Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

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Hydraulic Testing of the Lost Lake Aquifer Near Recovery Well RWM 8

K. L. Dixon

September 11, 2019

SRNL-STI-2019-00476, Revision 0

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Prepared for
U.S. Department of Energy

SRNL-STI-2019-00476
Revision 0

Keywords: *Environmental Hydraulic Conductivity*

Retention: *Permanent*

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REVIEWS AND APPROVALS

AUTHORS:

____

K. L. Dixon, SRNL Geosciences Date

TECHNICAL REVIEW:

____

D. G. Jackson, SRNL Geosciences Date

APPROVAL:

____

N. V. Halverson, Manager Date
Manager, SRNL Geosciences

____

B. J. Kramer, EC&ACP Engineering Date

____

J. E. Cardoso-Neto, EC&ACP Project Management Date

EXECUTIVE SUMMARY

At the time of installation (circa 1984), recovery well RWM 8 was configured with four 10-ft screens that spanned the Lost Lake Aquifer Zone (LLAZ) with a continuous gravel pack. The lowermost screen of RWM 8 was installed below the LLAZ in uncontaminated sediments. In order to better target volatile organic contamination in the LLAZ, a permanent packer was installed May 2019 to isolate the lowermost screen. The pump was relocated above the packer so that groundwater would primarily be extracted from the three uppermost screens. Based on the lithology of the LLAZ, there was concern that with the isolation of the lower screen, the well may not produce adequate water. Therefore, with the reconfiguration of RWM 8, testing was undertaken to determine the performance characteristics of the well and, to estimate aquifer hydraulic properties. Testing was conducted with the other wells in the recovery network operating at or near steady-state conditions so that any observed aquifer response could be attributed to testing at RWM 8.

A step-drawdown test was conducted to determine the specific capacity, well efficiency, and head loss coefficients for RWM 8. Based on the results of the step-drawdown test, the specific capacity of RWM 8 was determined to be approximately 5.6 gpm/ft of drawdown. At the end of the constant rate aquifer pumping test, the specific capacity of RWM 8 was determined to be about 4.5 gpm/ft (~ 8.8 ft drawdown at ~40 gpm). Well efficiency was inversely related to pumping rate and decreased from 90% to 80% over a pumping range of approximately 20 to 45 gpm. The aquifer head loss coefficient was determined to be 1.087 $ft/ft^3/min$ (0.15 ft/gpm) and the well loss coefficient was determined to be 0.05 min^2/ft^5 (0.006 ft/gpm^2). These coefficients are comparable to those determined at the time of installation (0.12 ft/gpm and 0.009 ft/gpm^2; Geraghty and Miller, 1987).

The head loss coefficients were used to estimate the maximum pumping capacity of RWM 8 using the top of the middle screen as the limit for drawdown. The maximum pumping capacity of RWM 8 in its new configuration was estimated to be about 95 gpm. With the water level at the top of the middle screen, there would be about 27 ft of head above the pump (which is placed 200 ft below top of casing). RWM 8 currently operates at a flow rate of about 40 gpm with water level

drawdown to the middle of the uppermost screen, which is about 45 ft above the pump. Based on these findings, it appears that isolation of the lowermost screen did not adversely affect the hydraulic performance of RWM 8. These results suggest that the pumping rate could be increased if necessary, to meet performance objectives.

Aquifer response to pumping at RWM 8 was measured in several nearby observation wells screened within the LLAZ. Drawdown data were collected during the step-drawdown test and during a 10-day constant rate pumping test. Recovery data were also collected following shutdown of RWM 8. These data were used to evaluate aquifer hydraulic properties using the Hantush-Jacob (1955, 1961a, and b) leaky aquifer model as implemented in the computer code AQTESOLV. The average transmissivity (T) of the aquifer based on all testing was determined to be 0.95 ft^2/min with a standard deviation of 0.10 ft^2/min. The average storativity of the aquifer was determined to be 0.002 with a standard deviation of 0.0054. Using an average aquifer thickness of 64.1 ft, the hydraulic conductivity of the LLAZ near RWM 8 was determined to be 21.2 ft/day with a standard deviation of 2.3 ft/day. For comparison, Dixon (2018a) reported an average transmissivity of 0.816 ft^2/day (K = 21.4 ft/day, b =55 ft) near RWM018. Geraghty and Miller (1987) reported a transmissivity of 1.49 ft^2/min (K = 38.9 ft/day, b =73 ft) for RWM 8 at the time of installation. Aquifer compaction due to the reduction in hydraulic head associated with operation of the recovery well network may explain the difference between transmissivity and storativity values calculated in this evaluation compared to values measured by Geraghty and Miller (1987) at the start of pump and treat operations.

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~	approximate, approximately
EC&ACP	Environmental Compliance and Area Completion Projects
CBCU	Crouch Branch Confining Unit
GCCU	Green Clay Confining Unit
gpm	gallons per minute
HWMF	Hazardous Waste Management Facility
LLAZ	Lost Lake Aquifer Zone
PCE	Perchloroethylene
PVC	Polyvinyl Chloride
SCDHEC	South Carolina Department of Health and Environmental Control
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
TCE	Trichloroethylene
UIC	Underground Injection Control Permit
VOC	Volatile Organic Compound

1.0 Introduction

Groundwater beneath the M-Area HWMF is contaminated with chlorinated ethenes including trichloroethylene (TCE) and tetrachloroethylene (PCE). SRS operates a network of recovery wells designed to hydraulically contain and capture the high concentration VOC plume in the Lost Lake Aquifer Zone (LLAZ) (Figure 1). The recovery wells are connected to the M-1 Air Stripper and the system is permitted by the South Carolina Department of Environmental Control (SCDHEC) to operate at a total flow of 610 gpm.

RWM 8, which is one of ten operational recovery wells, has historically operated at a flow rate of approximately 40 gpm. RWM 8 was installed with four separate 10-ft screens that spanned the LLAZ with a continuous gravel pack spaced as shown in Figure 2. The three uppermost screens are located within the LLAZ whereas the deepest screen is located within the middle sand of the Crouch Branch Confining Unit (CBCU). Area Closure Projects (ACP) installed a permanent packer in May 2019 to isolate the lowest screen from the pump with the goal being to target the zone of highest concentration in the LLAZ. ACP expressed concern that a substantial portion of the flow from RWM 8 comes from the lower screen. With this screen isolated from service, flow from the well may be below the desired operational envelope for the well.

The reconfiguration of RWM 8 presented an opportunity to re-evaluate the performance characteristics of the well. Following placement of the packer and relocation of the pump, the well was redeveloped. To assess the effects of eliminating the lower screen, a step-drawdown test was planned. The purpose of this test was to establish new baseline well performance properties including specific capacity, well efficiency, and well loss coefficients. Data from the step-drawdown testing was also used to estimate a maximum pumping rate for RWM 8 under the new configuration. The setup for the step-drawdown test facilitated a subsequent constant rate aquifer pumping test aimed at determining aquifer hydraulic properties. Properties estimated for the LLAZ included transmissivity and storativity. Following shutdown of RWM 8, recovery data were also collected and analyzed to estimate aquifer properties.

This report discusses the hydrologic tests conducted following the reconfiguration of RWM 8. The information provided in this report may serve as input to subsequent updates to the groundwater flow and contaminant transport model for A/M Area.

2.0 Hydrologic Test Methods and Objectives

The objectives of this testing were to determine the specific capacity, efficiency, and pumping capacity of RWM 8 in its new configuration and, to estimate aquifer hydraulic properties including transmissivity and storativity. These objectives were met by conducting a step-drawdown test and a constant rate aquifer pumping test. Testing at RWM 8 was conducted with the other wells in the recovery network operating at near steady-state conditions. This was done so that any observed aquifer response could be attributed to testing at RWM 8. The following sections describe the test methods used to meet the project objectives.

2.1 Review of Previous Aquifer Testing Near RWM 8

At the time of installation (circa 1984) of the recovery well network, several step-drawdown and aquifer pumping tests were conducted in order to estimate the performance properties of the recovery wells and the hydraulic properties of the LLAZ. The results of this work are presented by Geraghty and Miller (1987) and are summarized in Table 3. A transmissivity of 1.49 ft^2/min (K = 38.9 ft/day, b =73 ft) and storativity of 0.001 was reported for RWM 8. A step-drawdown test was also conducted to determine specific capacity and well efficiency. The specific capacity of RWM 8 was estimated to be 4.3 gpm/ft with an estimated maximum pumping rate of 115 gpm. Well efficiency was estimated to be 75% at 45 gpm.

In 2018, aquifer testing was conducted at RWM018 (Dixon, 2018a). Transmissivity near RWM018 was estimated to be 0.816 ft^2/min and storativity was estimated to be 0.00047. From the results of this testing, specific capacity of RWM 8 was estimated to be 4.0 gpm/ft with an estimated maximum pumping rate between 85 and 100 gpm (Dixon,2018b). Aquifer testing was also conducted near RWM 3 and RWM 5 (Dixon, 2018a). Transmissivity was estimated to be 0.992 ft^2/min and storativity was estimated to be 0.001. Further away at RWM 16, Hiergessell (1992) conducted testing of the LLAZ and found the transmissivity to range from 0.782 to 0.899 ft^2/min and storativity to range from 0.0005 to 0.0007.

Operation of the recovery well network began in the mid-1980s and the system has treated over 6.8 billion gallons of contaminated groundwater (Dixon, 2018a). The more recent estimates of transmissivity are slightly more than half the value at the start of system operations (RWM 8, 1.49 ft^2/min). This has been attributed to compaction of LLAZ sediments due to long term dewatering caused by operation of the recovery well network (Dixon, 2018a). Since operation of the recovery well network began, there has been a decrease in hydraulic head across the area of nearly 30 ft.

2.2 Hydrogeologic Conceptual Model

The location of RWM 8 and nearby monitoring wells is shown in Figure 3 and a generalized north-south geologic cross-section is given in Figure 4. A detailed description of the hydrostratigraphic setting in A/M area is provided by (Aadland and Bledsoe, 1990) and details pertinent to this test are summarized here. The generalized hydrostratigraphy pertinent to the study area consists of: 1) the M-Area aquifer zone (MAAZ), 2) the Green Clay Confining Zone (GCCZ), 3) the Lost Lake Aquifer Zone (LLAZ), and 4) the upper clay of the Crouch Branch Confining Unit (UC_CBCU).

The MAAZ is the water table aquifer and it overlies the GCCZ. The GCCZ ranges in thickness from about 5 to 8 ft across the RWM 8 study area with an average thickness of 6.1 ft. The GCCZ serves as the leaky confining layer in the subsequent analysis of RWM 8 pumping test data. The LLAZ ranges in thickness from about 51 to 73 ft across the study area with an average thickness of 64.1 ft. The LLAZ is bounded on the bottom by the UC_CBCU which is estimated to have a thickness of about 24.3 ft in the study area. The LLAZ can be divided into an upper (ULLAZ) and lower (LLLAZ) portion based on contaminant stratification. Near RWM 8, the LLAZ is comprised of a series of interbedded sands and clays with the sand of the ULLAZ having a higher percentage of silt than sands compared to the LLLAZ. The recovery wells are generally screened across both intervals.

The average layer thicknesses obtained from the generalized geologic cross-sections were used to establish the boundaries applied in the subsequent analyses for RWM 8.

2.3 Step Drawdown Pumping Tests

Step-drawdown tests are conducted to assess well performance and to identify the optimum pumping rate for a recovery well. A step-drawdown test is conducted as a series of short duration, constant-rate pumping tests consisting of a minimum of three steps that are of approximate equal duration (Kruseman and Ritter, 1994). This approach was used for a step-drawdown test conducted at RWM 8. The test was conducted at flow rates of about 20, 29, and 45 gpm. Drawdown in RWM 8 was monitored with a vented, data logging pressure transducer. Each individual pumping period lasted for approximately 100 minutes. Following the completion of the final step, pumping was terminated. Recovery of the pumping well was monitored, and these data were included in the analysis.

The specific capacity of a pumping well is defined as discharge per unit drawdown (Q/s) as measured in the pumping well (Kruseman and Ritter, 1994). It provides an indicator of initial well performance and is useful in quantifying subsequent declines in performance over time that may arise as pumping progresses. The specific capacity of RWM 8 was assessed by plotting drawdown as a function of discharge for each pumping interval for both step-drawdown tests.

Head loss coefficients for RWM 8 were determined by comparing discharge, Q, to the ratio of drawdown and pumping rate (s/Q). The ratio s/Q is defined as specific discharge. Jacob (1946) defined the relationship between well loss and drawdown as follows:

$$\boldsymbol{s_t = BQ + CQ^2} \qquad (2\text{-}1)$$

where s_t is the total drawdown, BQ is the laminar aquifer head loss, and CQ^2 is the turbulent well head loss. A plot of specific discharge as a function of pumping rate provides the coefficients B and C (Figure 5).

Well efficiency is the ratio of the theoretical drawdown (without well losses) expected in a pumping well and the observed drawdown in the well. Efficiency is calculated directly using this ratio if estimates of transmissivity and storativity are available. Efficiency may also be calculated from Equation 2-1 as follows:

$$\boldsymbol{E = \frac{BQ}{BQ + CQ^2} * 100} \qquad (2\text{-}2)$$

This is simply the aquifer head loss divided by the total head loss in the well. Simplifying Equation 2-2 gives:

$$\boldsymbol{E = \frac{100}{1 + \frac{CQ}{B}}} \qquad (2\text{-}3)$$

where B is the aquifer head loss coefficient and C is the well loss coefficient.

2.4 Aquifer Pumping Test

Following the step-drawdown test, a constant rate aquifer pumping test was conducted at RWM 8. Water was pumped from RWM 8 at a relatively constant flow rate of about 40 gpm for the duration of the test activities. During the pumping test at RWM 8, the system configuration (recovery wells in use and pumping rates) was maintained as close to constant as possible so that the measured aquifer response could be attributed entirely to RWM 8.

An extensive monitoring well network exists near RWM 8 and several of those wells are screened in the LLAZ. A subset of these wells were used to monitor aquifer response due to pumping at RWM 8 (Figure 3 and Table 1). Figure 2 shows a plot of screen intervals for RWM 8 compared to the monitoring wells chosen for this test.

For both the step-drawdown and aquifer pumping tests, vented, data logging pressure transducers were used to monitor aquifer response. Pressure transducers are submerged below the water column in the well and record the pressure due to the weight of the water column above the transducer. Changes in water level result in a change in pressure sensed by the transducer. The pressure measured by the transducer was recorded in feet of water above the sensor. These data were converted to elevation using the initial water level in the well (manually recorded using an electric water level tape) and the reference elevation for the top of casing. Barometric pressure was monitored continuously near RWM 8 (In-Situ, Inc., Barotroll).

RWM 8 is equipped with a direct reading flow meter and pressure gauge. In addition to the LCD display, the flow meter outputs a 4-20ma signal for logging pumping rate. For the RWM 8 aquifer pumping test, pumping rate was recorded using a 4-20ma data logger (Onset Inc., HOBO U12-008).

2.5 Analysis of Pumping Test Data

The LLAZ is considered a leaky confined aquifer being bounded by the GCCZ at the top and UC_CBCU on the bottom. The GCCZ in M-Area has been described as discontinuous (Marine and Bledsoe, 1984) and identified as a leaky confining layer (Hiergesell, 1992). Therefore, the method chosen for analyzing the bulk of data from the aquifer pumping tests considers leakage from an overlying confining layer. Initial estimates of aquifer properties were made using the Theis solution for confined aquifers (Theis, 1935).

The Theis equation is given as:

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

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

$$\boldsymbol{u = \frac{r^2 S}{4Tt}} \qquad (2\text{-}5)$$

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

Equation 2-4 is typically abbreviated as:

$$\boldsymbol{s = \frac{Q}{4\pi T}W(u)} \qquad (2\text{-}6)$$

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

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

$$\boldsymbol{W(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2*2!} + \frac{u^3}{3*3!} - \frac{u^4}{4*4!} + \cdots} \qquad (2\text{-}7)$$

Assumptions associated with the Theis method include:

- The aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness

- the pumping well is fully or partially penetrating
- flow to the pumping well is horizontal when the pumping well is fully penetrating
- aquifer is nonleaky confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of a pumping well is very small so that storage in the well can be neglected

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

$$\boldsymbol{s = \frac{Q}{4\pi T} W\left(u,\ \frac{r}{B}\right)} \tag{2-8}$$

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

$$\boldsymbol{W\left(u,\ \frac{r}{B}\right) = \int_u^\infty \frac{1}{y} e^{\left\{-y-\frac{\left(\frac{r}{B}\right)^2}{4y}\right\}} dy} \tag{2-9}$$

where u is defined by Equation 2-5 and:

$$\boldsymbol{\frac{r}{B} = \frac{r}{\sqrt{\left(\frac{Tb'}{k'}\right)}}} \tag{2-10}$$

where r is the radial distance from the pumping well, S is the storativity, t is time, b' is the confining layer thickness, and k' is the permeability of the confining layer. The assumptions of the Hantush-

Jacob solution are the same as those for the Theis solution with the exception of leakage from the confining layer.

Transmissivity is converted to hydraulic conductivity with following equation:

$$\boldsymbol{K} = \frac{\boldsymbol{T}}{\boldsymbol{b}} \tag{2-11}$$

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

The Hantush-Jacob method was implemented using a computer code named AQTESOLV (Duffield, 2007). Parameters used in the Hantush-Jacob model for leaky aquifers include the saturated thickness of the aquifer, the thickness of the overlying confining layer, and the zone of penetration of the pumping and observation wells. The hydrogeologic conceptual model described in Section 2.2 was used to establish the layer thicknesses used in AQTESOLV.

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

2.6 Barometric Effects

Fluctuations in barometric pressure can impact water level measurements in a confined aquifer even when vented pressure transducers are used because the well serves as a direct connection to the atmosphere for the aquifer. Any change in atmospheric pressure is immediately transmitted to the aquifer through the opening provided by the well screen. For wells near the pumping well, barometric effects may be minimal in comparison to the head change induced by pumping. However, for wells further away where the head change in the aquifer is smaller, barometric effects can be significant. Data collected during testing at RWM 8 were corrected for barometric effects.

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

$$\Delta w_{cor} = w_{obs} - B_{eff} * \Delta BP \tag{2-12}$$

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

$$B_{eff} = \frac{\Delta wl}{\Delta BP} \tag{2-13}$$

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

Water level measurements were made in the observation wells for several weeks prior to the RWM 8 aquifer test to establish baseline hydraulic conditions. These data were used to calculate the barometric efficiency of each well which was then used to correct the water level measurements collected during the test.

3.0 Results

Well performance and aquifer testing were conducted at RWM 8. The test methods employed are described in Section 2.0. Pretest monitoring began at most observation wells on or around March 27, 2019. Step-drawdown testing began at RWM 8 on May 20, 2019 following installation of the permanent packer and completion of associated redevelopment activities. Aquifer testing began on May 28, 2019 and active monitoring of water levels continued through June 27, 2019. Figure 6 shows a plot of aquifer response at RWM 8 over the course of test activities. Testing was conducted with the other wells in the recovery network operating at near steady-state conditions so that any observed aquifer response could be attributed to testing at RWM 8. The following sections provide a discussion and analysis of the results obtained from the hydrologic testing.

3.1 Barometric Efficiency

Prior to the RWM 8 aquifer pumping test, water level measurements were recorded for several weeks to evaluate the effects of barometric pressure. Barometric efficiencies were calculated for each observation well using the methods described in Section 2.6. Calculated barometric efficiencies for RWM 8 and nearby monitoring wells are presented in Table 4. Values ranged from 56 to 82% with an average value of 71%. Except where noted, these efficiencies were used to correct water level data prior to analysis using the methods outlined in Section 2.6. Figure 7 and Figure 8 show a subset of the hydrologic data collected for wells MSB 5B and MSB 106B. The effects of barometric pressure changes are evident as uncorrected water levels trend inversely with barometric pressure. These plots also show the effectiveness of the corrections made to the data as the corrected water levels show negligible correlation to barometric pressure.

3.2 Step Drawdown Testing

A step-drawdown test was conducted on RWM 8 on 5/20/2019 to determine well performance characteristics. The test consisted of three steps lasting approximately 100 minutes each with pumping rates of 20, 29, and 45 gpm. Drawdown was monitored in the pumping well and several nearby observation wells. Data from the pumping well were used to estimate well performance properties including specific capacity, well loss coefficients, and well efficiency. Due to the short duration of the step-drawdown test and the magnitude of drawdown observed in the pumping well, it was unnecessary to make corrections for barometric effects. Total drawdown observed in the pumping well was 8 ft whereas the maximum barometric fluctuation recorded over the duration of the test was less than 0.2 ft. The specific capacity of RWM 8 was calculated at the end of each pumping interval and the results are presented in Table 4. The specific capacity at the end of the final pumping period was determined to be 5.6 gpm/ft. At the time of installation, the specific capacity of RWM 8 was estimated to 5.3 gpm/ft at 45 gpm (Geraghty and Miller, 1987) and more recently 4.0 gpm/ft prior to installation of the packer (Dixon 2018b).

Specific discharge (inverse of specific capacity) was determined for each pumping period and plotted as a function of pumping rate (Figure 10). The slope and intercept of this plot were used to estimate the Jacob (1947) head loss coefficients, B and C. Well efficiency was calculated for each pumping period using Equation (2-3) and plotted as a function of pumping rate (Figure 11). The efficiency of RWM 8 at the end of the final pumping period was estimated to be 80%. This is comparable to previous estimates of efficiency for RWM 8 (Dixon 2018a and b, Geraghty and Miller, 1987) and suggest that RWM 8 is an efficient well. The head loss coefficients were used in Equation (2-1) to predict drawdown at the end of each pumping period for the step-drawdown test (Figure 12). Good agreement is noted between the predicted and observed drawdown.

The head loss coefficients, B and C, were also used to calculate drawdown as function of pumping rate (Figure 12). Because RWM 8 is an efficient well, well losses are small in comparison to aquifer losses. Figure 13 provides a plot of predicted drawdown in RWM 8 as a function of pumping rate (based on Equation (2-1) along with the placements for the middle and upper screen zones. Under the current operating conditions (~40 gpm), the water level in RWM 8 is in the middle of the upper screen. A pumping rate of 98 gpm would place the water level near the top of the middle screen which would be about 27 feet above the pump. This suggests that RWM 8 has additional capacity above the current pumping rate of 40 gpm.

3.3 RWM 8 Aquifer Test

Figure 6 shows a plot of operating history and water level measurements recorded at RWM 8 over the course of all test activities. Following the step-drawdown test, the aquifer was allowed to recover to near pre-test conditions. The RWM 8 constant rate aquifer pumping test commenced on 5/28/2019 at 11:19 AM as shown in Figure 6. On 6/9/2019, a nearby lightning strike caused an interruption in electrical power and the entire recovery well network shut down. This caused water levels to rise above pre-test values in RWM 8 and all observation wells ending the constant rate aquifer pumping test. Data selected for analysis covered the time period of 5/28/2019 11:19AM through 6/7/2019 11:19AM resulting in a 10-day test period.

Table 7 provides the maximum observed drawdown in RWM 8 and each of the observation wells. Wells to the south and east of the pumping well showed the greatest response. These wells include MSB 5B, MSB 13A, and MSB 62B. Wells located to the north of RWM 8 include MSB 10B, MSB 12B, MSB 17A, MSB 101B, and MSB 106B. To varying degrees, these well are influenced by RWM018 and, response to pumping at RWM 8 was generally less than observed in the wells to the south and east. Water levels measured at MSB 17A and MSB101B were on the same order of magnitude as barometric pressure changes during the RWM 8 testing. Therefore, these two wells were not considered further in this analysis. Figure 14 provides the steady-state drawdown due to pumping at RWM 8.

3.4 Analysis of LLAZ Hydraulic Properties

Aquifer response due to pumping at RWM 8 was monitored during the step-drawdown testing and during the constant rate aquifer test that followed. As mentioned in Section 3.3, due to a system wide shut down, the constant rate test was terminated at 10 days. The system was later returned to service and RWM 8 was subsequently turned off. This provided the opportunity to monitor the recovery of water levels in several wells. Therefore, three sets of data were analyzed to estimate LLAZ hydraulic properties: 1) step-drawdown data, 2) constant rate aquifer test data, and 3) recovery data after RWM 8 was shut down (while the remaining recovery wells remained operational).

Analysis of the data was conducted using AQTESOLV based on the hydrogeologic model described in Section 2.2. Based on previous testing of the LLAZ (Section 2.1), the Hantush-Jacob (1961) leaky, confined model was chosen for the analysis. The pumping well, RWM 8, was assumed to act as a fully penetrating well. With the installation of a permanent packer, RWM 8 is now comprised of three 10-ft well screens. These screens are spaced as shown in Figure 2. Although the well is not fully screened over the thickness of the aquifer, the assumption of full penetration is reasonable since all the observation wells are a distance from the pumping well greater than 1.5 times the aquifer thickness (Kruseman and de Ridder, 1994).

Data for the testing was collected on 1-minute intervals. A high sampling rate was selected due to the unpredictable operating conditions for the recovery well network. This resulted in the collection of thousands of data points for each observation well. As such, each data set was filtered using AQTESOLV to improve computational efficiency and, to improve the quality of fit to the observed data. Pumping rates were collected on the same frequency and were also filtered.

3.4.1 Analysis of Step-Drawdown Test Data

Data collected during the step-drawdown test from wells MSB 5B, MSB 13A, MSB 62B, and MSB 106B were analyzed to estimate aquifer hydraulic properties. The results of these analyses are presented in Table 8 and Figure 16 through Figure 19. Transmissivity values ranged from 0.82 to 1.2 ft^2/min with an average value of 0.941 ft^2/min (σ =0.134 ft^2/min). Transmissivity was converted to hydraulic conductivity using Equation 2-10. Hydraulic conductivity ranged from 18.5 to 26.2 ft/day with an average value of 22.6 ft/day (b = 64.1 ft). Storativity values ranged from 0.0001 to 0.0121 with an average value of 0.0026 (σ = 0.0053). Leakage values (r/B) ranged from 0.0009 to 0.3048 with an average value of 0.1530 (σ = 0.1227). Equation (2-11) was solved for K' which is the hydraulic conductivity of the overlying confining layer (GCCZ). Values for K' ranged from 0.001 to 0.014 ft/day with an average value of 0.005 ft/ day.

3.4.2 Analysis of Constant Rate Aquifer Test Data

Data collected during the constant rate aquifer test from wells MSB 5B, MSB 10B, MSB 12B, MSB 13A, MSB 62B, and MSB 106B were analyzed to estimate aquifer hydraulic properties. The results of these analyses are presented in Table 9 and Figure 20 through Figure 25. Transmissivity values ranged from 0.72 to 1.04 ft^2/min with an average value of 0.94 ft^2/min (σ =0.117 ft^2/min). Hydraulic conductivity ranged from 16.1 to 23.4 ft/day with an average value of 22.1 ft/day (b = 64.1 ft). Storativity values ranged from 0.0001 to 0.0184 with an average value of 0.0034 (σ =0.0074). Leakage values (r/B) ranged from 0.0637 to 0.7593 with an average value of 0.3098 (σ = 0.2965). The hydraulic conductivity of the overlying confining layer (GCCZ), K', ranged from 0.0001 to 0.0340 ft/day with an average value of 0.0004 ft/ day.

Derivative analysis was used to identify the flow regime and aquifer type based on the results of the constant rate aquifer test. The derivative of the drawdown type curve for each observation well is presented in Figure 20 through Figure 25. The shape of the derivative curve for each well is consistent with a leaky, confined aquifer with infinitely acting radial flow (Duffield, 2007). At the end of the constant rate aquifer pumping test, the specific capacity of RWM 8 was estimated to be 4.5 gpm/ft.

3.4.3 Analysis of Recovery Data following Cessation of Pumping at RWM 8

Data collected during the recovery test from wells MSB 5B, MSB 13A, MSB 62B, and MSB 106B were analyzed to estimate aquifer hydraulic properties. The results of these analyses are presented in Table 10 and Figure 26 through Figure 29. Transmissivity values ranged from 0.91 to 1.01 ft^2/min with an average value of 0.96 ft^2/min (σ =0.0473 ft^2/min). Hydraulic conductivity ranged from 20.4 to 22.9 ft/day with an average value of 21.5 ft/day (b = 64.1 ft). Storativity values ranged from 0.0001 to 0.0004 with an average value of 0.0002 (σ =0.0001). Leakage values (r/B) ranged from 0.0758 to 0.3659 with an average value of 0.1619 (σ = 0.1462). The hydraulic conductivity of the overlying confining layer (GCCZ), K' ranged from 0.0002 to 0.0009 ft/day with an average value of 0.0005 ft/ day.

3.4.4 Summary of Hydraulic Properties

Best estimate aquifer properties were determined by averaging the results from the step-drawdown test, the constant rate aquifer pumping test, and the recovery test (Table 11). The average transmissivity (T) of the aquifer based on all testing was determined to be 0.95 ft^2/min with a standard deviation of 0.10 ft^2/min. The average storativity of the aquifer was determined to be 0.002 with a standard deviation of 0.0054. Using an average aquifer thickness of 64.1 ft, the hydraulic conductivity of the LLAZ near RWM 8 was determined to be 21.2 ft/day with a standard deviation of 2.3 ft/day, which is comparable to a clean sand (Freeze and Cherry, 1979). The average hydraulic conductivity of the overlying confining layer (GCCZ), K', was determined to be 0.004 ft/day with a standard deviation of 0.009 ft/ day, which is indicative of silt/clay (Freeze and Cherry, 1979).

These results are comparable to those determined by Dixon (2018a) and Hiergessell (1992) which are presented in Table 3. Geraghty and Miller (1987) reported a transmissivity of 1.49 ft^2/min (K = 38.9 ft/day, b =73 ft) for RWM 8 at the time of installation (circa 1984). Aquifer compaction due to the reduction in hydraulic head (~30 ft) associated with operation of the recovery well network may explain the difference between transmissivity and storativity values calculated in this evaluation compared to values measured by Geraghty and Miller (1987) at the start of pump and treat operations.

4.0 Conclusions

A permanent packer was recently installed RWM 8 to isolate the lowermost screen from the other screens. The pump was relocated above the packer so that groundwater would only be extracted from the three uppermost screens. This was done to better target volatile organic contamination within the LLAZ. With the reconfiguration of RWM 8, testing was undertaken to determine the performance characteristics of the well and, to estimate aquifer hydraulic properties. Testing at RWM 8 was conducted with the other wells in the recovery network operating at near steady-state conditions. This was done so that any observed aquifer response could be attributed to testing at RWM 8.

A step-drawdown test was undertaken to determine the specific capacity, well efficiency, and head loss coefficients. Based on the results of the step-drawdown test, the specific capacity of RWM 8 was determined to be approximately 5.6 gpm/ft of drawdown. Well efficiency was inversely related to pumping rate and decreased from 90% to 80% over a pumping range of approximately 20 to 45 gpm. The aquifer head loss coefficient was determined to be 1.087 ft/ft^3/min (0.15 ft/gpm) and the well loss coefficient was determined to be 0.05 min^2/ft^5 (0.006 ft/gpm^2). These coefficients are comparable to those determined at the time of installation (0.12 ft/gpm and 0.009 ft/gpm^2).

The head loss coefficients were used to estimate the maximum pumping capacity of RWM 8 using the top of the middle screen as the limit for drawdown. The maximum pumping capacity of RWM 8 in its new configuration was estimated to be about 95 gpm. With the water level at the top of the middle screen, there would be about 27 ft of head above the pump (which is placed 200 ft below top of casing). RWM 8 currently operates at a flow rate of about 40 gpm. This puts the water level in the middle of the uppermost screen, which is about 45 ft above the pump. Therefore, the current pumping rate is well within the capability of RWM 8.

Aquifer response to pumping at RWM 8 was measured in several nearby observation wells screened within the LLAZ. Drawdown data were collected during the step-drawdown test and during a 10-day constant rate pumping test. Recovery data were also collected following a shutdown of RWM 8. These data were used to evaluate aquifer hydraulic properties using the Hantush-Jacob (1955, 1961a, and b) leaky aquifer model as implemented in the computer code AQTESOLV. The average transmissivity (T) of the aquifer based on all testing was determined to be 0.95 ft^2/min with a standard deviation of 0.10 ft^2/min. The average storativity of the aquifer was determined to be 0.002 with a standard deviation of 0.0054. Using an average aquifer thickness of 64.1 ft, the hydraulic conductivity of the LLAZ near RWM 8 was determined to be 21.2 ft/day with a standard deviation of 2.3 ft/day. For comparison, Dixon (2018a) reported an average transmissivity of 0.816 ft^2/day (K = 21.4 ft/day, b =55 ft) near RWM018. Geraghty and Miller (1987) reported a transmissivity of 1.49 ft^2/min (K = 38.9 ft/day, b =73 ft) for RWM 8 at the time of installation. Aquifer compaction due to the reduction in hydraulic head associated with operation of the recovery well network may explain the difference between transmissivity and storativity values calculated in this evaluation compared to values measured by Geraghty and Miller (1987) at the start of pump and treat operations.

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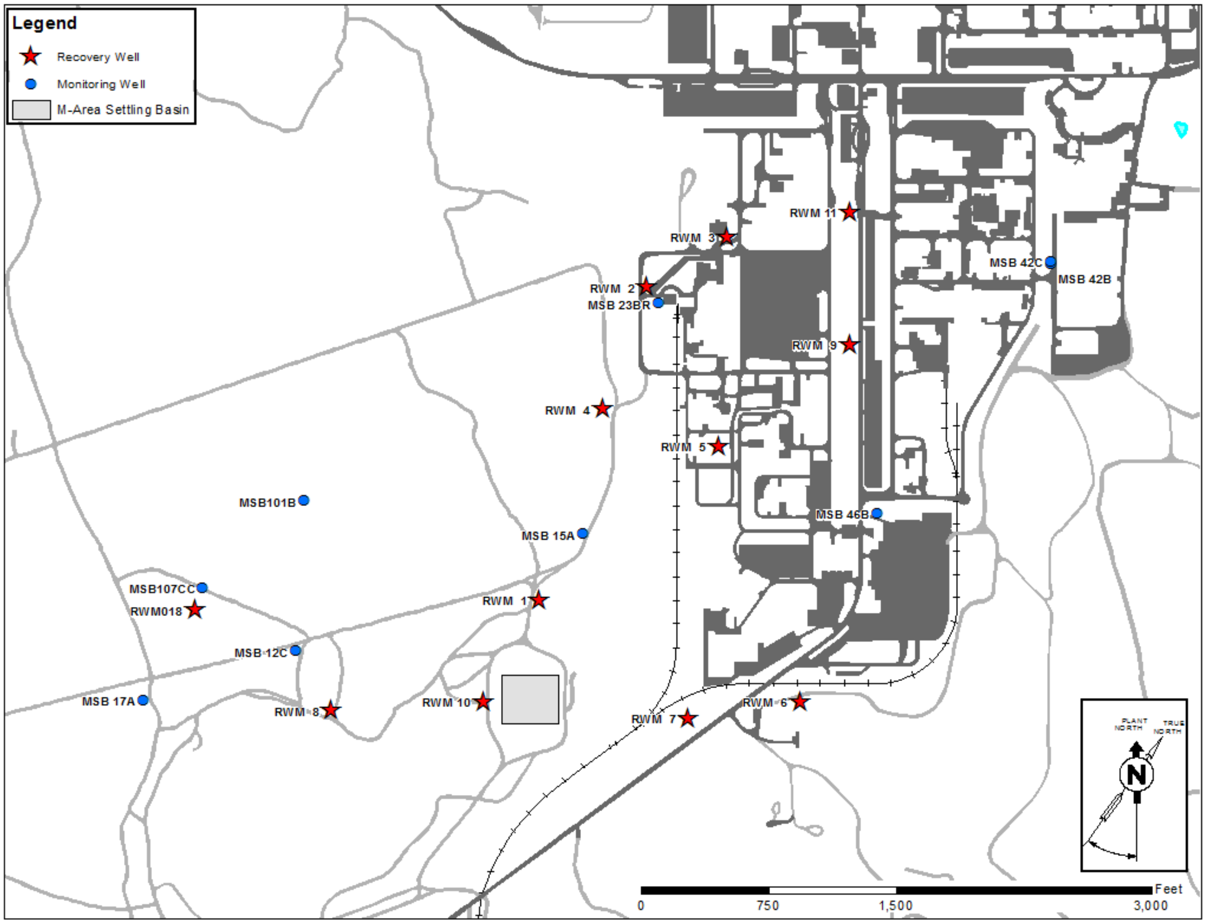

Figure 1. Location of Recovery Wells.

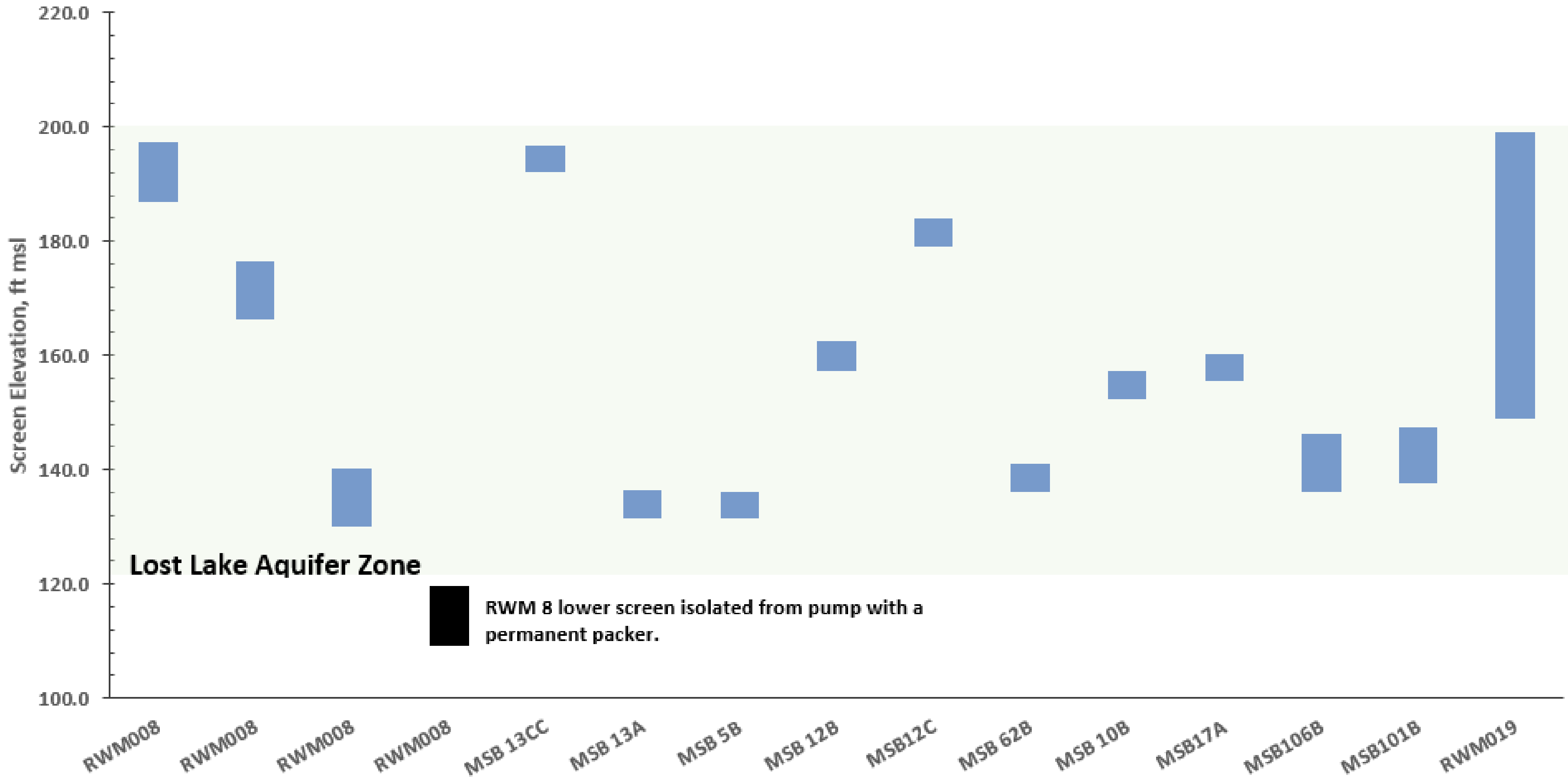

Figure 2. Screen Elevations for RWM 8 Aquifer Test Wells

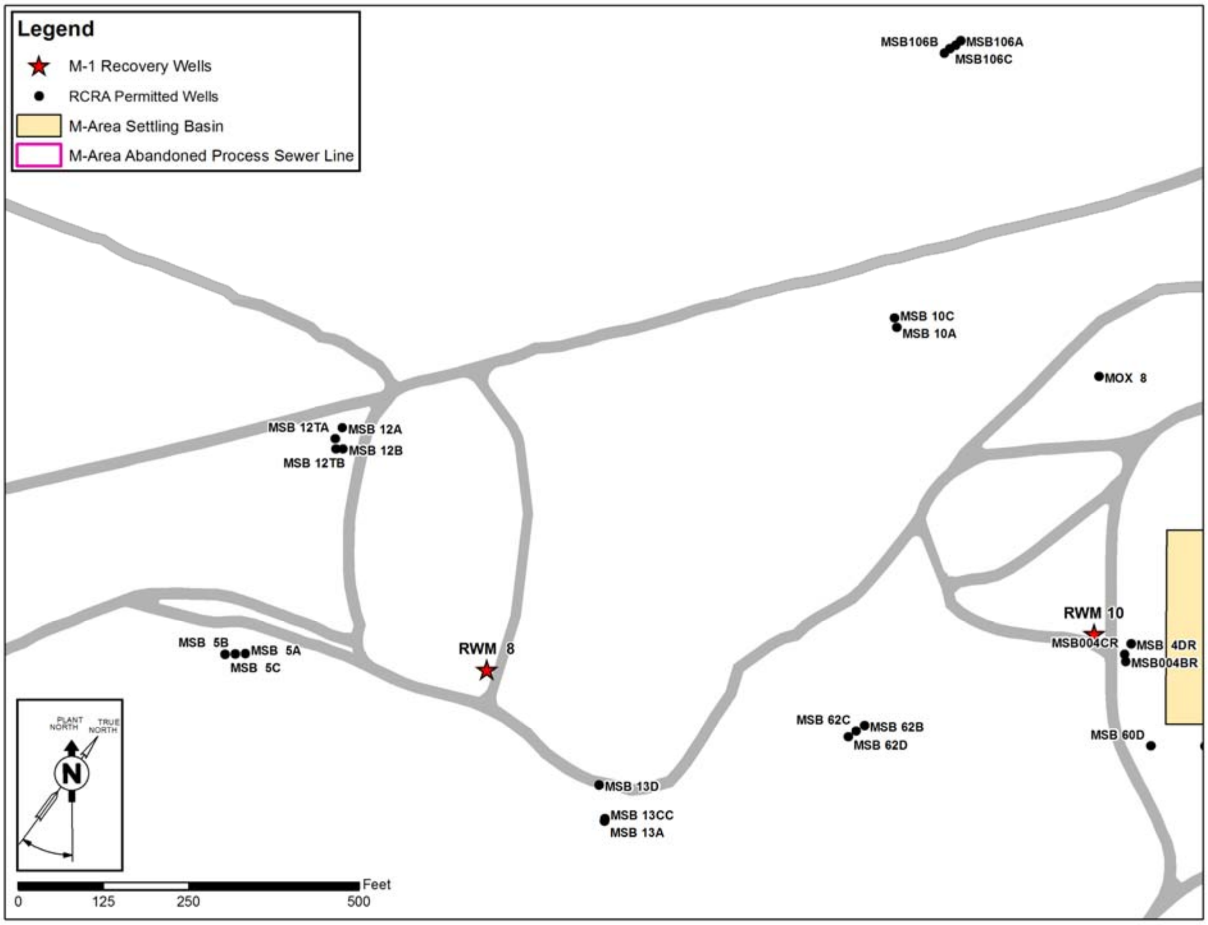

Figure 3. Location of Recovery Well RWM 8 and Nearby Monitoring Wells.

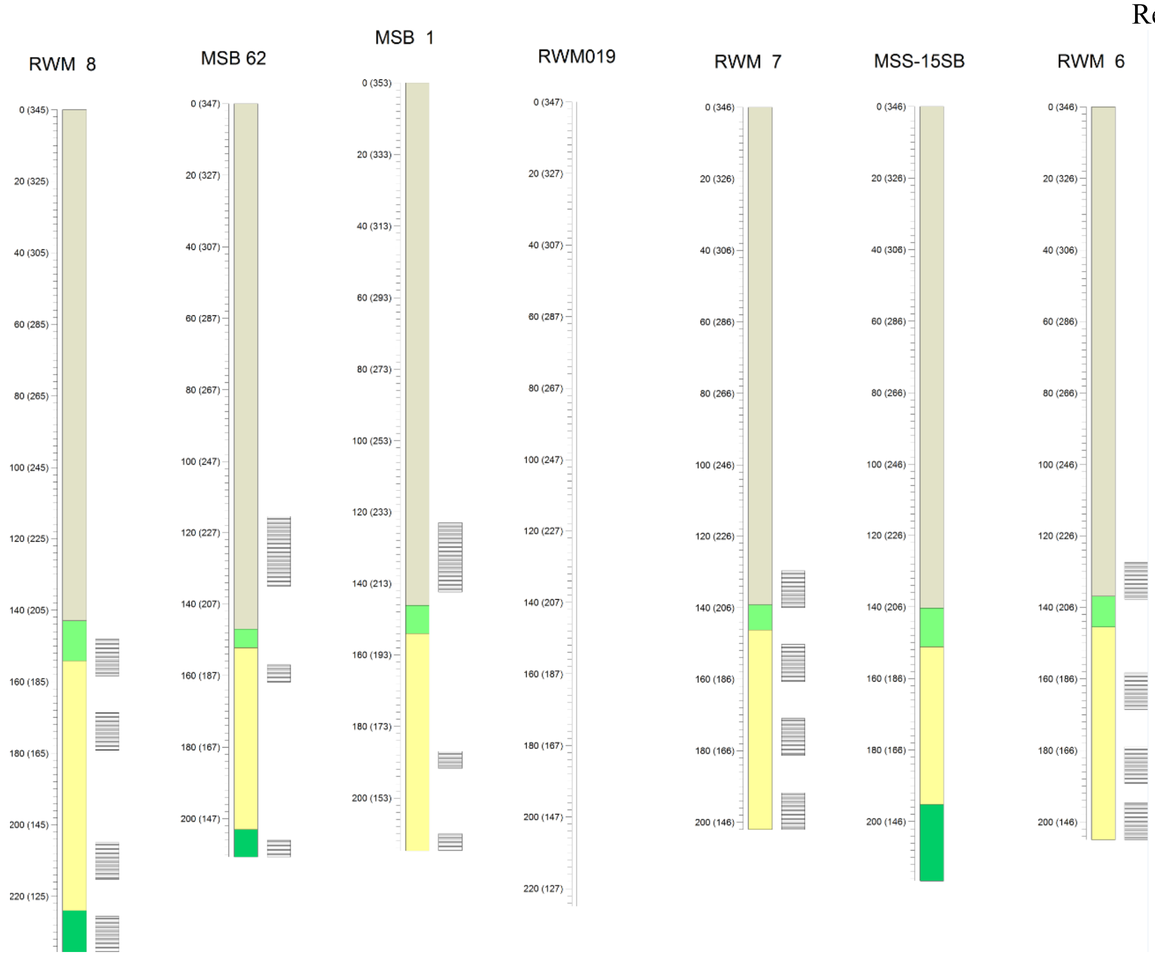

Figure 4: Generalized Lithologic Cross Section Near RWM 8

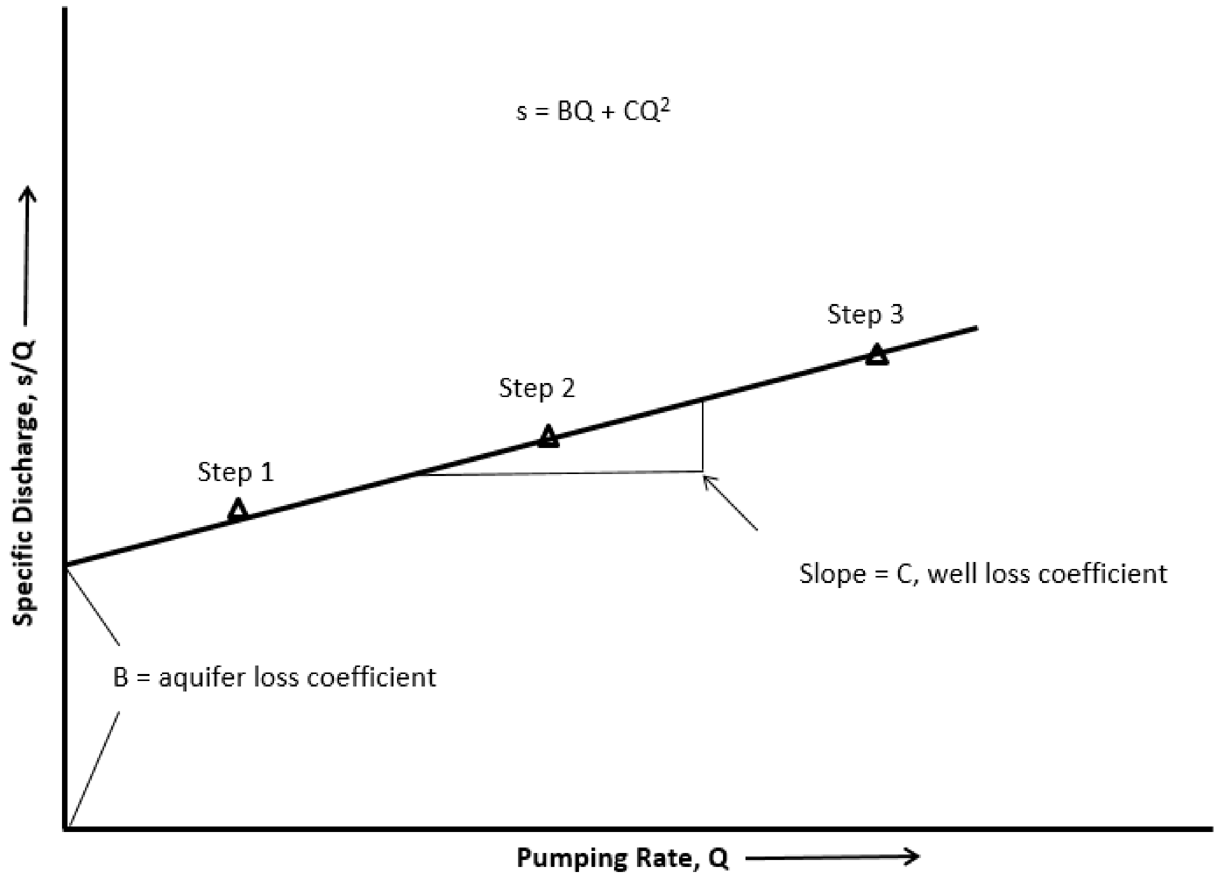

Figure 5: Plot for Calculating Formation Loss Coefficient B and Well Lose Coefficient C from Step Drawdown Tests (adapted from Spane and Newcomer, 2007).

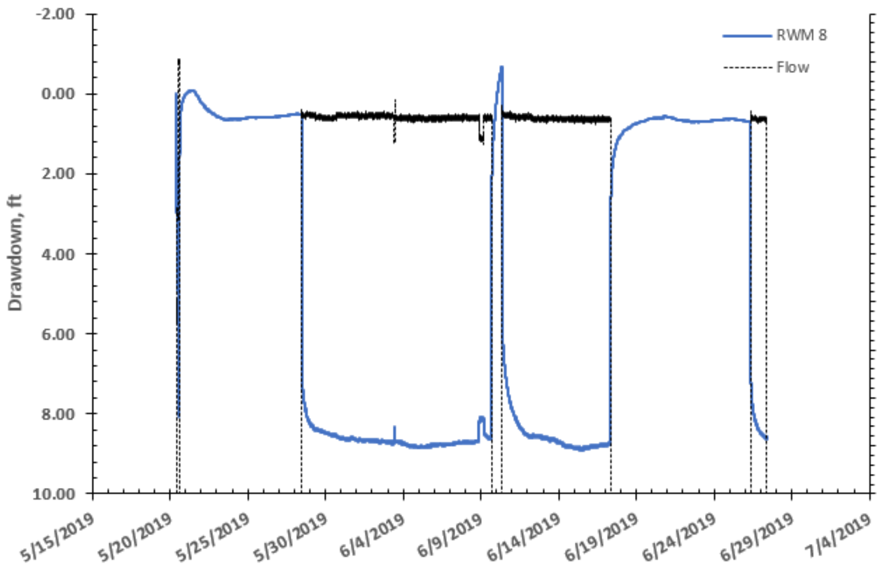

Figure 6. Drawdown at RWM 8 Due to Test Activities

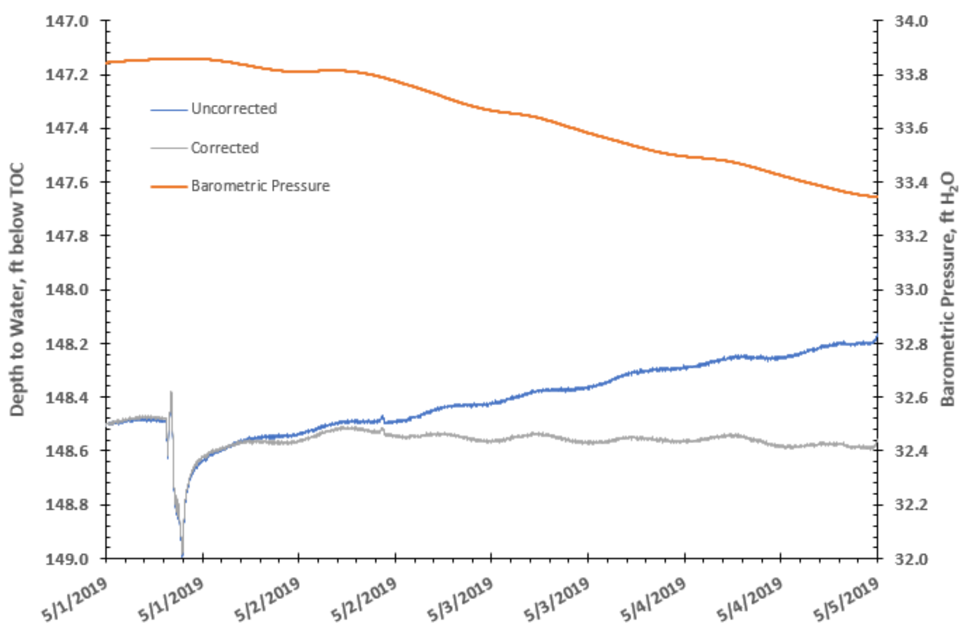

Figure 7: Effect of Barometric Efficiency Corrections to Water Level Data from MSB5B.

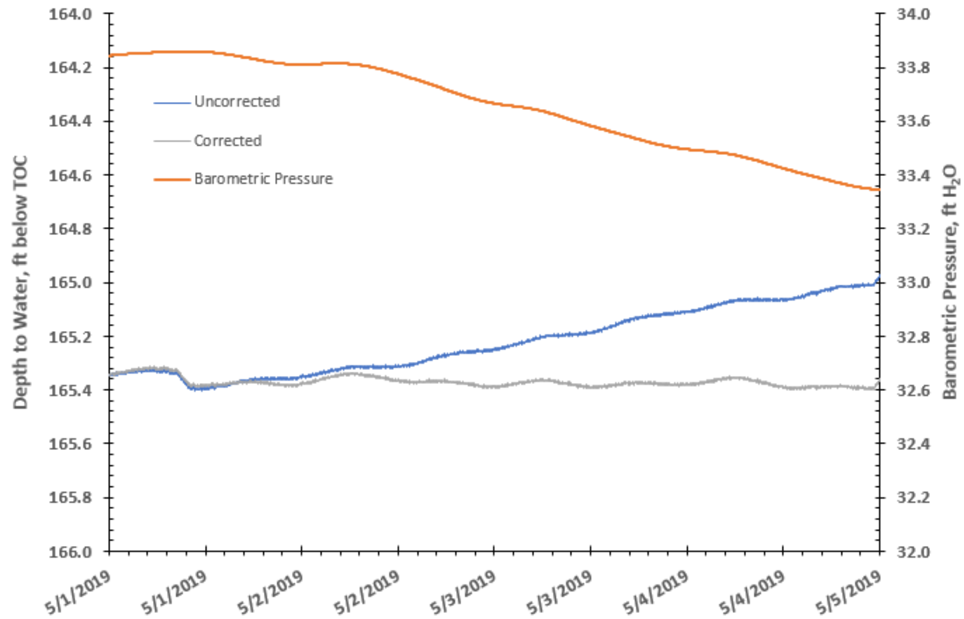

Figure 8: Effect of Barometric Efficiency Corrections to Water Level Data from MSB106B.

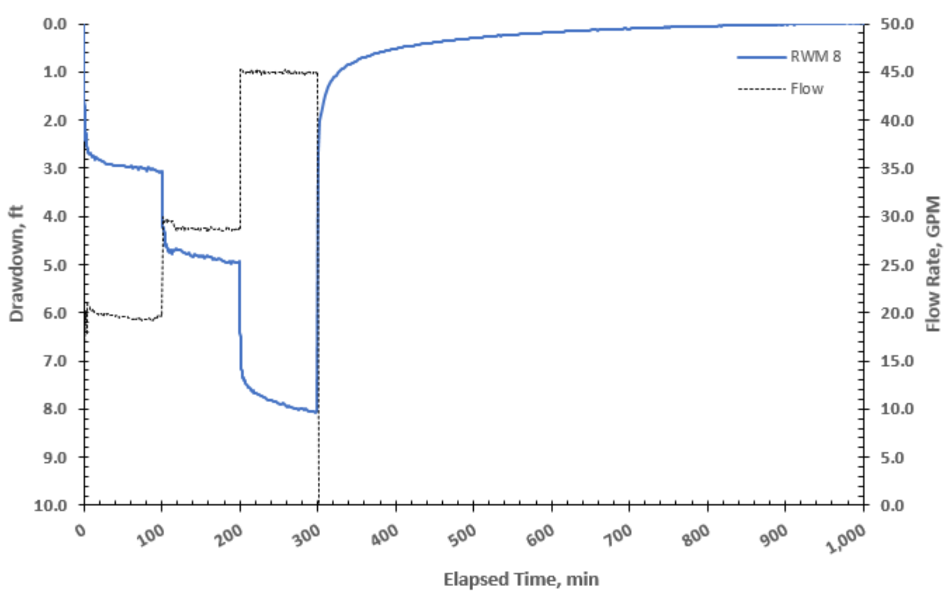

Figure 9. Drawdown as a Function of Time for RWM 8 Step Test

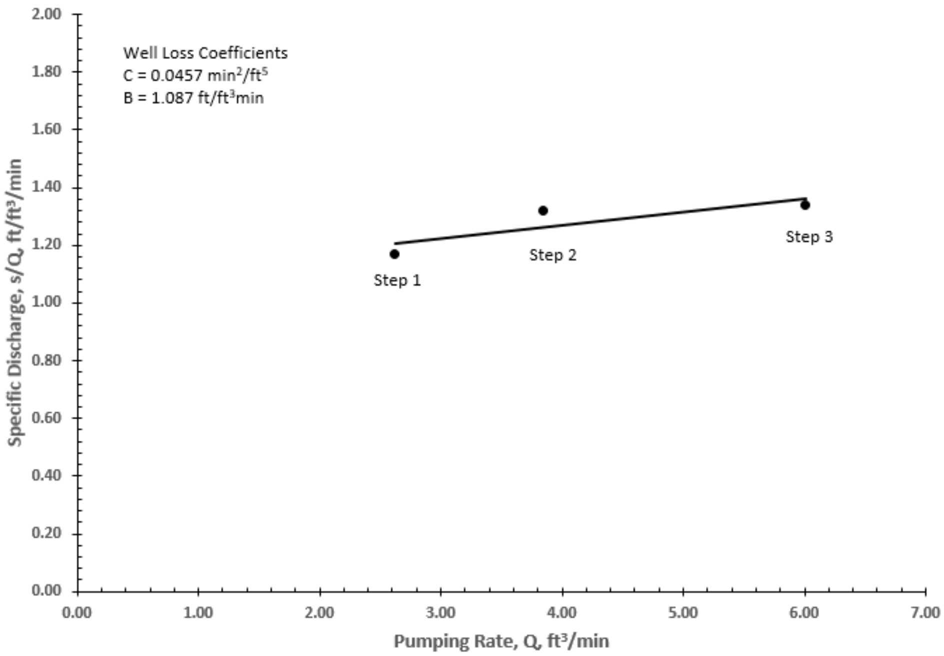

Figure 10. Specific Discharge as a Function of Pumping Rate for RWM018

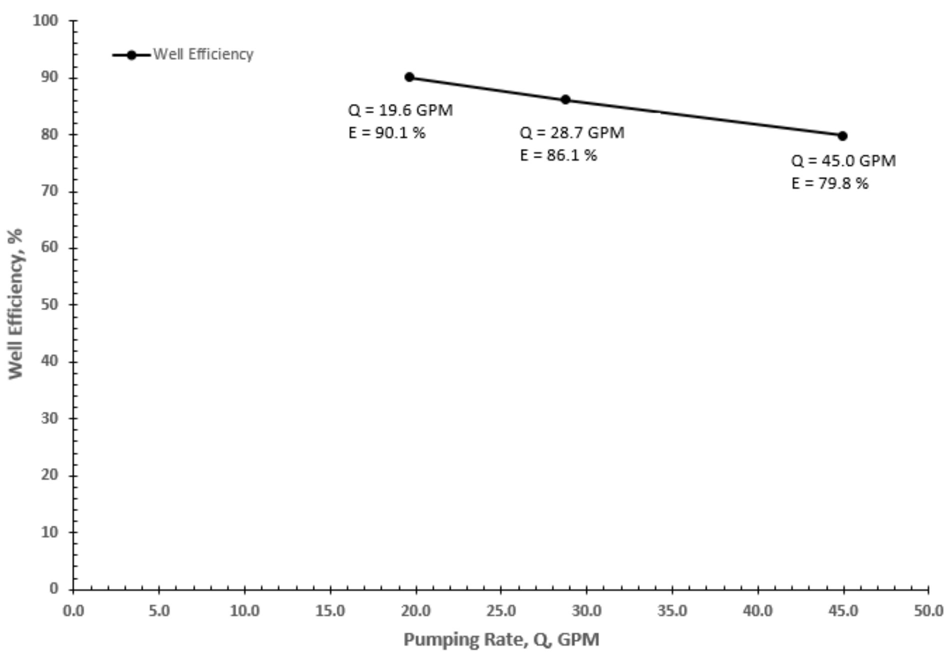

Figure 11. Well Efficiency as a Function of Pumping Rate for RWM 8

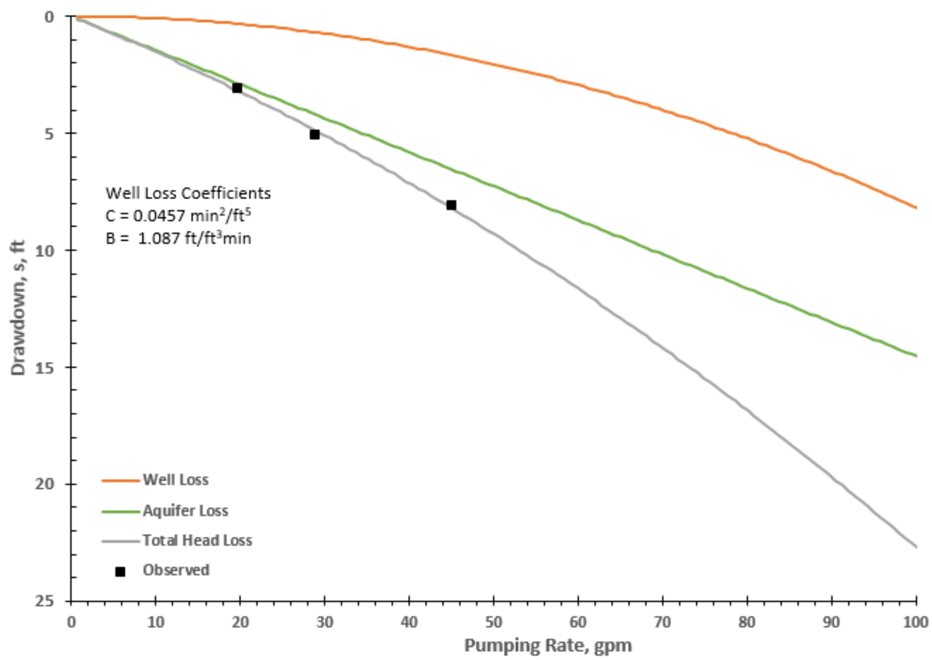

Figure 12. Head Loss Plot for Step-Drawdown Test at RWM 8

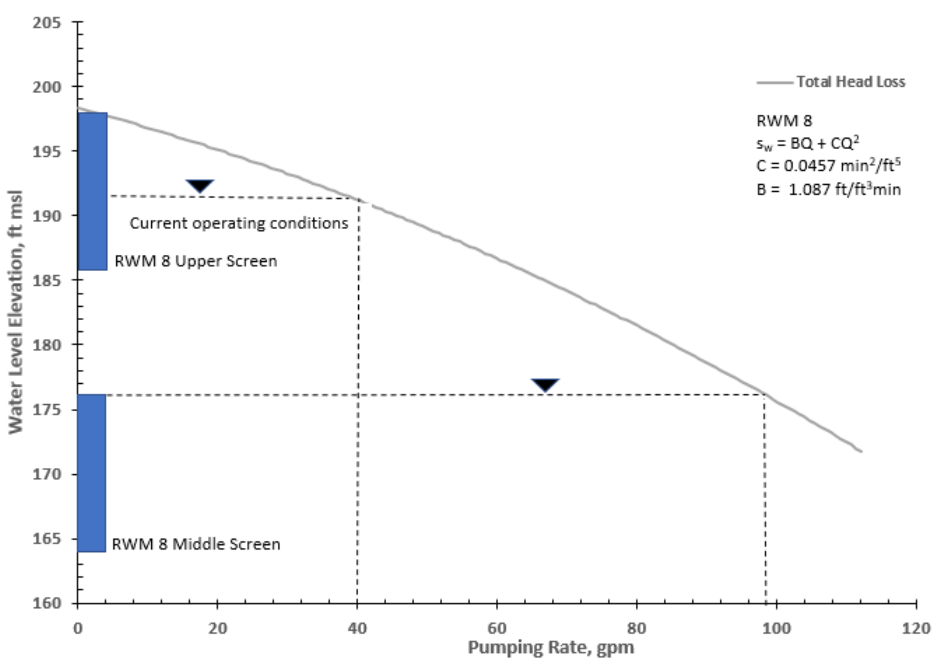

Figure 13. Head Loss Plot for RWM 8

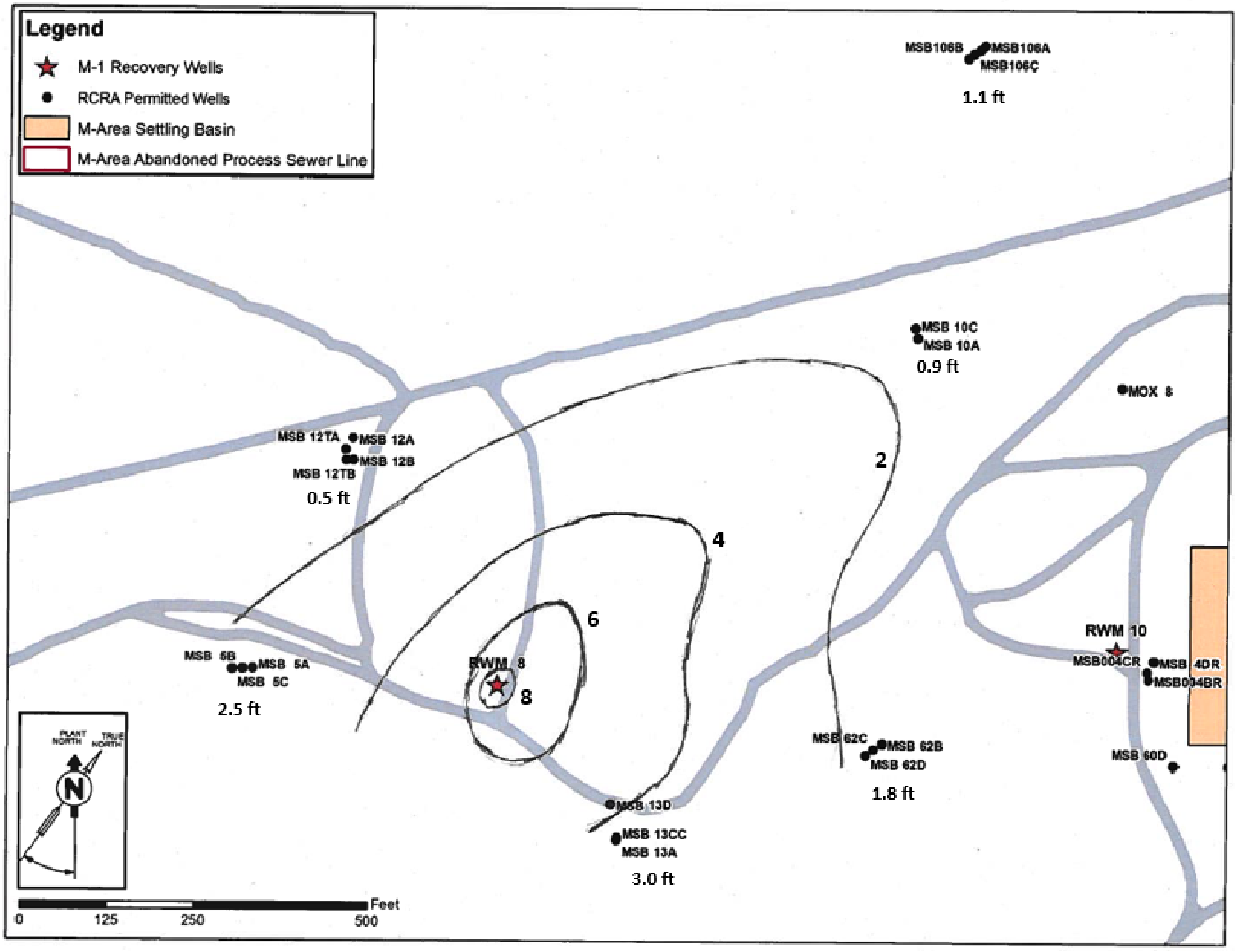

Figure 14. Steady State Drawdown in the LLAZ due to RWM 8 (Q~40 gpm)

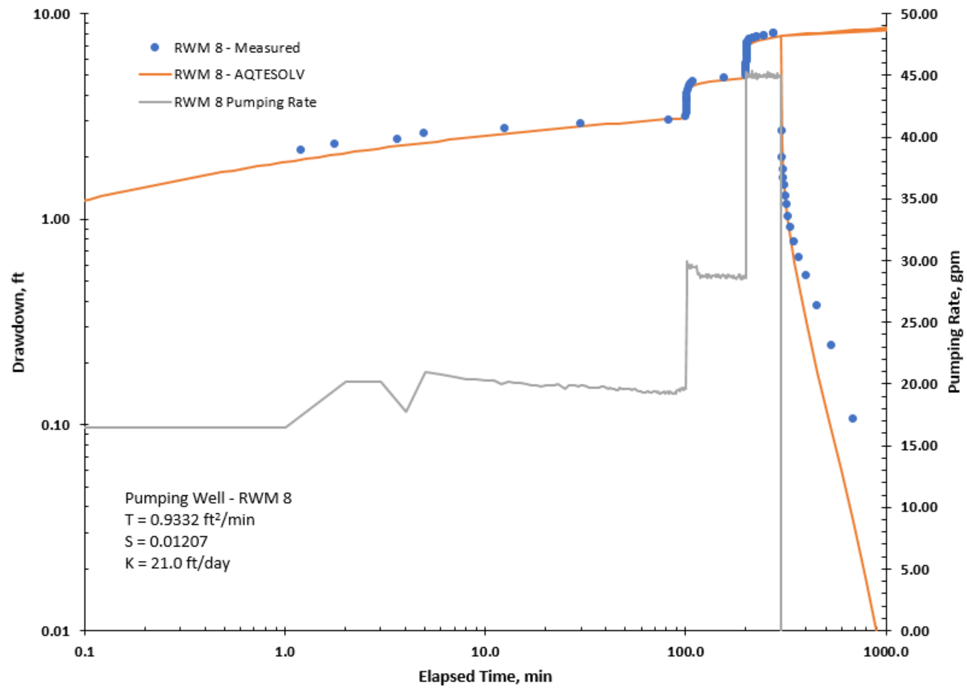

Figure 15. Step Test Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for RWM 8.

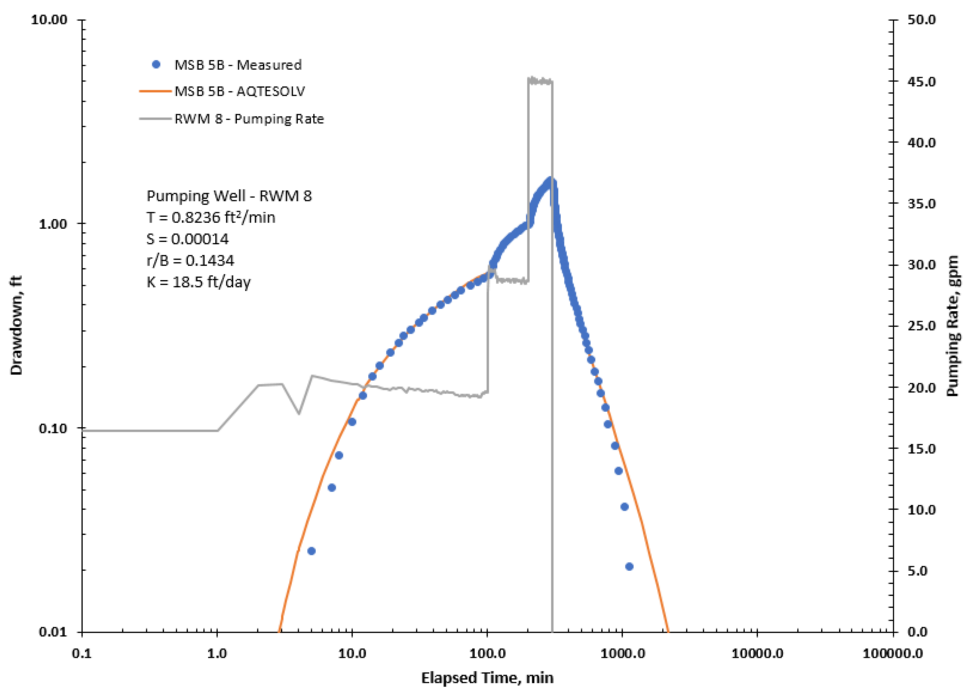

Figure 16. Step Test Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 5B.

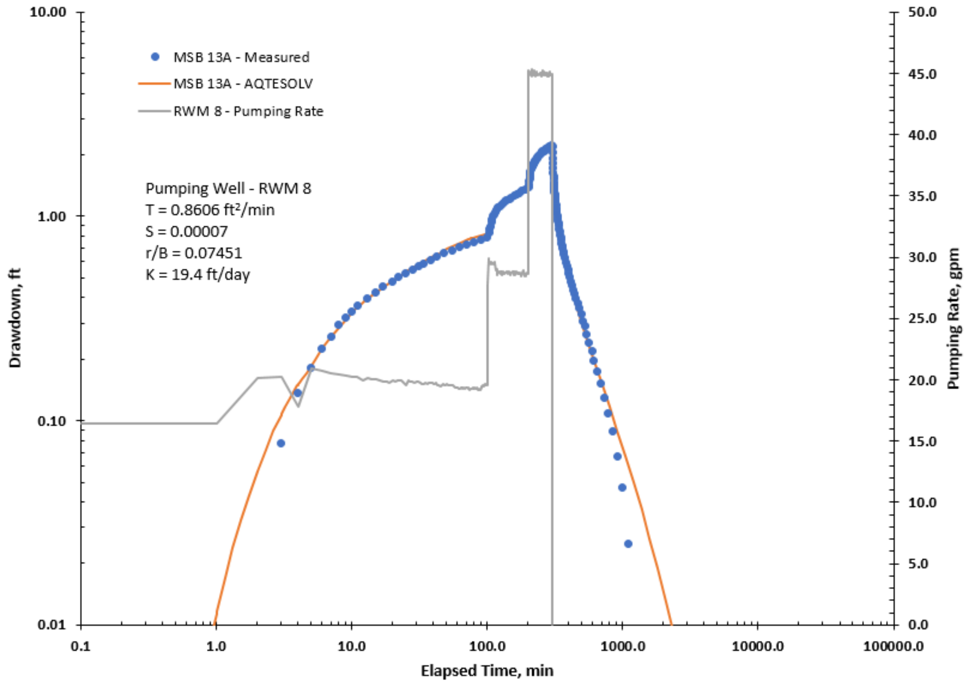

Figure 17. Step Test Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 13A.

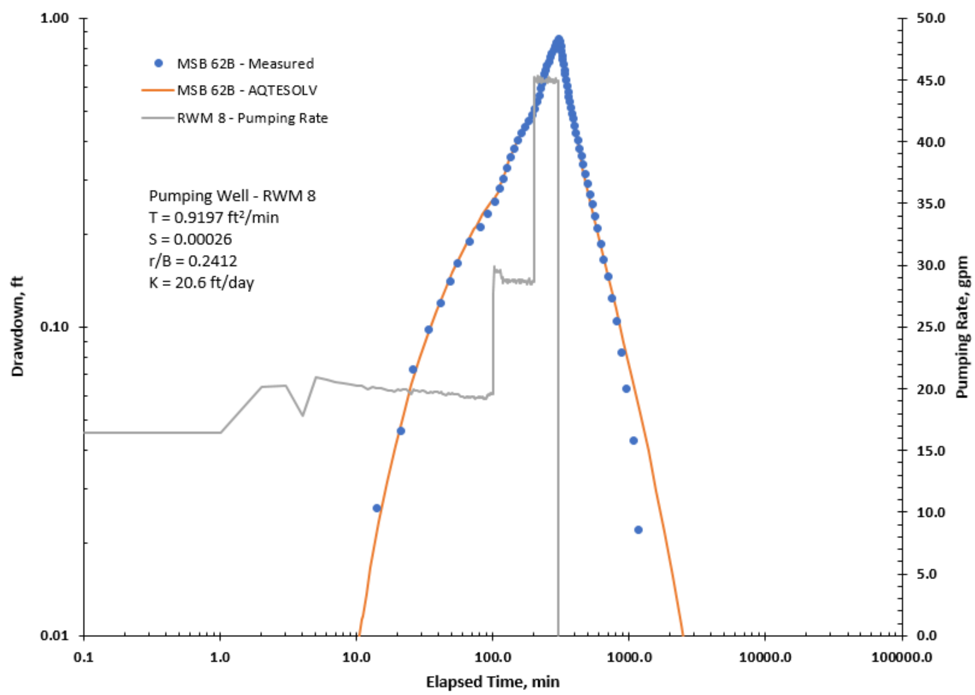

Figure 18. Step Test Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 62B.

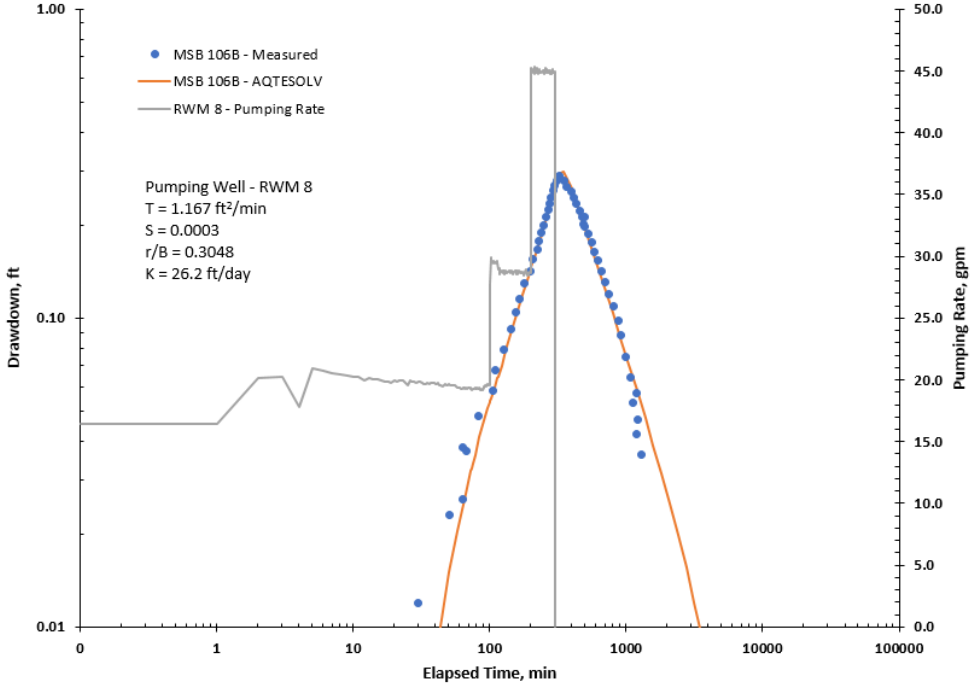

Figure 19. Step Test Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 106B.

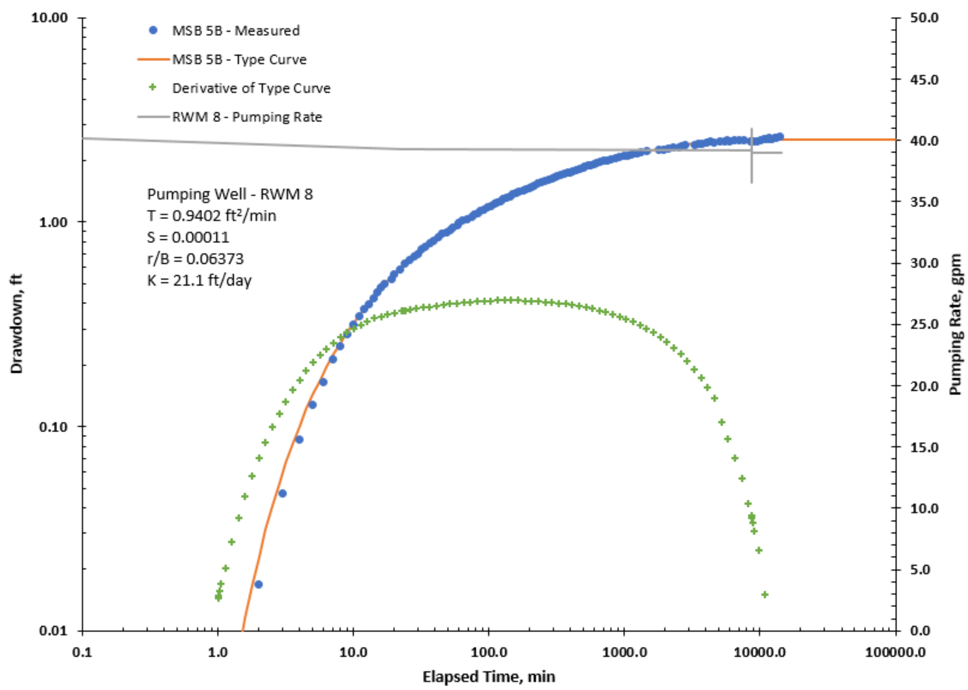

Figure 20. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 5B.

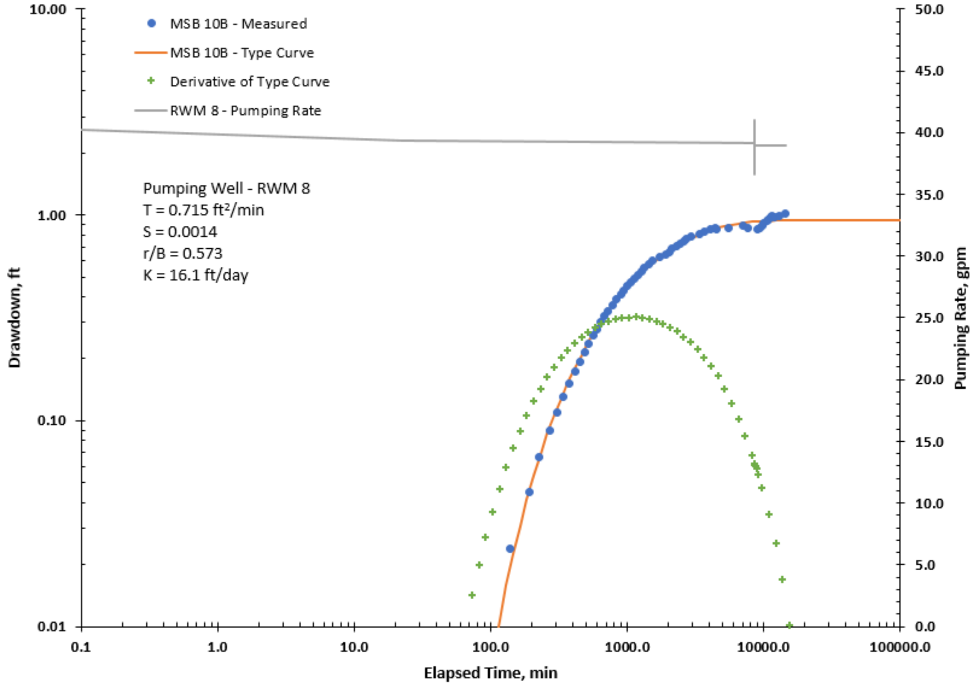

Figure 21. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 10B.

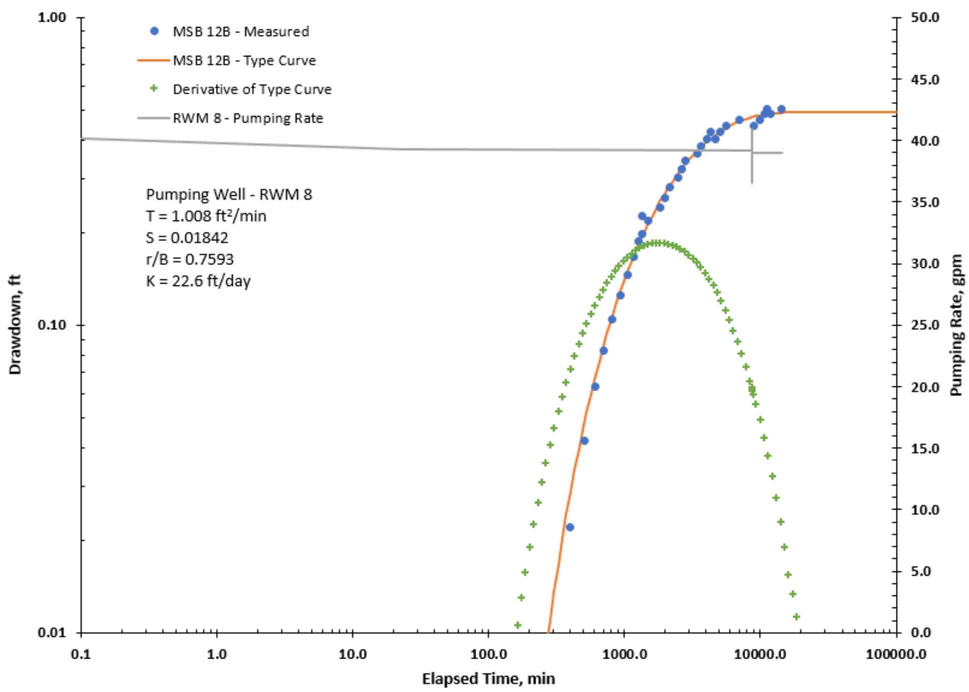

Figure 22. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 12B.

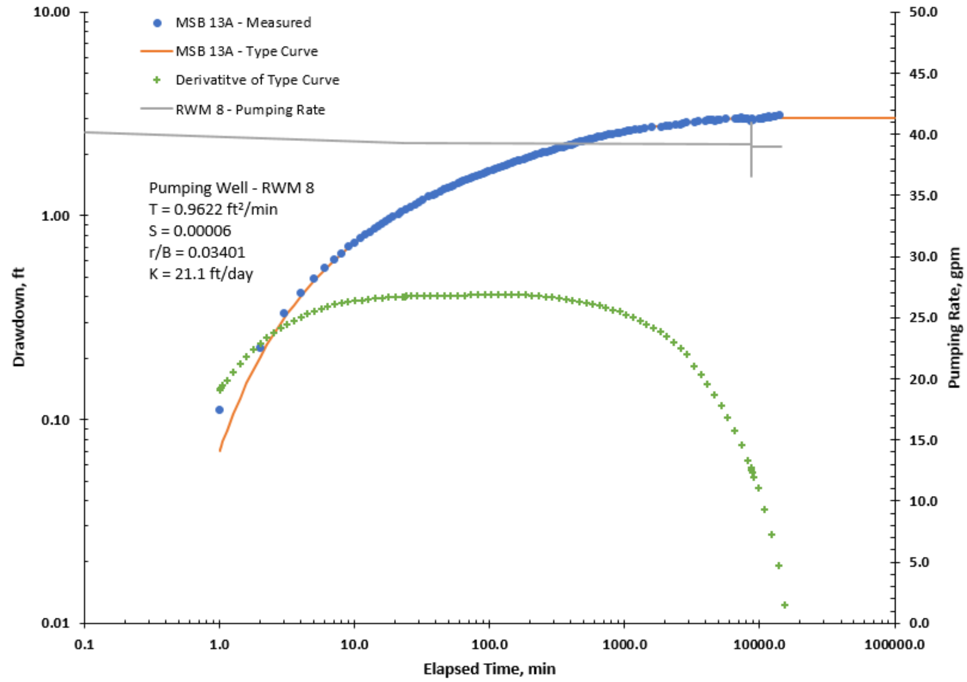

Figure 23. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 13A.

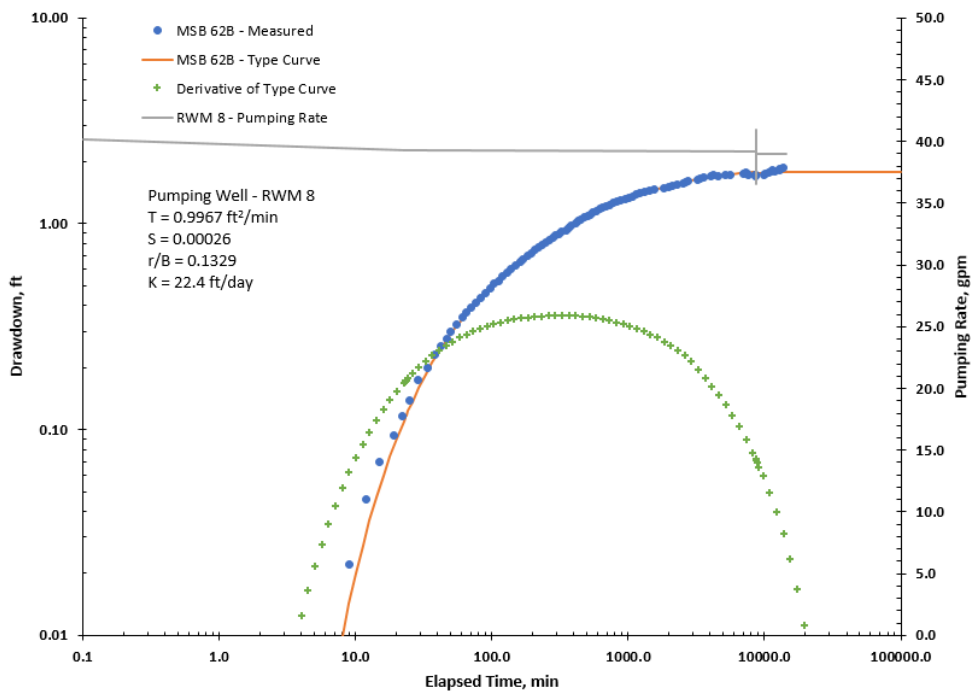

Figure 24. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 62B.

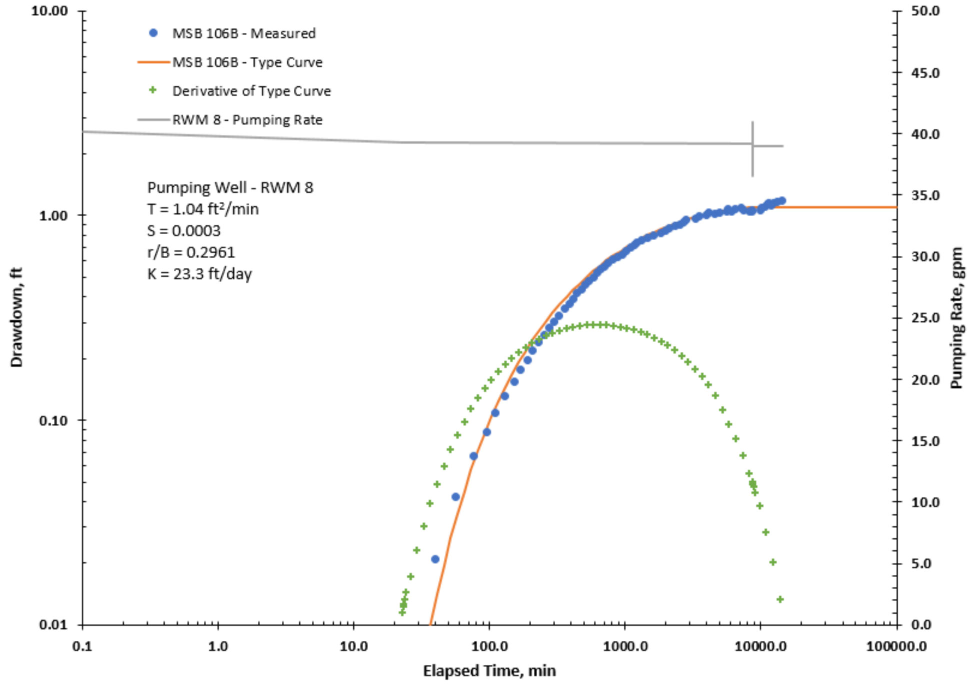

Figure 25. Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 106B.

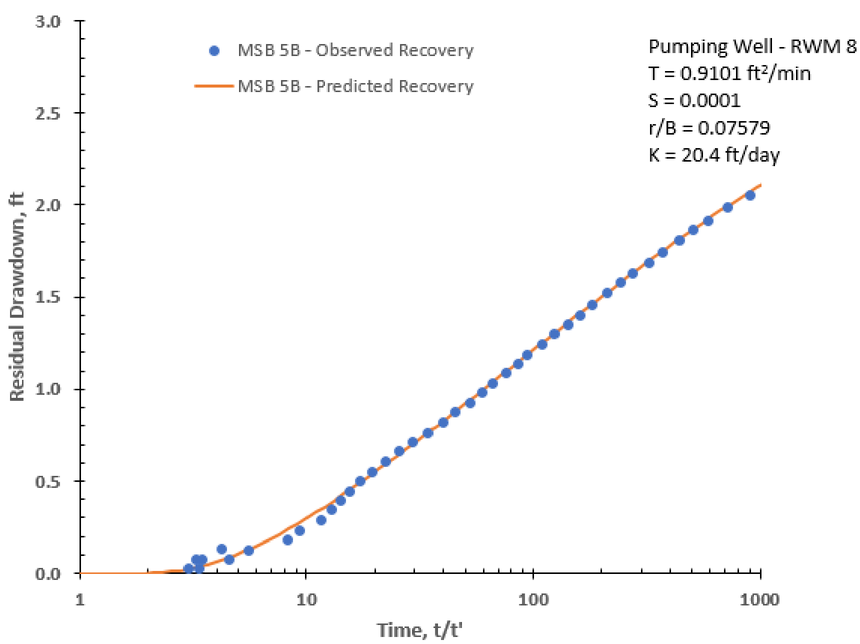

Figure 26. Residual Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 5B from Second Pumping Period.

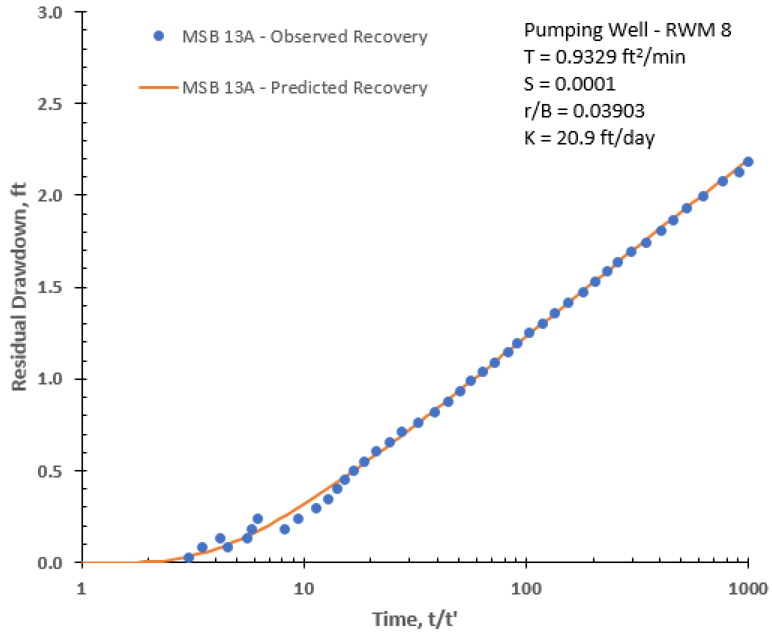

Figure 27. Residual Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 13A from Second Pumping Period.

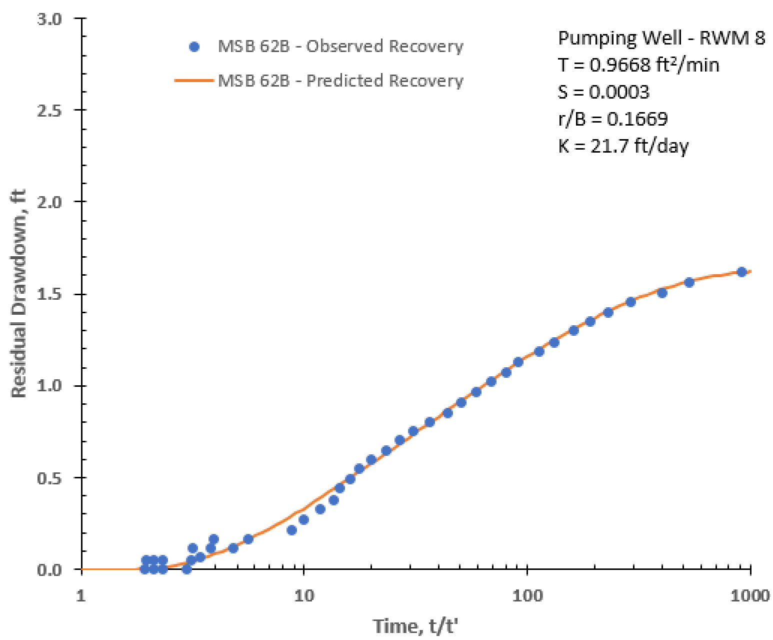

Figure 28. Residual Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 62B from Second Pumping Period.

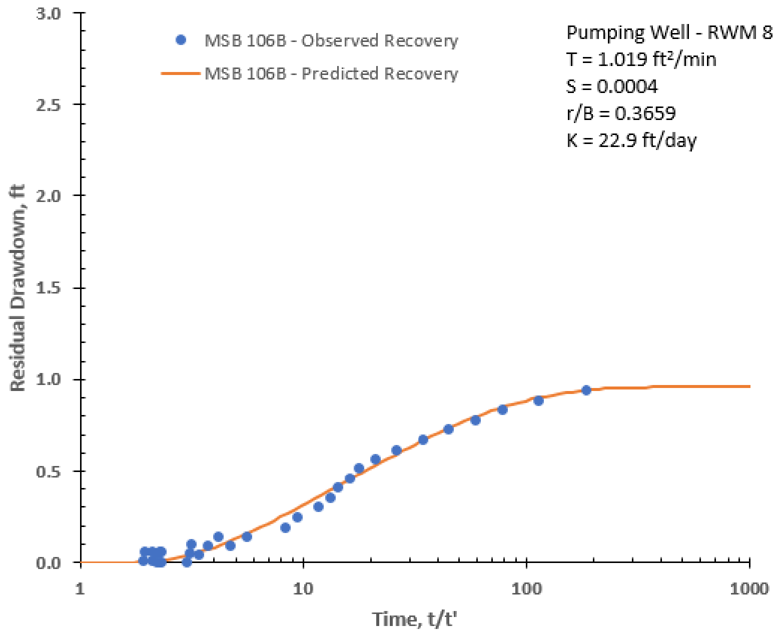

Figure 29. Residual Drawdown Data and Hantush-Jacob Leaky Aquifer Type Curve for MSB 106B from Second Pumping Period.

Table 1 Construction Details for Wells Used in Aquifer Test at RWM 8.

Well Name	Distance from RWM 8 (ft)	Diameter (in)	SRS East (ft)	SRS North (ft)	Top of Screen (ft msl)	Bottom of Screen (ft msl)	Top of Screen (ft bgsl)	Bottom of Screen (ft bgs)	Total Depth (ft)	Screen Length (ft)
RWM 8	0.00	8	47353.1	101948.2	197.20	109.30	148.10	236.00	225.66	88
MSB 5B	370.28	4	46983.6	101971.1	136.10	131.40	207.00	211.70	213.60	5
MSB12B	387.11	4	47142.1	102272.7	162.40	157.40	185.30	190.30	192.90	5
MSB12C	406.73	4	47140.9	102295.2	184.10	179.10	163.10	168.10	170.70	5
MSB 10B	799.73	4	47943.1	102488.2	157.40	152.40	198.20	203.20	205.20	5
MSB 13A	281.42	4	47525.4	101725.7	177.50	172.50	167.50	172.50	215.30	5
MSB 13CC	279.17	4	47525.7	101728.8	196.80	192.00	148.00	152.80	154.90	5
MSB17A	1110.34	4	46244.3	102006.6	160.60	155.60	196.70	201.70	203.70	5
MSB 62B	559.82	4	47906.8	101865.3	141.00	136.30	206.00	210.70	212.80	5
MSB101B	1239.85	4	47191.1	103177.4	147.60	137.60	199.80	209.80	215.00	10
MSB106B	1128.57	2	48024.3	102855.5	146.24	136.24	217.00	227.00	229.00	10
RWM019	1466.14		48785.0	101633.0	196.09	146.09	151.00	201.00	206.00	50

*Preferred wells for transducer installation.

Table 2: Relative Well Dimensions Used in AQTESOLV Analysis of RWM 8 Pumping Test Data.

	Distance from RWM 8 (ft)	Depth Below GCCZ (ft)	Screen Length[1] (ft)	Well Casing Radius[1] (ft)	Effective Radius (ft)
RWM 8	0.00	-3.24	67.20	0.33	0.67
MSB 5B	370.28	57.86	4.70	0.17	0.33
MSB12B	387.11	31.56	5.00	0.17	0.33
MSB12C	406.73	9.86	5.00	0.17	0.33
MSB 13A	281.42	16.46	5.00	0.17	0.33
MSB 13CC	279.17	-2.84	4.80	0.17	0.33
MSB17A	1110.34	33.36	5.00	0.17	0.33
MSB101B	1239.85	46.36	10.00	0.17	0.33
MSB106B	1128.57	47.72	10.00	0.08	0.17
RWM019	1466.14	-2.13	50.00	0.25	0.50
MSB 10B	799.73	36.56	5.00	0.17	0.33
MSB 62B	559.82	52.96	4.70	0.17	0.33

[1]As determined from BEIDMS well construction information.

Table 3. Previously Reported Hydraulic Properties of the Lost Lake Aquifer Zone

Well[a]	T[b] (ft²/min)	S[b]	r/B[c]	Observed Specific Capacity (gpm/ft)	Well Efficiency (%)
RWM 1	2.32	0.001	-	0.9	-
RWM 2	2.32	0.001	-	0.6	-
RWM 3[a]	2.32	0.001	-	4.2	-
RWM 4[a]	1.11	0.001	-	4.3	82
				3.9	75
				4.6	62
RWM 5[a]	3.53	0.00005	-	5.3	79
				5.8	65
				5.9	55
RWM 6[a]	1.76	0.0006	-	2.8	-
RWM 7[a]	1.95	0.0006	-	1.9	78
				1.8	64
				1.4	52
RWM 8[a]	1.49	0.001	-	5.3	75
				5.7	64
				4.3	53
RWM 9[a]	10.49	0.01	-	6.5	91
				6.8	87
				7.8	81
RWM 10[a]	2.32	0.0009	-	3.1	88
				2.9	85
				3.4	81
				2.8	75
				2.6	69
RWM 11[a]	9.10	0.0003	-	4.0	90
				4.3	85
				4.0	81
RWM 16PA[a,c]	0.899	0.00065	0.0823	-	-
RWM 16PB[a,c]	0.826	0.00073	0.0460	-	-
RWM018[a,c]	0.816	0.00047	0.2461	3.22	69.6
MSB-40B[a,c]	0.782	0.00053	0.0458	-	-

[a]Data compiled from Dixon (2018), Geraghty and Miller (1987), and Hiergesell (1992).
[b]Values determined using Theis confined aquifer method unless otherwise noted.
[c]Values determined using Hantush-Jacob leaky confined aquifer method (1955).

Table 4. Calculated Barometric Efficiencies for RWM 8 and Nearby Observation Wells.

Well ID	Barometric Efficiency (%)
RWM 8	56
MSB5B	79
MSB10B	64
MSB12B	56
MSB13A	80
MSB62B	82
MSB106B	78
Average	**71**
Median	**78**

Table 5. Specific Capacity and Efficiencies Calculated for RWM 8.

Well ID	Test	Q (gpm)	Q/s GPM/ft	Well Efficiency (%)
RWM 8	Step-Drawdown Test	19.6	6.4	90.1
		28.6	5.7	86.1
		45.0	5.6	79.8
RWM 8	Long Term Test	39.2	4.5[a]	88.3[b]

[a]At end of 10-day pumping test.
[b]Estimated at 1000 minutes.

Table 6. Well Loss Parameters Calculated for RWM 8.

Well ID	Test	B ($ft/ft^3/min$)	C (min^2/ft^5)	P
RWM 8	Step-Drawdown Test	1.0870	0.0457	2

Table 7. Maximum Observed Drawdown for Wells Near RWM 8 (Q=~40 gpm).

	SRS East	SRS North	Distance from RWM 18 (ft)	Maximum Observed Drawdown (ft H_2O)
RWM 8	47353.1	101948.2	0.0	8.92
MSB 5B	46983.6	101971.1	370.3	2.55
MSB 10B	47943.1	102488.2	799.7	0.91
MSB 12B	47142.1	102272.7	387.1	0.48
MSB 13A	47525.4	101725.7	281.4	3.04
MSB 62B	47906.8	101865.3	559.8	1.78
MSB106B	48024.3	102855.5	1128.6	1.10

Table 8. Hydraulic Properties of the Lost Lake Aquifer Near RWM 8 as Determined from Step-Drawdown Testing.

	Transmissivity (ft^2/min)	Hydraulic Conductivity (ft/day)	Storativity	r/B	Green Clay Hydraulic Conductivity (ft/day)	Aquifer Zone[1]
RWM 8	0.9332	20.95	0.01207	0.00088	1.4E-02	LLLAZ
MSB 5B	0.8236	18.49	0.00014	0.14340	1.1E-03	LLLAZ
MSB 13A	0.8606	19.32	0.00007	0.07457	5.3E-04	LLLAZ
MSB 62B	0.9197	20.65	0.00025	0.24120	1.5E-03	LLLAZ
MSB106B	1.1670	26.20	0.00030	0.30480	7.5E-04	LLLAZ
Average	0.9408	22.6	0.0026	0.1530	5.5E-03	
Median	0.9197	20.6	0.0003	0.1434	1.1E-03	
Standard Deviation	0.1340	3.0	0.0053	0.1227	5.9E-03	

[1]LLAZ – Lost Lake Aquifer Zone, ULLAZ – Upper Lost Lake Aquifer Zone, MLLAZ – Middle Lost Lake Aquifer Zone, LLLAZ – Lower Lost Lake Aquifer Zone

Table 9. Hydraulic Properties of the Lost Lake Aquifer Near RWM 8 as Determined from Constant Rate Aquifer Testing.

	Transmissivity (ft^2/min)	Hydraulic Conductivity (ft/day)	Storativity	r/B	Green Clay Hydraulic Conductivity (ft/day)	Aquifer Zone[1]
MSB 5B	0.9402	21.11	0.00011	0.06373	2.4E-04	LLLAZ
MSB10B	0.7150	16.05	0.00141	0.57300	3.2E-03	ULLAZ
MSB 12B	1.0080	22.63	0.01842	0.75930	3.4E-02	ULLAZ
MSB 13A	0.9622	21.60	0.00006	0.03401	1.2E-04	LLLAZ
MSB 62B	0.9967	22.38	0.00026	0.13290	4.9E-04	LLLAZ
MSB106B	1.0400	23.35	0.00030	0.29610	6.3E-04	LLLAZ
Average	0.9437	22.1	0.0034	0.3098	3.7E-04	
Median	0.9795	22.0	0.0003	0.2145	5.6E-04	
Standard Deviation	0.1174	2.6	0.0074	0.2965	1.4E-02	

[1]LLAZ – Lost Lake Aquifer Zone, ULLAZ – Upper Lost Lake Aquifer Zone, MLLAZ – Middle Lost Lake Aquifer Zone, LLLAZ – Lower Lost Lake Aquifer Zone

Table 10. Hydraulic Properties of the Lost Lake Aquifer Near RWM 8 as Determined from Recovery Data.

	Transmissivity (ft^2/min)	Hydraulic Conductivity (ft/day)	Storativity	r/B	Green Clay Hydraulic Conductivity (ft/day)	Aquifer Zone[1]
MSB 5B	0.9101	20.43	0.00010	0.07579	3.34E-04	LLLAZ
MSB 13A	0.9329	20.94	0.00005	0.03903	1.57E-04	LLLAZ
MSB 62B	0.9668	21.71	0.00028	0.16690	7.52E-04	LLLAZ
MSB106B	1.0190	22.88	0.00036	0.36590	9.38E-04	LLLAZ
Average	0.9572	21.5	0.0002	0.1619	5.5E-04	
Median	0.9499	21.3	0.0002	0.1213	5.4E-04	
Standard Deviation	0.0473	1.1	0.0001	0.1462	3.6E-04	

[1]LLAZ – Lost Lake Aquifer Zone, ULLAZ – Upper Lost Lake Aquifer Zone, MLLAZ – Middle Lost Lake Aquifer Zone, LLLAZ – Lower Lost Lake Aquifer Zone

Table 11. Average Hydraulic Properties of the Lost Lake Aquifer Near RWM 8

	Transmissivity (ft^2/min)	Hydraulic Conductivity (ft/day)	Storativity	r/B	Green Clay Hydraulic Conductivity (ft/day)
Average	0.9463	21.2	0.0023	0.2181	0.004
Median	0.9402	21.1	0.0003	0.1434	0.001
Standard Deviation	0.1029	2.3	0.0054	0.2152	0.009

[1]LLAZ – Lost Lake Aquifer Zone, ULLAZ – Upper Lost Lake Aquifer Zone, MLLAZ – Middle Lost Lake Aquifer Zone, LLLAZ – Lower Lost Lake Aquifer Zone

Distribution:

dennis.jackson@srnl.doe.gov
branden.kramer@srs.gov
joao.cardoso-neto@srs.gov
john02.bradley@srs.gov
larry.mullikin@srs.gov
j.ross@srs.gov
nancy.halverson@srnl.doe.gov
Records Administration (EDWS)