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Appendix 2.4.12B
Aquifer Pumping Test Results

2.4.12B Aquifer Pumping Test Results

2.4.12B.1 Introduction

2.4.12B.1.1 Purpose

The purpose of this appendix is to present the evaluation of the aquifer pumping test (APT) performed at the Clinch River Nuclear (CRN) Site and to provide estimates of transmissivity, storage coefficient, and hydraulic conductivity at the test locations in support of the Early Site Permit for the proposed small modular reactors at the CRN Site. There were 34 groundwater observation wells installed and developed at the CRN Site for hydrogeologic characterization and long-term water level monitoring, and 7 supplemental wells were installed for performing and monitoring the APT (Figure 2.4.12B-1).

2.4.12B.1.2 Hydrogeologic Setting

The geology of the site consists of Ordovician and Cambrian predominantly calcareous rocks overlain by regolith composed of clayey soils, saprolite, and fill. The bedrock units present in the site area are shown on the stratigraphic section in Figure 2.4.12B-2 (Reference 2.4.12B-1). The bedrock has been subjected to repeated folding and faulting that has produced a series of northeast-trending ridges and valleys typical of the Valley and Ridge Physiographic Province (Reference 2.4.12B-2) in which the site lies. At the site, the bedrock dips toward the southeast (Reference 2.4.12B-3). Typically a dip of about 30 degrees is observed, but the dip can vary between 20 degrees and 45 degrees (Reference 2.4.12B-4). The subsurface flow system in this region consists of a stormflow zone near the surface, a less permeable vadose zone below, and a saturated zone consisting of fractured bedrock with fracture frequency decreasing with depth (Reference 2.4.12B-5). Reference 2.4.12B-6 indicates that the transition from fractured bedrock to deeper, less fractured bedrock occurs at about 45 meters (m) (148 feet [ft]) below ground surface in Melton and Bethel Valleys in the adjacent Oak Ridge Reservation (ORR). The secondary porosity resulting from the fracture system is expected to dominate the flow regime in the groundwater-bearing rocks, since the rock matrix has a low primary porosity and hydraulic conductivity.

Previous investigations at the site have identified four orientations of discontinuities (joints and fractures) on the site: N52°E 37°SE, N52°E 58°NW, N25°W 80°SW, and N65°W 75°NE. The N52°E 37°SE oriented discontinuities represent bedrock bedding planes and are the predominant discontinuity set at the site (Reference 2.4.12B-3). This information was used to guide well placement as shown on Figure 2.4.12B-3. Measurements from the CRN Site subsurface investigation indicate a primary discontinuity set oriented N60°E 59°NW and a secondary set oriented N60°E 38°SE. Previous orientation measurements and the CRN Site measurements are within 8 degrees, suggesting a reasonable agreement between the two measurement sets.

2.4.12B.2 APT Design

The APT is a commonly used technique to characterize aquifer properties. Other methods, such as slug tests and packer tests, focus on the area immediately surrounding the well or borehole being tested. The APT utilizes a pumping well pumped at a constant rate to stress the aquifer and a group of spatially distributed observation wells to measure the effects of that stress. After completion of the pumping period of the test, the pump is shut off and water level recovery in the pumping and observation wells is observed.

Water level measurements were collected using electronic and manual methods. The electronic method utilizes pressure transducers to measure and record the water level. The transducers used for this test were Level Troll® model 500 or model 700 transducers manufactured by In-Situ, Inc. These transducers are vented to the atmosphere to allow compensation for barometric pressure changes. Data from the Level Troll® includes date/time, elapsed time in seconds of the logging period, pressure (pounds per square inch [psi]), temperature (°C), and depth (ft) (i.e., height of water above the pressure transducer).

Manual water level measurements were made using an electrical water level measurement device. Water levels are measured relative to the top of the well casing and are reported as feet below top of casing (ftbtc). Water level measurements were collected prior to (background) and during the APT.

Supplemental observation and pumping wells installed to perform the APT were screened in the Chickamauga Group, in the Eidson and Fleanor Members of the Lincolnshire Formation and the Blackford Formation. Figure 2.4.12B-4 is a geologic cross-section that includes the APT area and illustrates the stratigraphic relationships. The upper “U” monitoring zones are screened in the Eidson and Fleanor Members and the lower “L” monitoring zones are screened in the Blackford Formation, as is the lone deeper “D” well associated with the OW-423 observation well series. The pumping well is screened in both units. The Eidson Member of the Lincolnshire Formation consists primarily of limestone and the Fleanor Member consists of shale. The Blackford Formation consists primarily of maroon-colored calcareous siltstone with dolomitic limestone layers. Reference 2.4.12B-1 classifies these units as an aquitard as shown on Figure 2.4.12B-2.

2.4.12B.2.1 Observation Wells

Observation wells used for the test represent a subset of the site observation wells as shown on Figure 2.4.12B-1. The supplemental observation wells near the pumping well were installed around the pumping well as shown on Figure 2.4.12B-3 to characterize horizontal anisotropy. The well layout was designed to examine differences in response along the strike and dip of the discontinuity sets at the site. Observation well construction information can be found in Reference 2.4.12B-7. The screened intervals for the wells are summarized on Table 2.4.12B-1.

2.4.12B.2.2 Pumping Well

The pumping well consists of a 6-inch (in.) diameter well equipped with an electric submersible pump. The construction information for the pumping well is presented in Reference 2.4.12B-7 and the screened interval is presented on Table 2.4.12B-1. Prior to performing the APT, the pumping rate was determined for the test using a step-drawdown test. The objective of the step-drawdown test was to determine the pumping rate that will stress the aquifer without drawing the water level down to the test pump during the pumping duration. Based on the results of the step-drawdown test, a pumping rate of 14.5 gallons per minute (gpm) ±5 percent was established.

Discharge from the pumping well was measured using a Master Meter mechanical totalizing flow meter. Since the flow meter reads the total gallons pumped, the flow rate was determined by measuring the number of gallons pumped over a specific time period. Flow measurements are summarized on Table 2.4.12B-2. Figure 2.4.12B-5 presents a graphical representation of the pumping rate data, which shows that the pumping rate was within the specified tolerance for a majority of the test. The discharge from the pumping well was directed to a series of steel 21,000 gallon tanks connected in a manifold arrangement that allowed filling one tank at a time.

2.4.12B.3 Analysis Methodology

Data from the pumping well and observation well pressure transducers were prepared as follows:

1. The In-situ, Inc. WinSitu® (Reference 2.4.12B-8) software was used to convert the native file (wsl) to Microsoft Excel® format (csv). The converted files were compared to manual groundwater level measurements to confirm the accuracy of the conversion.

2. Microsoft Excel® was used to calculate drawdown and pumping time using 3/21/2014 12:00 as the test start time. It should be noted that for those wells with frequent early time measurements, the elapsed time in seconds of logging was used to resolve the individual time readings since the date/time did not contain sufficient detail for these readings. The pumping portion of the test continued for 4325 minutes (72 hours).

3. Plots of the background water level measurements and the measurements during the APT are presented in Attachment A to Appendix 2.4.12B on Figures 2.4.12B-A1 through 2.4.12B-A23.

The following information is derived or assumed:

- Saturated Thickness = Pumping well static water elevation of 741.36 ft North American Vertical Datum of 1988 (NAVD88) (Reference 2.4.12B-7)—Bottom of primary flow zone at elevation 587 ≈ 155 ft.

- Radius of pressure transducer cable = (0.25 in (Reference 2.4.12B-9) /12)/2 = 0.01 ft

- Volume displaced by the transducer = (0.72 in (Reference 2.4.12B-8) $/12/2)^2$ x (8.5/12) x π = 0.002 ft^3 ∴ transducer volume displacement is insignificant.

- Anisotropy ratio (K_z/K_r) vertical to horizontal hydraulic conductivity = 0.1—Typical for limestone/dolomite. The range of K_z is an order of magnitude lower than the range of K_r (Reference 2.4.12B-10). The assumed value is similar to results observed on the ORR (Reference 2.4.12B-6).

2.4.12B.3.1 External Influences

Common external influences that may influence APT data include barometric pressure fluctuations and changes in aquifer recharge.

Figure 2.4.12B-6 presents a plot of barometric pressure versus pumping time during the APT (Reference 2.4.12B-11). The figure indicates a maximum barometric pressure fluctuation of approximately 0.3 in. of mercury, which is approximately 0.34 ft of water. If the barometric efficiency of the aquifer were 100 percent, this would be the change in water level associated with the barometric pressure fluctuation. Reference 2.4.12B-12 indicates that barometric efficiencies of aquifers typically vary from 20 to 70 percent. Figure 2.4.12B-6 indicates the barometric pressure increases during late time period of the test. An increase in barometric pressure would cause a corresponding decrease in groundwater level. The relatively low magnitude of the barometric pressure fluctuation suggests that it would only have a significant impact on wells with less than 0.5 ft of drawdown.

Changes in recharge would include infiltration of pumping well discharge, rainfall events, and changes in surface water stage. Infiltration of pumping well discharge (recirculation) was mitigated by containerizing the discharge water thus preventing recharge to the aquifer. One rainfall event occurred during the test as shown on Figure 2.4.12B-7. The peak precipitation occurred at approximately 2460 minutes after the start of pumping. This event was regarded as being an insignificant recharge event due to its low intensity and short duration; however this event may explain the premature recovery observed in some of the observation wells. Changes in surface water stage in the Clinch River arm of the Watts Bar Reservoir, which surrounds the CRN Site on three sides, were documented at the Melton Hill Dam tailwater stage monitoring site approximately 4.5 miles (mi) upstream of the CRN Site. Figure 2.4.12B-8 presents the tailwater stage (as elevation in feet National Geodetic Vertical Datum of 1929 (NGVD29)) for the pumping and recovery periods. The graph indicates a maximum stage change of approximately 3 ft. Review of long-term monitoring data at the site indicates that changes in stage in the river have negligible impact on water levels at the CRN Site.

2.4.12B.3.2 Evaluation of Well Response

Examination of plots in Attachment A to Appendix 2.4.12B was performed to select wells for analysis. A total of 23 wells were monitored during the test and the data from 16 wells were rejected for reasons discussed below. Table 2.4.12B-1 presents a summary of the information.

Evaluation of background water levels prior to undertaking the pumping test indicates a number of wells (as identified below) showed a decreasing (downward) water level trend. The downward trend in these wells varied between 0.05 and 0.8 ft/day. This suggests that the local to regional water levels were trending downward prior to the test. Evaluation of the drawdown during the pumping test in the subject observation wells showed minimal drawdown (ranging from 0.2 to 1.1 ft). This range of drawdown is similar to that of the decreasing water level trend observed prior to the pumping test. Thus, it is difficult to discern whether the drawdown observed during the pumping test in these wells is due to the decreasing local to regional water level trend or stress caused by the pumping test. All of the subject wells are outside the immediate vicinity of the pumping well, and thus the effect of pumping (at about 15 gpm) on water levels in these wells is likely to be negligible. Thus, no further evaluation to determine hydrogeologic properties (such as hydraulic conductivity) was undertaken, using drawdown data from these wells, which included, PT-OW-U3, OW-423U, OW-423D, OW-202U, OW-202L, OW-202D, OW-428U, OW-428L, OW-428D, OW-409U, OW-409L, OW-101U, OW-101L, OW-101D, OW-417U, and OW-417L wells. Wells in the vicinity of the pumping well exhibited substantial drawdown as compared to the background decreasing water level trend, and evaluations to determine hydraulic conductivity were undertaken.

PT-PW: Figures 2.4.12B-A1 and 2.4.12B-A2 show the response of the well for the background, pumping, and recovery periods. The well shows a relatively stable background water level once recovery from the step test was complete. The pumping and recovery curves show adequate and reasonable response. The information from this well was retained for analysis.

PT-OW-U1: Figure 2.4.12B-A3 presents the response of the well for the background, pumping, and recovery periods. The well shows a relatively stable background water level once recovery from the step test was complete. During the pumping period, the water level in the well dropped below the transducer level as shown by periodic manual measurements. For analysis, the transducer readings are supplemented with the manual readings. Once pumping stopped, the water level in the well rapidly recovered to within 0.5 ft of the static level. The information from this well was retained for analysis.

PT-OW-L1: Figure 2.4.12B-A4 presents the response of the well for the background, pumping, and recovery periods. The well shows a relatively stable background water level once recovery from the step test was complete. The well shows adequate and reasonable response to pumping and recovery. The information from this well was retained for analysis.

PT-OW-U2: Figure 2.4.12B-A5 presents the response of the well for the background, pumping, and recovery periods. The background measurements for the well show no response to the step test and a downward trend of approximately 0.1 ft/d prior to start of the pumping test. The well shows response to pumping and recovery. The information from this well was retained for analysis.

PT-OW-L2: Figure 2.4.12B-A6 presents the response of the well for the background, pumping, and recovery periods. The well shows response to the step test and an upward trend of approximately 0.1 ft/d at the end of the background period. The well shows adequate and reasonable response to pumping and recovery. The information from this well was retained for analysis.

PT-OW-U3: Figure 2.4.12B-A7 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a response to the step test and a downward trend of approximately 0.1 ft/d at the end of the background period. The well continued to show influence due to the background trend during the pumping and recovery periods and the water level data show erratic variations, and therefore the information from this well was discarded from further analysis.

PT-OW-L3: Figure 2.4.12B-A8 presents the response of the well for the background, pumping, and recovery periods. The background plot shows response to the step test and a stable trend prior to the start of pumping. The well shows adequate and reasonable response to pumping and recovery. The information from this well was retained for analysis.

OW-423U: Figure 2.4.12B-A9 presents the response of the well for the background, pumping, and recovery periods. The background plot shows no response to the step test and a downward trend of approximately 0.2 ft/d prior to the start of pumping. The response of the well during pumping and recovery suggests that the well is being influenced by external factors, such as the precipitation event at 2460 minutes elapsed time. The information from this well was discarded from further analysis.

OW-423L: Figure 2.4.12B-A10 presents the response of the well for the background, pumping, and recovery periods. The background plot shows response to the step test and a stable but noisy trend prior to the start of the test. The well shows adequate and reasonable response to pumping and recovery. The information from this well was retained for analysis.

OW-423D: Figure 2.4.12B-A11 presents the response of the well for the background, pumping, and recovery periods. The background plot shows response to the step test and a stable but very noisy trend prior to the start of the test. The well shows response to pumping, but has no recovery, suggesting the well may be influenced by a downward trend in levels. This well is screened below the bottom of the primary flow zone, which coupled with the complex response resulted in the decision to discard this information from further analysis.

OW-202U: Figure 2.4.12B-A12 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.4 ft/d at the end of the background period. During the pumping period, the well shows drawdown, but the drawdown is consistent with the background trend in water levels. The well does not show any recovery. The well is at a distance of 508 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

OW-202L: Figure 2.4.12B-A13 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.1 ft/d. The well shows drawdown, but the drawdown is consistent with the background trend in water level. The well does not show any recovery. The well is at a distance of 524 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

OW-202D: Figure 2.4.12B-A14 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a stable but noisy trend. The pumping and recovery plot shows a complex and noisy response. This well is screened below the bottom of the primary flow zone, which coupled with the complex response resulted in the decision to discard this information from further analysis. Also, the well is at a distance of 558 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm.

OW-428U: Figure 2.4.12B-A15 presents the pumping period manual measurements from this well. Manual measurements were not collected during the background or recovery periods. The well response suggests response to pumping after 300 minutes followed by recovery after 3000 minutes as a result of the precipitation event. The paucity of data and uncertainty of external influences resulted in the decision to discard this information from further analysis. The well is at a distance of 810 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm.

OW-428L: Figure 2.4.12B-A15 presents the pumping period manual measurements from this well. Manual measurements were not collected during the background or recovery periods. The paucity of data and lack of response in the well resulted in the decision to discard this information from further analysis. The well is at a distance of 812 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm.

OW-428D: Figure 2.4.12B-A16 presents the pumping period manual measurements from this well. Manual measurements were not collected during the background or recovery periods. The well shows drawdown during the late period of the pumping test, but since no information is available to define a background trend in this well the cause of this drawdown is indeterminate. This coupled with the fact that the well is screened below the primary flow zone resulted in the decision to discard this information from further analysis. Also, the well is at a distance of 817 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm.

OW-409U: Figure 2.4.12B-A17 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.3 ft/d. The drawdown in the well during the pumping period is consistent with the background trend. The well is at a distance of 881 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis as a result of the background trend and erratic water level fluctuations.

OW-409L: Figure 2.4.12B-A18 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.3 ft/d. During the pumping period, the well shows drawdown consistent with the background trend, followed by early recovery to above the static level. Also, the well is at a distance of 866 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

OW-101U: Figure 2.4.12B-A19 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.8 ft/d. During the pumping period, the well shows drawdown consistent with the background trend, followed by early recovery to slightly below the static level. This well is at a distance of 1202 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

OW-101L: Figure 2.4.12B-A20 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.4 ft/d. During the pumping period, the well shows drawdown consistent with the background trend, followed by early recovery to below the static level. This well is at a distance of 1179 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

OW-101D: Figure 2.4.12B-A21 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.3 ft/d. During the pumping and recovery periods the well exhibits water level fluctuations consistent with those observed in the background period. This well is at a distance of 1168 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

OW-417U: Figure 2.4.12B-A22 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.2 ft/d. During the pumping and recovery periods the well exhibits water level fluctuations consistent with those observed in the background period. This well is at a distance of 2184 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

OW-417L: Figure 2.4.12B-A23 presents the response of the well for the background, pumping, and recovery periods. The background plot shows a downward trend of approximately 0.05 ft/d. During the pumping and recovery periods the well exhibits water level fluctuations consistent with those observed in the background period. This well is at a distance of 2224 ft from the pumping well and is unlikely to be influenced as a result of pumping at 14.5 gpm. The information from this well was discarded from further analysis.

Wells PT-OW-U2 and PT-OW-L2 show a background downward or upward trend in water levels. This trend was not corrected for in the data since there is uncertainty in the projection of this trend into the pumping and recovery periods, based on the responses of the wells beyond the influence of the test (e.g. OW-202U/L and OW-101U/L). The results of this evaluation are summarized on Table 2.4.12B-1. Data from tests identified in Table 2.4.12B-1 were entered into the AQTESOLV® program for further interpretation of the test results.

2.4.12B.3.3 Diagnostic Plots

Reference 2.4.12B-13 presents a discussion of using a diagnostic plot for evaluating aquifer test data. The diagnostic plot is a log-log plot of drawdown and the derivative of drawdown versus time. The derivative of the drawdown is calculated using (Reference 2.4.12B-10):

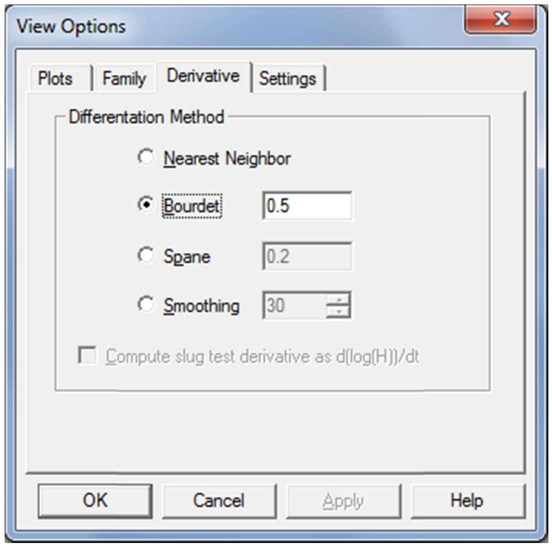
$$\left(\frac{\partial s}{\partial lnT}\right)_i = \frac{\left(\frac{\Delta s_{i-1}}{\Delta lnT_{i-1}}\right)\times \Delta lnT_{i+1} + \left(\frac{\Delta s_{i+1}}{\Delta lnT_{i+1}}\right)\times \Delta lnT_{i-1}}{\Delta lnT_{i-1} + \Delta lnT_{i+1}} \qquad \text{Equation 2.4.12B-1}$$

where:

T = appropriate time function (elapsed time or Agarwal equivalent)

s = drawdown

The derivative time function selected for use was the Bourdet method (Reference 2.4.12B-14). This method of calculating the derivative at data point i uses data points separated logarithmically in time by a differentiation interval, L, that normally ranges between 0.1 and 0.5 log cycles of time. A value of 0.5 was chosen for L based on trial and error. The following setting was used in AQTESOLV®:



The drawdown derivative represents the slope of the drawdown curve, if the rate of drawdown change is constant, then the derivative is a horizontal line. The derivative curve is more sensitive to subtle changes in the drawdown rate than are the direct drawdown measurements. The Agarwal equivalent time (t_{equiv}) for recovery measurements is determined from (Reference 2.4.12B-10):

$$t_{equiv} = \frac{t_p \times t'}{t_p + t'}$$ Equation 2.4.12B-2

where:

t' = time since pumping stopped

t_p = total time of pumping

The following diagnostic plots presented in Reference 2.4.12B-13 illustrate pumping and recovery responses to various hydrogeologic conditions:

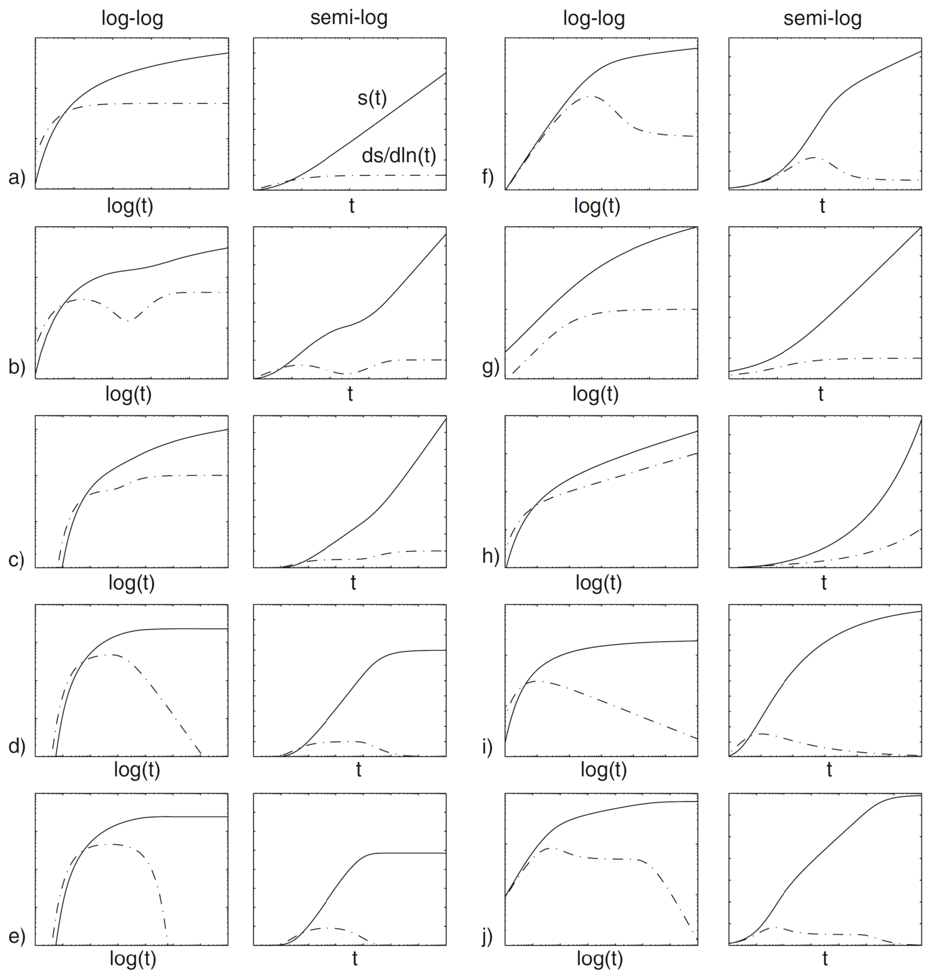


Fig. 2 Most typical diagnostic plots encountered in hydrogeology: **a** Theis model: infinite two-dimensional confined aquifer; **b** double porosity or unconfined aquifer; **c** infinite linear no-flow boundary; **d** infinite linear constant head boundary; **e** leaky aquifer; **f** well-bore storage and skin effect; **g** infinite conductivity vertical fracture.; **h** general radial flow—non-integer flow dimension smaller than 2; **i** general radial flow model—non-integer flow dimension larger than 2; **j** combined effect of well bore storage and infinite linear constant head boundary (modified from Renard 2005b)

Note: Plots above, including notes underneath, excerpted from Reference 2.4.12B-13

Figures 2.4.12B-9 through 2.4.12B-15 present the diagnostic plots for the wells selected for analysis. Examination of the diagnostic plots suggests that a majority of the wells exhibit a response approximating a leaky aquifer model when comparing the APT diagnostic plots to the responses depicted by Reference 2.4.12B-13 and shown above in graph e). An exception to this generalization is at OW-423L during the pumping period, which shows a response intermediate between a) the standard Theis confined aquifer model and e) the leaky aquifer model on the above graph.

Another method of examining the data is to use distance-drawdown plots. For these plots, the drawdown at a given time is plotted versus the well's distance from the pumping well. Figures 2.4.12B-16 and 2.4.12B-17 present the distance-drawdown plots at 2880 minutes after the start of pumping for the upper and lower monitoring zones respectively. Both plots suggest directional anisotropy in the observation well array. For isotropic conditions the drawdown would be the same at a given distance from the pumping well, regardless of the orientation of the observation point relative to the pumping well. Figures 2.4.12B-16 and 2.4.12B-17 show observation wells that are approximately the same distance from the pumping well have significant differences in drawdown, thus indicating directional anisotropy in the aquifer.

2.4.12B.3.4 Hantush Leaky Aquifer Method

AQTESOLV® contains a number of leaky aquifer analytical models, but the most commonly used are the Hantush leaky aquifer models, which includes a method without aquitard storage (Hantush-Jacob method) and a method with aquitard storage (Hantush method). The Hantush-Jacob method was selected for the analysis because it best represented the drawdowns and derivatives of drawdowns observed during the pumping test.
Reference 2.4.12B-15 presents the Hantush-Jacob solution for the unsteady drawdown near a well discharging from an infinite leaky aquifer. The discharge is supplied by the reduction of storage through expansion of water and compression of the aquifer matrix, and also by leakage through the confining bed. The leakage is assumed to be proportional to the drawdown. During the early time of pumping from the leaky aquifer, water is moving through the leaky aquifer and then later it moves through the leaky confined aquifer and the confining bed. Eventually, the pumping well discharge equilibrates with the leakage through the confining bed and the system is in steady-state. Storage in the confining bed is neglected and all the observation wells are assumed to be within the leaky confined aquifer.

This method includes two options: the complete solution and the early time solution. The complete solution was used for all wells except the pumping period for OW-423L, which used the early time solution. The early time solution is used for the transition period from confined to leaky flow. The Hantush-Jacob leaky aquifer method solution is obtained from (Reference 2.4.12B-12):

$$s = \frac{Q}{4\pi T} W(u, r/B)$$ Equation 2.4.12B-3

where:

s	=	drawdown [L]
T	=	transmissivity [L^2/T]
Q	=	Pumping rate [L^3/T]
r	=	distance from pumping well [L]
W(u,r/B)	=	Hantush leaky well function
u	=	r^2 S/4Tt
S	=	storativity
B	=	leakage factor [L]

$$\frac{r}{B} = \frac{r}{\sqrt{T/(K'/b')}}$$ Equation 2.4.12B-4

where:

K'	=	hydraulic conductivity of confining bed [L/T]
b'	=	thickness of confining bed [L]

The solution includes the following key conditions (Reference 2.4.12B-10):

- The pumping well is either fully or partially penetrating.

- The aquifer has infinite areal extent.
- The aquifer is homogeneous and of uniform thickness.
- The aquifer is leaky confined.
- The flow in the aquifer is unsteady.
- Water is released instantaneously from storage with decline of hydraulic head.
- The diameter of the pumping well is very small so that storage in the well can be neglected.
- The confining bed has infinite areal extent, uniform vertical hydraulic conductivity, and thickness.
- The confining bed is overlain or underlain by an infinite constant-head plane source.
- Flow is vertical in the confining bed.

The leakage through the confining bed is approximately proportional to drawdown in the leaky aquifer. The Hantush-Jacob solution does not include the impacts of skin effect in the pumping well.

The solution allows correction for partial penetration effects. Partial penetration effects become negligible when (Reference 2.4.12B-10):

$$r > \frac{1.5\,b}{\sqrt{K_z/K_r}} \qquad \text{Equation 2.4.12B-5}$$

where:

r	=	distance from pumping well [L]
b	=	aquifer thickness [L]
K_z/K_r	=	anisotropy ratio [dimensionless]

The aquifer thickness was taken to be 155 ft, which represents the difference between the static water level in the pumping well and the bottom elevation of the primary flow zone as described in Section 2.4.12B.3. (A review of the geologic log cores did not identify an overlying confining bed; it is presumed that leakage is derived from an underlying confining bed.) Using an aquifer thickness of 155 ft and an anisotropy ratio of 0.1 (Subsection 2.4.12B.3), a minimum distance from the pumping well of 735 ft is needed for partial penetration effects to become negligible. All of the supplemental wells and OW-423U/L/D are less than this distance from the pumping well.

The condition that the pumping well diameter is very small is valid for the observation wells, but is not valid for the pumping well. Therefore the water level data from the pumping well were not analyzed using this method.

2.4.12B.4 Results and Discussion

Figures 2.4.12B-18 through 2.4.12B-23 present the Hantush-Jacob solution with partial penetration for the observation wells. The results are summarized on Table 2.4.12B-3. The hydraulic conductivity values are calculated by dividing the transmissivity by the saturated thickness of the aquifer. The hydraulic conductivity represents an average for the thickness of the aquifer. Reference 2.4.12B-6 indicates that the bulk (or average) hydraulic conductivity is an aggregation of thin conductive (fractured) zones and thicker less conductive (unfractured) zones at the adjacent ORR.

Comparison of the results with the observation well orientations (Figure 2.4.12B-3) suggests that the maximum transmissivity and hydraulic conductivity occur in OW-423L, which is oriented with the N52°E strike of the bedding planes. Perpendicular to this orientation (N38°W), or along dip, the transmissivity and hydraulic conductivity are approximately an order of magnitude lower.

To evaluate the reasonableness of the results of this test, they were compared against multiple APTs performed in the Conasauga Group in Bear Creek Valley on the adjacent ORR, presented by Reference 2.4.12B-16. The test results were from the Nolichucky Shale and Maynardville Limestone Formations (Figure 2.4.12B-2) of the Conasauga Group, which have similar lithologies as the units tested during this investigation. The following are the ranges of properties:

	Reference 2.4.12B-16	CRN Site Investigation
Transmissivity (ft^2/d):	2.7–8120	7–410
Storage Coefficient (dimensionless):	9.0×10^{-6}–6.6×10^{-3}	8.1×10^{-3}–4.8×10^{-2}
Hydraulic Conductivity (ft/d):	0.0283–99	0.06–2.6

Comparison of the test results to the published results indicates that, with the exception of the storage coefficients determined at PT-OW-L1, PT-OW-U2, PT-OW-L2, and OW-423L, data from this test fall within the range of tests performed on the adjacent ORR. Insufficient information is available for the ORR tests to allow postulation of reasons for the deviation of the storage coefficient values.

The leakage factors (1/B) determined from the type curve solution (Figures 2.4.12B-18 through 2.4.12B-23) range from 1.3×10^{-2} to 5.7×10^{-2} ft^{-1}. This indicates that the leakage from the confining bed is consistent in the vicinity of the pumping well.

2.4.12B.5 Conclusion

An APT was performed at the CRN Site and was analyzed using AQTESOLV® to determine estimates of transmissivity, storage coefficient, and hydraulic conductivity. The results of the test indicate that horizontally anisotropic conditions are present, with the highest transmissivity and hydraulic conductivity along the strike of the bedding planes (N52°E). The results of the APT are used in the site groundwater flow model described in Appendix 2.4.12C.

The results in Subsection 2.4.12B.4 should be qualified by the fact that the APT was performed in a fractured rock environment, but the solution method used utilizes a homogeneous porous media model and the conceptual model inherent in the analytical solution may not be an exact representation of the site conditions. While this analysis approach is common in the industry, errors in these results could be up to an order of magnitude.

2.4.12B.6 References

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Table 2.4.12B-1 (Sheet 1 of 2)
Pumping and Observation Well Data

Well Name	Screened Interval[(a)] (ft bgs)	Well Casing Inner Diameter[(b)] (in)	Well Casing Inner radius[(c)] (ft)	Distance from Pumping Well (ft)	Data Quality Assessment	
					Background/Pumping and Recovery Plot Evaluation	Conclusion
PT-PW	39.3–169.3	6.031	0.251	0	Relatively stable background Good response to pumping	Retain for analysis
PT-OW-U1	41.8–61.8	2.049	0.086	81	Relatively stable background Good albeit truncated response to pumping—use manual readings	Retain for analysis
PT-OW-L1	139.7–159.7	2.049	0.086	61	Relatively stable background Good response to pumping	Retain for analysis
PT-OW-U2	42–62	2.049	0.086	74	Limited response during step test Apparent response to pumping with incomplete recovery	Retain for analysis
PT-OW-L2	139.8–159.8	2.049	0.086	59	Slight upward trend in background Good response to pumping but incomplete recovery	Retain for analysis
PT-OW-U3	42.6–62.6	2.049	0.086	83	Downward trend in background Apparent response to pumping but no recovery	Discarded from analysis—background trend
PT-OW-L3	140.5–160.5	2.049	0.086	62	Relatively stable background Good response to pumping	Retain for analysis
OW-423U	42.2–62.2	2.049	0.086	101	Downward trend in background Well recovers to above static at 3366 minutes	Discarded from analysis—background trend
OW-423L	139.6–159.6	1.913	0.080	81	Noisy transducer, relatively stable background Good response to pumping with incomplete recovery	Retain for analysis
OW-423D	248.1–268.1	1.913	0.080	42	Very noisy background Complex pumping response with no recovery	Discarded from analysis—not within primary flow zone
OW-202U	15.7–35.7	2.049	0.086	508	Variable background Apparent response to pumping with no recovery	Discarded from analysis—background trend
OW-202L	150.5–170.5	1.913	0.080	524	Slightly noisy background with downward trend Apparent response to pumping with no recovery	Discarded from analysis—background trend
OW-202D	276.4–296.4	1.913	0.080	558	Noisy background Noisy pumping period with complex response to pumping and no recovery	Discarded from analysis—not within primary flow zone
OW-428U	40.4–60.4	2.049	0.086	810	Limited manual measurements appears to show response to pumping	Discarded from analysis—insufficient data

Table 2.4.12B-1 (Sheet 2 of 2)
Pumping and Observation Well Data

Well Name	Screened Interval[(a)] (ft bgs)	Well Casing Inner Diameter[(b)] (in)	Well Casing Inner radius[(c)] (ft)	Distance from Pumping Well (ft)	Data Quality Assessment	
					Background/Pumping and Recovery Plot Evaluation	Conclusion
OW-428L	115.2–135.2	2.049	0.086	812	Limited manual measurements appears to show response to pumping	Discarded from analysis—insufficient data
OW-428D	190.2–210.2	1.913	0.080	817	Limited manual measurements appears to show response to pumping	Discarded from analysis—not within primary flow zone
OW-409U	54.9–74.9	2.049	0.086	881	Variable background Complex response to pumping	Discarded from analysis—background trend
OW-409L	89.1–109.1	2.049	0.086	866	Downward trend in background Apparent response to pumping with recovery above static level	Discarded from analysis—background trend
OW-101U	26–46	2.049	0.086	1202	Downward trend in background Apparent pumping response with incomplete recovery	Discarded from analysis—background trend
OW-101L	138–158	1.913	0.080	1179	Downward trend in background Apparent pumping response with incomplete recovery	Discarded from analysis—background trend
OW-101D	230.5–250.5	1.913	0.080	1168	Variable background Complex response to pumping	Discarded from analysis—not within primary flow zone
OW-417U	50–70	2.049	0.086	2184	Downward trend in background Complex response to pumping	Discarded from analysis—background trend
OW-417L	95–115	2.049	0.086	2224	Downward trend in background Complex response to pumping	Discarded from analysis—background trend

(a) Reference 2.4.12B-7.
(b) Reference 2.4.12B-17 for schedule 40 PVC and Reference 2.4.12B-18 for schedule 80 PVC.
(c) (Well Casing Inner Diameter/2)/12 in./ft.
bgs = below ground surface

Table 2.4.12B-2 (Sheet 1 of 3)
Well Pumping Rates Measured During the Constant Rate Test

Date/Time	Elapsed Time in (minutes)	Volume Pumped (gallons)	Calculated flow rate (gpm)	Notes
3/21/2014 12:00	0	7	14	30 second reading
3/21/2014 12:02	2	15	15	1 minute reading
3/21/2014 12:03	3	15	15	1 minute reading
3/21/2014 12:06	6	13.5	13.5	1 minute reading
3/21/2014 12:07	7	25	12.5	2 minute reading
3/21/2014 12:10	10	15.5	15.5	1 minute reading
3/21/2014 12:12	12	29	14.5	2 minute reading
3/21/2014 12:21	21	73	14.6	5 minute reading
3/21/2014 12:30	30	213	14.2	15 minute reading
3/21/2014 12:45	45	213	14.2	15 minute reading
3/21/2014 13:00	60	214	14.3	15 minute reading
3/21/2014 13:15	75	214	14.3	15 minute reading
3/21/2014 13:30	90	214	14.3	15 minute reading
3/21/2014 13:45	105	213	14.2	15 minute reading
3/21/2014 14:00	120	215	14.3	15 minute reading
3/21/2014 15:00	180	855	14.3	Start 1 hour readings
3/21/2014 16:00	240	852	14.2	
3/21/2014 17:00	300	857	14.3	
3/21/2014 18:00	360	854	14.2	
3/21/2014 19:00	420	857	14.3	
3/21/2014 20:00	480	855	14.3	
3/21/2014 21:00	540	859	14.3	
3/21/2014 22:00	600	857	14.3	
3/21/2014 23:00	660	860	14.3	
3/22/2014 0:00	720	856	14.3	
3/22/2014 2:05	845	14.5	14.5	1 minute reading
3/22/2014 2:41	881	73	14.6	5 minute reading
3/22/2014 4:00	960	862	14.4	
3/22/2014 5:00	1020	863	14.4	
3/22/2014 6:00	1080	863	14.4	
3/22/2014 7:00	1140	865	14.4	
3/22/2014 8:00	1200	862	14.4	
3/22/2014 9:00	1260	861	14.4	
3/22/2014 10:00	1320	863	14.4	
3/22/2014 11:00	1380	858	14.3	
3/22/2014 12:00	1440	860	14.3	
3/22/2014 13:00	1500	856	14.3	
3/22/2014 14:00	1560	856	14.3	

Table 2.4.12B-2 (Sheet 2 of 3)
Well Pumping Rates Measured During the Constant Rate Test

Date/Time	Elapsed Time in (minutes)	Volume Pumped (gallons)	Calculated flow rate (gpm)	Notes
3/22/2014 15:00	1620	859	14.3	
3/22/2014 16:00	1680	854	14.2	
3/22/2014 17:00	1740	859	14.3	
3/22/2014 18:00	1800	856	14.3	
3/22/2014 19:00	1860	859	14.3	
3/22/2014 20:00	1920	857	14.3	
3/22/2014 21:00	1980	860	14.3	
3/22/2014 22:00	2040	862	14.4	
3/22/2014 23:00	2100	860	14.3	
3/23/2014 0:00	2160	857	14.3	
3/23/2014 1:00	2220	866	14.4	
3/23/2014 2:00	2280	861	14.4	
3/23/2014 3:00	2340	863	14.4	
3/23/2014 4:00	2400	860	14.3	
3/23/2014 5:00	2460	862	14.4	
3/23/2014 6:00	2520	863	14.4	
3/23/2014 7:00	2580	860	14.3	
3/23/2014 8:00	2640	864	14.4	
3/23/2014 9:00	2700	861	14.4	
3/23/2014 10:00	2760	861	14.4	
3/23/2014 11:00	2820	862	14.4	
3/23/2014 12:00	2880	861	14.4	
3/23/2014 13:00	2940	862	14.4	
3/23/2014 14:00	3000	860	14.3	
3/23/2014 15:00	3060	859	14.3	
3/23/2014 16:00	3120	860	14.3	
3/23/2014 17:00	3180	857	14.3	
3/23/2014 18:00	3240	860	14.3	
3/23/2014 19:00	3300	859	14.3	
3/23/2014 20:00	3360	860	14.3	
3/23/2014 21:00	3420	864	14.4	
3/23/2014 22:00	3480	862	14.4	
3/23/2014 23:00	3540	863	14.4	
3/24/2014 0:00	3600	865	14.4	
3/24/2014 1:00	3660	863	14.4	
3/24/2014 2:00	3720	866	14.4	
3/24/2014 3:00	3780	863	14.4	
3/24/2014 4:00	3840	864	14.4	

Table 2.4.12B-2 (Sheet 3 of 3)
Well Pumping Rates Measured During the Constant Rate Test

Date/Time	Elapsed Time in (minutes)	Volume Pumped (gallons)	Calculated flow rate (gpm)	Notes
3/24/2014 5:00	3900	866	14.4	
3/24/2014 6:00	3960	864	14.4	
3/24/2014 7:00	4020	864	14.4	
3/24/2014 8:00	4080	866	14.4	
3/24/2014 9:00	4140	866	14.4	
3/24/2014 10:00	4200	864	14.4	
3/24/2014 11:00	4260	867	14.5	
3/24/2014 12:00	4320	870	14.5	
3/24/2014 12:05	4325	NC	NC	Pump Turned off

Notes:

NC = Not calculated

gpm = gallons per minute

Average Flow Rate = 14.3 gpm

Table 2.4.12B-3
Aquifer Pumping Test Results

Well Name	Screened Interval (ftbgs)	Transmissivity Pumping Period (ft^2/d) T_p	Transmissivity Recovery Period (ft^2/d) T_r	Storage Coefficient Pumping Period (dimensionless)	Hydraulic Conductivity $(T_p+T_r)/2/155$ ft (ft/d)
PT-OW-U1	41.8–61.8	10.6	7	5.37×10^{-4}	0.06
PT-OW-L1	139.7–159.7	129.3	128.7	3.10×10^{-3}	0.8
PT-OW-U2	42–62	28.4	22.2	4.83×10^{-2}	0.2
PT-OW-L2	139.8–159.8	28.1	30.3	2.28×10^{-3}	0.2
PT-OW-L3	140.5–160.5	11.8	8.0	2.73×10^{-4}	0.06
OW-423L	139.6–159.6	410.1	391.1	8.91×10^{-10} [a]	2.6

(a) A storage coefficient of 8.9×10^{-10} was reported for the pumping period at OW-423L and is considered a nonrealistic value; however, for the same well in the recovery period, a value of 8.1×10^{-3} was reported—the recovery period derivative data contained less noise.

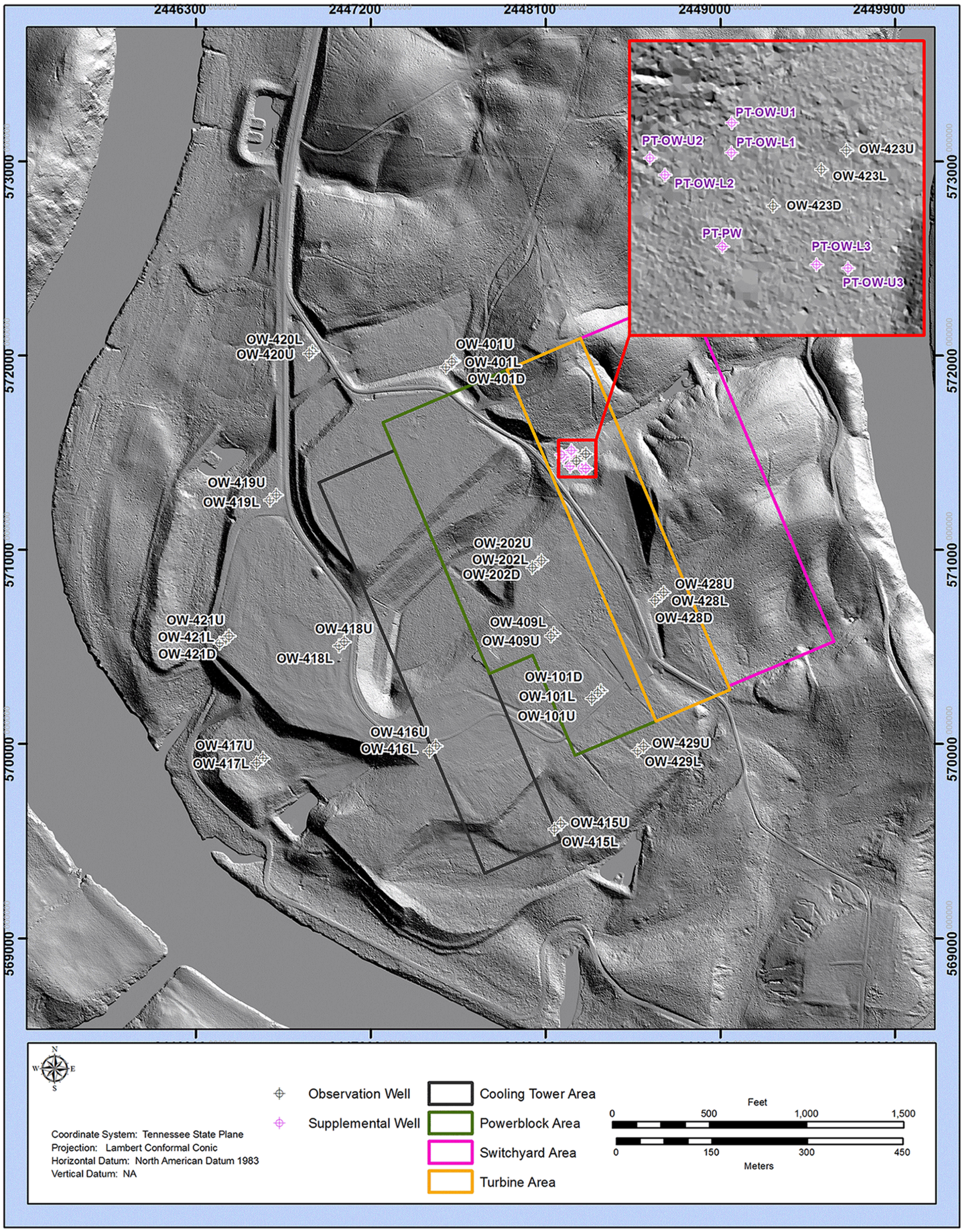
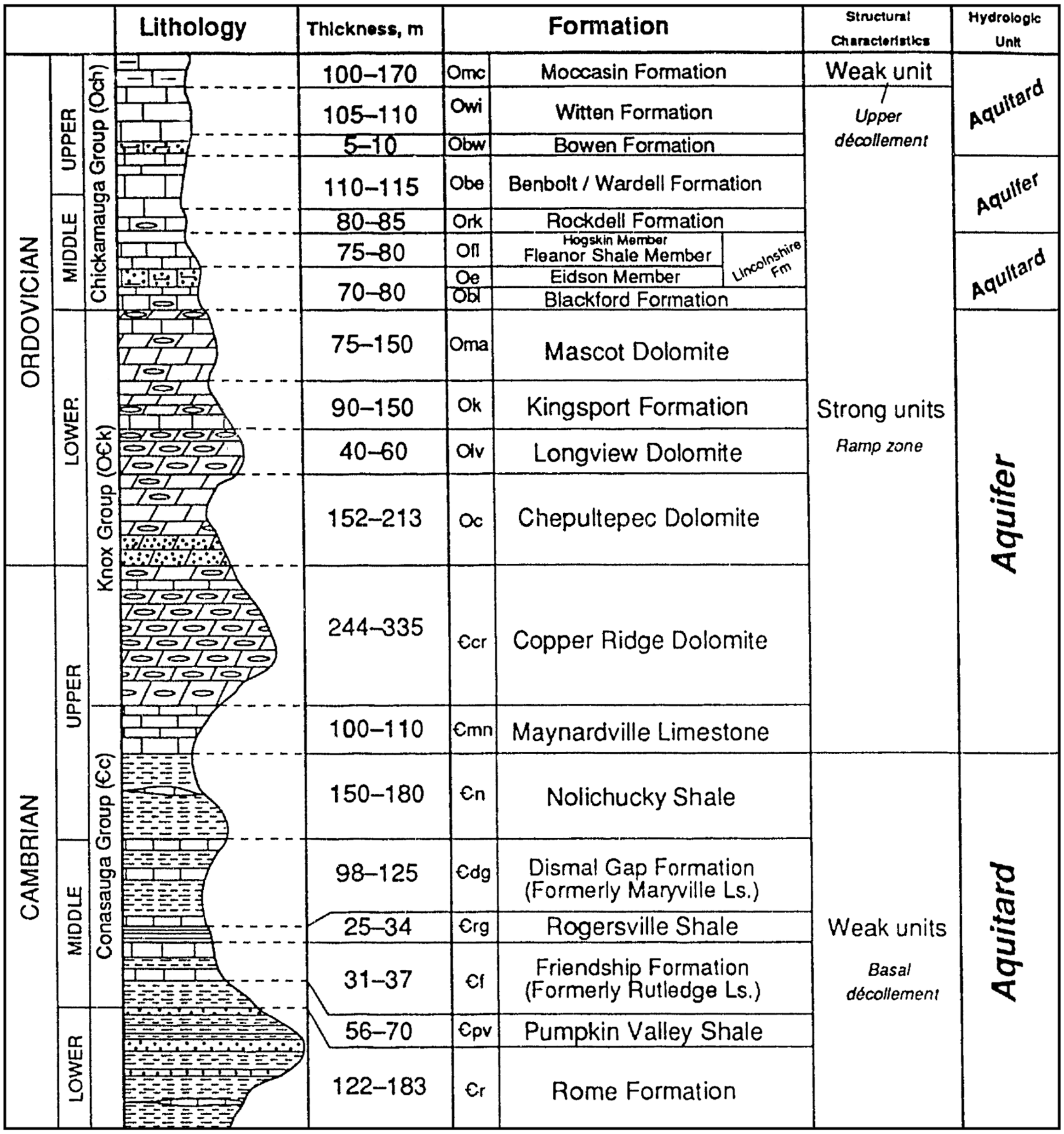


Figure 2.4.12B-1. Observation Well Locations



Source: Reference 2.4.12B-1

Figure 2.4.12B-2. Stratigraphic Section

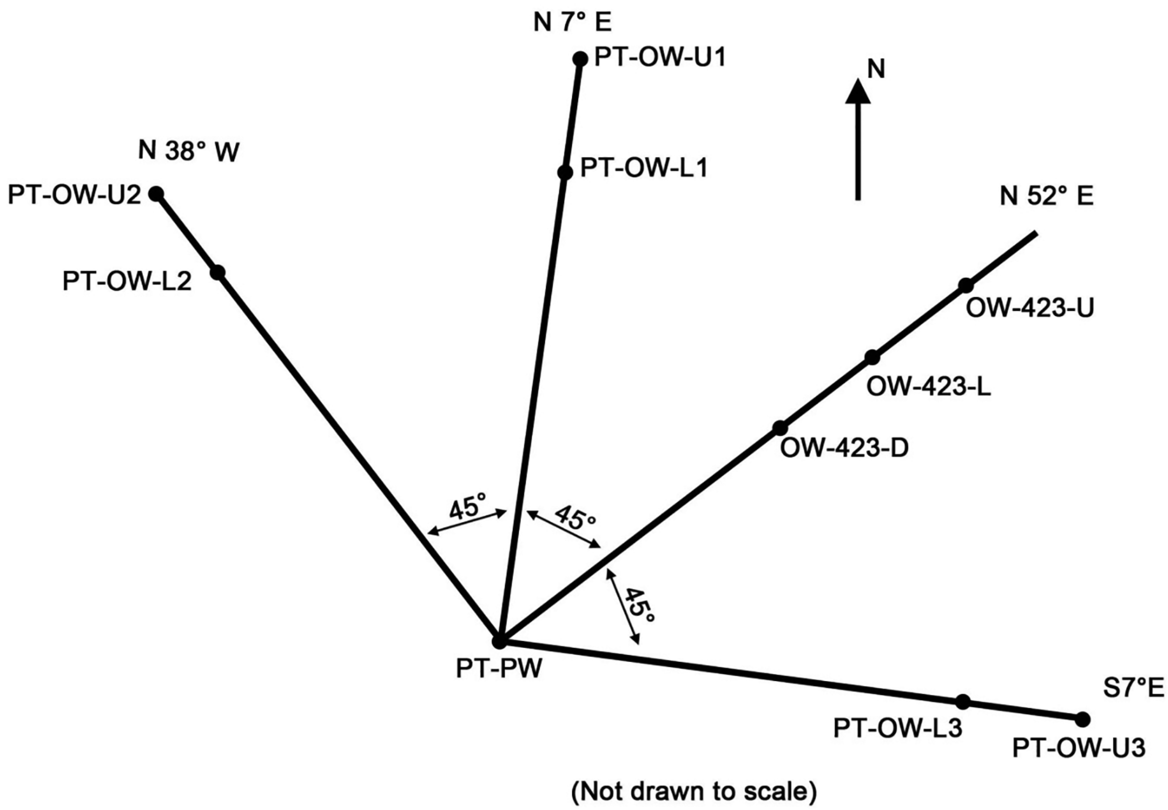


Figure 2.4.12B-3. Layout of the Supplemental Aquifer Pumping Test Wells

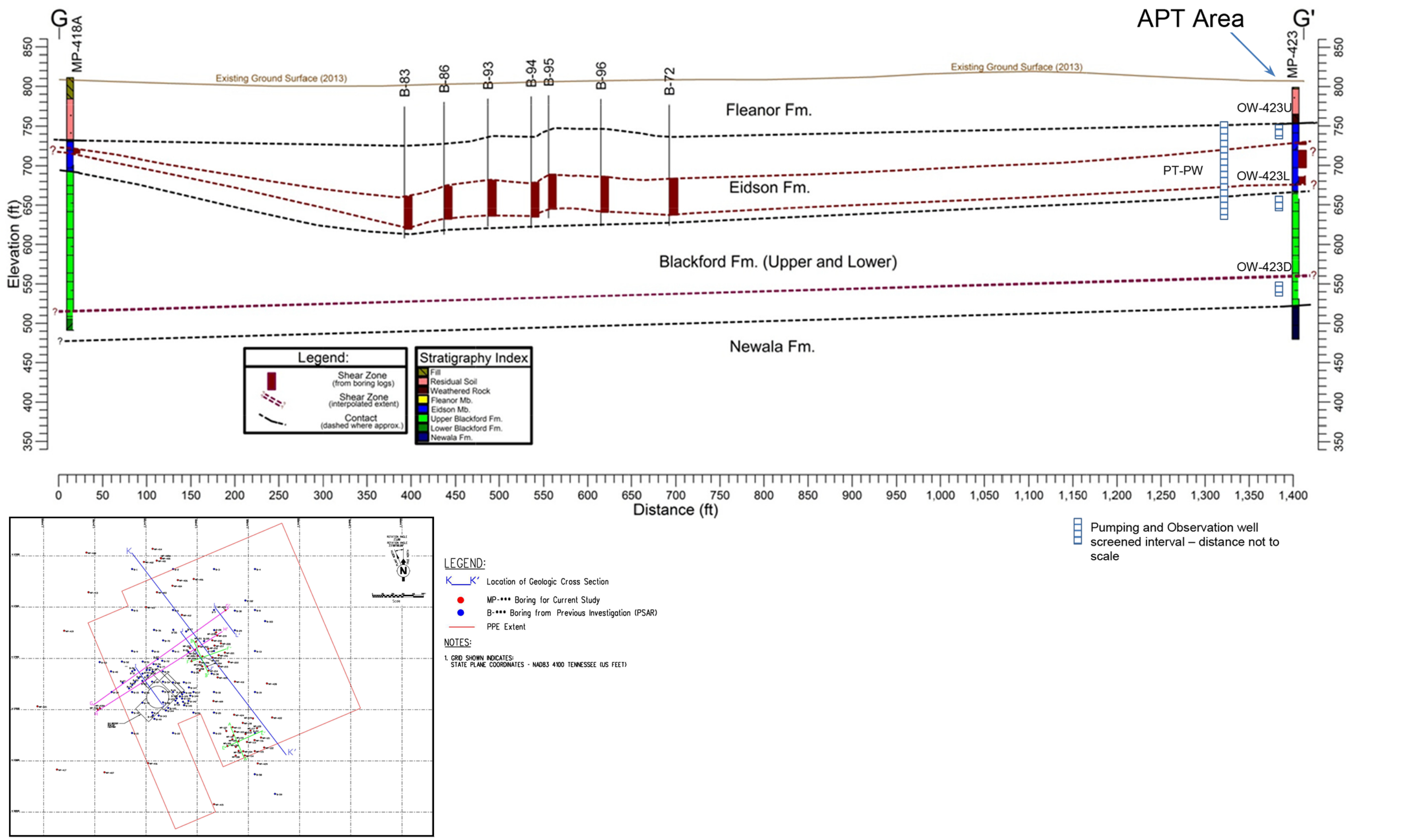


Figure 2.4.12B-4. Geologic Section Inclusive of the Aquifer Pumping Test Area

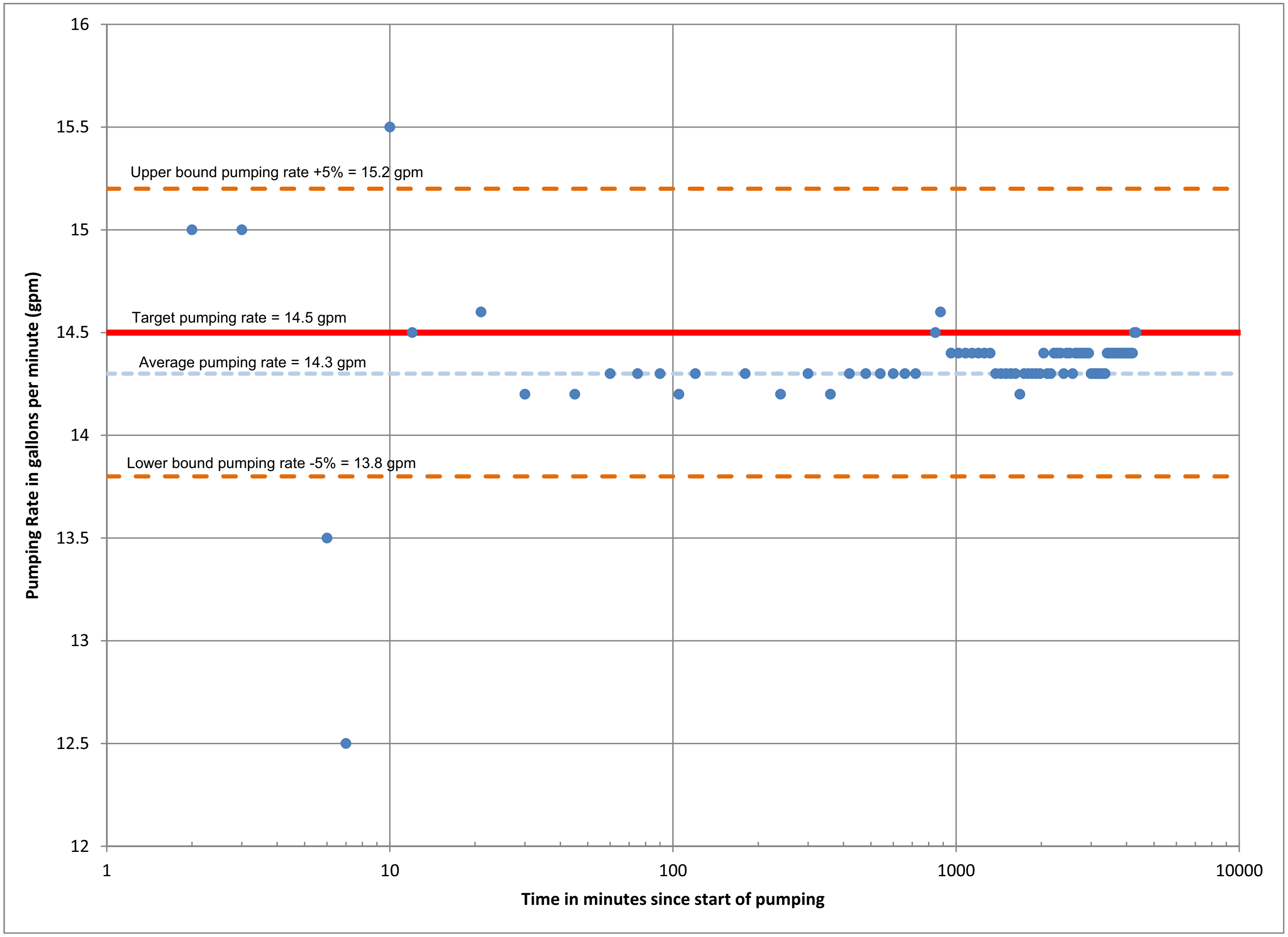
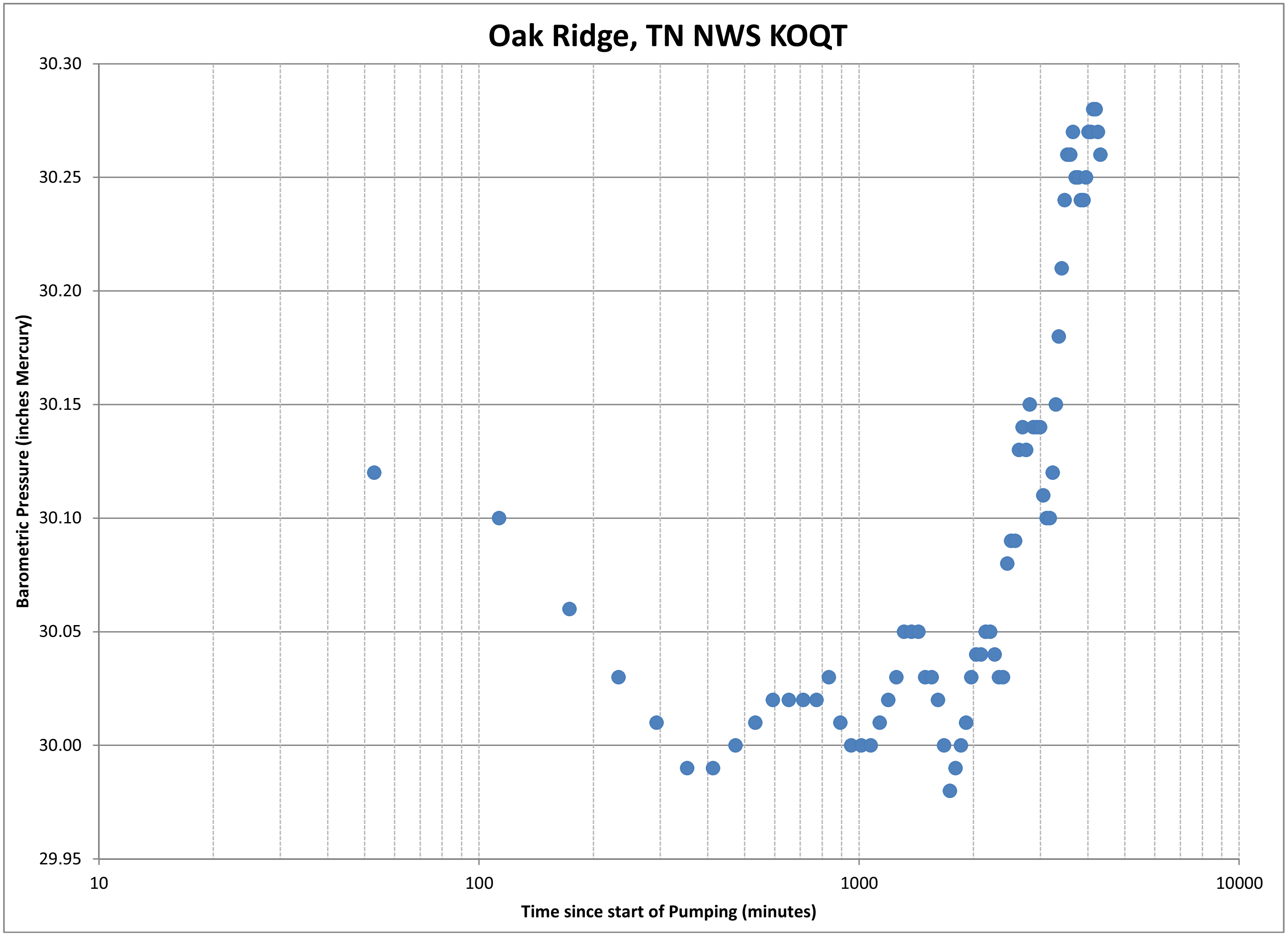


Figure 2.4.12B-5. Pumping Rate Versus Time



Note: NWS = National Weather Service

Figure 2.4.12B-6. Barometric Pressure During the Aquifer Pumping Test

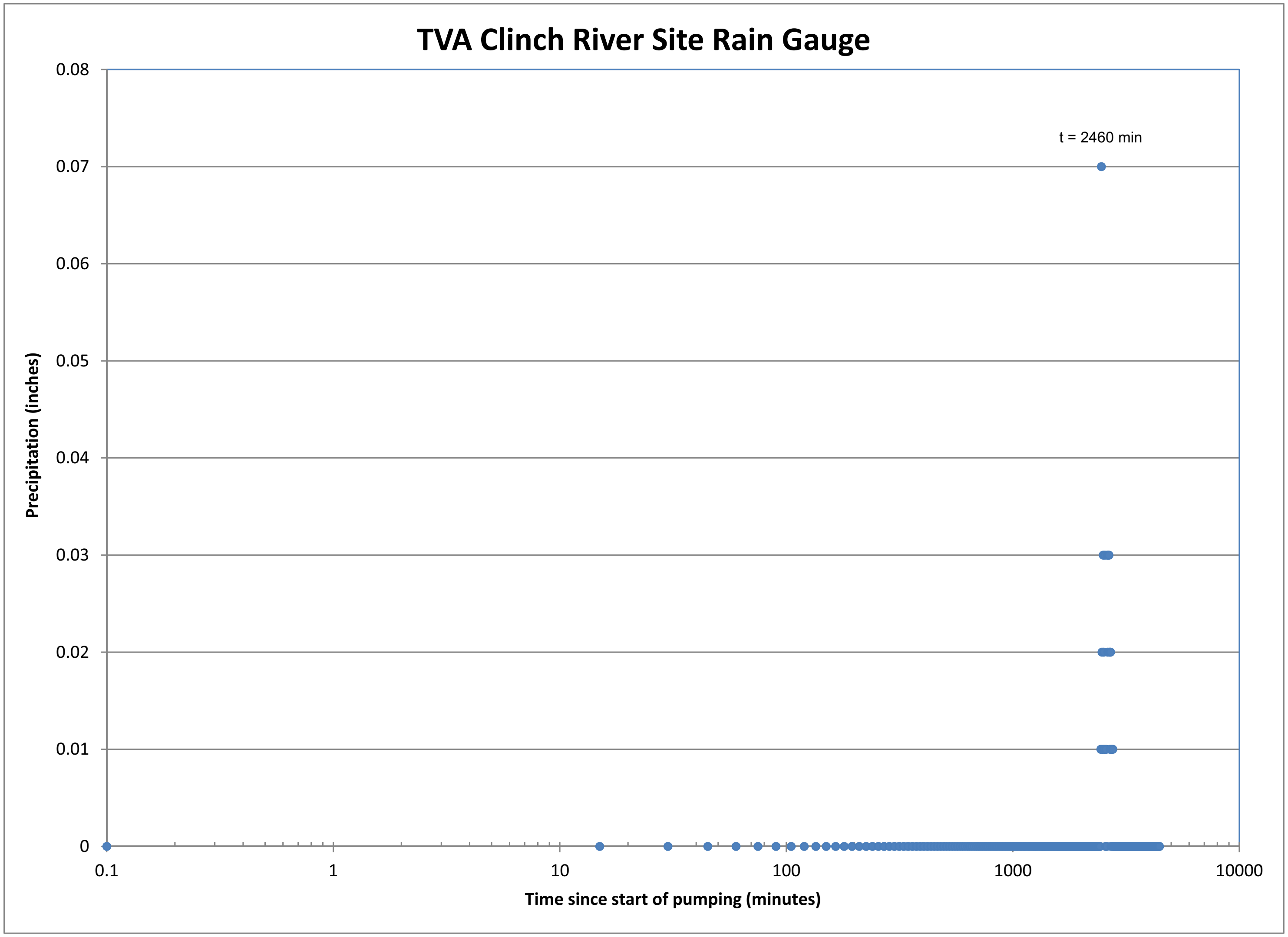


Figure 2.4.12B-7. Precipitation During the Aquifer Pumping Test

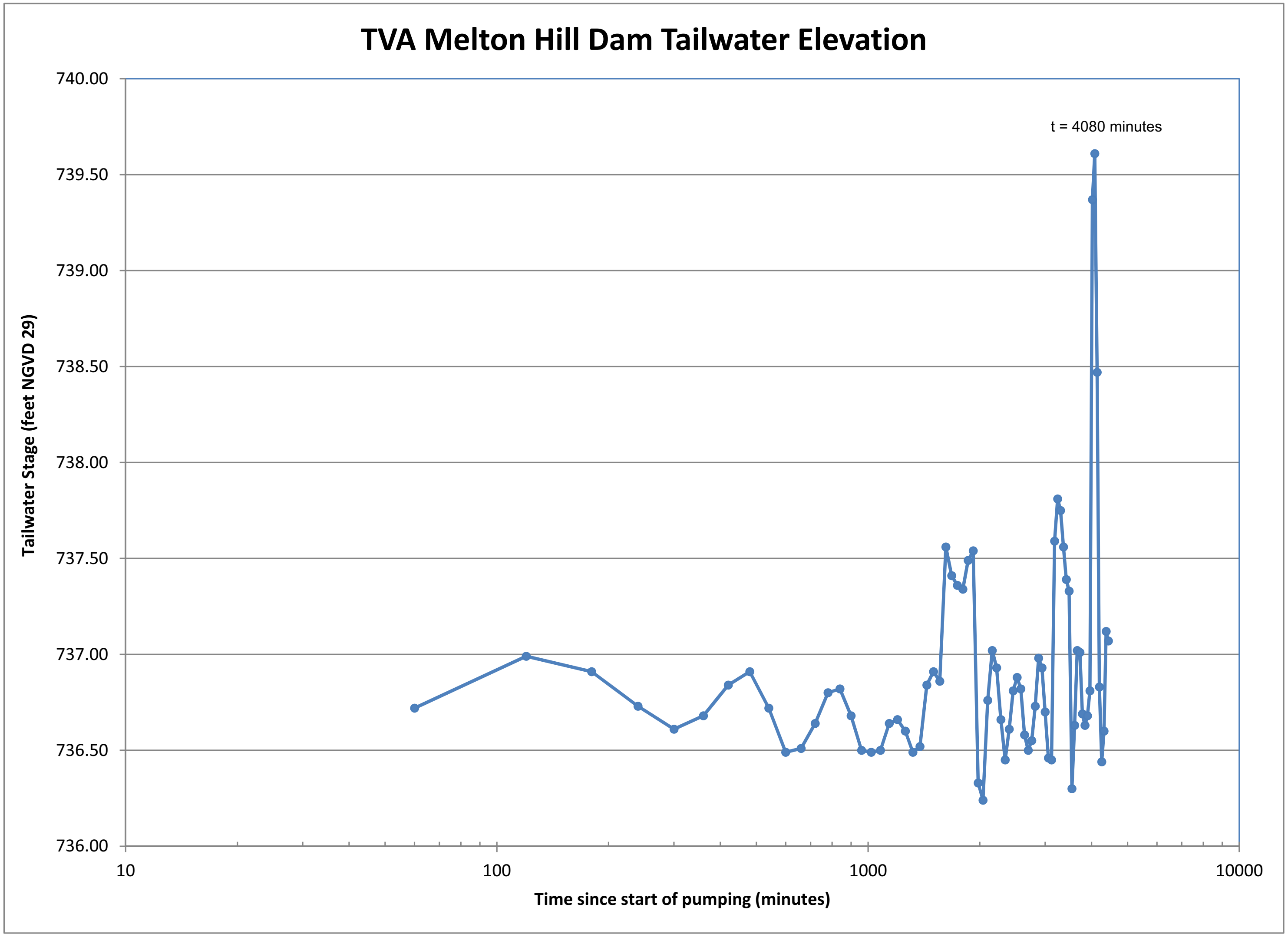
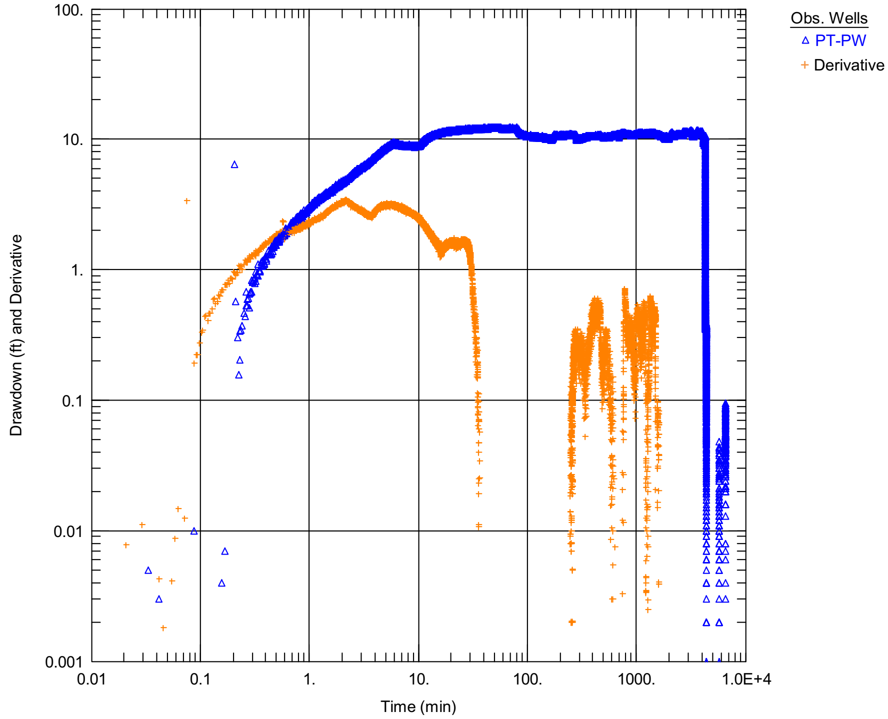
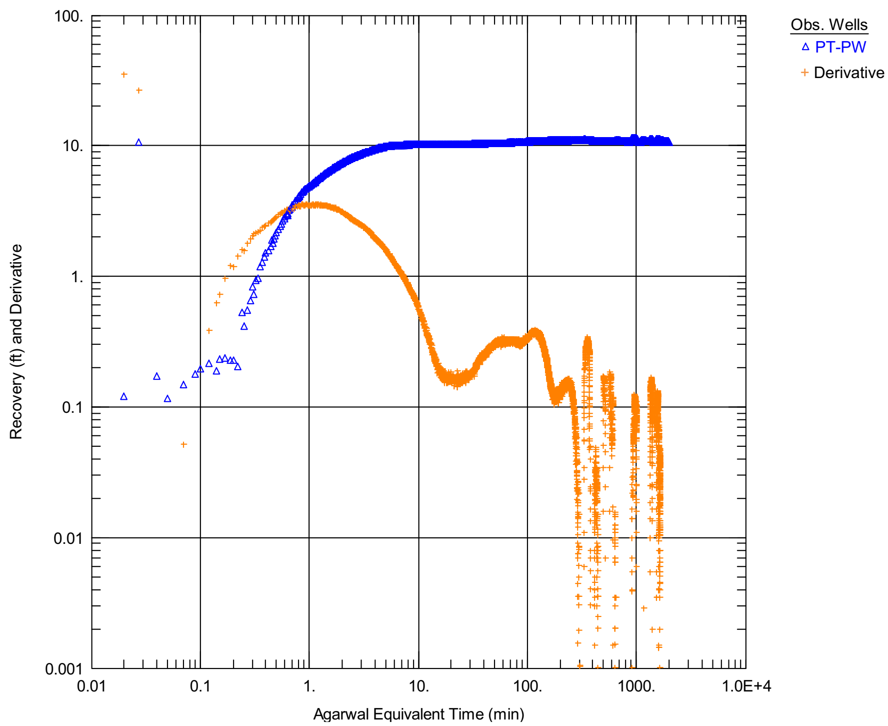


Figure 2.4.12B-8. Clinch River Stage Measurements During the Aquifer Pumping Test

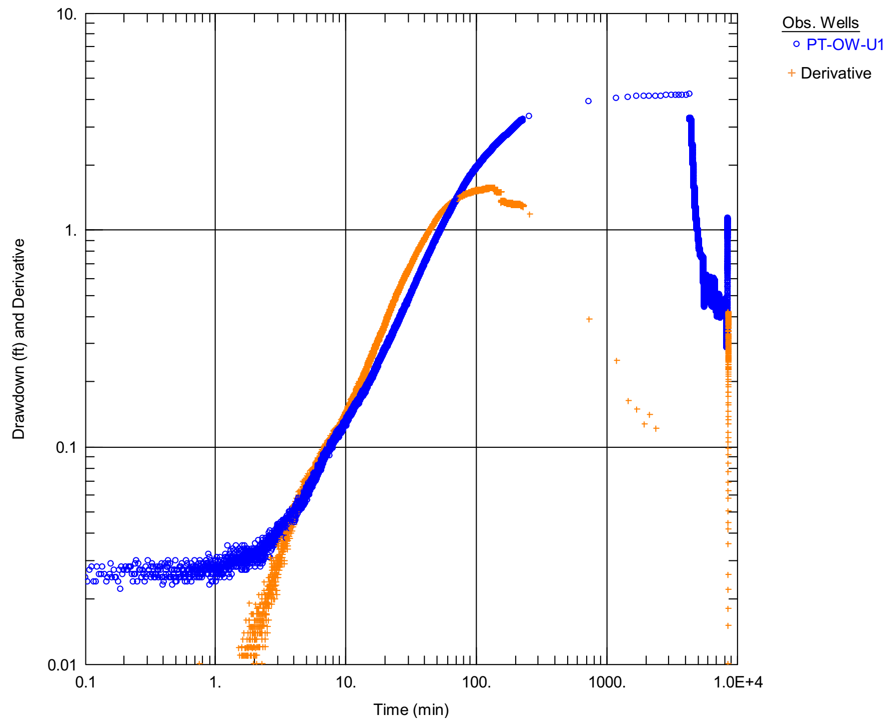


Pumping

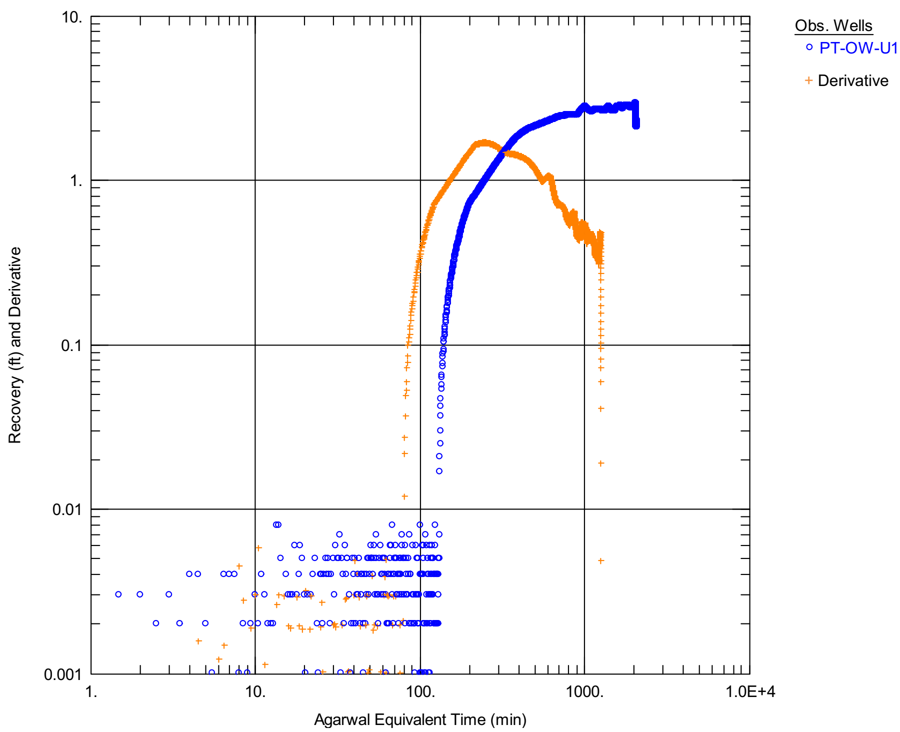


Recovery

Figure 2.4.12B-9. Pumping Well PT-PW Diagnostic Plots

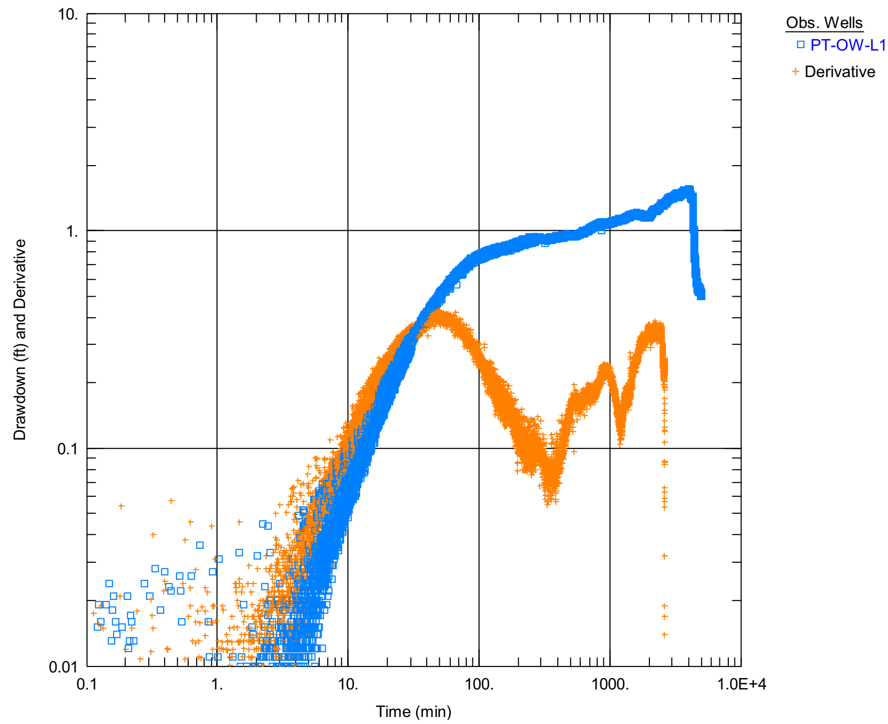


Pumping

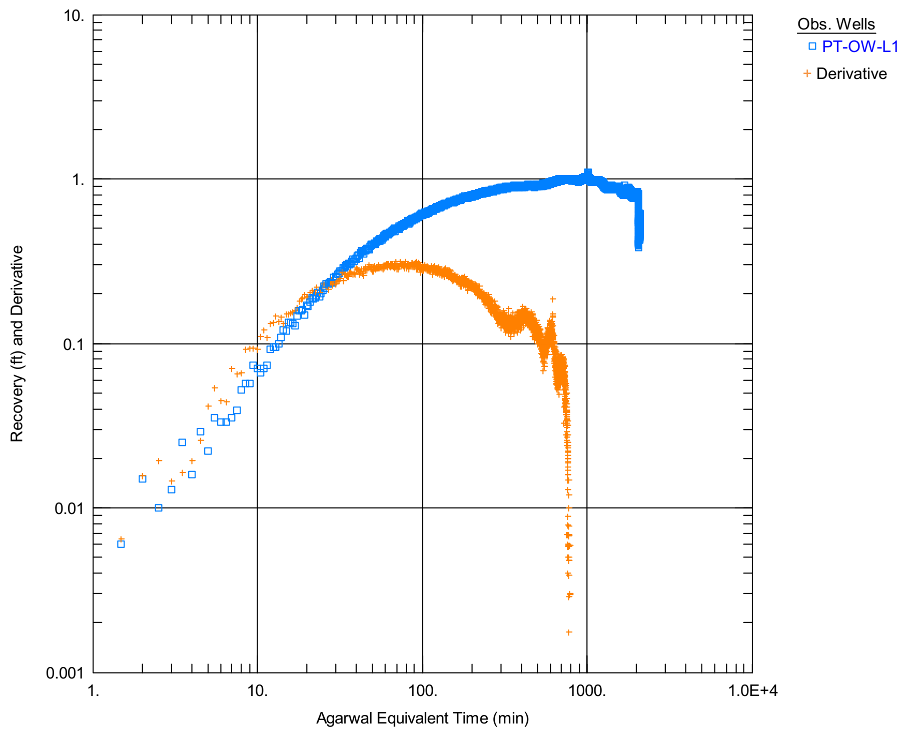


Recovery

Figure 2.4.12B-10. PT-OW-U1 Diagnostic Plots

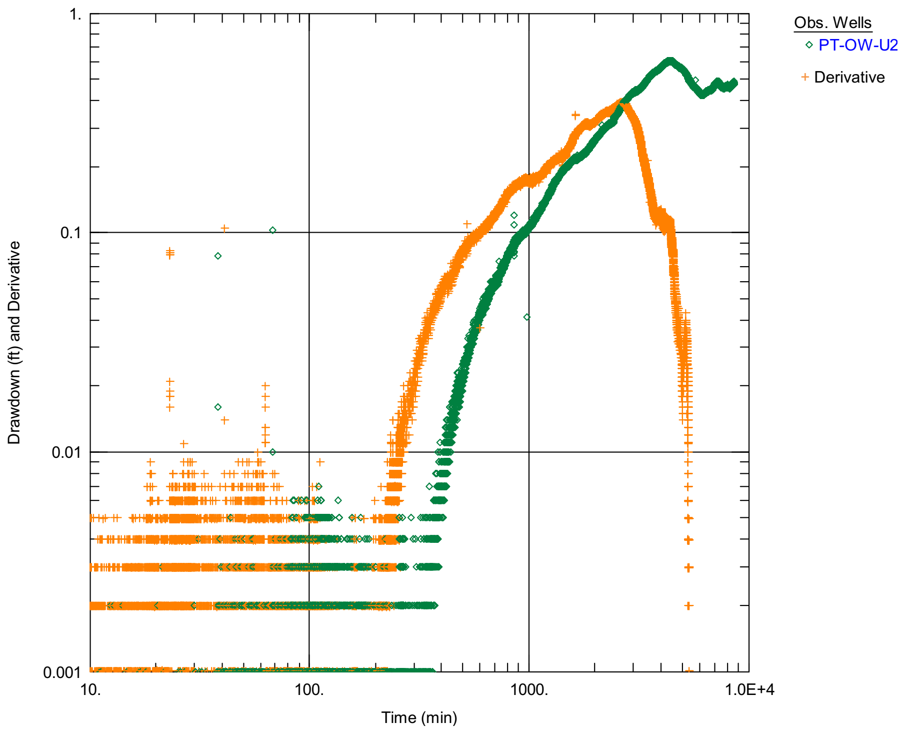


Pumping

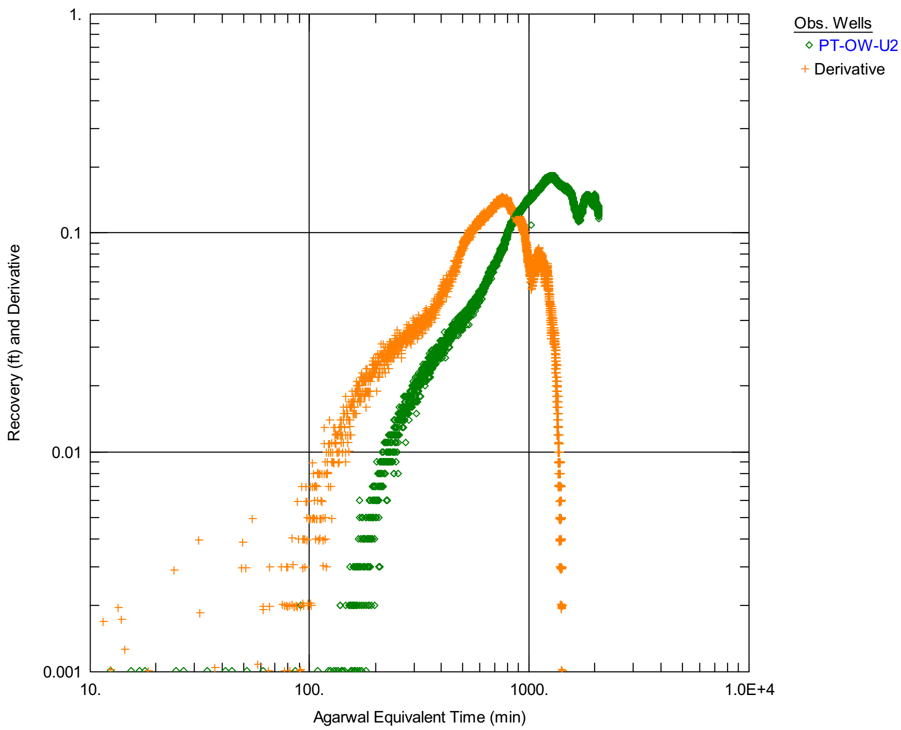


Recovery

Figure 2.4.12B-11. PT-OW-L1 Diagnostic Plots

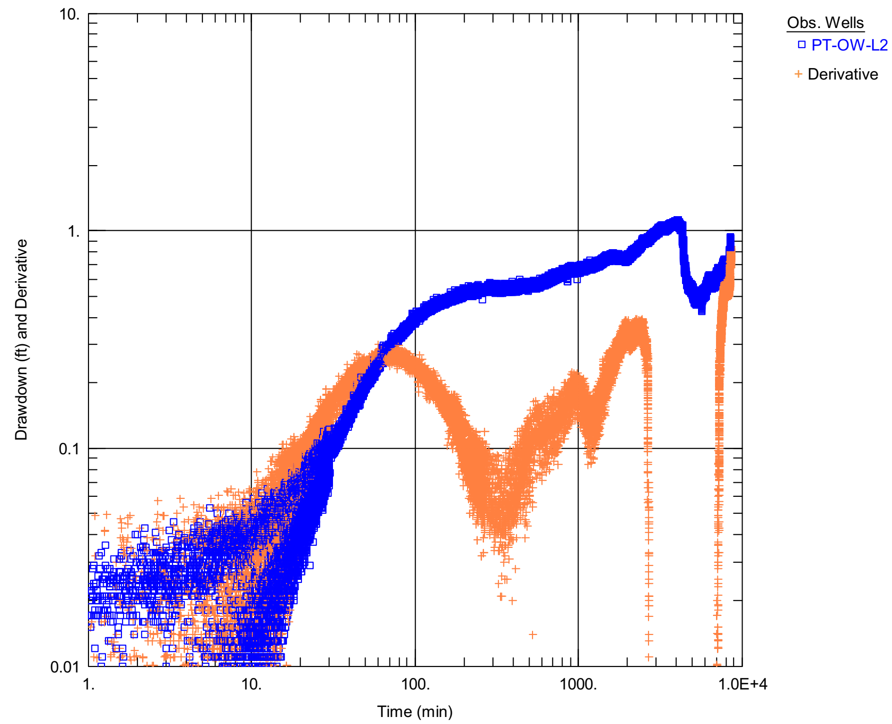


Pumping

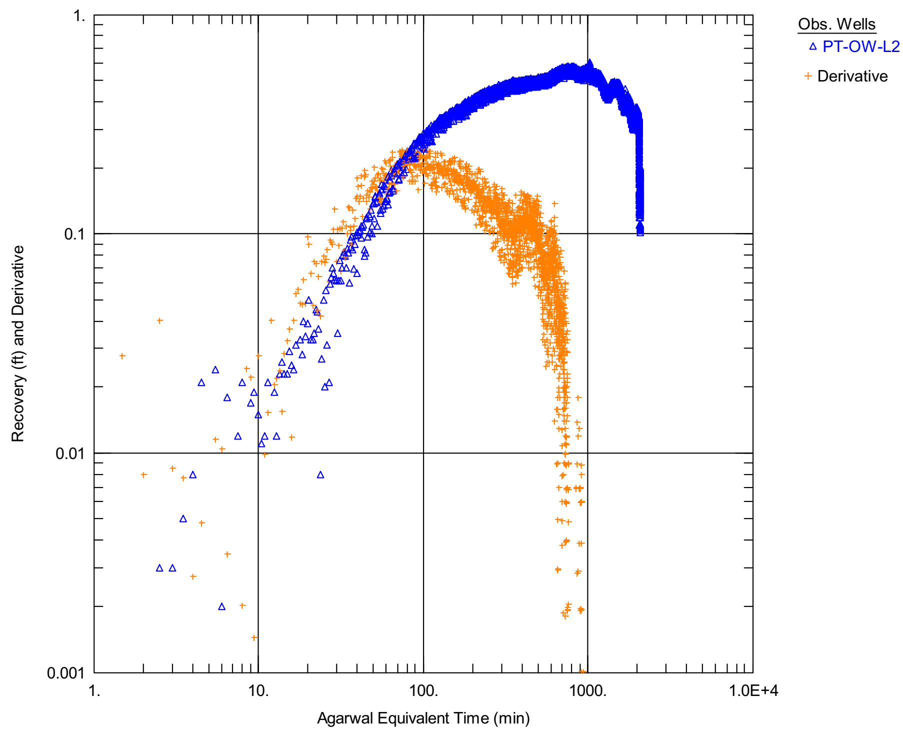


Recovery

Figure 2.4.12B-12. PT-OW-U2 Diagnostic Plots

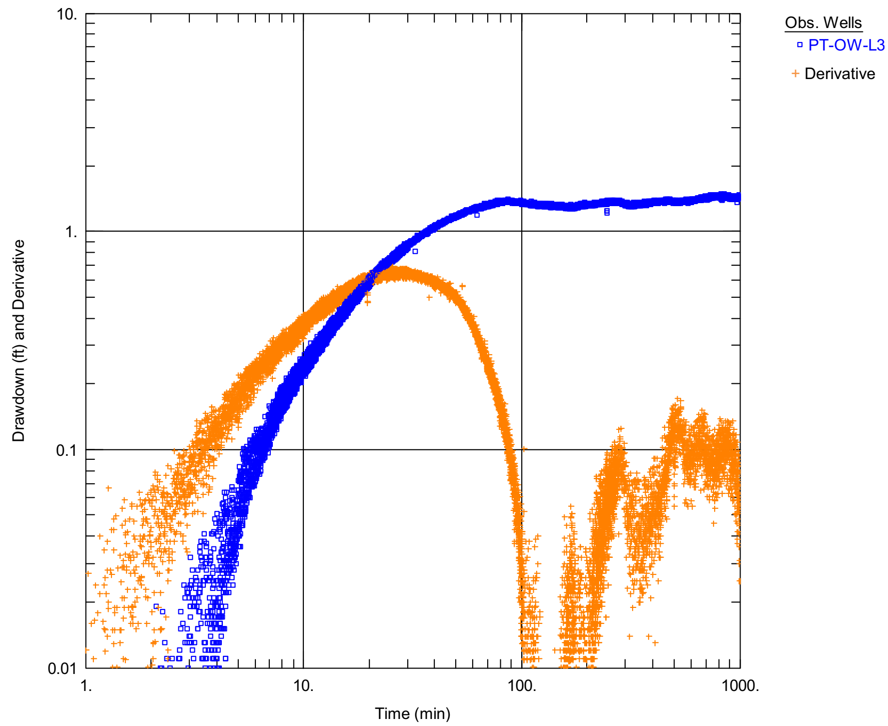


Pumping

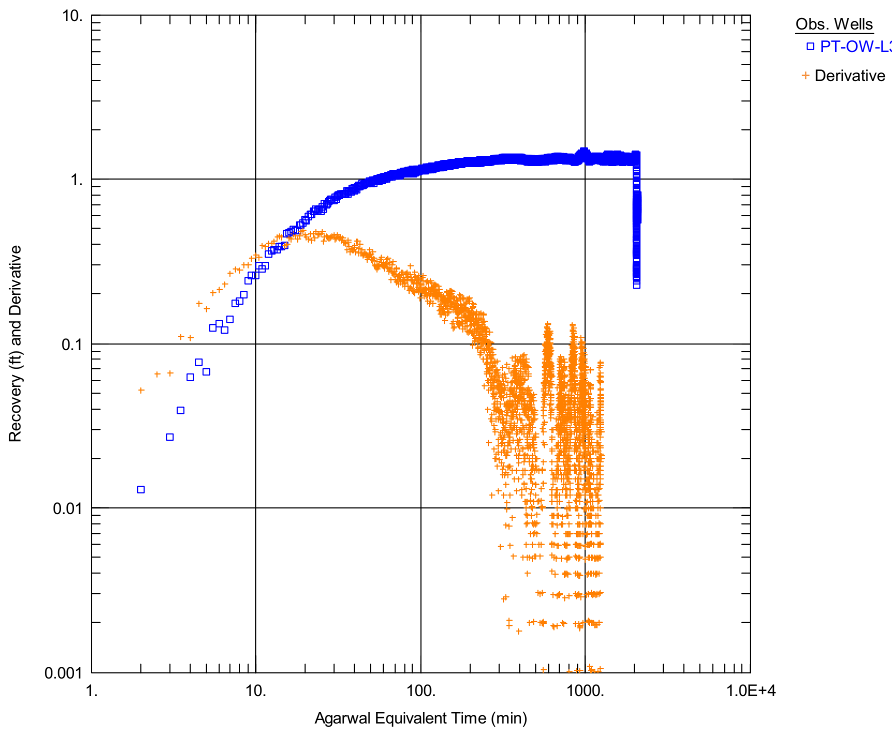


Recovery

Figure 2.4.12B-13. PT-OW-L2 Diagnostic Plots

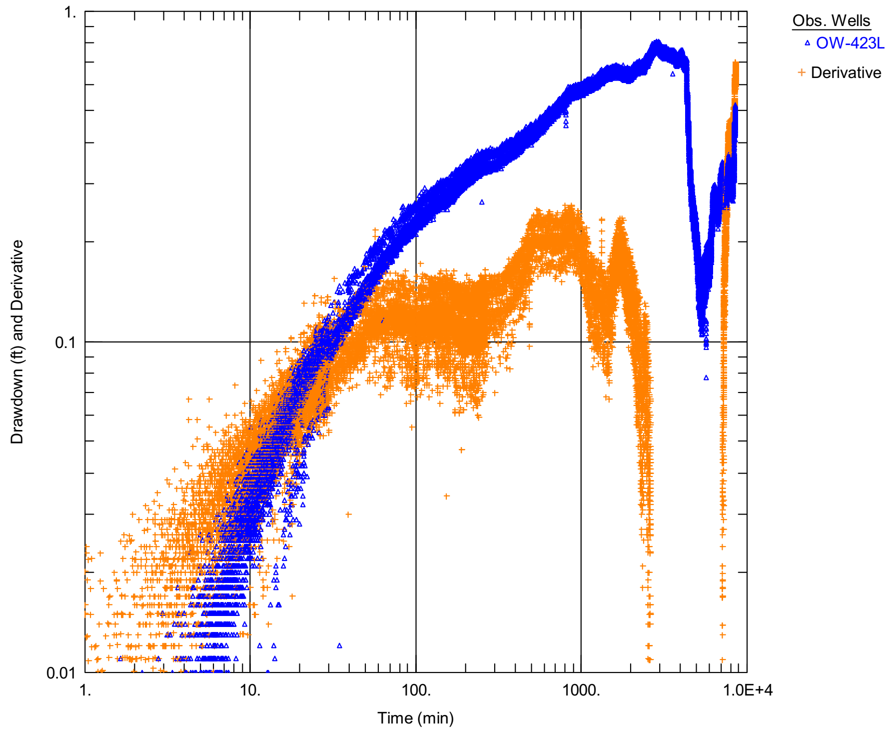


Pumping

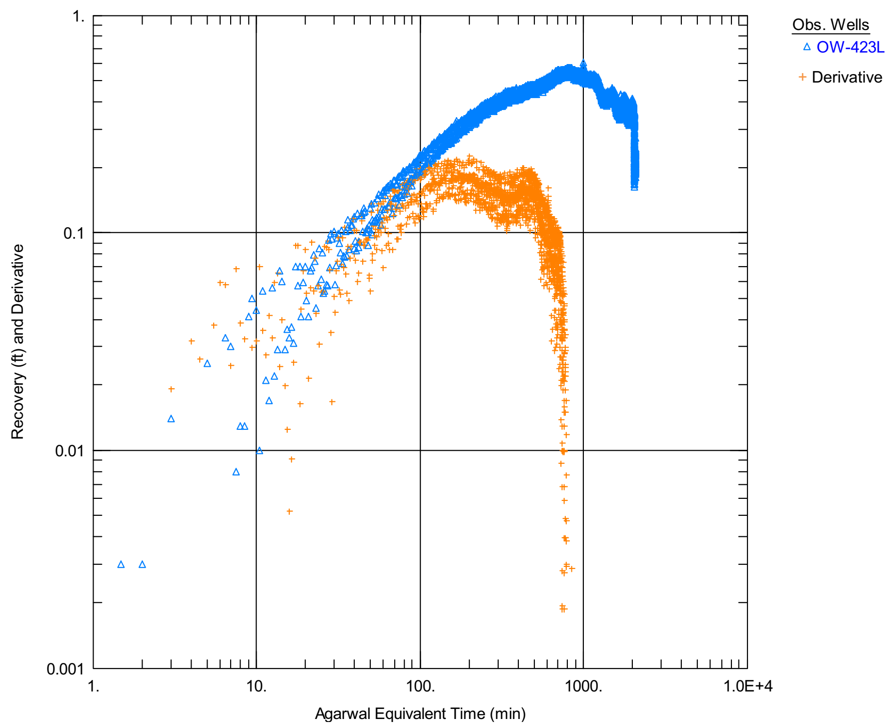


Recovery

Figure 2.4.12B-14. PT-OW-L3 Diagnostic Plots



Pumping



Recovery

Figure 2.4.12B-15. OW-423L Diagnostic Plots

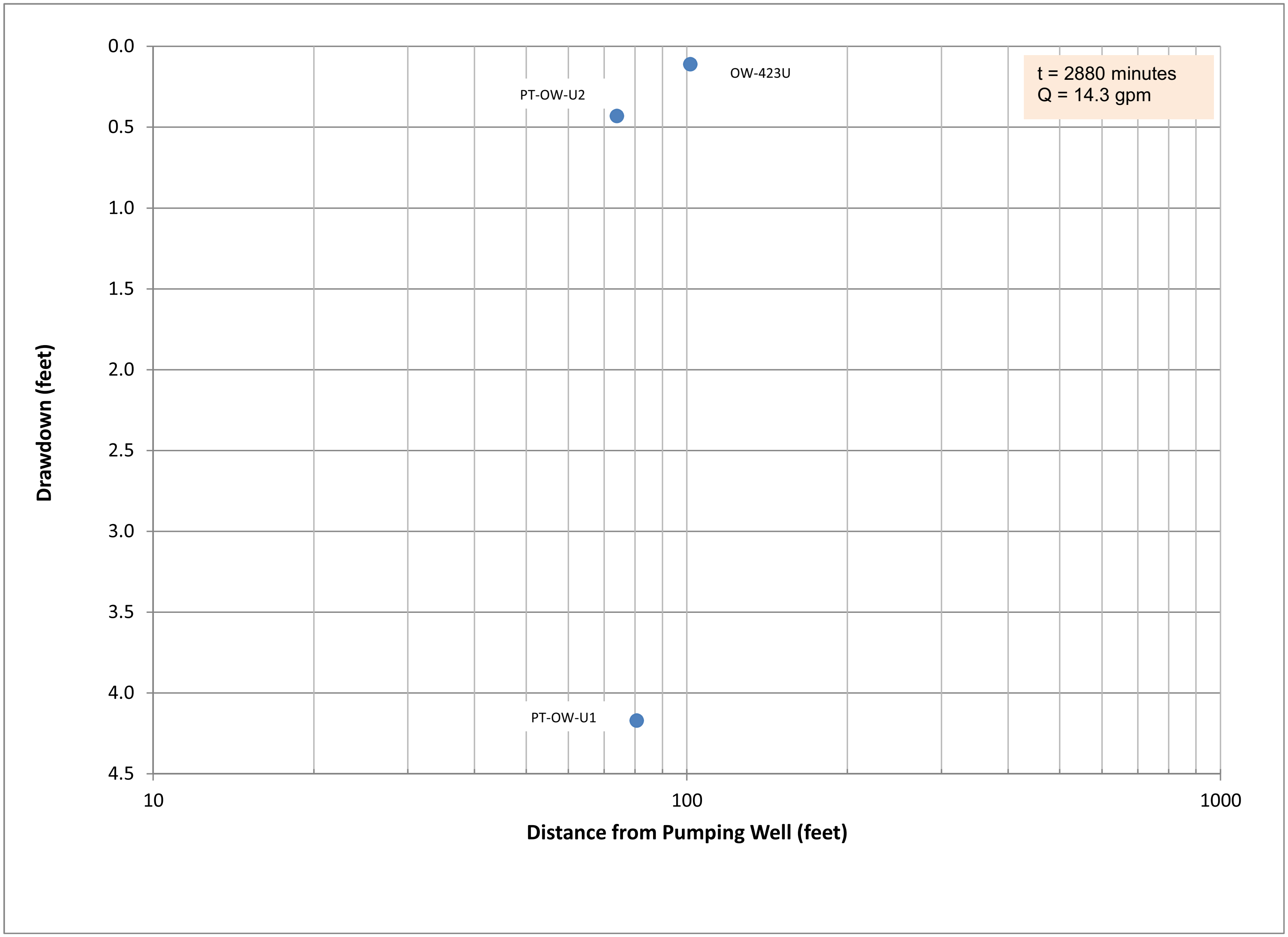


Figure 2.4.12B-16. Distance-Drawdown Plot Upper Monitoring Zone

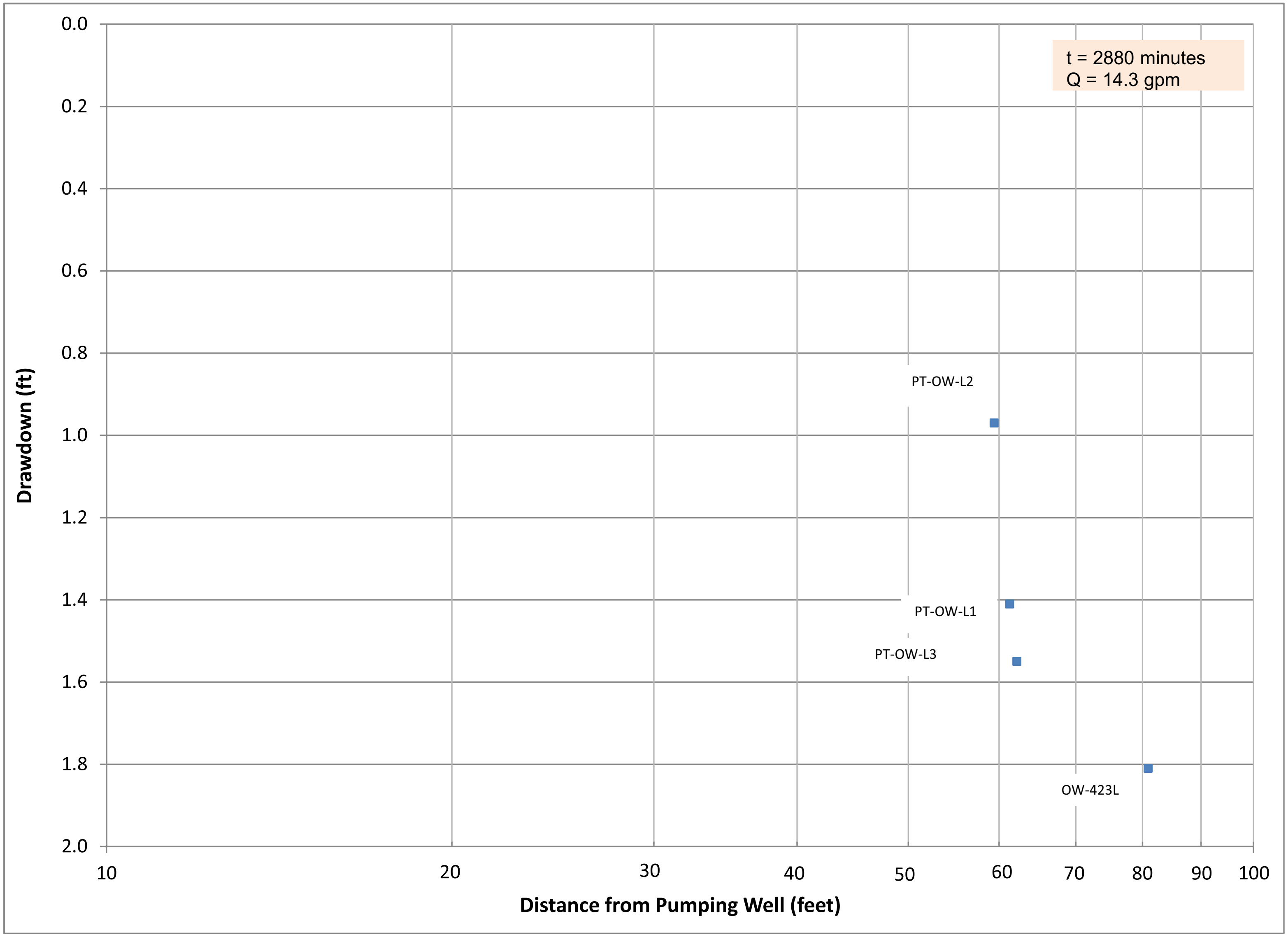
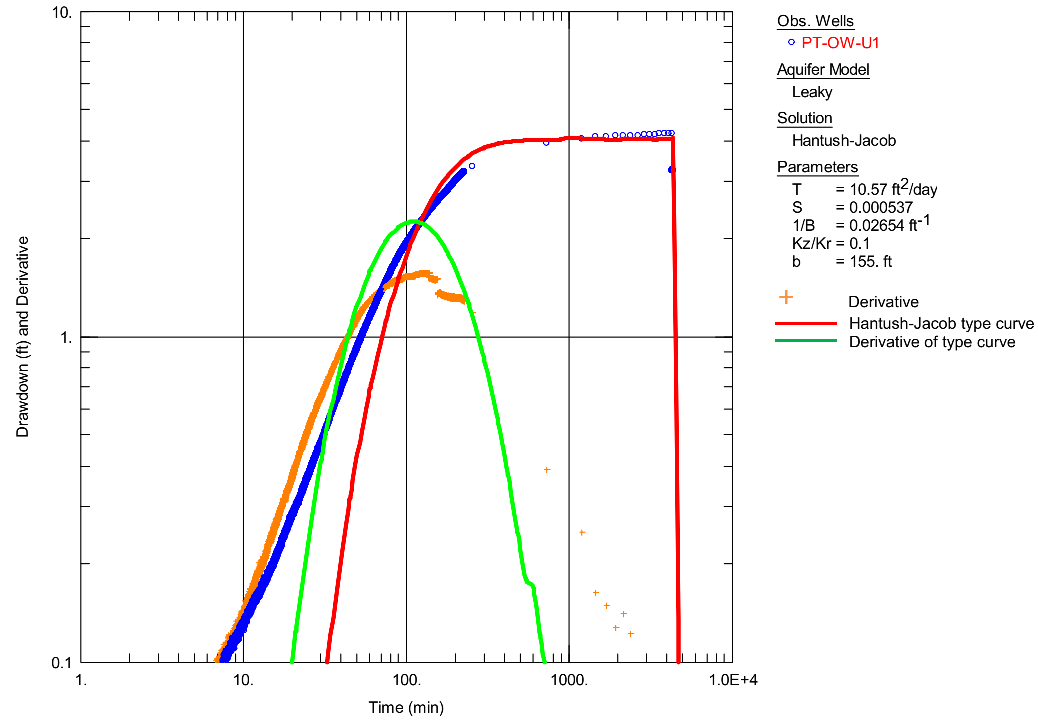
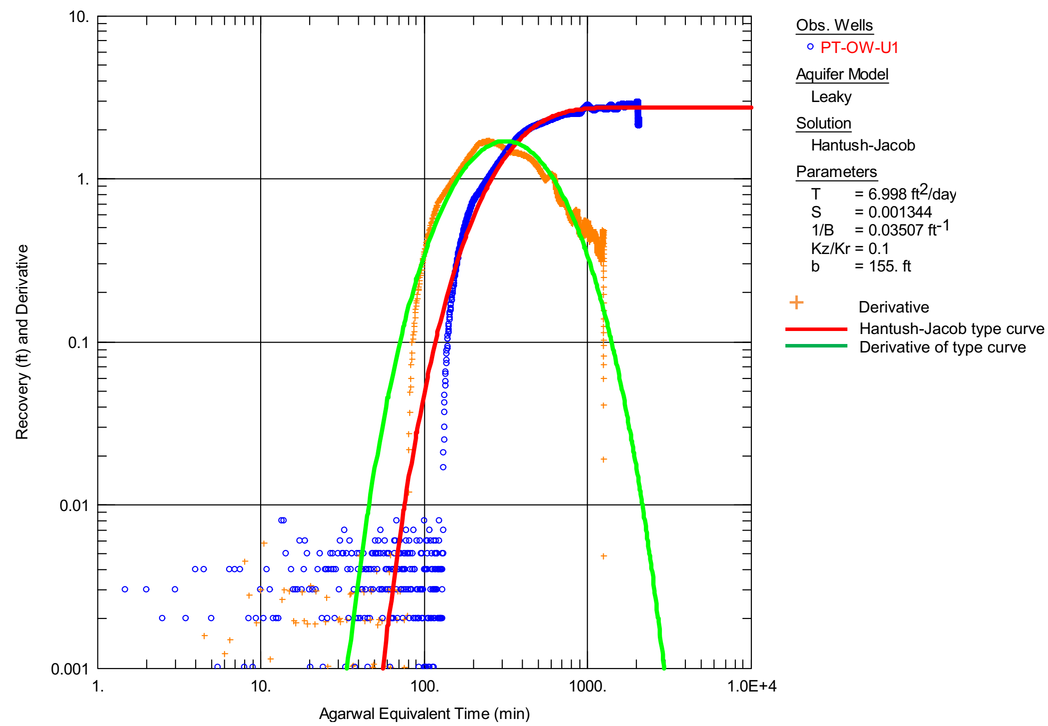


Figure 2.4.12B-17. Distance-Drawdown Plot Lower Monitoring Zone

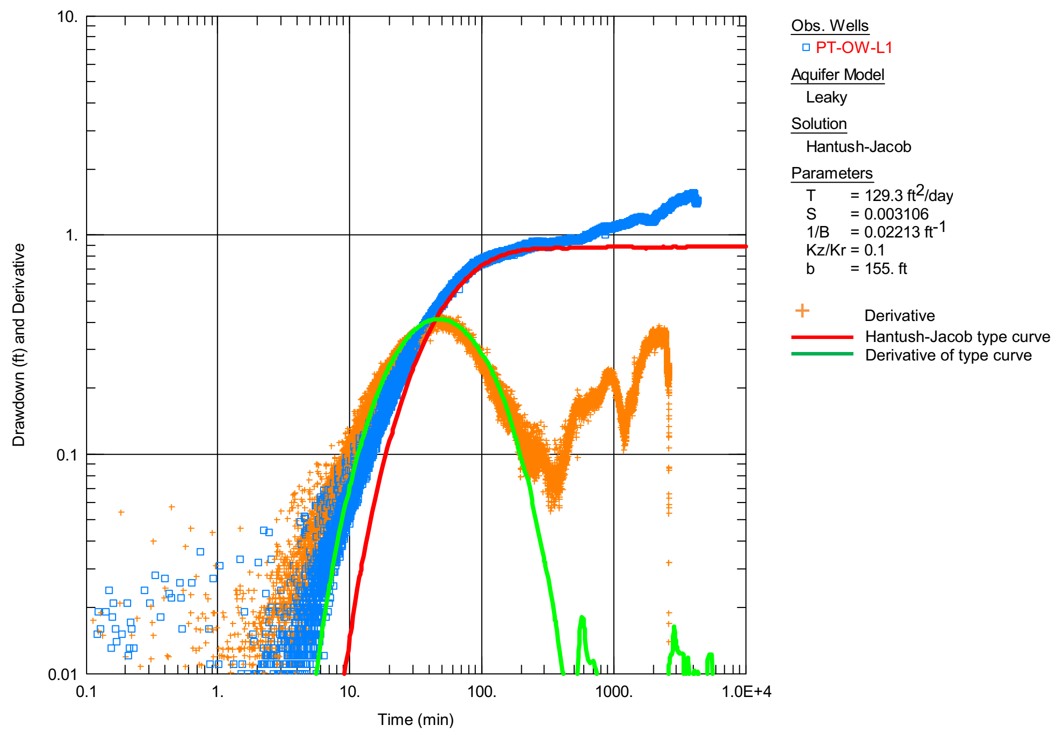


Pumping

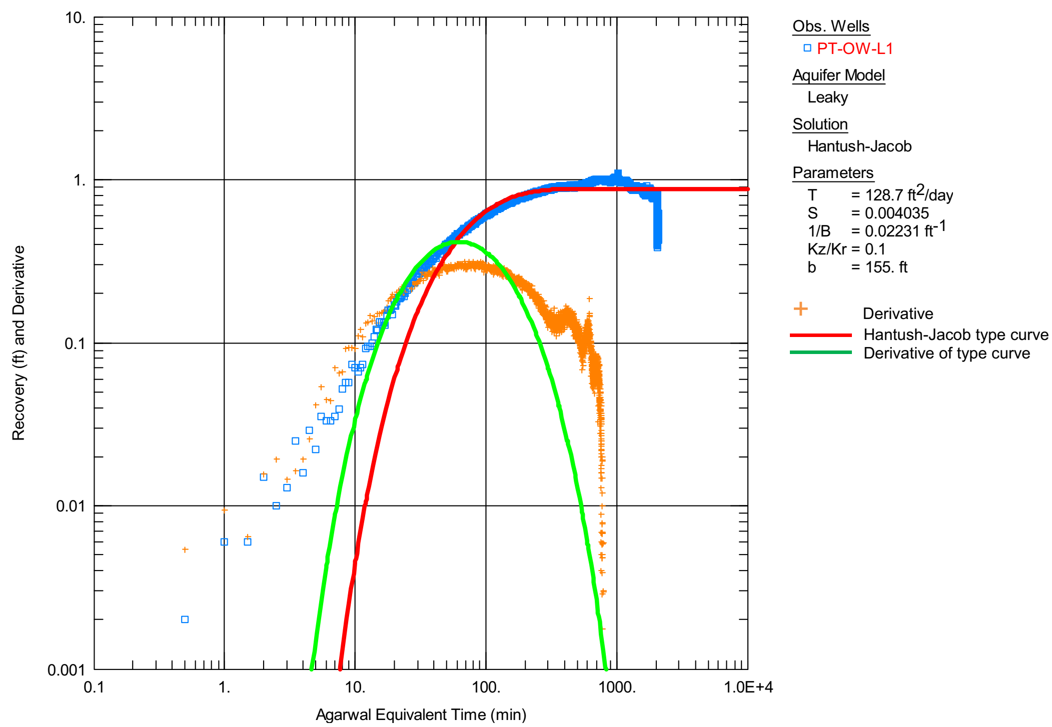


Recovery

Figure 2.4.12B-18. PT-OW-U1 Hantush-Jacob Leaky Aquifer Plots

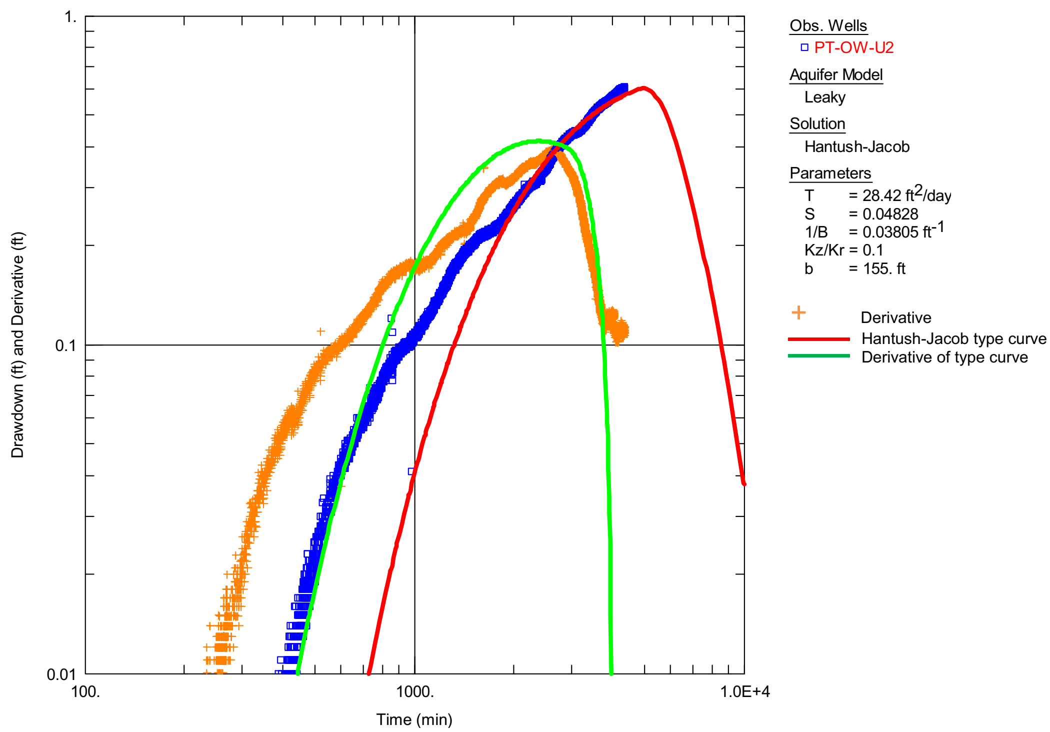


Pumping

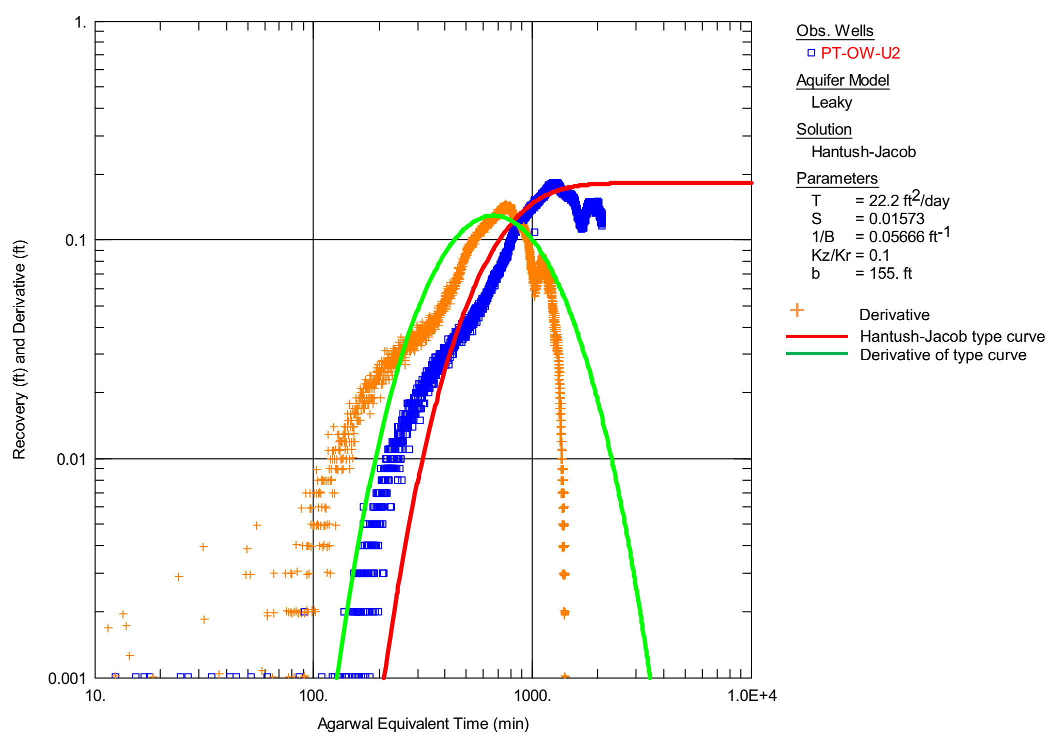


Recovery

Figure 2.4.12B-19. PT-OW-L1 Hantush-Jacob Leaky Aquifer Plots

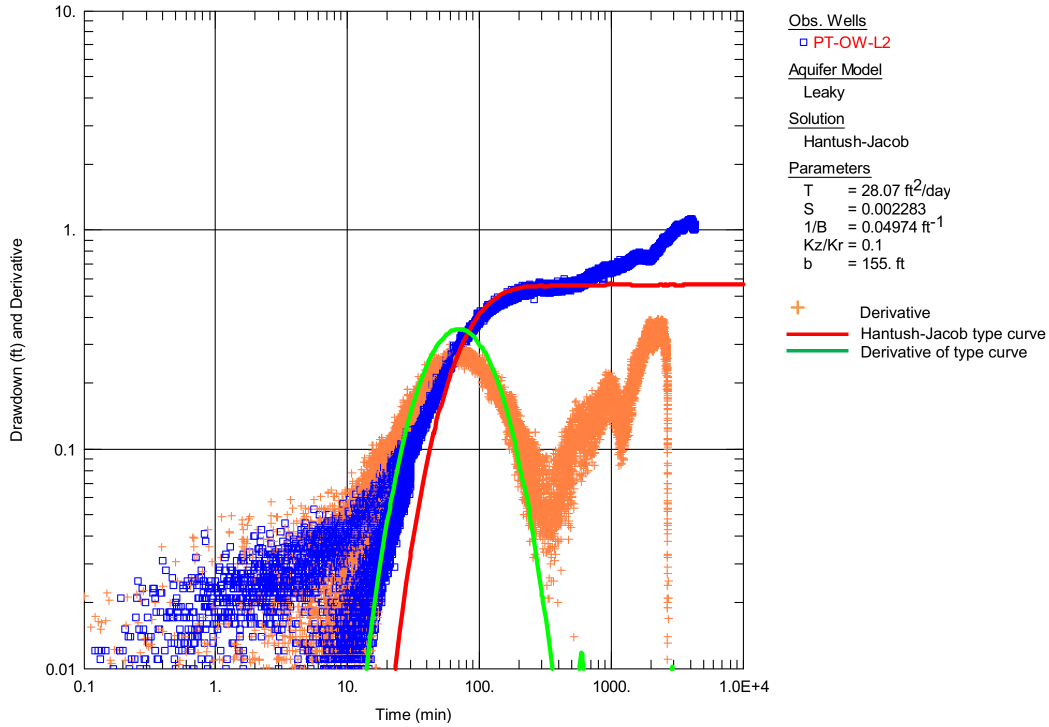


Pumping

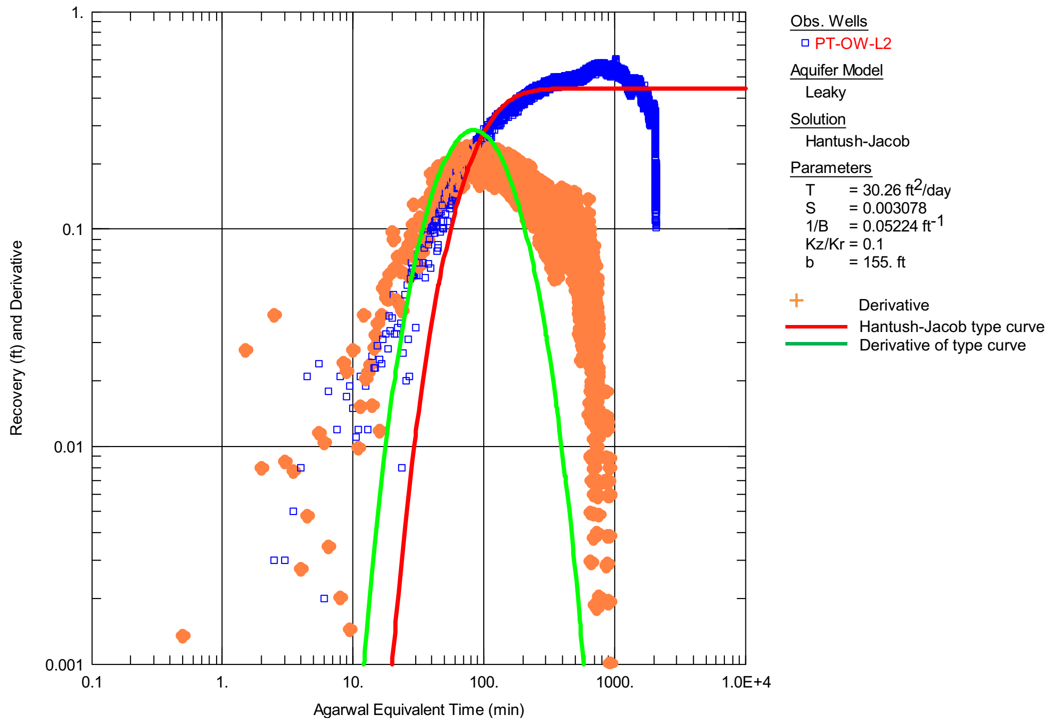


Recovery

Figure 2.4.12B-20. PT-OW-U2 Hantush Leaky Aquifer Plots

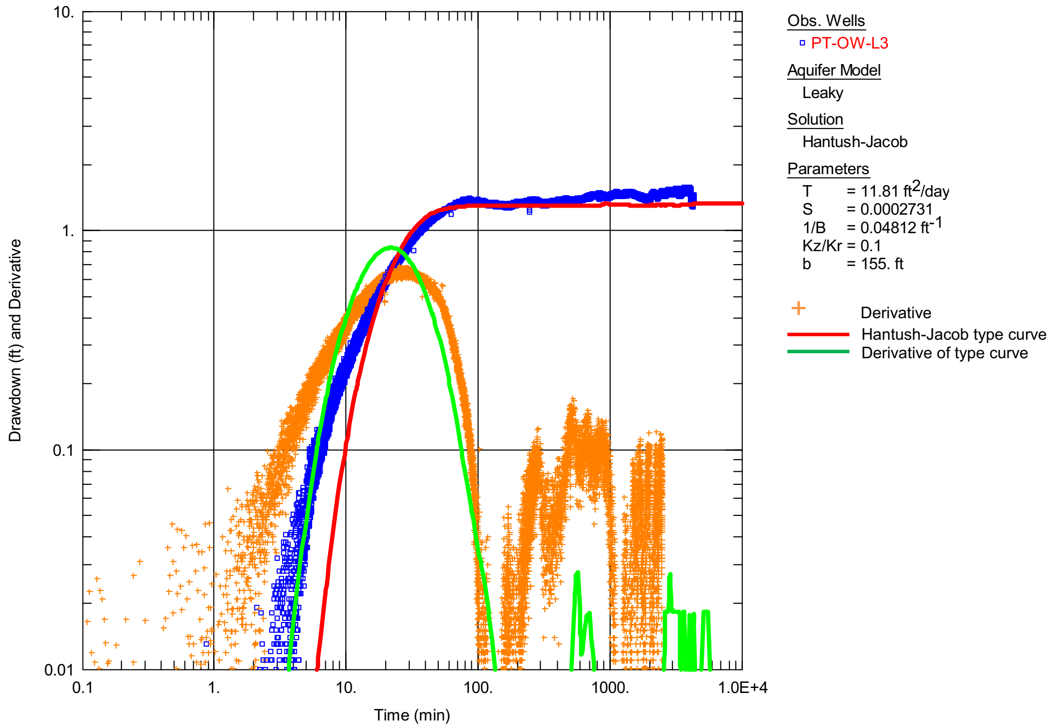


Pumping

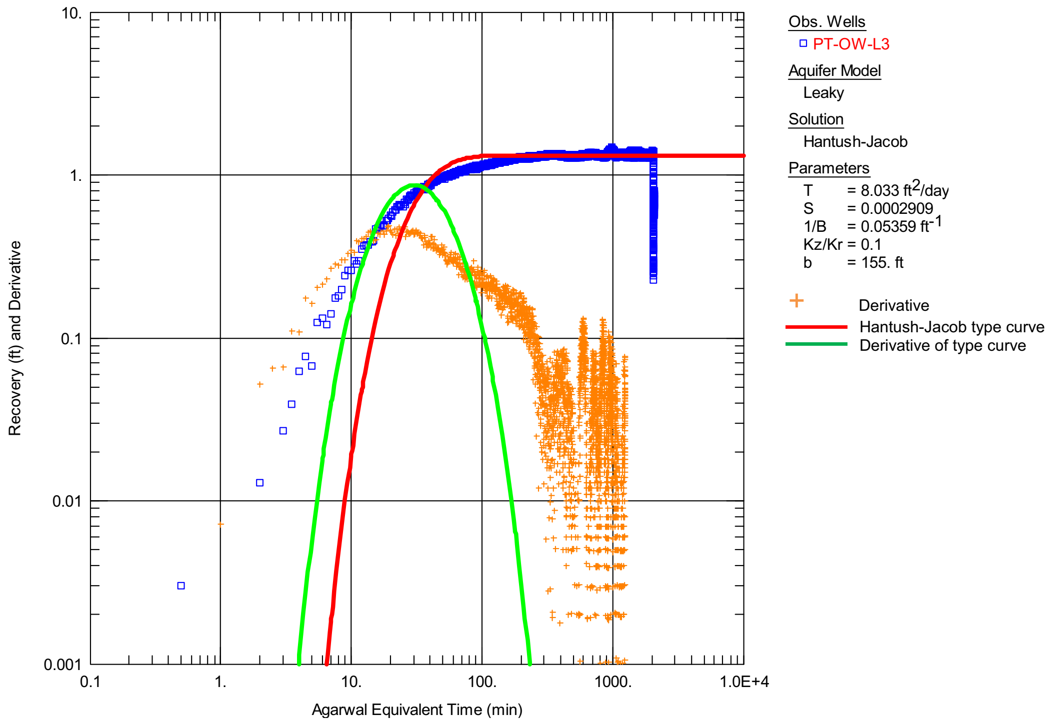


Recovery

Figure 2.4.12B-21. PT-OW-L2 Hantush Leaky Aquifer Plots

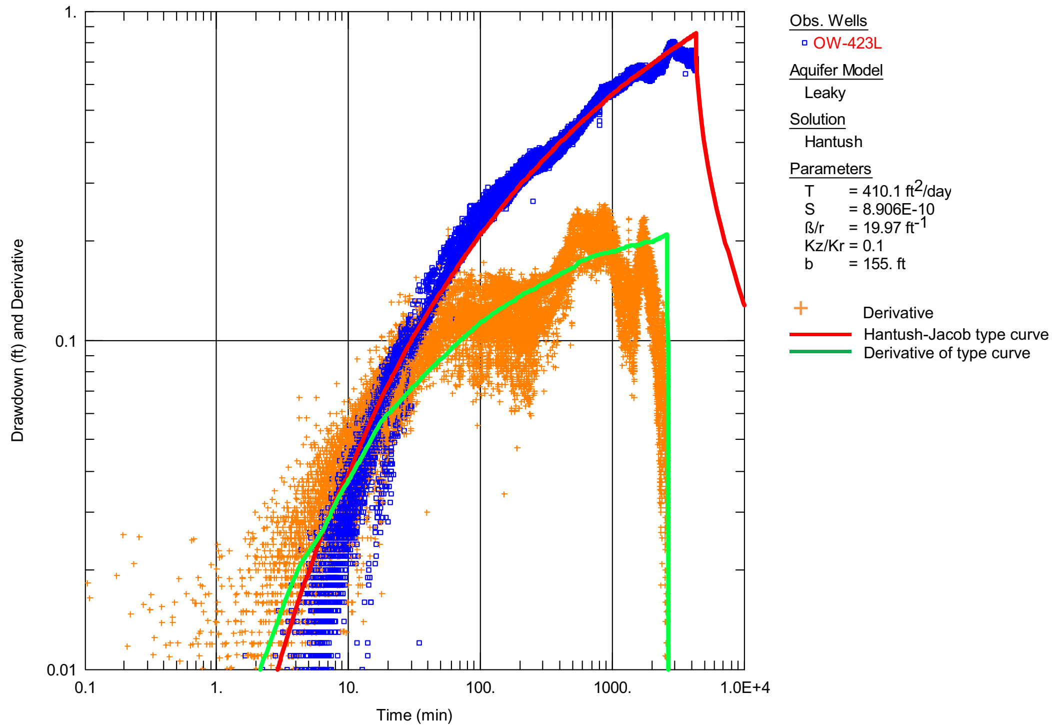


Pumping

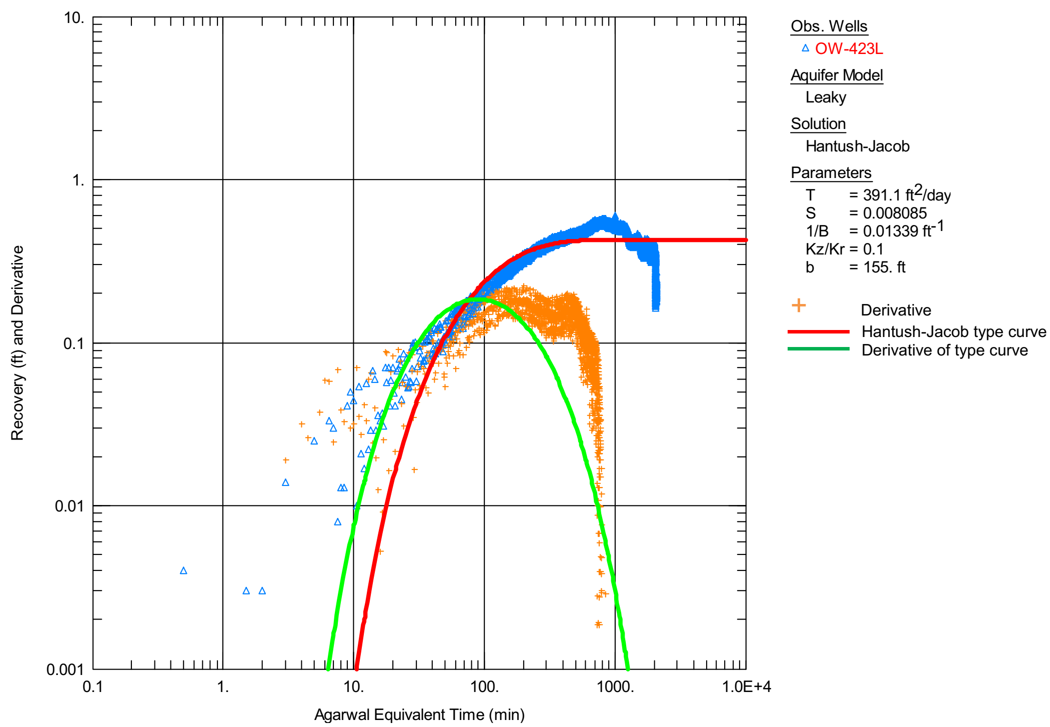


Recovery

Figure 2.4.12B-22. PT-OW-L3 Hantush Leaky Aquifer Plots



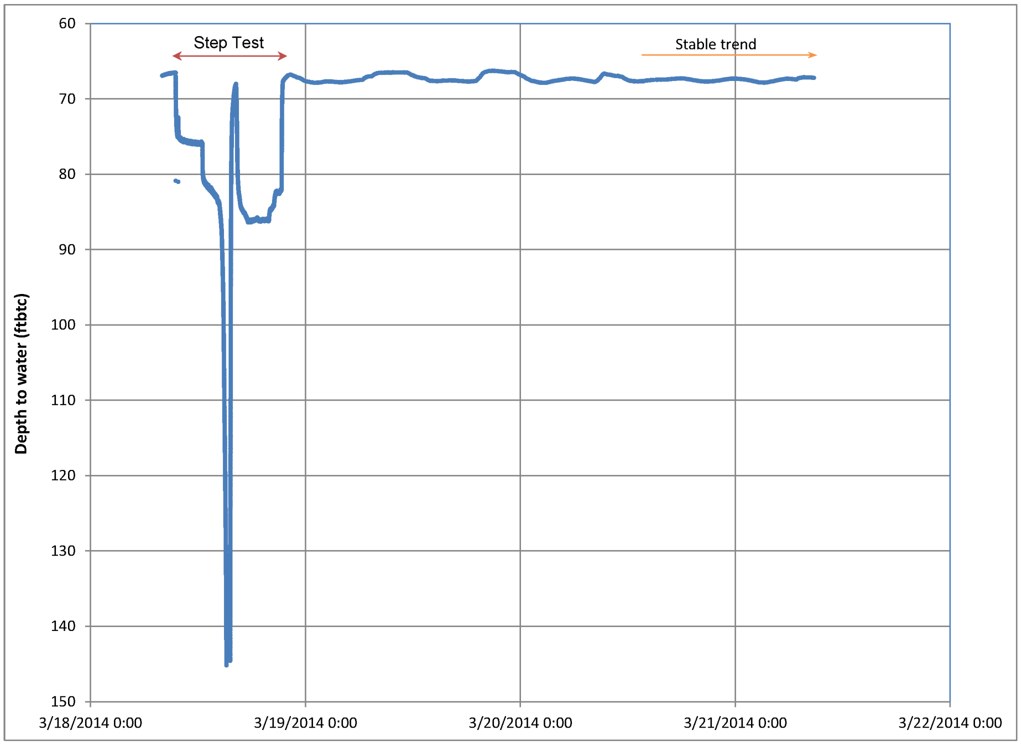
Pumping



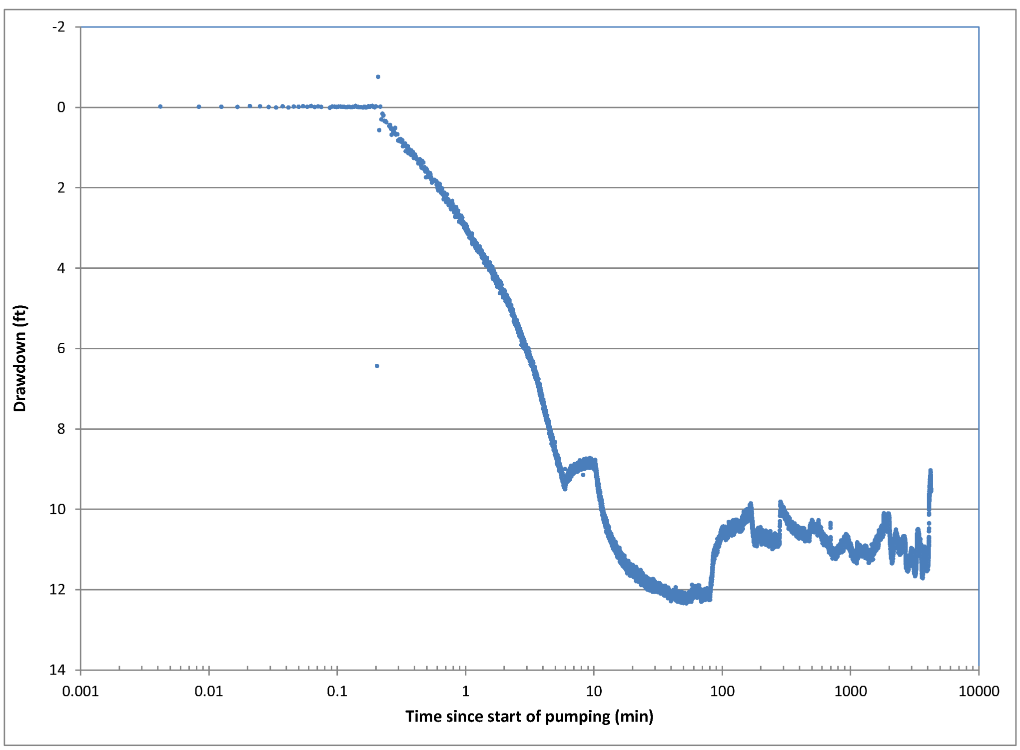
Recovery

Figure 2.4.12B-23. OW-423L Hantush Leaky Aquifer Plots

Attachment A of Appendix 2.4.12B
Background, Pumping, and Recovery Graphs



Background



Pumping Data

Figure 2.4.12B-A1. Pumping Well PT-PW Background and Pumping Data

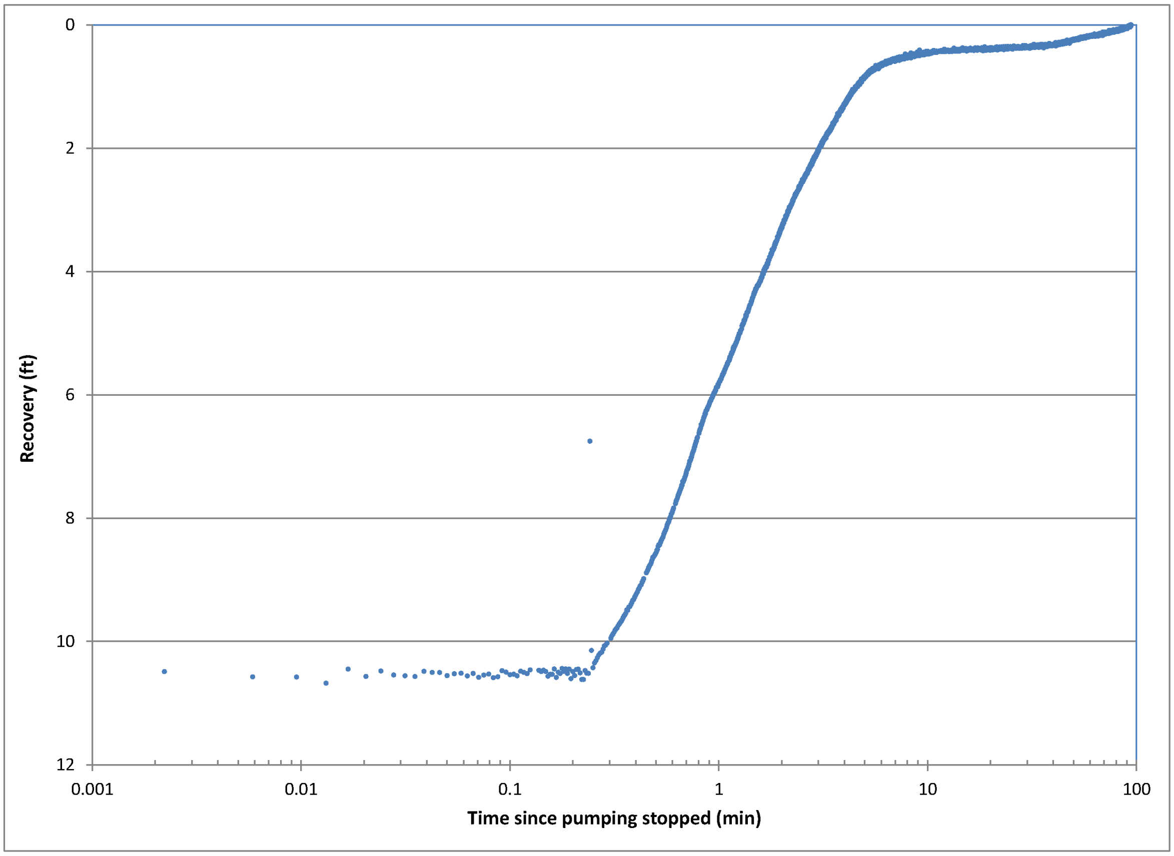
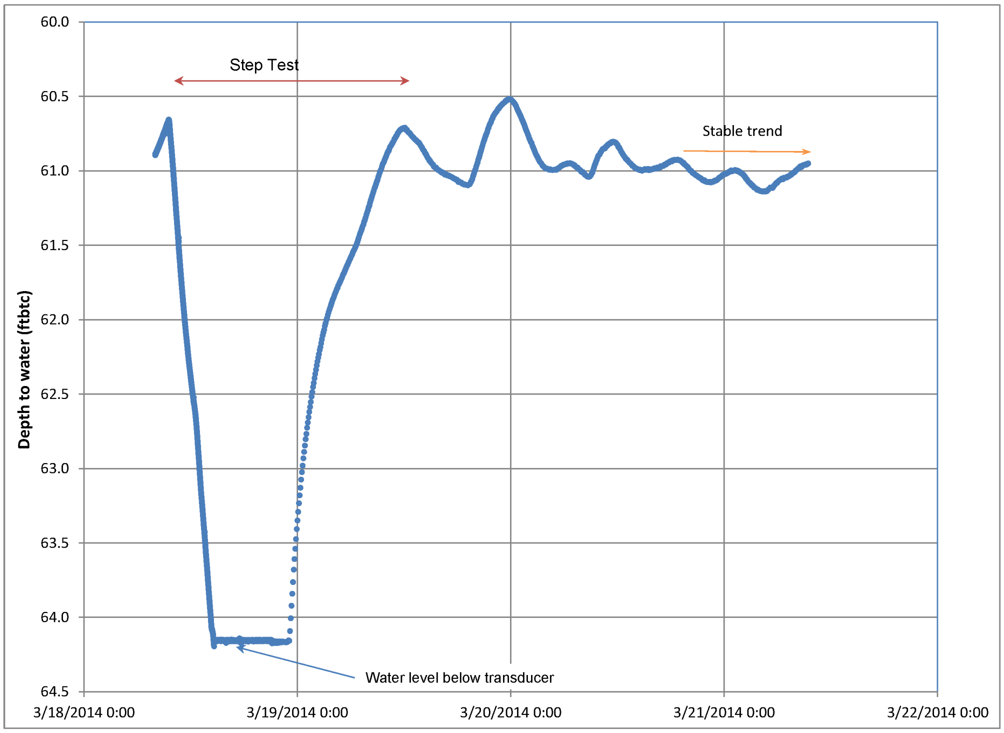
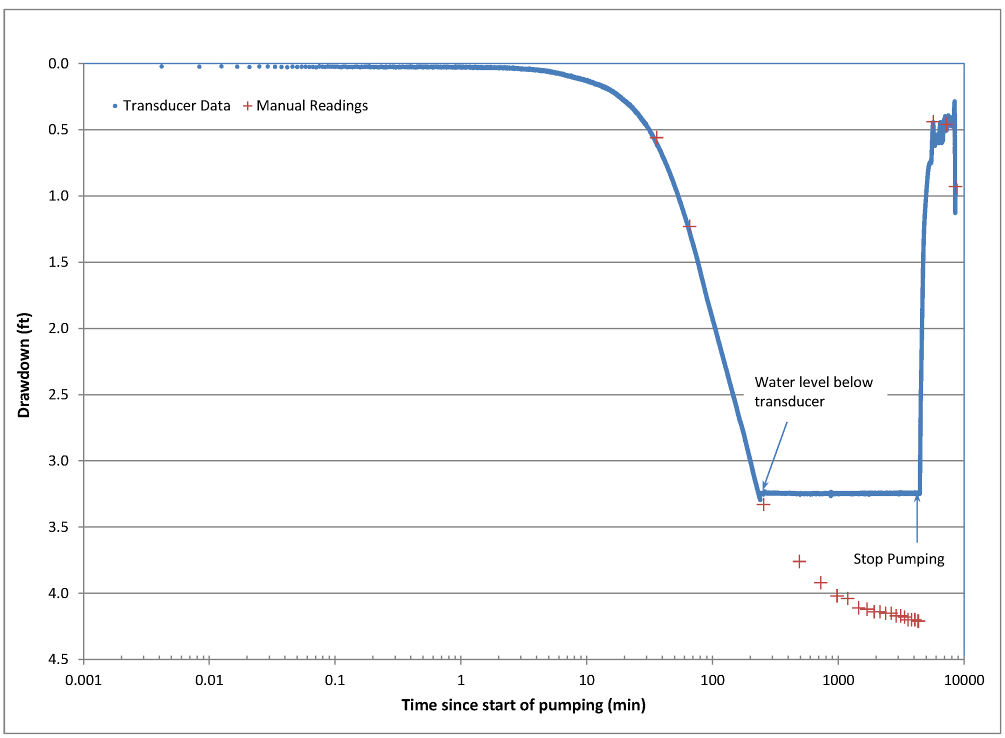


Figure 2.4.12B-A2. Pumping Well PT-PW Recovery

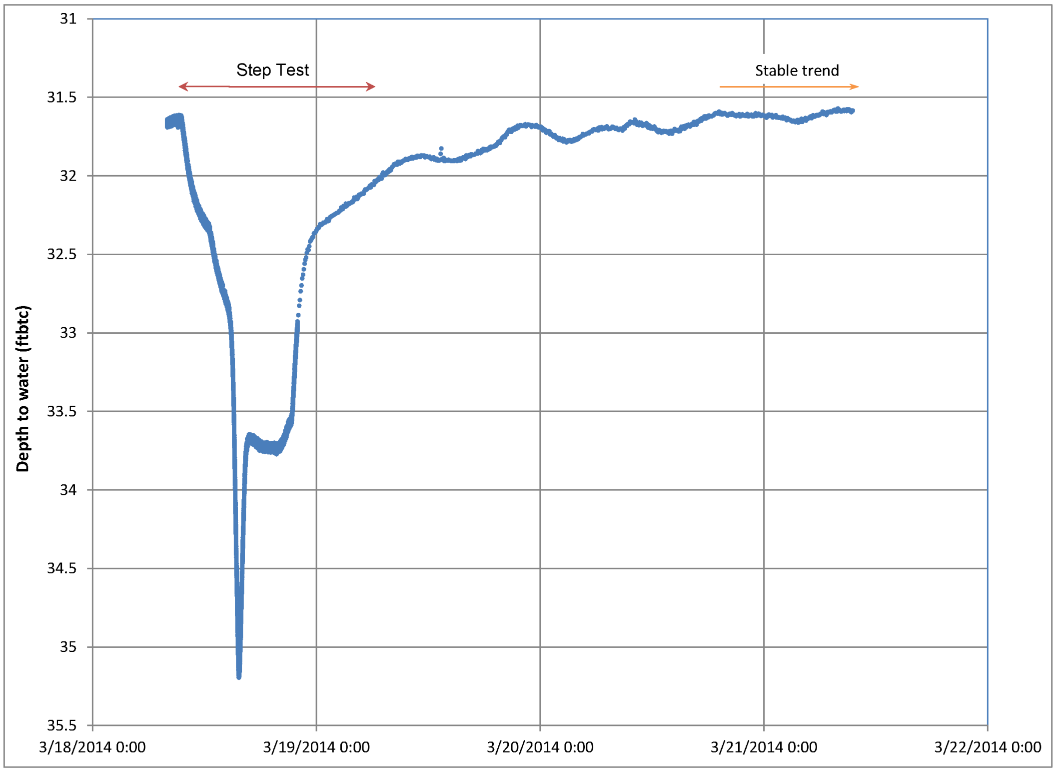


Background



Pumping and Recovery

Figure 2.4.12B-A3. PT-OW-U1 Background, Pumping, and Recovery



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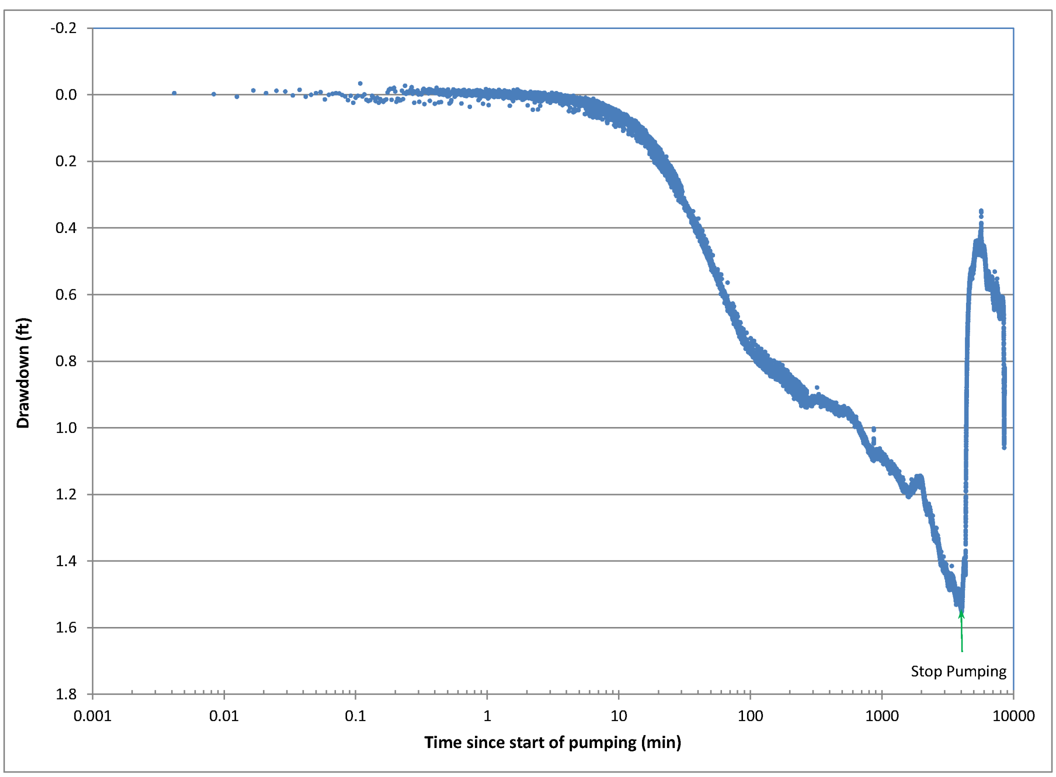
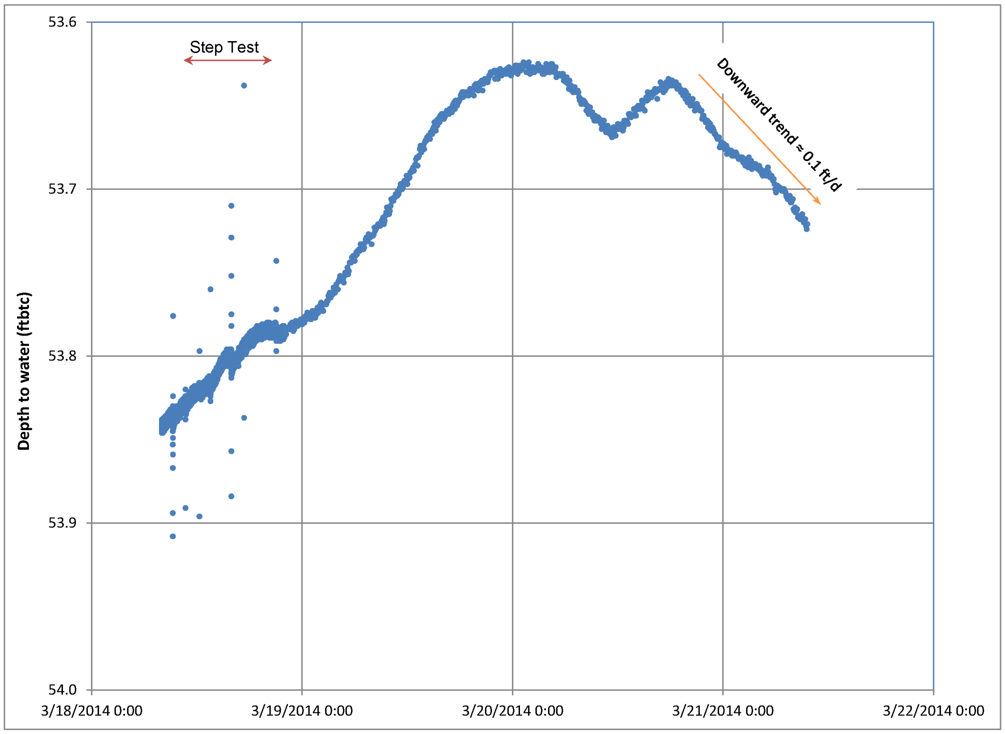


Pumping and Recovery

Figure 2.4.12B-A4. PT-OW-L1 Background, Pumping, and Recovery



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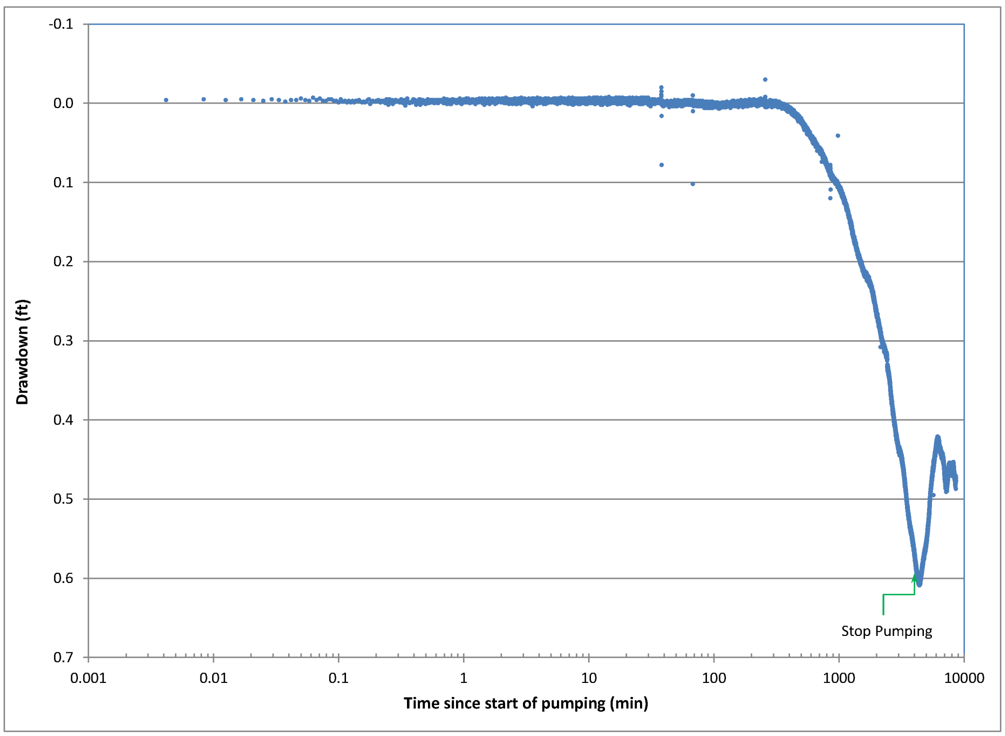
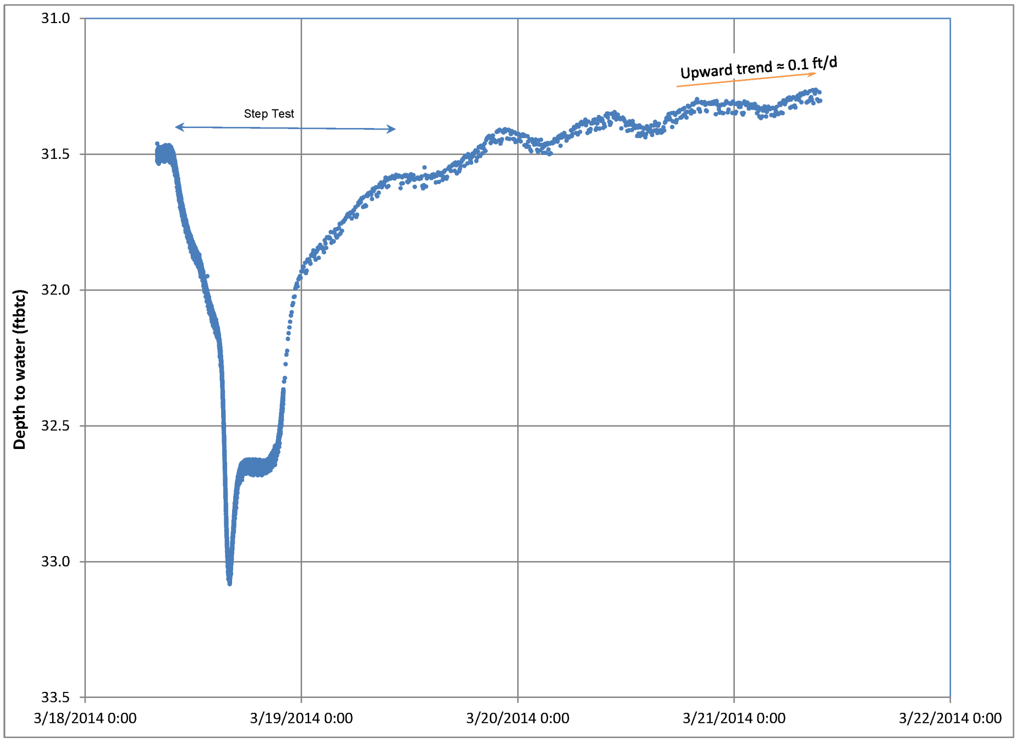


Pumping and Recovery

Figure 2.4.12B-A5. PT-OW-U2 Background, Pumping, and Recovery



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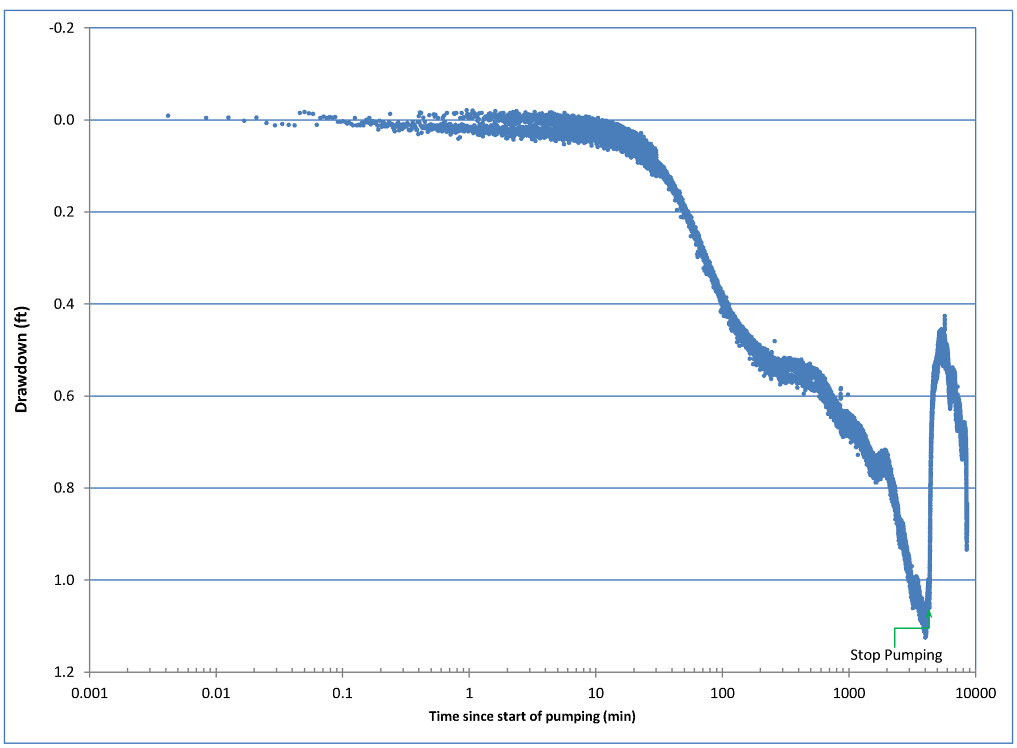
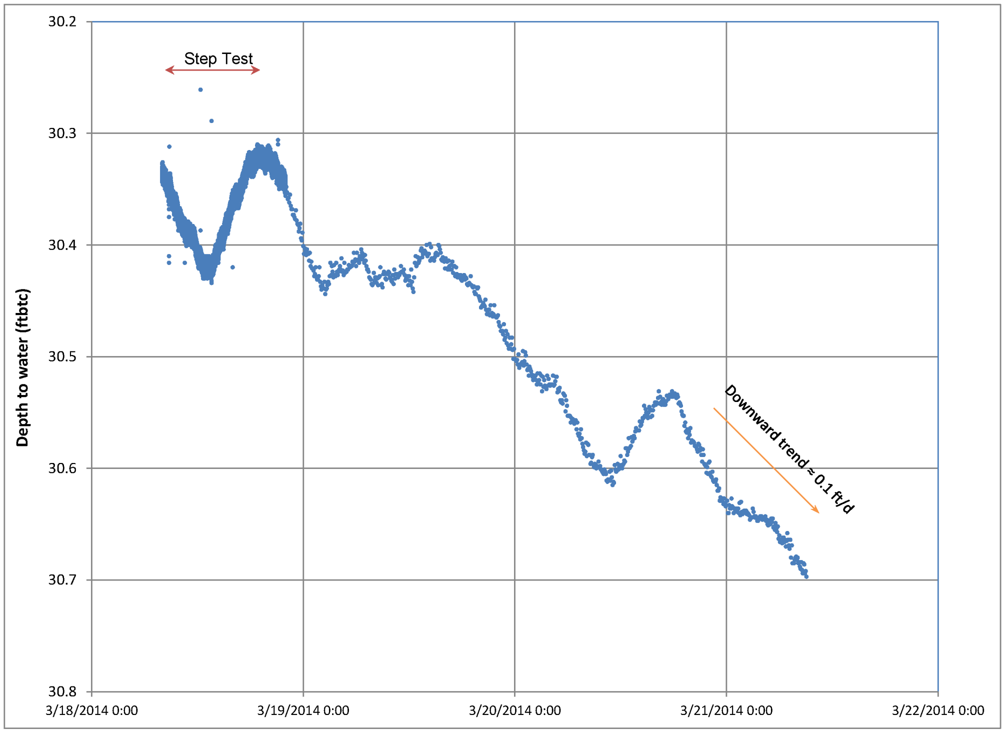


Pumping and Recovery

Figure 2.4.12B-A6. PT-OW-L2 Background, Pumping, and Recovery



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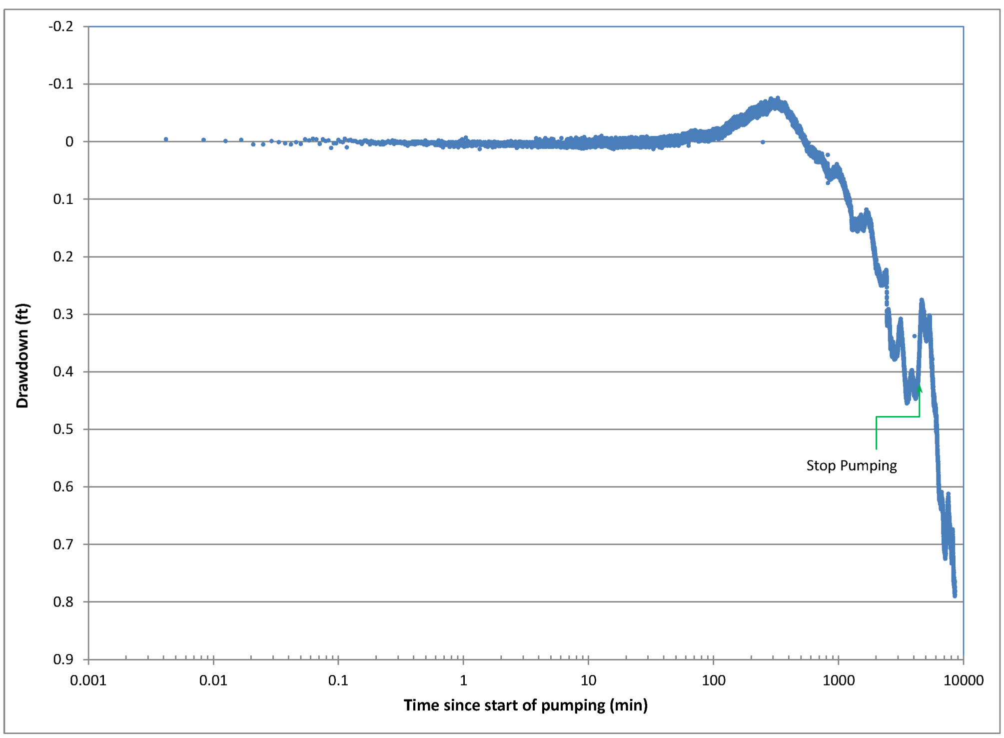
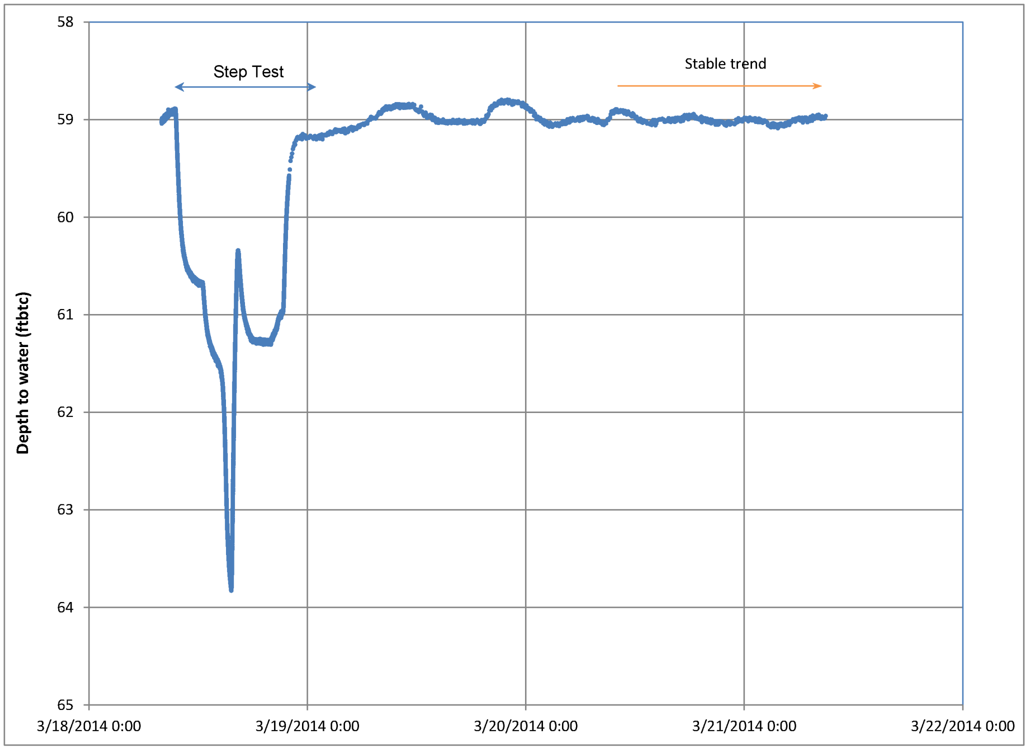
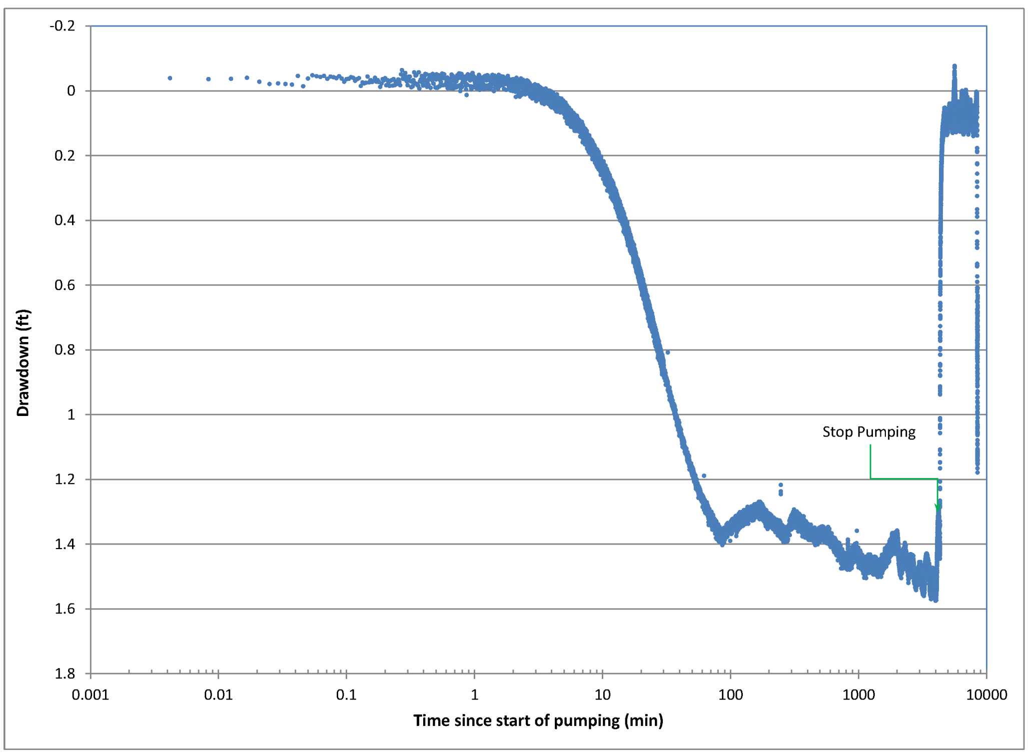


Pumping and Recovery

Figure 2.4.12B-A7. PT-OW-U3 Background, Pumping, and Recovery

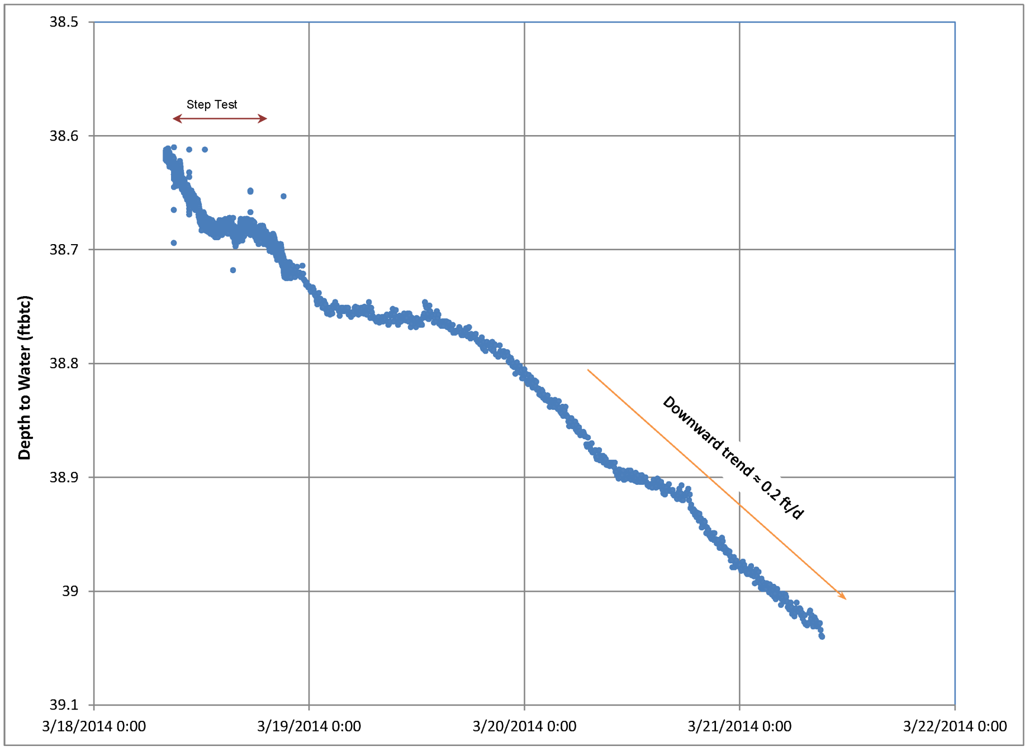


Background



Pumping and Recovery

Figure 2.4.12B-A8. PT-OW-L3 Background, Pumping, and Recovery



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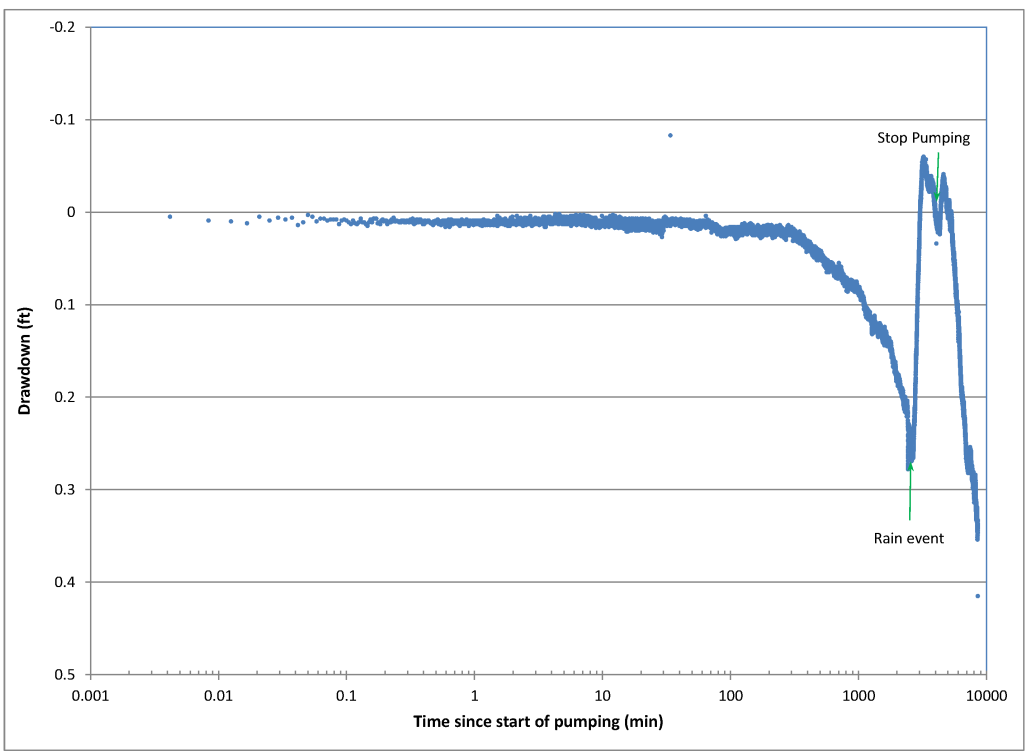
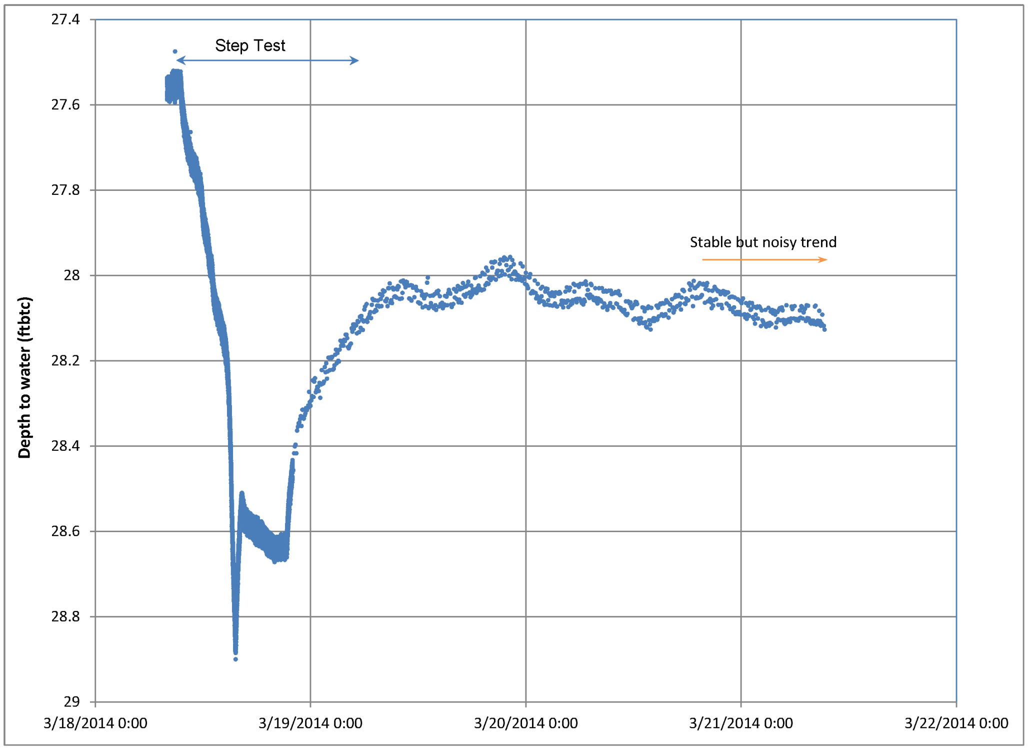


Pumping and Recovery

Figure 2.4.12B-A9. OW-423U Background, Pumping, and Recovery



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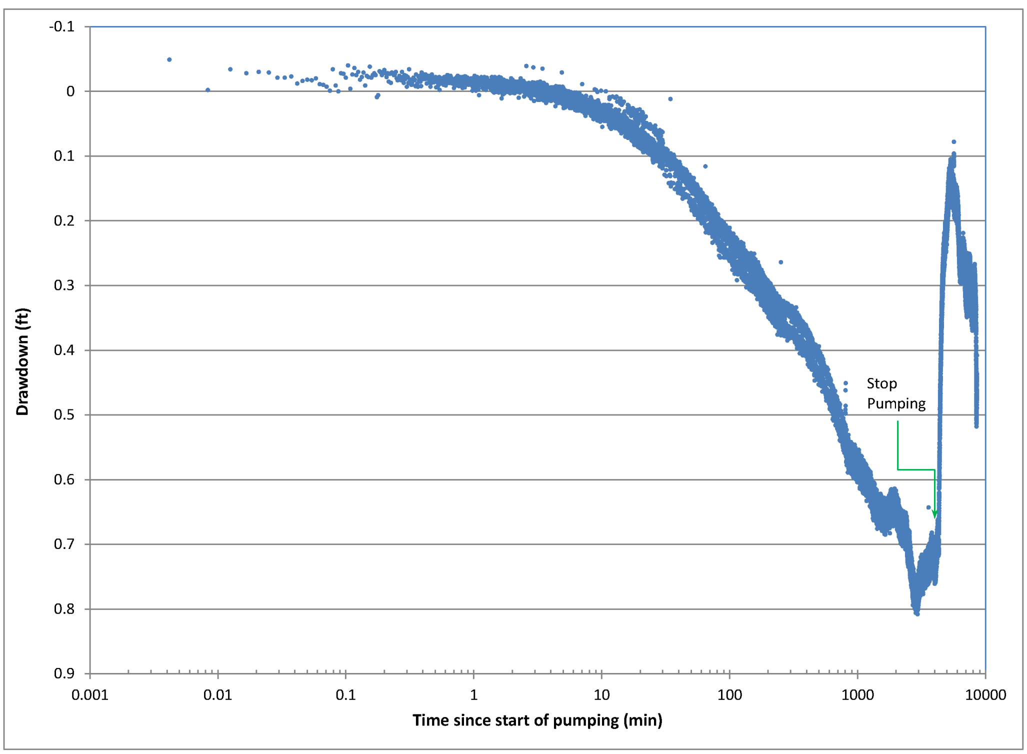
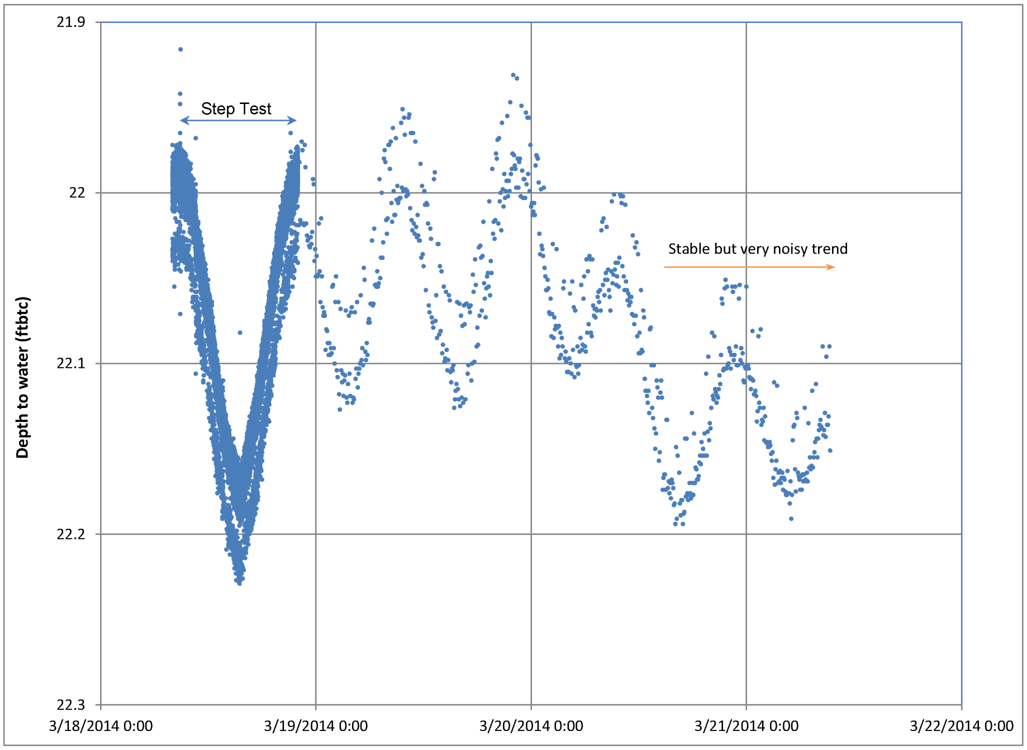
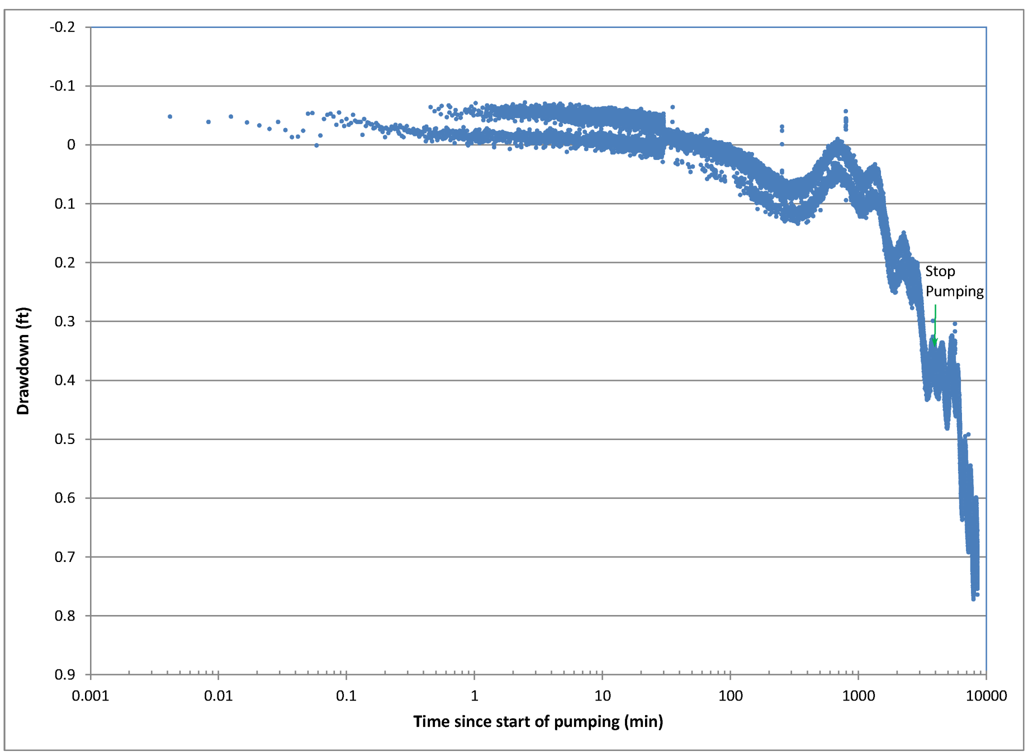


Pumping and Recovery

Figure 2.4.12B-A10. OW-423L Background, Pumping, and Recovery

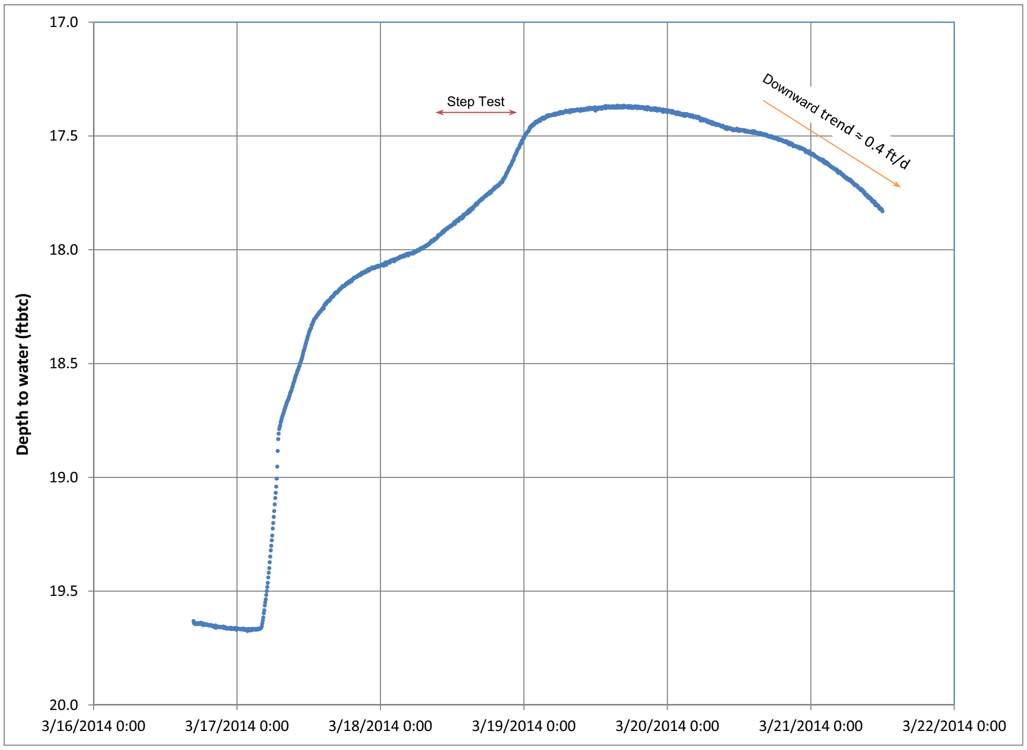


Background



Pumping and Recovery

Figure 2.4.12B-A11. OW-423D Background, Pumping and Recovery



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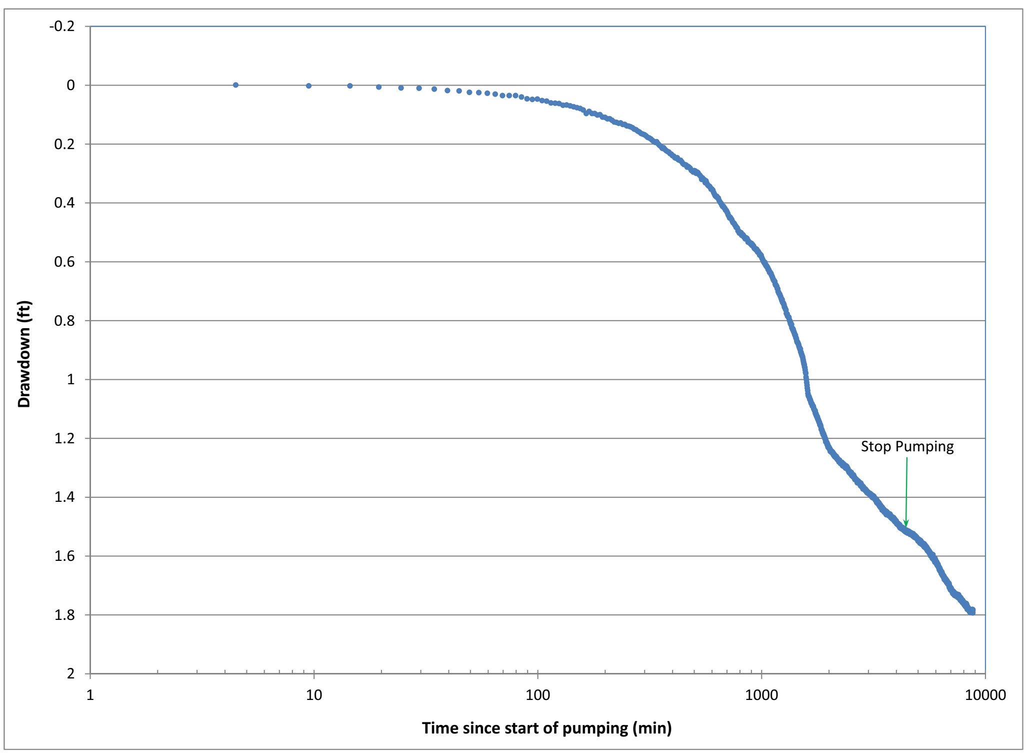
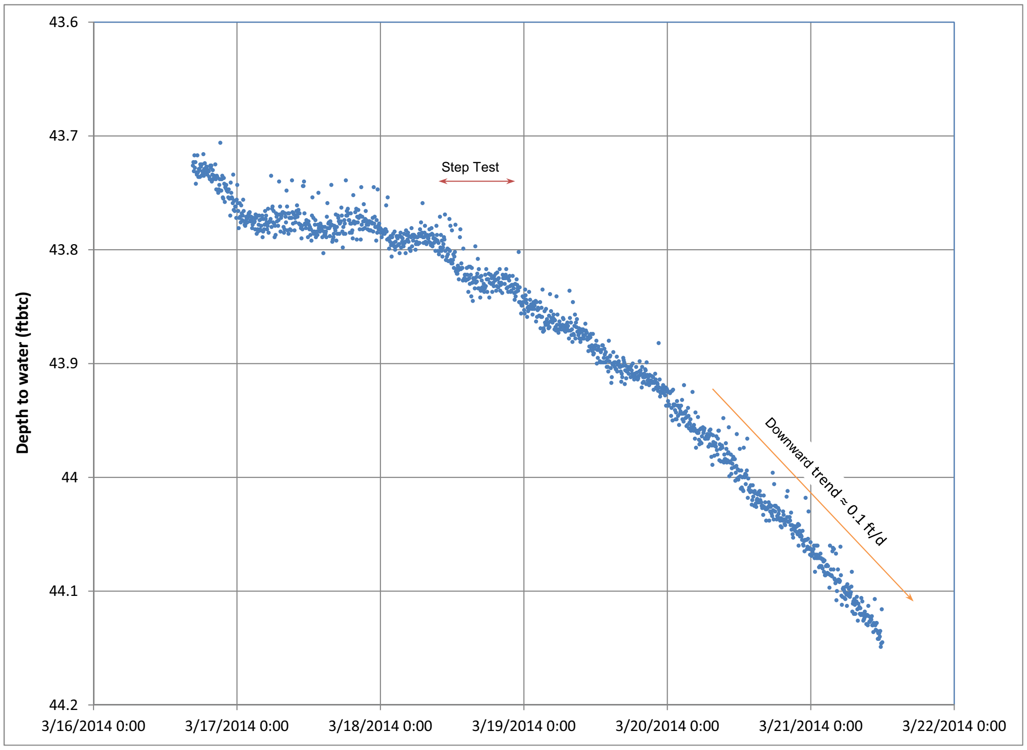


Pumping and Recovery

Figure 2.4.12B-A12. OW-202U Background, Pumping, and Recovery



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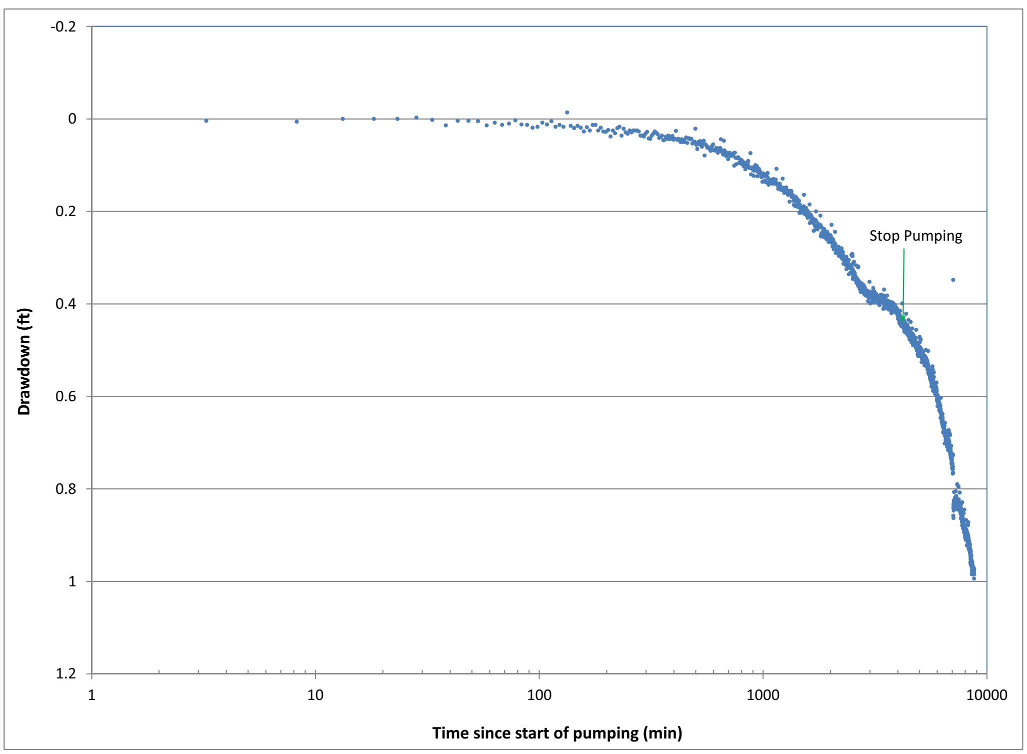
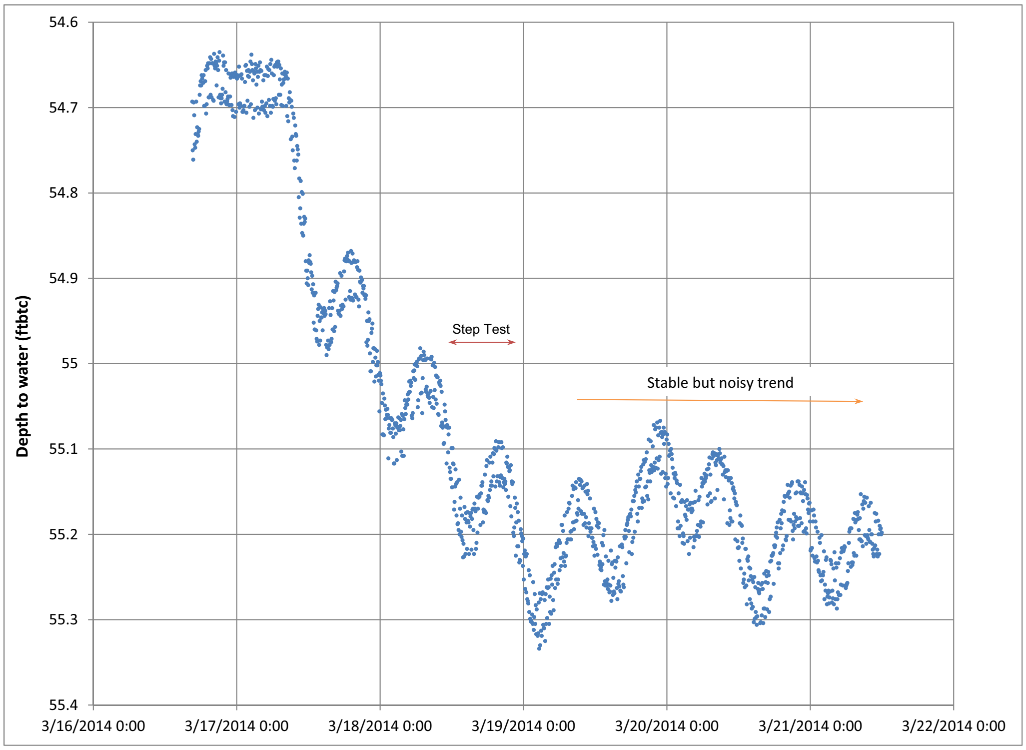
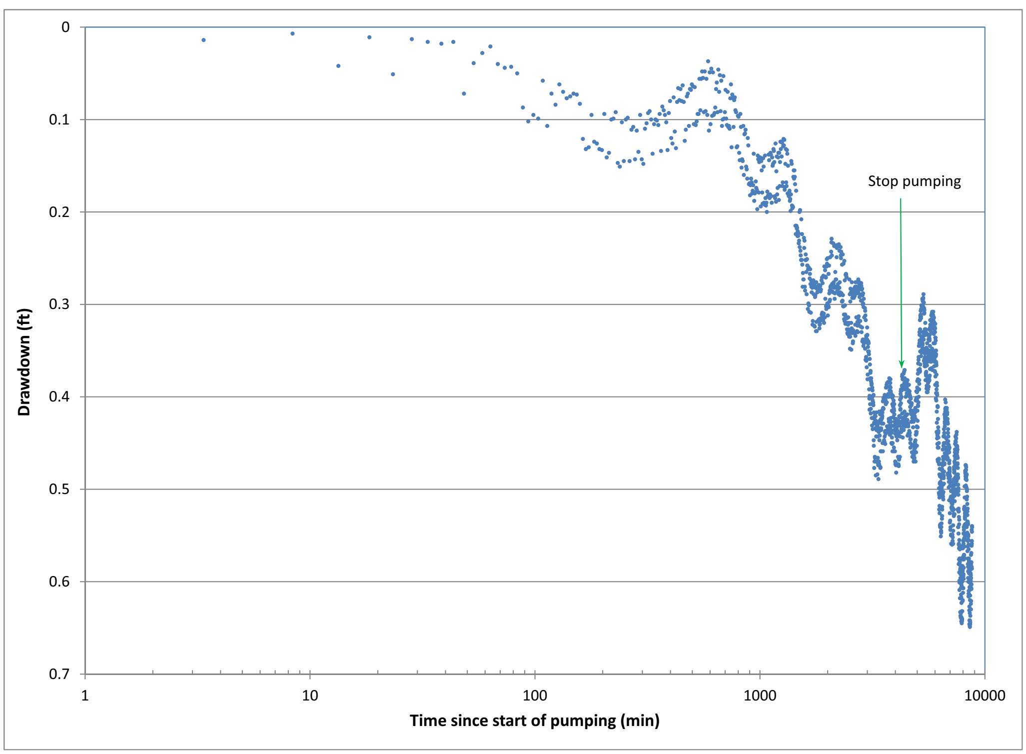


Pumping and Recovery

Figure 2.4.12B-A13. OW-202L Background, Pumping, and Recovery

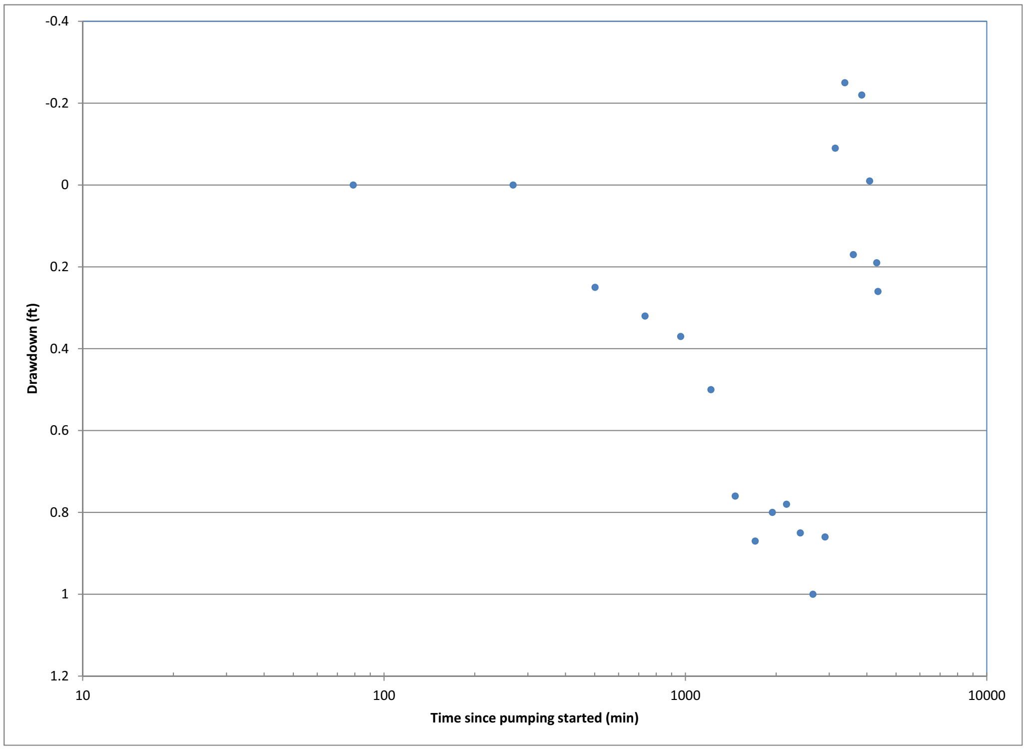


Background

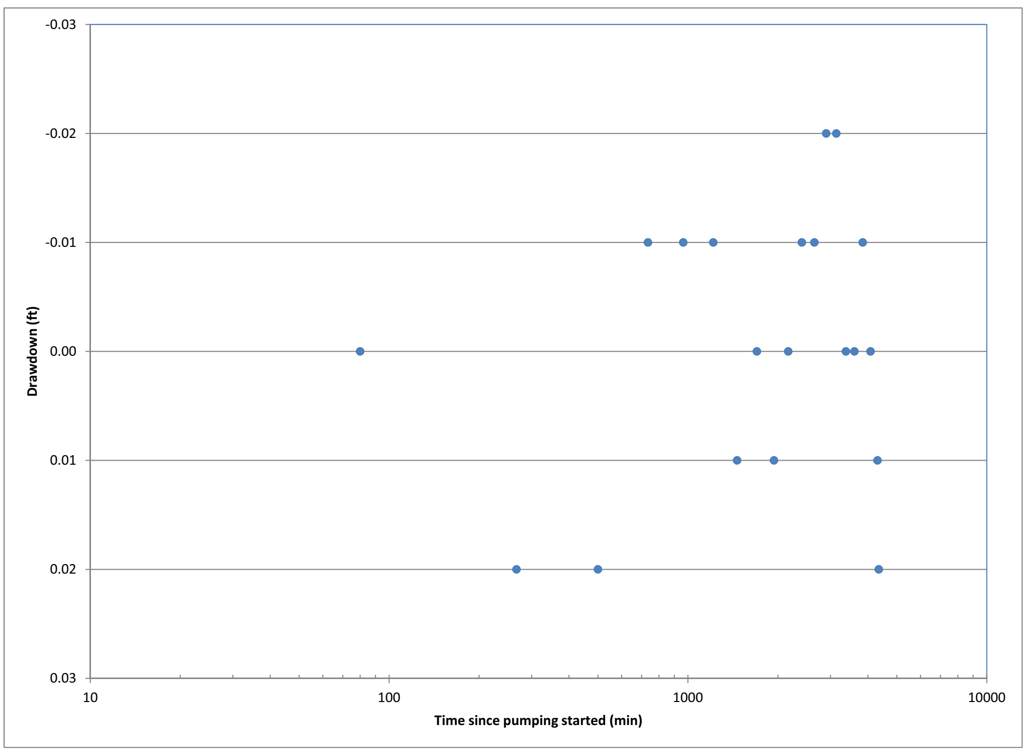


Pumping and Recovery

Figure 2.4.12B-A14. OW-202D Background, Pumping, and Recovery



OW-428U Manual Measurements



OW-428L Manual Measurements

Figure 2.4.12B-A15. OW-428U/L Manual Measurements

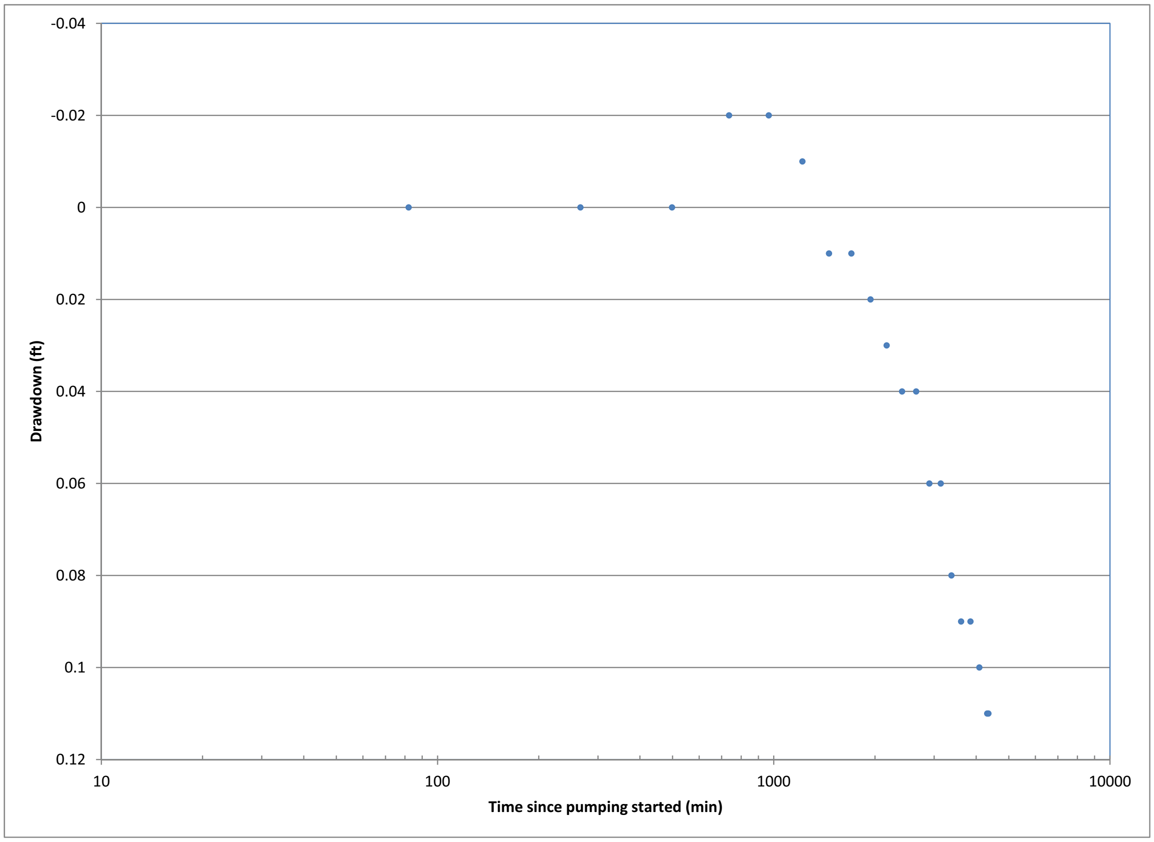
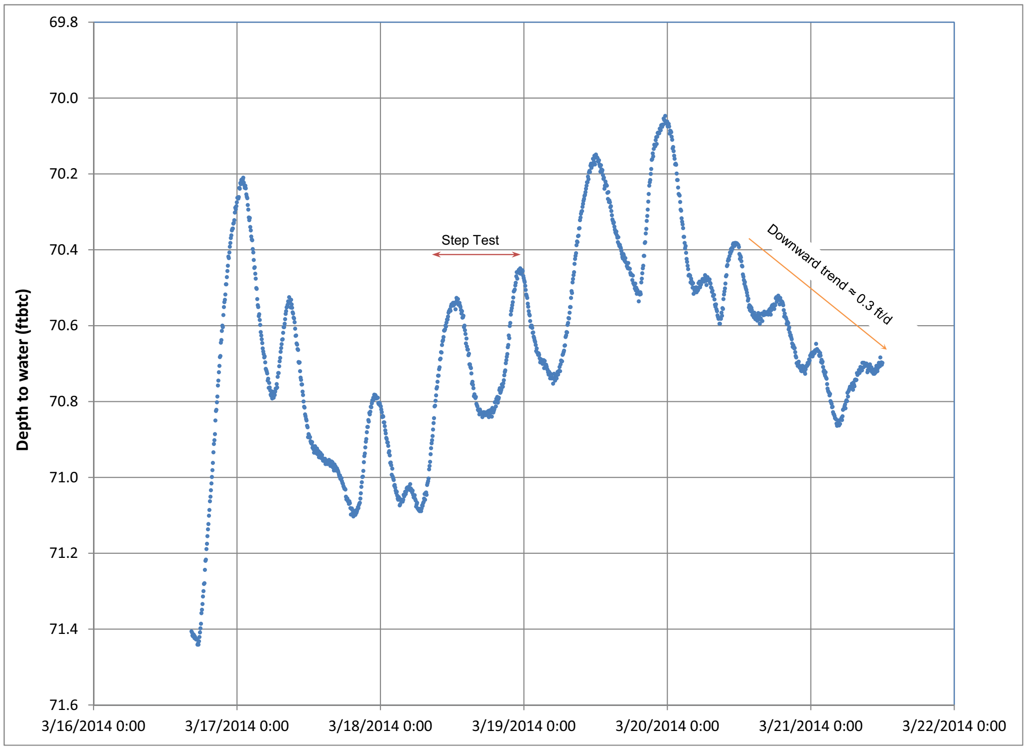


Figure 2.4.12B-A16. OW-428D Manual Measurements



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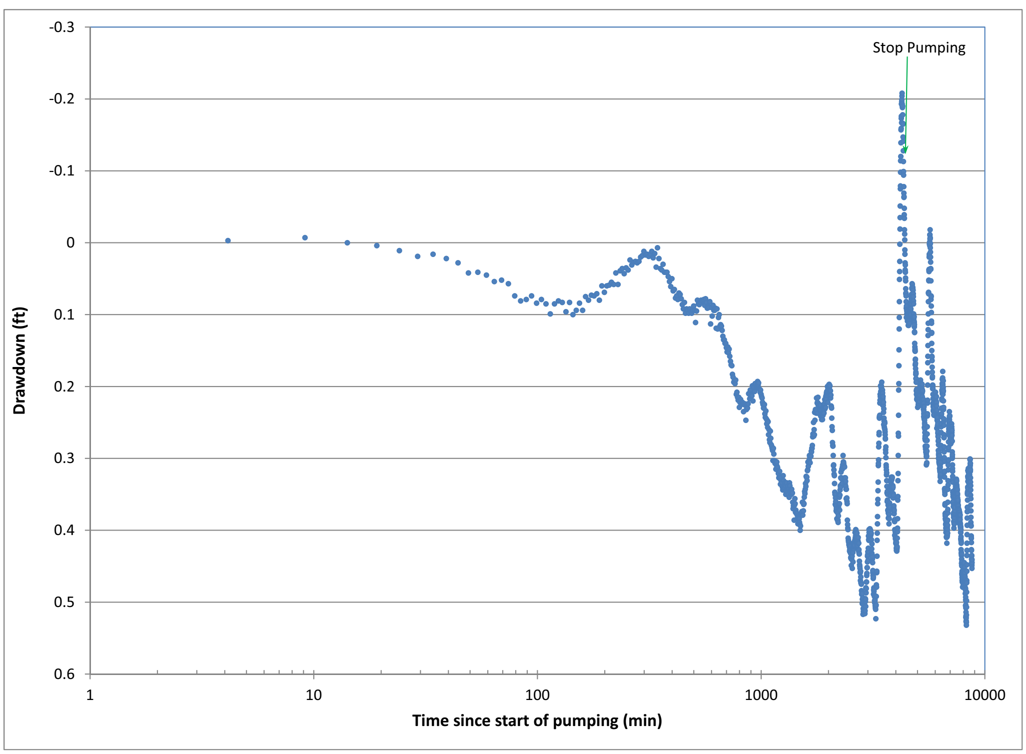
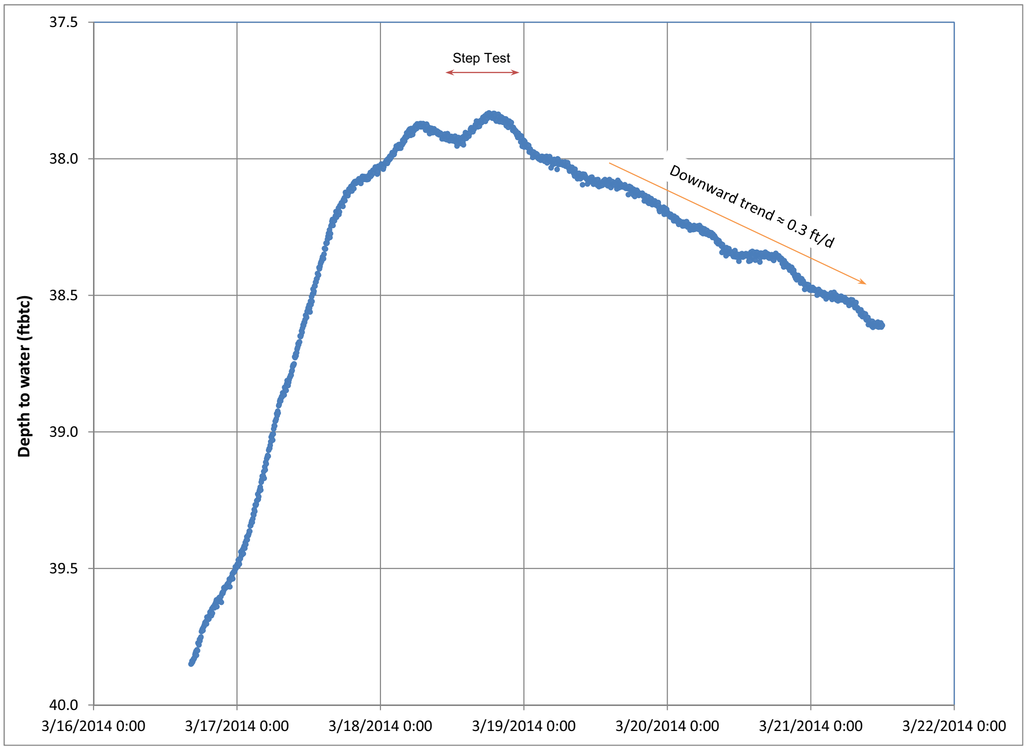


Pumping and Recovery

Figure 2.4.12B-A17. OW-409U Background, Pumping, and Recovery



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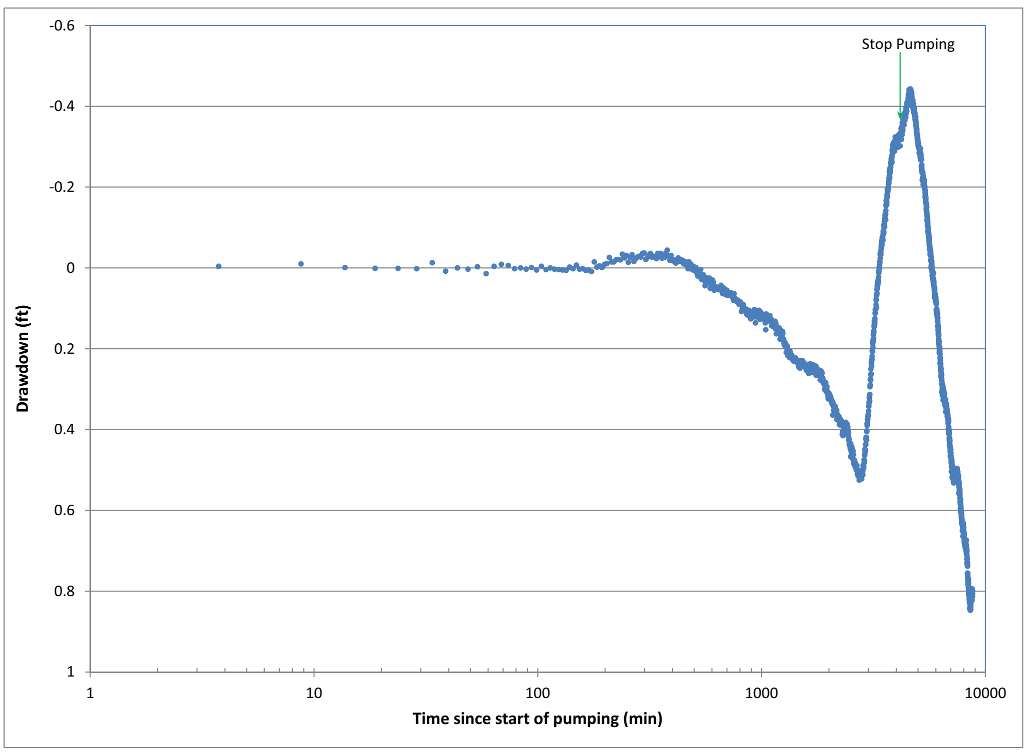
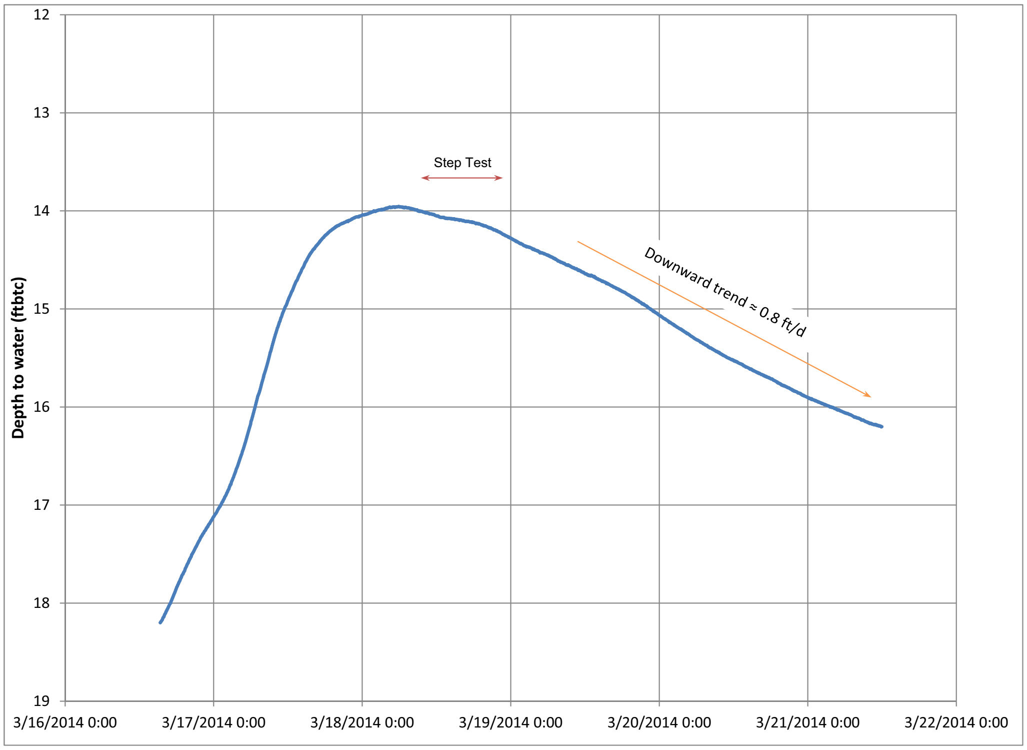


Pumping and Recovery

Figure 2.4.12B-A18. OW-409L Background, Pumping, and Recovery



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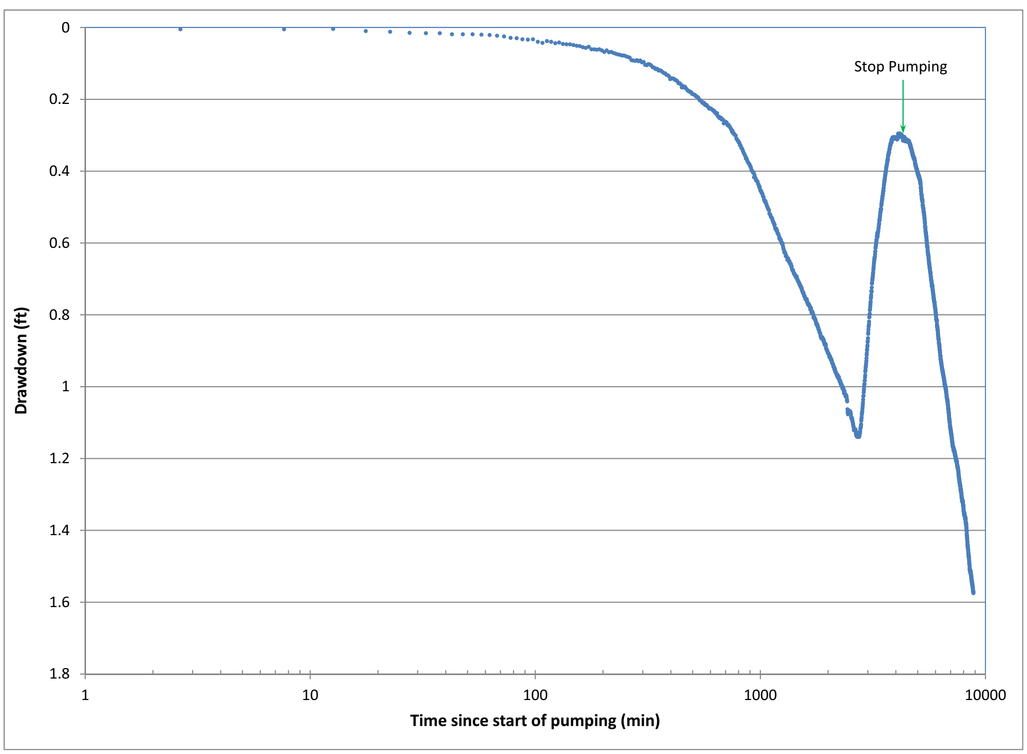
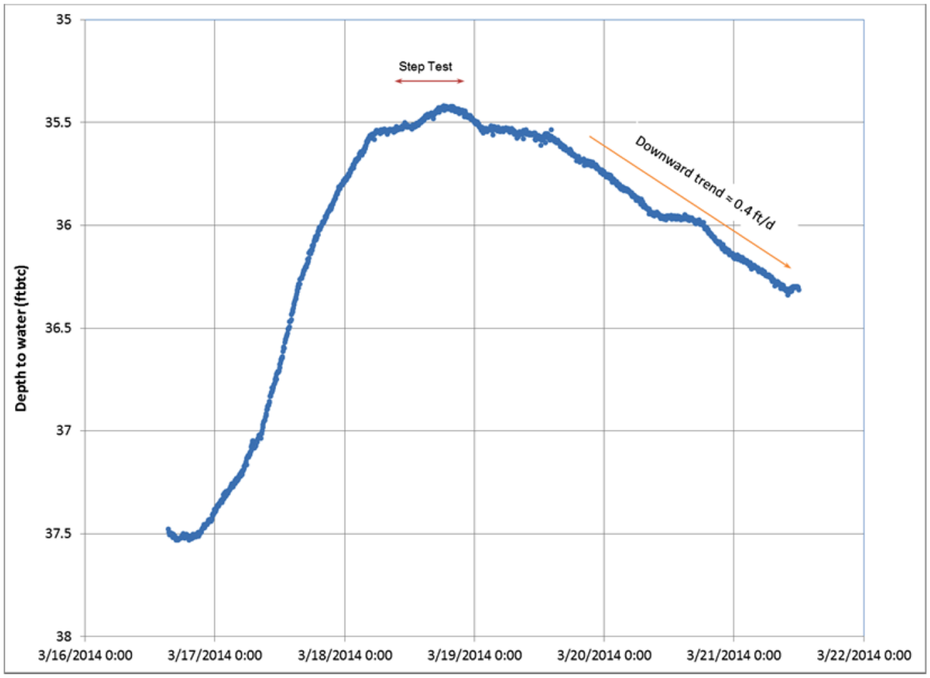


Pumping and Recovery

Figure 2.4.12B-A19. OW-101U Background, Pumping, and Recovery



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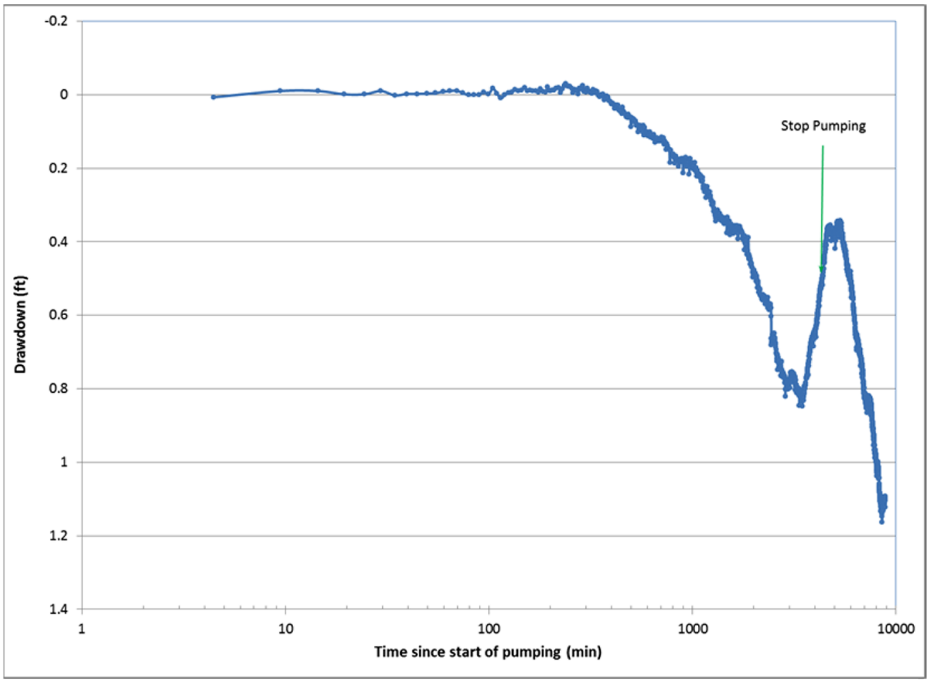
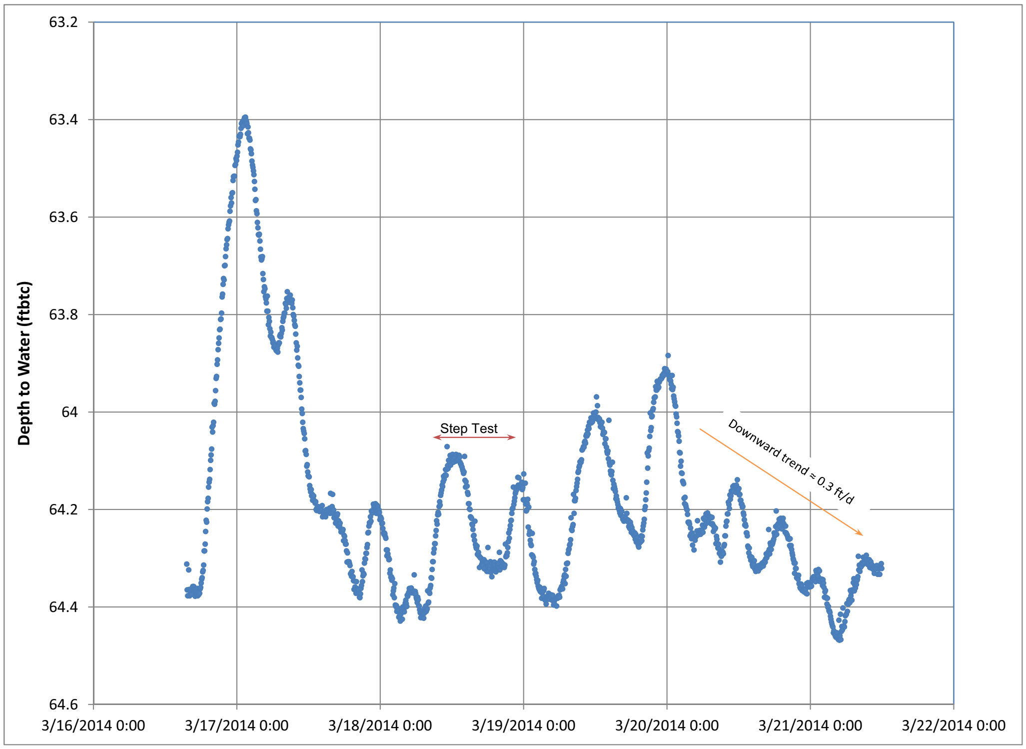


Pumping and Recovery

Figure 2.4.12B-A20. OW-101L Background, Pumping, and Recovery



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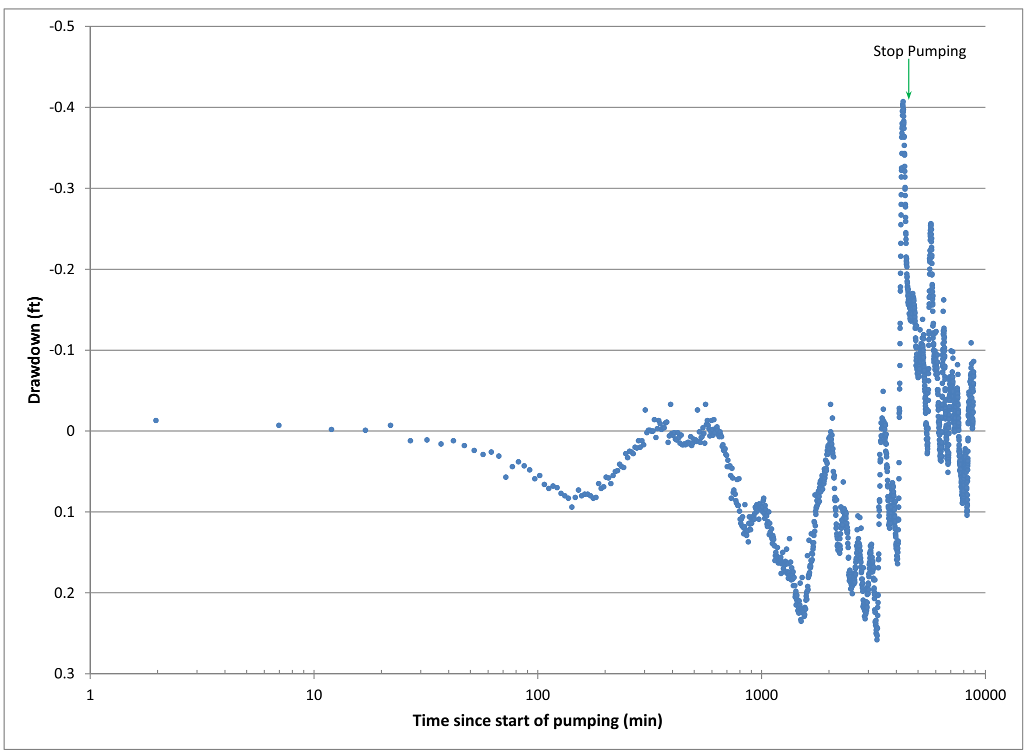
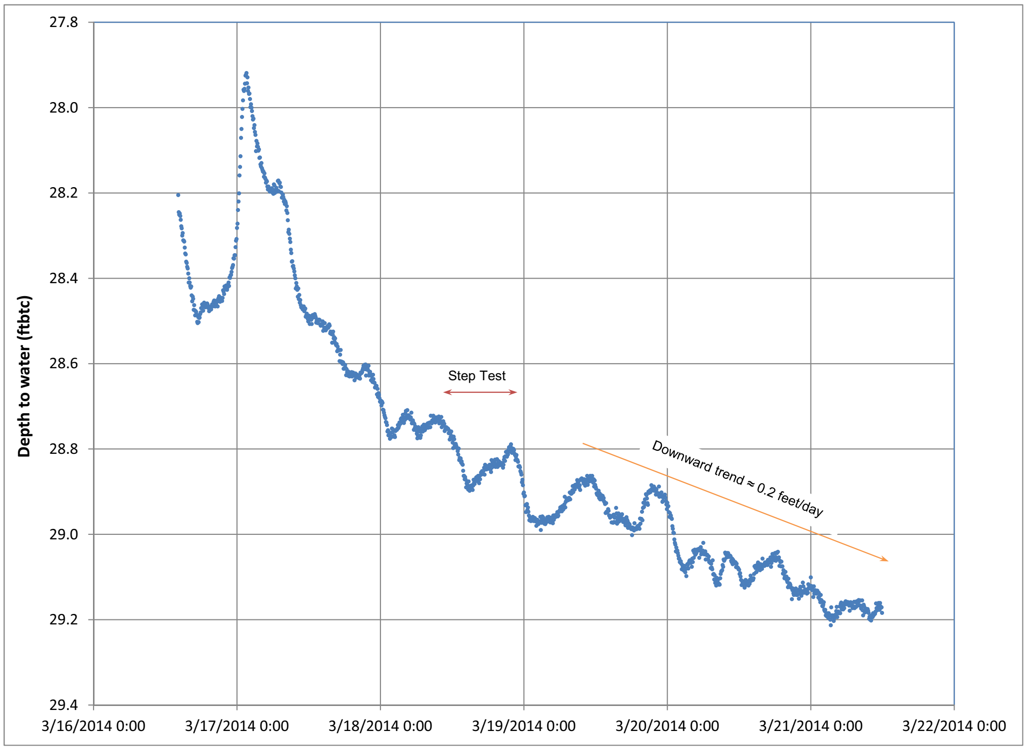


Pumping and Recovery

Figure 2.4.12B-A21. OW-101D Background, Pumping, and Recovery



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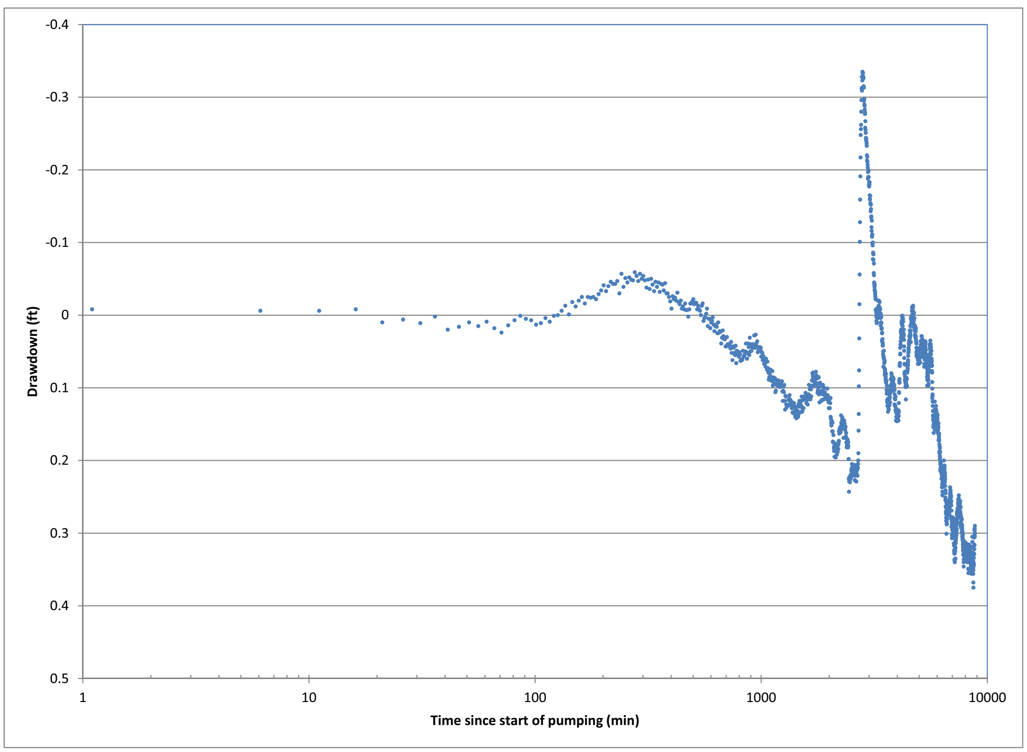
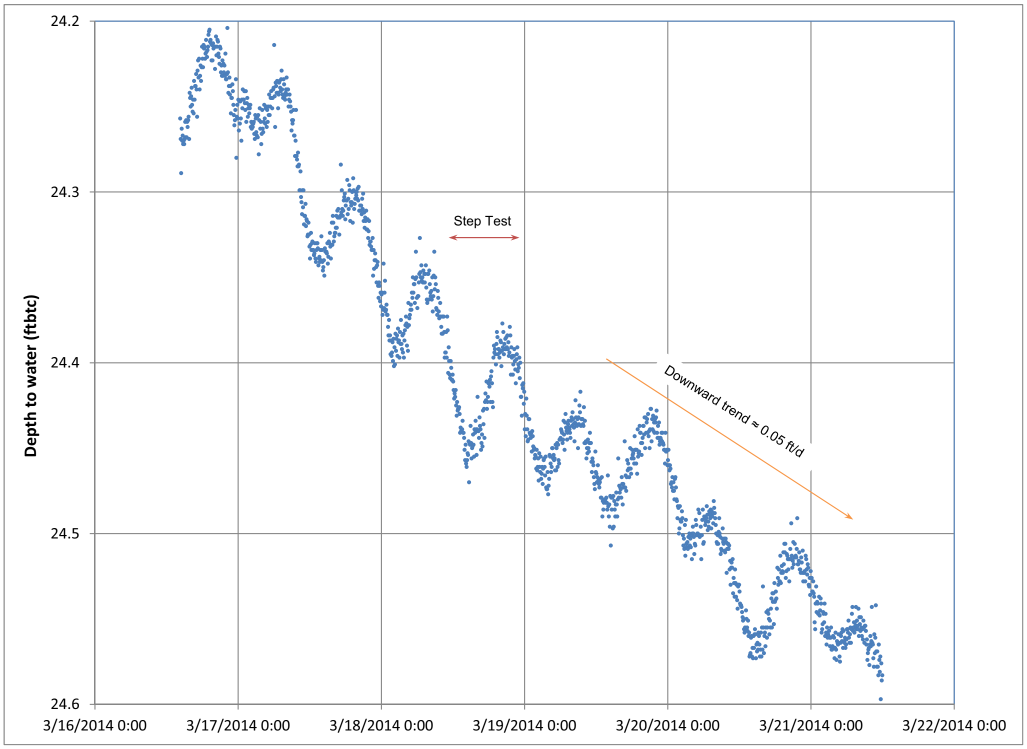


Pumping and Recovery

Figure 2.4.12B-A22. OW-417U Background, Pumping, and Recovery



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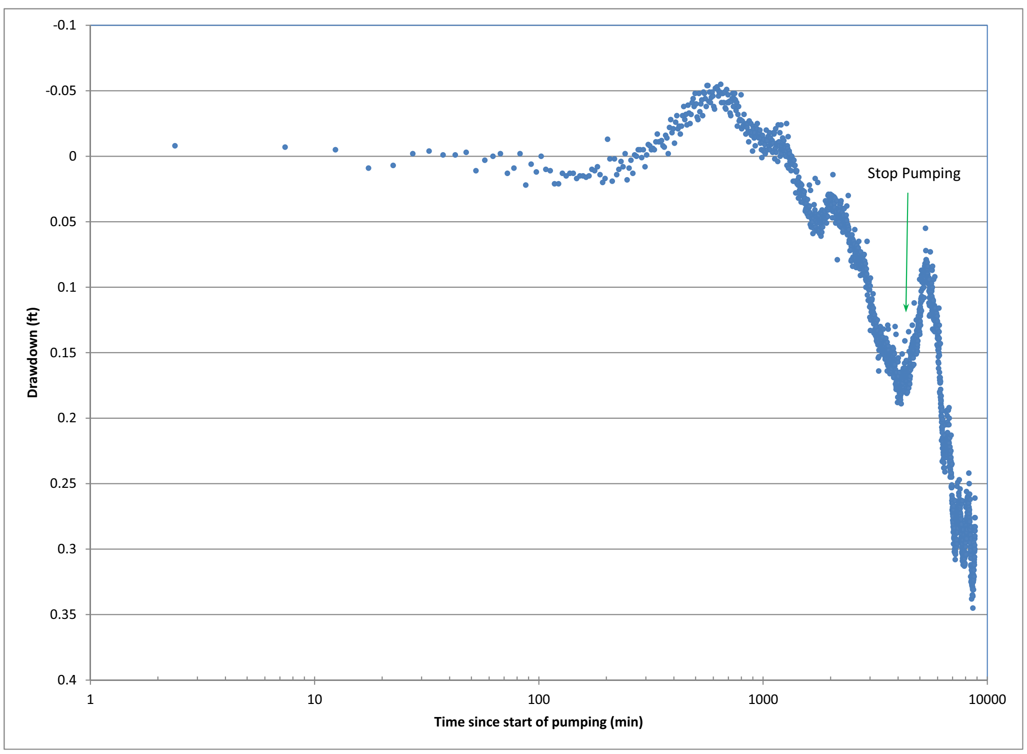

Pumping and Recovery

Figure 2.4.12B-A23. OW-417L Background, Pumping, and Recovery