run in stand-alone DOS or in the DOS-mode of Windows. BORE II was compiled using Microsoft Fortran PowerStation™ Version 4.0, but this software is not necessary to run the program.

BORE II Graphical Output

The primary user interface with BORE II is interactive, with the user responding to on-screen prompts to modify model parameters and choose options (described below) for the real-time graphical display of model results and data. The basic BORE II output screen consists of three windows.

- The borehole profile window shows FEC profiles as a function of depth and time. Simulation time t is shown in the upper left corner. Fluid flow rate at a user-specified depth in the wellbore, q_0, is shown in the middle of the top line (the depth at which q_0 is calculated is set by option P). The depth of a C-t plot is also shown.

- The inflow parameters window shows the feed-point characteristics for the model that can be modified with option M (location, flow rate, and concentration). Often there are more feed points than can be displayed at once on the screen. BORE II starts out showing the first few (deepest) feed points, then shows the feed points in the neighborhood of any point that is being modified.

- The dialog window allows the user to select options (described below) when running BORE II.

On computers with small screens, it may be desirable to run BORE II in full-screen mode, so that the entire BORE II screen can be seen at once without scrolling. Full-screen mode is entered by pressing Alt-VF (or on some computers by pressing Alt-Enter). Pressing Esc (or Alt-Enter) terminates full-screen mode. There are three potential problems associated with the use of full-screen mode.

(1) The status line describing what BORE II is doing (e.g., running, waiting for input) is not visible.

(2) Drawing an x-t plot (options X, S, D, F, and I), which creates a new window, may be very slow and the graphics quality poor.

(3) On some computers, text is difficult to read after closing the x-t plot window.

To address the latter two problems, one may terminate full-screen mode before using options X, S, D, F, and I. The new window will be small, but after drawing is complete it may be expanded by pressing Alt-VF to enter full-screen mode. Full-screen mode should be terminated before the new window is closed to avoid the final problem.

To print an image of the screen, press Alt-PrintScreen to copy the screen image into the clipboard. Then open a program such as Microsoft Paint and paste in the image. It can be manipulated, saved in a variety of graphics formats, or printed from Paint. The image can also be pasted directly into another Windows application such as MS Word.

Input/Output File Overview

Running BORE II requires one or two external files: a file with an initial set of model input parameters (mandatory, known as the input file) and a file with observed data (optional, known as the data file). These files are plain ASCII text, and must reside in the same folder as the BORE II executable. The input file contains model parameters such as the depth interval being studied, feed point characteristics, problem simulation time, and *C*-to-FEC conversion factors. The data file contains observed values of FEC and temperature, and optionally contains other fluid properties such as pH. Detailed instructions for preparing an input file and a data file are given below.

BORE II always creates a temporary file, called BOREII.TMP (see options C and R), and optionally creates a new input file (see option V), which is useful if model parameters have been changed during the BORE II run.

Line-by-line Instructions for Input File

After starting BORE II, the user is prompted to choose the input file from the list of files residing in the folder where the BORE II executable is. Input file names with more than 8 characters before a period or blanks will appear in the list of files in an abbreviated form. File names can be at most 20 characters long.

A sample input file is provided that can be modified as needed using a text editor such as Notepad or a word processor such as MS Word. If a word processor is used to create or modify an input file, be sure that the file is saved as plain ASCII text.

The input file is designed to be self-documenting, with header lines preceding data lines. These header lines must be present, but BORE II does not use the text on them. Data entries are read in free format, with individual entries on a given line separated by blanks, tabs, or commas. This means that entries cannot be left blank, even if they are not being used (e.g., concentration for an outflow point). Unused entries may be set to zero or any convenient value. Comments may be added on data lines, after the requisite number of entries. In the sample input file, comments begin with an exclamation point.

Item	**Computer Variables**	**Unit**	**Description**
1.	TITLE	–	A description of the problem, 80 characters maximum
2 header for wellbore geometry			

2.	RXMIN	m	Top of study area, x_{min}
	RXMAX	m	Bottom of study area, x_{max}
	RDIAM	cm	Wellbore diameter, d_w
3 header for flow parameters			
3.	RQW	L/min	Flow into (positive) or out of (negative) the bottom of the study area, q_w
	HALPHA	–	Factor to account for convergence of horizontal flow lines toward the wellbore, α_h (Drost, 1968) Range: 1.0 – 4.0; default value: 2.5 Only used for horizontal flow

4 header for feed points			
4.	IINFN	–	Number of feed points (maximum 180)
	IQFLAG	–	Variable flow-rate flag – a 3 digit integer used to identify feed points with variable flow (suggested value 999)
5 header for constant- flow-rate feed points			
5. Repeat IINFN times	RINFX	m	Location of feed point, x_i * For horizontal flow put two feed points at the same location, with equal magnitude, opposite sign flow rates
	RINFQ	L/min (m/day if IINFV=1)	Constant inflow rate (positive) or outflow rate (negative) of feed point, q_i For a variable flow rate, set RINFQ = IIIJJ, where III = IQFLAG, and JJ is a two digit integer giving the number of times in the variable-flow-rate table, which follows in 5a For horizontal flow, v_d replaces q_i if IINFV = 1
	RINFC	g/L	Constant feed point concentration, C_i - only used for inflow points For a variable concentration, set RINFQ = IIIJJ, where III = IQFLAG, and JJ is a two digit integer giving the number of times in the variable-flow-rate table, which follows in 5a
	RINFT	hr	Start time for constant feed point concentration, t_{0i} - only used for inflow points Feed point concentration is C_0 of cell containing feed point for t < t_{0i}
	IINFV	–	Horizontal flow Darcy-velocity flag (must be zero for non-horizontal flow case): = 0: RINFQ is flow rate q_i into/out of the wellbore in L/min = 1: RINFQ is +/–Darcy velocity v_d through the aquifer in m/day

5a header for variable-flow-rate table (only when RINFQ = IQFLAGJJ)			
5a. Repeat JJ times when RINFQ = IQFLAGJJ	RINFQT	hr	Time t_j (set $t_1 = 0$, set $t_{JJ} > t_{\max}$)
	RINFQQ	L/min (m/day if IINFV=1)	Volumetric flow rate q_j at time t_j For horizontal flow, v_d replaces q_j if IINFV = 1
	RINFCC	g/L	Concentration C_j at t_j
6 header for misc. parameters			
6.	TMAX	hr	Maximum simulation time, $t_{\max}$
	DPYMAX	μS/cm	Maximum FEC for plots
	RK	m^2/s	Diffusion coefficient, D_0
7 header for C-to-FEC conversion			
7.	RGAMMA	μS/cm	Conversion from C in g/L to FEC in μS/cm: $\mathrm{FEC} = \gamma + \beta C + \alpha C^2$ Default values (for 20°C): $\gamma = 0$, $\beta = 1870$, $\alpha = -40$ Set $\gamma = 0$, $\beta = 1$, $\alpha \approx$ 1.e-8 for FEC $\approx C$
	RBETA	[μS/cm]/[g/L]	
	RALPHA	$[\mu S/cm]/[g/L]^2$	
8 header for initial conditions			
8.	IC0FLAG	–	Initial concentration flag: = 0: $C_0 = 0$, no further input for item 8 < 0: read uniform non-zero C_0 in 8a > 0: read IC0FLAG $(x, C_0(x))$ pairs in 8b to describe variable initial concentration
8a header for uniform initial conditions (only when IC0FLAG < 0)			
8a. when IC0FLAG<0	RC0	g/L	Uniform non-zero C_0
8b header for non-uniform initial conditions (only when IC0FLAG > 0)			
8b. repeat IC0FLAG times when IC0FLAG>0	RX	m	x value*
	RC0	g/L	$C_0(x)$
9 header for data file name			
9.	CFDATA	–	Name of data file, 20 characters maximum; 'NONE' if there is no data file

*see Appendix 1, Section A1.5, for additional information on locating feed points and specifying non-uniform initial conditions

Sample Input File

An input file illustrating many of these options is shown below. Text or numbers following an exclamation point (!) are comments, and are not used by BORE II.

```
TITLE: Sample Input File with flow from below, horizontal flow, variable
flow
XMIN(m)      XMAX(m)      DIAM(cm)
.0000        60.00        7.600
QW(L/min)    HALPHA       !QW=flow from below; HALPHA=hor. flow
constriction
 0.50        0.           !default value of HALPHA will be used
#FEED_PTS    VARIABLE_FLOWRATE_IDENTIFIER
   4                999
DEPTH(m)     Q (L/min)     C(g/L)       T0(hr)       Q/V_FLAG
 25.         +1.           6.0          .0000        1 !1st 2 feed pts-hor.
flow
 25.         -1.           6.0          .0000        1 !C & T0 not used
(outflow)
 30.         99905.        6.0          .0000        0 !C & T0 not used
(table)
     T(hr)        Q(L/min)     C(g/L)       !#entries is two digits after
999
      .0000        .0000        6.          !first time in table is zero
      .3000        .2800E-01    5.
      .5000        .3200        4.
      1.000        .4600        3.
      1.500        .4600        2.          !last time in table is > tmax
 35.         .5            4.0          .2000        0 !final feed pt
TMAX(hr)     FECMAX       DIFFUSION_COEF.(m2/s)
 1.000       5000.        .7500E-09
RGAMMA       RBETA        RALPHA       !FEC = RGAMMA + C*RBETA + C*C*RALPHA
0.           0.           0.           !default values will be used
IC0FLAG      !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0)
pairs
    1
X(m)         C0(g/L)            !#entries is IC0FLAG
60.          2.                 !Concentration associated with Qw
DATA_FILE    !'NONE' if there is no data file
NONE
```

The first two feed points represent constant horizontal flow, and since the Q/V flag (IINFV) is one, flow rate is given as Darcy velocity through the aquifer in m/day. The third feed point has variable flow rate and concentration, with a five-entry table specifying the variation with time. The fourth feed point is an inflow point with constant flow rate and concentration and a non-zero concentration start time.

Note that the flow from below, q_w, is positive (into the wellbore section), so the corresponding concentration is specified as the initial condition of the lowermost cell in the wellbore (at $x = x_{\min}$) by using IC0FLAG = 1. If IC0FLAG = 0, the concentration associated with q_w would be zero, and if IC0FLAG = -1, the concentration associated with q_w would be the uniform non-zero initial concentration in the wellbore.

When BORE II writes an input file (option V), it changes several things to the file form shown above. Comments found in the original input file are not reproduced, but two comments are added. First, the cell height and the equation used to calculate it are shown on the line with $x_{\min}$, $x_{\max}$, and d_w. Second, if feed points represent horizontal flow, then the flag IINVF is set to 0, flow rate is given in L/min, and the corresponding Darcy velocity through the aquifer in m/day is added as a comment. Finally, if IC0FLAG > 0, BORE II sets IC0FLAG to the number of wellbore cells, and explicitly shows every (x, $C_0(x)$) pair. This option is useful for identifying the *x* values of various cells, which may expedite assignment of feed point locations or initial conditions. Part of the input file created by BORE II for the above sample is shown below.

```
TITLE: Sample Input File with flow from below, horizontal flow, variable
flow
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180,
DIAM/100)
 .0000       60.00       7.600      ! .3333
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow
constriction
 .5000       2.500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
    4               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 35.00       .5000       4.000       .2000        0
 30.00      99905.       6.000       .0000        0
     T(hr)       Q(L/min)    C(g/L)      !#entries is two digits after
999
      .0000       .0000       6.000
      .3000       .2800E-01   5.000
      .5000       .3200       4.000
      1.000       .4600       3.000
      1.500       .4600       2.000
 25.00       .4398E-01   6.000       .0000        0         ! 1.000
 25.00      -.4398E-01   6.000       .0000        0         !-1.000
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 1.000       5000.       .7500E-09
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1870.      -40.00
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0)
pairs
  179
X(m)        C0(g/L)           !#entries is IC0FLAG
 59.83       2.000
 59.50       .0000
 59.17       .0000
 58.83       .0000
…(169 entries with C0=0 not shown)…
 2.167       .0000
 1.833       .0000
 1.500       .0000
 1.167       .0000
 .8333       .0000
 .5000       .0000
DATA_FILE   !'NONE' if there is no data file
NONE
```

Line by Line Instructions for Data File

The data file is read in the fixed format shown below. If data are available in a different format, an auxiliary program should be used to convert it to this form (a simple preprocessor called PREBORE, described in Appendix 2, converts the data file format used by BORE to the new format shown below). Note that because a fixed format is used, blank entries are allowed; they are interpreted as zero.

Lines 1-8 are header lines, not used by BORE II.

Each line of the remainder of the file contains:

Variable	*x*	FEC	TEMP	DAT3	DAT4	DAT5	HR	MIN	SEC
Units	m	μS/cm	^{o}C				–	–	–
Format	F10.3	F10.3	F10.3	E10.3	E10.3	E10.3	I3	I2	I2
Columns	1-10	11-20	21-30	31-40	41-50	51-60	62-64	66-67	69-70

The entries DAT3, DAT4, and DAT5 represent optional data types that may be collected with certain logging tools, such as pH and dissolved oxygen (see options A and Y for ways to display this data). Note that there is one blank column before each of the HR, MIN, and SEC entries, to make the data file more readable. The first time entry corresponds to $t = 0$ for the model.

BORE II Options

The following options are available on the BORE II main menu. Either uppercase or lowercase letters may be used, and should be followed by pressing ENTER.

C – (C)-x plot – Displays FEC versus depth for data and/or model continuously in time (an animation); stores [*x* (m), *t* (sec), data FEC (μS/cm), model FEC (μS/cm)] in file BOREII.TMP for later use by option R or post-processing.

T – c-(T) plot – Displays FEC versus time for data and model for a chosen depth.

R – d/m cu(R)ve – Displays FEC versus depth plots for data and model at a series of times (snapshots of the option C display); uses results of most recent option C, read from BOREII.TMP. Does not work if there is no data file or if there are only data at one depth in data file.

N – i(N)flow-c – Displays inflow FEC for a chosen feed point as a function of time.

A – p(A)ram display – Displays all data profiles (FEC, TEMP, DAT3, DAT4, DAT5) simultaneously, using user-specified plot limits (selections 3-6). For selection 1, all points are connected on one continuous curve; for selection 2, points that are beyond depth or time limits start new curve segments.

X – (X)-t plot – Displays a color-coded plot of model FEC versus depth and time in a new window, then repeats the plot in the borehole profile window.

S – tool (S)tudy x-t plot – Same as X, but limits display to what would be obtained with a tool whose parameters (number of probes, gap between probes, and tool velocity) are specified by the user.

D – (D)ata x-t – Displays a color-coded plot of data traces versus depth and time in a new window, then repeats the plot in the borehole profile window (data type specified by option Y, default is FEC).

F – (F)ill data x-t – Same as D, except that data traces are interpolated to fill the *x*-*t* plane.

I – d/m d(I)ff x-t – Displays a color-coded plot of the difference between model and data FEC versus depth and time in a new window, then repeats the plot in the borehole profile window. User selects whether to show data traces (mode 1) or filled data (mode 2).

M – (M)odify inp– Opens interactive session for modifying location, flow rate, and concentration of feed points, or adding new feed points. User is prompted to enter feed point number and given the chance to modify or maintain current parameters. To add a new feed point, specify a feed point number greater than that for any existing feed point. If horizontal flow is implemented using option M, flow rate must be specified as volumetric flow rate through the wellbore in L/min.

P – (P)lot adjust – Sets new values of parameter minimum and maximum; t_{max}; difference range for option I; and depth for which wellbore flow rate q_0 is displayed in borehole profile window (default depth is x_{min}).

G – (G)rid – Sets grid spacing for new window showing x-t plots.

Y – data t(Y)pe – Chooses data type (FEC, TEMP, DAT3, DAT4, DAT5) to display in options C, T, D, and F. Model results always show FEC, so option C and T plots, which show both model and data, must be read carefully. Note that options R and I are not affected by the choice of data type, but always compare model and data FEC.

Z – print – Displays instructions for printing a screen image.

V – sa(V)e – Creates a new input file with current model parameters. User is prompted for new file name.

Q – (Q)uit – Terminates BORE II program.

4. Example Applications

Five example applications are presented to illustrate the capabilities of BORE II. Although BORE II simulates the forward problem (it produces wellbore FEC profiles given different inflow positions, rates, and concentrations), it is most commonly used in an inverse mode, in which inflow positions, rates and concentrations are varied by trial and error until the model matches observed values of wellbore FEC profiles. Initial guesses for the trial and error process may be obtained using direct integral methods (Tsang and Hale, 1989; Tsang et al., 1990) or other means (see example 2 below). Example applications 3, 4, and 5 demonstrate such comparisons to real data provided to us as typical field data sets by G. Bauer (private communication, 2000). The results of these example applications do not necessarily provide physically realistic flow rates and inflow concentrations, because they employ the artificial equality FEC = C. Furthermore, rough matches to real data, as are obtained here, can often be obtained equally well with a variety of different parameters (i.e., the solution of the inverse problem is non-unique). The input files for the example applications are shown in Appendix 3.

	Problem	Data File	Input File	Features
1	Up flow	up_num.dbt (numerically simulated)	up_num.inp	Advection and dilution, diffusion/dispersion minor
2	Horizontal flow	hor_an.dbt (analytical solution)	hor_an.inp	Dilution only, no advection or diffusion/dispersion One pair inflow/outflow points
3	Horizontal flow	hor_real.dbt (real data)	hor_real.inp	Dilution and diffusion/dispersion Multiple pairs inflow/outflow points Initial time added to data

4	Down flow	down_c.dbt (real data)	down_c.inp	Advection, dilution, and diffusion/dispersion Variable inflow concentration
5	Combination flow	comb_ic.dbt (real data)	comb_ic.inp	Advection, dilution, and diffusion/dispersion Non-uniform initial conditions

1. Up Flow – Numerically Simulated Data

Perhaps the most common application of BORE II is to the case of up flow - when one pumps from the top of the wellbore section, and fluid enters the wellbore at one or more feed points. Figure 1 shows *C* versus *x* for several times for a typical up flow case (obtained with BORE II option R). Each feed point has the same inflow rate and the same concentration, and there is also up flow from below. At early times, the feed points show up as individual FEC peaks, but as time passes, the deeper peaks merge with those above them, creating a step-like structure. The data set for this example is not real, but the results of a numerical simulation using the flow and transport simulator TOUGH2 (Pruess, 1987; 1991; 1995; 1998). TOUGH2 has been verified and validated against analytical solutions, other numerical models, and laboratory and field data. The TOUGH2 simulation uses a one-dimensional model with the same cell spacing as BORE II and constant mass sources located at the BORE II feed points. Thus, BORE II and TOUGH2 are solving the same problems, and comparing the results for wellbore FEC profiles verifies that the BORE II calculations are done correctly.

2. Horizontal Flow – Analytical Solution and Numerically Simulated Data

For horizontal flow in the absence of diffusion/dispersion along the wellbore, an analytical solution for the concentration observed in the wellbore as a function of time, $C(t)$, is given by (Drost, 1968):

$$C(t) = C_i - [C_i - C(0)]\exp\left(\frac{-2tv_d\alpha_h}{\pi r_w}\right), \qquad (1)$$

where C_i is the formation (inflow) concentration, t is time (s), v_d is the Darcy velocity through the aquifer (m/s), α_h is the aquifer-to-wellbore convergence factor, and r_w is the wellbore radius (m). Figure 2 shows the analytical solution and the BORE II results for this problem, obtained using option T. The agreement is excellent. Note that for small values of v_d, if C(0) = 0, the analytical solution becomes approximately

$$C(t) = C_i\left\lfloor 1 - \exp\left(\frac{-2tv_d\alpha_h}{\pi r_w}\right)\right\rfloor \approx C_i\left\lfloor 1 - \left(1 - \frac{2tv_d\alpha_h}{\pi r_w}\right)\right\rfloor = \frac{C_i\, 2tv_d\alpha_h}{\pi r_w}. \qquad (2)$$

Thus, any combination of C_i and v_d whose product is a constant gives the same value of C. This condition corresponds to the early-time straight-line portion of Figure 2. The analytical solution may be implemented in a spreadsheet to expedite the choice of BORE II parameters, by examining the solution for various values of v_d and C_i. Note that care must be taken to use a consistent set of units for t, v_d, and r_w in Equations (1) and (2). For example, when time is in seconds, BORE II input parameters v_d in m/day and r_w in cm must be converted to m/s and m, respectively.

Figure 2 also shows the evolution of concentration at and near a horizontal flow layer when diffusion/dispersion along the wellbore is significant ($D_0 = 10^{-5}$ m^2/s). For this case, the analytical solution is not applicable, but BORE II results compare very well to numerically simulated data obtained using TOUGH2. When dispersion is significant, use of the Drost solution generally results in an underestimation of C_i and an overestimation of v_d. These errors do not arise when using BORE II, since diffusion/dispersion can be explicitly included.

3. Horizontal Flow – Real Data

As indicated in Figure 2, the addition of diffusion or dispersion modifies the depth-FEC profile arising from a thin layer of horizontal flow, by widening the base of the FEC peak. A thick layer of horizontal flow produces a distinct signature, with an FEC response that has a wide peak as well as a wide base. To model a thick layer of horizontal flow, one may use several adjacent inflow/outflow point pairs in the model. Figure 3 compares model and data profiles (G. Bauer, private communication, 2000) of C versus x for several times, using option R. Seven pairs of inflow/outflow points are used, assigned to seven adjacent cells. By multiplying the number of inflow/outflow pairs by cell thickness, one may estimate the thickness of the layer of horizontal flow, in this case 2.3 m. See Appendix 1, Section A1.5, for additional information about assigning feed points to specific cells.

For this particular data set, the earliest observations show a variable FEC profile. One possible way to address this is to specify a non-uniform initial concentration distribution in the wellbore. An alternative approach (used here) is to add a dummy entry to the data file, specifying a time prior to the first real data time, at which the FCE distribution in the wellbore is assumed to be uniform. In general, it is not possible to determine when, if ever, the FEC distribution in the wellbore is uniform, but the approach can work quite well, as shown in Figure 4, which shows C versus t at the center of the horizontal flow zone (option T). The data zero time taken from the header of the data file, where the date and time of the logging run are specified.

4. Down Flow – Real Data

Figure 5 compares model and data profiles (G. Bauer, private communication, 2000) of C versus x for several times (option R) for a case with primarily down flow. A uniform non-zero initial concentration is used (IC0FLAG < 0) to approximate the low, slightly variable initial concentration. Two shallow inflow points have variable concentrations that increase in time, which suggests that de-ionized water penetrated into the fractures when it was introduced into the wellbore to establish low-concentration initial conditions for logging. A low-concentration feed point at x = 158.5 m creates up flow above it, but the remainder of the wellbore section shows down flow.

5. Combination Flow – Real Data

Figure 6 compares model and data profiles (G. Bauer, private communication, 2000) of C versus x for several times (option R) for a case with combination flow. A non-uniform initial condition has been used, which is extracted from the data file using the preprocessor PREBORE (see Appendix 2). Note that there are more entries in the initial condition specification (232) than there are cells in the model (179). Thus, some cells are assigned more than one initial condition. For cells where this occurs, only the final initial condition assigned is used. See Appendix 1, Section A1.5, for additional information on specifying non-uniform conditions. Figure 7 shows the same information as Figure 6, but plotted in a different way, with the difference between data and model FEC plotted as an x-t plot (option I). The blue and orange diagonal features indicate that the largest discrepancy between model and data gradually deepens with time.

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Appendix 1: Mathematical Background and Numerical Approach

The principal equation governing wellbore FEC variation is the equation for the transport of mass (or ion concentration) in the wellbore. However, additional consideration must be given to the determination of FEC as a function of ion concentration and the temperature dependence of FEC.

A1.1 FEC as a Function of Concentration

The relationship between ion concentration and FEC is reviewed, for example, by Shedlovsky and Shedlovsky (1971), who give graphs and tables relating these two quantities. Hale and Tsang (1988) made a sample fit for the case of NaCl solution at low concentrations and obtained

$$\mathrm{FEC} = 1{,}870\, C - 40\, C^2, \tag{A.1}$$

where C is ion concentration in kg/m^3 (≈ g/L) and FEC is in μS/cm at 20^{o}C. The expression is accurate for a range of C up to ≈ 6 kg/m^3 and FEC up to 11,000 μS/cm. The quadratic term can be dropped if one is interested only in values of C up to ≈ 4 kg/m^3 and FEC up to 7,000 μS/cm, in which case the error will be less than 10%.

Fracture fluids typically contain a variety of ions, the most common being Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-. If a hydrochemical analysis has been completed, various methods are available for computing an equivalent NaCl concentration for other ions. Schlumberger (1984) presents charts of multiplicative factors that convert various solutes to equivalent NaCl concentrations with respect to their effect on electric conductivity.

A1.2 Temperature Dependence of FEC

BORE II calculations are made assuming a uniform temperature throughout the wellbore. Actual wellbore temperatures generally vary with depth, so temperature corrections must be applied to field FEC data to permit direct comparison with model output.

The effect of temperature T on FEC can be estimated using the following equation (Schlumberger, 1984)

$$\mathrm{FEC}(20^o\,\mathrm{C}) = \frac{\mathrm{FEC}(\mathrm{T})}{1 + \mathrm{S}(\mathrm{T} - 20^o\,\mathrm{C})}, \tag{A.2}$$

where S = 0.024.

Generally, temperature increases with depth below the land surface. If full temperature logs are available, these data can be used to correct the corresponding FEC values. However, if no complete logs are available, a simplifying assumption may be made that the temperature variation in the wellbore is linear and can be modeled by:

$$T = Ax + B, \tag{A.3}$$

where A and B are parameters determined by fitting any available temperature versus depth data. If the fit is unsatisfactory, other relationships with higher order terms must be used.

A1.3 Governing Equation

The differential equation for mass or solute transport in a wellbore is:

$$\frac{\partial}{\partial x}\left(D_o \frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial x}(Cv) + S = \frac{\partial C}{\partial t}, \qquad \text{(A.4)}$$

where x is depth, t is time, and C is ion concentration. The first term is the diffusion term, with D_0 the diffusion/dispersion coefficient in m^2/s, the second term is the advective term, with v the fluid velocity in m/s, and S is the source term in kg/m^3s. This one-dimensional partial differential equation is solved numerically using the finite difference method, with upstream weighting used in the advective term. The following initial and boundary conditions are specified:

$$C(x,0) = C_0(x), \qquad \text{(A.5)}$$

$C(x_{min},t) = C_0(x_{min})$ for flow into the wellbore from above,

$C(x_{max},t) = C_0(x_{max})$ for flow into the wellbore from below,

$D_0 = 0$ for $x < x_{min}$ and $x > x_{max}$.

The first condition allows for the specification of initial ion concentrations in the wellbore. The second and third conditions allow for advective flow of ions into the wellbore interval from above and below. The final condition indicates that diffusion and dispersion do not take place across the boundaries of the wellbore interval. In general, advection will be the dominant process at the boundaries. If diffusion or dispersion is dominant for a particular problem, the boundaries should be extended in order to prevent improper trapping of electrolyte.

A1.4 Discretization in Time

Time stepping is explicit, with the time step Δt determined by stability constraints for advection

$$\Delta t \le \frac{\pi d_w^{\,2} \Delta x}{8 q_{max}}, \qquad \text{(A.6)}$$

and diffusion

$$\Delta t \le \frac{\Delta x^2}{4 D_0}, \qquad \text{(A.7)}$$

where q_{max} (m^3/s) is the maximum fluid flow rate anywhere in the wellbore. BORE II starts its calculation at $t = 0$. The first time in the data file is also identified with $t = 0$. If it is apparent that model and data times are not synchronized, then one may insert an additional line into the data file after the header lines, with an earlier time than the first real data time, in order to reset the data zero time. On the inserted line, FEC, x, and other data entries may be left blank or copied from the first real data line.

A1.5 Discretization in Space

The wellbore interval between $x_{\min}$ and $x_{\max}$ is uniformly divided into N cells and it is assumed that the wellbore has uniform diameter, d_w. Cell height Δx is determined as the larger of $(x_{\max} - x_{\min})/180$ and d_w. Position values indicate depth in the wellbore and thus x is zero at the surface and increases downward. The cell index increases upward, with cells 1 and N located at the bottom and top, respectively, of the wellbore interval. In general, the ith node (the center of the ith cell) is located at

$$x_i = x_{\max} - (i\text{-}1/2)\Delta x, \tag{A.8}$$

with the ith cell extending from $x_{\max} - (i - 1)\Delta x$ to $x_{\max} - i\Delta x$.

BORE II assigns feed points and initial concentrations to cell i if the location of the feed point or $C_0(x)$ value lies within the boundaries of the ith cell. If multiple feed points are assigned to the same cell, they will all be accounted for, but if multiple initial conditions are assigned to the same cell, only the final one assigned will be used. By definition, the lower boundary of cell 1 is at $x_{\max}$, but due to round-off errors, the upper boundary of cell N may not be at $x_{\min}$. Hence, it is often useful to know the x coordinates of each node. These are displayed in the input file written by BORE II (option V) when IC0FLAG > 0. Thus, if the user sets IC0FLAG = 1, inputs one $(x, C_0(x))$ pair, and uses option V, then a new input file will be created with IC0FLAG = N and a complete list of the x coordinates for all nodes, with $C_0 = 0$ for all cells except the one identified in the original input file. Alternatively, if the initial conditions are taken from the data file with PREBORE (or taken from any source that is independent of the nodal coordinates), then using option V will create an input file that shows the actual initial conditions assigned to each cell.

The list of nodal x coordinates may be useful when modeling a thick fracture zone or aquifer, in order to place one feed point in each cell over a given depth range. Similarly, when using IC0FLAG > 0 to specify non-uniform initial concentrations, one must assign a C_0 value to each cell in the interval of interest in order to obtain a continuous C profile, because no interpolation is done between scattered initial concentrations. Finally, knowing the coordinate of the top cell in the model is useful for assigning the initial concentration that serves as the boundary condition for inflow into the wellbore interval from above. For inflow from below, either $x = x_1$ or $x = x_{\max}$ may be used.

A1.6 Calculation of Flow Rates

Feed point flow rates may be constant in time, in which case a steady-state flow field is assumed in the wellbore, or variable, with feed point flow rates determined by linear interpolation between tabulated values. Although feed point flow rate may vary, true transient wellbore flow including fluid compressibility effects is not considered. Rather, the wellbore fluid flow field is assumed to change instantly from one steady-state flow field to another. In other words, the flow rate out of cell i is always the sum of the flow rates from all feed point locations within the boundaries of cell i plus the flow rate out of cell i-1.

Appendix 2: The Preprocessor PREBORE

PREBORE is a simple Fortran program that does preprocessing for BORE II. It runs under either Windows or DOS. PREBORE converts the old BORE data file format into the new BORE II data file format. Depth is converted from feet to meters, and other data columns are realigned. PREBORE can also create a file with (x,C_0) pairs to be added to the BORE II input file as initial conditions (this option requires that x values steadily increase or steadily decrease in each profile).

If data file conversion is being done, the user is prompted to enter the old and new data file names.

If a file with initial conditions is being created, the user is prompted for the following information: the name of the BORE II data file; a name for the initial condition file; which profile in the data file to use; the direction of logging (downward assumes x values increase in the data file, upward assumes they decrease, and both assumes the profiles alternately increase and decrease in x); and the conversion factors (γ, β, α) between FEC and C (default values 0, 1870, -40). In addition to creating an ASCII text file with (x,C_0) pairs, which may be added to the BORE II input file using a text editor or word processor, PREBORE prints out the number of pairs on the screen, which should be used for IC0FLAG. Note that IC0FLAG may be greater than the number of cells in the model (usually about 180), but that in this case not all the C_0 values will be used (see Appendix 1, Section A1.5).

Data file conversion and initial condition creation can be done in the same PREBORE run. In this case the user must specify both old and new data file names in addition to the parameters describing the creation of initial conditions.

Appendix 3: Input Files for Example Applications

A2.1 Example Application 1 – Up Flow – up_num.inp

```
TITLE: up flow with flow from below, compare to synthetic data
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180,
DIAM/100)
 .0000       180.0       14.00      ! 1.000
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow
constriction
 .7500       2.500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
    3               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 160.5       .7500       100.0       .0000        0
 130.5       .7500       100.0       .0000        0
 50.50       .7500       100.0       .0000        0
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 24.00       100.0       .7500E-09
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1.000       .1000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0)
pairs
    0
DATA_FILE   !'NONE' if there is no data file
up_num.dbt
```

A2.2 Example Application 2 – Horizontal Flow Analytical Solution – hor_an.inp

```
TITLE: Horizontal Flow - Compare to Analytical Solution
XMIN(m)     XMAX(m)     DIAM(cm)
0.000       50.000      7.600
QW(L/min)   HALPHA
0.          2.850000
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
       2    999
DEPTH(m)    Vd(m/d)     C(g/L)      T0(hr)      Q/V_FLAG
  25.0000     1.        1000.     .0000          1
  25.0000    -1.        1000.     .0000          1
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
3.0000      1000.       1.e-10
RGAMMA      RBETA       RALPHA
0.000000    1.000000    1.e-08
IC0FLAG
0
DATA_FILE
hor_an.dbt
```

The input file for the case with significant dispersion is identical, except that the diffusion coefficient is increased from 10^{-10} m^2/s to 10^{-5} m^2/s.

A2.3 Example Application 3 – Horizontal Flow - hor_real.inp

```
TITLE: Horizontal Flow Example
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180,
DIAM/100)
 .0000       60.00       7.600      ! .3333
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow
constriction
 .0000       2.500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
   14              999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/d)
 26.73       .5295E-02   730.0       .0000        0         ! .1204
 26.73      -.5295E-02   .0000       .0000        0         !-.1204
 26.39       .5295E-02   730.0       .0000        0         ! .1204
 26.39      -.5295E-02   .0000       .0000        0         !-.1204
 26.06       .5295E-02   730.0       .0000        0         ! .1204
 26.06      -.5295E-02   .0000       .0000        0         !-.1204
 25.73       .5295E-02   730.0       .0000        0         ! .1204
 25.73      -.5295E-02   .0000       .0000        0         !-.1204
 25.39       .5295E-02   730.0       .0000        0         ! .1204
 25.39      -.5295E-02   .0000       .0000        0         !-.1204
 25.06       .5295E-02   730.0       .0000        0         ! .1204
 25.06      -.5295E-02   .0000       .0000        0         !-.1204
 24.73       .5295E-02   730.0       .0000        0         ! .1204
 24.73      -.5295E-02   .0000       .0000        0         !-.1204
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 4.000       400.0       .7500E-04
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1.000       .1000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0)
pairs
    0
DATA_FILE   !'NONE' if there is no data file
hor_real.dbt
```

A2.4 Example Application 4 – Down Flow – down_c.inp

```
TITLE: downflow, variable source conc., uniform non-zero initial conc.
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180,
DIAM/100)
 140.0       240.0       7.600      ! .5556
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow
constriction
 .0000       2.850
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
   12               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 239.0      -.7000       .0000       .4000        0
 212.0      -1.000       .0000       .4000        0
 187.0       .7500       1800.       .4000        0
 183.0       .1900       1900.       .4000        0
 181.0       .1200       1900.       .4000        0
 178.0       .5000E-01   1900.       .4000        0
 176.0       .4000E-01   1900.       .4000        0
 174.0       .3000E-01   1900.       .4000        0
 171.0       .1000E-01   1900.       .4000        0
 164.4      99905.       1900.       .4000        0
     T(hr)       Q(L/min)    C(g/L)      !#entries is two digits after
999
      .0000       .4400       80.00
      .4000       .4400       100.0
      1.200       .4400       1100.
      1.900       .4400       1650.
      4.500       .4400       1950.
 162.0      99904.       1800.       .0000        0
     T(hr)       Q(L/min)    C(g/L)      !#entries is two digits after
999
      .0000       .6000E-01   80.00
      .4000       .6000E-01   200.0
      1.900       .6000E-01   1650.
      4.500       .6000E-01   1950.
 158.5       .1000       80.00       .0000        0
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 4.400       1700.       .1000E-02
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1.000       .1000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0)
pairs
   -1
C0 (g/L)    !Uniform, non-zero C0
 80.00
DATA_FILE   !'NONE' if there is no data file
down_c.dbt
```

A2.5 Example Application 5 – Combination Flow – comb_ic.inp

```
TITLE: Combination flow example, non-uniform initial concentration
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180,
DIAM/100)
 .00000      50.000      7.6000     ! .2778
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow
constriction
 .00000      2.8500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
   12               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 45.000     -.13000      .00000      .00000       0
 33.300      .11000      800.00      .15000       0
 33.300     -.31000      .00000      .00000       0
 27.500     -1.0500      .00000      .00000       0
 25.700      .30000      810.00      .15000       0
 25.400      .30000      810.00      .15000       0
 25.140      .30000      810.00      .15000       0
 24.900      .30000      810.00      .15000       0
 23.500      .12000      800.00      .15000       0
 21.500      .40000E-01  800.00      .15000       0
 14.000      .15000E-01  750.00      .15000       0
 12.200      .10000E-01  750.00      .15000       0
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 1.0000      1000.0      .50000E-03
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .00000      1.0000      .10000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0)
pairs
  232
X(m)        C0(g/L)           !#entries is IC0FLAG
1.524       2
1.615       2
1.707       3
1.829       3
1.951       3
2.073       3
2.225       3
2.377       3
2.53        3
2.713       3
2.865       3
3.018       3
3.353       589
3.536       597
3.719       588
3.871       583
4.054       584
…(208 entries not shown)…
43.282      2
43.8        2
43.983      2
44.166      1
44.318      1
44.501      1
44.684      1
DATA_FILE   !'NONE' if there is no data file
comb_ic.dbt
```

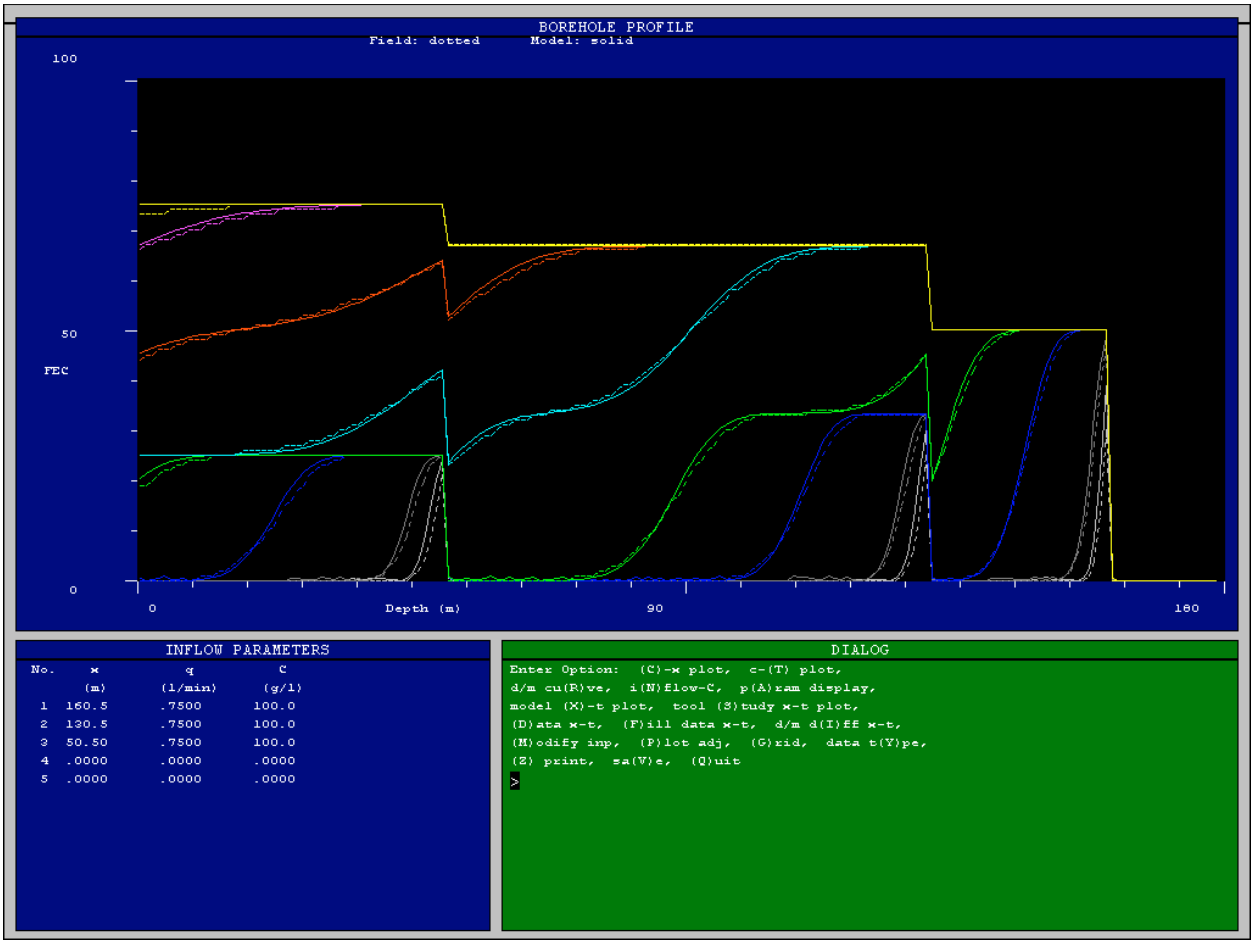


Figure 1. Concentration (=FEC) versus depth at a series of times for example application 1 - up flow. Data are numerically simulated using the TOUGH2 code. Figure is a BORE II screen-print after running option R.

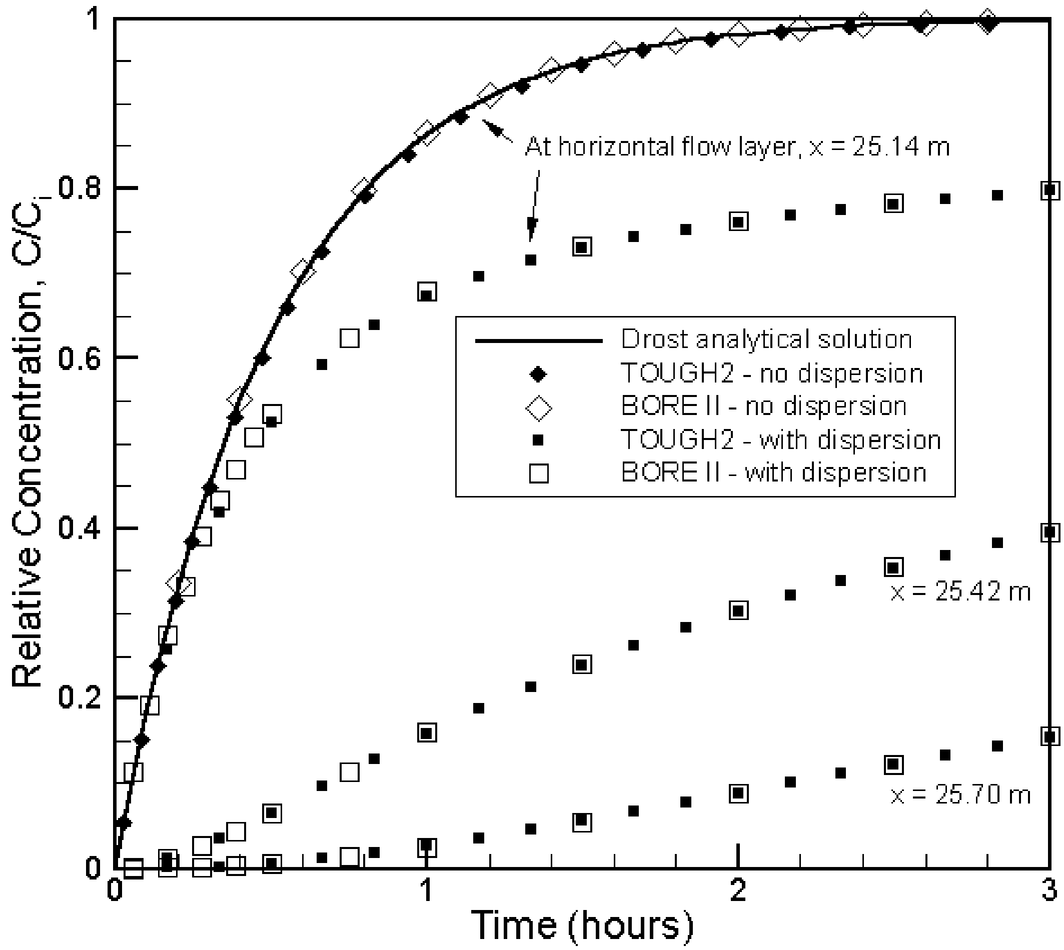


Figure 2. Relative concentration versus time for example application 2 – horizontal flow. When diffusion/dispersion is negligible, the concentration increase only occurs at the depth of the horizontal flow layer. The solid line shows the analytical solution as given by Drost (1968), Equation (1).

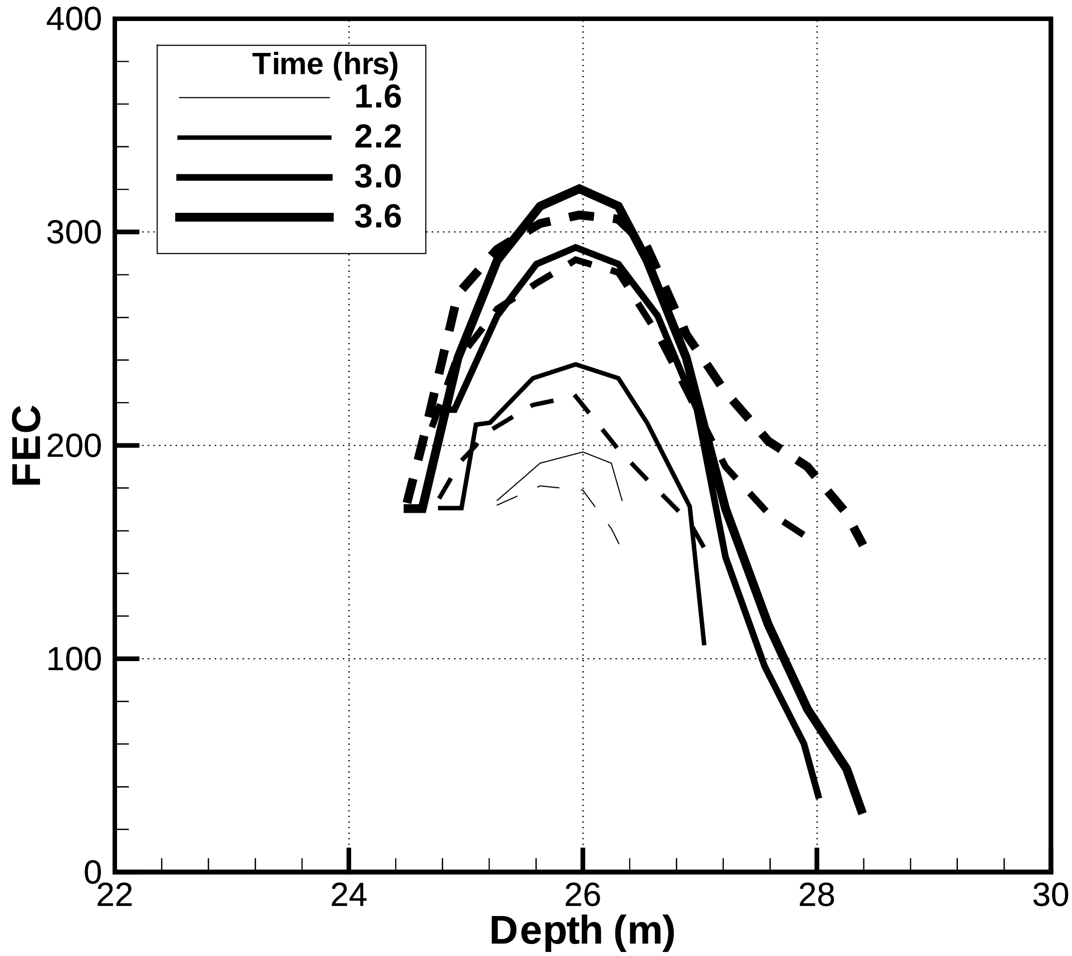


Figure 3. Concentration (= FEC) versus depth at a series of times for example application 3 – a thick layer of horizontal flow. Dashed lines represent field data, solid lines represent BORE II results. Diffusion/dispersion is significant.

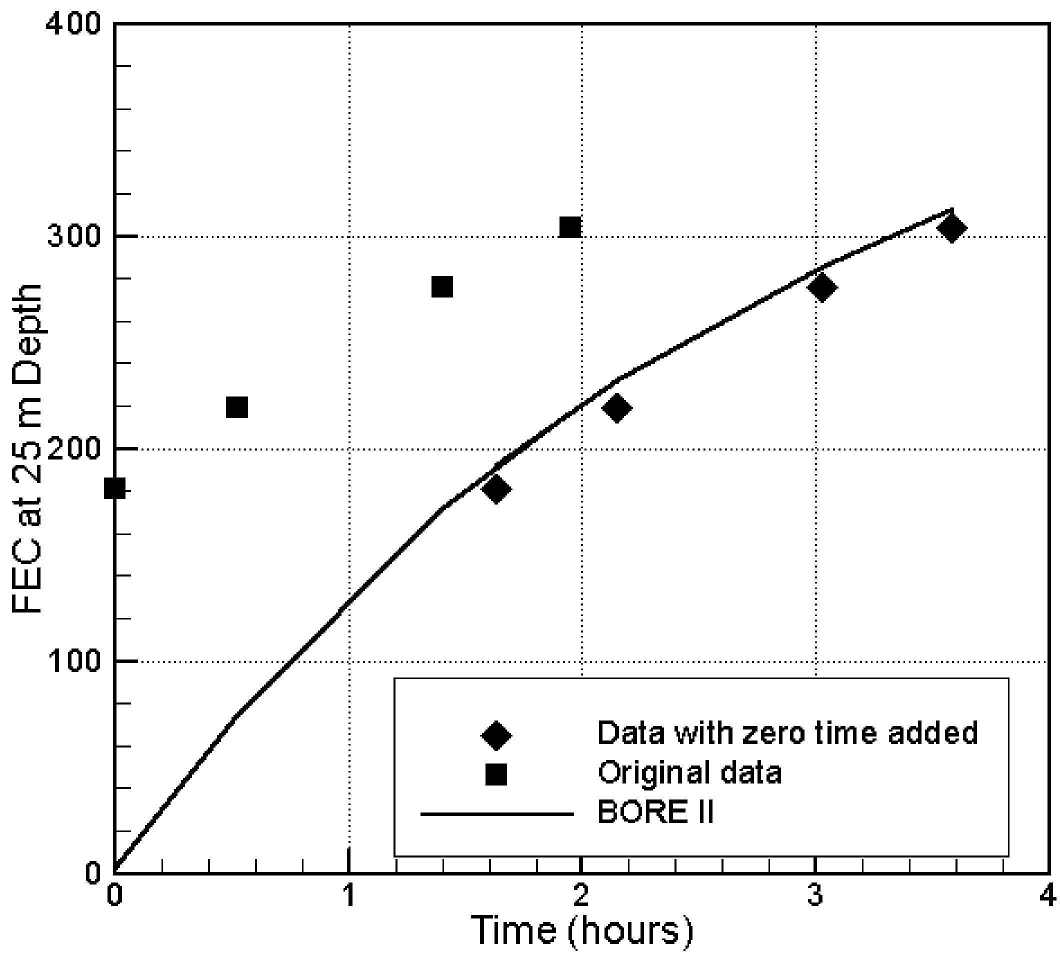


Figure 4. Concentration (= FEC) versus time at the center of the horizontal flow zone of example application 3, illustrating the addition of a data zero time.

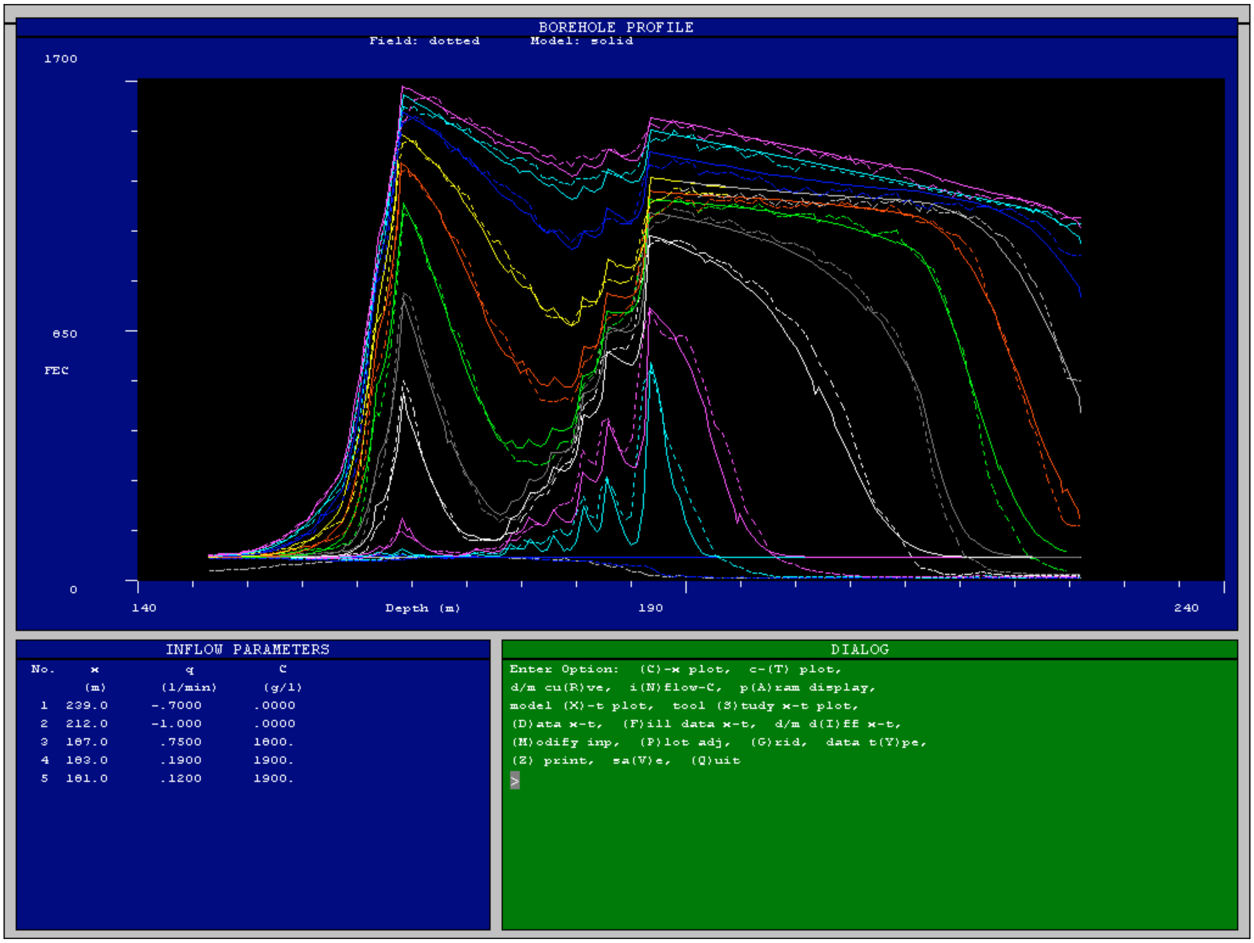


Figure 5. Concentration (= FEC) versus depth at a series of times for example application 4 – down flow. Figure is a BORE II screen-print after running option R.

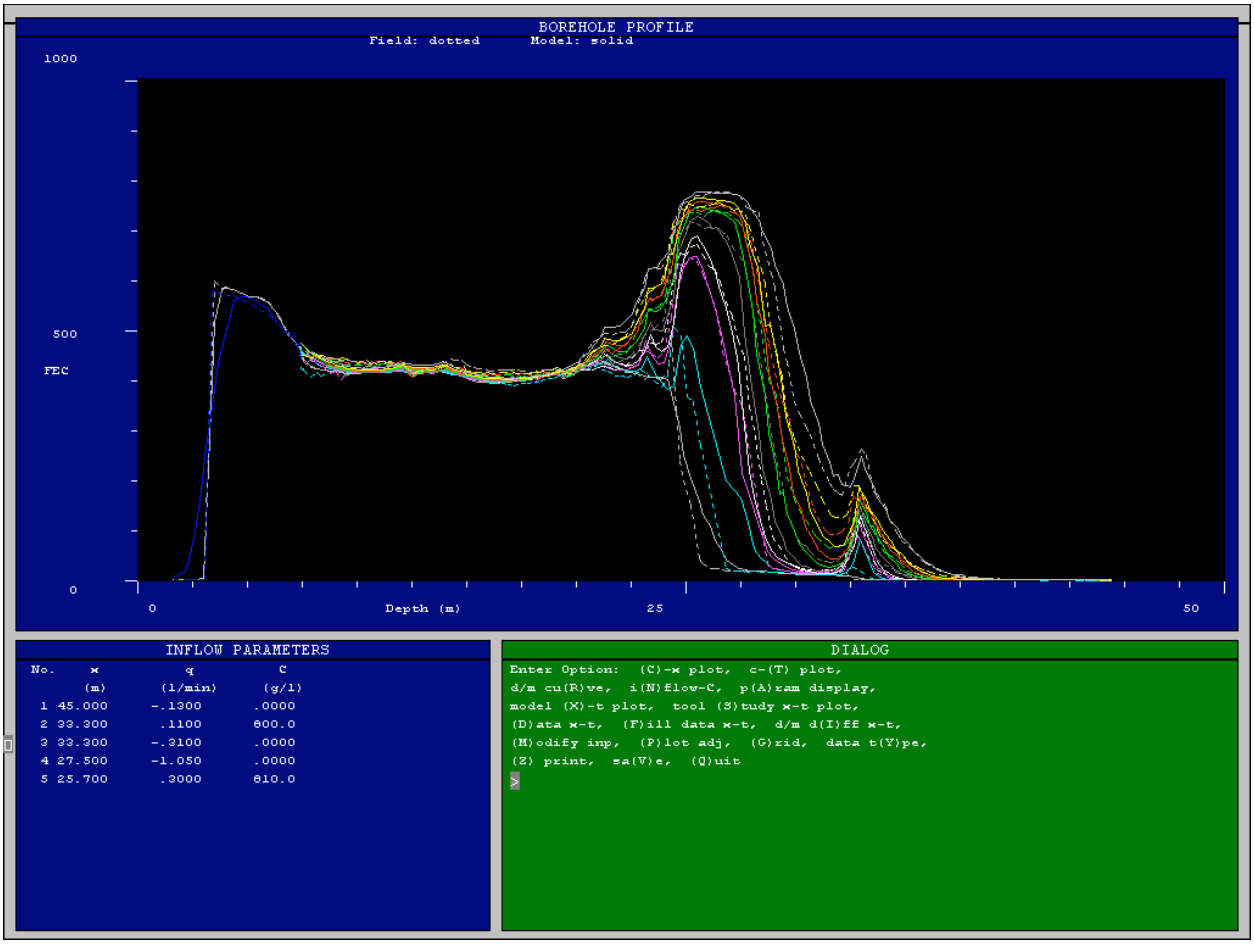


Figure 6. Concentration (= FEC) versus depth at a series of times for example application 5 – combination flow. Figure is a BORE II screen-print after option R.

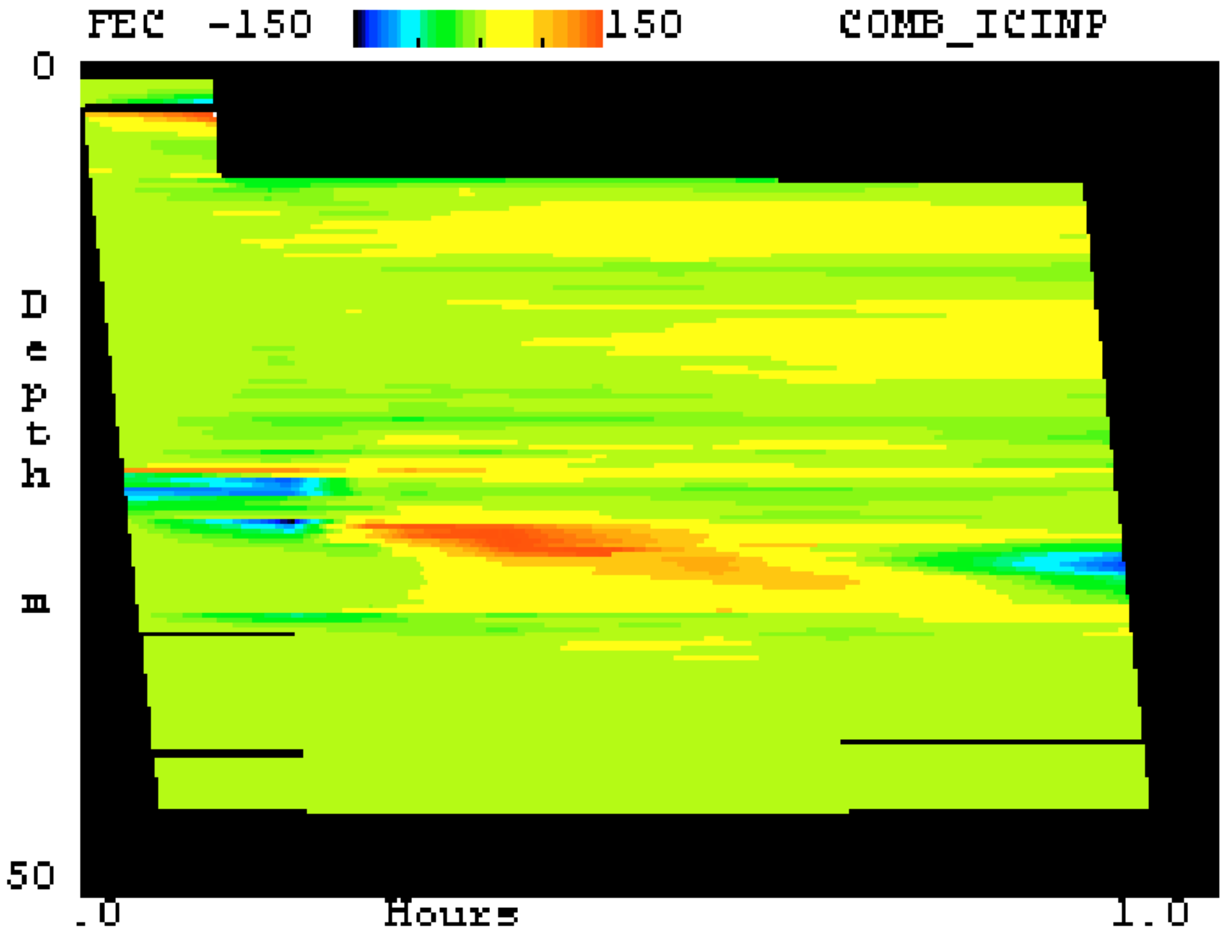


Figure 7. FEC difference between model and data as a function of depth and time (an *x*-*t* plot) for example application 5 – combination flow. Figure is a BORE II screen-print after option I, mode 2.

APPENDIX C

LIMITATIONS

LIMITATIONS

COLOG's logging was performed in accordance with generally accepted industry practices. COLOG has observed that degree of care and skill generally exercised by others under similar circumstances and conditions. Interpretations of logs or interpretations of test or other data, and any recommendation or hydrogeologic description based upon such interpretations, are opinions based upon inferences from measurements, empirical relationships and assumptions. These inferences and assumptions require engineering judgment, and therefore, are not scientific certainties. As such, other professional engineers or analysts may differ as to their interpretation. Accordingly, COLOG cannot and does not warrant the accuracy, correctness or completeness of any such interpretation, recommendation or hydrogeologic description.

All technical data, evaluations, analysis, reports, and other work products are instruments of COLOG's professional services intended for one-time use on this project. Any reuse of work product by Client for other than the purpose for which they were originally intended will be at Client's sole risk and without liability to COLOG. COLOG makes no warranties, either express or implied. Under no circumstances shall COLOG or its employees be liable for consequential damages.

Appendix D - Water-Quality Reports

PETROLEUM LABORATORIES, INC.

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

109 Cleveland Street
Houma, Louisiana 70363
985-868-4820

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 04/27/11

Lab No: LDW-0370
Non-Regulatory

Location: Baton Rouge Water Co.

Fresh Water Complete Analysis

Scavenger Well
#1882-0757 (Depth 1631)
Sample Date: 04-23-11 @ 1554 hrs.
Received Date: 04-25-11

Parameters - units	Results
pH - s.u.	7.67
Turbidity - NTU	0.83
Color - Apparent	5
Conductivity - mS/cm	6.09
Calcium Chloride - mg/l	76.48
Calcium Carbonate - mg/l	<0.1
Calcium Bicarbonate - mg/l	106.27
Magnesium Carbonate - mg/l	<0.1
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	<0.1
Sodium Bicarbonate - mg/l	<0.1
Sodium Sulfate - mg/l	<0.1
Sodium Chloride - mg/l	3,091.62
Magnesium Chloride - mg/l	40.27
Nitrogen As Nitrate - mg/l	<0.01
Silica As Silicon Dioxide - mg/l	34
Manganese - mg/l	1.81
Chloride - mg/l	1,955
Iron - mg/l	0.68
Carbonate - mg/l	<0.1
Bicarbonate - mg/l	80.03
Sulfate - mg/l	<1
Calcium - mg/l	53.8
Magnesium - mg/l	10.3
Sodium - mg/l	1,215.51
Fluoride - mg/l	*
Potassium - mg/l	3.87
Total Dissolved Solids- mg/l	3,355.0 **
Total Hardness Calcium Carbonate- mg/l	176.73
"P" Alkanlinity As Calcium Carbonate- mg/l	<0.1
"MO" Alkalinity As Calcium Carbonate- mg/l	65.60

* Fluoride - results pending.
** TDS - will change when Fluoride results are in.

Attest: ______

PETROLEUM LABORATORIES, INC.

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

109 Clevcland Street
Houma, Louisiana 70363
985-868-4820

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Report Date: 04/27/11

Lab No: LDW-0371
Non-Regulatory

Location: Baton Rouge Water Co.

Attn: Mr. Bruce Duhe

Fresh Water Complete Analysis

Scavenger Well
#1882-0757 (Depth 1631)
Sample Date: 04-23-11 @ 1635 hrs.
Received Date: 04-25-11

Parameters - units	Results
pH - s.u.	7.79
Turbidity - NTU	0.75
Color - Apparent	5
Conductivity - mS/cm	4.03
Calcium Chloride - mg/l	7.49
Calcium Carbonate - mg/l	<0.1
Calcium Bicarbonate - mg/l	168.48
Magnesium Carbonate - mg/l	<0.1
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	<0.1
Sodium Bicarbonate - mg/l	<0.1
Sodium Sulfate - mg/l	<0.1
Sodium Chloride - mg/l	2,191.95
Magnesium Chloride - mg/l	35.19
Nitrogen As Nitrate - mg/l	<0.01
Silica As Silicon Dioxide - mg/l	33
Manganese - mg/l	0.93
Chloride - mg/l	1,233
Iron - mg/l	0.14
Carbonate - mg/l	<0.1
Bicarbonate - mg/l	126.88
Sulfate - mg/l	<1
Calcium - mg/l	44.3
Magnesium - mg/l	9.0
Sodium - mg/l	778.77
Fluoride - mg/l	*
Potassium - mg/l	3.07
Total Dissolved Solids- mg/l	2,229.09 **
Total Hardness Calcium Carbonate- mg/l	147.66
"P" Alkanlinity As Calcium Carbonate- mg/l	<0.1
"MO" Alkalinity As Calcium Carbonate- mg/l	104.00

* Fluoride - results pending.
** TDS - will change when Fluoride results are in.

Attest: ______________

PETROLEUM LABORATORIES, INC.

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

109 Cleveland Street
Houma, Louisiana 70363
985-868-4820

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 04/27/11

Location: Baton Rouge Water Co.

Lab No: LDW-0372
Non-Regulatory

Fresh Water Complete Analysis

Scavenger Well
#1682-0757 (Well Head)
Sample Date: 04-23-11 @ 1700 hrs.
Received Date: 04-25-11

Parameters - units	Results
pH - s.u.	8.05
Turbidity - NTU	0.38
Color - Apparent	5
Conductivity - umhos/cm	1,680
Calcium Carbonate - mg/l	<0.1
Calcium Bicarbonate - mg/l	63.18
Magnesium Carbonate - mg/l	<0.1
Magnesium Bicarbonate - mg/l	18.84
Sodium Carbonate - mg/l	<0.1
Sodium Bicarbonate - mg/l	100.35
Sodium Sulfate - mg/l	7.40
Sodium Chloride - mg/l	739.9
Nitrogen As Nitrate - mg/l	<0.01
Silica As Silicon Dioxide - mg/l	34
Manganese - mg/l	0.33
Chloride - mg/l	449
Iron - mg/l	0.15
Carbonate - mg/l	<0.1
Bicarbonate - mg/l	136.15
Sulfate - mg/l	5
Calcium - mg/l	15.6
Magnesium - mg/l	3.14
Sodium - mg/l	320.77
Fluoride - mg/l	*
Potassium - mg/l	1.37
Total Dissolved Solids- mg/l	965.51 **
Total Hardness Calcium Carbonate- mg/l	51.88
"P" Alkanlinity As Calcium Carbonate- mg/l	<0.1
"MO" Alkalinity As Calcium Carbonate- mg/l	111.60

* Fluoride - results pending.
** TDS - will change when Fluoride results are in.

Attest:

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 07/18/11

Lab No: LDZ-0239
Non-Regulatory

Location: Baton Rouge Water Co.
Scavenger 1610'

Fresh Water Complete Analysis

OBS Well
Sample Date: 07-14-11 @ 1105 hrs.
Received Date: 07-15-11

Parameters - units	Results
pH - s.u.	8.08
Turbidity - NTU	
Color - Apparent	
Conductivity - mS/cm	0.648
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	199.39
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	0.18
Chloride - mg/l	121
Iron - mg/l	1.24
Carbonate - mg/l	<0.01
Bicarbonate - mg/l	34.16
Sulfate - mg/l	5.5
Calcium - mg/l	5.99
Magnesium - mg/l	1.22
Sodium - mg/l	84.72
Fluoride - mg/l	
Phosphate - mg/l	3.08
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkanlinity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	

Attest: Sharon G. Touchet

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 07/18/11

Lab No: LDZ-0240
Non-Regulatory

Location: Baton Rouge Water Co.
Scavenger 1630'

Fresh Water Complete Analysis

OBS Well
Sample Date: 07-14-11 @ 1200 hrs.
Received Date: 07-15-11

Parameters - units	Results
pH - s.u.	7.68
Turbidity - NTU	
Color - Apparent	
Conductivity - mS/cm	2.87
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	1,268.71
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	1.07
Chloride - mg/l	846
Iron - mg/l	0.95
Carbonate - mg/l	<0.01
Bicarbonate - mg/l	31.72
Sulfate - mg/l	<1
Calcium - mg/l	39.74
Magnesium - mg/l	8.18
Sodium - mg/l	498.95
Fluoride - mg/l	
Phosphate - mg/l	3.08
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkanilnity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	

Attest: Sharon G. Touchet

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 07/18/11

Lab No: LDZ-0241
Non-Regulatory

Location: Baton Rouge Water Co.
Scavenger 1650'

Fresh Water Complete Analysis

OBS Well
Sample Date: 07-14-11 @ 1315 hrs.
Received Date: 07-15-11

Parameters - units	Results
pH - s.u.	7.35
Turbidity - NTU	
Color - Apparent	
Conductivity - mS/cm	5.43
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	2,516.20
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	2.01
Chloride - mg/l	1,671
Iron - mg/l	2.34
Carbonate - mg/l	<0.01
Bicarbonate - mg/l	24.40
Sulfate - mg/l	<1
Calcium - mg/l	68.02
Magnesium - mg/l	12.90
Sodium - mg/l	989.28
Fluoride - mg/l	
Phosphate - mg/l	11.47
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkanlinity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	

Attest: Sharon G. Touchet

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 07/18/11

Lab No: LDZ-0242
Non-Regulatory

Location: Baton Rouge Water Co.
Scavenger 1660'

Fresh Water Complete Analysis

OBS Well
Sample Date: 07-14-11 @ 1400 hrs.
Received Date: 07-15-11

Parameters - units	Results
pH - s.u.	7.26
Turbidity - NTU	
Color - Apparent	
Conductivity - mS/cm	5.88
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	2,848.38
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	1.54
Chloride - mg/l	1,834
Iron - mg/l	4.69
Carbonate - mg/l	<0.01
Bicarbonate - mg/l	24.40
Sulfate - mg/l	<1
Calcium - mg/l	52.86
Magnesium - mg/l	8.89
Sodium - mg/l	1,119.88
Fluoride - mg/l	
Phosphate - mg/l	21.70
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkanlinity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	

Attest: Sharon G. Touchet

PETROLEUM LABORATORIES, INC.

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 08/10/11

Lab No: LEA-0215
Non-Regulatory

Location: Baton Rouge Water Co.

Fresh Water Complete Analysis

OBS - 1a
1610'
Sample Date: 08-04-11 @ 1015 hrs.
Received Date: 08-08-11

Parameters - units	Results
pH - s.u.	7.942
Turbidity - NTU	13.6
Color - Apparent	
Conductivity - umhos/cm	467
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	110.41
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	1.08
Chloride - mg/l	67
Iron - mg/l	1.34
Carbonate - mg/l	
Bicarbonate - mg/l	
Sulfate - mg/l	
Calcium - mg/l	
Magnesium - mg/l	
Sodium - mg/l	
Fluoride - mg/l	
Potassium - mg/l	0.75
Phosphate - mg/l	0.85
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkanlinity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	
Arsenic - mg/l	0.004

Attest: Karen F Roy

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company:	Layne Christensen Co. - Prairieville Location 1220 PO Box 1652 Prairieville, LA 70769	Report Date: 08/10/11 Location: Baton Rouge Water Co.	Lab No: LEA-0216 Non-Regulatory
Attn:	Mr. Bruce Duhe		

Fresh Water Complete Analysis

OBS - 1a
1630'
Sample Date: 08-04-11 @ 1115 hrs.
Received Date: 08-08-11

Parameters - units	Results
pH - s.u.	7.471
Turbidity - NTU	2.91
Color - Apparent	
Conductivity - umhos/cm	2,160
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	995.32
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	0.47
Chloride - mg/l	604
Iron - mg/l	1.09
Carbonate - mg/l	
Bicarbonate - mg/l	
Sulfate - mg/l	
Calcium - mg/l	
Magnesium - mg/l	
Sodium - mg/l	
Fluoride - mg/l	
Potassium - mg/l	2.09
Phosphate - mg/l	0.53
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkalinity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	
Arsenic - mg/l	0.0034

Attest: Karen F. Roy

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 08/10/11

Lab No: LEA-0217
Non-Regulatory

Location: Baton Rouge Water Co.

Fresh Water Complete Analysis

OBS - 1a
1650'
Sample Date: 08-04-11 @ 1200 hrs.
Received Date: 08-08-11

Parameters - units	Results
pH - s.u.	7.341
Turbidity - NTU	3.09
Color - Apparent	
Conductivity - umhos/cm	4,940
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	2705.83
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	1.03
Chloride - mg/l	1,642
Iron - mg/l	2.56
Carbonate - mg/l	
Bicarbonate - mg/l	
Sulfate - mg/l	
Calcium - mg/l	
Magnesium - mg/l	
Sodium - mg/l	
Fluoride - mg/l	
Potassium - mg/l	4.44
Phosphate - mg/l	5.85
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkanlinity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	
Arsenic - mg/l	0.008

Attest: Karen F. Roy

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company: Layne Christensen Co. - Prairieville
Location 1220
PO Box 1652
Prairieville, LA 70769

Attn: Mr. Bruce Duhe

Report Date: 08/10/11

Location: Baton Rouge Water Co.

Lab No: LEA-0218
Non-Regulatory

Fresh Water Complete Analysis

OBS - 1a
1660'
Sample Date: 08-04-11 @ 1320 hrs.
Received Date: 08-08-11

Parameters - units	**Results**
pH - s.u.	7.376
Turbidity - NTU	12.4
Color - Apparent	
Conductivity - µmhos/cm	4,960
Calcium Carbonate - mg/l	
Calcium Bicarbonate - mg/l	
Magnesium Carbonate - mg/l	
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	
Sodium Bicarbonate - mg/l	
Sodium Sulfate - mg/l	
Sodium Chloride - mg/l	2500.47
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	0.93
Chloride - mg/l	1,566
Iron - mg/l	4.45
Carbonate - mg/l	
Bicarbonate - mg/l	
Sulfate - mg/l	
Calcium - mg/l	
Magnesium - mg/l	
Sodium - mg/l	
Fluoride - mg/l	
Potassium - mg/l	3.18
Phosphate - mg/l	6.10
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	
"P" Alkanlinity As Calcium Carbonate- mg/l	
"MO" Alkalinity As Calcium Carbonate- mg/l	
Arsenic - mg/l	0.009

Attest: Jason F. Roy

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

PETROLEUM LABORATORIES, INC.

Company: Layne Christensen Co. - Rayne
Location 1067
202 West LA. Ave.
Rayne, LA 70578

Attn: Mr. Bruce Duhe

Report Date: 09/07/11

Lab No: LEB-0033
Non-Regulatory

Location: Baton Rouge Water Co.
Scavenger Well

Fresh Water Complete Analysis

Well EB 918
900 Gallons Sample
Sample Date: 09-02-11
Received Date: 09-06-11

Parameters - units	Results
pH - s.u.	8.276 *
Turbidity - NTU	3.38
Color - Apparent	<5
Conductivity - ms/cm	7.79
Calcium Chloride - mg/l	643.61
Calcium Carbonate - mg/l	<0.01
Calcium Bicarbonate - mg/l	71.28
Magnesium Carbonate - mg/l	<0.01
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	<0.01
Sodium Bicarbonate - mg/l	<0.01
Sodium Sulfate - mg/l	<0.01
Sodium Chloride - mg/l	3489.07
Calcium Sulfate - mg/l	1.42
Magnesium Chloride - mg/l	89.92
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	1.05
Chloride - mg/l	2,596
Iron - mg/l	0.48
Carbonate - mg/l	<0.1
Bicarbonate - mg/l	53.68
Sulfate - mg/l	1
Calcium - mg/l	250
Magnesium - mg/l	23.0
Sodium - mg/l	1371.77
Fluoride - mg/l	
Potassium - mg/l	5.07
Phosphate - mg/l	0.03
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	718.92
"P" Alkanlinity As Calcium Carbonate- mg/l	<0.01
"MO" Alkalinity As Calcium Carbonate- mg/l	44.00
Arsenic - mg/l	<0.010

* pH @ 26 °C

Attest: [signature]

PETROLEUM LABORATORIES, INC.

333 East Kaliste Saloom Road
Lafayette, Louisiana 70508
337-234-7414

Company: Layne Christensen Co. - Rayne
Location 1067
202 West LA. Ave.
Rayne, LA 70578

Attn: Mr. Bruce Duhe

Report Date: 09/07/11

Lab No: LEB-0034
Non-Regulatory

Location: Baton Rouge Water Co.
Scavenger Well

Fresh Water Complete Analysis

Well EB 918
1880 Gallons Sample
Sample Date: 09-02-11
Received Date: 09-06-11

Parameters - units	Results
pH - s.u.	8.066 *
Turbidity - NTU	2.62
Color - Apparent	<5
Conductivity - ms/cm	7.43
Calcium Chloride - mg/l	589.37
Calcium Carbonate - mg/l	<0.01
Calcium Bicarbonate - mg/l	77.76
Magnesium Carbonate - mg/l	<0.01
Magnesium Bicarbonate - mg/l	
Sodium Carbonate - mg/l	<0.01
Sodium Bicarbonate - mg/l	<0.01
Sodium Sulfate - mg/l	<0.01
Sodium Chloride - mg/l	3358.46
Calcium Sulfate - mg/l	1.42
Magnesium Chloride - mg/l	83.39
Nitrogen As Nitrate - mg/l	
Silica As Silicon Dioxide - mg/l	
Manganese - mg/l	0.99
Chloride - mg/l	2,477
Iron - mg/l	0.34
Carbonate - mg/l	<0.10
Bicarbonate - mg/l	58.56
Sulfate - mg/l	1
Calcium - mg/l	232
Magnesium - mg/l	21.3
Sodium - mg/l	1320.42
Fluoride - mg/l	
Potassium - mg/l	4.88
Phosphate - mg/l	<0.010
Total Dissolved Solids- mg/l	
Total Hardness Calcium Carbonate- mg/l	666.97
"P" Alkanlinity As Calcium Carbonate- mg/l	<0.10
"MO" Alkalinity As Calcium Carbonate- mg/l	48.00
Arsenic - mg/l	<0.010

* pH @ 25 °C

Attest:

Appendix E - Progress Park Well Spinner Flow Meter Test Results

SCAVENGER WELL 18820757

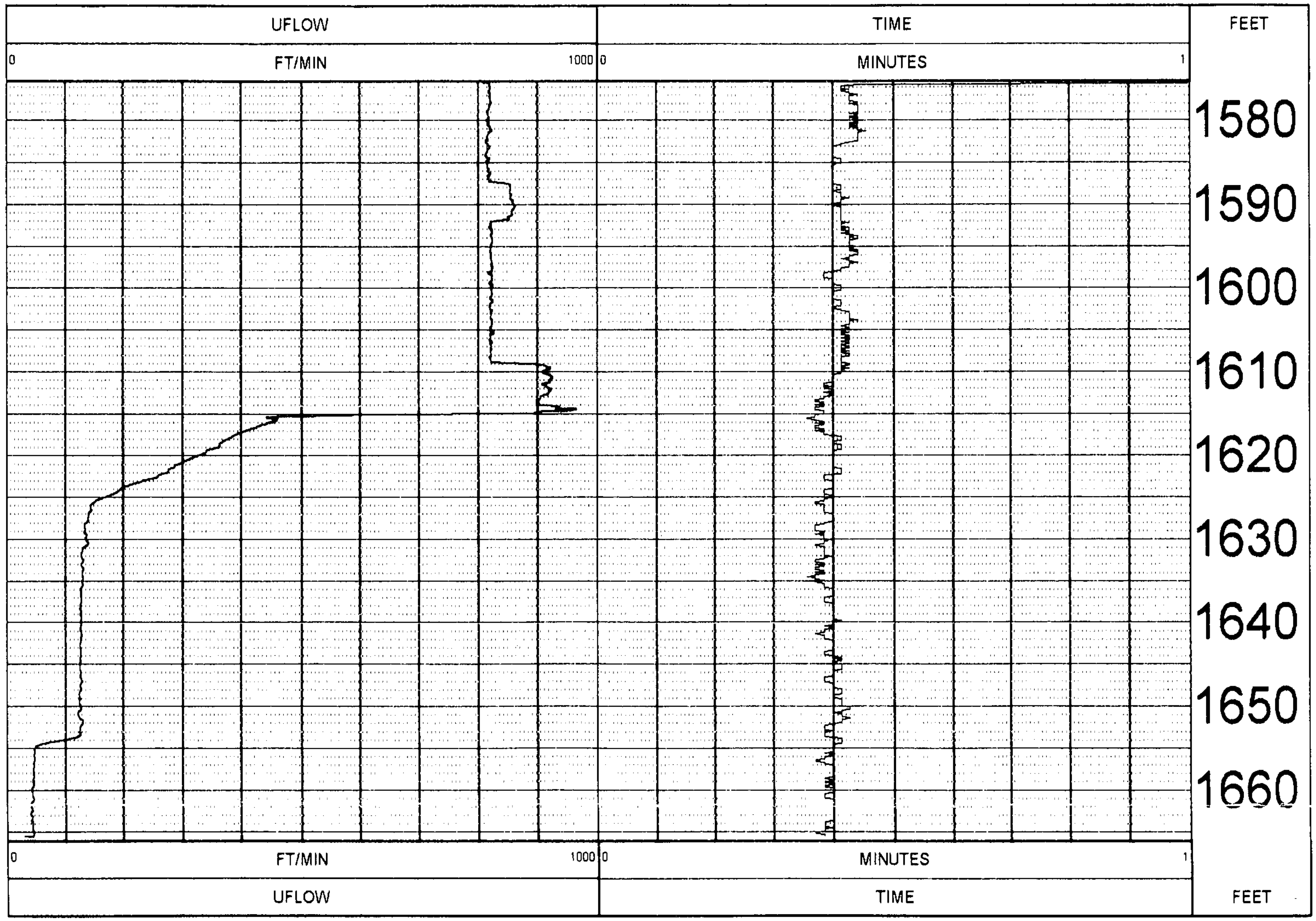
COMPANY	BATON ROUGE WATER CO.
WELL	SCAVENGER WELL 18820757
FIELD	
COUNTY	E BATON ROUGE
STATE	LOUISANA

OTHER SERVICES:
NONE
NONE
NONE

LOCATION	
SECTION	
TOWNSHIP	
RANGE	
API NO.	
UNIQUE WELL ID.	

PERMANENT DATUM		ELEVATION KB:	NONE
LOG MEASURED FROM:	G.L	ELEVATION DF:	
DRL MEASURED FROM:	G.L	ELEVATION GL:	

DATE	07/13/11
DEPTH DRILLER	1665
BIT SIZE	6
LOG TOP	1575.30
LOG BOTTOM	1665.80
CASING OD	6
CASING BOTTOM	
CASING TYPE	
BOREHOLE FLUID	0
RM TEMPERATURE	0
MUD RES	0
MUD WEIGHT	
WITNESSED BY	
RECORDED BY	MARK RUTH
REMARKS 1	FLOW LOG 2
REMARKS 2	


UFLOW
FT/MIN
0
1000
TIME
MINUTES
0
1
FEET
1580
1590
1600
1610
1620
1630
1640
1650
1660
FT/MIN
0
1000
MINUTES
0
1
UFLOW
TIME
FEET

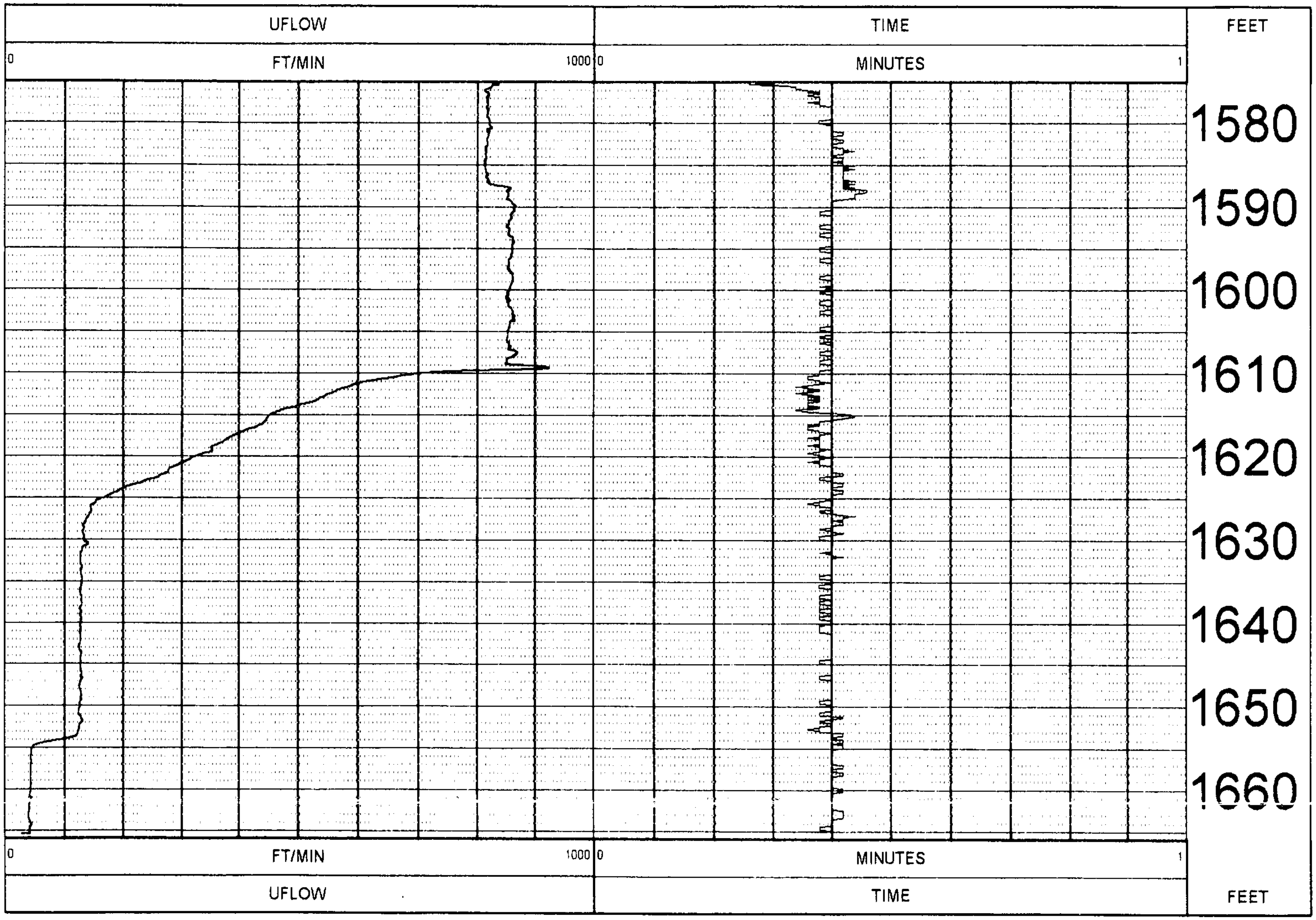
SCAVENGER WELL 18820757

COMPANY	: BATON ROUGE WATER CO.	OTHER SERVICES:
WELL	: SCAVENGER WELL 18820757	NONE
FIELD	:	NONE
COUNTY	: E BATON ROUGE	NONE
STATE	: LOUISANA	

LOCATION	:
SECTION	:
TOWNSHIP	:
RANGE	:
API NO.	:
UNIQUE WELL ID.	:

PERMANENT DATUM	:	ELEVATION KB:	NONE
LOG MEASURED FROM:	G.L	ELEVATION DF:	
DRL MEASURED FROM:	G.L	ELEVATION GL:	

DATE	: 07/13/11
DEPTH DRILLER	: 1665
BIT SIZE	: 6
LOG TOP	: 1575.00
LOG BOTTOM	: 1665.60
CASING OD	: 6
CASING BOTTOM	:
CASING TYPE	:
BOREHOLE FLUID	: 0
RM TEMPERATURE	: 0
MUD RES	: 0
MUD WEIGHT	:
WITNESSED BY	:
RECORDED BY	: MARK RUTH
REMARKS 1	: FLOW LOG 3
REMARKS 2	:


UFLOW
0
FT/MIN
1000
TIME
0
MINUTES
1
FEET
1580
1590
1600
1610
1620
1630
1640
1650
1660
0
FT/MIN
1000
0
MINUTES
1
UFLOW
TIME
FEET