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Summary Report for the 2013 Chromium Groundwater Aquifer Tests at R-42, R-28, and SCI-2



Prepared by the Environmental Programs Directorate

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March 2014

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1.0 INTRODUCTION

This report summarizes the results of aquifer testing activities conducted in 2013 at three monitoring wells, R-28, R-42, and SCI-2, within the Chromium Investigation monitoring group. These activities were conducted in accordance with the "Interim Measures Work Plan for Evaluation of Chromium Mass Removal (hereafter, the IMWP) (LANL 2013, 241096), submitted on April 30, 2013, in response to requirements in a letter from the New Mexico Environment Department (NMED), dated January 25, 2013 (NMED 2013, 521862). NMED subsequently issued an "Approval with Modification, Interim Measures Work Plan for the Evaluation of the Chromium Mass Removal, dated June 26, 2013 (NMED 2013, 522947).

The results of the aquifer tests were used to satisfy the two primary objectives of the scope of work outlined in the IMWP: (1) to provide hydraulic data that may help to determine the location for a pilot extraction test well and (2) to evaluate chromium removal efficiencies from the pumped wells to assess the potential for long-term removal of chromium from the regional aquifer. Pumping at SCI-2 was conducted to evaluate the potential for mass removal from the perched-intermediate zone. Figure 1.0-1 shows the locations of regional aquifer monitoring wells R-28 and R-42 and perched-intermediate monitoring well SCI-2. Figure 1.0-2 shows the locations of all monitoring wells within the chromium monitoring group, including wells used to monitor water-level responses to the long-term pumping events. Figure 1.0-2 also shows the locations of nearby water-supply wells. Figure 1.0-3 shows the location of the chromium and perchlorate plumes in the study area.

The data presented for all three aquifer tests include pumping rates, water-level responses, geochemical trends in groundwater samples collected during pumping and rebound sampling, and chromium mass removal. The report also provides information on the water treatment system and disposition of the treated water, the mass of chromium removed during the aquifer tests in both the perched-intermediate zone and the regional aquifer, and the geochemical trends observed at each well during pumping and rebound.

Information on radioactive materials and radionuclides, including the results of sampling and analysis of radioactive constituents, is voluntarily provided to NMED in accordance with U.S. Department of Energy policy.

2.0 AQUIFER TEST DETAILS

2.1 Aquifer Test Details and Chronology

2.1.1 Pump Replacement

Before the aquifer tests were conducted, the dedicated sampling systems in wells R-42 and R-28 were removed and larger pumping systems were installed. Well R-42 was reconfigured between May 16 and May 22, 2013. The dedicated, environmentally retrofitted sampling pump in R-42 was removed, and a Grundfos 10S50-48DS pump and 5 horsepower (hp) motor were installed inside a Baski 4.25-in. thin-walled pump shroud on 2.0-in. pipe. The pump control panel was modified for the larger pump. Figure 2.1-1 shows the pump configuration and depths of key components in R-42 at the start of the aquifer test.

R-28 was reconfigured between June 2 and June 4, 2013. The dedicated, environmentally retrofitted sampling pump in R-28 was removed, and a Berkeley L30MGS100-M pump end with a Franklin Electric 10 hp motor was installed within a custom thin-walled pump shroud. The pump control panel was modified for the larger pump. The pump configuration and depths of key components at the start of the R-28 aquifer test are shown on Figure 2.1-2. Although the pump and shroud were initially installed in the sump below the well screen, this configuration was revised after the pump in R-28 failed on August 30, 2013. The pump

was removed from the shroud, repaired, and then set in an alternate configuration above the screen, as shown in Figure 2.1-3.

The pumping test at SCI-2 was conducted with the dedicated Bennett pump sampling system already installed in the well, and no reconfiguration was necessary. Figure 2.1-4 shows the SCI-2 as-built construction diagram.

2.1.2 R-42 Aquifer Test

Pumping at R-42 started on June 17, 2013, and ended on August 21, 2013. A step-drawdown test was first conducted to establish an optimum pumping rate. Pumping on June 17 started at an initial pumping rate set to 9 gallons per minute (gpm). Based on observed water level declines in R-42, this rate was subsequently reduced to a target rate of 7 gpm on June 18. Thereafter, for the duration of the test, the pumping rate remained at approximately 7 gpm.

A pump failure caused an interruption in the test starting on the evening of July 7 and ending the morning of July 11, 2013. The pump and motor were replaced as a unit; a subsequent investigation determined that the motor had failed. R-42 was continuously pumped for the remainder of the test, from July 12 to August 21, 2013, when the aquifer test was terminated. A total of 676,000 gal. of water was pumped from R-42 over the 66-d pumping period. Rebound groundwater sampling began shortly after the aquifer test was terminated and continued to December 5, 2013.

2.1.3 R-28 Aquifer Test

A step-drawdown test was also conducted at the start of the R-28 aquifer test to establish an optimum pumping rate. Pumping at R-28 started on August 28, 2013, at the “full open” rate of 29.7 gpm. Shortly thereafter, this rate was reduced to 28 gpm, and drawdown responses at this lower rate were monitored overnight. Drawdown stabilized at approximately 2 ft, and based on this response, the pumping rate was increased on the morning of August 29 to the “full open” rate of 29.7 gpm. During the remainder of the test, the pump was operated at the maximum flow rate available from the pumping system, stabilizing at approximately 29 gpm.

The aquifer test at R-28 continued until November 22, 2013, at an average pumping rate of about 29 gpm with several intervals when pumping ceased as a result of problems with the pump. On August 30, 2013, the pump failed as a result of faulty wiring, and the pump was removed from the shroud, repaired, and then set in an alternate configuration above the screen rather than in the sump. Pumping resumed on September 7, 2013. On November 6, 2013, the pump shut off as a result of a tripped generator, and pumping resumed the following day. The aquifer test at R-28 was terminated on November 22, 2013, when freezing ground conditions required land application to cease in accordance with the temporary permission for land application granted by the NMED–Ground Water Quality Bureau (GWQB) on May 2 and October 4, 2013, respectively, for R-42 and R-28 (see section 2.3). A total of 3,217,000 gal. of water was pumped from R-28 during the 87 d of pumping. Rebound groundwater sampling continued at R-28 to March 3, 2014.

2.1.4 SCI-2 Pumping Test

Pumping at SCI-2 started on October 24, 2013, with pumping conducted using the SCI-2 dedicated pneumatic pump sampling system. The well was pumped until November 23, 2013, at an approximate rate of about 0.7 gpm, with negligible interruptions during the test. A total of 28,000 gal. of water was pumped from SCI-2 during the 30 d of pumping. Rebound groundwater sampling continued at SCI-2 to January 13, 2014.

2.2 Data Collection

Section 2.2.1 summarizes the hydraulic data collected during testing, and section 2.2.2 discusses the collection of samples for geochemical analyses.

2.2.1 Hydraulic Data

Water-level data were measured with pressure transducers in the pumping wells and at other regional aquifer monitoring wells located within the Chromium Investigation monitoring group, including R-1, R-11, R-13, R-15, R-33 screens 1 and 2, R-35b, R-36, R-43 screens 1 and 2, R-44 screens 1 and 2, R-45 screens 1 and 2, R-50 screens 1 and 2, R-61 screens 1 and 2, and R-62. The spreadsheets in Appendix B (on CD) provide the raw transducer data for the above-mentioned wells for the period from June 17, 2013, to December 18, 2013. Where applicable, the data are also corrected to account for the effects of barometric pressure to differentiate pumping effects from atmospheric effects. Some of the R-28 and R-42 data collected using absolute transducers do not need barometric-pressure corrections (there may be barometric pressure effects in the absolute transducer data, but these effects are negligible). Detailed analysis of the water-level responses is presented in Appendix B and discussed in section 3.0 of this report.

During the aquifer testing, water-supply pumping occurred at nearby Los Alamos County municipal wells O-4, PM-2, PM-3, PM-4, and PM-5. Well O-4 was active during the entire aquifer test period; PM-1, PM-2, PM-3 and PM-5 were pumped intermittently, and PM-4 became active on June 27, 2013, and continued to pump until November 16, 2013. Municipal water-supply pumping details are included in Attachment B-1 in Appendix B (on CD).

Figure 2.2-1 shows barometric pressure–corrected water-level data for R-42, R-28, and nearby observation wells R-11, R 15, R-28, R-43, R-44, R-45, R-50, and R-61. Periodic rises in the water levels at R-42 and R-28 were observed during pumping, when the generator was turned off for refueling; periodic declines also occurred during rebound when water samples were collected.

Figure 2.2-2 shows barometric pressure–corrected water-level data for SCI-2 and the nearby observation wells MCOI-5 and MCOI-6, completed in perched-intermediate groundwater. No drawdown responses were observed in any nearby observation wells.

2.2.2 Analytical Data

Sampling Frequency

Samples were collected daily from the three pumped wells, R-42, R-28, and SCI-2, through the duration of each aquifer test (except during periods of pump failure). Samples were collected daily during the initial portion of the rebound test. The sampling frequency for rebound samples was later reduced to three times per week and eventually to once per week.

Sample Analyses

Table 2.2-1 lists the analytes sampled during the pumping and rebound phases of each test. Samples were analyzed for the following constituents: metals, dissolved organic carbon (DOC), anions, alkalinity and pH, total organic carbon (TOC), chromium isotopes, polymerase chain reaction (PCR) for organic deoxyribonucleic acid, and tritium.

Most of the analyses were conducted on-site at the Geochemistry and Geomaterials Research Laboratory (GGRL). Biweekly tritium samples were sent to GEL for analysis. Chromium isotope analyses were conducted to assess variations in isotope fractionation during pumping and rebound. PCR analyses were used to determine microbial activity.

The frequency of analyses varied for some constituents, depending on variability observed in the results. In some cases, samples were collected daily, but not all samples were analyzed if the results showed little or no variability in constituent results (see section 2.2.3).

Field water quality parameters were measured at the time of sampling to evaluate groundwater conditions and to provide early insights into any changes in groundwater quality or conditions in the well. The field parameters measured included pH, temperature, specific conductance, dissolved oxygen (DO), turbidity, and oxidation-reduction potential (ORP).

Hach kits were used to measure chromium(VI), total chromium, and several redox-sensitive species in R-42, R 28, and SCI-2 water during pumping. The kits were also used for measurements during post-aquifer-test rebound in the wells. Rebound samples were collected after purging at least 1 casing volume. Besides providing qualitative screening of chromium concentrations in water samples, the objective of the field Hach kit measurements was to screen for redox-sensitive species that can indicate whether geochemical conditions in the aquifer are capable of reducing chromium(VI) to chromium(III). The measurements were conducted over time during both pumping and rebound of the wells so that any observed changes in chromium concentrations could be evaluated for correlations with changes in the concentrations of redox-sensitive species. The Hach kit data are discussed in Appendix A, and the full set of Hach data are included in that appendix.

Samples Taken

A considerable number of samples were collected during pumping and rebound at R-42, R-28, and SCI-2. The full set of samples taken tables for samples collected during pumping and rebound at each well are presented in Appendix D (on CD) along with associated field water-quality parameters (pH, temperature, specific conductance, DO, turbidity, and ORP measured at the time of sampling).

In some cases, samples were collected daily, but not all samples were analyzed if the results showed little or no variability in constituent results. A separate table in Appendix D lists the samples analyzed with the data available in the online analytical database, IntellusNM, and compiled in the Environmental Information Management database. The complete set of analytical data collected during 2013 aquifer testing activities is also included in Appendix D (on CD).

2.3 Water Treatment and Disposition

Groundwater pumped during the aquifer test was treated using ion exchange resin to remove chromium and nitrate. Treated water was sampled to ensure concentrations were below the approved land-application limit of 45 µg/L for chromium and 9 mg/L for nitrate. Treated water was then disposed of via land application at six land-application zones within Mortandad Canyon (Appendix C) in accordance with the temporary permission granted by NMED-GWQB.

2.3.1 Treatment Methodology

The Laboratory applied for and received temporary permission to discharge for R-42 and, separately, for R-28. The temporary permission allows for storage of groundwater in aboveground frac tanks, treatment of groundwater using ion exchange for chromium removal, and storage of treated groundwater in

synthetically lined lagoons. It also authorized land application on 77 acres of roadways and 6 acres of open area. The Laboratory operated the system during regular work hours. Since the wells were to be pumped continuously, it was necessary to use portable frac tanks of nominal 20,000-gal. capacity to store water for the periods when the treatment system was not operating.

Ion exchange resin was selected for treatment of the groundwater. Specifically, Siemens AGW resin was selected because it was used previously at the Laboratory with good results and is recommended for removal of chromium. This ion-exchange resin is an anionic type in the chloride state. Thus, it will remove a wide variety of anions and exchange these ions with a chloride ion on a one-for-one charge basis. The chromium in groundwater is the anionic form, and bonds with oxygen. In addition to chromium, other major ions removed are sulfate and nitrate. Schematics of the treatment systems are presented in Appendix C (on CD). Additionally, photographs of the R-42 treatment system's ion exchange vessels and the overall R-28 treatment site are shown in Figures 2.3-1 and 2.3-2.

Approximately 3 wk into operations at R-42, nitrate concentrations began to increase, indicating the start of "breakthrough." Up until this point, chromium, sulfate, and nitrate had all been removed to levels near the detection limits. As the nitrate was pushed out by chromium and sulfate (primarily sulfate from the much higher concentrations in R-42), "nitrate flooding" was observed. While the nitrate has always been below the land-application limit (9.0 mg/L nitrate as nitrogen), nitrate flooding quickly increased the concentration to nearly 16 mg/L. The effluent was stored in the effluent holding lagoon, and no water exceeding the limit was applied. After checking the nitrate concentration in effluent basin, Laboratory personnel re-treated the high-nitrate effluent, and the treatment system returned to normal operation. For the duration of the R-42 treatment, the ion exchange vessels were changed out at the first sign of nitrate breakthrough, and no further problems were encountered. Figure 2.3-3 shows influent and effluent nitrate concentrations during R-42 treatment operations

During the aquifer testing, well R-42 was pumped first, followed by R-28. There was no overlap in well pumping. The treatment system was operated at an average flow rate of 74 gpm from June 19 to August 21, 2013. Well R-28 treatment system was operated from August 30 to November 21, 2013, with an average flow rate of 212 gpm. Additionally, water from SCI-2 was trucked to the influent storage tanks at R-28 from October 24 to November 22, 2013, and treated at the R-28 treatment system. Figure 2.3-4 shows influent and effluent nitrate concentrations during R-28 treatment operations.

In late July, the influent concentration to the R-42 treatment system dropped considerably as a result of re-treating. Consequently, some water exhibited high nitrate concentrations, but not chromium. R-28 manifested nitrate flooding as well. However, since the process utilized three parallel treatment trains the effects of flooding were muted. Toward the end of the well pumping at R-28, chromium was first observed to exhibit breakthrough, rising slightly in the effluent from the first stage treatment in one of the three trains. No groundwater from either well was applied in excess of land-application limitations.

Figures 2.3-5 and 2.3-6 detail the chromium influent and effluent concentrations for the R-42 and R-28 treatment system, respectively. The average concentration of chromium in the effluent from R-42 was 4.2 µg/L and was 5.2 µg/L for R-28. Each represents a 99% removal of the influent concentrations. During the 2013 aquifer testing, a total of 3,921,000 gal. of water was pumped from the regional aquifer and perched-intermediate zone, with 11.9 lb of hexavalent chromium removed from the regional aquifer, and 0.1 lb of chromium removed from the perched-intermediate zone of saturation.

2.3.2 Disposition of Treated Water

All groundwater was treated via ion exchange before being land-applied in accordance with the temporary permission issued by NMED. The dates, locations, and volumes of water discharged were documented in Laboratory submittals included in Appendix C (on CD). Treated groundwater was dispositioned via land

application at six land-application zones within Mortandad Canyon, as approved by the NMED-GWQB in the temporary permission (Appendix C).

Appendix C also includes the final project reports submitted to NMED within 30 d of the final cessation of land application. These reports, entitled “Final Project Report, Land Application of Treated Groundwater from Monitoring Wells R-28 and SCI-2, DP-1793” and “Final Project Report, Land Application of Treated Groundwater from Monitoring Well R-42, DP-1793,” provide information in Enclosure 2 about the water that was land applied for each of the aquifer tests, including sample and batch numbers, date applied, volume applied, location of application, and chromium and nitrate concentrations. Enclosure 3 of each report includes a map of the land application sites for each aquifer test.

3.0 SUMMARY OF AQUIFER TEST RESULTS

3.1 Water-Level Observations

Appendix B provides detailed descriptions and analyses of the water-level data, including figures showing the temporal and spatial behavior of the observed pressure transients during the 2013 aquifer tests. The analyzed water-level data were obtained from the Laboratory database record of the water levels measured at the monitoring wells on the Pajarito Plateau. Regional aquifer water-level data are provided in an Excel file in Appendix B (on CD).

The following is a summary of the aquifer test results.

- PM-4 pumping caused measurable declines of the water levels in the regional aquifer during the 2013 aquifer tests at R-42 and R-28 (especially the water levels observed at R-15). The effects of pumping at PM-4 and other municipal pumping wells on the water levels were successfully accounted for during the R-42 and R-28 aquifer tests using long-term model analyses of the collected water-level data.
- R-42 pumping produced limited drawdown effects; the only well that clearly showed effects was R-43, where responses were measured in both screens (Figure 3.1-1).
- In contrast, R-28 pumping produced drawdowns at most of the nearby monitoring wells, except R-1 and R-36 (Figure 3.1-2). Responses were observed in R-11, R-13, R-15, R-35b, R-43 screens 1 and 2, R-44 screens 1 and 2, R-45 screens 1 and 2, R-50 screens 1 and 2, R-61 screens 1 and 2, and R-62. Figure 3.1-2 also presents contours of the pumping drawdowns at the end of the R-28 pumping test.
- R-28 pumping potentially produced drawdowns at R-35b. However, R-35b minimally responds to pumping from nearby water-supply well PM-3. The minimal response at R-35b likely reflects pronounced local hydraulic separation between the deep sections of the aquifer that are pumped by PM-3 and zones monitored by other nearby monitoring wells, including R-35a.
- During the R-28 aquifer test, R-42 and R-43 screens 1 and 2 produced anomalously low drawdowns compared with other nearby monitoring wells (e.g., R-62). This observation may be an indication of either a low-permeability zone around R-43/R-42, a flow barrier between R-28 and R-42, or a recharge (infiltration) zone, or any combination of three.
- The drawdown curves observed during R-28 aquifer test show drawdown stabilization towards the end of the aquifer test. This drawdown stabilization can be caused by various factors, including (1) delayed yield from the vadose zone (phreatic aquifer effects), (2) leakage for the deeper hydrostratigraphic units (leaky aquifer), (3) lateral boundary effects (high-permeability zones), and (4) infiltration recharge from the vadose zone.

- The 2013 R-28 aquifer test data demonstrate a greater degree of heterogeneity than indicated by the data collected during the 10-d aquifer test at R-28. The heterogeneity is demonstrated by pronounced deviations of the drawdowns at individual monitoring wells from the uniform theoretical curve (Figure B-34).
- The observed aquifer heterogeneity will be important for determining the efficiency of remediation strategies that include aquifer pumping for source removal and plume control. Aquifer heterogeneity will affect the width and length (upgradient and downgradient) of the capture zones (CZ) associated with pumping wells. For example, aquifer heterogeneity can have a beneficial effect by reducing the number of pumping wells needed to establish a CZ if pumping occurs in an elongated, highly transmissive aquifer zone oriented perpendicular to the groundwater flow direction.
- The 2013 R-28 aquifer test data suggest lower-effective large-scale aquifer transmissivity than the 2012 R-28 aquifer test data. The effective large-scale transmissivity of the regional aquifer might be about transmissivity (T) of 30,000 gallons per day (gpd) per foot (transmissivity was estimated at 40,500 gpd/ft based on the 2012 test data); however, existing uncertainties indicate it is possible that the large-scale transmissivity may be even lower. The analyses are complicated because of the pronounced aquifer heterogeneity suggested by the 2013 aquifer test data.
- The SCI-2 pumping did not produce drawdowns in the perched intermediate zone other than in SCI-2; no drawdowns were detected at MCOI-5 or MCOI-6. The estimated transmissivity based on the SCI-2 aquifer test data is 1600 gpd/ft (or 20 m^2/d).
- None of the pumping from any of the wells in this study caused drawdowns in the municipal water-supply wells.
- Pumping at the water-supply wells affects the pressures observed in the monitoring wells in the Chromium Investigation monitoring group. However, the pressure responses from the water-supply well pumping may not influence the flow direction in the shallow portion of the regional aquifer within the area of the chromium plume. The pumping influence from the water-supply wells was observed to be relatively uniform in the shallow portion of the regional aquifer.

3.2 Capture Zone Analysis for R-42 and R-28

The 2013 aquifer tests provide important information about aquifer properties that can be applied to estimate the pumping CZs. It is important to distinguish between a CZ and a zone of influence (ZOI, cone of depression). Here the ZOI is the area within which measurable drawdown (greater than 0.01 m) can be detected (theoretically, very small nonmeasurable drawdowns will be manifested everywhere in the aquifer). The CZ represents the portion of the aquifer that is influenced by a pumping well in such a way that all the groundwater within the CZ will eventually be pumped out by the well, if continuous pumping occurs.

In the case of a uniform isotropic aquifer, the shape of the ZOI and CZ will be similar; it will be a circle centered at the pumping well. The radius of the circle will depend on the pumping rate and duration. Typically, the ZOI is bigger than the CZ. However, in the case of ambient flow, the CZ will be elongated in shape with a predominantly upstream spatial extent (Figure B-37). In general, the CZ of pumping wells has a three-dimensional shape characterized by three-dimensional structure and properties of the regional groundwater flow during the aquifer test.

The R-42 ZOI is very limited (Figure 3.1-1). In contrast, the R-28 ZOI is extensive (Figure 3.1-2). However, the shape and size of the CZs of these wells are expected to be much smaller. Laterally, the CZ of R-28 and R-42 during the 2013 aquifer tests can be assumed to be circular with a radius of about

30 m (90 ft) and 15 m (50 ft), respectively. These estimates ignore the influence of ambient groundwater flow. As a result, the actual CZs are expected to be elongated upgradient with limited downgradient extent from a pumping well. The vertical extent of the CZ is expected to be close to the size of the pumped screen interval (or about 1.5 times the screen length).

The CZ estimates above are representative for short pumping periods (less than 100 to 300 d depending on the aquifer properties). However, the aquifer test data may also be used to estimate the long-term CZs if R-42 and R-28 are pumped indefinitely. In this case, the shape of the CZs will be close to the conceptual representation in Figure B-37. However, given the hydrogeological complexities in the regional aquifer, the CZs are expected to have more complicated shapes and be affected by (1) aquifer stratification, heterogeneity, and anisotropy, and (2) spatial and temporal variability in aquifer recharge.

3.3 Aquifer Properties

Table 3.3-1 summarizes the estimated aquifer properties for the regional aquifer based on the R-42 and R-28 aquifer tests. The results of the extended aquifer testing at R-28 and R-42 in 2013 indicate the effective large-scale transmissivity (T) for the regional aquifer may be on the order of 30,000 gpd/ft or lower, and the effective large-scale storativity (S) is 0.01. The 2013 aquifer test data also showed pronounced aquifer heterogeneity, which was not observed during the 2012 10-d aquifer test. This heterogeneity is reflected in the variability of the estimates for T and S for the individual wells determined from paired analyses with pumping wells R-42 and R-28.

4.0 CHROMIUM REMOVAL AND GEOCHEMICAL ANALYSES

In addition to the hydraulic analysis described above, data were also collected to evaluate chromium concentration trends during pumping and rebound. This section presents information on the transients of key constituents during pumping and rebound and the amount of chromium removed during the aquifer tests. Plots of several other key geochemical parameters during pumping and rebound at each of the wells are also presented.

4.1 R-42 Chromium Removal and Water Volumes Treated

Figure 4.1-1 shows the chromium concentrations detected during the R-42 aquifer test and the recovery period, and corresponding water levels. The vertical lines indicating the timing of the pump failure/restart and the end of the pump test. Over the 66-d aquifer test at R-42, concentrations decreased from an initial value of 932 µg/L to 675 µg/L, or a 27% decline. For the 106-d rebound period through December 5, 2013, chromium concentrations in R-42 recovered to approximately 850 µg/L. That concentration is considered reasonably representative of pre-pumping concentrations given the high variability in chromium concentrations in the well even under ambient flow conditions. The complete set of analytical data for R-42 is presented in Appendix A (on CD).

Figure 4.1-2 shows the chromium concentrations detected during the R-28 aquifer test and the recovery period and corresponding water levels. The vertical lines indicating the timing of the pump failure/restart and the end of the pump test. Over the 86-d aquifer test at R-28, concentrations dropped from an initial value of approximately 350 µg/L to 280 µg/L, or a 20% decline. For the 106-d rebound period through March 4, 2014, chromium concentrations in R-42 recovered to approximately 330 µg/L. The complete set of analytical data for R-28 is presented in Appendix A (on CD).

Figure 4.1-3 shows the chromium concentrations detected during the SCI-2 aquifer test and the recovery period and corresponding water levels. Over the 30-d aquifer test at SCI-2, concentrations typically ranged between 350 µg/L and 450 µg/L. No trends are apparent during pumping and recovery. The complete set of analytical data for R-28 is presented in Appendix A (on CD).

Table 4.1-1 summarizes the aquifer test duration, volume of water pumped (in thousands of gallons), and total chromium removed during each aquifer test. For comparison purposes, the data from the 10-d aquifer test at R-28 in 2012 are also included in the table.

Figure 4.1-4 shows the total chromium mass removal as a function of the volume of groundwater pumped for each of the three aquifer tests and total chromium mass removal as a function of time. A total of 5.5 kg (12.0 lb) of chromium was removed during all three tests in 2013, with approximately 3,921,000 gal. of water pumped.

4.2 Other Geochemical Trends

During the aquifer tests, a considerable number of samples were collected to evaluate transient concentration trends of key geochemical constituents. The samples collected and the analytical data are discussed in section 2.2. The full set of analytical results is included in Appendix D (on CD).

Appendix A also includes tables and plots showing trends in redox-sensitive species measured with using a Hach DR 890 field spectrometer. Species analyzed using the Hach kits include chromium and chromium(VI), manganese, nitrate, nitrite and ammonia, and sulfide. Additional details on the Hach methodology used are presented in Appendix A.

Figures 4.2-1, 4.2-2, and 4.2-3 show time-series trends for sulfate, nitrate, and chromium in R-42, R-28, and SCI-2, respectively, during pumping and rebound. Of the constituents plotted, chromium seems to show the most significant transient trends over time, with concentrations decreasing ~20% to 27% in R-28 and R-42, respectively, as discussed in section 4.1. Transient trends in sulfate concentrations in pumping and rebound samples are observed as well, with increasing trends observed in sulfate near the end of the aquifer test and fairly significant variations in sulfate concentrations at the start of the rebound period.

Chromium isotope sampling was conducted throughout the three aquifer tests and during rebound. Most of the isotope samples from the R-42, R-28, and SCI-2 aquifer tests were batched and are currently undergoing analysis. However, samples from the early part of the R-42 pump test collected between June 19 and July 13, 2013, have been analyzed for chromium isotopes. Values were identical within error (approximately ±0.2 ‰ based on duplicate pairs of field samples) at approximately 0.9‰ but slightly lower than the long-term average of values measured at this site (1‰ to 1.2‰; LANL 2011, 206234). These results suggest that pumping during this time did not access waters with significantly different degrees of chromium(VI) reduction relative to initial conditions.

5.0 CONCLUSIONS

Extended-duration aquifer tests were conducted at R-42 and R-28 in the regional aquifer and at SCI-2 in the perched-intermediate zone. The tests addressed the two primary objectives of the scope of work outlined in the IMWP: (1) to provide hydraulic data that may help to determine the location for a pilot extraction test well and (2) to evaluate chromium removal efficiencies from the pumped wells to assess the potential for long-term removal of chromium from the regional aquifer.

The hydraulic data collected during the 2013 aquifer tests provided a better understanding of the effective large-scale transmissivity and storativity for the regional aquifer and were used to help determine the location for the proposed pilot extraction well, CrEX-1.

Key findings of the aquifer tests conducted at R-42 and R-28 include observations at both wells that concentrations of chromium during pumping at R-42 and R-28 declined to approximately 27% and 20%, respectively, from the initial concentrations. Chromium concentrations also rebounded in both wells, though at different rates. The aquifer-test data also showed significant hydraulic heterogeneity of the aquifer in the vicinity of R-42 and R-28. These factors have implications on contaminant-mass removal rates that may be expected during long-term pumping from wells more specifically designed for mass removal. The reasons for the chromium concentration decline and associated rebound may be a combination of several physical and geochemical processes. These include partitioned chromium concentrations at small spatial scales (e.g., spatially variable and stratified concentrations within layers with different particle-size distribution and/or porosity) near the well or pumping of some percentage of groundwater from cleaner zones upgradient or below the pumped intervals. Additional pumping within the contaminant plume and further evaluation of observed transients in hydraulic pressures, in chromium and other co-contaminant concentrations, and in geochemical indicators may help resolve this uncertainty. The rebound in chromium concentration values that was observed at both wells has significant implications on operational strategies that may potentially be used for source removal.

Even though these tests were conducted with existing monitoring wells, the results indicate that more efficient contaminant mass removal can be achieved by pumping at large rates from the highly transmissive portion of the aquifer in the R-28 area. Although these conclusions are affected by factors such as aquifer heterogeneity and monitoring well design at these wells, the results may also indicate the formation in shallow portions of the regional aquifer near R-42 might not be as optimal for large-scale mass removal as the area near R-28. However, if the area near R-42 is a primary drip point for chromium from the vadose zone, an appropriately designed well could be sited to achieve significant and important mass-removal objectives.

The observations of a large and roughly symmetric ZOI does not imply that pumping in the R-42 and/or R-28 areas would create a CZ sufficient to significantly influence chromium concentrations very far downgradient of either well. Thus, pumping in the area of R-42 and R-28 would not likely manifest as decreasing concentrations in key downgradient wells such as R-50 for up to 5 to 10 yr or more.

6.0 RECOMMENDATIONS

Based on the results of studies conducted to date under the IMWP, two key areas of additional work are proposed and described below.

Pilot Extraction Well CrEX-1

To further characterize the aquifer properties and to evaluate the potential to capture chromium flux towards the Laboratory boundary, a pilot extraction well is being proposed for installation. The drilling work plan for the pilot extraction well, CrEX-1, was submitted to NMED on March 18, 2014, and fulfills a schedule commitment of the IMWP to propose additional work by March 31, 2014. It also fulfills a requirement of NMED's approval with direction on the IMWP, dated June 26, 2013 (NMED 2013, 522947) to submit a work plan for a pilot pumping well by March 31, 2014. The objectives, the location, and preliminary design for CrEX-1 are provided in the drilling work plan (LANL 2014, 254824).

Characterization Coreholes

Geochemical characterization studies are included in the IMWP. The key objective of these studies is to characterize whether chromium reduction or adsorption may be occurring within the vadose zone and regional aquifer. Characterization has begun on archived cuttings obtained from several wells in the Chromium Investigation monitoring group. It is recognized, however, that use of archived cuttings could lead to significant uncertainties in the results. For this reason, collection and characterization of representative core (as opposed to analyzing cuttings) from key locations within the plume is recommended. The Laboratory will prepare and submit to NMED for its review a separate work plan to discuss the objectives and locations for a number of proposed coreholes before implementation of field activities.

7.0 REFERENCES

The following list includes all documents cited in this report. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the NMED Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

LANL (Los Alamos National Laboratory), September 2011. "Phase II Investigation Work Plan for Upper Sandia Canyon Aggregate Area, Revision 1," Los Alamos National Laboratory document LA-UR-11-4912, Los Alamos, New Mexico. (LANL 2011, 206234)

LANL (Los Alamos National Laboratory), April 2013. "Interim Measures Work Plan for the Evaluation of Chromium Mass Removal," Los Alamos National Laboratory document LA-UR-13-22534, Los Alamos, New Mexico. (LANL 2013, 241096)

LANL (Los Alamos National Laboratory), March 2014. "Drilling Work Plan for Groundwater Extraction Well CrEX-1," Los Alamos National Laboratory document LA-UR-14-21478, Los Alamos, New Mexico. (LANL 2014, 254824)

NMED (New Mexico Environment Department), January 25, 2013. "Response, Proposal to Submit Interim Measures Work Plan for Chromium Contamination in Groundwater," New Mexico Environment Department letter to P. Maggiore (DOE-LASO) and J.D. Mousseau (LANL) from J.E. Kieling (NMED-HWB), Santa Fe, New Mexico. (NMED 2013, 521862)

NMED (New Mexico Environment Department), June 26, 2013. "Approval with Modification, Interim Measures Work Plan for the Evaluation of Chromium Mass Removal," New Mexico Environment Department letter to P. Maggiore (DOE-LASO) and J.D. Mousseau (LANL) from J.E. Kieling (NMED-HWB), Santa Fe, New Mexico. (NMED 2013, 522947)

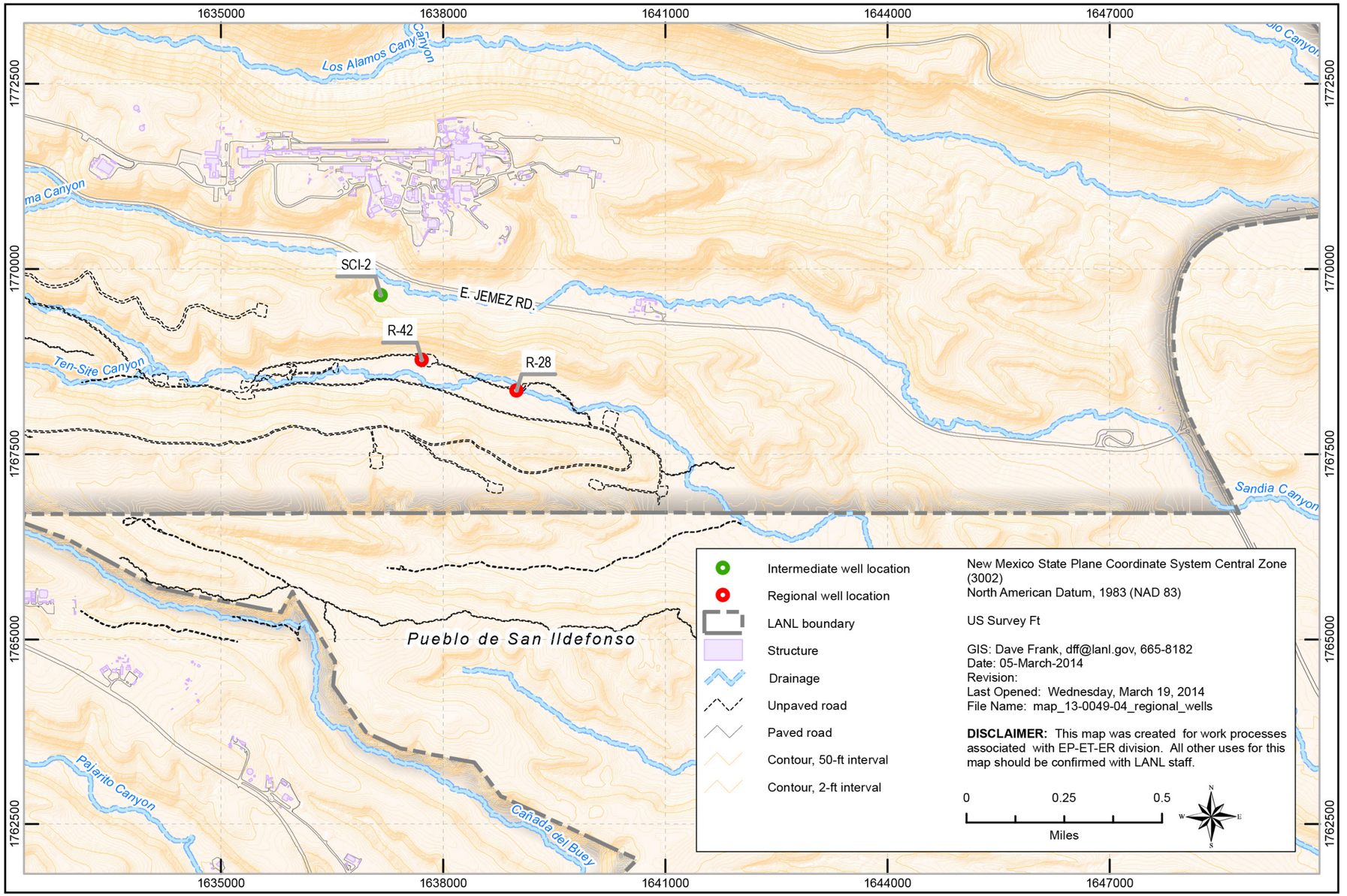


Figure 1.0-1 Location of monitoring wells R-28, R-42, and SCI-2

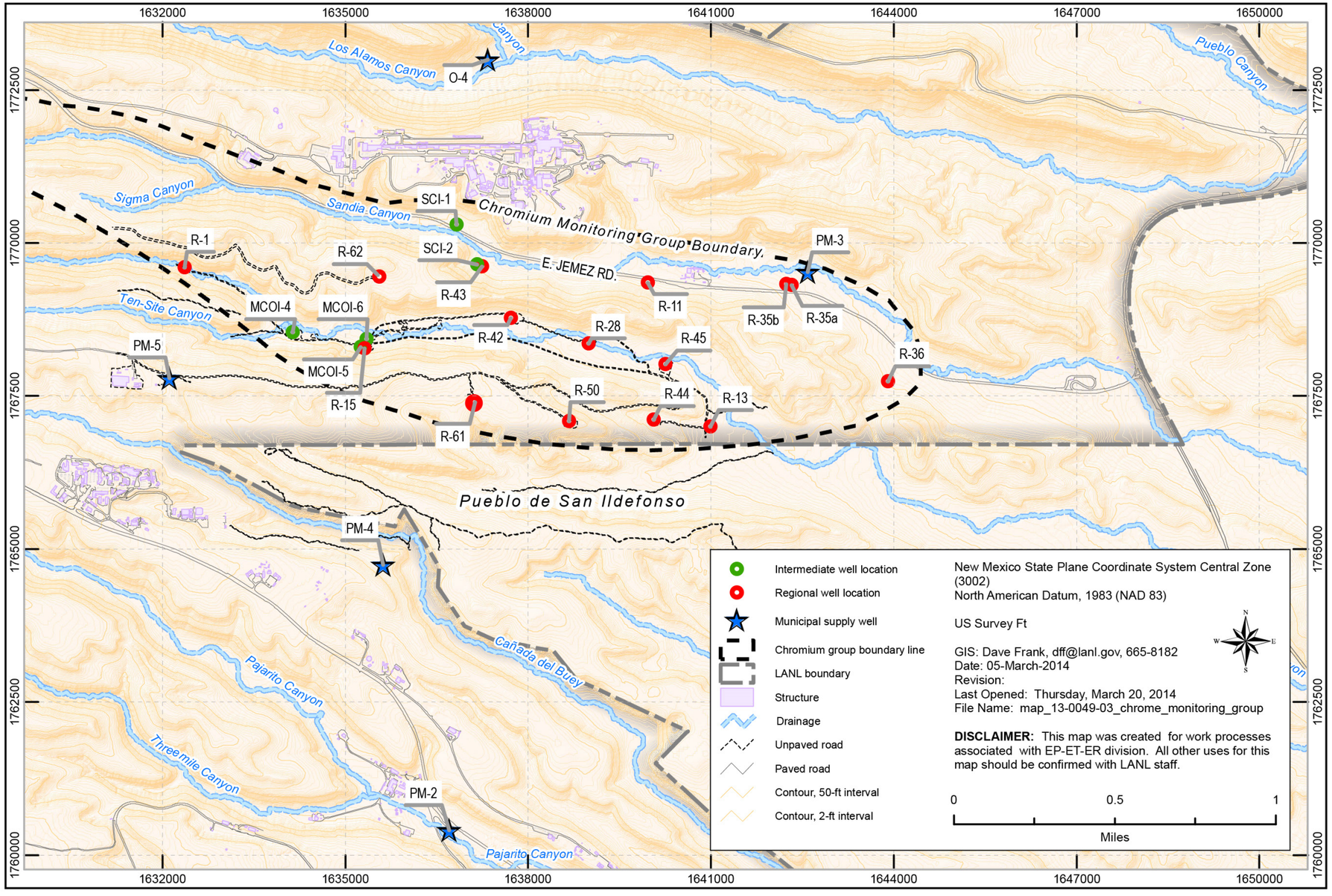


Figure 1.0-2 Chromium Investigation monitoring group wells and nearby municipal water-supply wells

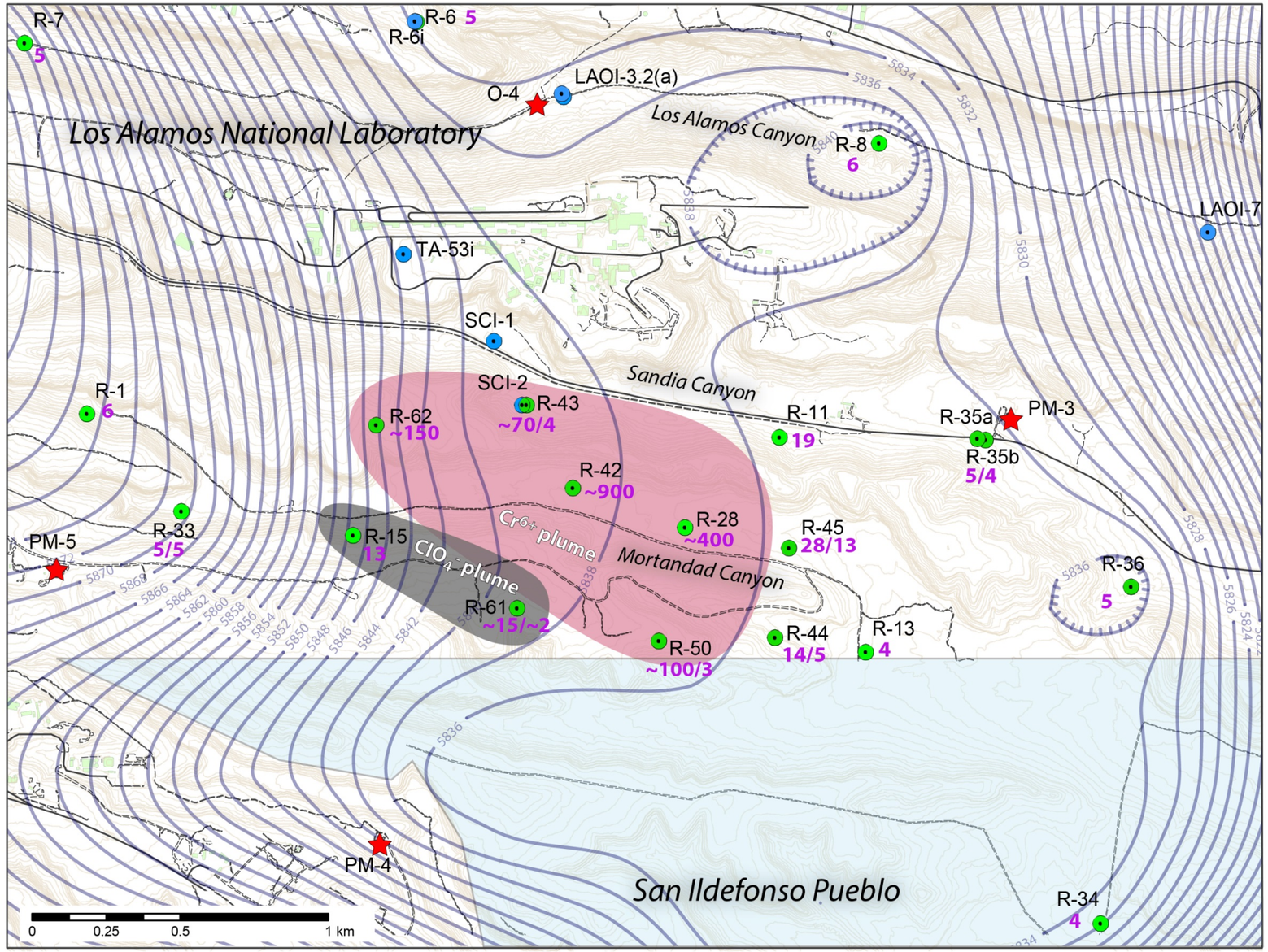


Figure 1.0-3 **Chromium plume and locations of wells R-28 and R-42. The pink area shows chromium plume with concentrations greater than 50 µg/L; the gray area shows the perchlorate plume with concentrations greater than 4 µg/L.**

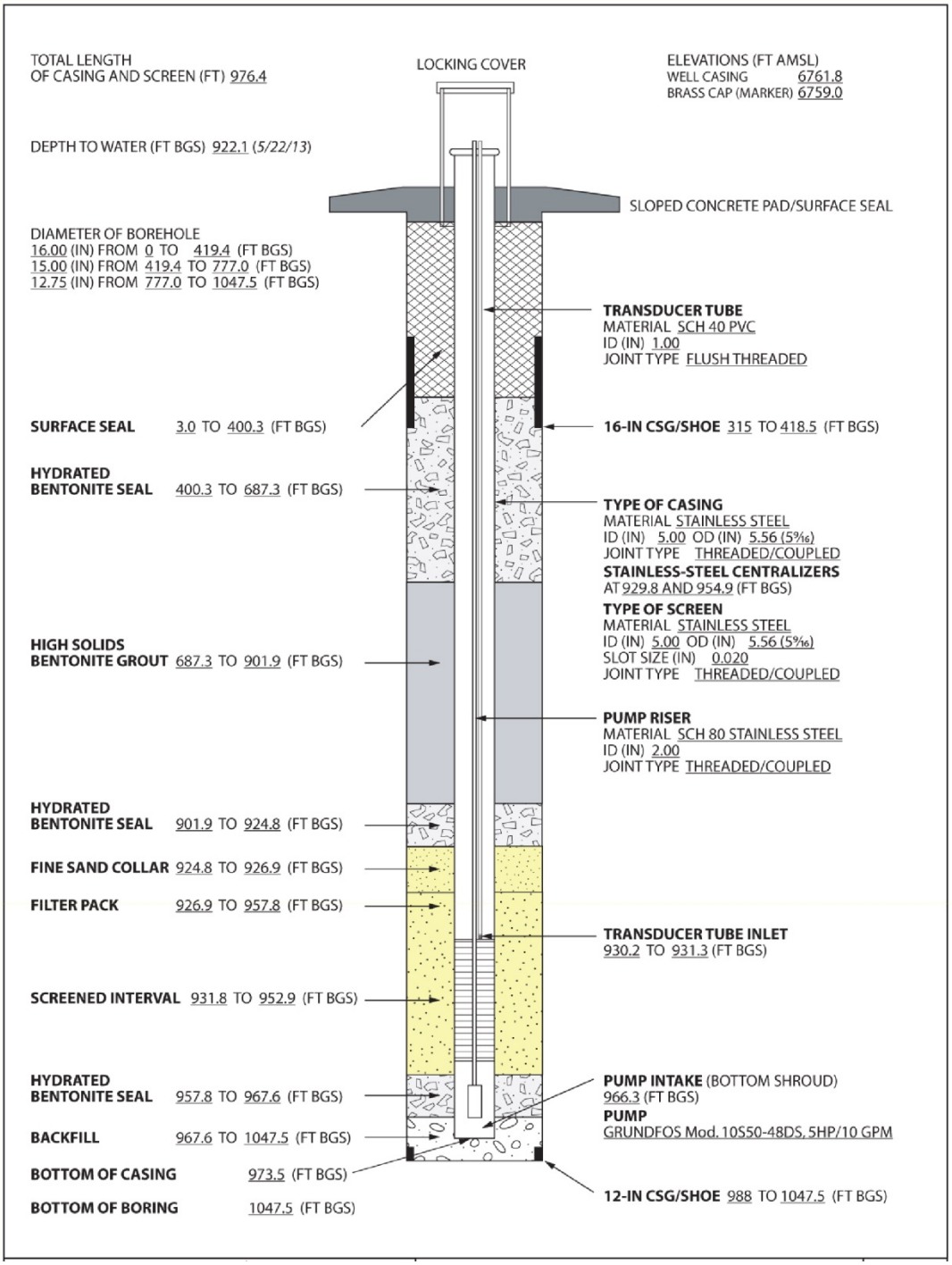


Figure 2.1-1 Pump configuration and depths of key components in R-42 at the start of the aquifer test

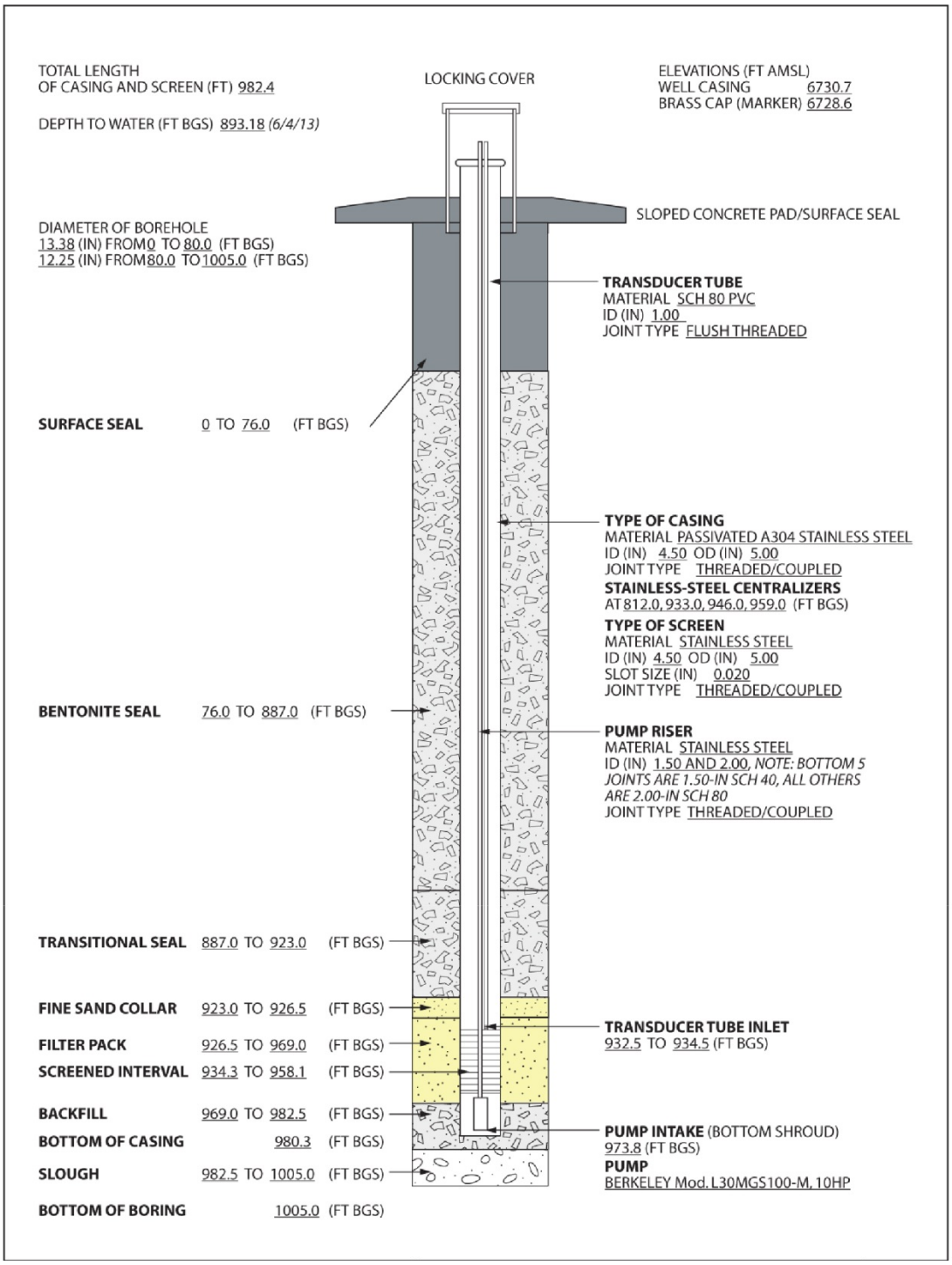


Figure 2.1-2 Pump configuration and depths of key components in R-28 at the start of the aquifer test

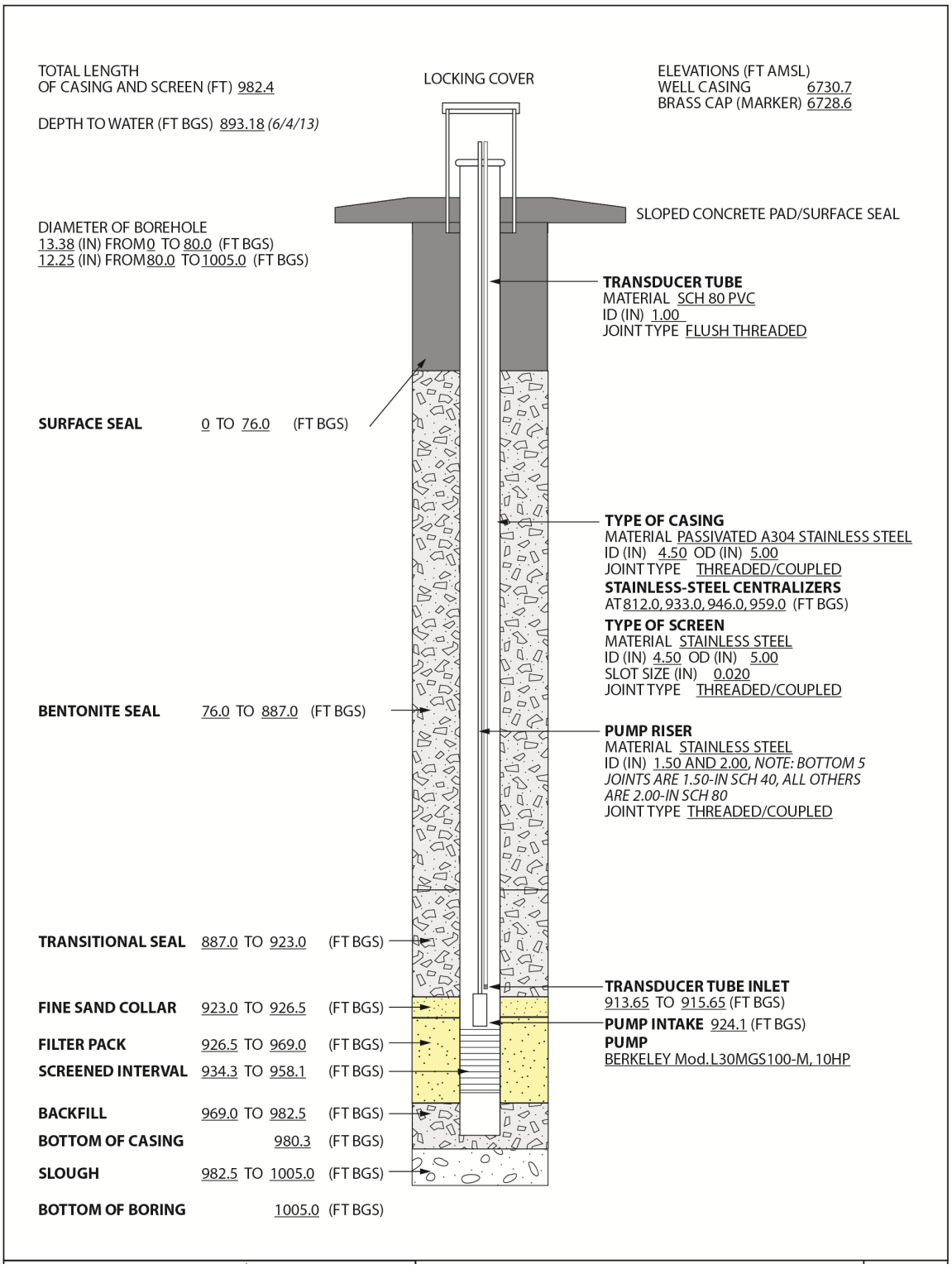


Figure 2.1-3 Reconfiguration of pump and shroud in R-28 after initial pump failure

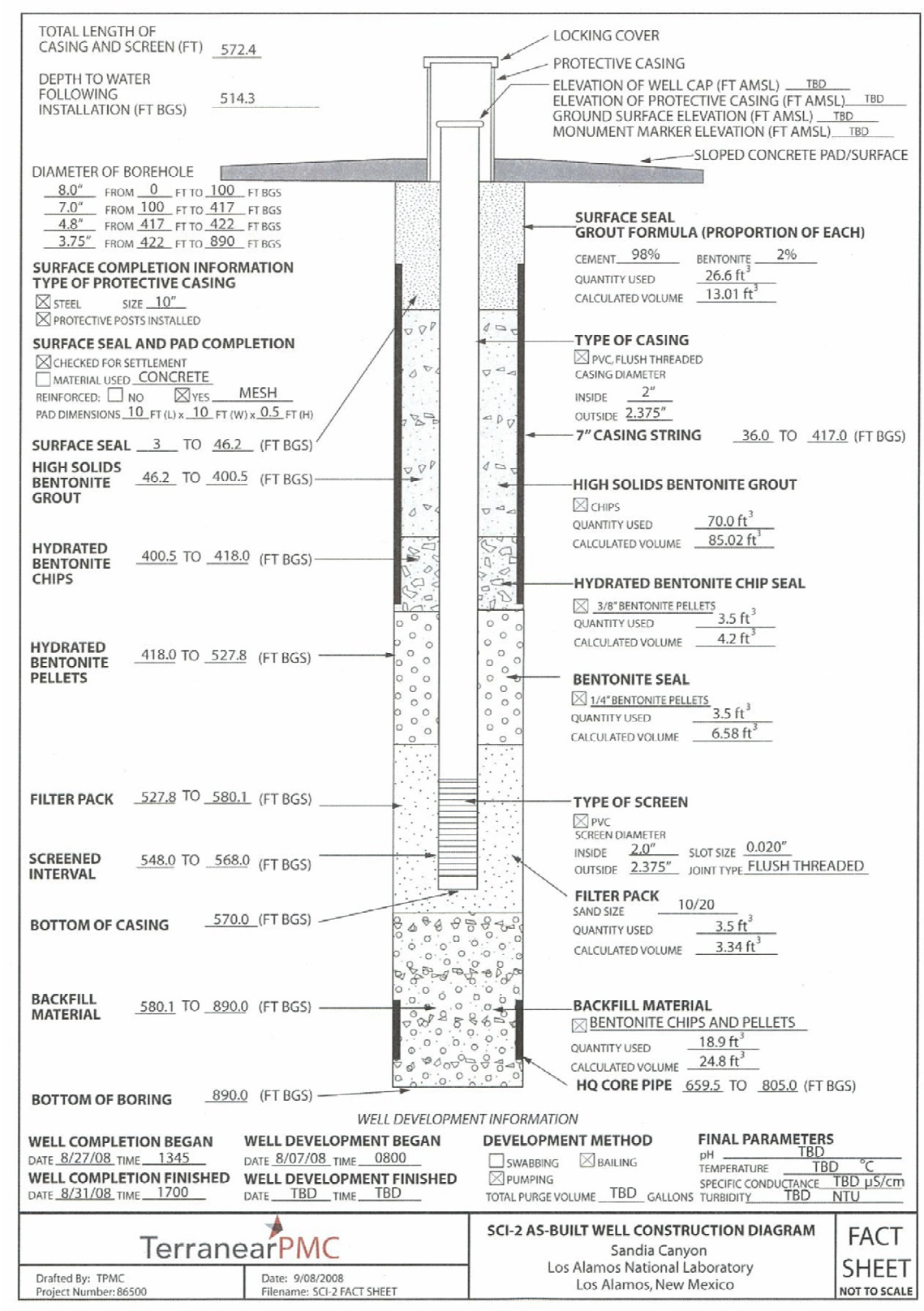


Figure 2.1-4 As-built construction diagram for SCI-2

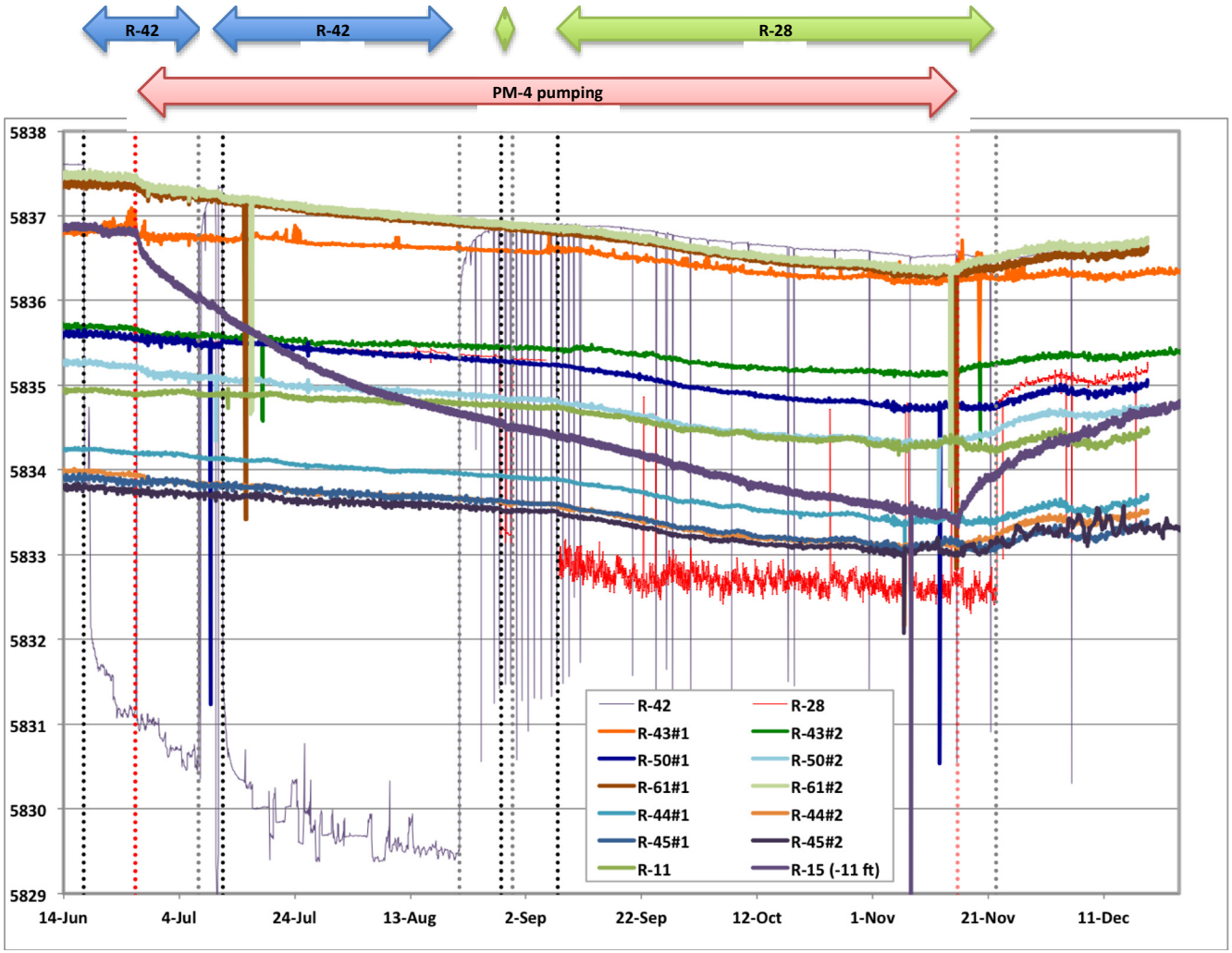


Figure 2.2-1 **Barometric pressure-corrected water levels at the various monitoring wells near R-42 and R-28 during the 2013 aquifer tests (the vertical scale for the R-15 data was adjusted to fit the plot)**

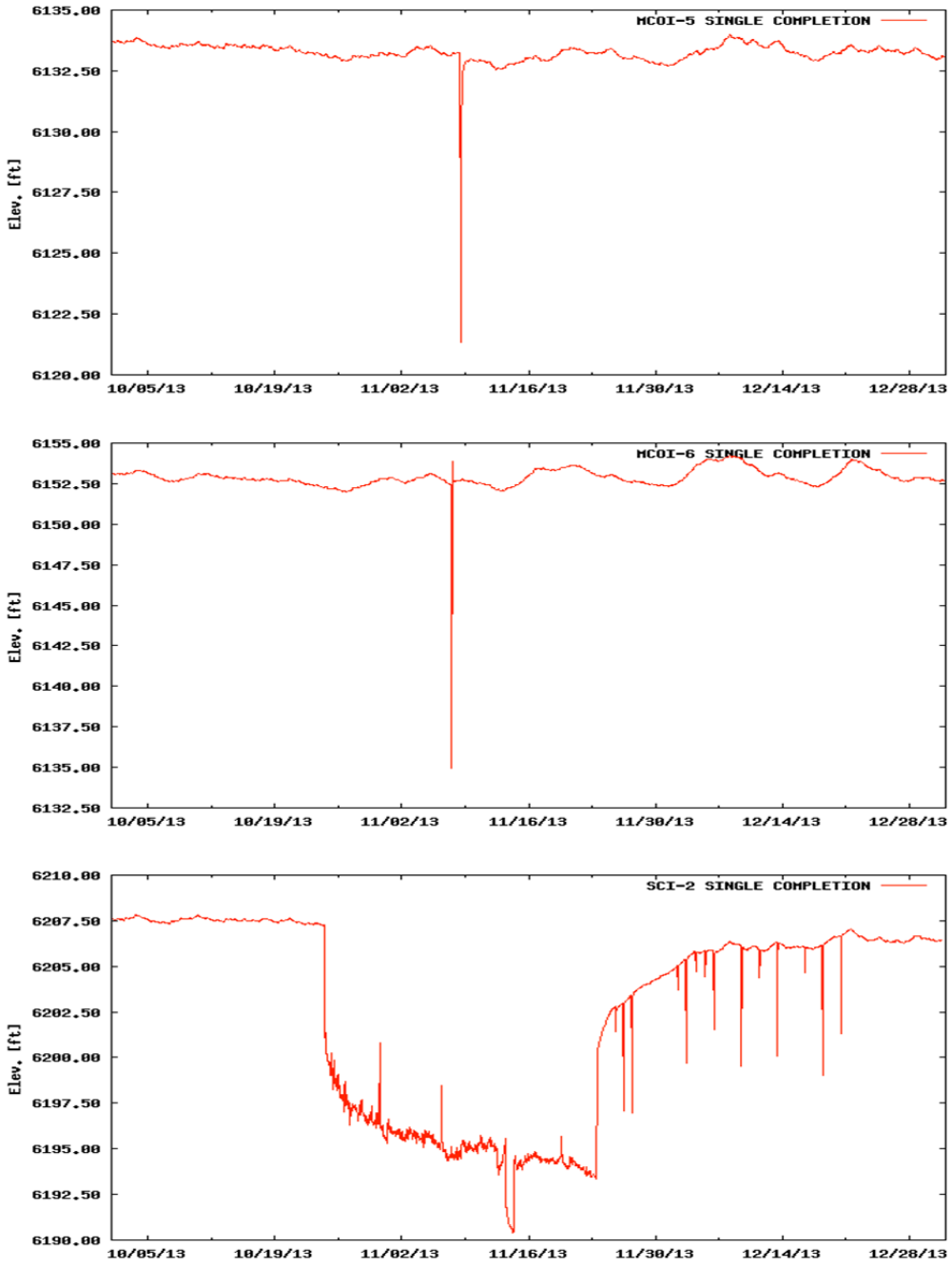


Figure 2.2-2 Barometric pressure–corrected water levels at SCI-2 and the nearby observation wells MCOI-5 and MCOI-6 during the 2013 pumping test



Figure 2.3-1 R-42 ion exchange treatment system



Figure 2.3-2 View of R-28 treatment and well water storage

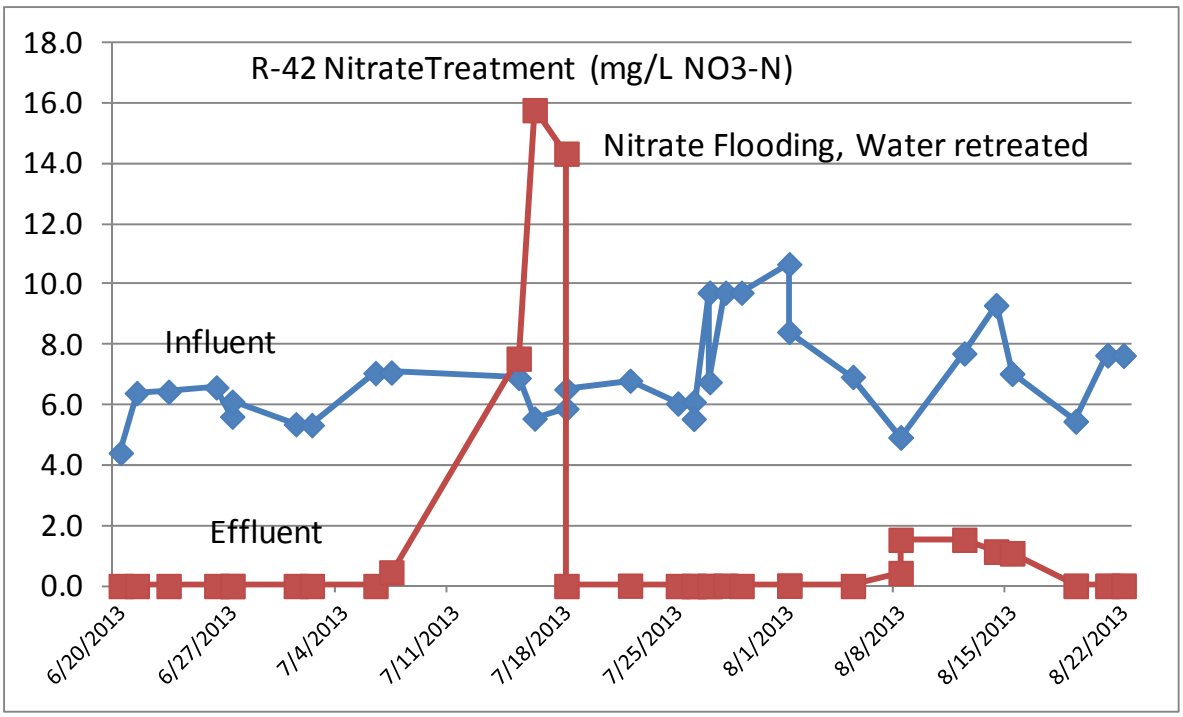


Figure 2.3-3 R-42 treatment system nitrate-n influent and effluent concentration

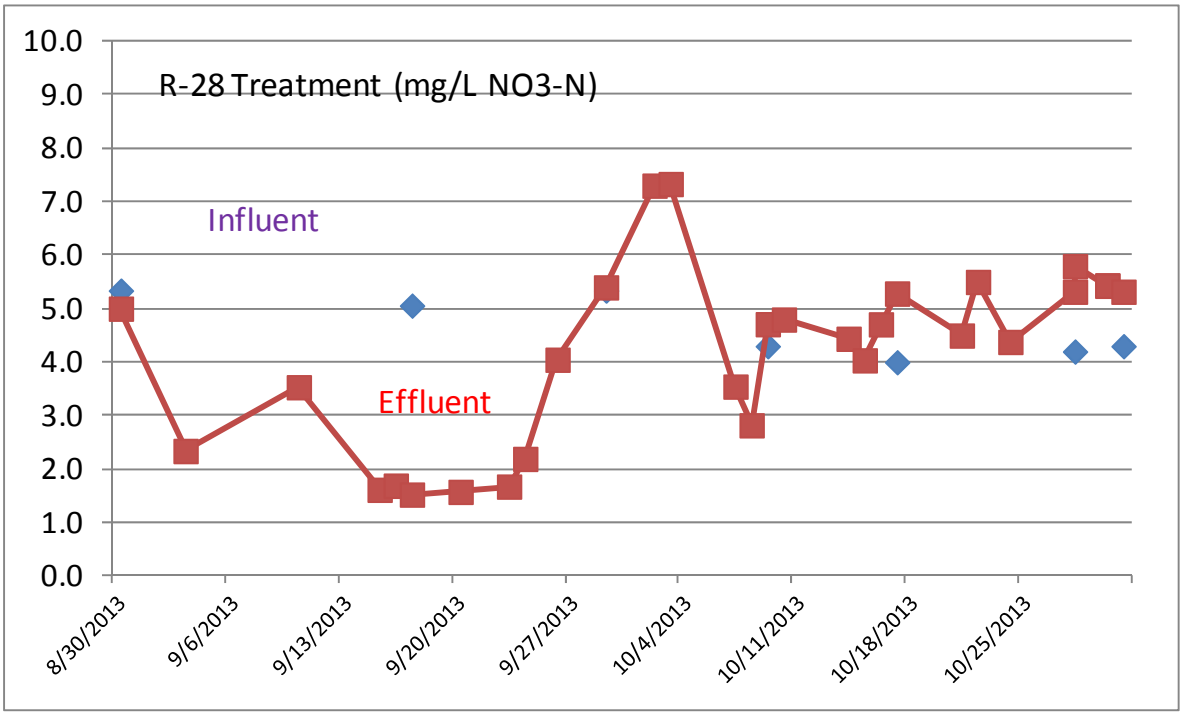


Figure 2.3-4 R-28 treatment system nitrate-n influent and effluent concentration

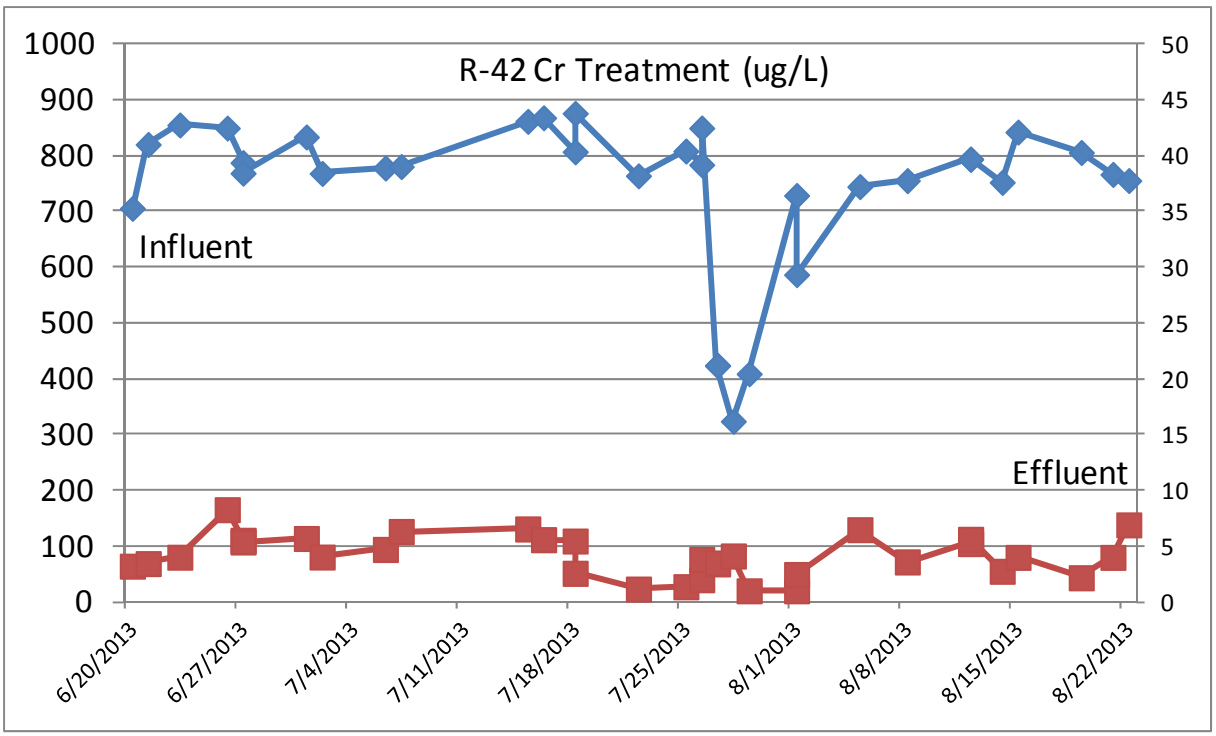


Figure 2.3-5 R-42 treatment system chromium influent and effluent concentration

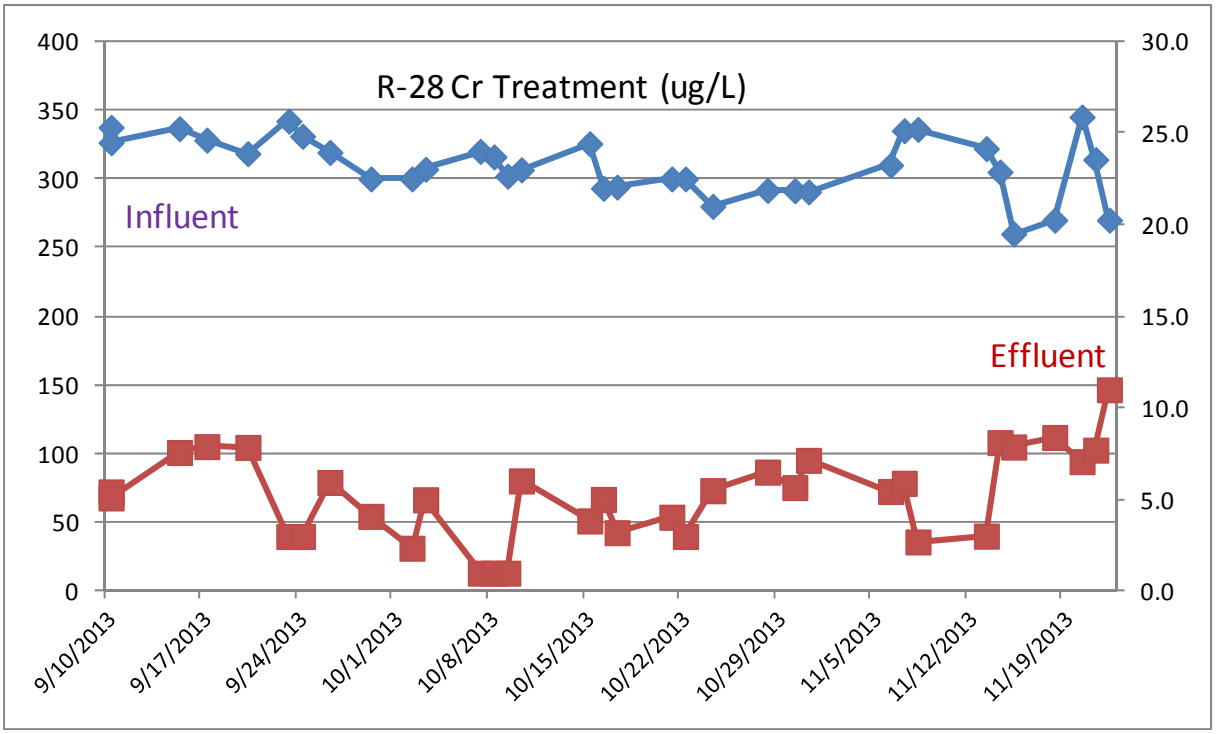
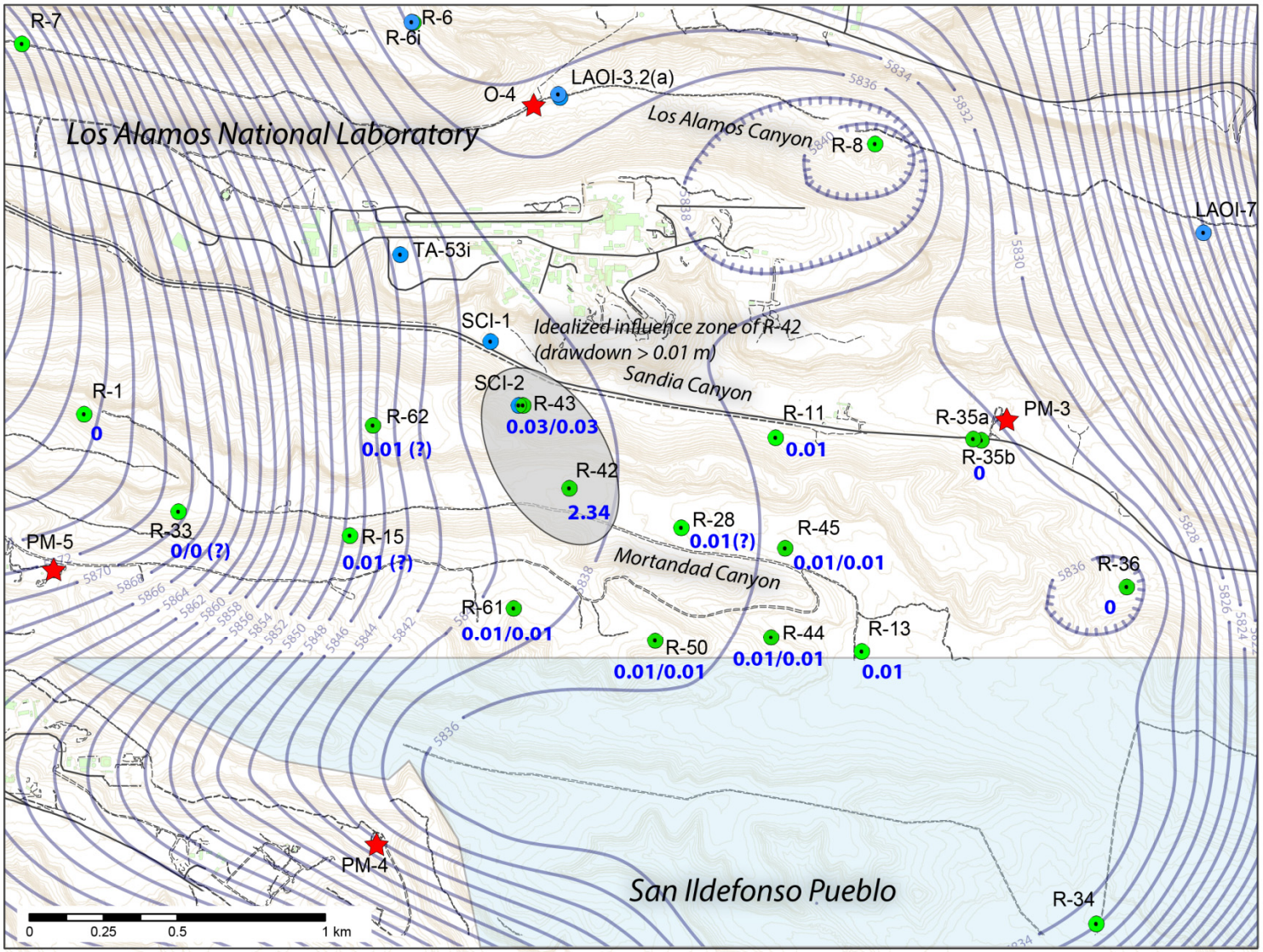
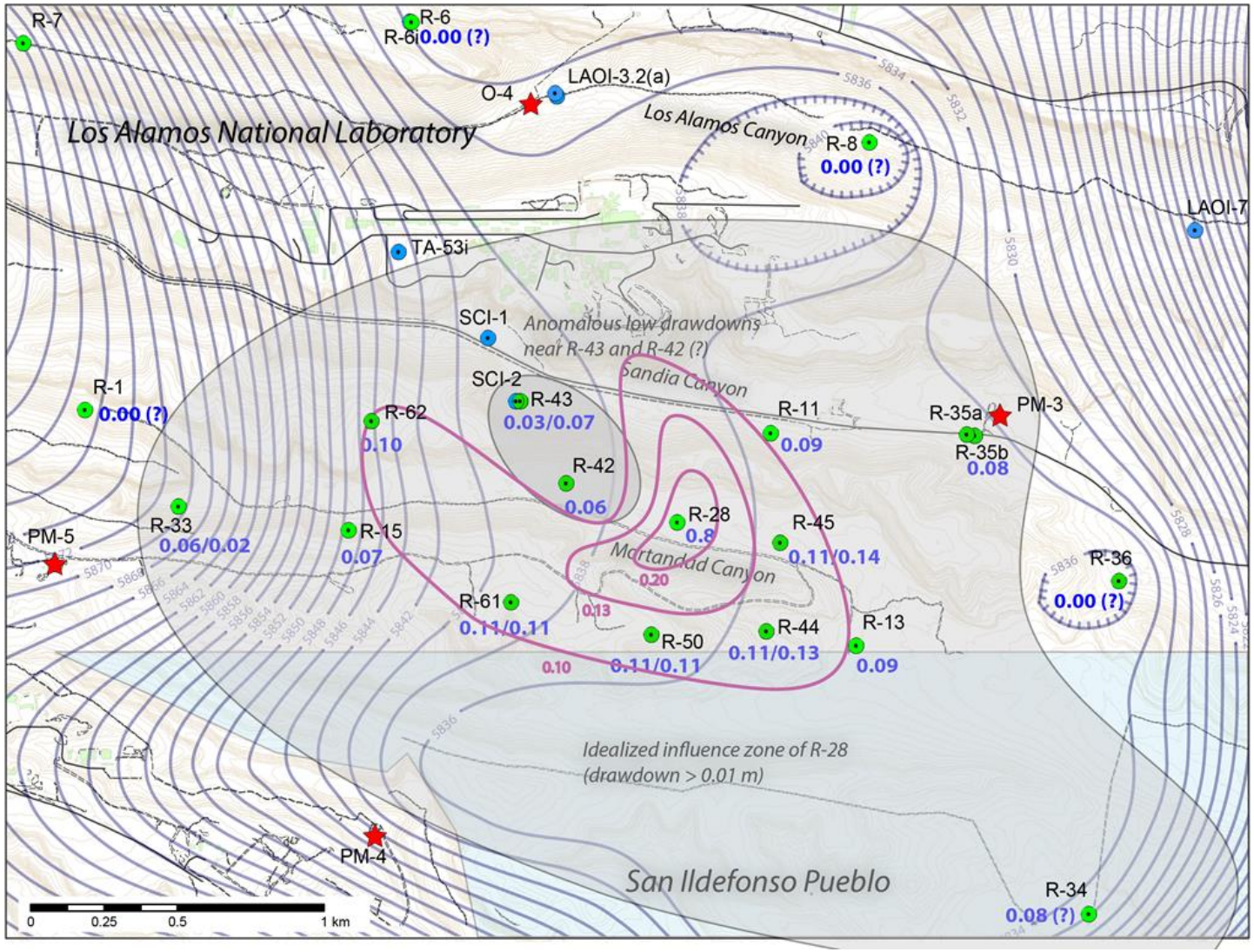


Figure 2.3-6 R-28 treatment system chromium influent and effluent concentration



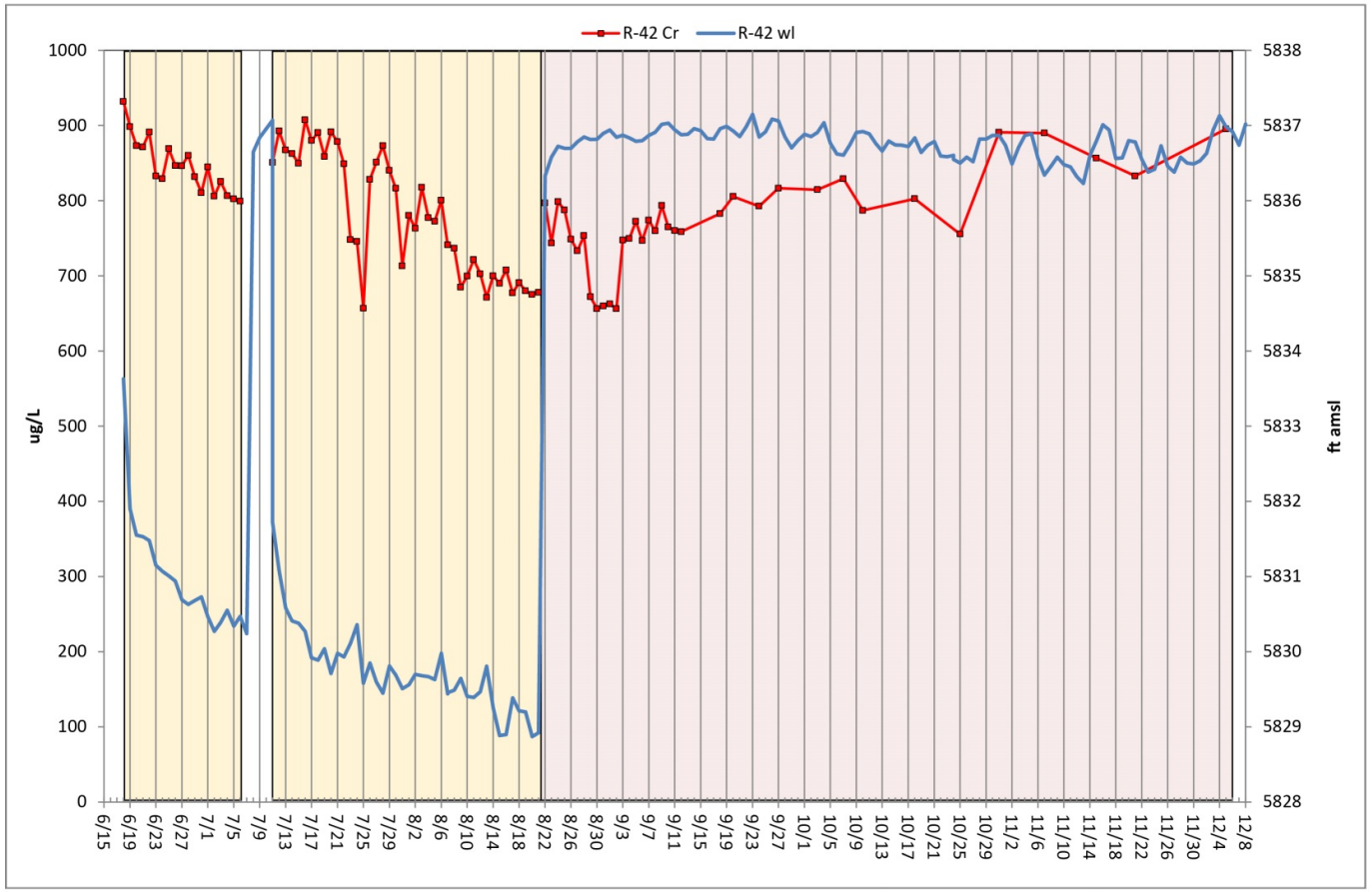
Note: Both upper and lower screen drawdown values in meters are shown in blue text.

Figure 3.1-1 Spatial distribution of the pumping drawdowns in meters at the end of the R-42 aquifer test (shown in blue text)



Note: Both upper and lower screen drawdown values in meters are shown in blue text. Drawdown contour lines are shown in red.

Figure 3.1-2 Spatial distribution of the pumping drawdowns in meters at the end of the R-28 aquifer test (shown in blue text). The contour lines (in pink) show the spatial distribution of the R-28 cone of depression (ZOI).



Chronology of pumping and rebound				
Well	Pumping	Pump failure	Rebound	Average Discharge Rate
R-42	6/18 - 7/6/13; 7/12 - 8/21/13	7/7 - 7/11/13	8/22 - 12/5/13	7 gpm*

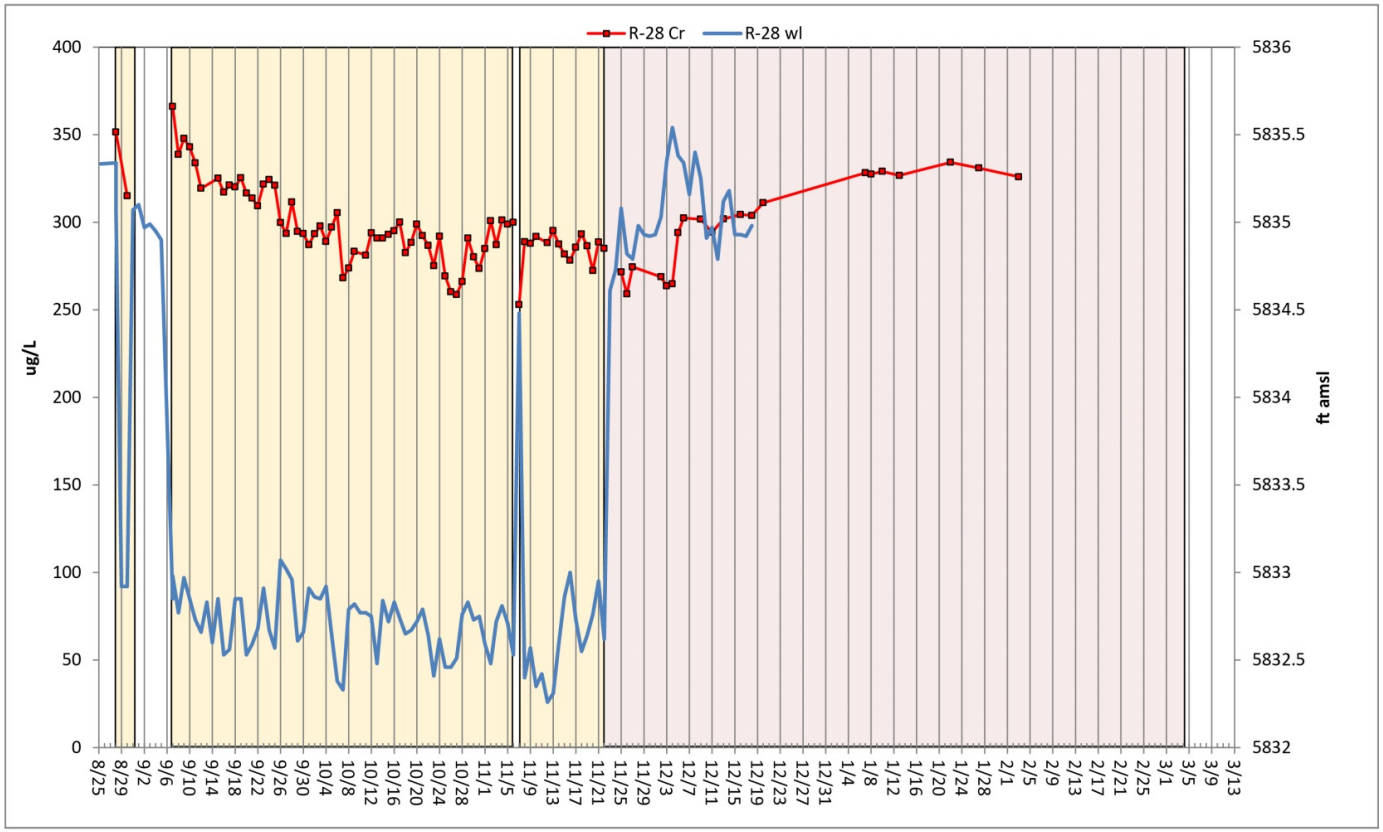
*gpm = gallons per minute

pumping

recovery

R-42 time series plot for chromium and water level during pumping and rebound sampling.

Figure 4.1-1 Chromium concentrations (red line) detected during the R-42 aquifer test and the recovery period, with vertical lines indicating the timing of the pump failure/restart and the end of the pump test. Water levels (wl) are shown in blue in feet above mean sea level (ft amsl).



Chronology of pumping and rebound

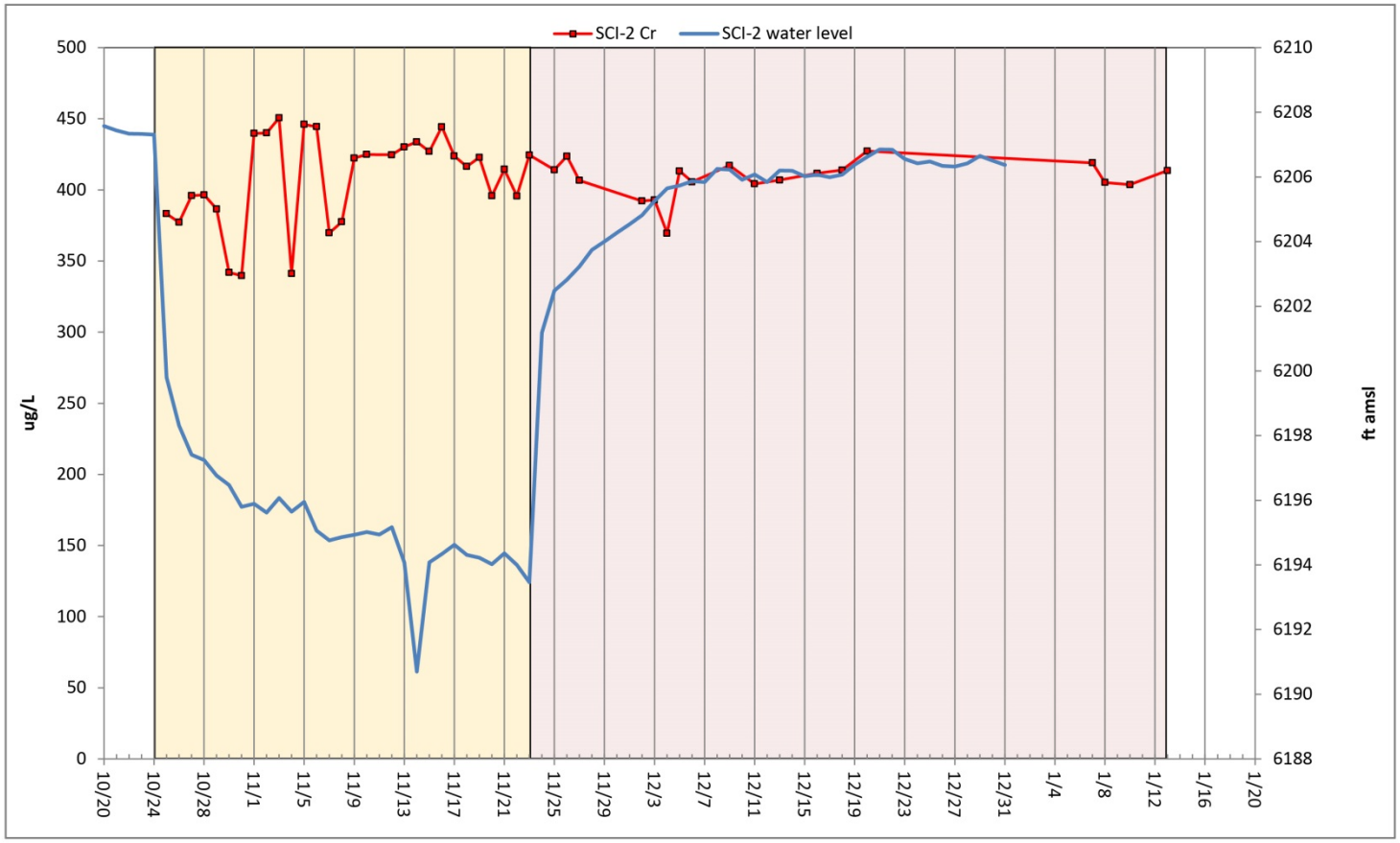
Well	Pumping	Pump failure	Rebound	Average Discharge Rate
R-28	• 8/28 - 8/30/13 (pump set in shroud in sump below screen) • 9/7-11/6 (pump removed from shroud and reset above screen) • 11/7-11/22/13	• 8/30 - 9/7/13 • 11/6 (1730 hrs) - 11/7/13 (0700 hrs) generator tripped	11/22/13 - 3/4/14	28.9 gpm*

pumping
recovery

*gpm = gallons per minute

R-28 time series plot for chromium and water level during pumping and rebound sampling.

Figure 4.1-2 Chromium concentrations (red line) detected during the R-28 aquifer test and the recovery period, with vertical lines indicating the timing of the pump failure/restart and the end of the pump test. Water levels are shown in blue in feet above mean sea level.



Chronology of pumping and rebound				
Well	Pumping	Pump failure	Rebound	Average Discharge Rate
SCI-2	10/24 - 11/23/13	negligible	11/24/13 - 1/13/14	0.65 gpm*

*gpm = gallons per minute

pumping
recovery

SCI-2 time series plot for chromium and water level during pumping and rebound sampling.

Figure 4.1-3 Chromium concentrations detected during the SCI-2 aquifer test and the recovery period. Water levels are shown in blue in feet above mean sea level.

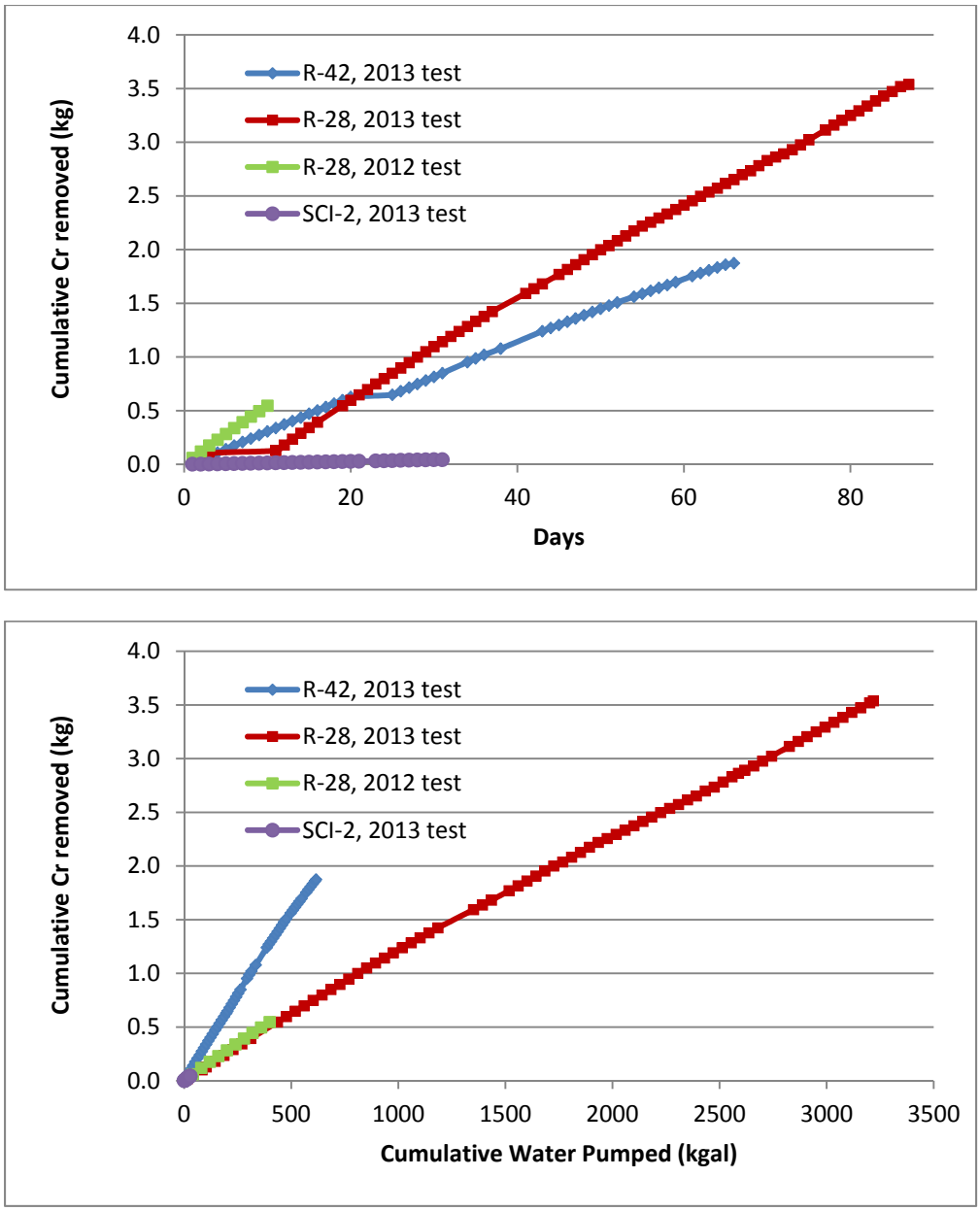
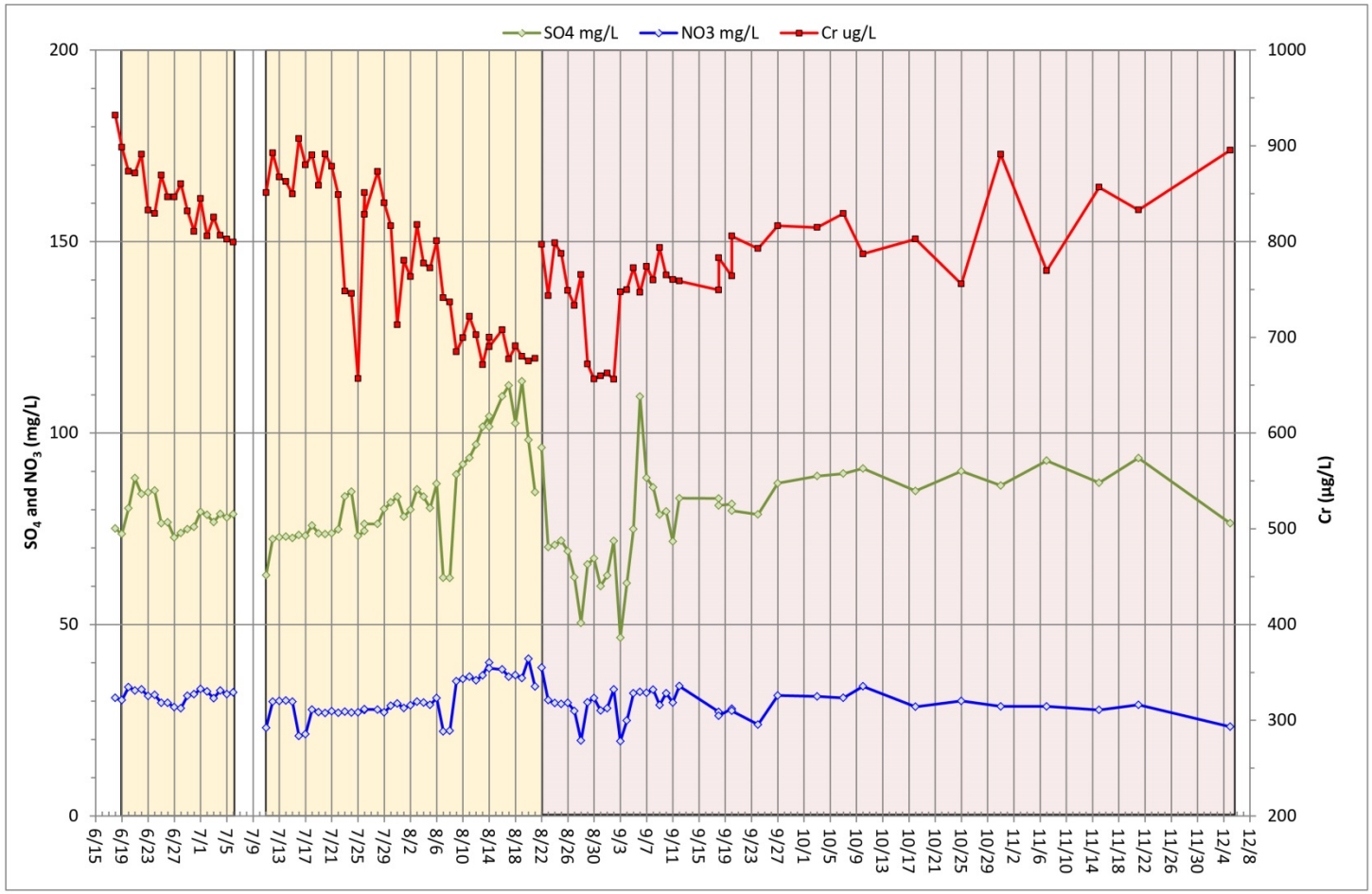


Figure 4.1-4 Total chromium removed as a function of time and cumulative water volume pumped at R-42, R-28, and SCI-2



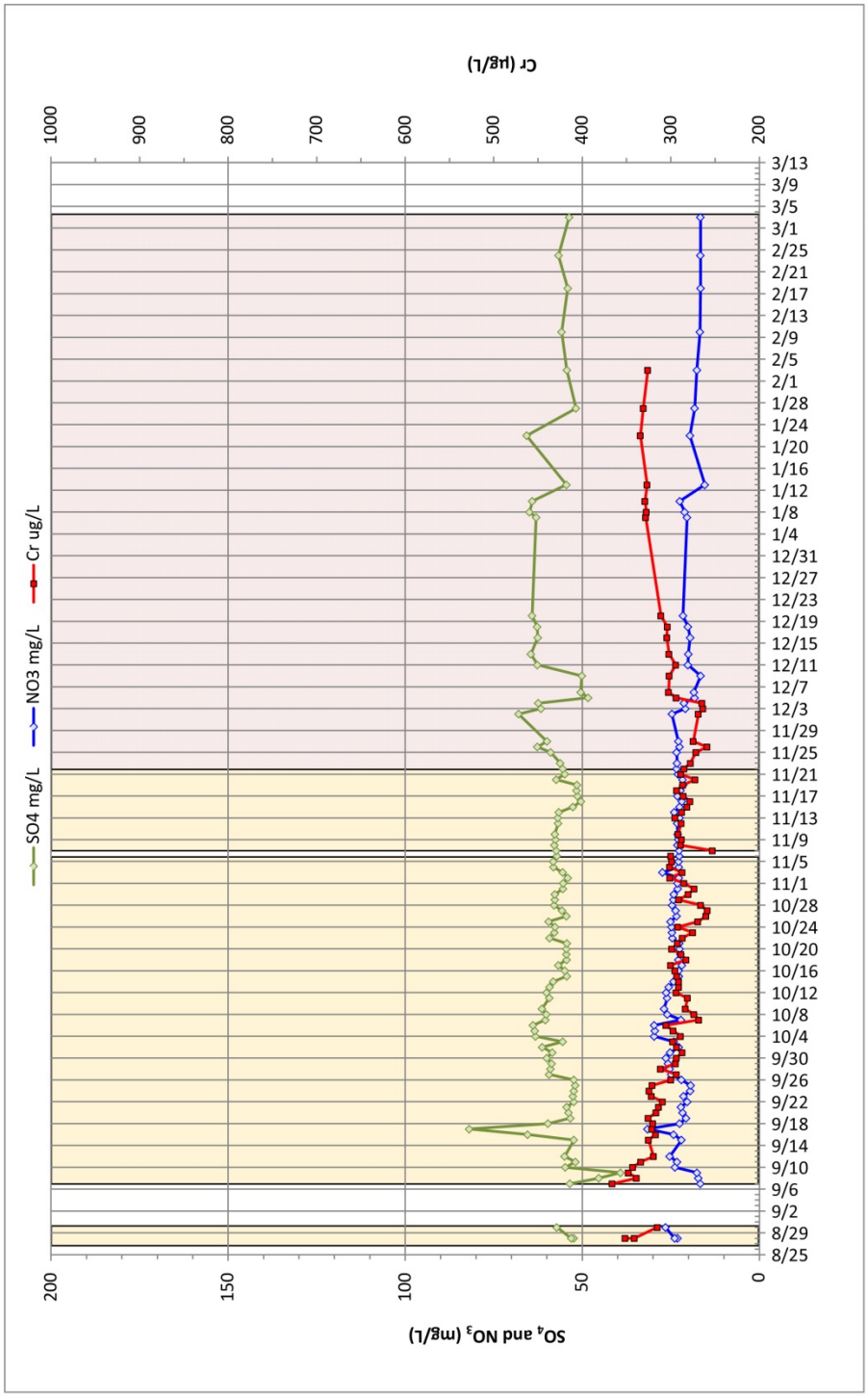
Chronology of pumping and rebound				
Well	Pumping	Pump failure	Rebound	Average Discharge Rate
R-42	6/18 - 7/6/13; 7/12 - 8/21/13	7/7 - 7/11/13	8/22 - 12/5/13	7 gpm*

*gpm = gallons per minute

pumping
recovery

R-42 time series plots for chromium, sulfate, and nitrate during pumping and rebound sampling.

Figure 4.2-1 Time-series trends for sulfate, nitrate, and chromium in R-42 during pumping and recovery

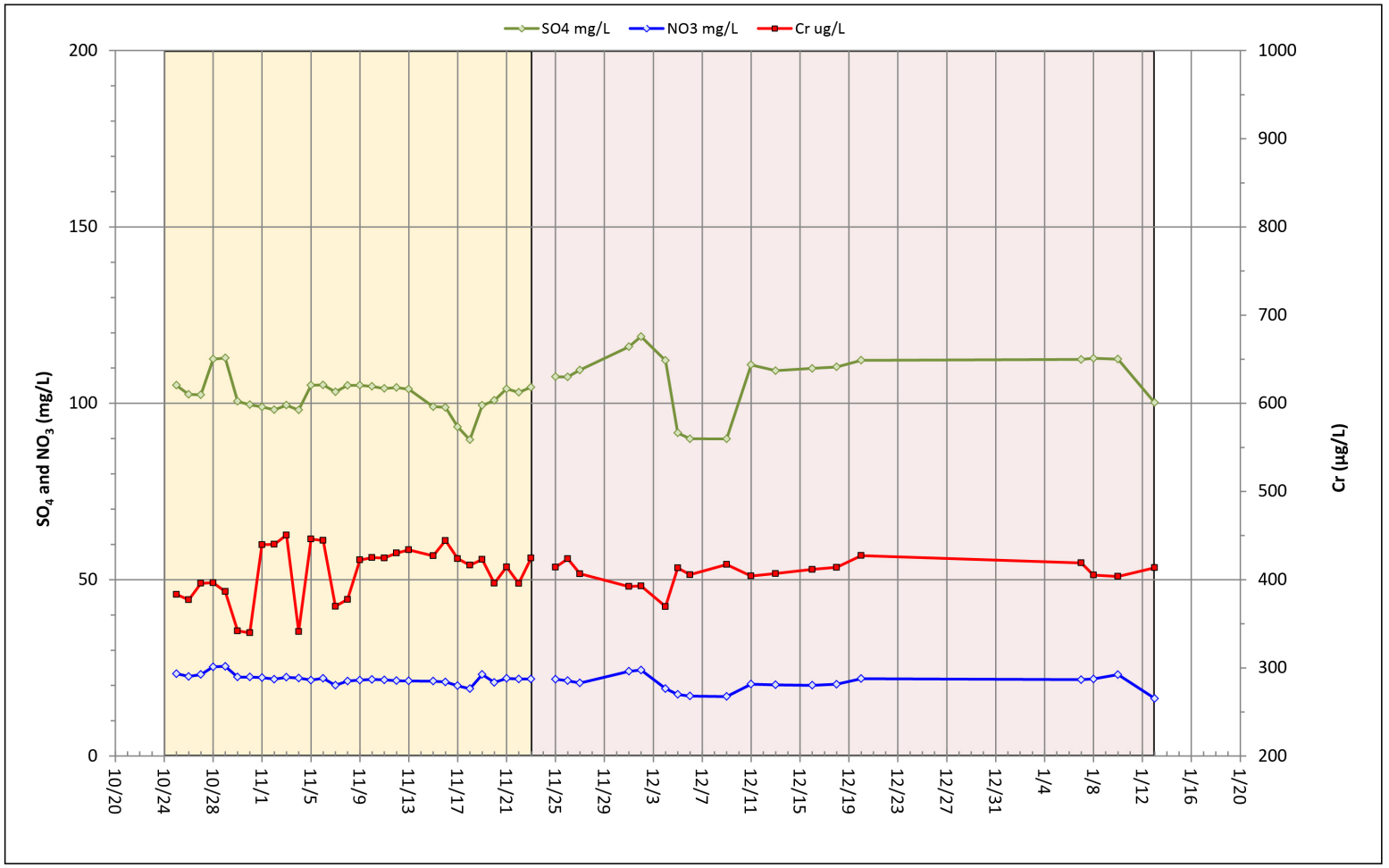


Chronology of pumping and rebound				
Well	Pumping	Pump failure	Rebound	Average Discharge Rate
R-28	• 8/28 - 8/30/13 (pump set in shroud in sump below screen) • 9/7-11/6 (pump removed from shroud and reset above screen) • 11/7-11/22/13	• 8/30 - 9/7/13 • 11/6 (1730 hrs) - 11/7/13 (0700 hrs) generator tripped	11/22/13 - 3/4/14	28.9 gpm*

*gpm = gallons per minute

R-28 time series plots for chromium, sulfate, and nitrate during pumping and rebound sampling.

Figure 4.2-2 Time-series trends for sulfate, nitrate, and chromium in R-28 during pumping and recovery



Chronology of pumping and rebound				
Well	Pumping	Pump failure	Rebound	Average Discharge Rate
SCI-2	10/24 - 11/23/13	negligible	11/24/13 - 1/13/14	0.65 gpm*

*gpm = gallons per minute

pumping
recovery

Figure 4.2-3 Time-series trends for sulfate, nitrate, and chromium in SCI-2 during pumping and recovery

Table 2.2-1
Analytes Sampled during Pumping and Rebound at R-42, R-28, and SCI-2

Analysis	Included in Appendix D (on CD)
Field Analyses	
Hach Kit: Total Cr, Cr(VI), NO_3, NO_2, NH_3, Total Fe, Fe(II), Mn	Yes
Field Parameters: pH, temperature, conductivity, DO, turbidity, ORP	Yes
Laboratory Analyses	
Metals	Yes
DOC	Yes
Anions	Yes
Alkalinity/pH	Yes
TOC	Yes
Tritium (GGRL)	Yes
Cr Isotopes	Partial data set
PCR	No
Tritium (EPA:906)	Yes

Table 3-3-1
Estimated Effective Aquifer Properties
Based on 2013 Aquifer Tests at R-42 and R-28

Observation Well	Pumping Well R-42		Pumping Well R-28	
	T [m^2/d]	S [–][a]	T [m^2/d]	S [–]
R-11	1300	0.003	570	0.01
R-13	910	0.003	480	0.006
R-15	490	0.002	470	0.005
R-28	2500	0.004	340	0.002
R-33#1	3400	0.004	250	0.006
R-33#2	850	0.003	1700	0.004
R-34	n/a[b]	n/a	340	0.001
R-35b	n/a	n/a	220	0.01
R-36	n/a	n/a	260	0.003
R-42	20	0.007	40	0.03
R-43#1	650	0.003	1800	0.006
R-43#2	650	0.003	790	0.005
R-44#1	n/a	n/a	290	0.02
R-44#2	n/a	n/a	350	0.01
R-45#1	n/a	n/a	590	0.008

Table 3-3-1 (continued)

Observation Well	Pumping Well R-42		Pumping Well R-28	
	T [m^2/d]	S [–]	T [m^2/d]	S [–]
R-45#2	n/a	n/a	240	0.02
R-50#1	1500	0.004	350	0.02
R-50#2	1600	0.004	410	0.01
R-61#1	2900	0.004	180	0.02
R-61#2	3100	0.004	200	0.02
R-62	2400	0.004	310	0.004

[a] [–] = Unitless.

[b] n/a = Not applicable because it cannot be estimated reliably.

Table 4.1-1
Test Duration, Volume of Water Pumped,
and Total Chromium Removed at R-42, R-28, and SCI-2 in 2013 Aquifer Tests

Pump Test, Date	Duration (d)	Water Pumped (kgal)	Chromium Removed (kg, lb)
R-28, 2012	10	399	0.55 (1.2)
R-42, 2013	66*	676	1.87 (4.1)
R-28, 2013	86*	3217	3.54 (7.8)
SCI-2, 2013	30	28	0.043 (0.1)
Total for 2013	**182**	**3921**	**5.45 (12.0)**

*Includes periods of pump interruption

Appendix A

Hach Data and Geochemical Plots

A-1.0 HACH KIT MEASUREMENTS

Hach kits were used to measure chromium(VI), total chromium, and several redox-sensitive species in R-42, R-28, and SCI-2 water as these wells were pumped. The kits were also used for measurements during recovery/rebound of the wells (with samples taken after at least one casing volume of extraction). Hach kits are colorimetric "cookbook" methods that use reagents obtained from Hach Company that react with analytes of interest to produce a color in a water sample that absorbs light over a specified range of wavelengths if the analyte is present, with the absorbance being proportional to the analyte concentration. A Hach DR 890 colorimeter was used for all the field measurements. This colorimeter has built in software to automatically select the appropriate incident light wavelength for each analyte, with options of 420 nm, 520 nm, 560 nm, and 610 nm. For all methods, the meter reading is first "zeroed" using a blank solution that contains no analyte and/or no reagent, and then a vial containing the sample of interest (after adding appropriate reagents and allowing reactions for a specified time) is inserted into the meter to obtain an absorbance reading that is directly translated into an analyte concentration.

Besides providing qualitative screening of chromium concentrations in water samples, the objective of the field Hach kit measurements was to screen for redox-sensitive species that can give indications of whether geochemical conditions exist in the aquifer that are capable of reducing chromium(VI) to chromium(III). The measurements were conducted over time during both pumping and recovery of the wells so that any observed changes in chromium concentrations could be evaluated for correlations with changes in the redox-sensitive species concentrations. The species analyzed by Hach kits are listed in Table A-1, along with the specific Hach method used for each analyte. Detailed information on all of the methods can be downloaded from www.hach.com.

The rationale for analyzing the species listed in Table A-1 is that each provides an indication of a representative oxidation-reduction potential, or Eh value (mV relative to the standard hydrogen electrode potential at which protons are reduced to hydrogen gas), in a water sample that can be related to a table of standard electrochemical potentials to qualitative assess whether the geochemical conditions in the aquifer are conducive to reduction (or oxidation) of a given species or not. Concentrations of redox couples (i.e., both the reduced and oxidized species of a redox half-reaction [e.g., NO_3^- and NO_2^- in the half-reaction, $NO_3^- + H_2O + 2e- > NO_2^- + 2OH^-$]) are particularly useful for identifying representative redox potentials using the Nernst equation (Langmuir 1997, 056037):

$$Eh = E^o + \frac{RT}{F} ln \frac{[Ox]}{[Red]} \qquad \textbf{Equation 1}$$

where, E = standard potential of redox half-reaction, volt,

R = universal gas constant, 0.001987 kcal/K-mol,

T = absolute temperature, K,

F = Faraday's constant, 23.061 kcal/volt,

[Ox] = activity product of aqueous species on oxidized side of half reaction, and

[Red] = activity product of aqueous species on reduced side of half reaction.

Eh estimates obtained by inserting measured species concentrations into Equation 1 for any given half reaction should not be considered absolute; rather they should be taken as qualitative indicators of redox conditions along with other measurements such as dissolved oxygen concentrations and oxidation-reduction potential (ORP) measurements (using a commercially available electrode designed to give relatively rapid responses). It is common to obtain Eh estimates from different redox half-reactions,

dissolved oxygen measurements, and ORP measurements that are in poor agreement with each other. These discrepancies are generally attributed to either (1) lack of true equilibrium in redox conditions in the aquifer (kinetic limitations), (2) poor redox "poising" of waters, meaning that they are not well buffered with respect to redox, (3) mixing of waters of different redox conditions in a sampling well, (4) contamination of oxygen or redox-sensitive species resulting from drilling additives, completion materials, or liquid-gas exchange (including atmospheric contamination) during pumping of water to the surface, or (5) a combination of these things. Langmuir (1997, 056037, pp. 409-415) provides a detailed discussion of several of these points as well as an excellent discussion of measured (i.e., using a Pt or Ag/AgCl electrode) versus theoretical Eh values based on redox couple measurements in natural waters. This discussion includes plots showing comparisons of measured vs. theoretical values for many different redox couples in many different systems (e.g., Langmuir 1997, 056037, Figure 11.8). This reference also provides additional perspective on the reliability and confidence that can be placed in redox couple measurements in a variety of settings.

Table A-2 summarizes the relevant half reactions for the constituents measured with the Hach kits (also including dissolved oxygen). This table also includes the calculated Eh values (using Equation 1) for the various half-reactions using a combination of (1) constituent concentrations measured in R-42 water, (2) assumed concentrations in R-42 water if not measured directly (e.g., Cr^{3+}), and (3) Hach method detection limits if the constituents were not regularly detected in R-42 water. The redox couples and half-reactions in Table A-2 are listed in order from highest to lowest Eh or from most oxidizing conditions to most reducing conditions. The Eh values with the grey backgrounds are considered the most reliable indicators of Eh in the R-42 water because they are constrained by consistent non-zero Hach-kit measurements of the most reduced species in the half-reactions (Mn^{2+} and NO_2^-). The R-28 and R-42 measurements indicate similar Eh values in those wells (see plots of constituent concentrations in Figures A-1 through A-3).

The implications of Table A-2 are that the prevailing redox conditions in the regional aquifer at R-42 and R-28 and in the perched-intermediate aquifer at SCI-2 are not quite reducing enough to cause the reduction of chromium(VI) to chromium(III). The Eh value for the chromium(VI)/chromium(III) couple in Table A-2 [assuming 1 ppb chromium(III) in equilibrium with chromium(VI)] is just below the redox potential of the MnO_2/Mn^{2+} and NO_2^-/NO_2^- couples for which the more reduced species is consistently measured. However, the Hach analytical result plots (Figures A-1 through A-3) show that there were occasional detections of NH_3 and Fe^{2+} in the wells, which, if valid, would indicate redox conditions conducive to reduction of chromium(VI) to chromium(III) in the water because the Eh values of the NO_2^-/NH3 and $Fe(OH)_3/Fe^{2+}$ half-reactions at the detection limits of NH_3 and Fe^{2+} are lower than the theoretical value needed to reduce chromium(VI). Thus, one possible conclusion is that prevailing redox conditions are on the fringe of being sufficient to support the reduction of chromium(VI) to chromium(III). However, caution is advised in drawing this conclusion because many caveats must be considered. The most important of these are summarized below.

- The consistent presence of Mn^{2+} and NO_2^- in the waters along with elevated levels of dissolved oxygen are theoretically incompatible and suggest the possibility of small flows of more reduced waters (perhaps from secondary porosity or low-permeability zones) mixing with an abundance of oxygenated water in the boreholes. If this conceptualization is true, the reduced waters are likely to be considerably more reduced than the Eh values of Table A-2 indicate (because of dilution), but they are also likely to be of relatively minor importance for large-scale advective transport of chromium(VI), with diffusion being required to for the chromium(VI) to enter the more reduced zones. Also, the lack of the consistent presence of NH_3 and Fe^{2+} suggest that even if such reduced zones exist, it is unlikely that they are reducing enough to cause reduction of chromium(VI).

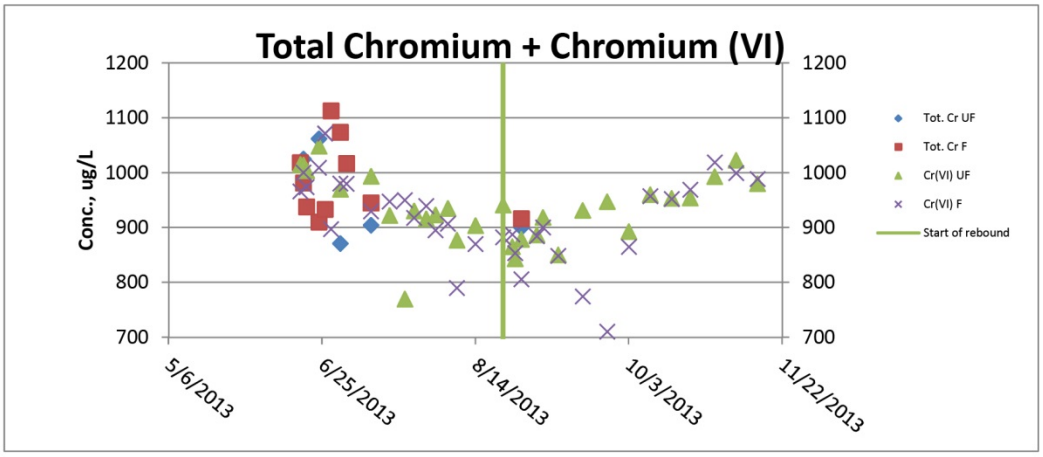
- The Eh estimates only provide indications of the *thermodynamic potential* for redox reactions to occur. There may be kinetic limitations that inhibit redox reactions from occurring even when the thermodynamics are favorable. Also, the presence or absence of redox-sensitive species in the solution phase is not necessarily a good indicator of surface-mediated reactions that may occur in an aquifer system.

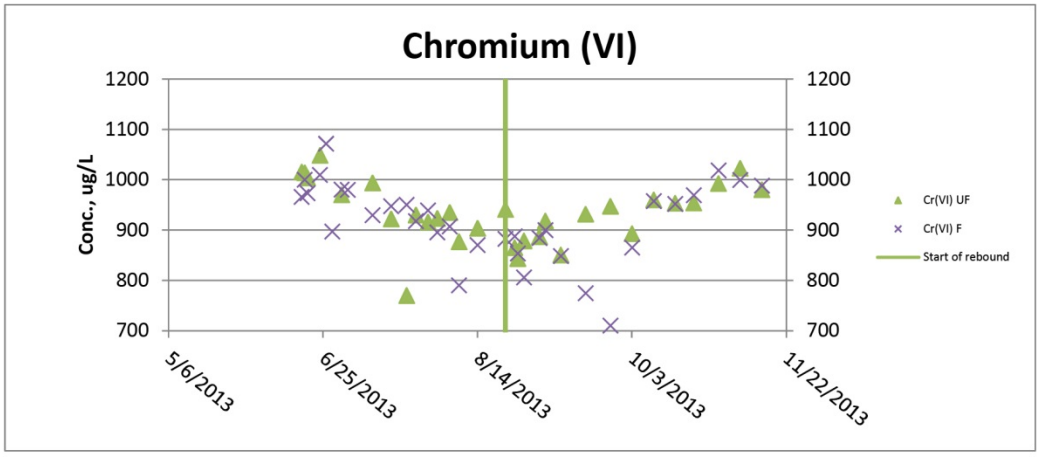
A-2.0 REFERENCE

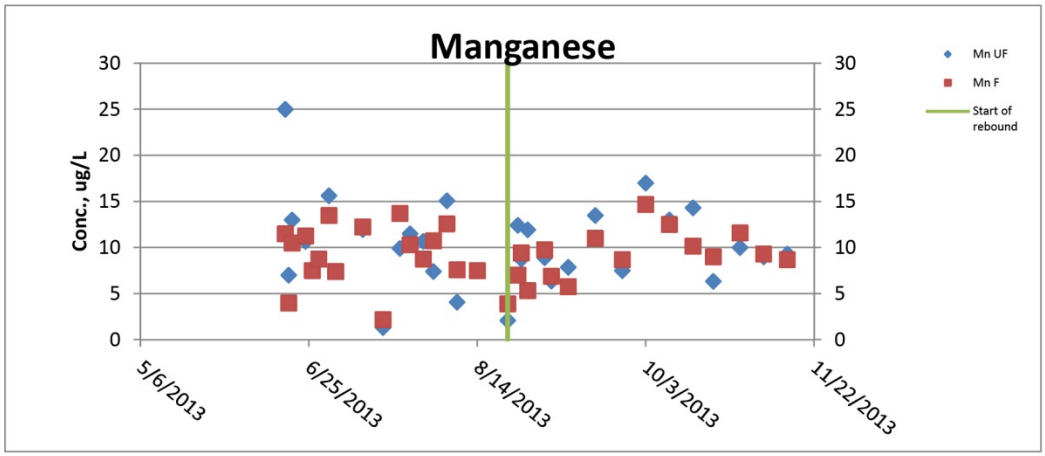
The following list includes all documents cited in this appendix. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the New Mexico Environment Department Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

Langmuir, D., 1997. *Aqueous Environmental Geochemistry*, Prentice Hall, Inc., Upper Saddle River, New Jersey. (Langmuir 1997, 056037)

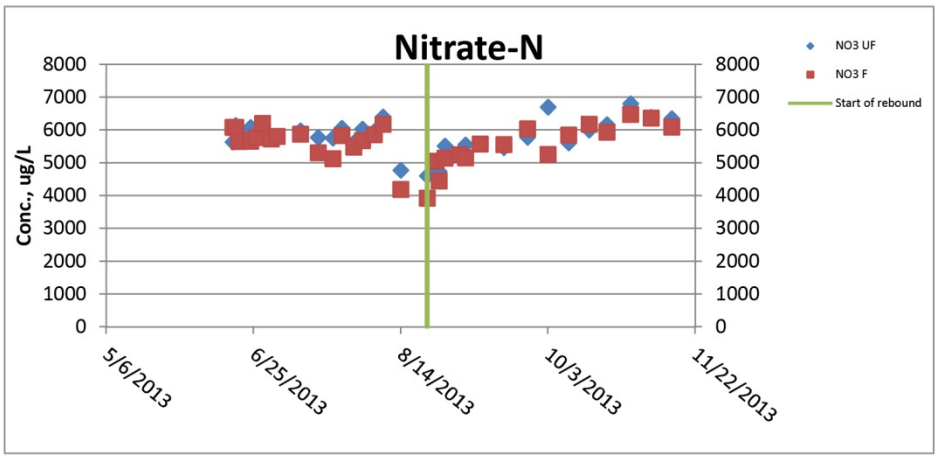


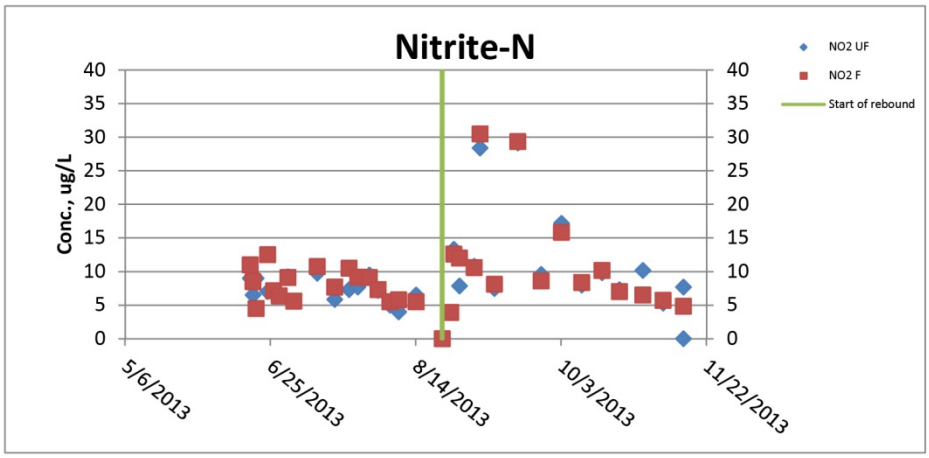


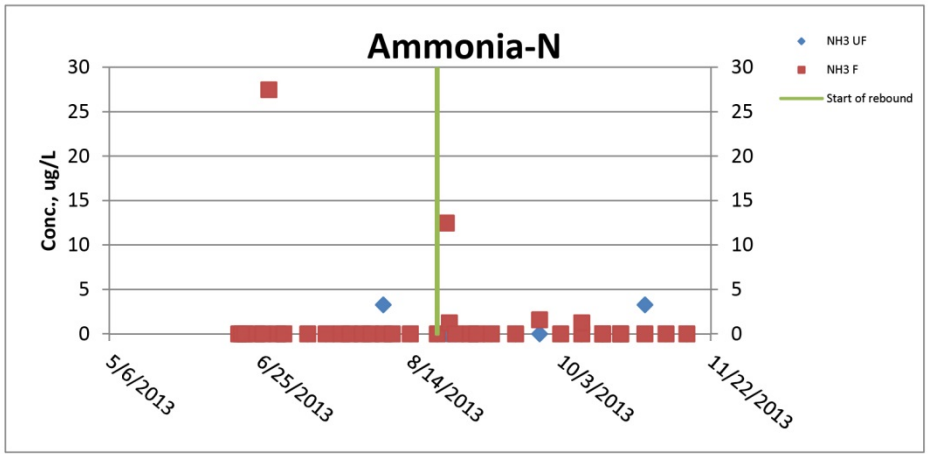


a

Figure A-1 Hach analytical results for pumping and rebound at R-42

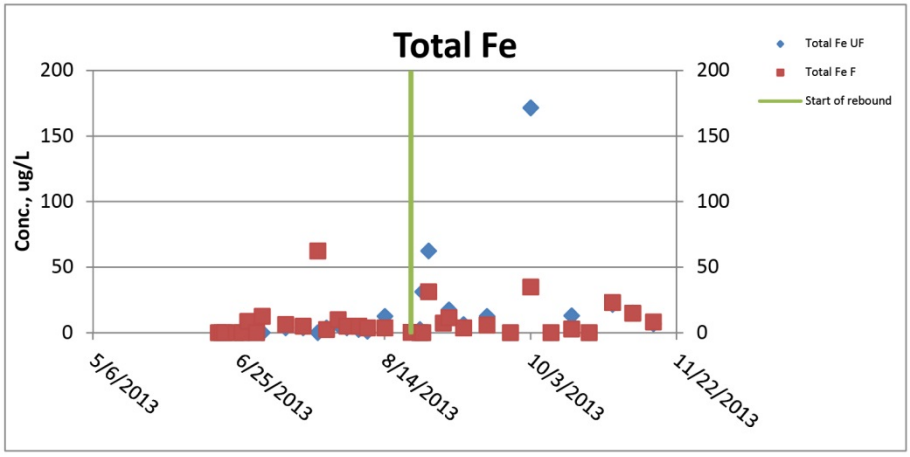


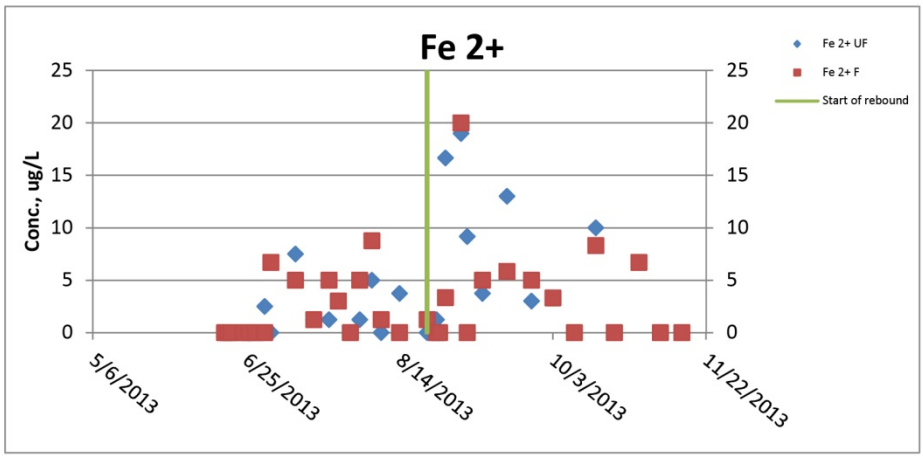


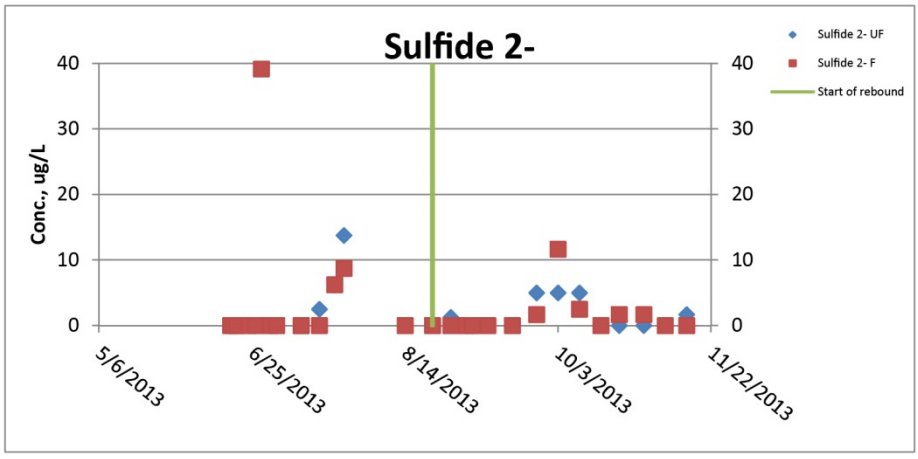


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Figure A-1 (continued)

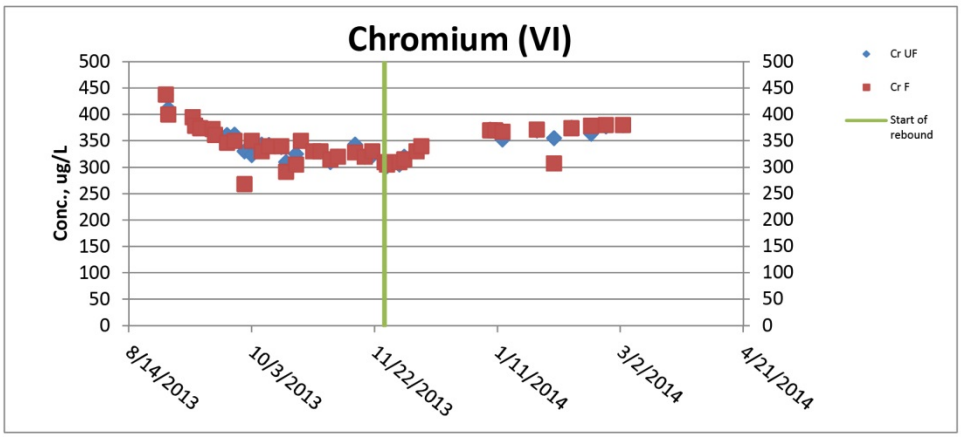


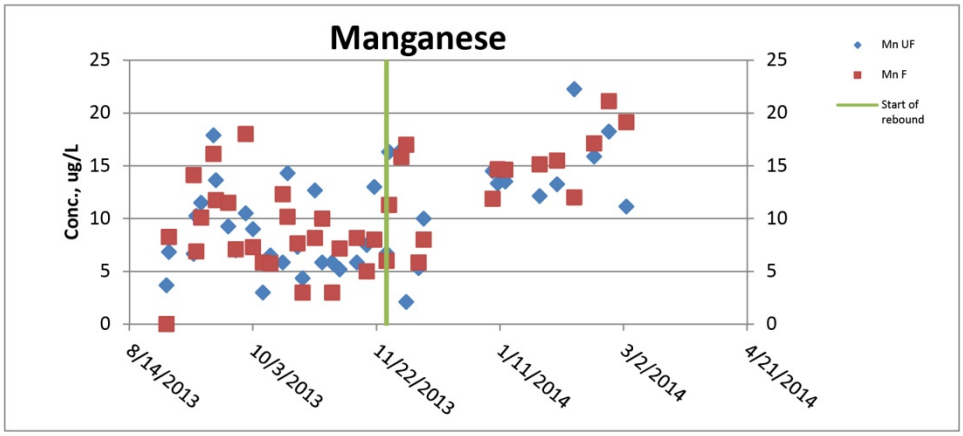




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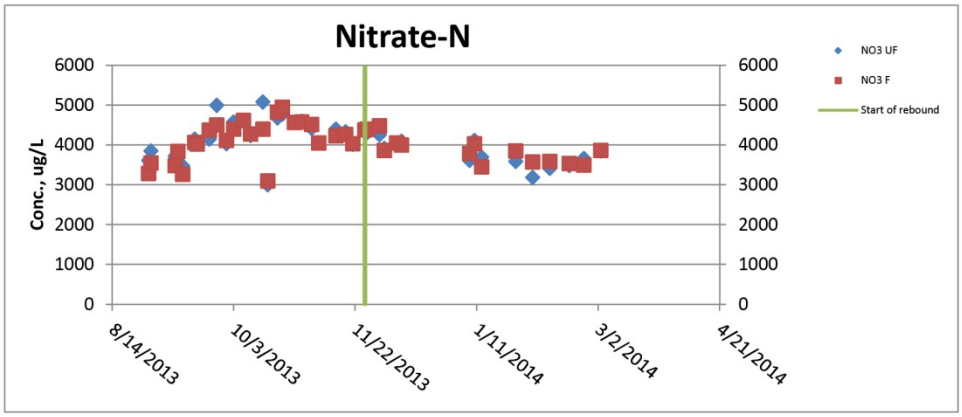
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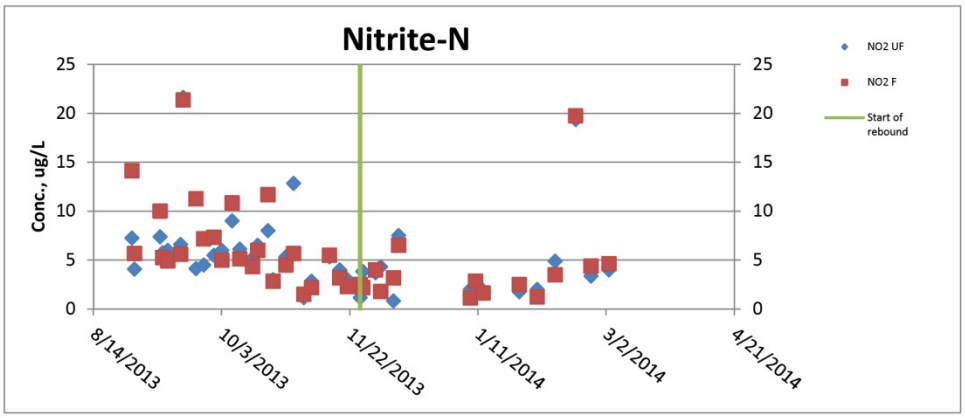


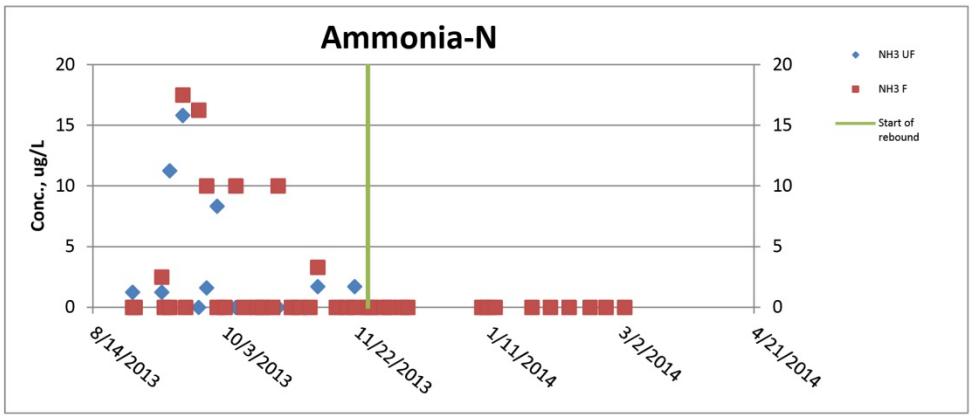


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Figure A-2 Hach analytical results for pumping and rebound at R-28

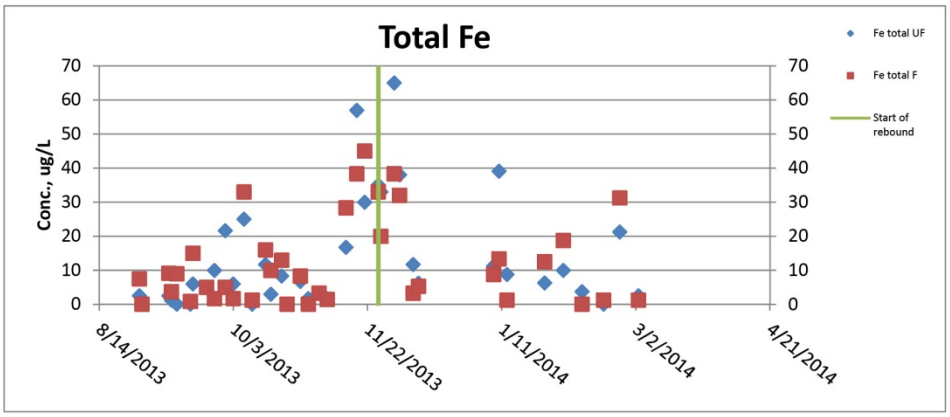


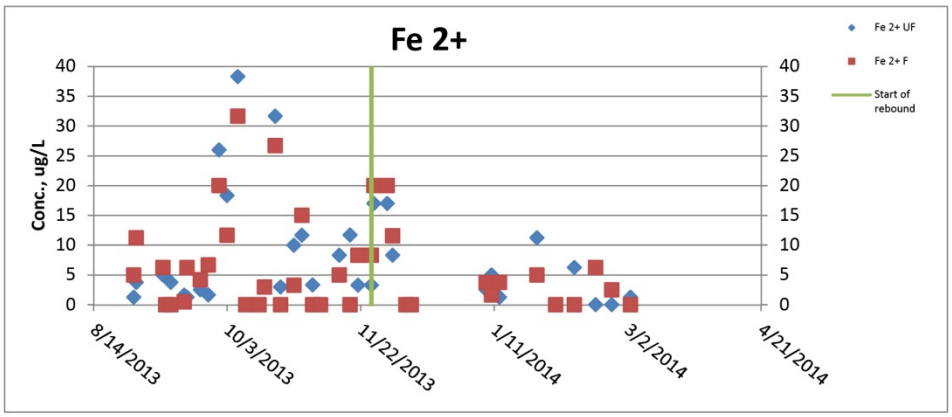


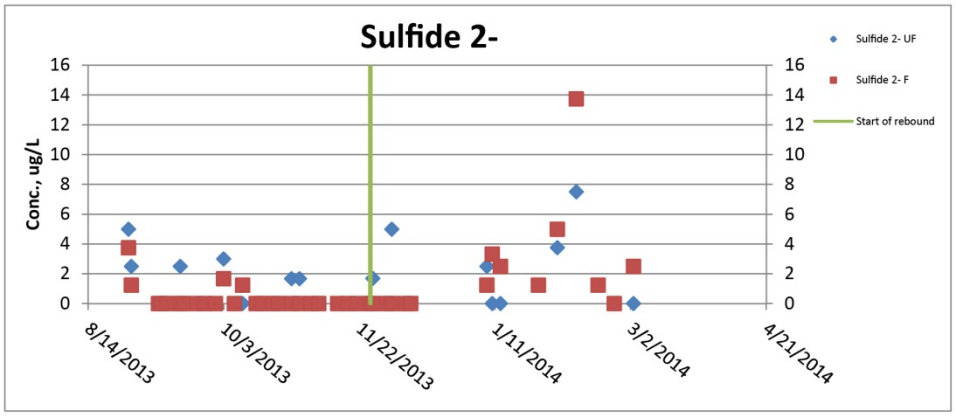


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Figure A-2 (continued)

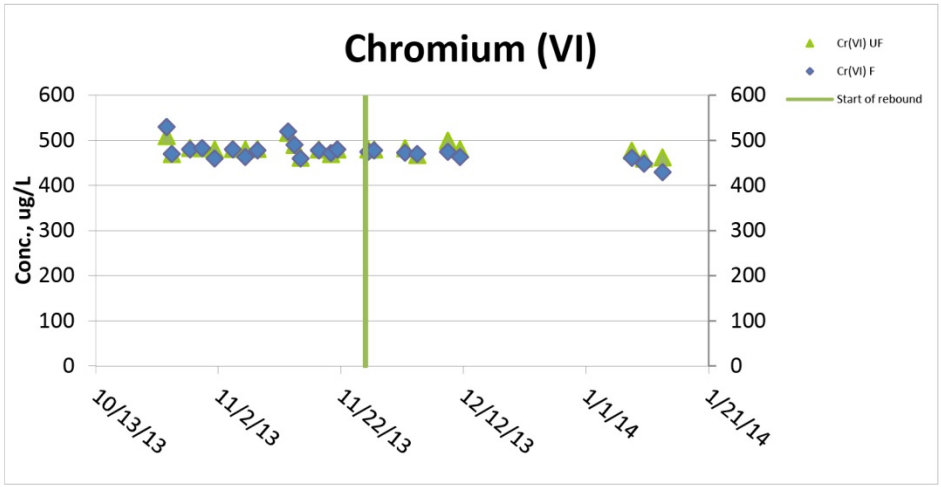


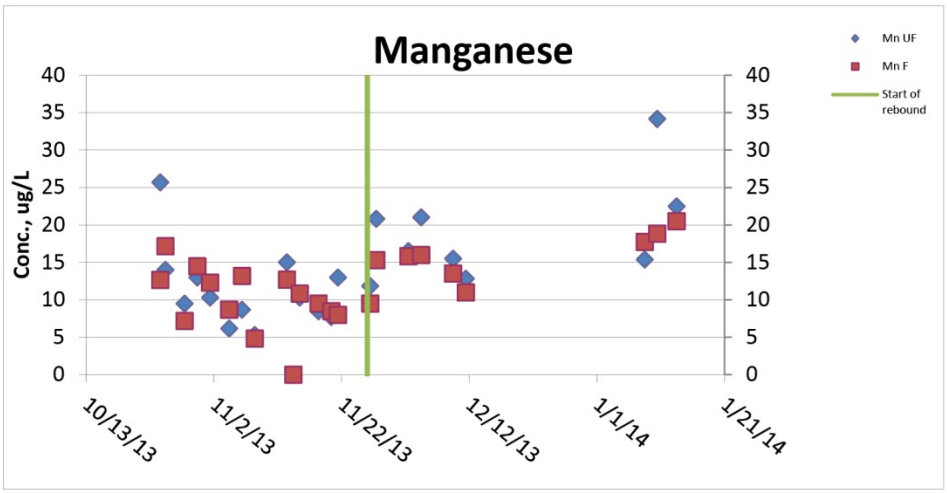




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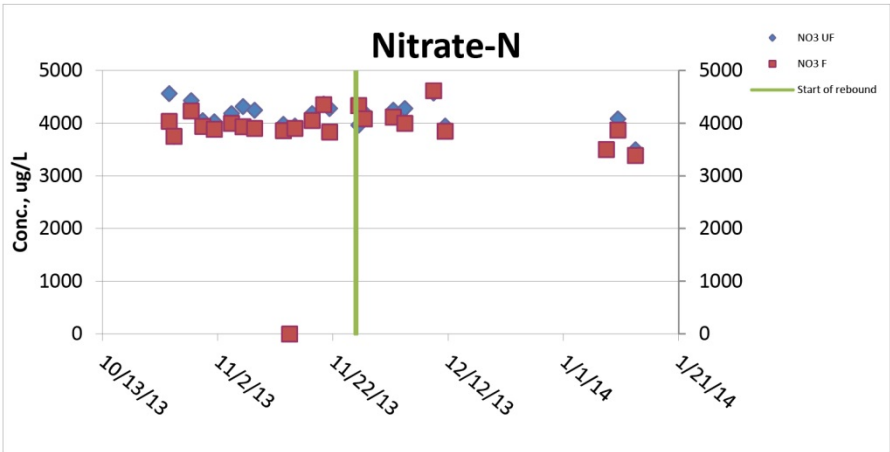
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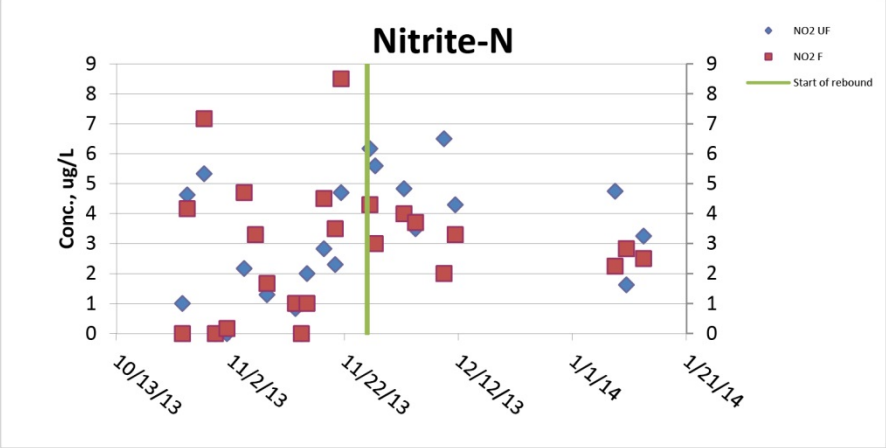


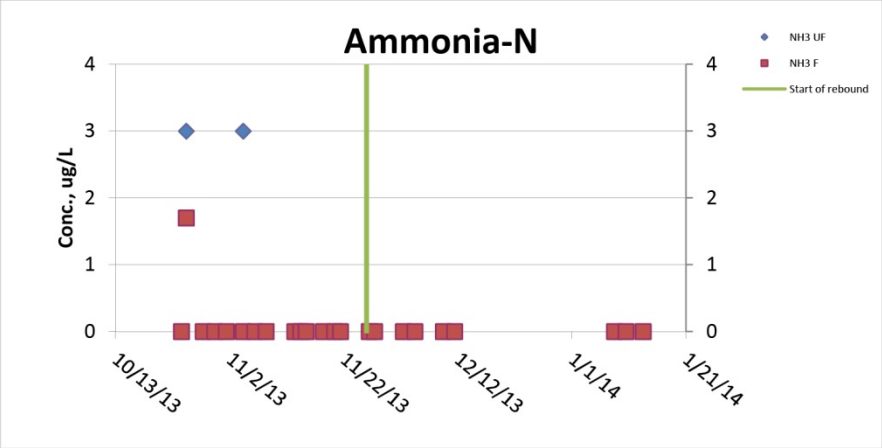


a

Figure A-3 Hach analytical results for pumping and rebound at SCI-2

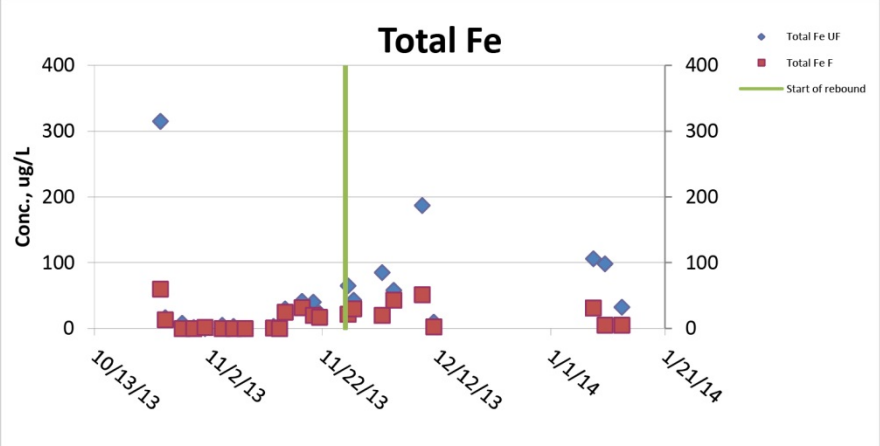


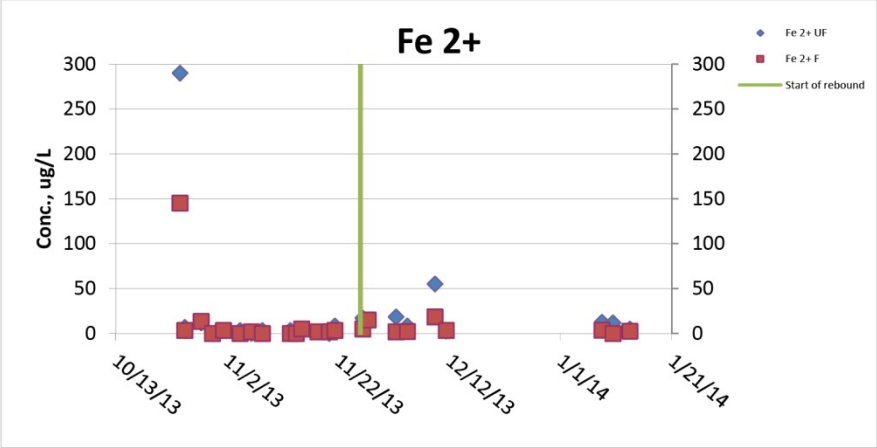


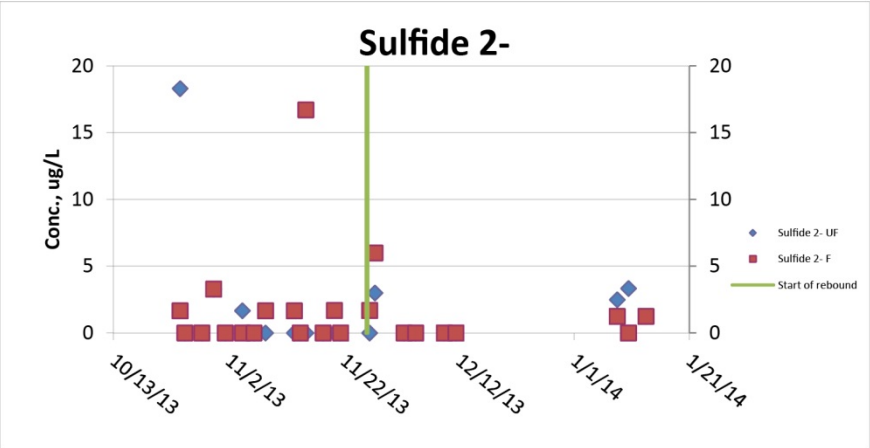


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Figure A-3 (continued)







c

Figure A-3 (continued)

Table A-1
Hach Kit Analytes and Method Numbers

Analyte	Hach Method
Cr(VI)	8023
Total Cr	8024
NO_3^- (Nitrate)	8171
NO_2^- (Nitrite)	8507
NH_3 (Ammonia)	8155
Total Mn	8149
Fe(II)	8146
Total Fe	8008
S^{2-} (Sulfide)	8131

Table A-2
Eh Values Associated with Various Half-Reactions Involving Hach Kit Analytes (and Oxygen)
Calculated Using Equation 1 with Constituent Concentrations Measured in R-42

Redox Couple	Half-Reaction	Eh (R-42), V	Assumptions
O_2/H_2O	$O_2 + 4H^+ + 4e^- > 2H_2O$	0.754	Dissolved O_2 = 7 mg/L
O_2/H_2O	$O_2 + 4e^- + 2H_2O > 4OH^-$	0.712	Dissolved O_2 = 7 mg/L
MnO_2/Mn^{2+}	$MnO_2(s) + 4H^+ + 2e^- > Mn^{2+} + 2H_2O$	0.507	Mn^{2+} = 0.01 mg/L
NO_3^-/NO_2^-	$NO_3^- + H_2O + 2e^- > NO_2^- + 2OH^-$	0.459	NO_2^--N = 0.01 mg/L
$Cr_2O_7^=/Cr^{3+}$	$Cr_2O_7^{2-} + 14H^+ + 6e^- > 2Cr^{3+} + 7H_2O$	0.360	Cr^{3+} = 1 ppb (assumed)
NO_2^-/NH_3	$NO_2^- + 5H_2O + 6e^- > NH_3 + 7OH^-$	0.262	If NH_3 at Hach det. lim.
$Fe(OH)_3/Fe^{2+}$	$Fe(OH)_3 + 3H^+ + e^- > Fe^{2+} + 3H_2O$	0.076	If Fe^{2+} at Hach det. lim.
$SO_4^=/HS^-$	$SO_4^= + (9/2)H_2O + 8e^- > HS^- + (17/2)OH^-$	-0.268	If $S^=/HS^-$ at Hach det. lim.

Note: Shaded cells are considered the most reliable values of Eh in the R-42 water because they are constrained by consistent non-zero Hach-kit measurements of the more reduced species in the corresponding half-reactions (Mn^{2+} and NO_2^-).

Table A-3
Hach Analytical Data for R-42

Location	Date	Pumping Hours	Purge Volume (CV)	Total Cr (µg/L), UF	Total Cr (µg/L), F	Cr(VI) (µg/L), UF	Cr(VI) (µg/L), F	Mn (µg/L), UF	Mn (µg/L), F	Nitrate (µg/L), UF	Nitrate (µg/L), F	Nitrite (µg/L), UF	Nitrite (µg/L), F	Fe2+ (µg/L), UF	Fe2+ (µg/L), F	Total Fe (µg/L), UF	Total Fe (µg/L), F	Sulfide (µg/L), UF	Sulfide (µg/L), F
Significant Figures—Lowest Meter Reading				**0.01**	**0.01**	**0.01**	**0.01**	**0.001**	**0.001**	**0.1**	**0.1**	**0.001**	**0.001**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
R-42	6/18/2013	20.80	CP[a]	1015.63	1018.21	1015.31	965.59	25.00	11.50	5632.69	6082.47	9.00	11.00	0.00	0.00	0.00	0.00	0.00	0.00
R-42	6/19/2013	43.22	CP	1024.79	981.18	1013.77	1000.00	7.00	4.00	6139.22	6079.61	6.50	8.50	0.00	0.00	0.00	0.00	0.00	0.00
R-42	6/20/2013	66.80	CP	702.80*	937.50	1004.00	973.27	13.00	10.50	5900.00	5647.14	9.00	4.50	0.00	0.00	0.00	0.00	0.00	0.00
R-42	6/24/2013	163.47	CP	1061.52	909.83	1048.32	1009.12	10.67	11.25	6076.39	5655.99	7.00	12.50	0.00	0.00	0.00	0.00	—	—
R-42	6/26/2013	211.55	CP	—[b]	933.04	—	1071.43	—	7.50	—	5773.00	—	7.13	—	0.00	—	0.00	—	—
R-42	6/28/2013	259.38	CP	—	1112.52	—	897.06	—	8.75	—	6199.12	—	6.38	—	0.00	—	8.75	—	39.17
R-42	7/1/2013	332.38	CP	870.80	1073.50	970.00	980.40	15.63	13.50	5739.90	5724.10	9.25	9.13	2.50	0.00	1.25	0.00	0.00	0.00
R-42	7/3/2013	379.47	CP	—	1016.60	-	979.70	—	7.40	—	5803.10	—	5.60	—	6.70	—	12.50	—	—
R-42	7/11/2013	575.30	CP	904.17	945.00	993.54	929.18	11.95	12.25	5972.78	5870.16	9.75	10.75	7.50	5.00	3.75	6.25	—	—
R-42	7/17/2013	716.80	CP	—	—	922.00	947.20	1.33	2.17	5770.80	5303.90	5.83	7.67	1.25	1.25	3.75	5.00	2.50	0.00
R-42	7/22/2013	835.72	CP	—	—	770.00	950.00	9.90	13.70	5754.00	5122.90	7.30	10.50	1.25	5.00	0.00	62.50	6.25	6.25
R-42	7/25/2013	907.38	CP	—	—	930.18	917.75	11.50	10.30	6049.10	5828.40	7.67	9.17	3.00	3.00	3.75	2.50	13.75	8.75
R-42	7/29/2013	1003.67	CP	—	—	916.00	939.00	10.67	8.75	5605.20	5478.20	9.50	9.13	0.00	0.00	6.25	10.00	—	—
R-42	8/1/2013	1075.88	CP	—	—	923.00	895.00	7.42	10.75	6024.00	5675.00	7.17	7.33	1.25	5.00	3.75	5.00	—	—
R-42	8/5/2013	1171.55	CP	—	—	935.00	907.00	15.08	12.58	5952.40	5857.00	5.00	5.50	5.00	8.75	2.50	5.00	—	—
R-42	8/8/2013	1243.77	CP	—	—	877.00	790.00	4.08	7.58	6400.00	6174.60	4.00	5.80	0.00	1.25	1.25	3.75	—	—
R-42	8/14/2013	1387.62	CP	—	—	903.60	870.10	7.50	7.50	4768.08	4183.33	6.50	5.50	3.75	0.00	12.50	3.75	—	—
R-42	8/23/2013	—	ND[c]	—	—	941.25	882.35	2.10	3.90	4600.00	3918.65	0.00	0.00	0.00	1.25	1.25	0.25	—	—
R-42	8/26/2013	—	ND	—	—	865.34	887.50	12.42	7.00	4850.00	5050.00	3.92	3.92	1.25	0.00	2.50	0.00	—	—
R-42	8/27/2013	—	ND	—	—	843.33	853.40	8.75	9.42	4731.00	4447.14	13.33	12.58	0.00	0.00	31.25	0.00	—	—
R-42	8/29/2013	—	ND	900.00	916.15	878.50	805.59	11.92	5.33	5515.40	5139.53	7.88	12.00	16.67	3.33	62.50	31.25	1.25	0.00
R-42	9/3/2013	—	ND	—	—	886.74	884.33	8.92	9.75	5268.10	5240.67	10.80	10.60	19.00	20.00	8.75	7.50	—	—
R-42	9/5/2013	—	ND	—	—	918.37	900.00	6.38	6.88	5544.00	5154.46	28.38	30.50	9.16	0.00	17.50	11.60	—	—
R-42	9/10/2013	—	ND	—	—	850.50	848.31	7.88	5.75	5572.20	5571.35	7.50	8.13	3.75	5.00	6.25	3.75	—	—
R-42	9/18/2013	—	ND	—	—	931.37	774.41	13.50	11.00	5457.29	5550.26	29.13	29.38	13.00	5.83	12.50	6.00	—	—
R-42	9/26/2013	—	ND	—	—	947.17	710.18	7.50	8.70	5776.98	6035.95	9.60	8.60	3.00	5.00	0.00	0.00	5.00	1.70
R-42	10/3/2013	—	ND	—	—	892.94	865.00	17.00	14.67	6693.33	5252.76	17.16	15.83	3.30	3.30	171.67[c]	35.00[c]	5.00	11.67
R-42	10/10/2013	—	ND	—	—	960.08	957.12	13.00	12.50	5605.16	5848.30	8.00	8.38	NM	NM	0.00	0.00	5.00	2.50
R-42	10/17/2013	—	ND	—	—	953.65	951.90	14.30	10.16	6000.00	6175.59	9.83	10.16	10.00	8.30	13.00	3.00	—	—

Table A-3 (continued)

Location	Date	Pumping Hours	Purge Volume (CV)	Total Cr (µg/L), UF	Total Cr (µg/L), F	Cr(VI) (µg/L), UF	Cr(VI) (µg/L), F	Mn (µg/L), UF	Mn (µg/L), F	Nitrate (µg/L), UF	Nitrate (µg/L), F	Nitrite (µg/L), UF	Nitrite (µg/L), F	Fe^{2+} (µg/L), UF	Fe^{2+} (µg/L), F	Total Fe (µg/L), UF	Total Fe (µg/L), F	Sulfide (µg/L), UF	Sulfide (µg/L), F
Significant Figures—Lowest Meter Reading				**0.01**	**0.01**	**0.01**	**0.01**	**0.001**	**0.001**	**0.1**	**0.1**	**0.001**	**0.001**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
R-42	10/23/2013	—	ND	—	—	953.80	969.04	6.33	9.00	6161.42	5929.69	7.30	7.00	0.00	0.00	—	—	0.00	1.67
R-42	10/31/2013	—	ND	—	—	992.84	1018.52	10.00	11.60	6800.00	6477.37	10.17	6.50	6.70	6.70	21.67	23.00	0.00	1.67
R-42	11/7/2013	—	ND	—	—	1022.82	999.08	9.00	9.30	6391.46	6358.01	5.30	5.70	0.00	0.00	15.15	15.00	0.00	0.00
R-42	11/14/2013	—	ND	—	—	980.39	988.34	9.30	8.70	6340.94	6089.33	7.67	4.83	0.00	0.00	6.70	8.30	1.67	0.00

Notes: From 7/3–7/11/2013: Pump failure occurred. On 8/23/2013 rebound sampling began.

[a] CP = Continuous pumping.

[b] — = Dashes mean not measured on that date.

[c] ND = No purge volume data available.

[d] Erroneous measurement.

Table A-4
Hach Analytical Data for R-28

Location	Date	Pumping Hours	Purge Volume (CV)	Total Cr (µg/L), UF	Total Cr (µg/L), F	Cr(VI) (µg/L), UF	Cr(VI) (µg/L), F	Mn (µg/L), UF	Mn (µg/L), F	Nitate (µg/L), UF	Nitate (µg/L), F	Nitrite (µg/L), UF	Nitrite (µg/L), F	Fe^{2+} (µg/L), UF	Fe^{2+} (µg/L), F	Total Fe (µg/L), UF	Total Fe (µg/L), F	Sulfide (µg/L), UF	Sulfide (µg/L), F
Significant Figures—Lowest Meter Reading (mg/L)				**0.01**	**0.01**	**0.01**	**0.01**	**0.001**	**0.001**	**0.1**	**0.1**	**0.001**	**0.001**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
R-28	8/29/2013	17.38	CP[a]	466.25	438.75	437.50	437.50	3.67	0.00	3612.50	3287.50	7.25	14.13	1.25	5.00	2.50	7.50	5.00	3.75
R-28	8/30/2013	40.88	CP	398.75	361.25	411.25	400.00	6.83	8.25	3850.00	3550.00	4.08	5.67	3.75	11.25	1.25	0.00	2.50	1.25
R-28	9/9/2013	281.88	CP	—[b]	—	390.00	395.00	6.66	14.13	3725.00	3487.50	7.38	10.00	5.00	6.25	2.50	9.17	—	—
R-28	9/10/2013	305.97	CP	—	—	378.75	378.75	10.25	6.88	3512.50	3837.50	5.75	5.25	0.00	0.00	1.25	3.75	—	—
R-28	9/12/2013	354.22	CP	—	—	380.00	374.00	11.50	10.10	3475.00	3262.50	6.00	4.90	3.75	0.00	0.00	9.00	—	—
R-28	9/17/2013	473.30	CP	—	—	370.00	372.50	17.88	16.13	4150.00	4066.00	6.58	5.58	1.60	0.50	0.00	0.83	2.50	0.00
R-28	9/18/2013	498.55	CP	—	—	370.00	361.25	13.63	11.75	4058.30	4025.00	21.63	21.38	1.25	6.25	6.00	15.00	—	—
R-28	9/23/2013	618.38	CP	—	—	361.25	346.25	9.25	11.50	4150.00	4375.00	4.13	11.25	2.50	4.17	5.00	5.00	—	—
R-28	9/26/2013	690.30	CP	—	—	361.70	350.00	7.00	7.10	5000.00	4500.00	4.50	7.16	1.67	6.70	10.00	1.67	0.00	0.00
R-28	9/30/2013	786.22	CP	—	—	330.00	268.30	10.50	18.00	4030.00	4116.60	5.50	7.33	26.00	20.00	21.60	5.00	—	—
R-28	10/3/2013	857.63	CP	—	—	323.00	350.00	9.00	7.30	4583.00	4400.00	6.00	5.00	18.33	11.67	6.00	1.67	3.00	1.67
R-28	10/7/2013	954.38	CP	—	—	343.00	330.00	3.00	5.83	4600.00	4616.00	9.00	10.83	38.30	31.67	25.00	33.00	—	—
R-28	10/10/2013	1026.38	CP	—	—	342.50	340.00	6.50	5.75	4237.50	4275.00	6.13	5.13	—	—	0.00	1.25	0.00	1.25
R-28	10/15/2013	1149.55	CP	—	—	338.30	340.00	5.83	12.30	5083.30	4400.00	5.17	4.33	—	—	11.66	16.00	—	—
R-28	10/17/2013	1194.47	CP	—	—	310.00	291.60	14.30	10.16	3000.00	3100.00	6.50	6.00	3.00	3.00	3.00	10.00	—	—
R-28	10/21/2013	1289.97	CP	—	—	325.00	305.00	7.33	7.66	4683.00	4817.00	8.00	11.67	31.67[c]	26.70[c]	8.30	13.00	—	—
R-28	10/23/2013	1337.97	CP	—	—	350.00	350.00	4.33	3.00	4783.00	4950.00	3.00	2.83	3.00	0.00	—	—	0.00	0.00
R-28	10/28/2013	1458.22	CP	—	—	330.00	330.00	12.67	8.17	4566.00	4566.00	5.33	4.50	10.00	3.30	6.70	8.30	1.67	0.00

Table A-4 (continued)

Location	Date	Pumping Hours	Purge volume (CV)	Total Cr (µg/L), UF	Total Cr (µg/L), F	Cr(VI) (µg/L), UF	Cr(VI) (µg/L), F	Mn (µg/L), UF	Mn (µg/L), F	Nitate (µg/L), UF	Nitate (µg/L), F	Nitrite (µg/L), UF	Nitrite (µg/L), F	Fe^{2+} (µg/L), UF	Fe^{2+} (µg/L), F	Total Fe (µg/L), UF	Total Fe (µg/L), F	Sulfide (µg/L), UF	Sulfide (µg/L), F
Significant Figures—Lowest Meter Reading (mg/L)				**0.01**	**0.01**	**0.01**	**0.01**	**0.001**	**0.001**	**0.1**	**0.1**	**0.001**	**0.001**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
R-28	10/31/2013	1530.22	CP	—	—	330.00	330.00	5.83	10.00	4600.00	4583.00	12.83	5.67	11.67	15.00	1.67	0.00	1.67	0.00
R-28	11/4/2013	1626.80	CP	—	—	310.00	315.00	5.83	3.00	4417.00	4517.00	1.17	1.50	3.33	0.00	3.30	3.30	0.00	0.00
R-28	11/7/2013	1699.80	CP	—	—	320.00	320.00	5.17	7.17	4060.00	4050.00	2.83	2.17	0.00	0.00	1.60	1.50	0.00	0.00
R-28	11/14/2013	1867.97	CP	—	—	343.00	328.00	5.83	8.16	4400.00	4233.00	5.33	5.50	8.33	5.00	16.70	28.30	0.00	0.00
R-28	11/18/2013	1962.97	CP	—	—	320.00	320.00	7.50	5.00	4333.00	4267.00	4.00	3.17	11.70	0.00	57.00	38.30	0.00	0.00
R-28	11/21/2013	2035.55	CP	—	—	322.00	330.00	13.00	8.00	4017.00	4033.00	3.00	2.30	3.30	8.30	30.00	45.00	0.00	0.00
R-28	11/26/2013		5	—	—	312.00	310.00	6.70	6.00	4433.00	4383.00	1.17	2.50	3.30	8.30	35.00	33.00	0.00	0.00
R-28	11/27/2013		ND[c,]	—	—	302.00	305.00	16.30	11.30	4317.00	4400.00	3.83	2.17	17.00	20.00	33.00	20.00	1.70	0.00
R-28	12/2/2013		1	—	—	305.00	310.00	16.50	15.83	4260.00	4483.00	3.70	4.00	17.00	20.00	65.00	38.30	0.00	0.00
R-28	12/4/2013		ND[d]	—	—	320.00	315.00	2.10	17.00	3917.00	3867.00	4.30	1.80	8.30	11.60	38.00	32.00	5.00	0.00
R-28	12/9/2013		ND	—	—	330.00	330.00	5.30	5.83	4017.00	4050.00	0.83	3.17	0.00	0.00	11.70	3.30	0.00	0.00
R-28	12/11/2013		ND	—	—	338.00	340.00	10.00	8.00	4100.00	4000.00	7.50	6.50	0.00	0.00	6.17	5.33	0.00	0.00
R-28	1/8/2014		ND	—	—	371.25	370.00	14.50	11.88	3612.50	3787.50	2.00	1.13	2.50	3.75	11.25	8.75	2.50	1.25
R-28	1/10/2014		3	—	—	370.00	370.00	13.33	14.67	4116.67	4033.33	2.00	2.83	5.00	1.67	39.10	13.33	0.00	3.33
R-28	1/13/2014		3	—	—	352.50	367.50	13.50	14.63	3700.00	3450.00	1.88	1.63	1.25	3.75	8.75	1.25	0.00	2.50
R-28	1/27/2014		3	—	—	370.00	371.25	12.13	15.13	3587.50	3850.00	1.75	2.50	11.25	5.00	6.25	12.50	1.25	1.25
R-28	2/3/2014		3	—	—	355.00	307.50	13.25	15.50	3187.50	3575.00	2.00	1.25	0.00	0.00	10.00	18.75	3.75	5.00
R-28	2/10/2014		3	—	—	375.00	373.75	22.25	12.00	3412.50	3587.50	4.88	3.50	6.25	0.00	3.75	0.00	7.50	13.75
R-28	2/18/2014		3	—	—	363.75	378.75	15.88	17.13	3487.50	3537.50	19.38	19.75	0.00	6.25	0.00	1.25	1.25	1.25
R-28	2/24/2014		3	—	—	377.50	380.00	18.25	21.13	3662.50	3500.00	3.38	4.38	0.00	2.50	21.25	31.25	0.00	0.00
R-28	3/3/2014		3	—	—	380.00	380.00	11.13	19.13	3850.00	3862.50	4.00	4.63	1.25	0.00	2.50	1.25	0.00	2.50

Note: On 11/26/2013 rebound sampling began.

[a] CP = Continuous pumping.

[b] — = Dashes mean not measured on that date.

[c] ND = No purge volume data available.

[d] Erroneous measurement.

Table A-5
Hach Analytical Data for SCI-2

Location	Date	Pumping Hours	Purge volume (CV)	Total Cr (µg/L), UF*	Total Cr (µg/L), F*	Cr(VI) (µg/L), UF	Cr(VI) (µg/L), F	Mn (µg/L), UF	Mn (µg/L), F	Nitrate (µg/L), UF	Nitrate (µg/L), F	Nitrite (µg/L), UF	Nitrite (µg/L), F	Fe^{2+} (µg/L), UF	Fe^{2+} (µg/L), F	Total Fe (µg/L), UF	Total Fe (µg/L), F	Sulfide (µg/L), UF	Sulfide (µg/L), F
Significant Figures–Lowest Meter Reading (mg/L)				**0.01**	**0.01**	**0.01**	**0.01**	**0.001**	**0.001**	**0.1**	**0.1**	**0.001**	**0.001**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
SCI-2	10/24/2013	00:50	CP[a]	—[b]	—	510.00	530.00	25.67	12.67	4567.00	4033.00	1.00	0.00	290.00	145.00	315.00	60.00	18.30	1.67
SCI-2	10/25/2013	21:00	CP	—	—	470.00	470.00	14.00	17.17	3750.00	3750.00	4.63	4.17	6.67	3.33	16.67	13.33	0.00	0.00
SCI-2	10/28/2013	92:00	CP	—	—	483.30	480.00	9.50	7.17	4433.00	4233.00	5.33	7.17	11.66	13.30	8.30	0.00	0.00	0.00
SCI-2	10/30/2013	140:15	CP	—	—	483.00	483.00	13.00	14.50	4050.00	3940.00	0.00	0.00	0.00	0.00	1.67	0.00	3.30	3.30
SCI-2	11/1/2013	188:30	CP	—	—	480.00	460.00	10.30	12.30	4030.00	3883.00	0.00	0.17	3.30	3.30	0.00	1.67	0.00	0.00
SCI-2	11/4/2013	260:25	CP	—	—	481.70	480.00	6.17	8.70	4183.00	4000.00	2.17	4.70	3.30	0.00	5.00	0.00	1.67	0.00
SCI-2	11/6/2013	308:25	CP	—	—	480.00	463.00	8.70	13.17	4320.00	3933.00	3.30	3.30	0.00	1.70	3.30	0.00	0.00	0.00
SCI-2	11/8/2013	356:30	CP	—	—	481.70	478.30	5.30	4.83	4250.00	3900.00	1.30	1.67	3.30	0.00	0.00	0.00	0.00	1.67
SCI-2	11/13/2013	476:51	CP	—	—	517.00	520.00	15.00	12.70	3983.00	3860.00	0.83	1.00	3.30	0.00	3.30	1.00	0.00	1.67
SCI-2	11/14/2013	501:40	CP	—	—	490.00	490.00	—	—	—	—	—	—	—	—	—	—	—	—
SCI-2	11/15/2013	524:50	CP	—	—	462.00	460.00	10.30	10.83	3950.00	3900.00	2.00	1.00	3.30	5.00	30.00	25.00	0.00	16.70
SCI-2	11/18/2013	596:20	CP	—	—	480.00	478.00	8.50	9.50	4183.00	4050.00	2.83	4.50	1.70	1.70	41.70	31.70	0.00	0.00
SCI-2	11/20/2013	644:10	CP	—	—	470.00	472.00	7.70	8.50	4367.00	4350.00	2.30	3.50	ND	1.70	40.30	20.00	0.00	1.70
SCI-2	11/21/2013	669:20	CP	—	—	480.00	480.00	13.00	8.00	4283.00	3833.00	4.70	8.50	8.30	3.30	23.00	17.00	0.00	0.00
SCI-2	11/26/2013		1	—	—	480.00	475.00	11.83	9.50	3967.00	4333.00	6.17	4.30	17.00	5.00	65.00	21.70	0.00	1.70
SCI-2	11/27/2013		1	—	—	480.00	478.00	20.80	15.30	4200.00	4083.00	5.60	3.00	13.00	15.00	43.00	30.00	3.00	6.00
SCI-2	12/2/2013		ND[c]	—	—	483.00	473.00	16.50	15.83	4250.00	4117.00	4.83	4.00	18.30	1.70	85.00	20.00	0.00	0.00
SCI-2	12/4/2013		ND	—	—	468.00	470.00	21.00	16.00	4283.00	4000.00	3.50	3.70	8.30	2.16	58.30	43.00	0.00	0.00
SCI-2	12/9/2013		ND	—	—	500.00	475.00	15.50	13.50	4577.00	4618.00	6.50	2.00	55.00	18.30	187.00	51.20	0.00	0.00
SCI-2	12/11/2013		ND	—	—	480.00	463.00	12.83	11.00	3950.00	3850.00	4.30	3.30	2.67	3.30	9.67	2.67	0.00	0.00
SCI-2	1/8/2014		3	—	—	477.50	461.25	15.38	17.75	3500.00	3500.00	4.75	2.25	12.50	3.75	106.25	31.25	2.50	1.25
SCI-2	1/10/2014		5	—	—	460.00	448.33	34.17	18.83	4083.33	3866.67	1.63	2.83	11.67	0.00	98.33	5.00	3.33	0.00
SCI-2	1/13/2014		3	—	—	462.50	430.00	22.50	20.50	3500.00	3387.50	3.25	0.25	5.00	2.50	32.50	5.00	1.25	1.25

Note: On 11/26/2013 rebound sampling began.

[a] CP = Continuous pumping.

[b] — = Dashes mean not measured on that date.

[c] ND = No purge volume data available.

Appendix B

Aquifer Test Results and Capture Zone Analysis

B-1.0 INTRODUCTION

This appendix presents a detailed analysis of the results of aquifer tests conducted at regional aquifer monitoring wells R-28 and R-42 and at perched-intermediate monitoring well SCI-2 at Los Alamos National Laboratory (LANL or the Laboratory) (Figure 1.0-1 of the report). Figure 1.0-2 shows the locations of all monitoring wells within the Chromium Investigation monitoring group, including wells used to monitor water-level responses to the long-term pumping events. The analysis of the chromium interim measures aquifer testing also includes a discussion of the effects of the 10-d aquifer test conducted in 2012 on water levels observed in nearby regional monitoring wells.

Regional Aquifer Tests

Pumping at R-42 started on June 17, 2013, and ended on August 21, 2013. A step-drawdown test was first conducted to establish an optimum pumping rate. Pumping on June 17 started at an initial pumping rate set to 9 gallons per minute (gpm). Based on observed water level declines, this rate was subsequently reduced to a target rate of 7 gpm on June 18. Thereafter, for the duration of the test, the pumping rate remained at approximately 7 gpm. A pump failure caused an interruption in the test starting on the evening of July 7 and ending the morning of July 11, 2013. The pump and motor were replaced as a unit; a subsequent investigation determined that the motor had failed. R-42 was continuously pumped for the remainder of the test, from July 12 to August 21, 2013, when the aquifer test was terminated. A total of 616,000 gal. of water was pumped from R-42 over the 66-d pumping period. Rebound groundwater sampling began shortly after the aquifer test was terminated and continued to December 5, 2013.

A step-drawdown test was also conducted at the start of the R-28 aquifer test to establish an optimum pumping rate. Pumping at R-28 started on August 28, 2013, at the “full open” rate of 29.7 gpm. Shortly thereafter, this rate was reduced to 28 gpm, and drawdown responses at this lower rate were monitored overnight. Drawdown stabilized at approximately 2 ft, and based on this response, the pumping rate was increased on the morning of August 29 to the “full open” rate of 29.7 gpm. During the remainder of the test, the pump was operated at the maximum flow rate available from the pumping system, stabilizing at approximately 29 gpm.

The aquifer test at R-28 continued until November 22, 2013, at an average pumping rate of about 29 gpm. On August 30, 2013, the pump failed as a result of faulty wiring, and the pump was removed from the shroud, repaired, and then set in an alternate configuration above the screen rather than in the sump. Pumping resumed on September 7, 2013. On November 6, 2013, the pump shut off as a result of a tripped generator, and pumping resumed the following day. The aquifer test at R-28 was terminated on November 22, 2013, when freezing ground conditions required land application to cease in accordance with the temporary permission for land application granted by the New Mexico Environment Department (NMED) Ground Water Quality Bureau. A total of 3,317,000 gal. of water was pumped from R-28 during the 87 d of pumping. Rebound groundwater sampling continued at R-28 to March 3, 2014.

The water levels in the regional aquifer were affected by drawdown from the aquifer test pumping as well as by several other factors, including changes in water levels from barometric pressure fluctuations and drawdown caused by pumping of several nearby Pajarito Plateau municipal water supply wells. In particular, the pumping of water supply well PM-4 from June 26 to November 15, 2013 influenced water levels in some of the regional observation wells for the R-42 and R-28 aquifer tests.

No attempts were made to remove the effects of earth tides in the analysis presented here. The tidal effects fluctuate and peaks occur every 12 to 25 h (controlled by the relative positions of the moon and the sun). The tidal effects increase and decrease in time; the peak in the tidal effects are observed on

approximately 14-d periods. In the past, the tidal effects were estimated and removed using the code BETCO. However, the code does now allow for automated data processing and required manual data import and export.

To avoid any data quality assurance issues, the analyses presented here were performed using an automated computational framework, which pulls the data from the LANL database, preprocesses the data to remove the barometric effects, and performs the analyses without any human intervention. In the future, the tidal-effect removal will be incorporated into this process. However, in the current analysis, the tidal effects were not accounted for because only daily data (with a 24-h interval) are applied in the analysis, and tidal effects are filtered out. Multiple tidal periods are observed during the relatively long aquifer tests (66 and 87 d at R-42 and R-28, respectively). Therefore, the fluctuations from tidal effects are expected to have minimal impact on the estimated drawdowns over the long-term pumping period. The drawdowns caused by the pumping of R-42 and R-28 are model estimated based on the matching of the observed data (by matching the collected) rather than computed manually based on the observed pressures. As a result, the drawdown estimates are determined with a relatively high confidence regardless the impact of tidal effects on the observed pressures.

Perched-Intermediate Zone Tests

A shorter duration (30 d) pumping test was conducted at SCI-2 to evaluate the potential for chromium source removal within the contaminated perched-intermediate zone beneath Sandia Canyon. Pumping at SCI-2 started on October 24, 2013, using the SCI-2 dedicated pneumatic pump sampling system. The well was pumped until November 23, 2013, at an approximate rate of about 0.7 gpm, with negligible interruptions during the test. A total of 28,000 gal. of water was pumped from SCI-2 during the 30 d of pumping. Rebound groundwater sampling continued at SCI-2 to January 13, 2014.

During the SCI-2 pumping test, water levels in nearby perched-intermediate monitoring wells were monitored for pressure changes.

B-2.0 ANALYSIS OF WATER-LEVEL DATA

The regional aquifer water-level data are included in an Excel spreadsheet (on CD). Barometric data from the Laboratory's meteorological station at Technical Area 54 (available at http://weather.lanl.gov) were used for the analysis. Pumping records for the Los Alamos County water supply wells were obtained from the Los Alamos County database.

Figures B-1 through B-6 show the water levels at different wells during the aquifer test period after barometric pressure effects were removed. It is important to note that the drawdown curves observed during the R-28 aquifer test show drawdown stabilization in the nearby monitoring wells towards the end of the aquifer test. This drawdown stabilization can be caused by various factors, including (1) delayed yield from the vadose zone (phreatic aquifer effects), (2) leakage from deeper hydrostratigraphic units (leaky aquifer), (3) lateral boundary effects (high- or low-permeability zones), and (4) infiltration recharge from the vadose zone.

SCI-2 Data Analysis

Water levels during the SCI-2 pumping are presented in Figure B-7. The pumping produced approximately 13 ft of drawdown at SCI-2. However, the water-level decline did not reach equilibrium, and pressures continued to decline throughout the 30-d aquifer test. After the pumping was terminated, the water levels at SCI-2 recovered rapidly. However, the available data do not provide sufficient information to indicate whether the water levels recovered completely; a long-term record is needed to evaluate the

effect of the SCI-2 pumping on the water levels in this perched-intermediate zone. The transmissivity of the perched intermediated saturated zone is estimated to be 20 m^2/d (1600 gallons per day per foot [gpd/ft]). The water levels observed in nearby perched-intermediate monitoring wells (MCOI-5 and MCOI-6) did not show apparent response to the pumping at SCI-2.

R-42 and R-28 Data Analysis

The water-level data for the regional aquifer tests in R-42 and R-28 were analyzed using the method described in (Harp and Vesselinov 2010, 111220) to estimate the drawdowns attributable to each pumping well (water-supply and monitoring wells). The analyses utilize two open-source codes developed at the Laboratory: WELLS (http://wells.lanl.gov) and MADS (http://mads.lanl.gov). WELLS is applied to simulate the drawdowns caused by the pumping at the water-supply and monitoring wells. MADS is applied to (1) deconstruct pumping drawdowns caused by different pumping wells and (2) estimate aquifer properties by matching the simulated and observed hydraulic heads at the observation wells.

Figures B-8 through B-32 present the results of this analysis. Each figure shows the model-based deconstruction of the water-level transients observed in each monitoring well during the 2013 aquifer tests at R-42 and R-28. The upper plot in each figure depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the wells where extended pumping occurred: water-supply wells O-4, PM-2, PM-3, PM-4, and PM-5 and monitoring wells R-42 and R-28.

Table B-1 lists the maximum estimated drawdowns (at the end of the aquifer tests) caused by R-42 and R-28 pumping at each of the monitoring wells based on this analysis.

Table B-2 lists the estimated effective aquifer properties between the pumping and observation wells. Table B-2 suggests pronounced aquifer heterogeneity with transmissivity ranging between 20 to 3400 m^2/d (22 to 36,000 ft^2/d) and storativity ranging between 0.03 and 0.002 (the variability in the effective storativity is indicative of heterogeneity in the aquifer permeability as well). Although the transmissivity estimates based on the aquifer tests vary by 2 orders of magnitude, the variability of permeability within the regional aquifer is expected to exceed the variability in transmissivity estimates.

Large uncertainties are associated with estimates of aquifer properties based on the R-42 pumping data because of the small magnitude of the drawdowns measured in observation wells. The average transmissivity based on the R-28 aquifer test data is about 500 m^2/d (~40,000 gpd/ft). This value is consistent with transmissivity values derived from the 2012 aquifer test at R-28 (500 m^2/d or ~40,500 gpd/ft).

Figure B-33 shows the predicted drawdowns and the estimated aquifer properties using the data from the R-28 aquifer test conducted in 2012 (Table B-1), assuming the aquifer is homogenous (T = 40,500 gpd/ft; S=0.02). The 2013 pumping test estimates are consistent with the 2012 pumping test data. However, the 2013 transmissivity estimates represent a larger-scale perspective of the aquifer because the duration of pumping was significantly longer. Figure B-34 shows the estimated aquifer properties using the data from aquifer tests conducted in 2012 and 2013 at R-28, assuming the aquifer is homogenous (T = 30,000 gpd/ft; S=0.01).

Although uncertainties are associated with these estimates for transmissivity (T) and storativity (S), the 2013 aquifer test data nonetheless suggest a lower large-scale aquifer transmissivity than the 2012 analyses. The R-28 capture zone (CZ) analysis presented below is based on the assumption that the large-scale effective transmissivity is 30,000 gpd/ft; however, fairly significant uncertainties are associated with the CZ analysis estimate because of the substantial heterogeneity observed in the regional aquifer.

The 2013 R-28 aquifer test data also demonstrate a greater degree of heterogeneity than indicated by the 2012 R-28 aquifer test data (Figure B-34). The heterogeneity is demonstrated by pronounced deviations of the drawdowns at individual monitoring wells from the uniform theoretical curve (Figure B-34).

B-3.0 CAPTURE ZONE ANALYSIS

Figures B-35 and B-36 show the spatial distribution of the pumping drawdowns at the end of the R-42 and R-28 aquifer tests. The figures also show the zones of influence (ZOI) of both wells, based on the 2013 aquifer test results. Here, the ZOI is identified as the area within which measurable pumping drawdown greater than 0.01 m can be detected. Note that theoretically, very small (nonmeasurable) drawdowns will be manifested throughout the regional aquifer. However, practically speaking, ZOI is defined as the zone where drawdown greater than 0.01 m can be detected.

The R-42 ZOI is very limited in aerial extent (Figure B-35). The only observation well where significant drawdown was observed as a result of the R-42 pumping is R-43, with 0.03 m of drawdown observed in each screen. Smaller drawdowns on the order of 0.01 m were potentially observed in both screens of R-61, R-50, and R-62. However, drawdowns on this small scale are difficult to measure and to quantify.

At R-43 screen 1, the R-42 pumping also potentially caused a reverse drawdown (increased rather than decreased pressures), called the Noordbergum effect. This effect is the result of faster propagation of the elastic deformations than the hydraulic pressures.

In contrast, the R-28 ZOI is extensive (Figure B-36). The only wells that were not apparently influenced by R-28 pumping are R-1, R-6, R-8, and R-36. It is important to note that both R-43 and R-42 produced very low drawdowns compared with the other wells nearby (Figure B-35). This is consistent with the limited ZOI during the R-42 pumping (Figure B-35). The limited drawdowns in R-43 and R-42 during the R-28 aquifer test may be caused by either a zone of low effective (large-scale) aquifer permeability near R-43 and R-42 or a low-permeability zone of groundwater flow between R-42 and R-28. It is also possible preferential infiltration (aquifer recharge) near R-43 and R-42 may limit the drawdown in this area caused by pumping.

All these factors may combine to influence the observed drawdowns at R-43 and R-42 during the R-28 pumping. Note that the local (small-scale) hydraulic conductivity observed during the short-term 24-h aquifer tests at R-43 and R-42 are not very low (~10 ft/d) (LANL 2009, 105296; LANL 2009, 105026). Other wells in the area are characterized with much lower hydraulic conductivities (e.g., R-15, 3 ft/d; R-33 2 ft/d) (Longmire et al. 2001, 070103; Kleinfelder 2005, 092385). It is also important to note that a groundwater mound is observed near R-42 that may indicate local infiltration recharge. The aquifer tests currently planned for 2014 will further improve the conceptualization and characterization of the aquifer properties in the study area.

The ZOI during aquifer pumping is different than the CZ. The CZ represents the portion of the aquifer that is affected by the pumping well in such a way that all the groundwater within the CZ will be eventually pumped out by the well. In the case of a uniform isotropic aquifer, the shape of ZOI and CZ will be similar; it will be a circle centered at the pumping well. The radius of the circle will depend on the pumping time. Typically, the ZOI is bigger than the CZ.

However, in the case of ambient flow, the shape of the CZ will have an elongated form with a predominantly upstream spatial extent (Figure B-37). The CZ estimate typically assumes only an advective steady-state groundwater flow (Figure B-37). However, because of groundwater dispersion, some of the groundwater within the CZ will escape capture while some of the groundwater outside the CZ

will be captured. As a result of transients, the CZ will grow around the pumping well until a quasi-steady-state regime is established around the pumping well.

Under the quasi-steady-state, the pressures still decline from pumping; however, the hydraulic gradients equilibrate to the final steady-state values. The zone of quasi-state-state flow regime (ZQSS) grows in time around the pumping well, and the rate of propagation depends on the aquifer properties and the pumping rate. Both the ZOI and the ZQSS are expected to have a similar shape (circular in the case of a uniform aquifer). The CZ shape depends on the ambient flow properties (Figure B-37). The CZ extent upgradient grows in time and depends on both the pumping duration and rate and on the ambient groundwater flow properties. The CZ extent downgradient reaches an inflection point after a given period of pumping and cannot be increased further.

B-3.1 Evaluation of Capture Zones of R-42 and R-28

In general, the capture zones of pumping wells have a three-dimensional shape characterized by three-dimensional structure and properties of the regional groundwater flow during the aquifer test. As a result, the CZ depends on various hydrogeologic factors:

- pumping rate and duration;
- shape of the regional water table;
- aquifer thickness;
- spatial and temporal distribution in aquifer flow velocities controlled, predominantly by heterogeneity and anisotropy in aquifer properties (permeability, storativity, etc.);
- spatial and temporal variability in aquifer recharge controlled, predominantly by heterogeneity and anisotropy in vadose zone properties and spatial and temporal distribution of infiltration along the nearby canyons; and
- influence of water-supply pumping at the municipal wells nearby (PM-3, PM-5, PM-4, and PM-2). Water-supply pumping causes small changes in the water levels measured at R-28 and other nearby wells; as a result, it is expected that the water-supply pumping does not significantly affect the R-28 and R-42 CZs.

The magnitude of aquifer recharge can be an important factor affecting the size of the estimated R-28 and R-42 CZs. In general, the magnitude of aquifer recharge on the Pajarito Plateau is relatively small (less than 1 mm/yr), and recharge at this scale is not expected to significantly substantially influence the shape of the CZs of pumping wells. In this case, for modeling purposes, the regional water table can be approximated as a no-flow boundary. However, higher recharge rates related to focused recharge along Sandia and Mortandad canyons may significantly influence the shape of the CZ's.

B-3.2 Capture Zone Estimate Based on the Pumped Volume

The CZs at R-28 and R-42 can be estimated based on the volume of water pumped. This approach allows for better approximation of the CZ size at early times when the pumping period is relatively short (for example, less than 100 to 300 d).

In this case, the CZ is assumed to have a cylindrical shape with a constant vertical height *H* (depending on the well screen length) and time-varying horizontal radius *R*. To account for the three-dimensional component of groundwater flow near the well screen, the vertical height *H* is assumed to be approximately 1.5 times the screen length; for example, *H* is ~11 m (36 ft) for R-42 and R-28. The cylinder radius can be computed using the following formula:

$$R = \sqrt{\frac{Q_P t}{\pi \phi_S H}}$$

where Q_p is the pumping rate, *t* is pumping duration, ϕ_S is the water storage porosity. If the total water-filled porosity is assumed to be 0.3, the CZ around R-28 after 78 d of pumping has a radius of 35 m (~110 ft) around the well. For R-42, the CZ around R-42 after 62 d of pumping had a radius of about 15 m (~50 ft). However, this CZ estimate approach ignores the ambient groundwater flow in the aquifer.

B-3.3 Capture Zone Estimate Based on Ambient Aquifer Flow

The CZ can also be estimated based on the width of groundwater flow within which the ambient groundwater flux is equal to the pumping rate (Figure B-37). In this case, the CZ grows upgradient until reaching a width within which the ambient groundwater flow rate is equal to the pumping rate (Figure B-37). This approach allows for a better approximation of the CZ size at late stages in pumping when the pumping period is relatively long, allowing establishment of a quasi-steady state flow regime near the pumping well. This approach is best applied for long-duration pumping periods, greater than 100 to 300 d. In this case, the width of the CZ perpendicular to the groundwater flow direction becomes a constant in time once a quasi-steady-state is attained.

Assuming uniform confined groundwater flow conditions, the flow rate *Q* through a vertical section in the regional aquifer with a horizontal width *W* can be computed as

$$Q = ITW$$

The width *W* can be computed as

$$W = \frac{Q_P}{IT}$$

The ambient groundwater flow in the aquifer near R-28 has hydraulic gradient of about 0.001. For pumping rate of 28.7 gpm and transmissivity of 30,000 gpd/ft, the width of R-28 CZ upgradient from the well is about 420 m (~1300 ft) perpendicular to the groundwater flow direction. Note that the capture width adjacent to R-28, W_w (Figure B-37), is exactly half of the upgradient width *W*, or about 210 m (~800 ft). For R-42, *W* and W_w are approximately 240 m (~780 ft) and 120 m (~390 ft), respectively (*Q* = 7 gpm; T = 15,000 gpd/ft).

The maximum length of capture in the downgradient direction, L_0, from the pumping well (Figure B-37) can be expressed as follows:

$$L_0 = \frac{Q_p}{2\pi TI}$$

For a pumping rate of 28.7 gpm, the length of R-28 CZ in the downgradient direction, L_0, is about 70 m (~220 ft). For the case of R-42, L_0 is about 40 m (~120 ft).

Once the equilibrium between the pumping and ambient flow rates has been established, the pumped well will capture the groundwater flowing toward the well in the CZ. The length *L* of the CZ upgradient from R-28 (Figure B-37) depends on the groundwater flow pore velocity and the pumping duration.

The dimension of the CZs computed above is estimates for long-term pumping. For example, if the R-28 pumping was turned on indefinitely (for more than 100 to 300 d), the CZ estimates presented here will be valid estimates, assuming that the aquifer is uniform. However, the 2013 aquifer test data also demonstrate that the aquifer is also highly heterogeneous. As a result, the shape of the steady-state CZ would likely have a much more complicated shape.

The CZs estimated from the 2013 aquifer tests (because of the relatively short duration of the tests) are expected to be more consistent with the estimates based on the pumped volume. Therefore, the CZs of R-28 and R-42 during the 2013 aquifer tests can be assumed to have radii of about 30 m (90 ft) and 15 m (50 ft), respectively.

B-4.0 CONCLUSIONS

The analyses of the aquifer testing data provide the following conclusions.

- PM-4 pumping caused measurable declines of the water levels in the regional aquifer during the 2013 aquifer tests at R-42 and R-28 (especially, the water levels observed at R-15). The effects of pumping at PM-4 and other municipal pumping wells on the water levels were successfully accounted for during the R-42 and R-28 aquifer tests using long-term model analyses of the collected water-level data.

- R-42 pumping produced limited drawdown effects; the only well that clearly showed effects was R-43, where responses were measured in both screens

- In contrast, R-28 pumping produced drawdowns at most of the nearby monitoring wells except R-1 and R-36. Responses were observed in R-11, R-13, R-15, R-34, R-35b, R-43 screens 1 and 2, R-44 screens 1 and 2, R-45 screens 1 and 2, R-50 screens 1 and 2, R-61 screens 1 and 2, and R-62.

- R-28 pumping potentially produced drawdowns at R-35b, whereas R-35b minimally responds to pumping from nearby water-supply well PM-3. The minimal response at R-35b to PM-3 pumping likely reflects pronounced local hydraulic separation between the deep sections of the aquifer that are pumped by PM-3 and zones monitored by other nearby monitoring wells including R-35a.

- During the R-28 aquifer test, R-42 and R-43 screens 1 and 2 produced anomalously low drawdowns compared with other nearby monitoring wells (e.g., R-62). This observation may be an indication of either a low-permeability zone around R-43/R-42, or a flow barrier between R-28 and R-42, or a recharge (infiltration) zone, or any combination of these.

- The drawdown curves observed during R-28 aquifer test at the monitoring wells surrounding R-28 show drawdown stabilization towards the end of the aquifer test. This drawdown stabilization can be caused by various factors. These include (1) delayed yield from the vadose zone (phreatic aquifer effects), (2) leakage for the deeper hydrostratigraphic units (leaky aquifer), (3) lateral boundary effects (high-permeability zones), and (4) infiltration recharge from the vadose zone.

- The 2013 R-28 aquifer test data demonstrate a greater degree of heterogeneity than indicated by the data collected during the 10-d aquifer test of R-28 conducted in 2012. The heterogeneity is demonstrated by pronounced deviations of the drawdowns at individual monitoring wells from the uniform theoretical curve (Figure B-34).

- The observed aquifer heterogeneity will be important for determining the efficiency of remediation strategies than include aquifer pumping for source removal and plume control. Aquifer heterogeneity will affect the width and length (upgradient and downgradient) of the capture zones associated with the pumping wells. For example, aquifer heterogeneity can have a beneficial effect by reducing the number of pumping wells needed to establish a CZ if pumping occurs in an elongated highly transmissive aquifer zone oriented perpendicular to the groundwater flow direction.

- The 2013 R-28 aquifer test data suggest lower effective large-scale aquifer transmissivity than the 2012 R-28 aquifer test data. The effective large-scale transmissivity (T) of the regional aquifer might be about T = 30,000 gpd/ft (transmissivity was estimated about 40,500 gpd/ft based on the 2012 test data); however, given the existing uncertainties, it is possible the large-scale transmissivity might be even lower. The analyses are complicated because of the pronounced aquifer heterogeneity suggested by the 2013 aquifer test data.

- The SCI-2 pumping did not produce drawdowns in the perched intermediate zone; no drawdowns were detected at MCOI-5 and MCOI-6. The estimated transmissivity based on the SCI-2 aquifer test data is 20 m^2/d or 1600 gpd/ft.

- None of the pumping from any of the wells in this study caused drawdowns in the municipal water-supply wells.

- Pumping at the water-supply wells affects the pressures observed in the monitoring wells in the Chromium Investigation monitoring group. However, the pressure responses from the water-supply well pumping may not influence the flow direction in the shallow portion of the regional aquifer within the area of the chromium plume. The pumping influence from the water-supply wells was observed to be relatively uniform in the shallow portion of the regional aquifer.

B-4.0 REFERENCES

The following list includes all documents cited in this appendix. Parenthetical information following each reference provides the author(s), publication date, and ER ID. This information is also included in text citations. ER IDs are assigned by the Environmental Programs Directorate's Records Processing Facility (RPF) and are used to locate the document at the RPF and, where applicable, in the master reference set.

Copies of the master reference set are maintained at the New Mexico Environment Department Hazardous Waste Bureau and the Directorate. The set was developed to ensure that the administrative authority has all material needed to review this document, and it is updated with every document submitted to the administrative authority. Documents previously submitted to the administrative authority are not included.

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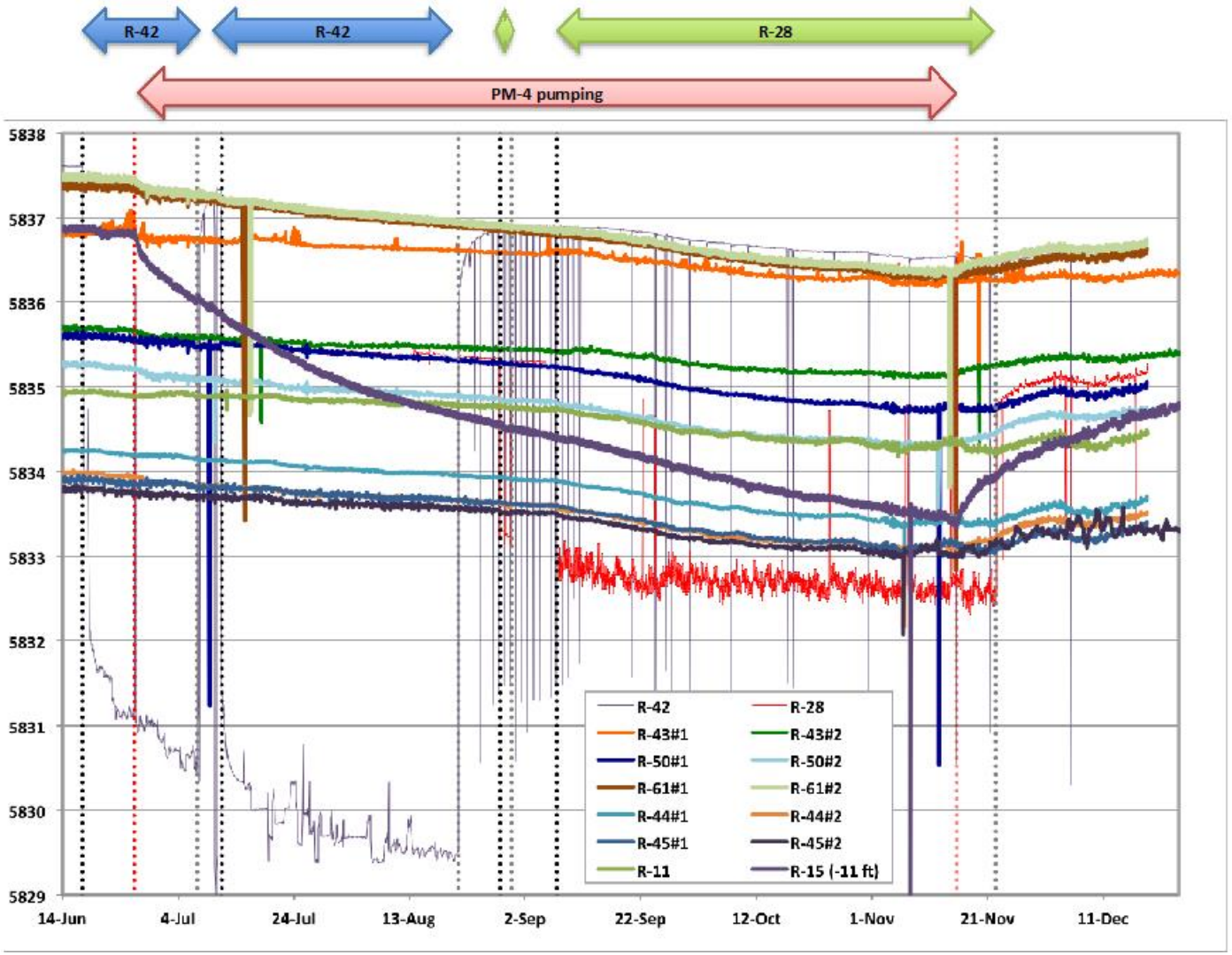


Figure B-1 **Water levels at the various monitoring wells near R-42 and R-28 during the 2013 aquifer tests. (The R-15 data have been adjusted to fit the plot.)**

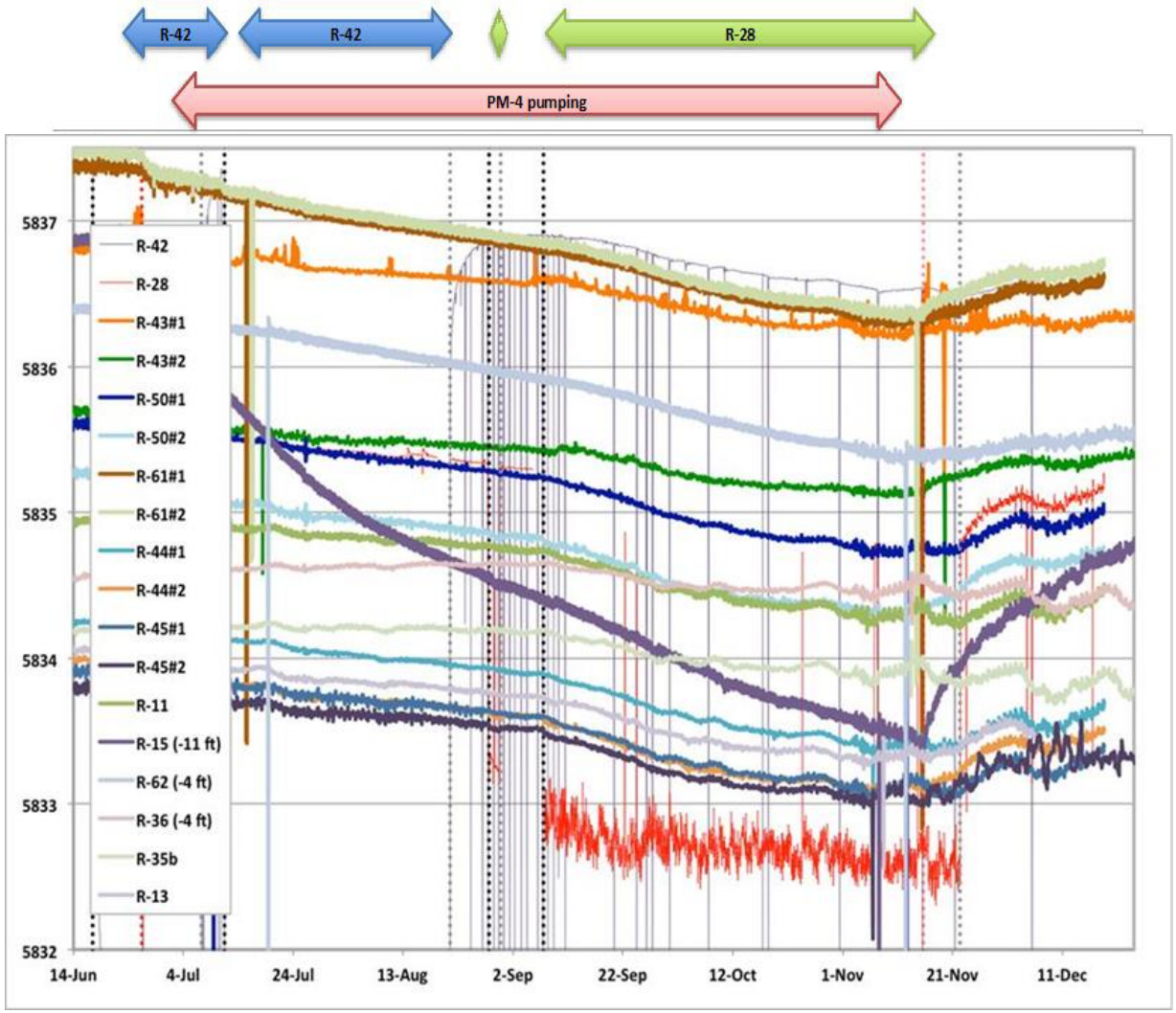


Figure B-2 **Water levels at the various monitoring wells near R-42 and R-28 during the 2013 aquifer tests (The R-15, R-62, and R-36 data have been adjusted to fit the plot.)**

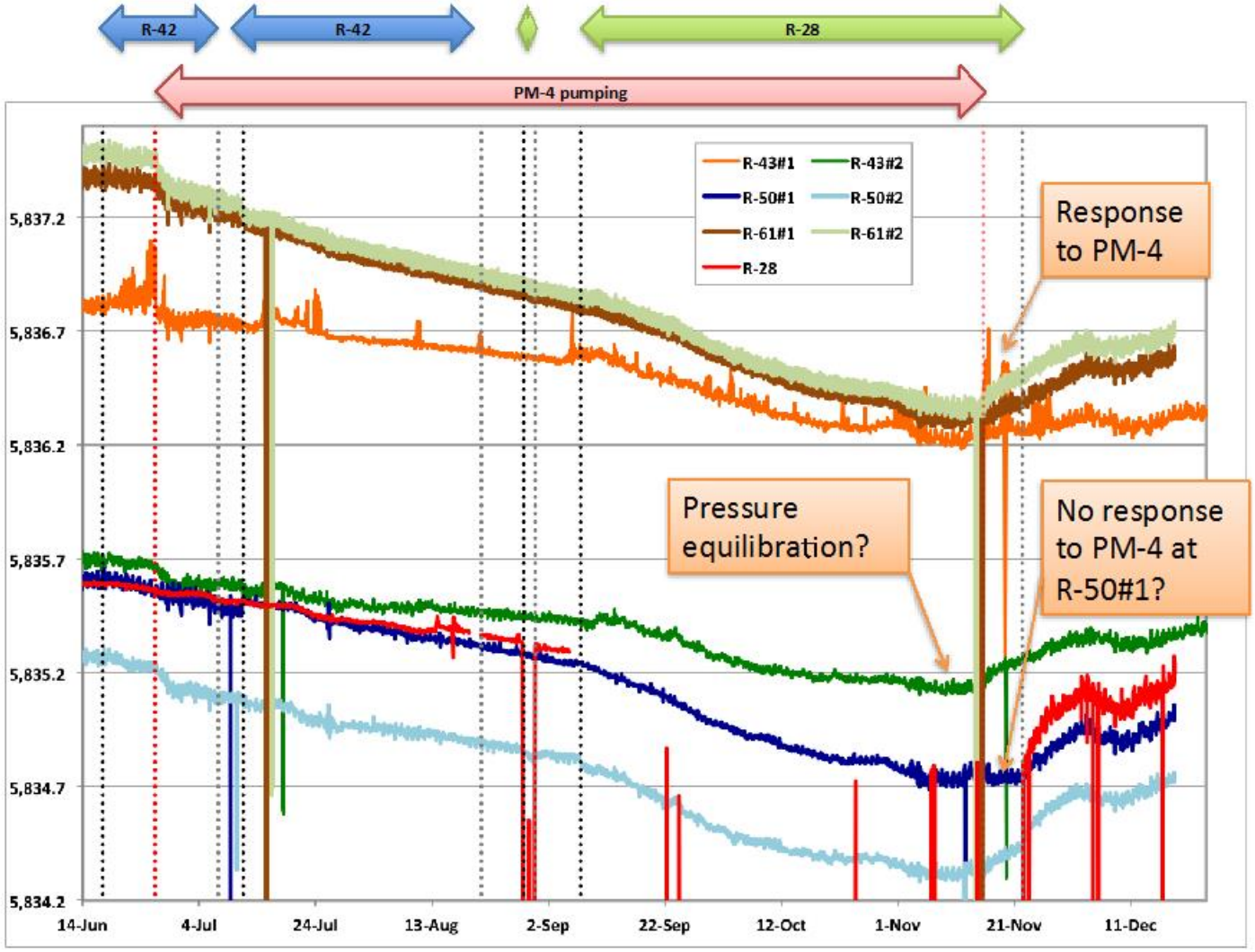


Figure B-3 **Water levels at R-43 screens 1, 2; R-50 screens 1, 2; R-61 screens 1, 2; and R-28 during the 2013 aquifer tests at R-42 and R-28**

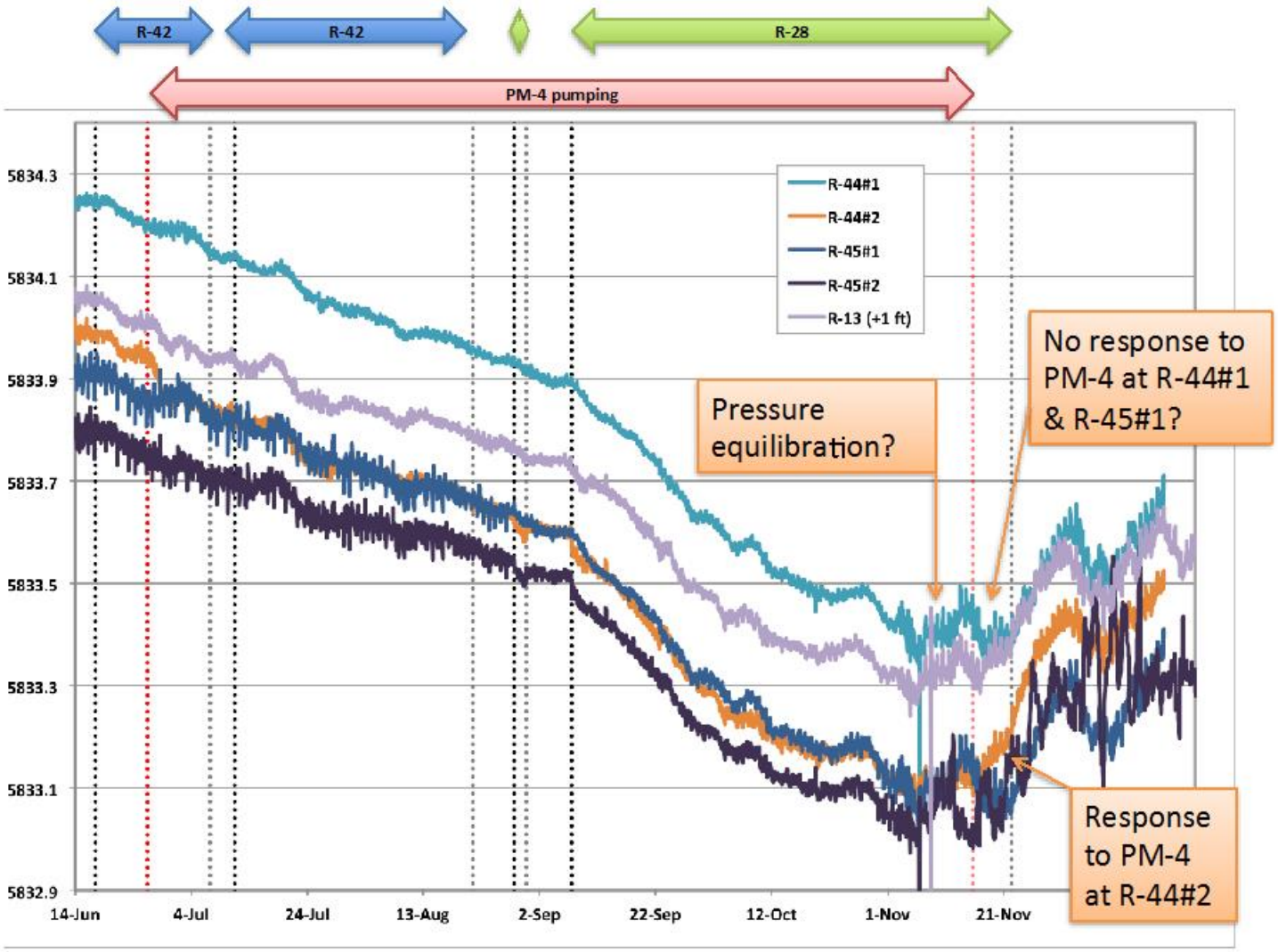


Figure B-4 **Water levels at R-44 screens 1, 2; R-45 screens 1, 2; and R-13 (adjusted) during the 2013 aquifer tests at R-42 and R-28**

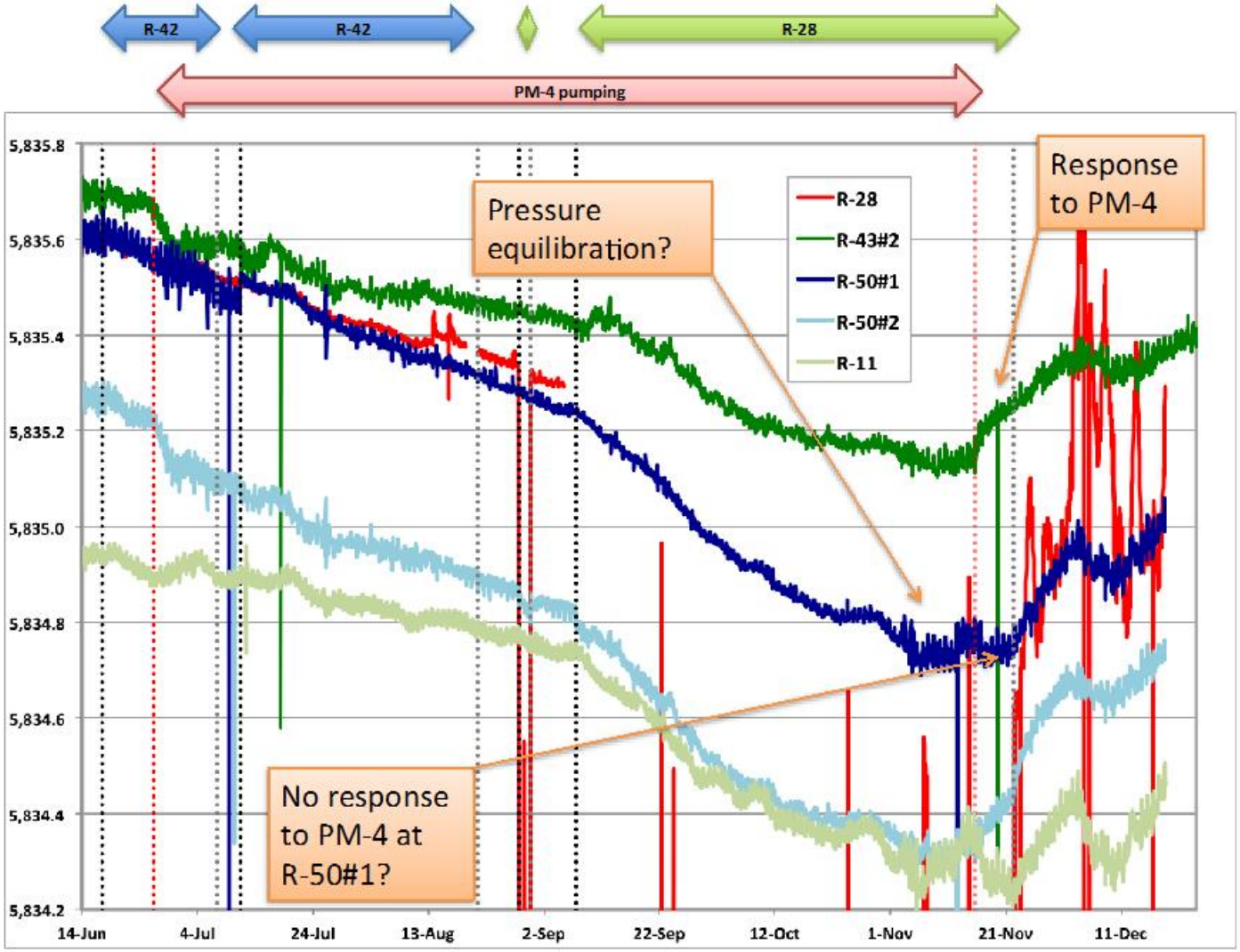


Figure B-5 **Water levels at R-28; R-43 screen 2; R-50 screens 1, 2; and R-11 during the 2013 aquifer tests at R-42 and R-28**

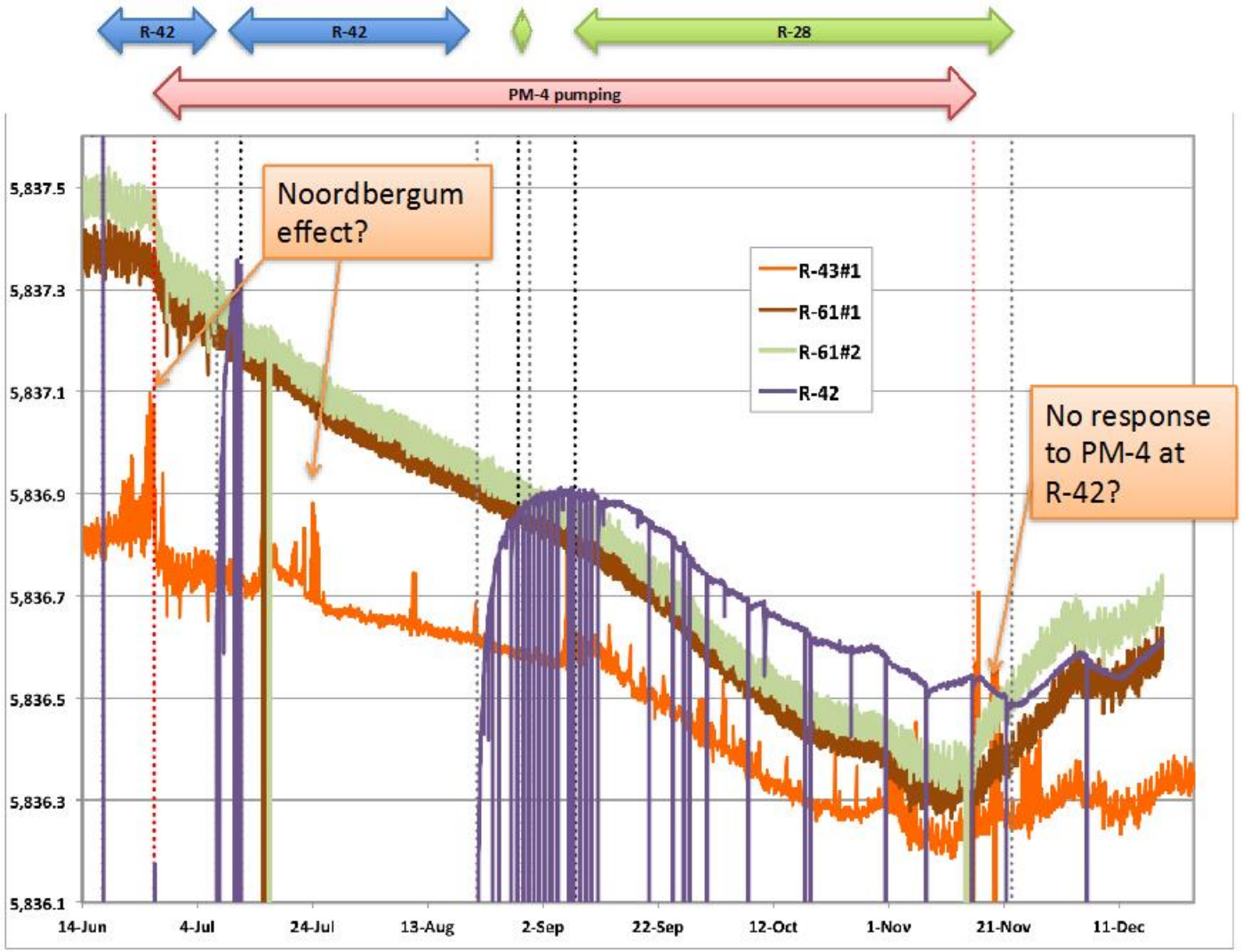


Figure B-6 **Water levels at R-43 screen 1; R-61 screen 1, 2; and R-42 during the 2013 aquifer tests at R-42 and R-28**

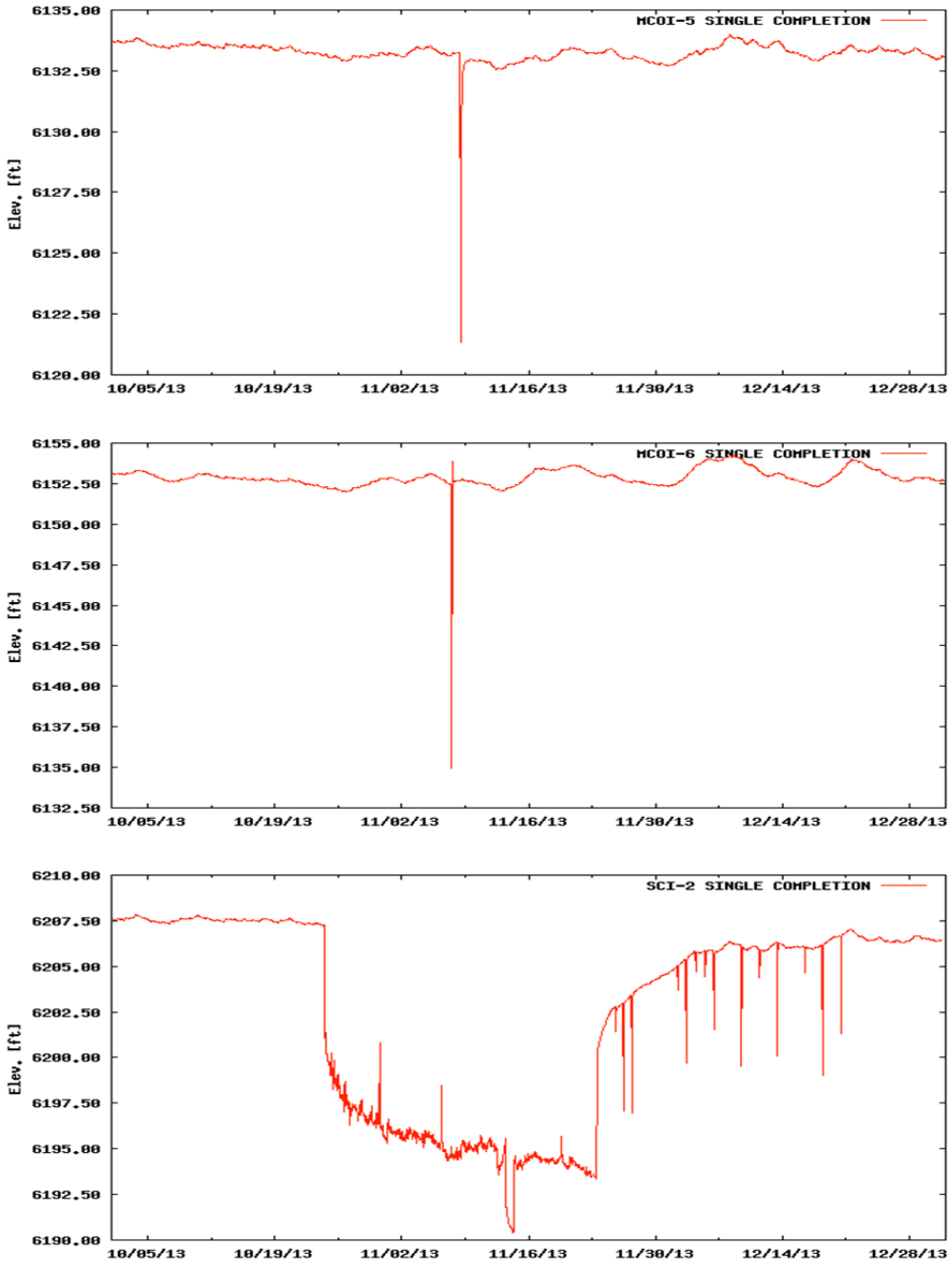


Figure B-7 **Water levels at MCOI-5, MOCI-6, and SCI-2 during the 2013 pumping test at SCI-2**

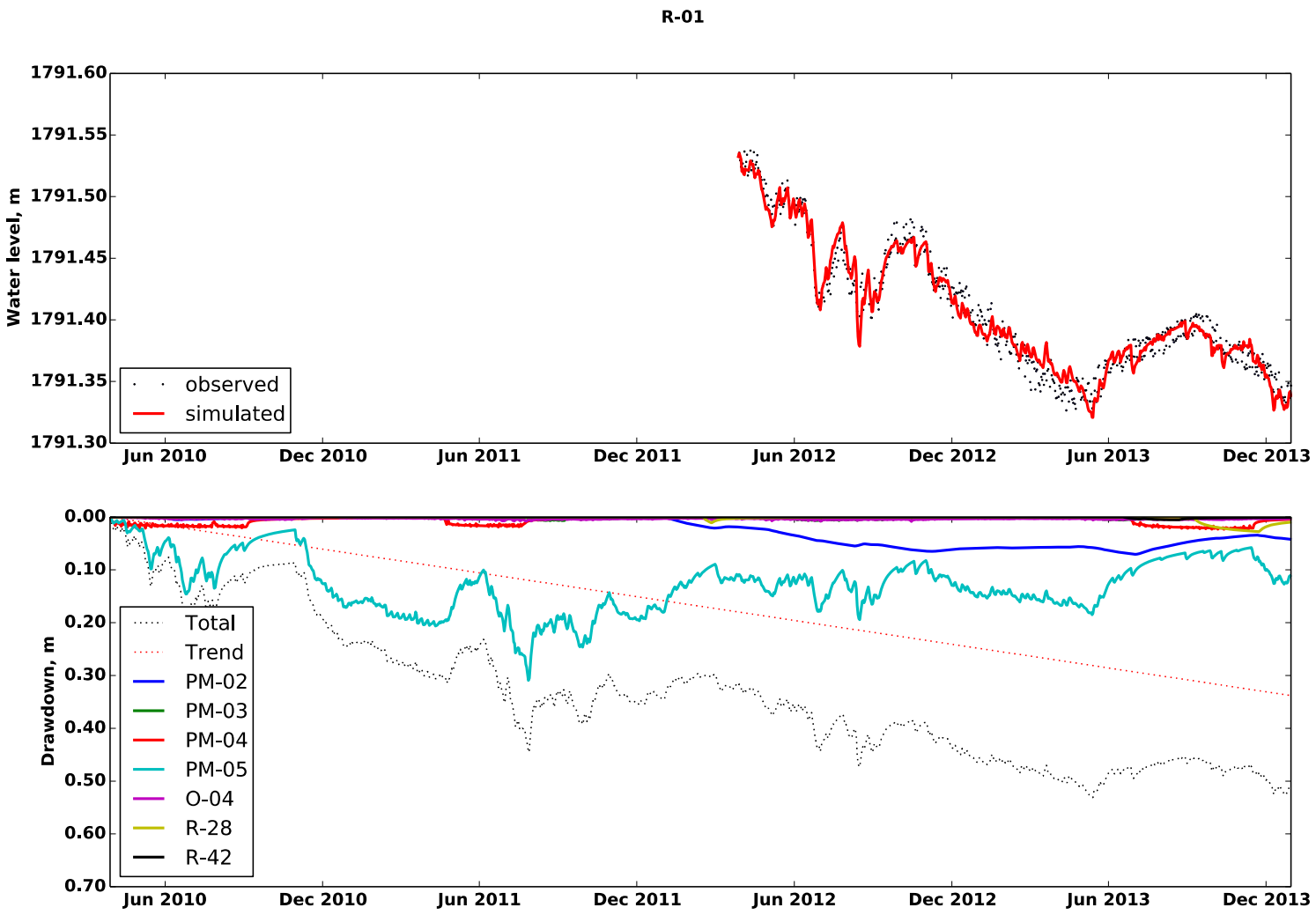


Figure B-8 **Deconstruction of R-1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

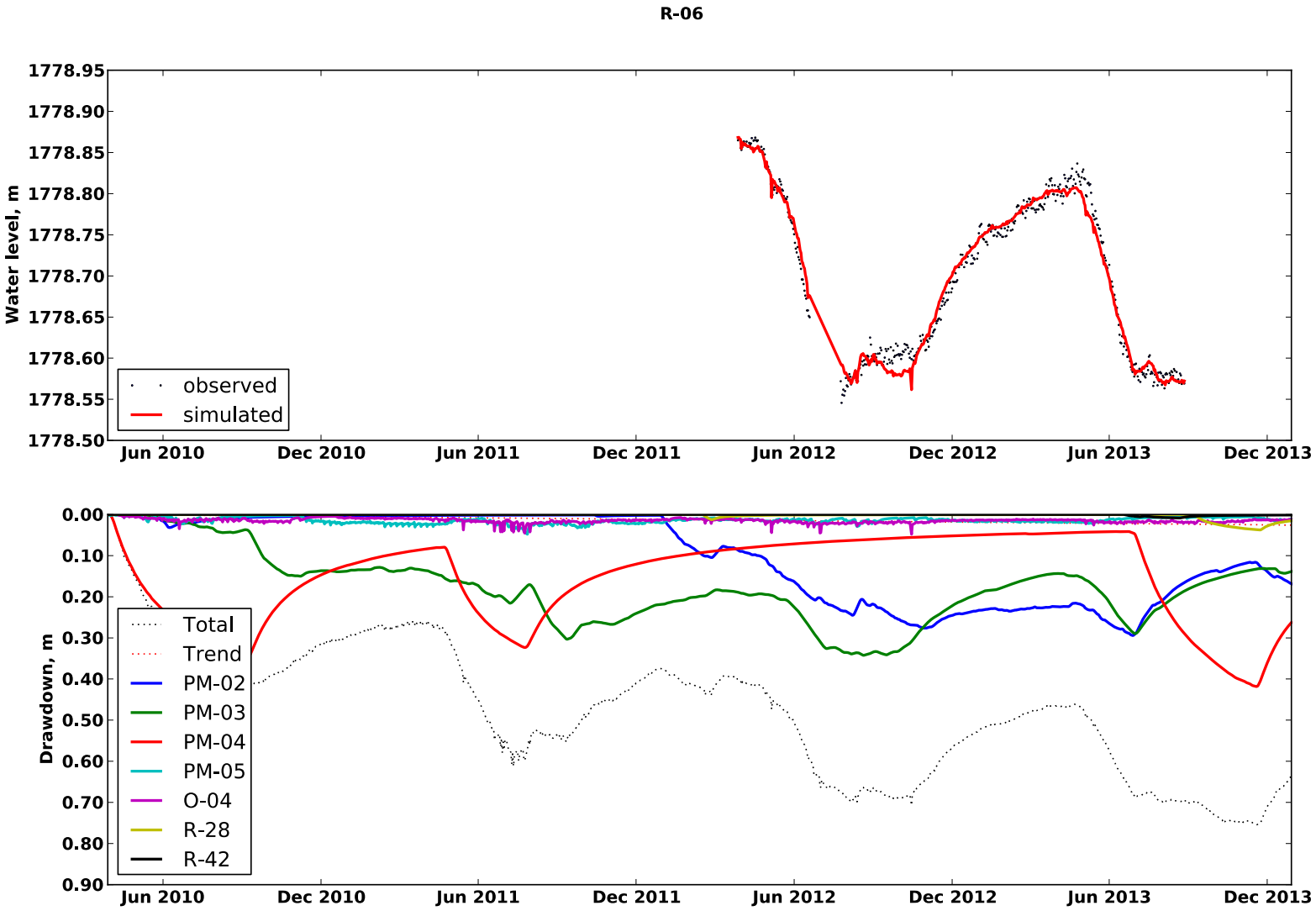


Figure B-9 **Deconstruction of R-6 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

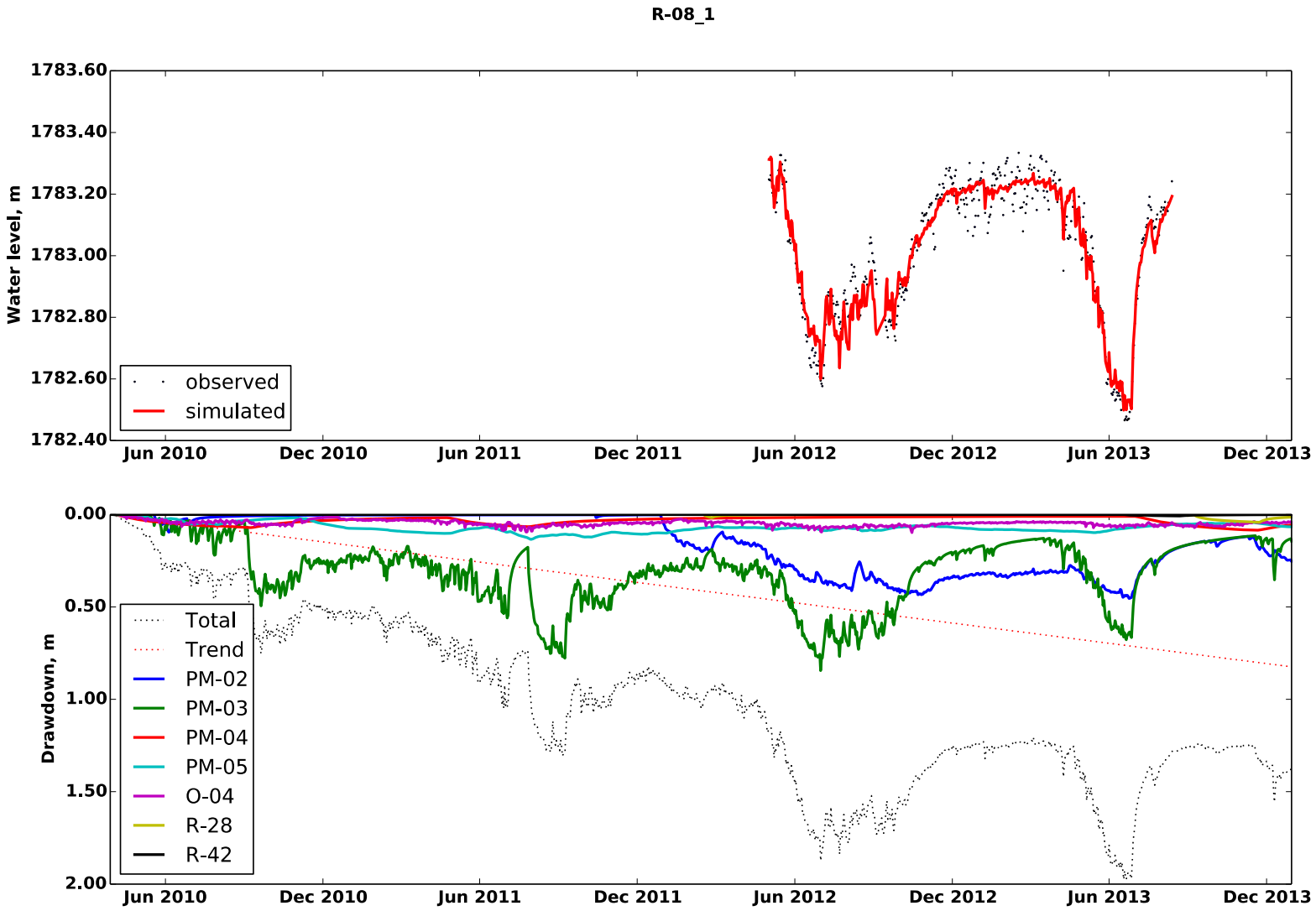


Figure B-10 **Deconstruction of R-8 screen 1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

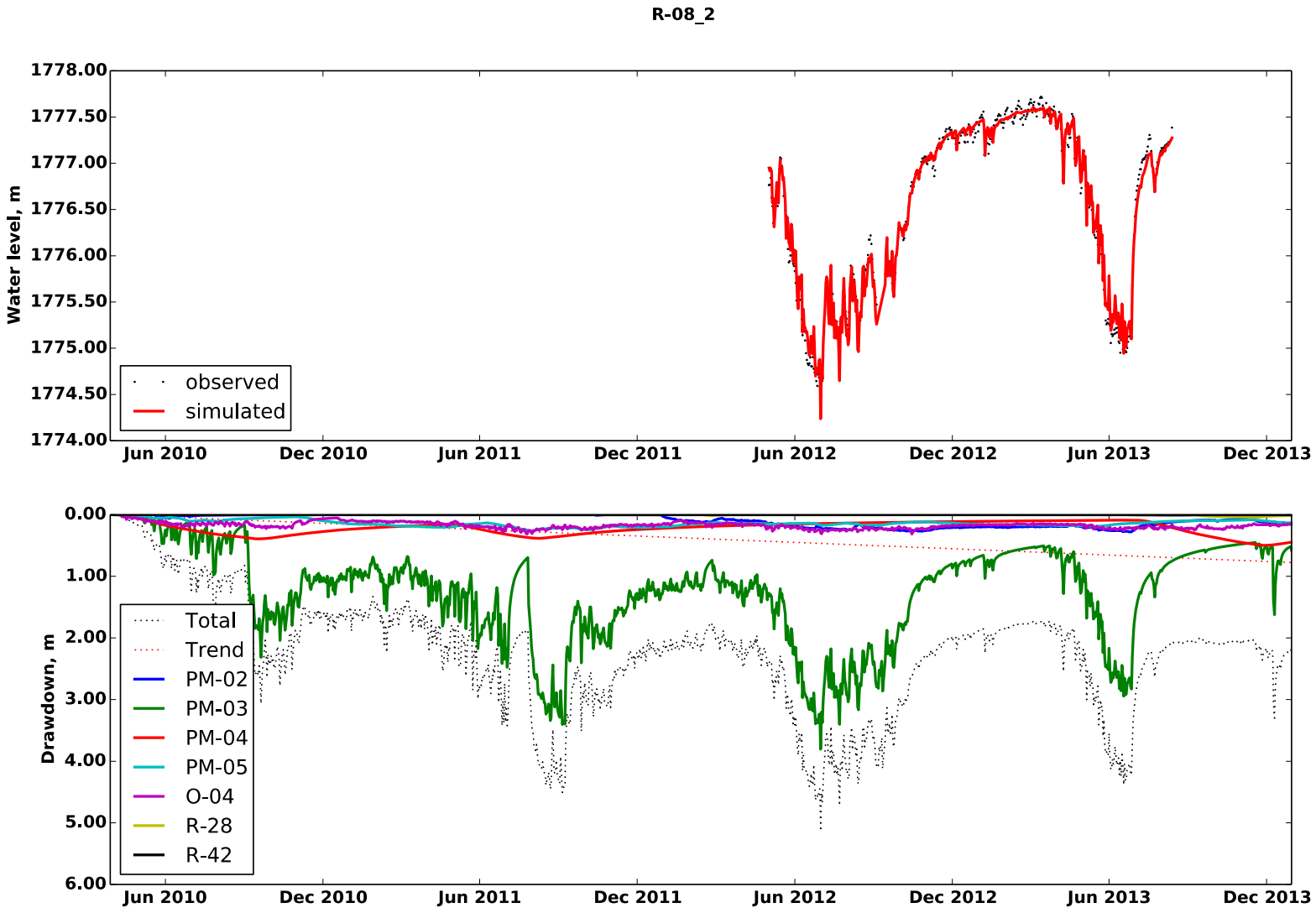


Figure B-11 **Deconstruction of R-8 screen 2 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

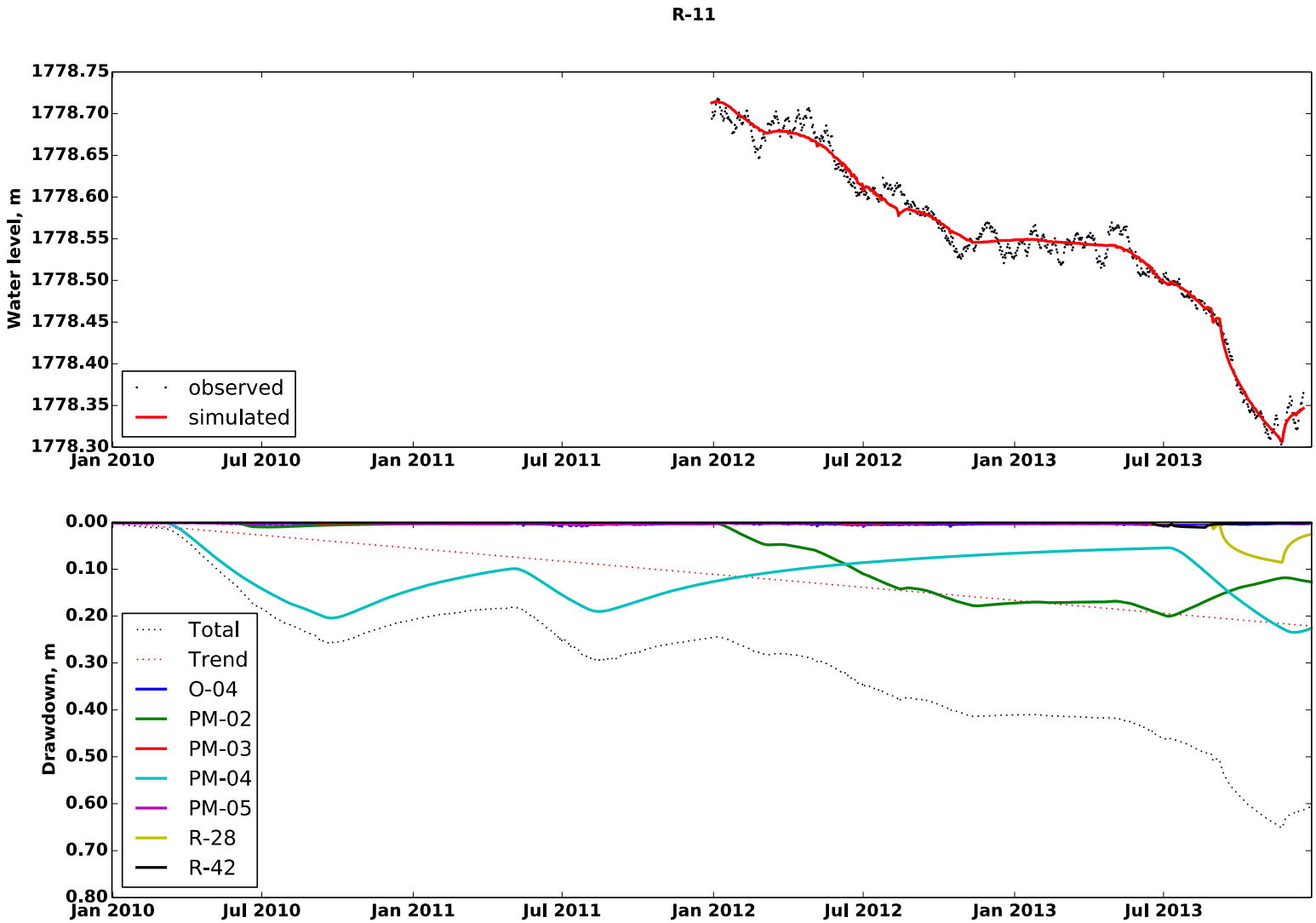


Figure B-12 **Deconstruction of R-11 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

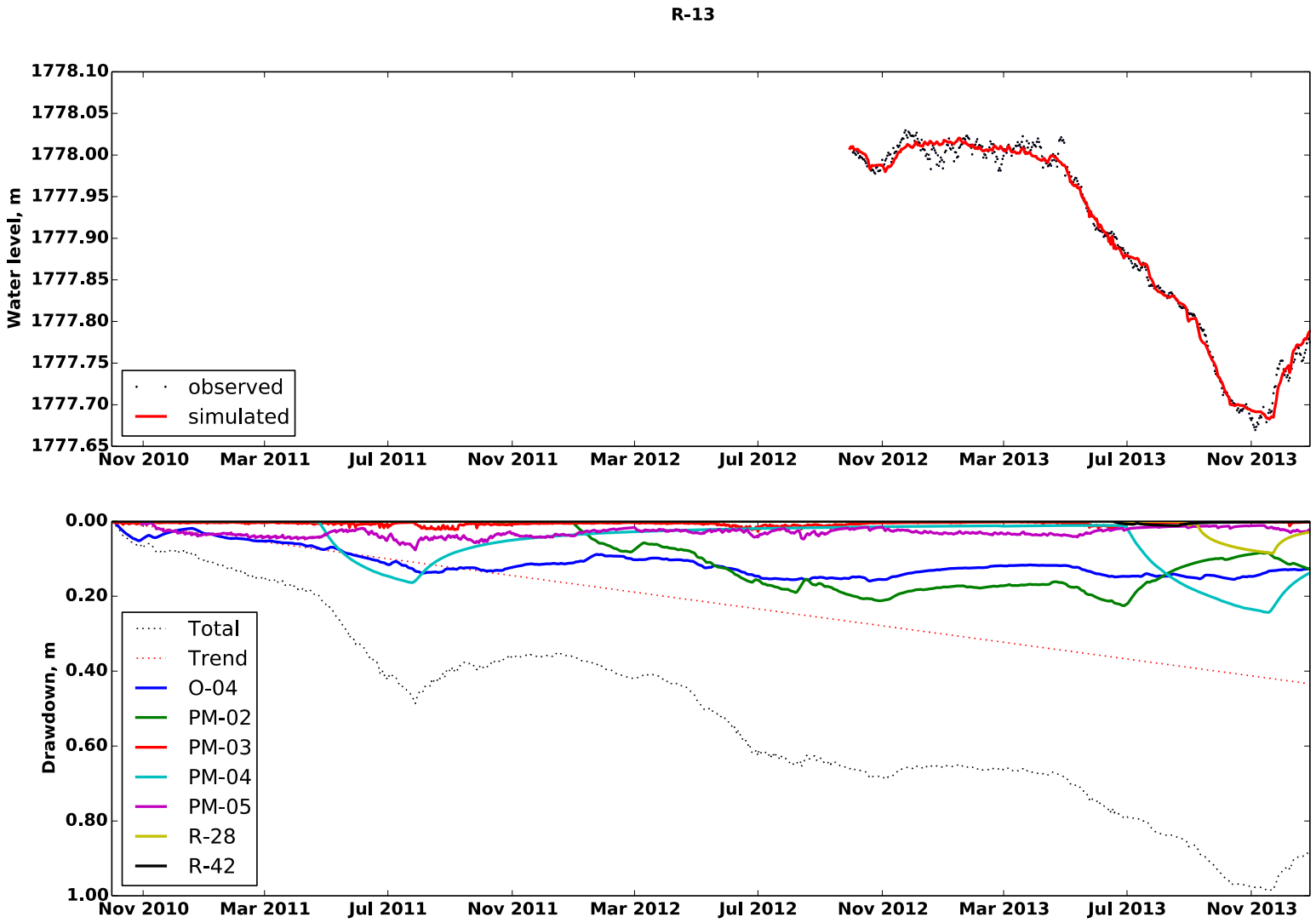


Figure B-13 **Deconstruction of R-13 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

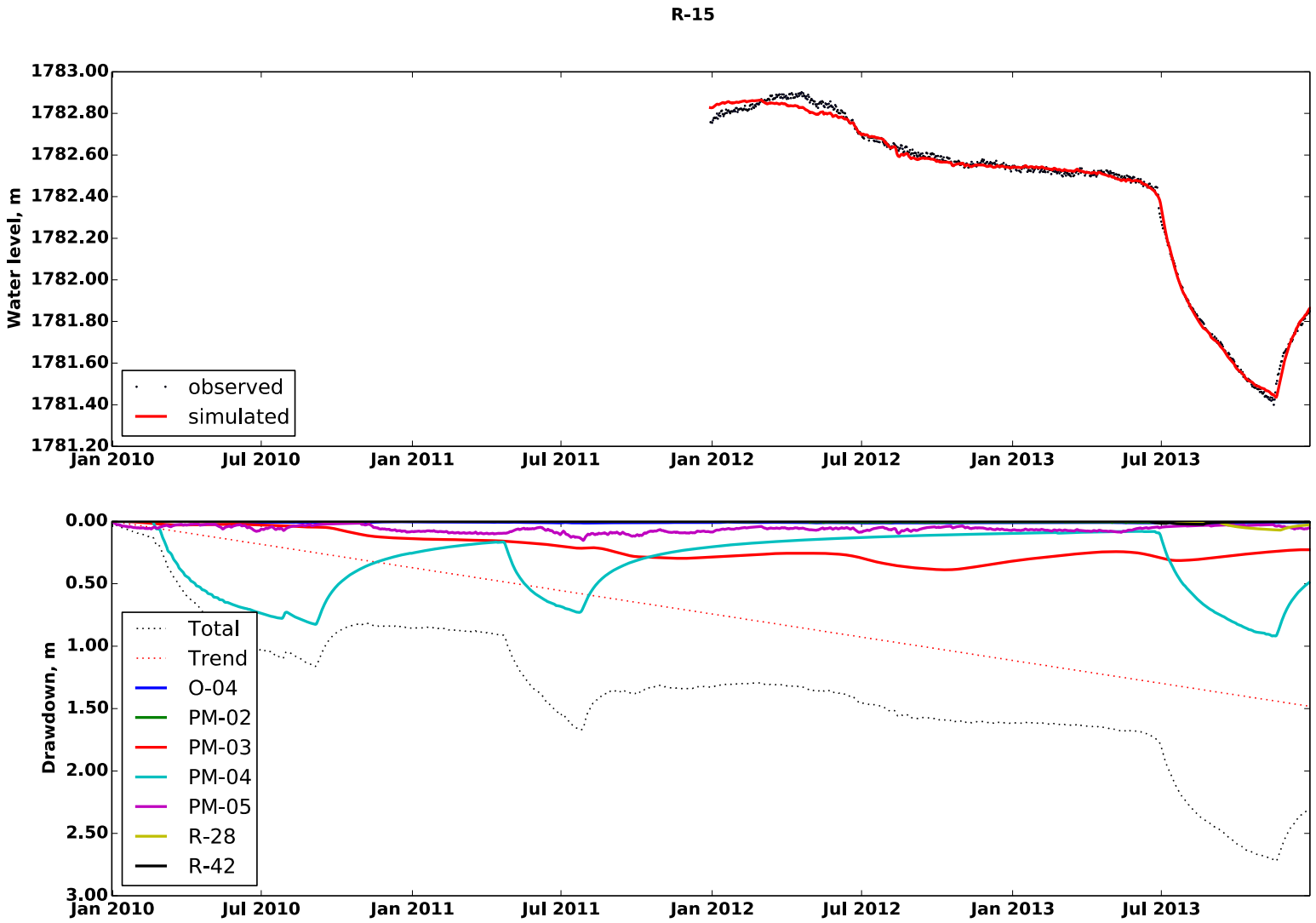


Figure B-14 **Deconstruction of R-15 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

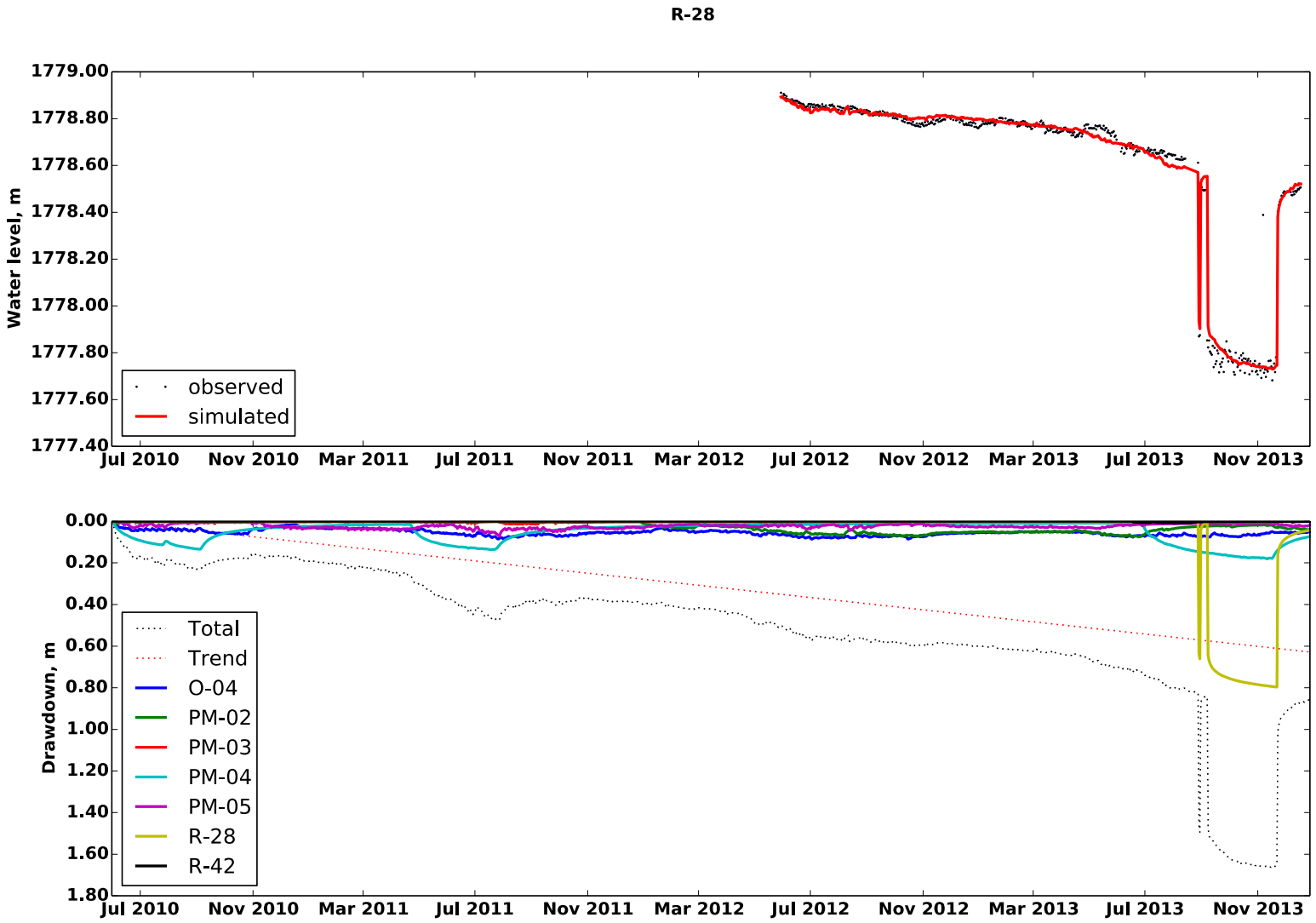


Figure B-15 **Deconstruction of R-28 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

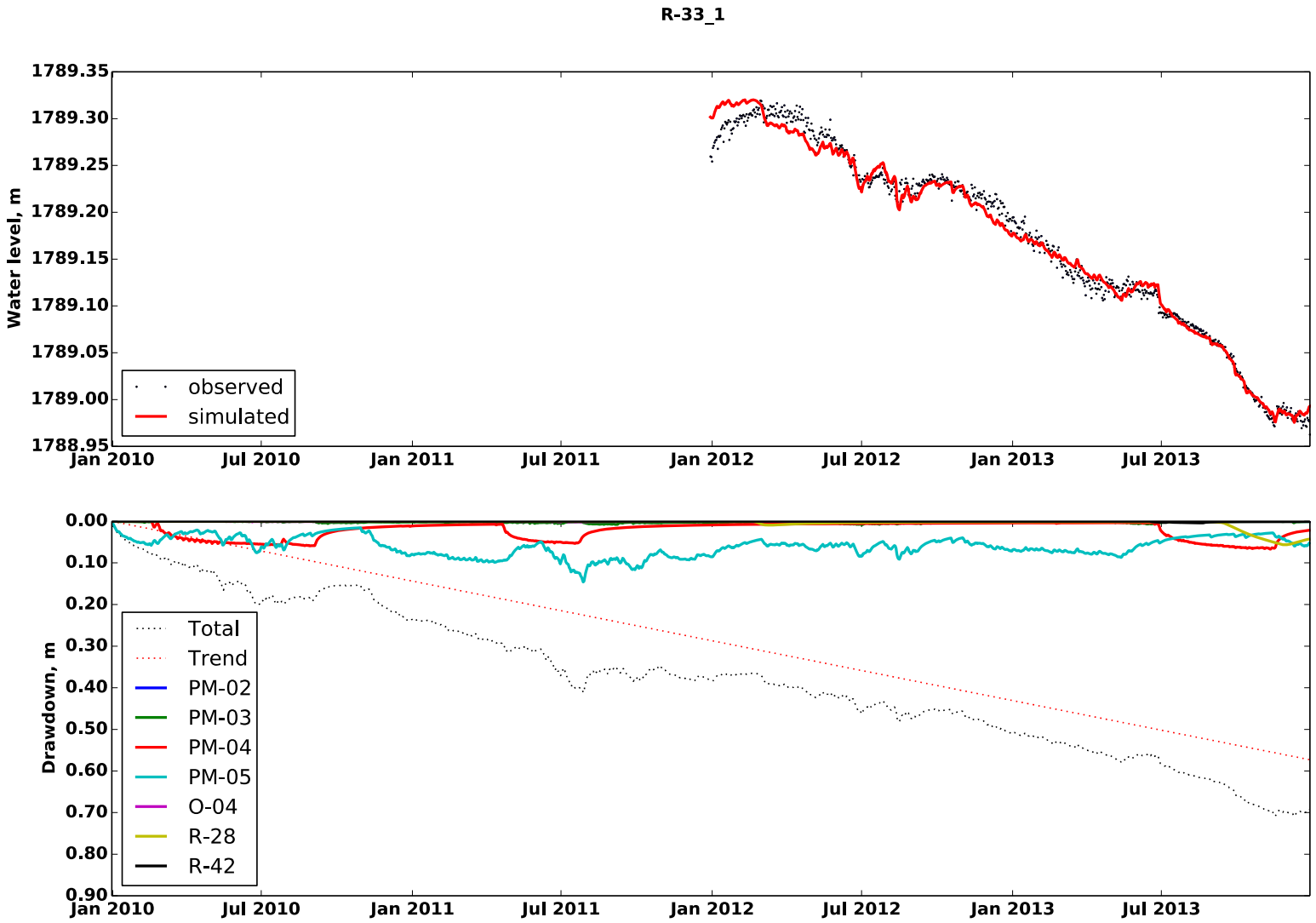


Figure B-16 **Deconstruction of R-33 screen 1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

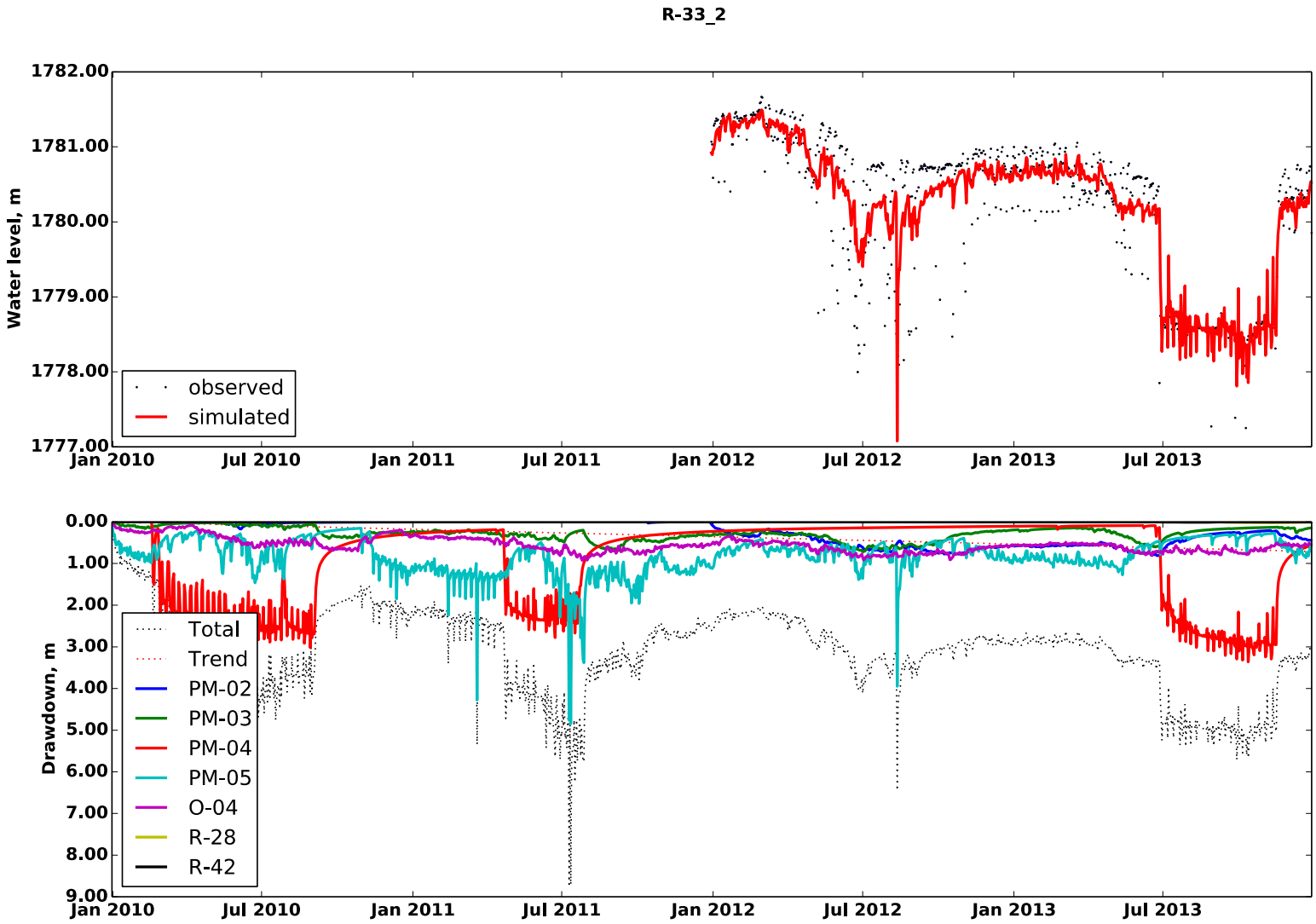


Figure B-17 **Deconstruction of R-33 screen 2 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

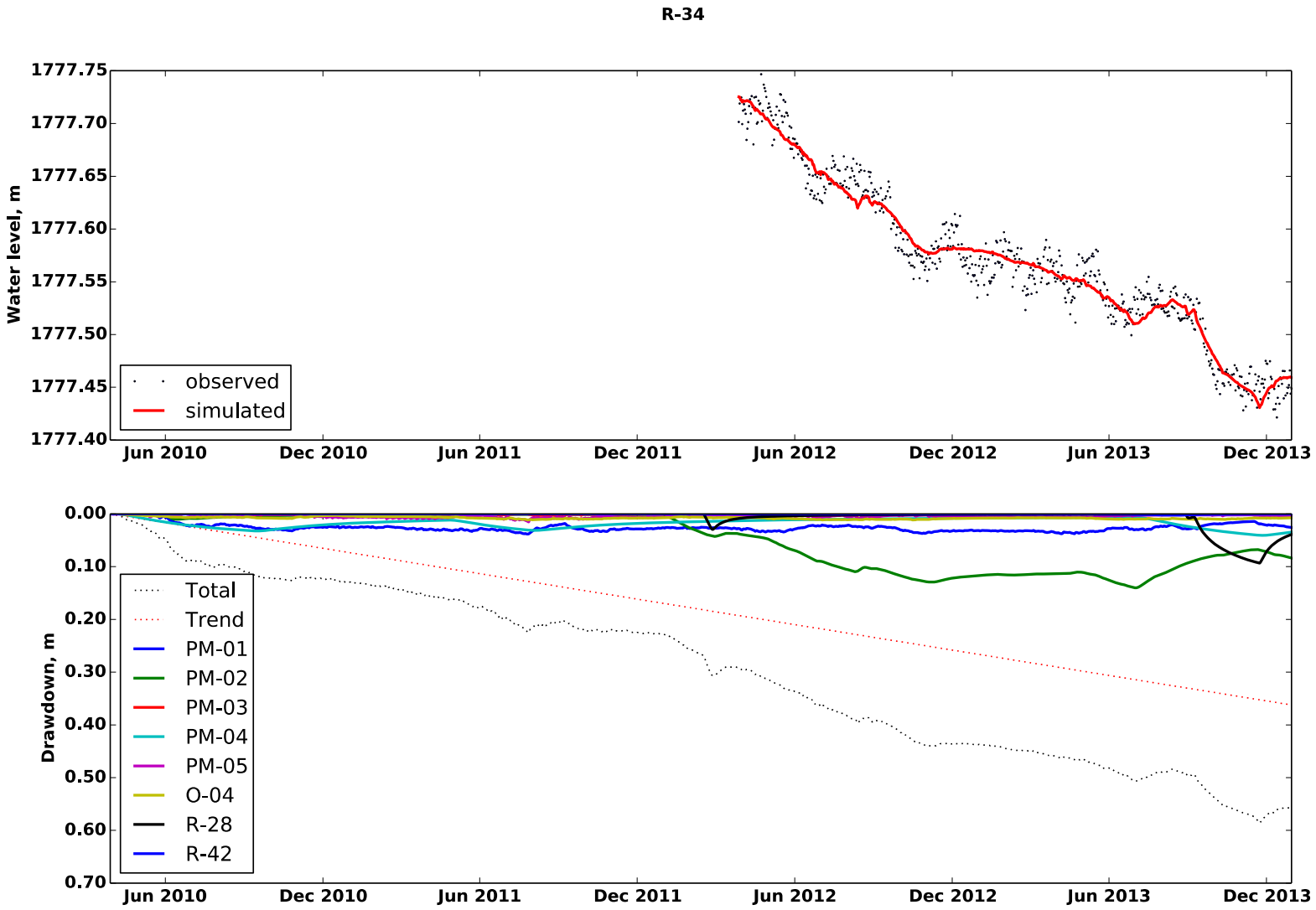


Figure B-18 **Deconstruction of R-34 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

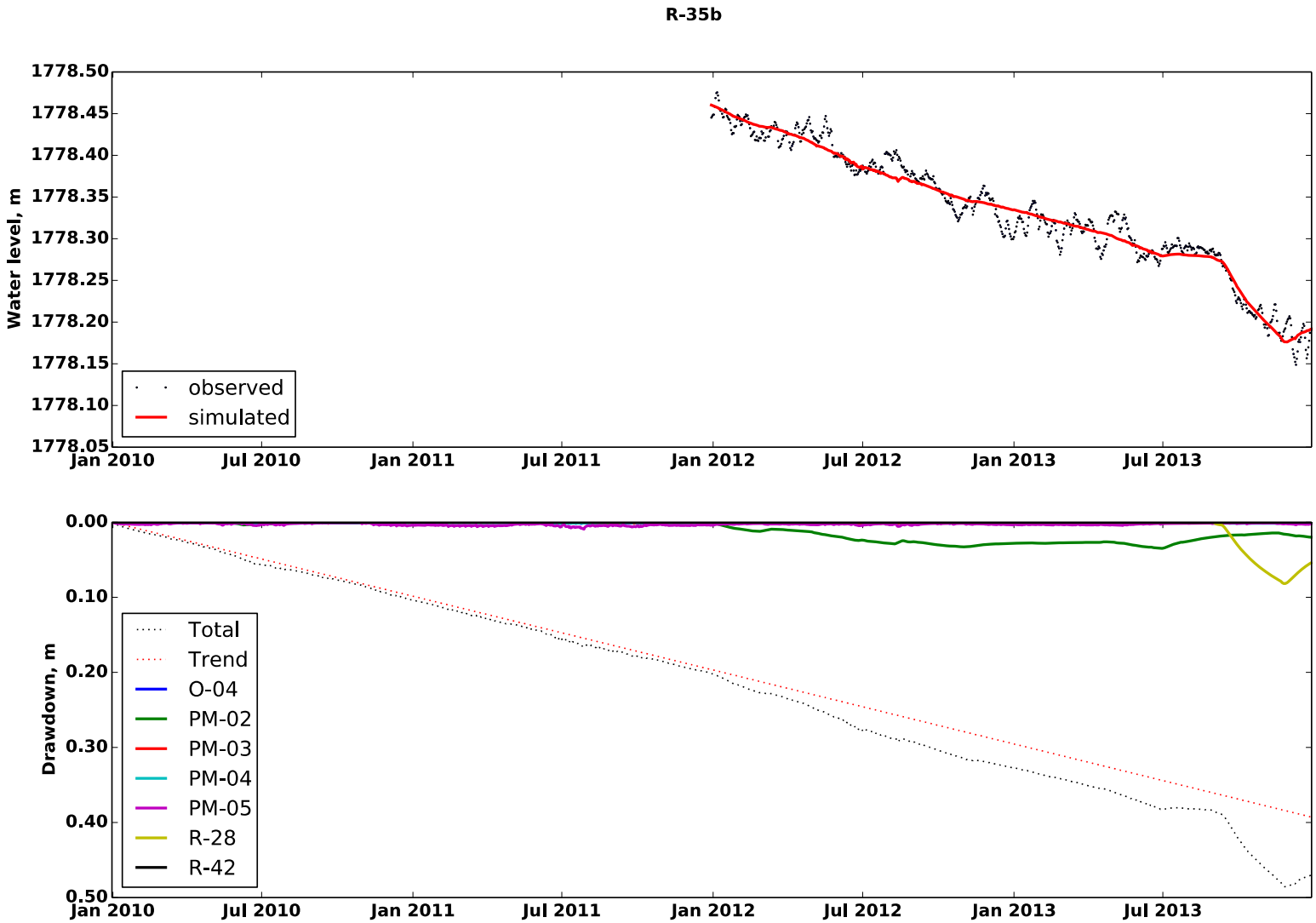


Figure B-19 **Deconstruction of R-35b water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

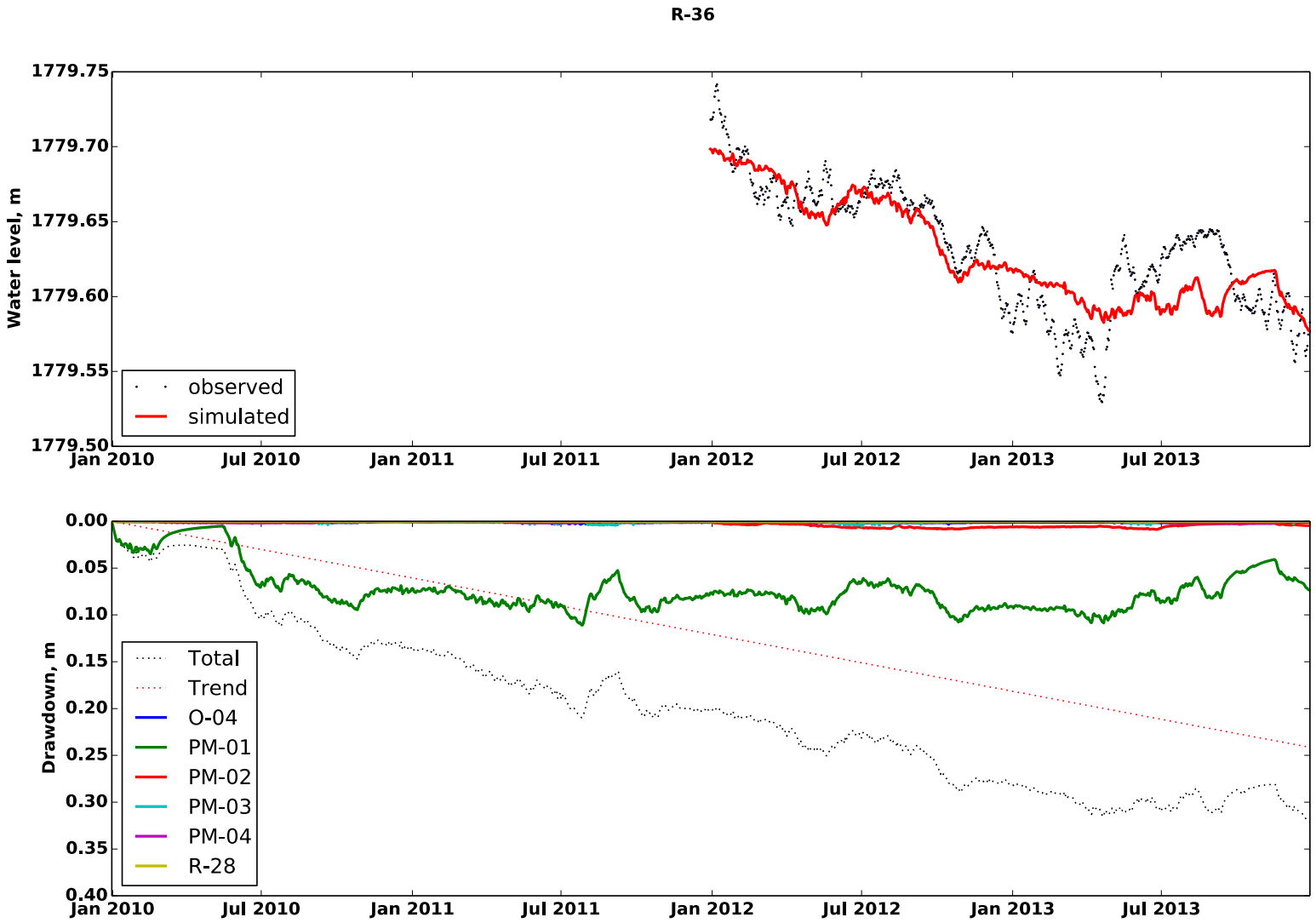


Figure B-20 **Deconstruction of R-36 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

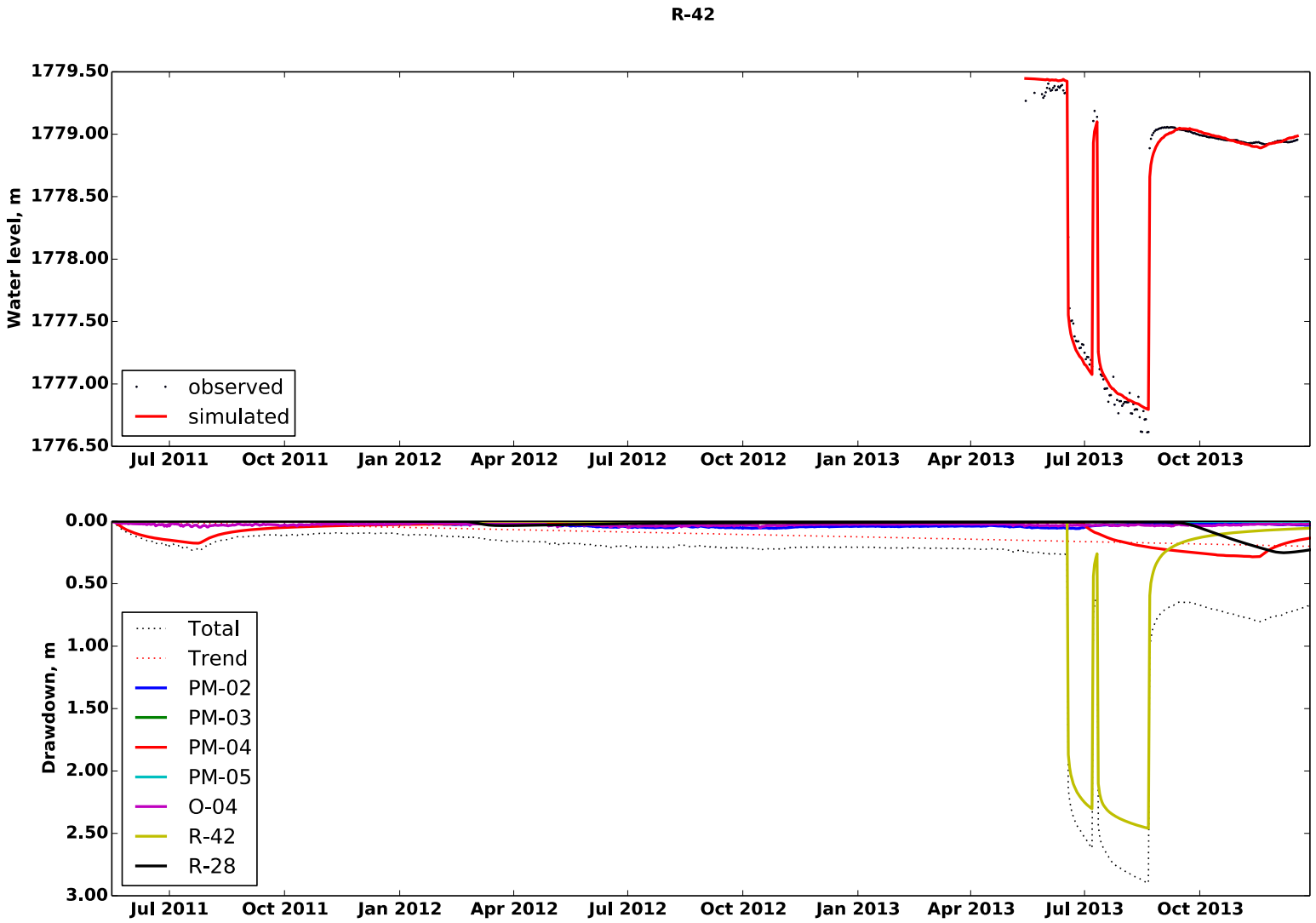


Figure B-21 **Deconstruction of R-42 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

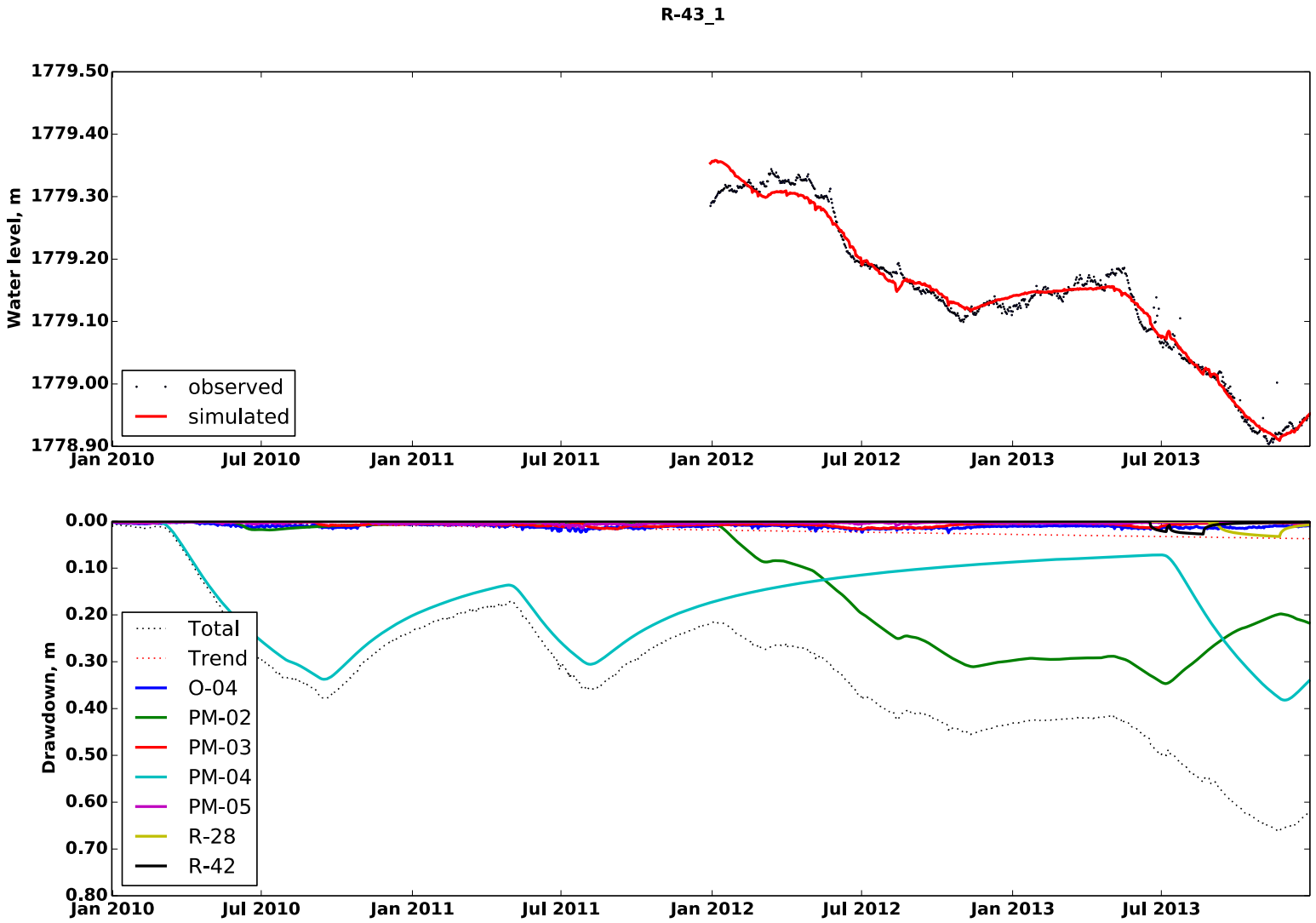


Figure B-22 **Deconstruction of R-43 screen 1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

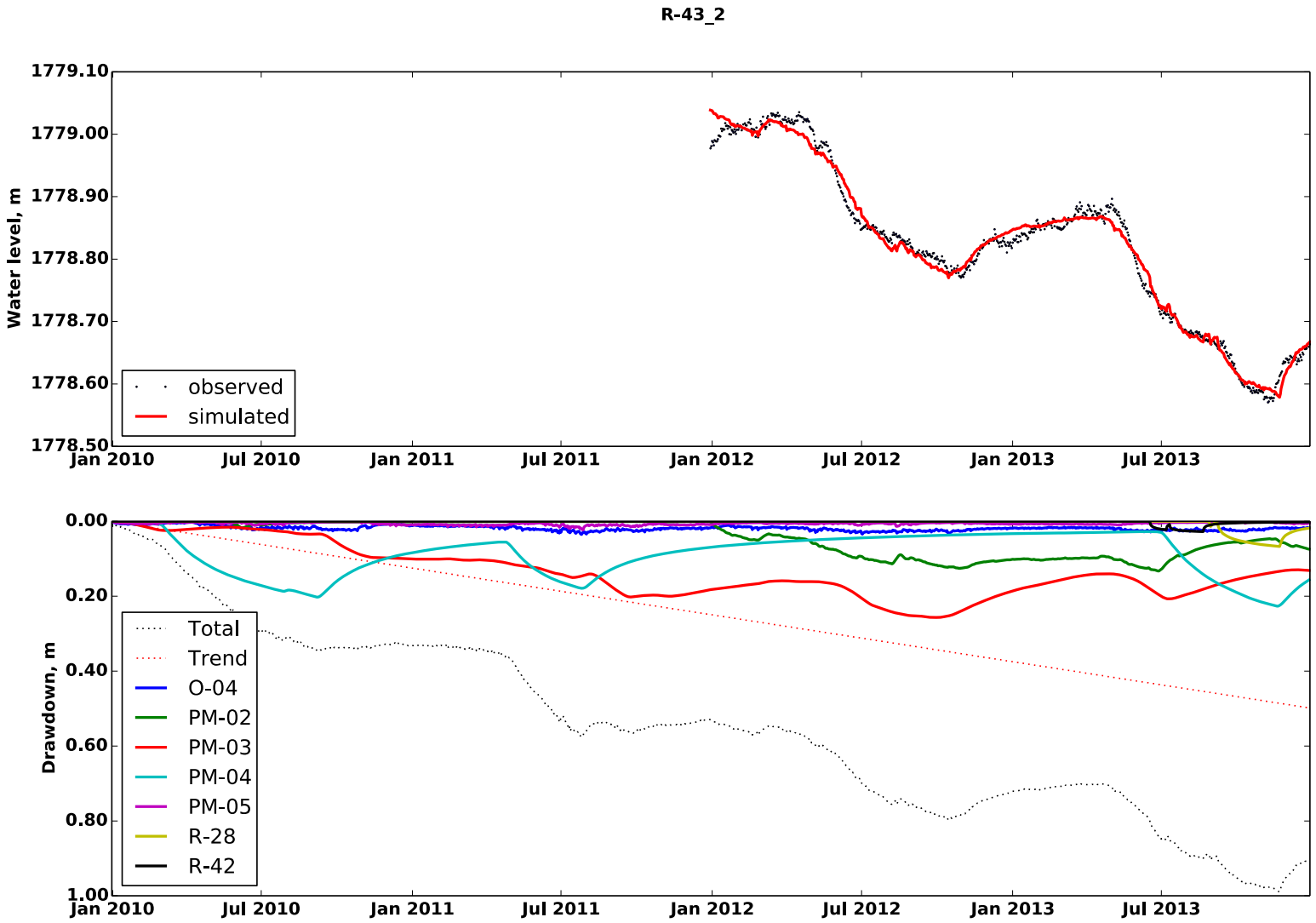


Figure B-23 **Deconstruction of R-43 screen 2 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

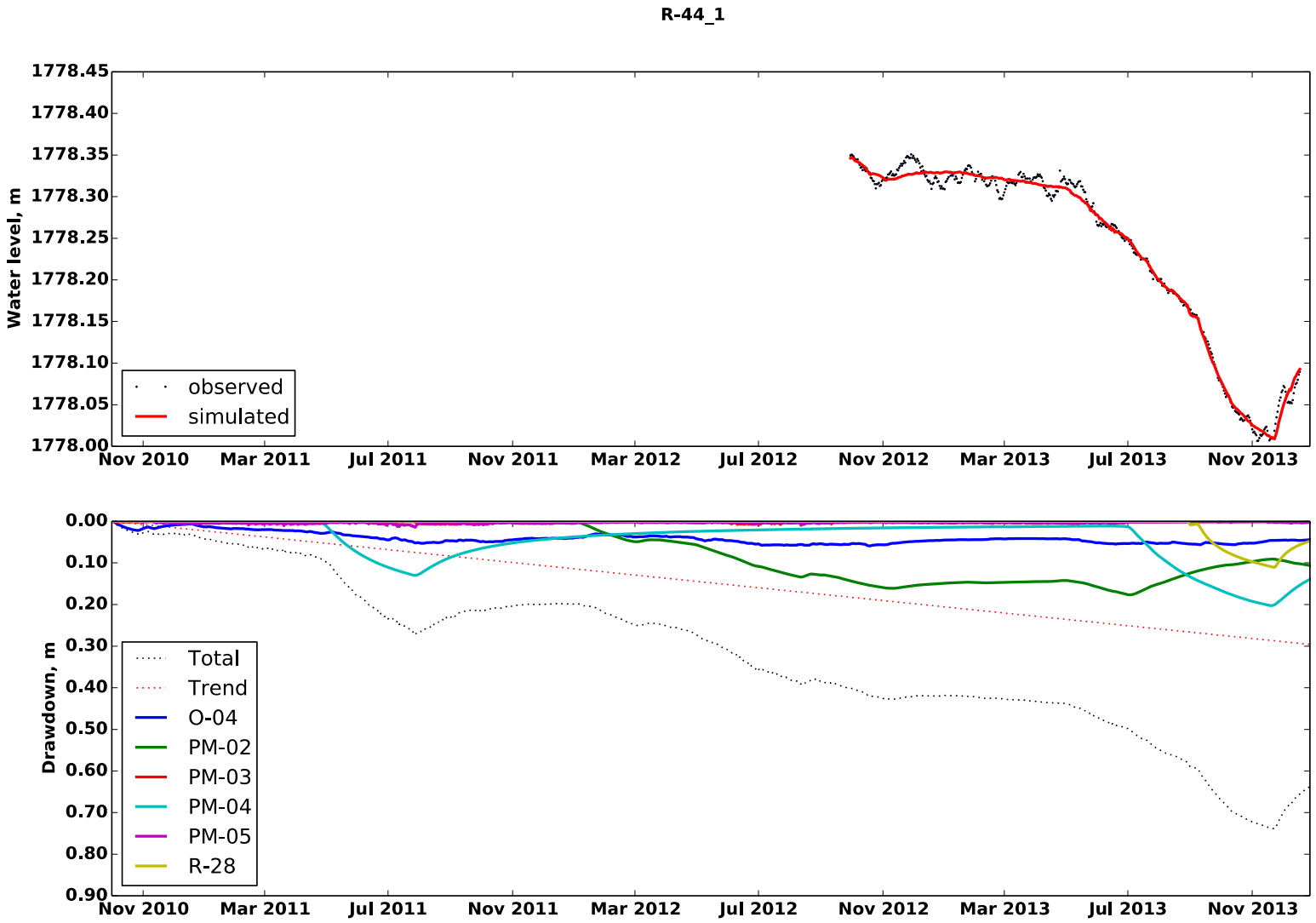


Figure B-24 **Deconstruction of R-44 screen 1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

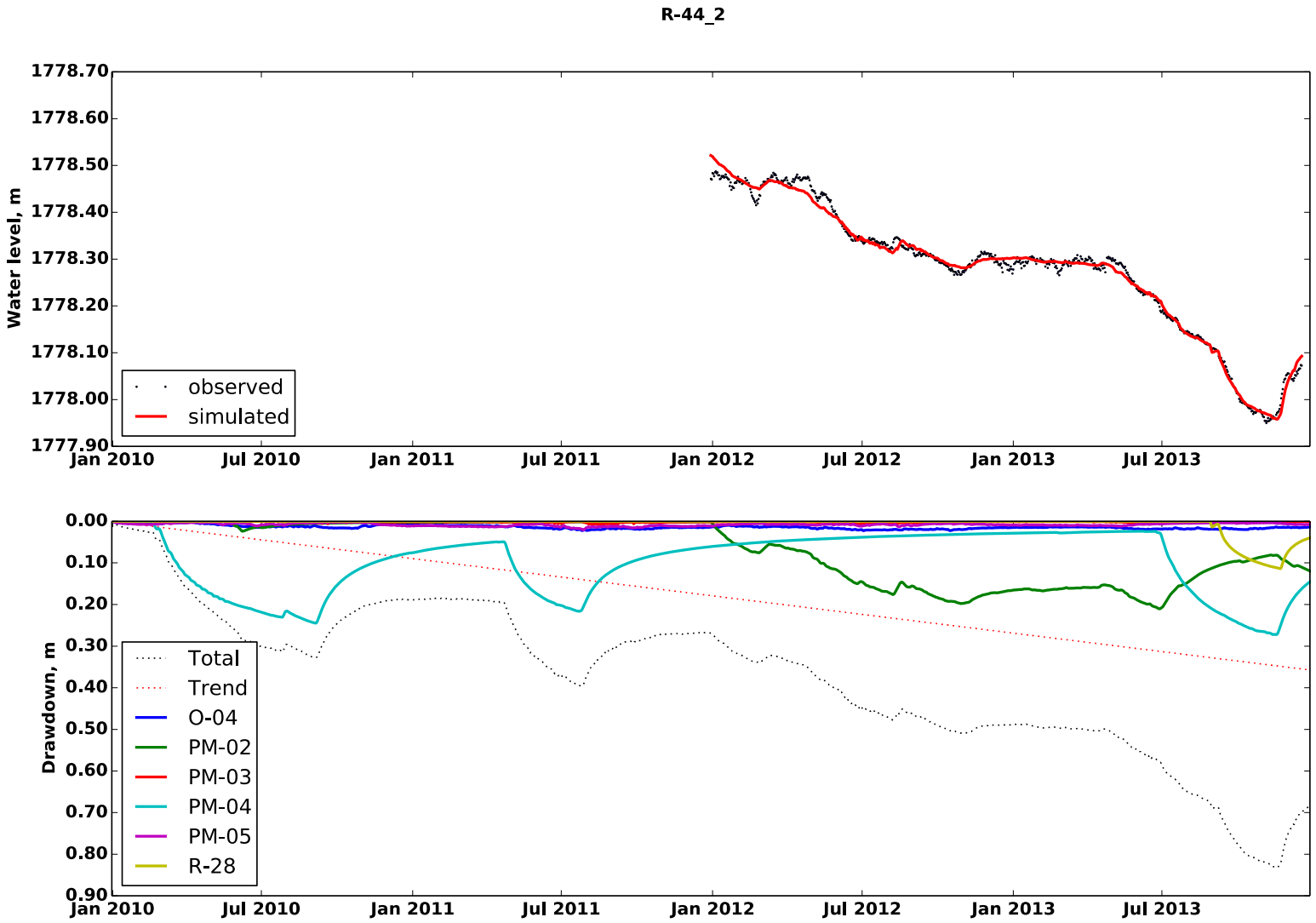


Figure B-25 **Deconstruction of R-44 #2 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

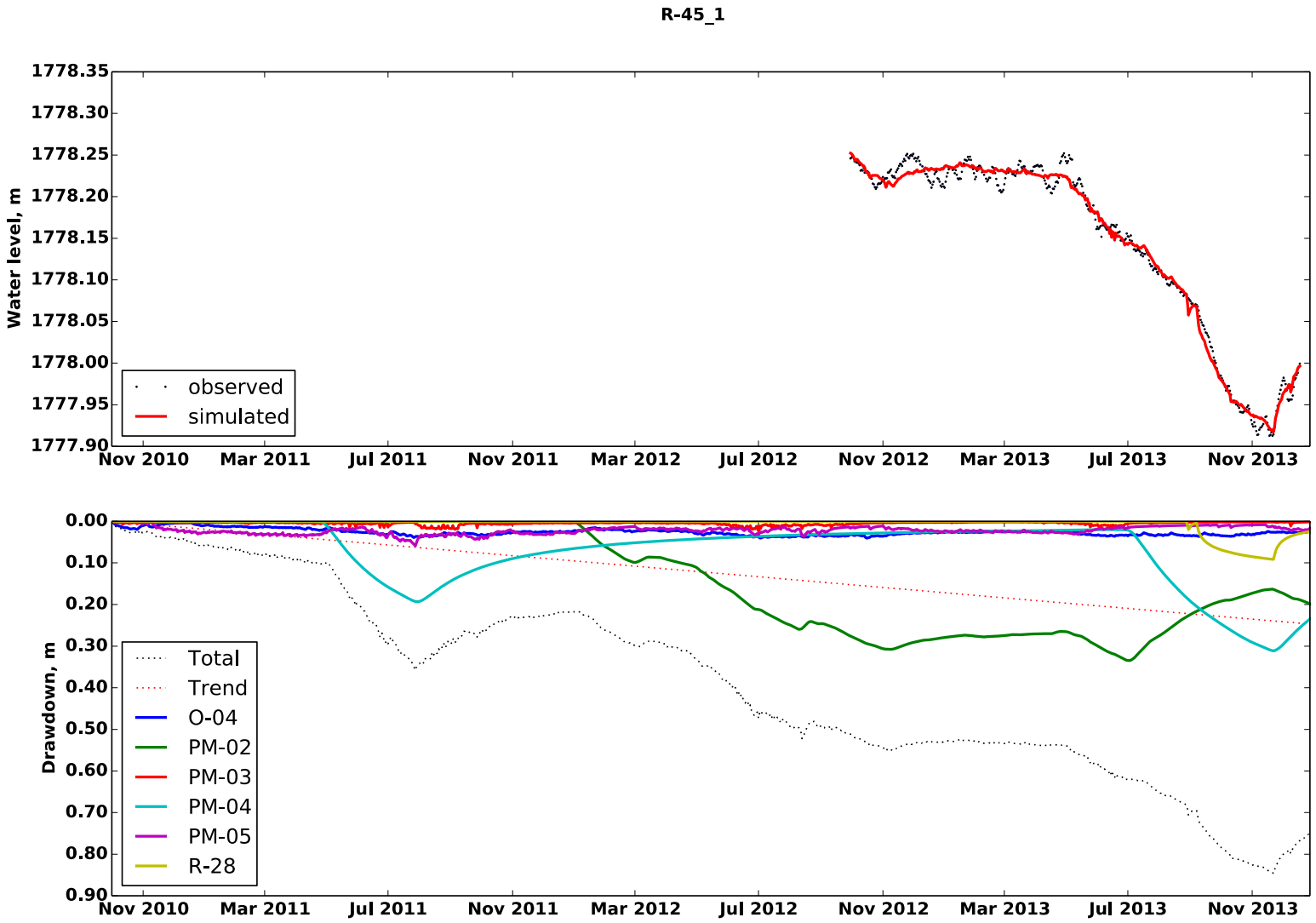


Figure B-26 **Deconstruction of R-45 screen 1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

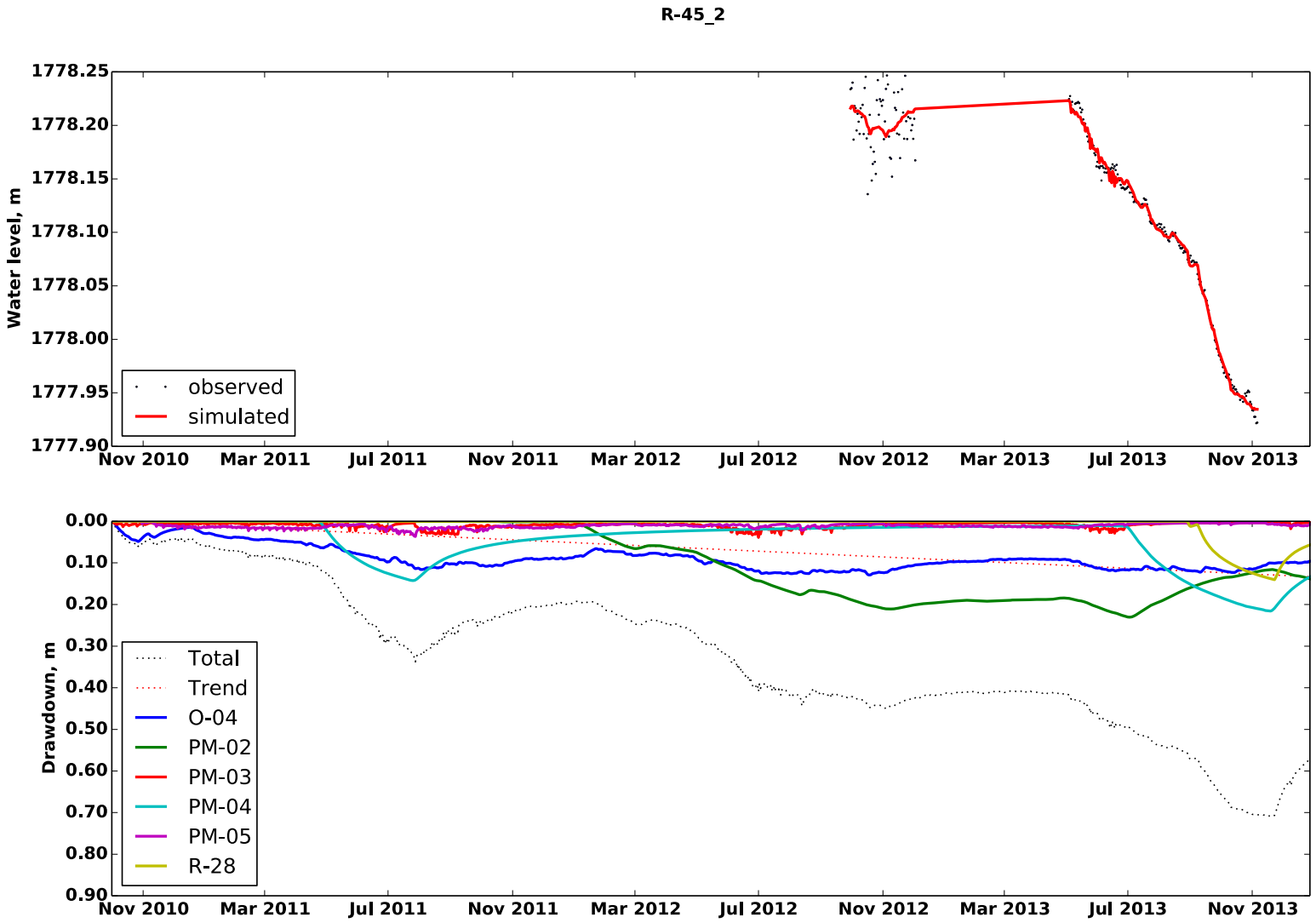


Figure B-27 **Deconstruction of R-45 screen 2 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

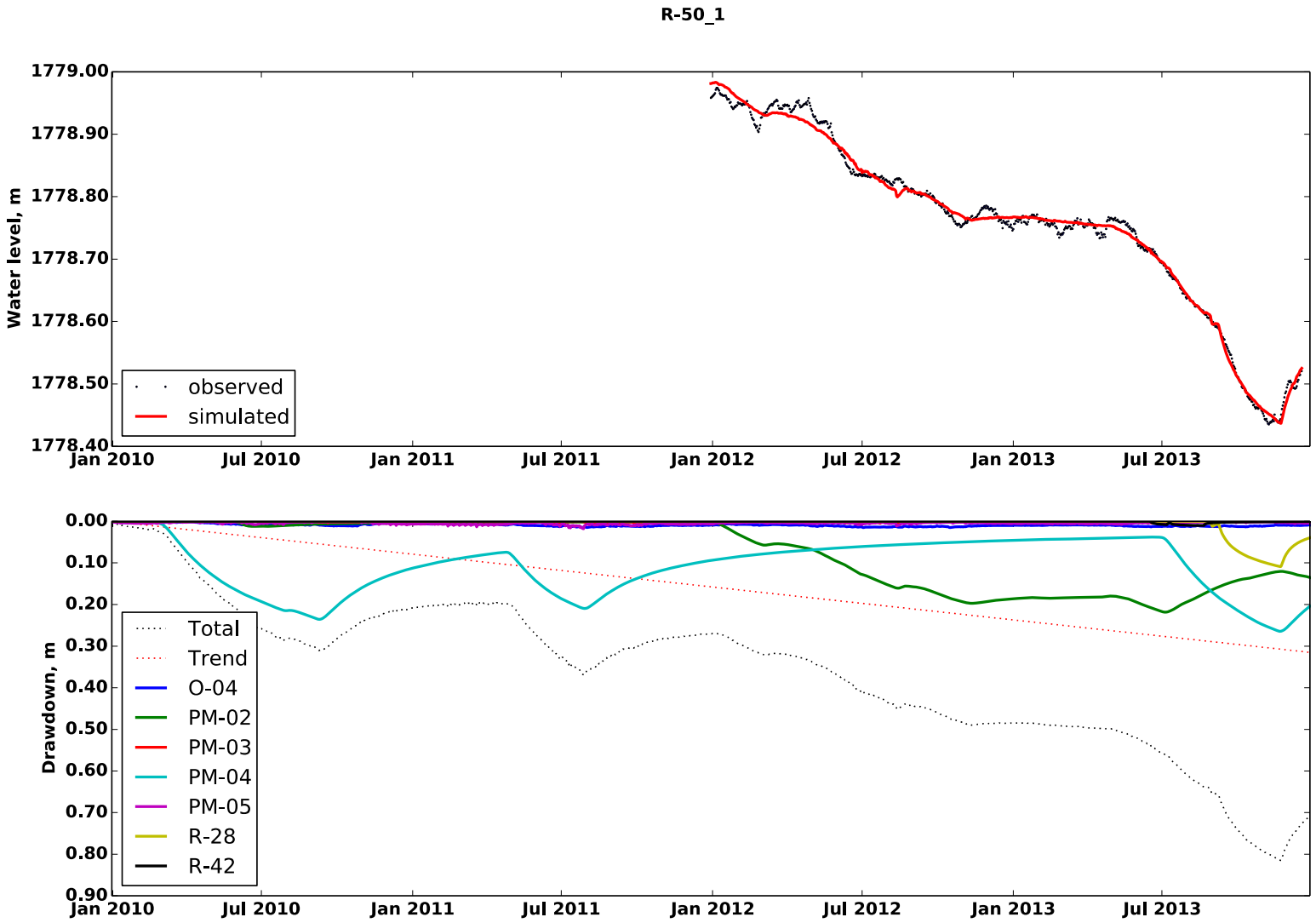


Figure B-28 **Deconstruction of R-50 screen 1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

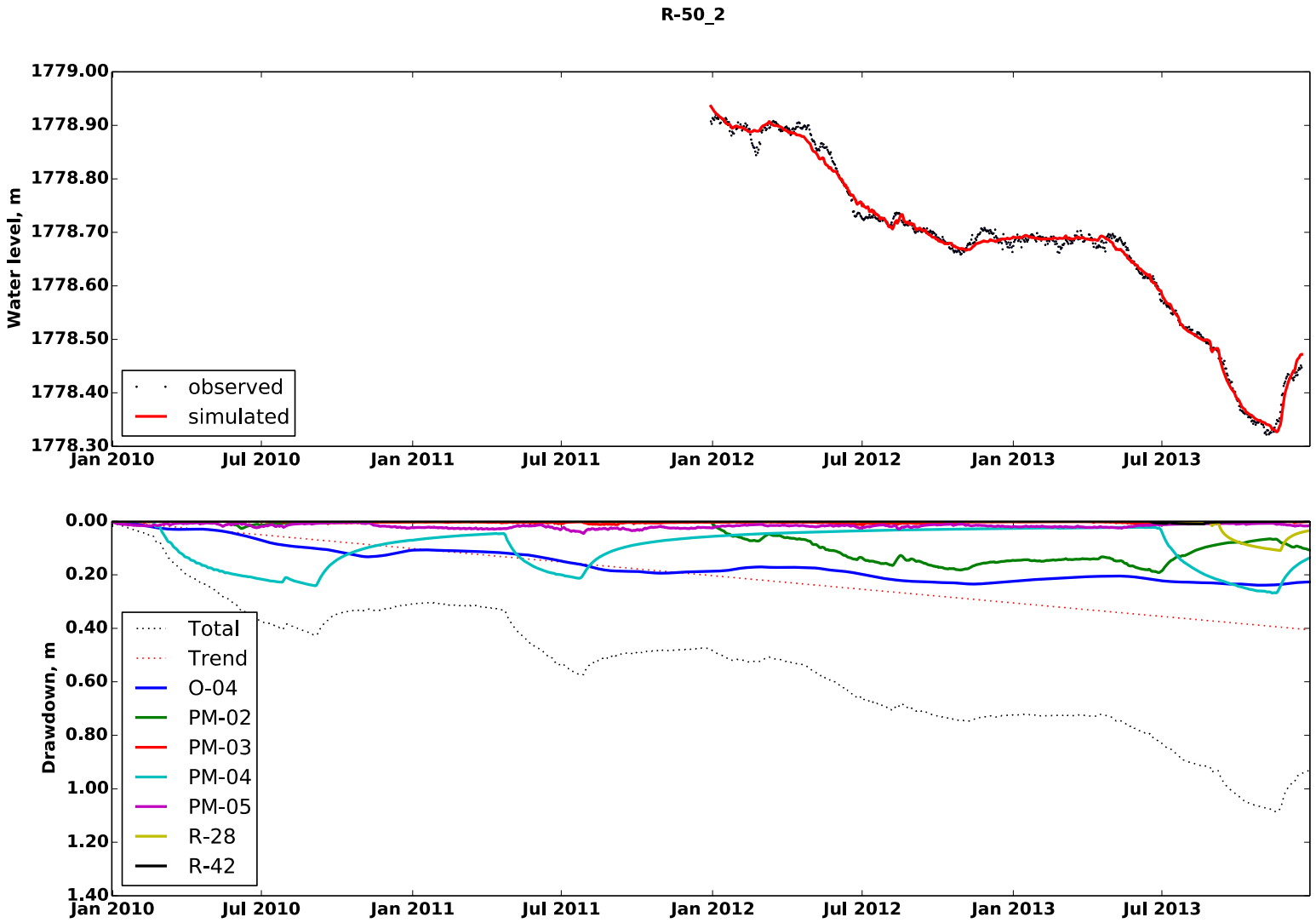


Figure B-29 **Deconstruction of R-50 screen 2 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

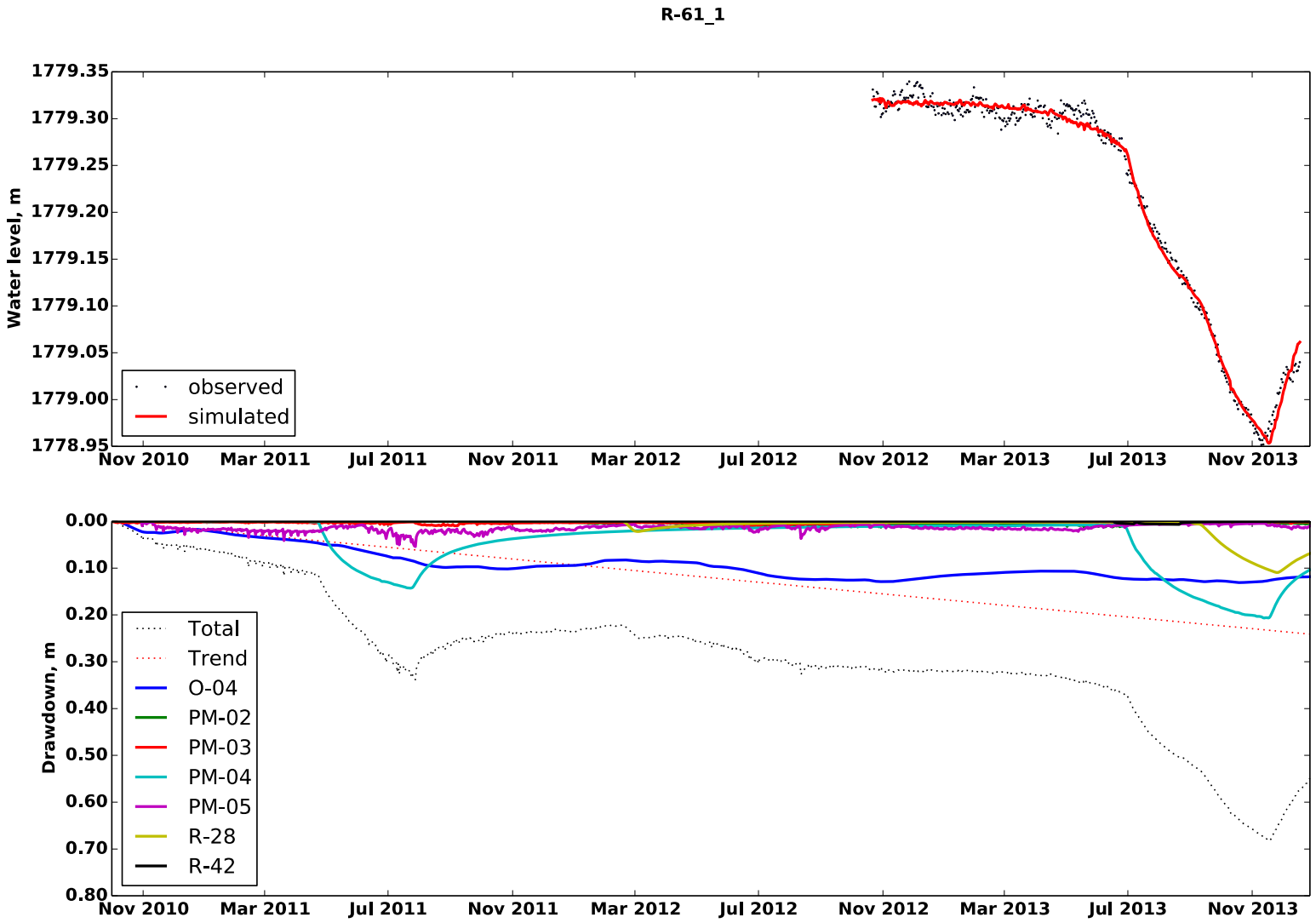


Figure B-30 **Deconstruction of R-61 screen 1 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

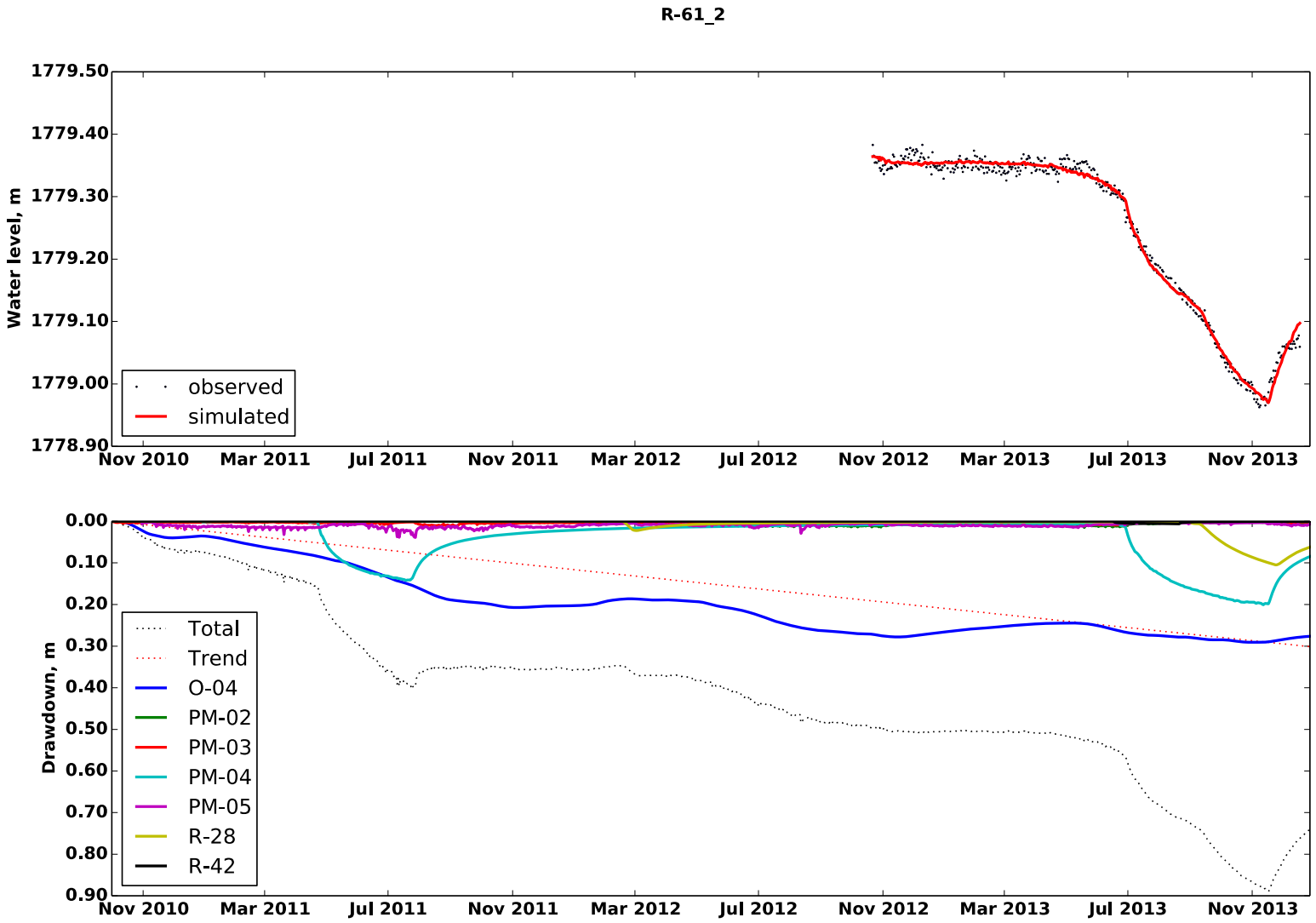


Figure B-31 **Deconstruction of R-61 screen 2 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

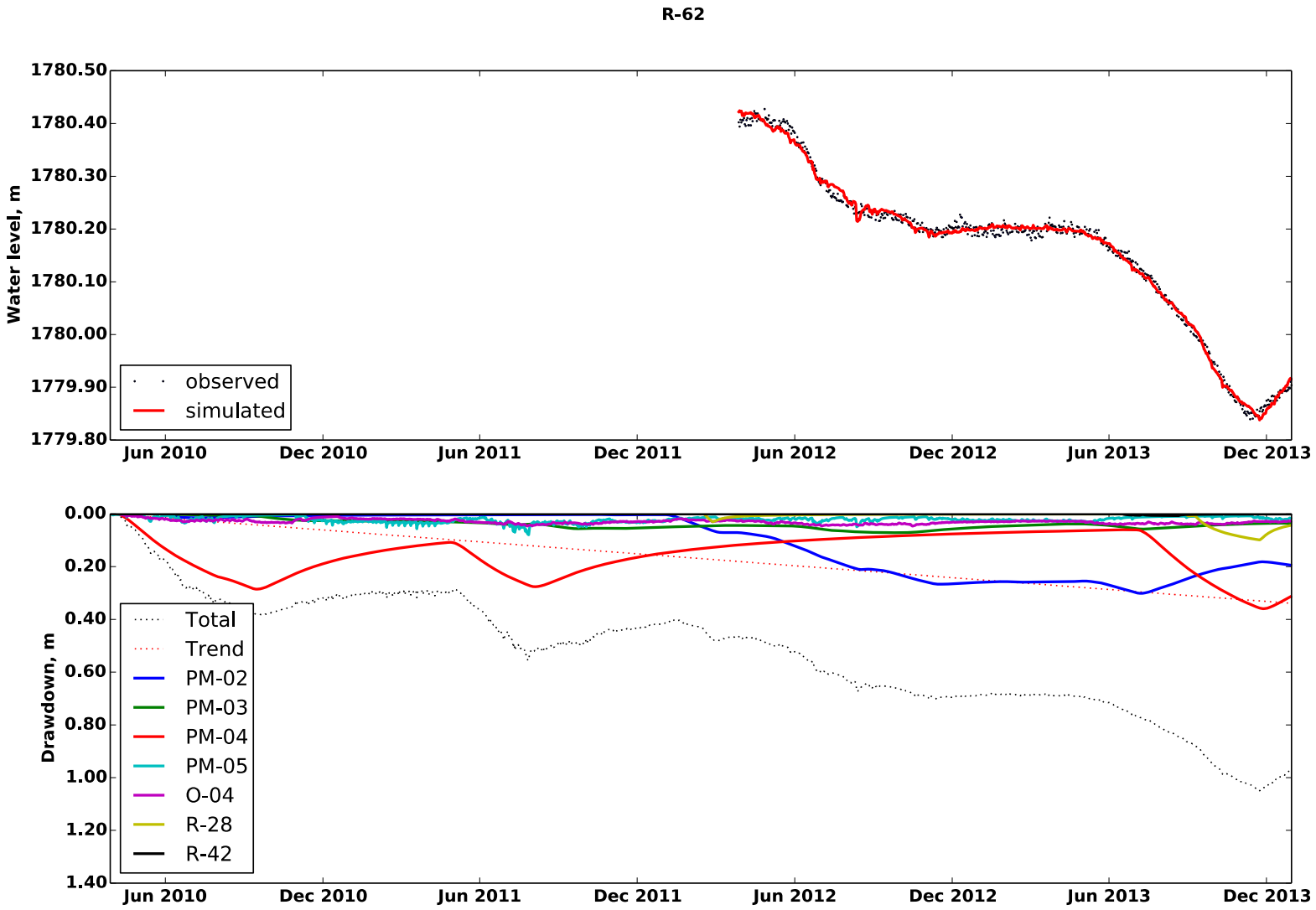


Figure B-32 **Deconstruction of R-62 water-level transients during 2013 aquifer test at R-42 and R-28. The upper plot depicts the observed and simulated water levels at the monitoring well, and the lower plot depicts the attribution of the drawdown to each of the pumping wells (O-4, PM-2, PM-3, PM-4, PM-5, R-42, and R-28).**

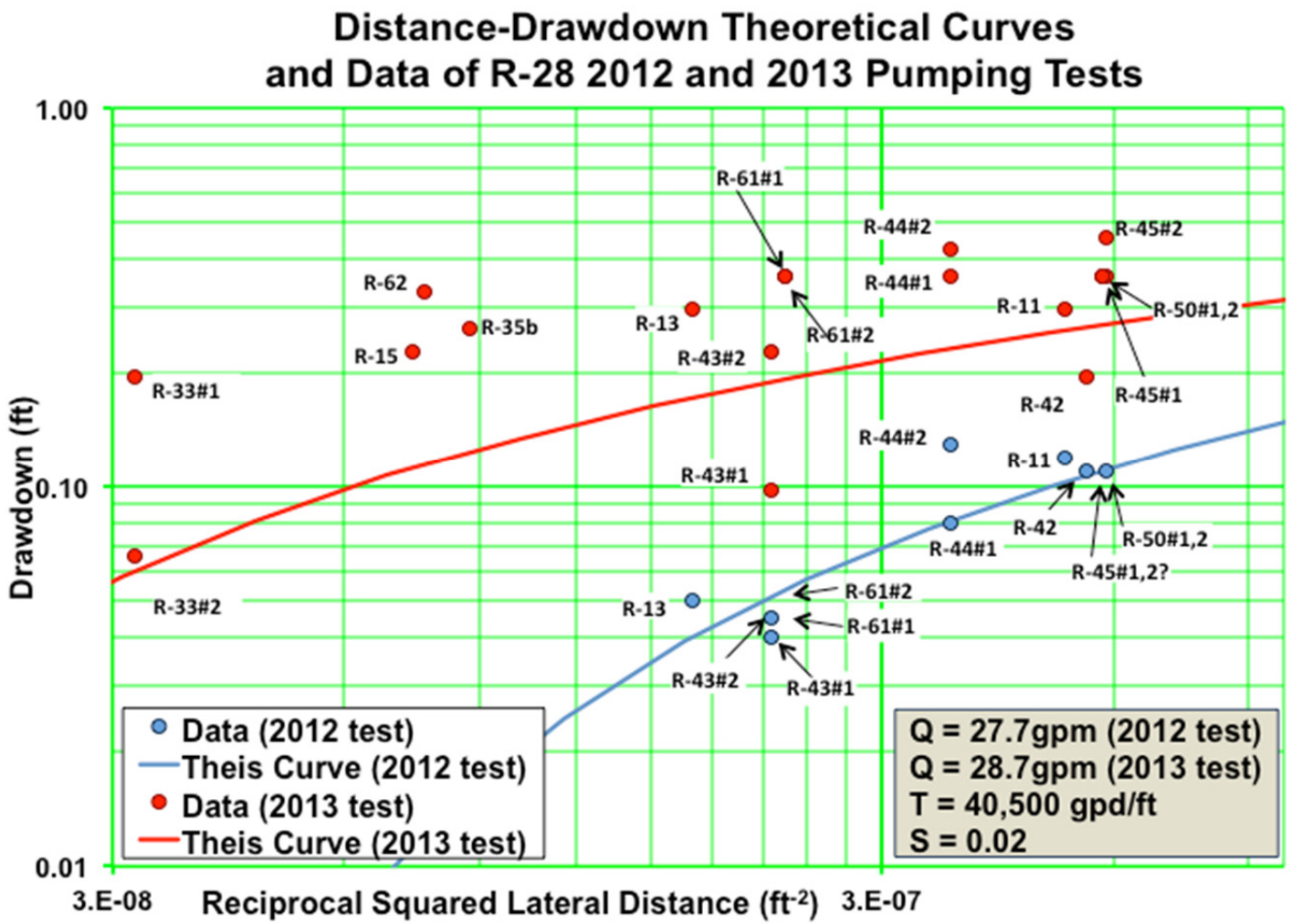


Figure B-33 Drawdowns and estimated drawdowns using the best homogeneous parameters based on the 2012 test results

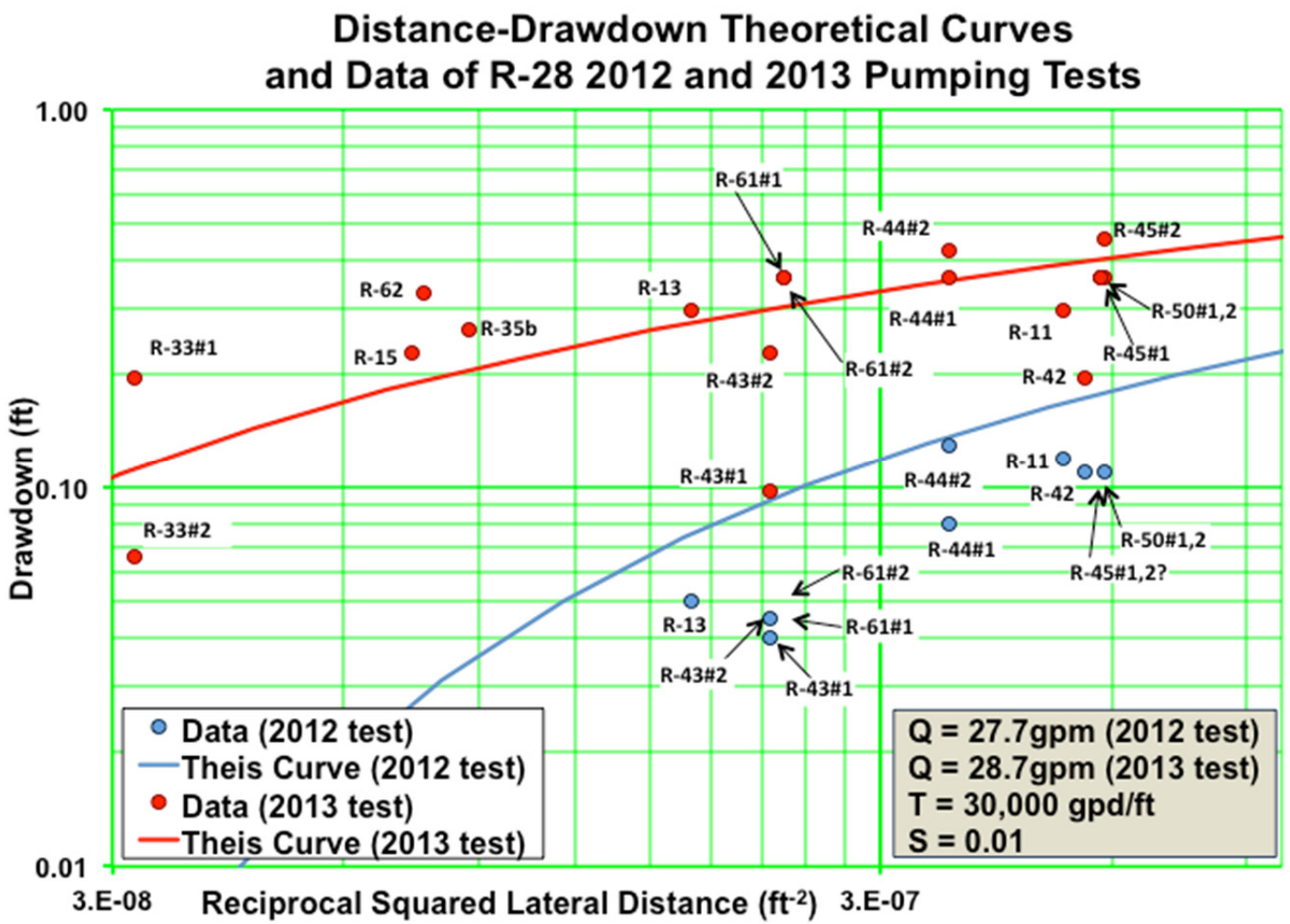


Figure B-34 Drawdowns and estimated drawdowns using the best homogeneous parameters based on the 2012 and 2013 test results

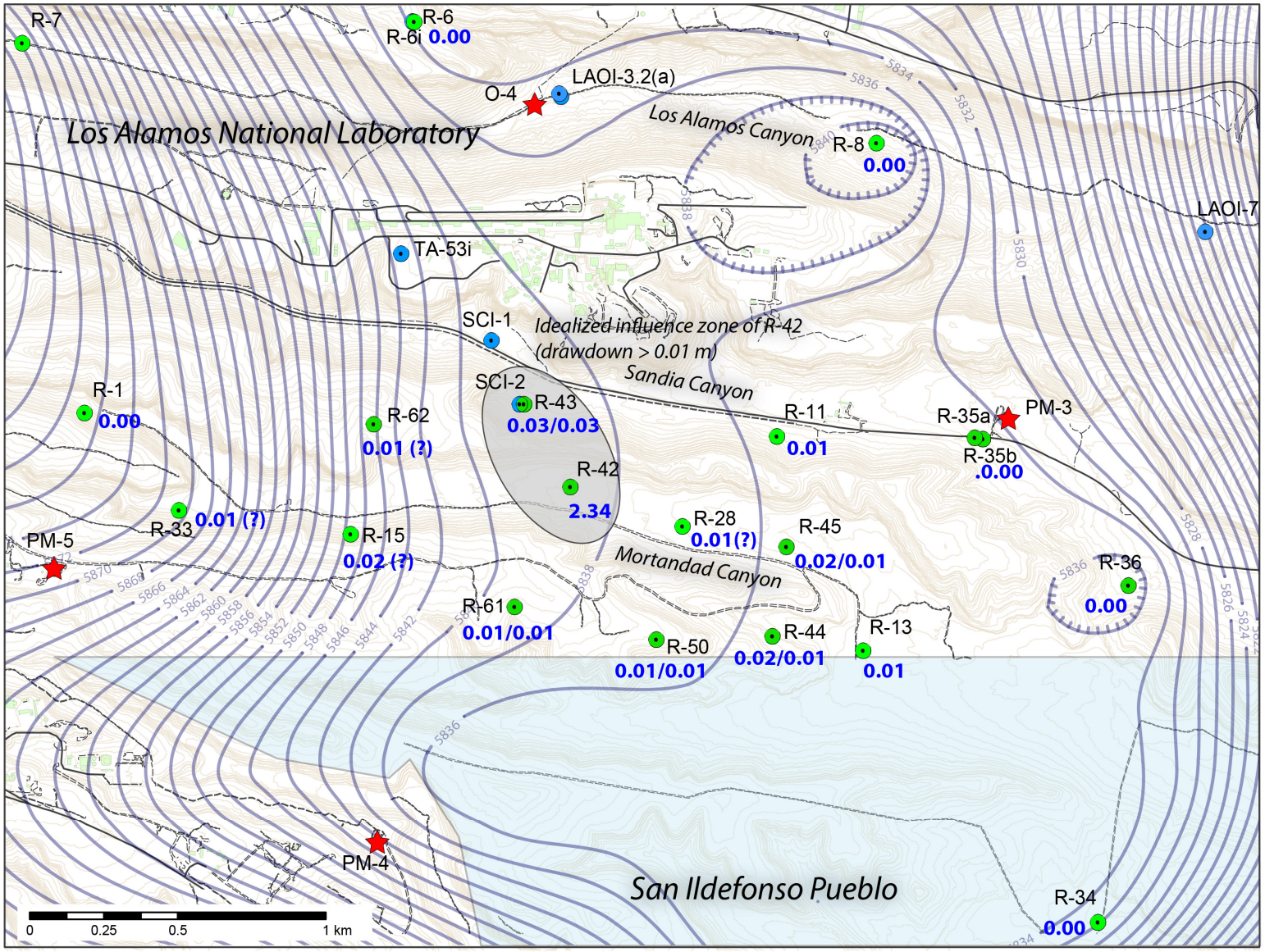


Figure B-35 Spatial distribution of the pumping drawdowns in meters at the end of the R-42 aquifer test (shown in blue text)

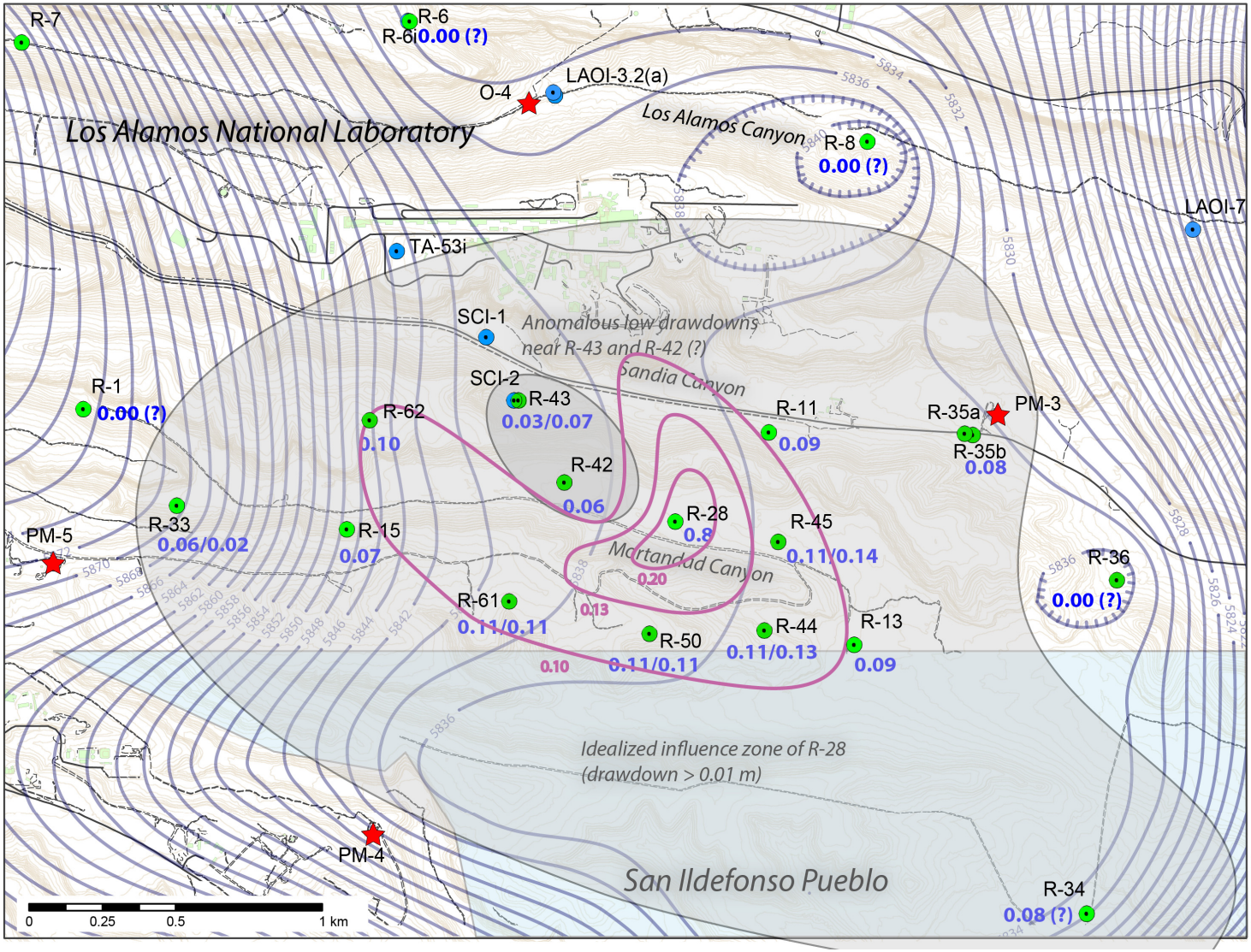


Figure B-36 **Spatial distribution of the pumping drawdowns in meters at the end of the R-28 aquifer test (shown in blue text). The contour lines (in pink) show the spatial distribution of the R-28 cone of depression (ZOI).**

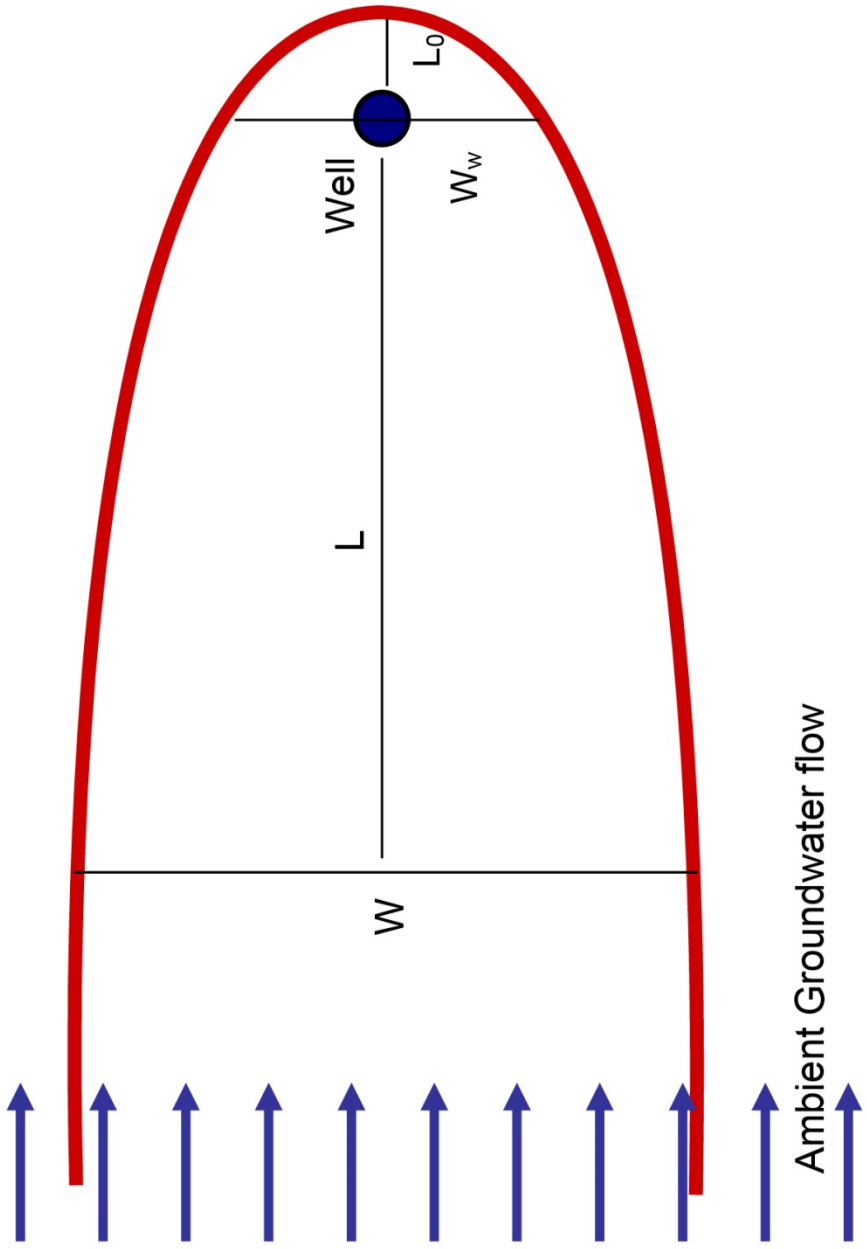


Figure B-37 Schematic representation of estimated CZ at R-28 and R-42 taking into account ambient groundwater flow through the regional aquifer

Table B-1
Estimated Maximum Drawdowns in
Observation Wells during the R-42 and R-28 Aquifer Tests

Observation Well	Pumping Well R-42		Pumping Well R-28		Comment
	Effect (Yes/No/Maybe)	Max Drawdown (m)	Effect (Yes/No/Maybe)	Max Drawdown (m)	
R-1	No	0.00	No	0 00 (?)	
R-6	No	0.00	No	0.00 (?)	
R-8 #1	No	0.00	Maybe	0.00 (?)	Water-level transients substantially influenced by water-supply pumping
R-8 #2	No	0.00	Maybe	0.00 (?)	Water-level transients substantially influenced by water-supply pumping
R-11	Maybe	0.01 (?)	Yes	0.09	
R-13	Maybe	0.01 (?)	Yes	0.09	
R-15	Maybe	0.01 (?)	Yes	0.07	
R-28	Maybe	0.01 (?)	Yes	0.80	
R-33 #1	No	0.00	Maybe	0.06	Water-level transients difficult to characterize; more data needed
R-33 #2	No	0.00	Maybe	0.02	Water-level transients substantially influenced by water-supply pumping
R-34	No	0.00	Yes	0.08 (?)	
R-35b	No	0.00	Yes	0.08	
R-36	No	0.00	No	0.0 (?)	Water-level transients difficult to characterize; more data needed
R-42	Yes	2.34	Yes	0.06	
R-4 3#1	Yes	0.03	Yes	0.03	Potentially Noordbergum effect during R-42 pumping
R-43 #2	Yes	0.03	Yes	0.07	
R-44 #1	Maybe	0.01 (?)	Yes	0.11	Best fit without pumping influence of R-42
R-44 #2	Maybe	0.01 (?)	Yes	0.13	Best fit without pumping influence of R-42
R-45 #1	Maybe	0.01 (?)	Yes	0.11	Best fit without pumping influence of R-42
R-45 #2	Maybe	0.01 (?)	Yes	0.14	Best fit without pumping influence of R-42
R-50 #1	Maybe	0.01 (?)	Yes	0.11	
R-50 #2	Maybe	0.01 (?)	Yes	0.11	
R-61 #1	Maybe	0.01 (?)	Yes	0.11	
R-61 #2	Maybe	0.01 (?)	Yes	0.11	
R-62	Maybe	0.01	Yes	0.10	

Table B-2
Summary of the Estimated Effective Aquifer Properties between the Pumping Wells R-42 and R-28 and Observation Wells in 2013 Aquifer Tests

Observation Well	Pumping Well R-42		Pumping Well R-28		Comment
	T [m^2/d]	S [–][a]	T [m^2/d]	S [–]	
R-11	1300	0.003	570	0.01	
R-13	910	0.003	480	0.006	
R-15	490	0.002	470	0.005	
R-28	2500	0.004	340	0.002	
R-33#1	3400	0.004	250	0.006	
R-33#2	850	0.003	1700	0.004	Difficult to characterize because of supply well pumping
R-34	n/a[b]	n/a	340	0.001	
R-35b	n/a	n/a	220	0.01	Best fit without pumping influence of R-42
R-36	n/a	n/a	260	0.003	Best fit without pumping influence of R-42
R-42	20	0.007	40	0.03	Uncertain estimates; potential low-permeability zone near R-42
R-43#1	650	0.003	1800	0.006	
R-43#2	650	0.003	790	0.005	
R-44#1	n/a	n/a	290	0.02	Best fit without pumping influence of R-42
R-44#2	n/a	n/a	350	0.01	Best fit without pumping influence of R-42
R-45#1	n/a	n/a	590	0.008	Best fit without pumping influence of R-42
R-45#2	n/a	n/a	240	0.02	Best fit without pumping influence of R-42
R-50#1	1500	0.004	350	0.02	
R-50#2	1600	0.004	410	0.01	
R-61#1	2900	0.004	180	0.02	
R-61#2	3100	0.004	200	0.02	
R-62	2400	0.004	310	0.004	

[a] [–] = Unitless.

[b] n/a = Not applicable because it cannot be estimated reliably.

Attachment B-1

Numerical Analysis of Water-Level Data
(on CD included with this document)

Appendix C

Water Treatment and Disposition Details
(on CD included with this document)

Appendix D

Samples Taken and Analytical Data
(on CD included with this document)