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Date: September 30, 2022
Refer To: N3B-2022-0387

Justin Ball, Chief
Ground Water Quality Bureau
New Mexico Environment Department
1190 S. St. Francis Drive
Santa Fe, NM 87502-5469

Subject: Submittal of the Regional Aquifer Monitoring Well R-45 Action Plan

Dear Mr. Ball:

Enclosed please find two hard copies with electronic files of the "Regional Aquifer Monitoring Well R-45 Action Plan." This action plan contains a description of actions proposed by the U.S. Department of Energy Environmental Management Los Alamos Field Office (EM-LA) to satisfy New Mexico Environment Department Ground Water Quality Bureau (NMED-GWQB) expectations for addressing chromium contamination in the regional aquifer.

On June 6, 2022, NMED-GWQB issued a notice of violation to EM-LA based on measured concentrations of total dissolved chromium in the regional aquifer at well R-45 screen 2 that exceeded the 20.6.2.3103 New Mexico Administrative Code groundwater standard of 0.050 mg/L. EM-LA reported this exceedance to NMED-GWQB on February 26, 2021, in the fourth quarterly monitoring report for calendar year 2020.

The action plan will be executed with continued engagement with NMED-GWQB at both the senior management and technical staff levels.

Ron Sholdt
GWQB
9/30/22

If you have questions, please contact Christian Maupin at (505) 695-4281 (christian.maupin@em-la.doe.gov) or Cheryl Rodriguez at (505) 414-0450 (cheryl.rodriguez@em.doe.gov).

Sincerely,

Robert Macfarlane
Program Manager
Environment, Safety, Health and Quality
N3B-Los Alamos

Sincerely,

ARTURO DURAN
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Arturo Q. Duran
Office of Quality and Regulatory Compliance
U.S. Department of Energy
Environmental Management

Enclosure(s): Two hard copies with electronic files:

1. Regional Aquifer Monitoring Well R-45 Corrective Action Plan (EM2022-0318)

cc (letter with CD/DVD enclosure[s]):
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David Nickless, EM-LA
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September 2022
EM2022-0318

Regional Aquifer Monitoring Well R-45 Action Plan

Regional Aquifer Monitoring Well R-45 Action Plan

September 2022

Responsible program director:

Joseph Sena		Director, Water Program Oversight	Water Program	September 28, 2022
Printed Name	Signature	Title	Organization	Date

Responsible N3B representative:

Troy Thomson		Program Manager	N3B Environmental Remediation Program	September 28, 2022
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Responsible DOE EM-LA representative:

Arturo Q. Duran	ARTURO DURAN Digitally signed by ARTURO DURAN Date: 2022.09.30 07:09:07 -06'00'	Compliance and Permitting Manager	Office of Quality and Regulatory Compliance	
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EXECUTIVE SUMMARY

This action plan contains a description of actions proposed by the U.S. Department of Energy Environmental Management Los Alamos Field Office (EM-LA) to satisfy New Mexico Environment Department Ground Water Quality Bureau (NMED-GWQB) expectations for addressing chromium contamination in the regional aquifer.

On June 6, 2022, NMED-GWQB issued a notice of violation (NOV) to EM-LA based on measured concentrations of total dissolved chromium in the regional aquifer at well R-45 screen 2 that exceeded the 20.6.2.3103 New Mexico Administrative Code groundwater standard of 0.050 mg/L. EM-LA reported this exceedance to NMED-GWQB on February 26, 2021, in the fourth quarterly monitoring report for calendar year 2020. This action plan includes the following:

1. Qualitative and quantitative analyses examining the cause for concentration increases at regional aquifer monitoring well R-45 screen 2 and predicted trends
2. Simulation plan for identifying alternative extraction and injection rates to decrease chromium concentrations below the 0.050 mg/L standard at R-45 screen 2
3. New regional aquifer monitoring wells, one downgradient of R-45 (R-80) and one located in the northeastern region of the plume (R-79)
4. Continued monitoring to evaluate plume mass movement within the regional aquifer using the existing well network

These four actions are discussed in more detail in sections 2.1 to 2.4 of this action plan.

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Appendix

1.0 BACKGROUND

The Chromium Plume Control Interim Measures (IM) for hydraulic plume control was planned in 2015 and installed under the New Mexico Environment Department– (NMED-) approved 2015 “Interim Measures Work Plan for Chromium Plume Control” (LANL 2015, 600458; NMED 2015, 600959). The IM was planned and installed based on information known about the plume at that time, where chromium concentrations in well R-50 near the boundary with the Pueblo de San Ildefonso was above 50 ppb and that the plume was within the top 50 ft of the regional aquifer (based on the dual screened wells installed at that time). Hydraulic control of the plume was planned with six injection wells along the downgradient edge of the plume based on the characterization data available in 2015. The 2015 depiction of the plume is shown in Figure 1.0-1.

In 2017, along the eastern portion of the plume, a sixth injection well (CrIN-6) was planned for hydraulic plume control. CrIN-6 concentrations of 250–300 µg/L indicated that the plume extended further east and was likely deeper than previously conceptualized. In response to this finding, CrIN-6 and the surface infrastructure was then converted to extraction well CrEX-5 (Figure 1.0-2). In mid-2019, samples collected from R-70 screen 1 and screen 2 showed that concentrations in excess of 200 µg/L extend significantly farther east than originally assumed, and those high concentrations were present at depths at least 90 ft below the water table (the depth of the top of R-70 screen 2). Conversely, R-70 screen 1, a screen closer to the water table, yields much lower chromium concentrations, which demonstrates that contamination is submerged and resides at greater depths in the eastern plume area (N3B 2019, 700715). Even though CrEX-5 is likely capturing chromium mass from this location, the current array of injection and extraction wells is screened at shallower depths and may not provide complete access to the depths required to fully control the plume in this area. The current conceptualization is shown in Figure 1.0-2, which depicts both a shallow and deep chromium plume within the regional aquifer.

Well R-45, a two-screen well located southwest of R-70 and flanked by injection wells CrIN-1 and CrIN-2 to the west, is a monitoring point that has provided important information on the influence of IM operations in the eastern plume area. Pre-IM concentrations in the shallow and deep screens were below 50 µg/L but above background and rising since the well was first sampled in 2009, climbing to about 40 µg/L in screen 1 (the shallow screen) and 20 µg/L in screen 2 (Figures 1.0-3 and 1.0-4, respectively). Although chromium concentrations have decreased to near background at R-45 screen 1 after sustained IM operations, the concentrations at R-45 screen 2 have consistently measured above the chromium concentration standard of 50 µg/L since 2021.

1.1 Action Plan

This action plan contains a description of actions proposed by the U.S. Department of Energy Environmental Management Los Alamos Field Office (EM-LA) to satisfy New Mexico Environment Department Ground Water Quality Bureau (NMED-GWQB) expectations for addressing chromium contamination in the regional aquifer.

On June 6, 2022, NMED-GWQB issued a notice of violation (NOV) to EM-LA based on measured concentrations of total dissolved chromium in the regional aquifer at well R-45 screen 2 that exceeded the 20.6.2.3103 New Mexico Administrative Code groundwater standard of 0.050 mg/L (NMED 2022, 702153). EM-LA reported this exceedance to NMED-GWQB on February 26, 2021, in the fourth quarterly monitoring report for calendar year 2020 (N3B 2021, 701249).

As shown in Figure 1.0-2, Well R-45 is located along the eastern portion of a chromium plume in groundwater beneath the Los Alamos National Laboratory (LANL or the Laboratory). The IM for hydraulic control of the chromium plume has influenced chromium concentrations at R-45. Additionally, the IM has been instrumental in decreasing chromium concentrations at well R-50 located along the southern plume boundary. The IM is a plume control system of extraction within the plume, treatment of the extracted water to less than Discharge Permit 1835 (DP-1835) requirements before injection, followed by injection along the downgradient plume edge.

EM-LA will continue engaging with NMED-GWQB at both the senior management and technical staff levels so that the action plan meets NMED-GWQB expectations for addressing chromium contamination at R-45 screen 2.

In addition to NMED-GWQB engagement, EM-LA has consulted with the Pueblo de San Ildefonso, and will consult with Pueblo de San Ildefonso, as appropriate, on matters associated with IM operational decisions. EM-LA will also confer with Los Alamos County on this action plan.

2.0 ACTIONS

The proposed set of activities for this action plan fall into two categories:

1. analyses that provide the decision basis for evaluating concentrations at R-45 screen 2 and examining potential modifications to IM operations; and
2. monitoring to further characterize the nature and extent of the chromium plume.

These activities provide feedback to one another and a technical basis for decision-making. Data obtained from the existing monitoring network, as well as its expansion, will continue to drive the analyses associated with management of the IM within the regional aquifer and at well R-45.

2.1 Qualitative and Quantitative Analyses

A first step is to determine potential reasons for chromium concentration increases at R-45 screen 2. The qualitative and quantitative analyses are complementary, providing a more comprehensive understanding of why an increase in concentration has occurred.

2.1.1 Qualitative Analysis

To examine plume behavior mechanisms at R-45, a qualitative, data-driven analysis has been performed, examining geochemical data (e.g., chromium, chloride, sulfate, and nitrate) in relation to the conceptual site model for chromium migration in groundwater (Appendix A). The analysis demonstrated that the chromium plume has been migrating into the region near R-45, CrIN-1, and CrIN-2 (see map of well locations in Figure 1.0-2) since the early 2000s. Concentrations within the plume in the vicinity of R-45 indicate that they are at their maximum in a zone located between screens 1 and 2 at well R-45, with chromium concentrations increasing in both screens before installation and operation of the IM. The data-driven analysis suggests that the IM addressed chromium concentrations in screen 1, lowering chromium concentrations to background. However, injection water from IM operations has pushed the chromium mass located between screens 1 and 2 into the screen 2 horizon, causing a moderate rise in chromium concentrations at screen 2. The analysis also suggests that the maximum concentrations in this region are still between screens 1 and 2. If concentrations greater than 50 ppb exist at depths significantly below screen 2, they would have had to migrate there before commencement of the IM. To date, there is no indication of contamination at these depths.

2.1.2 Quantitative Analysis

A quantitative analysis has also been executed using a calibrated numerical model of the chromium investigation area. Concentration predictions match historical chromium concentrations and trends at R-45, including the concentration decrease at R-45 screen 1 from the start of IM operations to present day, and the more recent increases in chromium concentrations at screen 2 (Figures 1.0-3 and 1.0-4). Multiple simulations have been executed to account for uncertainty and show a potential range of peak concentrations and arrival times, but for the sake of simplicity, results from a single representative simulation are shown in Figure 2.1-1. Three vertical concentration profiles at the R-45 location are shown for the same representative simulation in Figure 2.1-1 for three different calendar years, 2016, 2022, and 2025. In 2016, before the initiation of IM operations, chromium concentrations in both screens were increasing, with a peak concentration of approximately 90 ppb located between screens 1 and 2. However, as time proceeds, the peak concentration has dampened and moved deeper into the regional aquifer by 2022, with a peak concentration of approximately 80 ppb at screen 2. By 2025, the peak concentration will have fallen below the 50 ppb standard, located at approximately 150 ft below the water table. Without any changes in current operations, the chromium concentration will likely decrease to below the 0.05 mg/L (50 ppb) standard within 18 months. The concentration decrease occurs because the IM is effective at capturing chromium mass upgradient from R-45. Hence, the model predicts that the chromium concentrations continue to decline and eventually reach background concentrations.

Figure 2.1-2 shows the simulated concentrations at approximately 120 ft below the water table, which is approximately the bottom of R-45 screen 2. The concentration distributions are also depicted for calendar years 2016, 2022, and 2025. In 2016, the leading edge of the chromium plume reached R-45 at the depth of screen 2, as indicated by the 50 ppb contour line. By 2022, the 50 ppb contour line extends to the east of R-45, but with continued injection and sustained upgradient extraction, the concentrations decrease to below 50 ppb at R-45 screen 2. This is shown in the concentration distribution for 2025, where the 50 ppb line is depicted to the west of R-45. Under current IM operational conditions, the impact of injecting clean water and continued extraction pushes the 50 ppb contour line to the extraction wells located to the west of R-45, and R-45 screen 2 concentrations would attain very low values.

The chromium plume at R-45 will continue to be evaluated, incorporating new data into both qualitative and quantitative analyses as they become available. The evaluation will include updating the conceptual model at R-45, and throughout the regional chromium plume. These types of analyses will support the primary IM objective of hydraulic control of the chromium plume and evaluating the IM ability to prevent migration of chromium concentrations above 50 ppb beyond the Laboratory boundary.

2.2 Simulation Plan for Identifying Alternative IM Operations

In addition to the quantitative and qualitative analyses, simulations will be executed to determine if alternative extraction and injection configurations will mitigate chromium concentrations at R-45 screen 2. Although the principal objective is to lower chromium concentrations at R-45 screen 2, unintended consequences of changing injection and extraction rates, such as reduced chromium plume control or increasing chromium concentrations above the standard at other wells, will also be evaluated. Simulations will use historical IM extraction and injection rates until present day (Table 2.2-1), but will implement alternative extraction and injection scenarios as outlined below. If injection rates are reduced (or ceased) in one or more injection wells, extraction rates will also need to be reduced to load balance the system. At the point where there is no injection, there will be no extraction.

Simulations will primarily focus on the impact of reducing or ceasing injection at CrIN-1, CrIN-2, and CrIN-3, with a concomitant reduction in extraction rates. The impact on reducing chromium concentrations at R-45 screen 2 will be initially evaluated by ceasing injection at CrIN-1, and then in tandem with CrIN-2 and CrIN-3. Effects of CrEX-5 extraction rates will also be examined for impacts to R-45 screen 2.

The ability to extract chromium mass from R-45 screen 2 will also be investigated, although there are operational constraints that may make extraction impractical. For example, the existing sampling system configuration only operates at a maximum of 3 gallons per minute (gpm), which would need to be operated with a generator since no line power currently exists at R-45. If the sampling system was replaced so that higher extraction rates could be achieved, then monitoring in screen 1 would be lost, but a higher capacity pump could be installed. Aquifer testing performed at R-45 indicated a potential maximum extraction rate on the order of 20 gpm (LANL 2009, 106427). Simulations will be used to assess the potential benefits of such a change to the system.

2.3 New Monitoring Wells

Simulations were also used to determine the location of two new monitoring wells, one located to the south and east of R-45 and the other located to the north and east, R-80 and R-79, respectively. Both wells will help determine the lateral and vertical extent of the chromium plume located to the east of the IM infrastructure wells (e.g., CrIN-1, CrIN-2, CrIN-3, and CrEX-5).

The primary goal for new monitoring wells with respect to R-45 is to identify a downgradient and lateral location where the chromium plume is still near background (approximately 7 ppb), indicating that the chromium plume would not have migrated to that location. Therefore, the goal is equivalent to providing information that defines a *bounding box* where hydraulic control of the chromium plume is needed. However, given natural variability in background chromium concentrations, a target concentration to encounter at a new monitoring well is one that is clearly above background, yet still below the 50 ppb standard. A concentration of 20 ppb (or higher) would indicate that the chromium plume has migrated downgradient, but not yet at concentrations above standard. This would suggest that the leading edge of the plume has reached that location.

The images shown in Figure 2.1-2 display concentration distributions at 120 ft below the water table, the equivalent well screen depth for R-45 screen 2. The leading edges of the plume for years 2022 and 2025 were used to identify the locations for R-79 and R-80. The lower screen target depth is at approximately 150 ft below the water table to determine if deep migration is occurring beneath the depth of R-45 screen 2. This depth would place the screen at or near the bottom of the Miocene Pumiceous Sediments (Tjfp) at this location. However, actual screen depths will be dependent on field conditions, such as the geologic unit encountered at depth and hydraulic conductivity.

The rationale for selecting the locations for R-79 and R-80 are discussed below. However, the locations for R-79 and R-80 may need to be adjusted based on physical and cultural constraints. Well locations will be in a location practical for establishing a drill pad and placing a drill rig within the canyon.

2.3.1 R-80

The X-Y location for R-80 was first identified by the need to monitor chromium migration downgradient of R-45 that could occur due to conditions that existed prior to IM operations, or due to the IM influence on groundwater flow directions. The goal is to locate it to the south of the deeper plume located near CrEX-5 and R-70, so that R-80 represents a downgradient response to R-45. Figures 2.1-1 and 2.1-2 indicate that chromium concentrations will decrease below standard by 2025 due to extraction at CrEx-5 and injection at CrIN-1 and CrIN-2. Hence, its location was selected based on the objective of identifying a concentration of 20 ppb or less, aligning it in the X-Y plane with R-13 and R-70, which may have the benefit of estimating a mass flux across a vertical plane that intersects these three wells. The new monitoring location is shown in Figure 2.1-2 outside the 50 ppb contour.

2.3.2 R-79

The X-Y location for R-79 was based on the need to identify both lateral and vertical extent of the chromium plume near the area where chromium mass has been measured at depth. In addition, the area to the north and east of R-45 may require additional infrastructure wells for chromium plume control, which may influence concentration trends at R-45. For R-79, the X-Y location was selected as a mid-point between R-70, a well with high chromium concentrations at depth, and R-35b, a sentinel well for the Los Alamos County supply well (PM-3) that measures background chromium concentrations. The new monitoring location is shown in Figure 2.1-2 outside the 50 ppb contour.

2.4 Continued Monitoring and Evaluation

Since predictive simulations have indicated that concentrations at R-45 screen 2 will decrease to below 50 ppb under current IM operational conditions, continued monitoring of chromium concentrations under these conditions with the current performance monitoring well network is recommended for the next 12 to 18 months. If concentrations continue to rise at the end of this period, additional actions may be necessary to address the increase in concentrations. This additional data can help validate the model and provide support for its use in decision-making. Continued monitoring of chromium and other analytes within the existing well network will also provide ongoing updates to the conceptual site model. Simulations that investigate alternative extraction and injection strategies can also help identify the potential to accelerate concentration decreases at R-45 without negative impacts to maintaining chromium plume control along the southern and eastern boundaries. Ongoing monitoring will continue to support the predictive assessments, and in turn, simulations can aid in interpreting monitoring data.

3.0 SCHEDULE

The start date for implementation of activities described in this action plan is contingent upon receiving NMED-GWQB approval. Drilling work plans will be required for monitoring wells R-79 and R-80, which are planned for fiscal year 2023. Simulation work is also planned for fiscal year 2023. Well installation will follow approval of the drilling work plans and is currently proposed for early to mid-fiscal year 2024.

Performance monitoring within the existing well network will continue throughout execution of the action plan, integrating new data into the conceptual model at R-45 and the chromium plume within the regional aquifer. The numerical model will also be updated with new monitoring data, providing a technical basis for modifying IM operations.

4.0 REFERENCES

The following reference list includes documents cited in this plan. Parenthetical information following each reference provides the author(s), publication date, and ERID, ESHID, or EMID. ERIDs were assigned by Los Alamos National Laboratory's (the Laboratory's) Associate Directorate for Environmental Management (IDs through 599999); ESHIDs were assigned by the Laboratory's Associate Directorate for Environment, Safety, and Health (IDs 600000 through 699999); and EMIDs are assigned by Newport News Nuclear BWXT-Los Alamos, LLC (*N3B) (IDs 700000 and above).*

LANL (Los Alamos National Laboratory), May 2009. "Completion Report for Regional Aquifer Well R-45," Los Alamos National Laboratory document LA-UR-09-3065, Los Alamos, New Mexico. (LANL 2009, 106427)

LANL (Los Alamos National Laboratory), May 2015. "Interim Measures Work Plan for Chromium Plume Control," Los Alamos National Laboratory document LA-UR-15-23126, Los Alamos, New Mexico. (LANL 2015, 600458)

N3B (Newport News Nuclear BWXT-Los Alamos, LLC), December 2019. "Assessment Work Plan for the Evaluation of Conditions in the Regional Aquifer Around Well R-70," Newport News Nuclear BWXT-Los Alamos, LLC, document EM2019-0458, Los Alamos, New Mexico. (N3B 2019, 700715)

N3B (Newport News Nuclear BWXT-Los Alamos, LLC), March 2021. "Quarterly Report for the Discharge of Treated Groundwater to the Regional Aquifer under Discharge Permit 1853, Calendar Year 2020 Quarter 4," Newport News Nuclear BWXT-Los Alamos, LLC, document EM2021-0056, Los Alamos, New Mexico. (N3B 2021, 701249)

NMED (New Mexico Environment Department), October 15, 2015. "Approval with Modifications, Interim Measures Work Plan for Chromium Plume Control," New Mexico Environment Department letter to D. Hintze (DOE-NA-LA) and M. Brandt (LANL) from J.E. Kieling (NMED-HWB), Santa Fe, New Mexico. (NMED 2015, 600959)

NMED (New Mexico Environment Department), June 6, 2022. "Notice of Violation, Los Alamos National Laboratory Underground Injection Control Wells, DP-1835," New Mexico Environment Department letter to J. Murdoc (N3B) and A.Q. Duran (DOE EM-LA) from J. Ball (NMED-GWQB), Santa Fe, New Mexico. (NMED 2022, 702153)

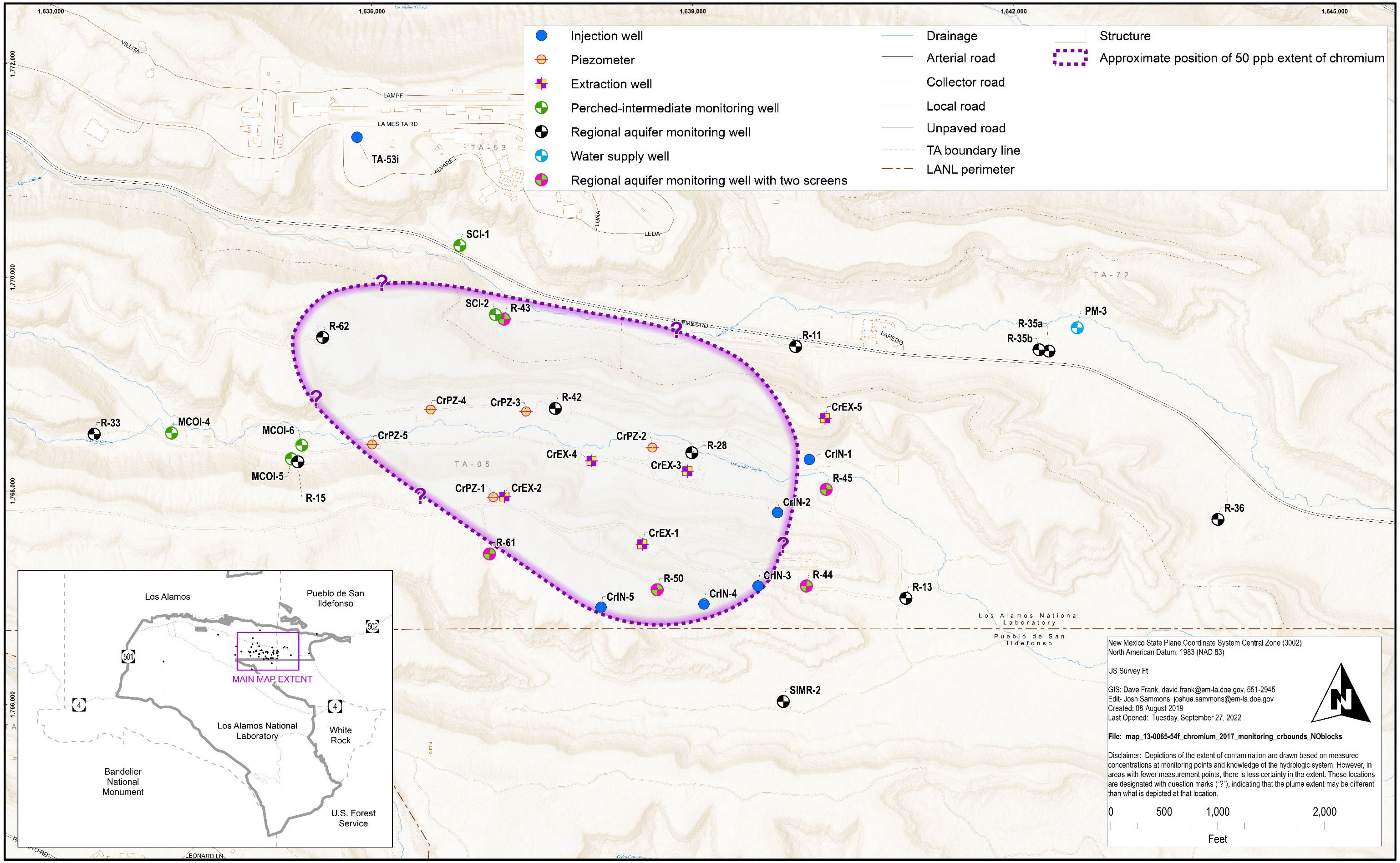


Figure 1.0-1 Map of chromium investigation area showing 2015 plume depiction with 2015 well locations

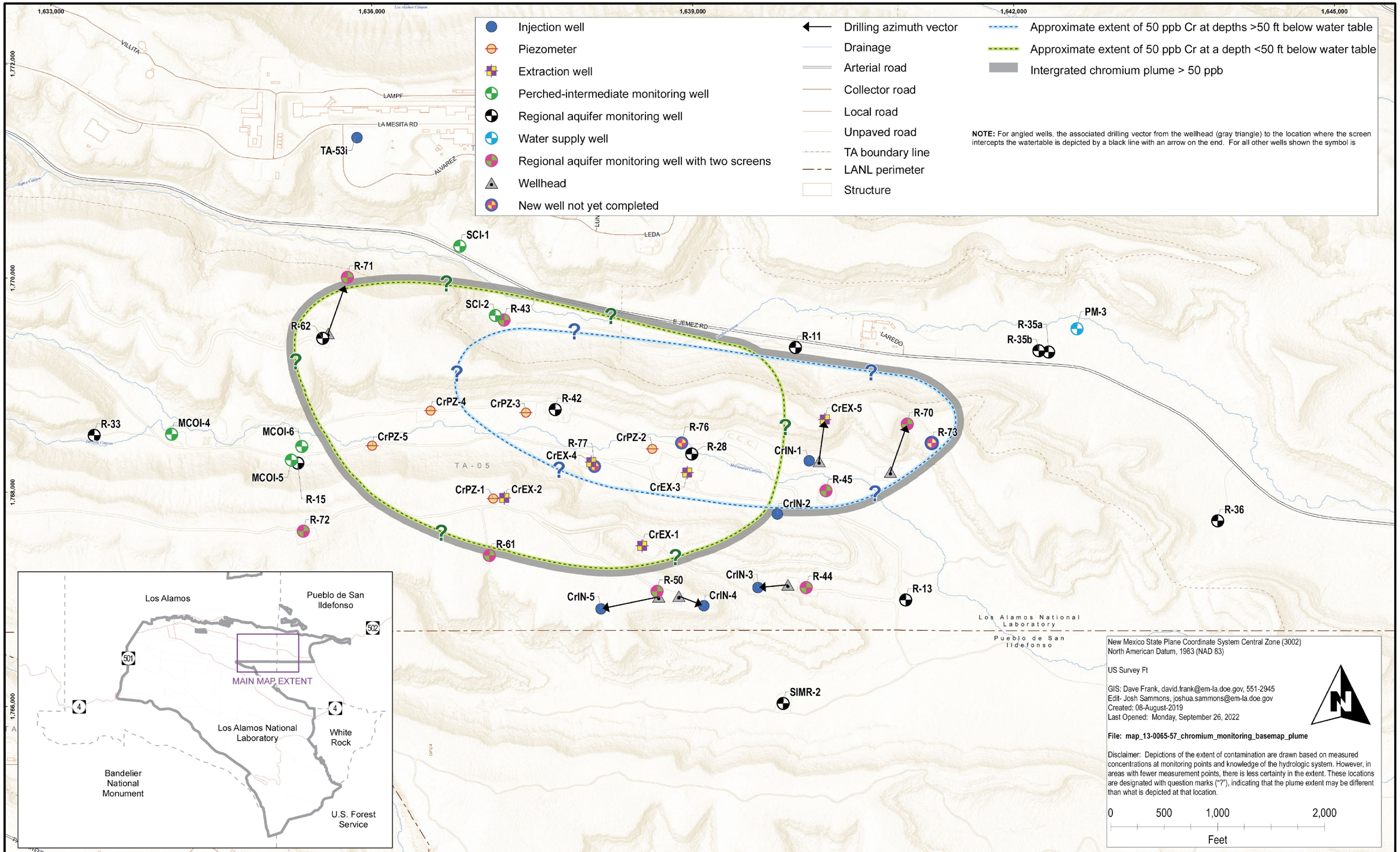
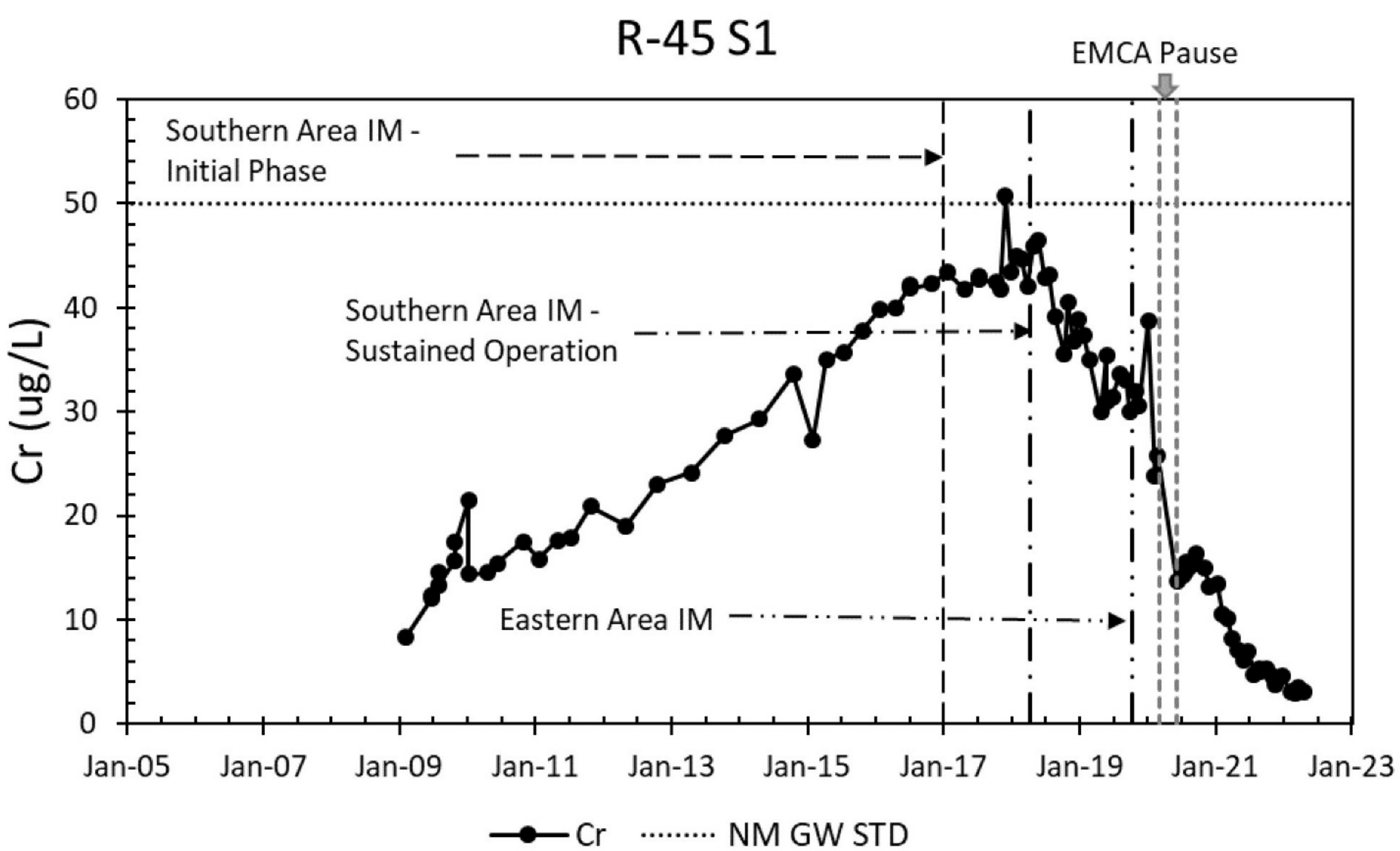
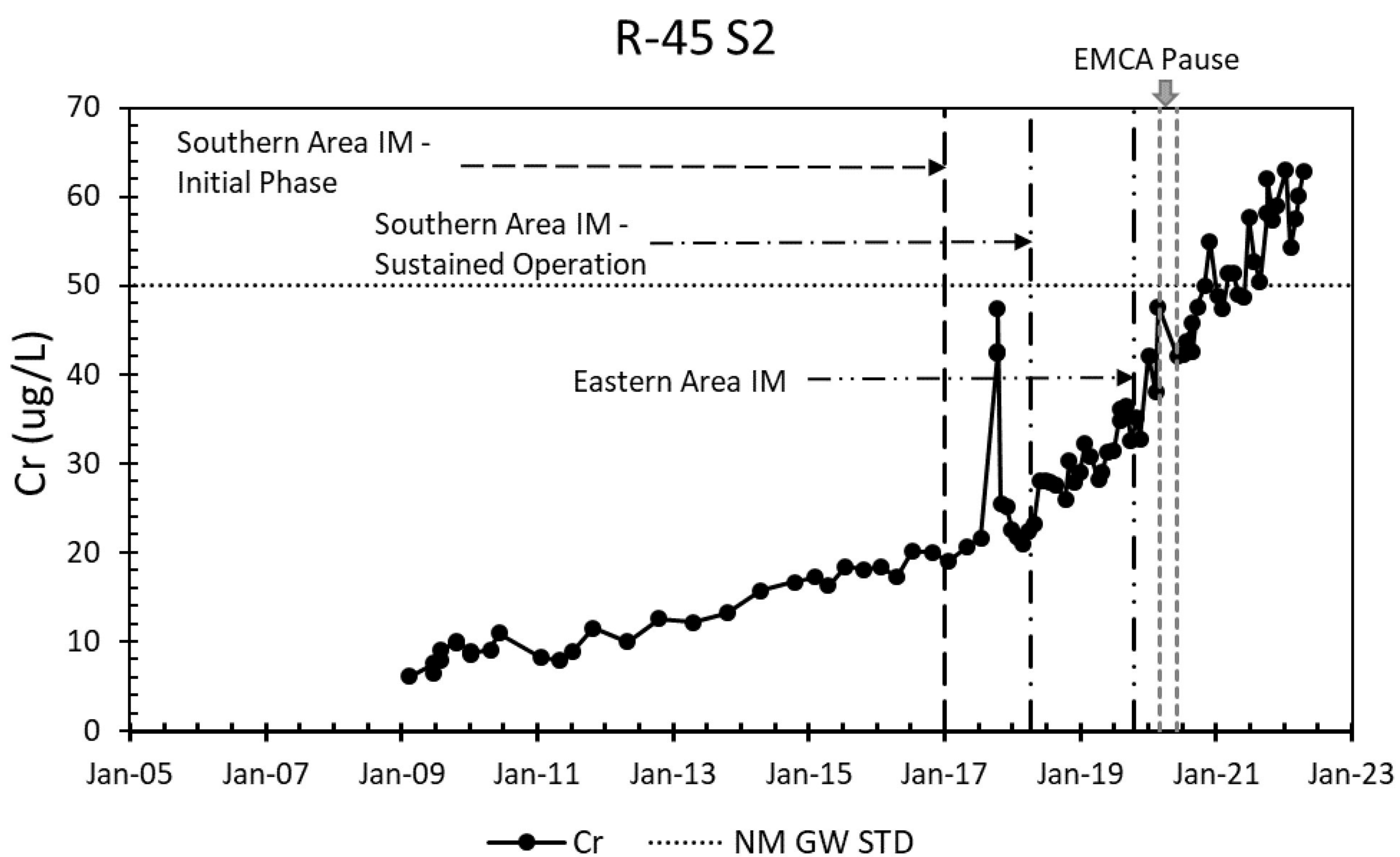


Figure 1.0-2 Chromium investigation area showing present day plume depiction and well locations



Note: IM operational periods are also shown, including the essential mission critical activities (EMCA) pause. S1 = screen 1. NM GW STD = New Mexico groundwater standard.

Figure 1.0-3 Chromium concentrations over time at R-45 screen 1 with the New Mexico groundwater standard shown at 50 µg/L



Note: IM operational periods are also shown, including the essential mission critical activities (EMCA) pause. S2 = screen 2. NM GW STD = New Mexico groundwater standard.

Figure 1.0-4 Chromium concentrations over time at R-45 screen 2 with the New Mexico groundwater standard shown at 50 µg/L

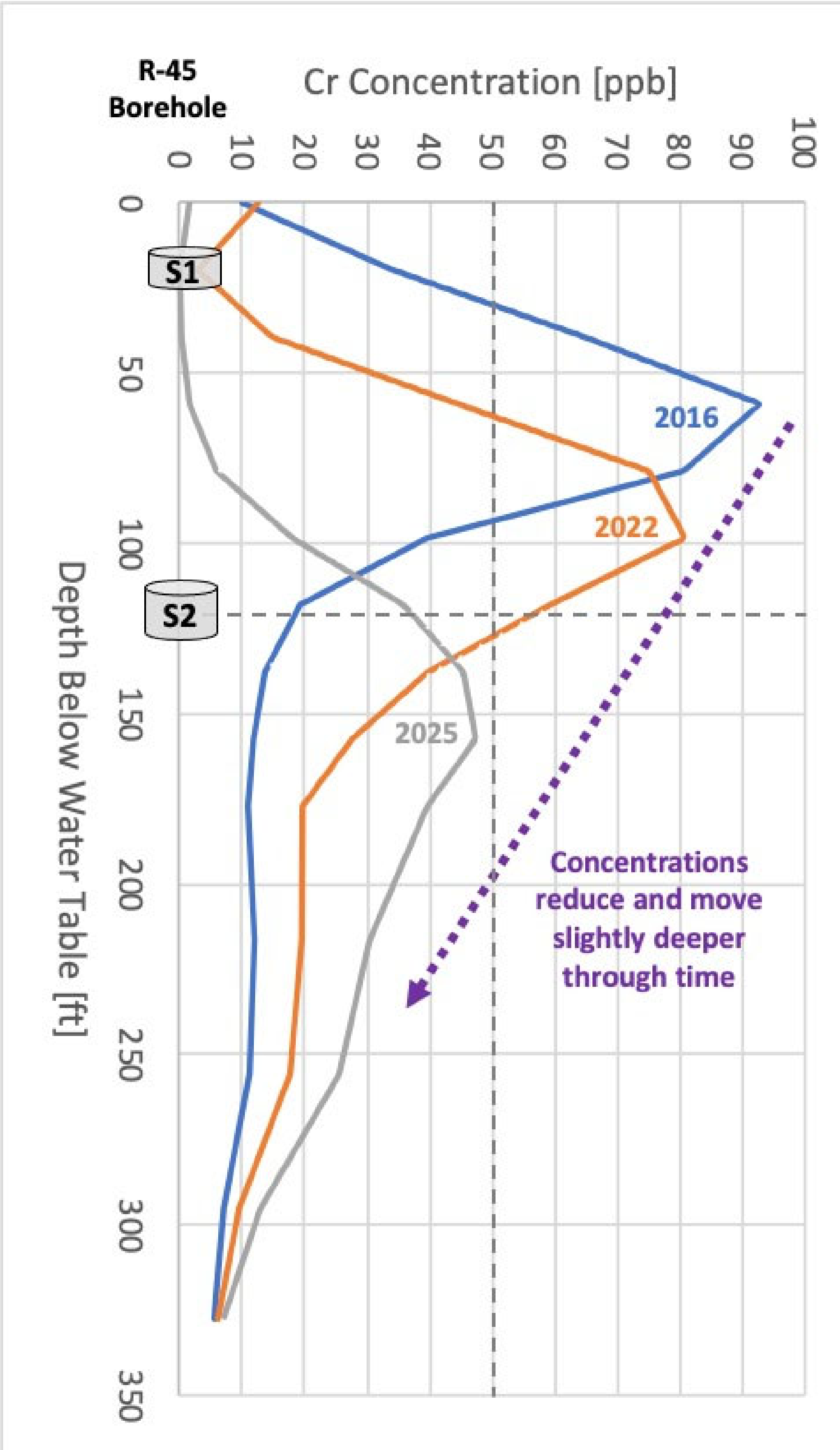
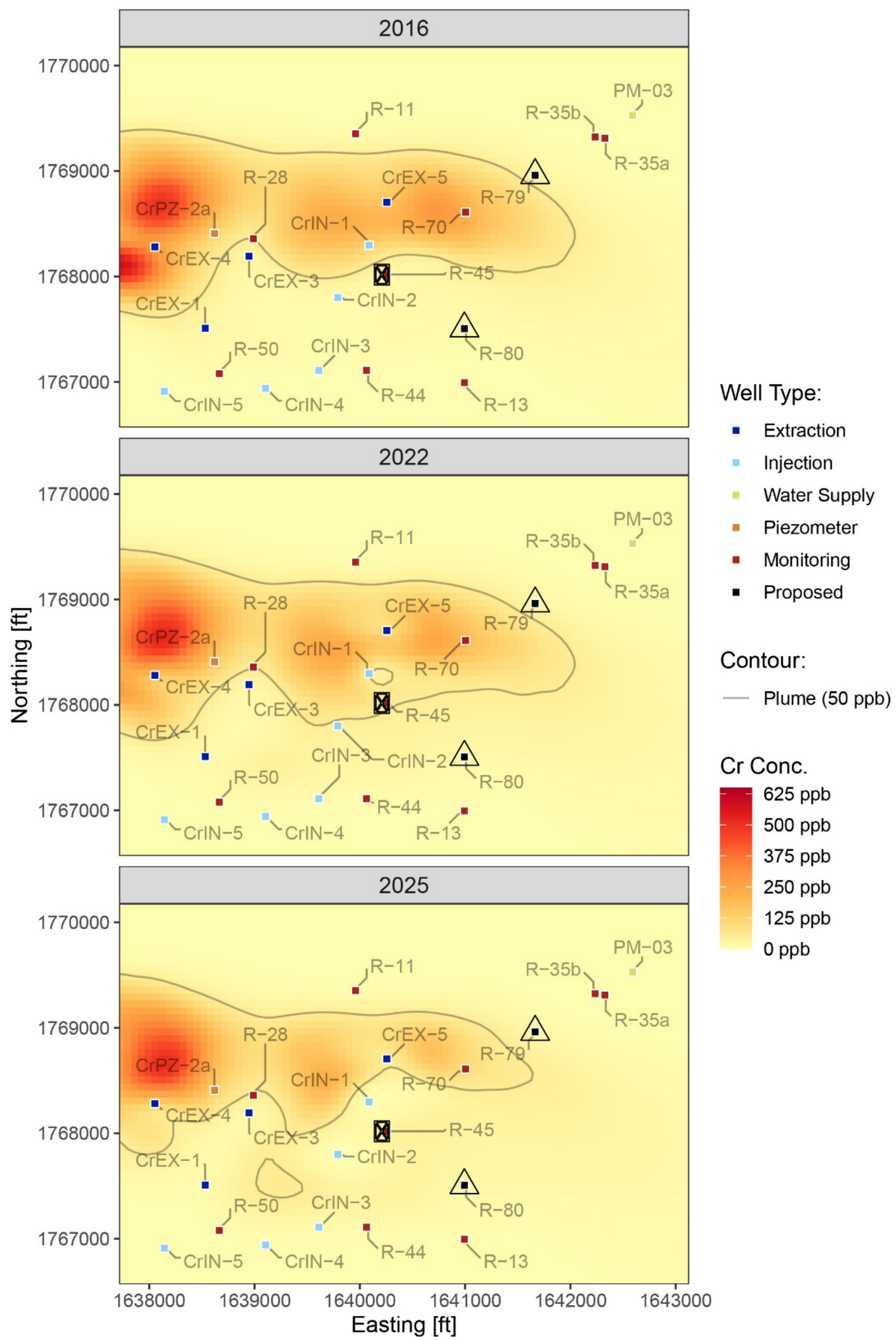


Figure 2.1-1 Simulated chromium concentrations at R-45 with depth over time



The contour represents the 50 ppb.

Figure 2.1-2 Simulated concentration distributions over time at approximately 120 ft below the water table, an equivalent depth to screen 2

Table 2.2-1
Current Nominal Extraction (CrEX) and Injection (CrIN) Well Rates for the Chromium Plume Control IM

Well ID	Flow Rate (gpm)
Injection	
CrIN-1	60
CrIN-2	60
CrIN-3	40
CrIN-4	60
CrIN-5	60
Extraction	
CrEX-1	75
CrEX-2	60
CrEX-3	30
CrEX-4	50
CrEX-5	65

Appendix A

A Conceptual Model Based on Analysis of Pre- and Post-IM Plume Behavior in the Vicinity of R-45

A Conceptual Model Based on Analysis of Pre- and Post-IM Plume Behavior in the Vicinity of R-45

July 5, 2022

This analysis examines data and trends in the concentrations of hexavalent chromium (Cr) and major anions at wells R-45 and nearby wells to understand the behavior of the plume both before and subsequent to the initiation of the chromium Interim Measure (IM).

Observations at R-45 Screen 2 (R-45 S2) have been the subject of a Notice of Violation from the NMED-GWQB due to recent concentrations exceeding the 50 ppb groundwater standard for Cr. This white paper develops a conceptual model through the examination of geochemistry data, including Cr, chloride ion (Cl^-), sulfate ion (SO_4^{2-}), and Nitrate/Nitrite as N (abbreviated as NO_3^- since this species is anticipated to be predominantly nitrate ion in the aquifer).

Site Location and IM Details

Figure 1 shows the location of R-45 and other wells used in this analysis (e.g., R-28, CrIN-1, and CRIN-2). Figure 2 plots the cumulative quantities of fluid extracted and injected in the IM infrastructure wells, that is, extraction wells CrEX-1, -2, -3, -4, and -5, and injection wells CrIN-1, -2, -3, -4, and -5. On a cumulative volume plot, the slope of the curve equals the flow rate: an upward slope indicates operation of the injection or extraction well, whereas a plateau indicates no injection or extraction. Also included on this figure are the times of several key events in IM operation, including the initiation of operations in the southern plume area (initial and sustained), initiation of eastern area operation, and the extended pause in operation for COVID-19-related reasons (EMCA – Essential Mission Critical Activities – pause). These time markers are displayed on subsequent plots to facilitate the data interpretation.

Concentration Trends Prior to IM Operations

Figure 3 shows the time-varying concentrations of Cr, Cl^-, SO_4^{2-}, and NO_3^- at R-45 S1 and S2 from 2009 to the present day. Each of these constituents is expected to be a conservative, nonsorbing, nonreactive species under the geochemical conditions of the aquifer. From 2009 to 2016, prior to IM operations and amendment injections, concentrations of Cr and all major anions had been gradually increasing at both screens at R-45, indicative of an upstream source of elevated concentrations of Cr, Cl^-, SO_4^{2-}, and NO_3^- migrating to the east. This increasing concentration trend is characteristic of a concentration front arriving at a downstream location. During the pre-IM period, chromium and anion concentrations were modestly higher in S1 than in S2. Figure 4 shows the 2016 annual average concentrations of Cr and the anionic species along a flow path from west to east (illustrated in Figure 1), using R-28, CrIN-1, and R-45 S1 analyses in 2016. Data prior to 2017 in CrIN-1 and CrIN-2 correspond to the period prior to injection, and thus represent monitoring data unaffected by fluid injection. The relatively constant, higher concentrations exhibited at R-28 represent a source for down-gradient locations. Concentrations at CrIN-1 and R-45 S1 for Cr and the anion species suggest that by 2016, the plume front had reached R-45 at levels approaching 10% of the upgradient concentrations. Had that source not been influenced by the IM, concentrations would be expected to continue to rise.

To further examine the nature of the plume in the vicinity of R-45, concentrations in the cluster of wells R-45, CrIN-1, and CrIN-2 are treated as a group to visualize the depth dependence of the plume concentration in that area. Figure 5 shows a series of plots of Cr vertical profiles (Figure 5a) and profiles of other species (pre-IM in Figure 5b; discussion of the post-IM data in Figure 5c is deferred until the next section). The data points are located at depths representing the midpoint of the screen associated with the sample, and the intervals of the four screens are shown on Figure 5d. The pre-IM profiles are averages from data collected from these three wells in early- to mid-2016. The pre-IM Cr profile indicates a high-concentration zone between the two screens at R-45 prior to the initiation of the IM. In the vicinity of R-45, a maximum in Cr concentration in the profile at values up to about 100 ppb existed between the two screens of R-45 *before IM operations began*. Concentrations measured in CrIN-1 and CrIN-2 at that time, ranging between about 80 and 100 ppb, were in excess of any value measured in R-45 S2 to date, even those recently measured that are above the 50 ppb standard. A similar pattern of higher concentrations at an intermediate depth (between the R-45 screens) is present in the pre-IM anion profile (Figure 5b). This condition existed before the IM began in 2016.

Concentration Trends Post-IM Operations

R-45 S1 concentrations of all species reached a plateau by the beginning of 2018. Sustained injection into the southern injection area (CrIN-3, CrIN-4, and CrIN-5) began in May 2018, and injections may have played a role in the declines in all concentrations from this point to the start of injection at CrIN-1 and CrIN-2. However, since correlation does not prove causality, it is not possible to prove that the declines are IM related. In late 2019, upon sustained injection of fluid into the eastern plume area, Figure 3 shows an inflection point at which Cr concentration continues to drop, and concentrations of Cl^-, SO_4^{2-}, and NO_3^- concomitantly increase. These trends indicate invasion of injection water into the S1 screened interval. The increases in anion concentrations are most definitive, whereas the continued drop on Cr concentration to very low values suggests that had injection of Cr-free water not occurred, the decrease would have been much more gradual. This is in contrast to the earlier, Cr plume arrival trends, which appear as a gradual increase in concentrations.

For R-45 S2, starting in 2018, there is an increase in the rate of change of concentrations of all species concurrent with IM injection water initiated in the southern injection area starting in May 2018. When the eastern plume area began receiving injection fluid in late 2019, the concentrations of all species continued to increase, but without the signature of injection water having entered the monitoring horizon, as was observed in S1. Given the proximity of CrIN-1 and CrIN-2 to R-45, and the definitive impact of that injection on S1, it is likely that eastern area injection has had some impact on R-45 S2 concentrations as well. However, a more quantitative analysis will assist in understanding of the source of injection water impacts.

These effects are also reflected in the post-IM concentration profiles in Figure 5. Post-IM samples were collected from the injection wells after the 2020 COVID-related pause, before resuming IM operation. The interval encompassing R-45 S1, CrIN-1, and CrIN-2 have the characteristic of injection fluid, with low Cr concentration (Figure 5a) and anions reaching concentrations associated with injection water (Figure 5c). R-45 S2 post-IM values of all species are more indicative of their pre-IM values, with trends as described above.

Conceptual Model of IM Injection Water Impacts at R-45

After initiation of the IM in the eastern area, a zone heavily influenced by injection water was created from R-45 S1 down to at least the depth of the bottom of CrIN-1 and CrIN-2 (about 60 ft below the water table). This injection water is characterized by low Cr concentrations and high concentrations of Cl^- and SO_4^{2-}. Nitrate concentrations in the aquifer at this location are relatively unchanged by injection because the concentration in the injection fluid is approximately equal to aquifer concentrations. Since the injection fluid geochemical signature, with low Cr and high Cl^- and SO_4^{2-} concentrations, is not observed in R-45 S2, this implies that the spatial extent of the injected water in the vertical downward direction is in between the bottom depth of the CrIN-well screens (approximately 60 ft below the water table) and R-45 S2. Given that there is no removal of Cr mass in this location, the Cr contamination maximum between S1 and S2 was likely pushed downward, increasing concentrations at R-45 Screen 2. Along with this displacement, the maximum Cr concentrations in the R-45 vertical profile are reduced due to dilution. The modest increases in Cr, Cl^-, and SO_4^{2-} concentrations in R-45 S2 since the initiation of the IM are consistent with this explanation, as the Cr/Cl^-/SO_4^{2-} plume is displaced to greater depths.

In this conceptualization, the peak concentration of Cr in the vertical profile at R-45 is still between the elevation of S1 and S2 (i.e., between the bottom of the CrIN-well screens and R-45 S2), and due to dilution is less than the 95 ppb observed at CrIN-2 in the pre-IM samples. The peak concentration in the profile is likely shifted downward due to injection, with decreasing Cr concentrations over time due to dilution. This outcome is shown schematically in Figure 6, in which conceptual concentration profiles (the curves in the figure) are drawn along with the data for the pre-IM and post-IM time frames and present day (March 2022 for this analysis). A conceptual present-day profile that honors measured concentrations at R-45 S1 and S2 as of March, 2022 is also drawn. If this conceptual model is valid, continued injection in this area will eventually be seen through signatures of injection fluid at R-45 S2. A plateau and eventual decline in Cr concentration (eventually approaching non-detect levels), and further increases of Cl^- and SO_4^{2-} to values representative of injection fluid (~20-25 ppm for each of these anions) would provide additional confidence in this data-based conceptual model.

Uncertainties in this depiction arise from the relatively long screens in CrIN-1 and CrIN-2, which result in depth-averaged concentrations, preventing a precise profile from being plotted. Nevertheless, the depiction of a gradual shift of the plume to greater depths is more consistent with the data than the alternative of a large vertical downward displacement of the center of Cr mass to depths greater than R-45 S2, because the latter would have already been accompanied by a distinct geochemical signature indicative of injection fluid (low Cr, high Cl^- and SO_4^{2-} concentrations) at the lower screen, which was not observed. This conceptual model is also supported by observations at well R-50. At that two-screen well, which is similarly positioned near a multi-well injection zone, there is no indication of large downward displacement of the plume. The rate of downward displacement due to injection appears to be a relatively slow process.

While it is possible that a deep plume exists beneath R-45 S2, it would have been the result of pre-IM migration at depths below R-45 S2 (~120 ft below the water table), rather than as a result of IM operation. To date, there is no information that indicates that the plume has been travelling through this portion of the aquifer at these depths. Future monitoring wells would provide additional confirmation of this conclusion.

Finally, this analysis provides a simple, data-driven description of the likely processes taking place near R-45 both before and after commencement of IM operations. It is possible that the IM could also be inducing more complex plume dynamics such as shifts in lateral migration and the curtailment of the upstream source by extraction. The potential effects of these processes, as well as the vertical flow component postulated in this white paper, should be examined quantitatively with a numerical model.

Summary

- Concentrations at R-45, as well as CrIN-1 and CrIN-2 before initiation of the IM, indicate that a Cr front accompanied by elevated anion concentrations has been migrating from the core of the plume into this region of the aquifer since at least the early 2000's;
- Cr concentrations within the plume in the vicinity of R-45 appear to be at their maximum at depths between R-45 S1 and S2;
- The concentrations at R-45 at this intermediate depth were well in excess of 50 ppb, even before the initiation of the IM;
- Injection fluid from the IM has been directly detected at R-45 S1;
- Injection appears to have impacted the geochemistry at R-45 S2 indirectly via a process of dilution and pushing the plume downward into the S2 horizon, causing a moderate rise in concentration at the S2 horizon;
- The maximum concentrations in this region are still between S1 and S2, rather than having been pushed below S2. If concentrations greater than 50 ppb exist at depths significantly below S2, they would have had to migrate there before commencement of the IM. To date, there is no indication of contamination at these depths;
- An additional monitoring location in this region would provide additional information to strengthen the conceptual model;
- Results from a calibrated numerical model will help to validate or disprove this conceptual model, uncover other relevant mechanisms, and provide the ability to quantify the impacts and identify the most effective corrective action to reduce chromium concentrations.

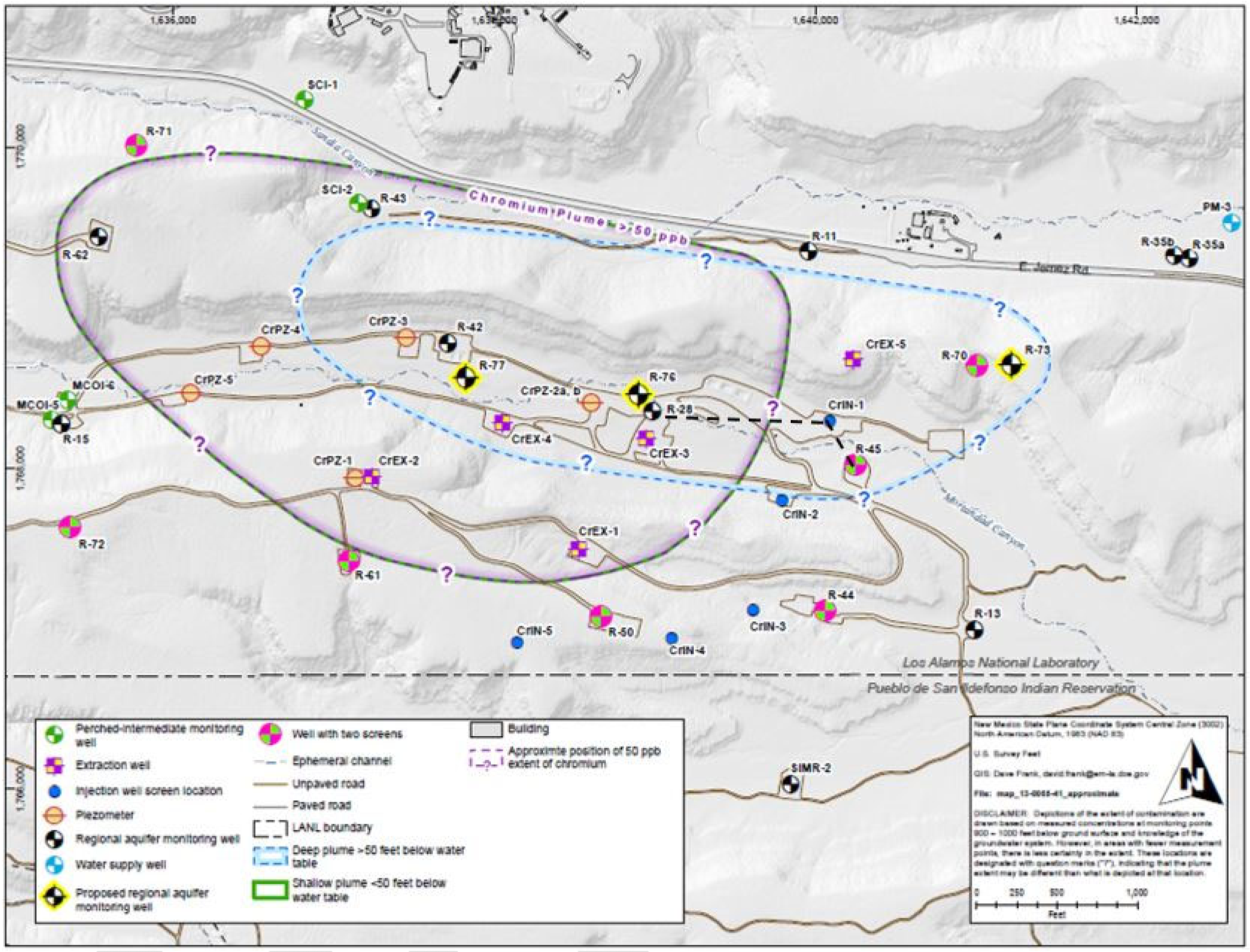


Figure 1. Location map and depiction of shallow and deep plumes at the Chromium plume. Dashed black line shows a “fence line” from R-28 to CrIN-1 to R-45, used to illustrate the concentration profiles along the plume transport pathway.

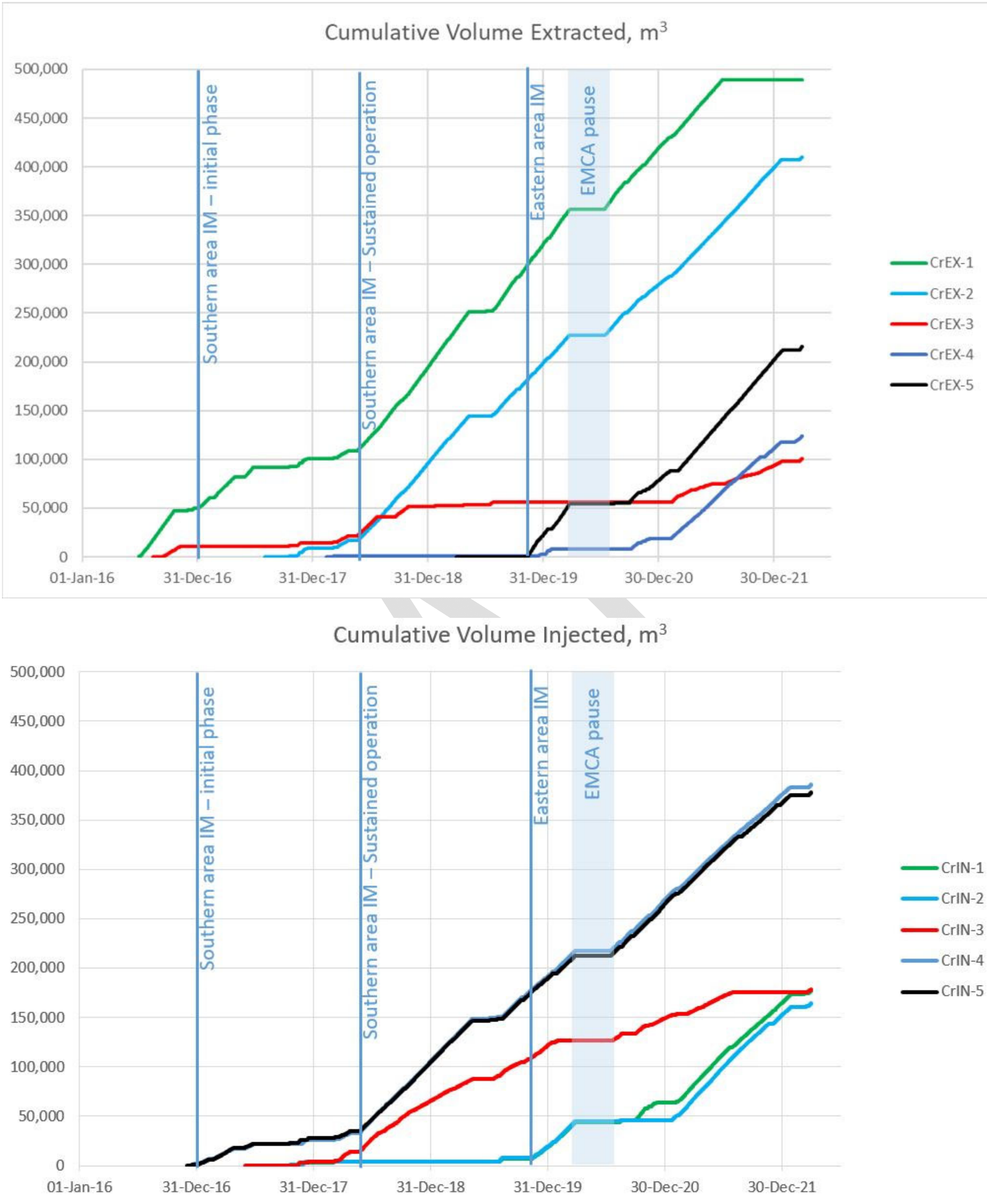


Figure 2. Cumulative extraction volumes (upper panel) and injection volumes (lower panel) throughout the operation of the Interim Measure. Vertical lines represent time markers for key changes in IM operations.

R-45 S1 R-45 S2

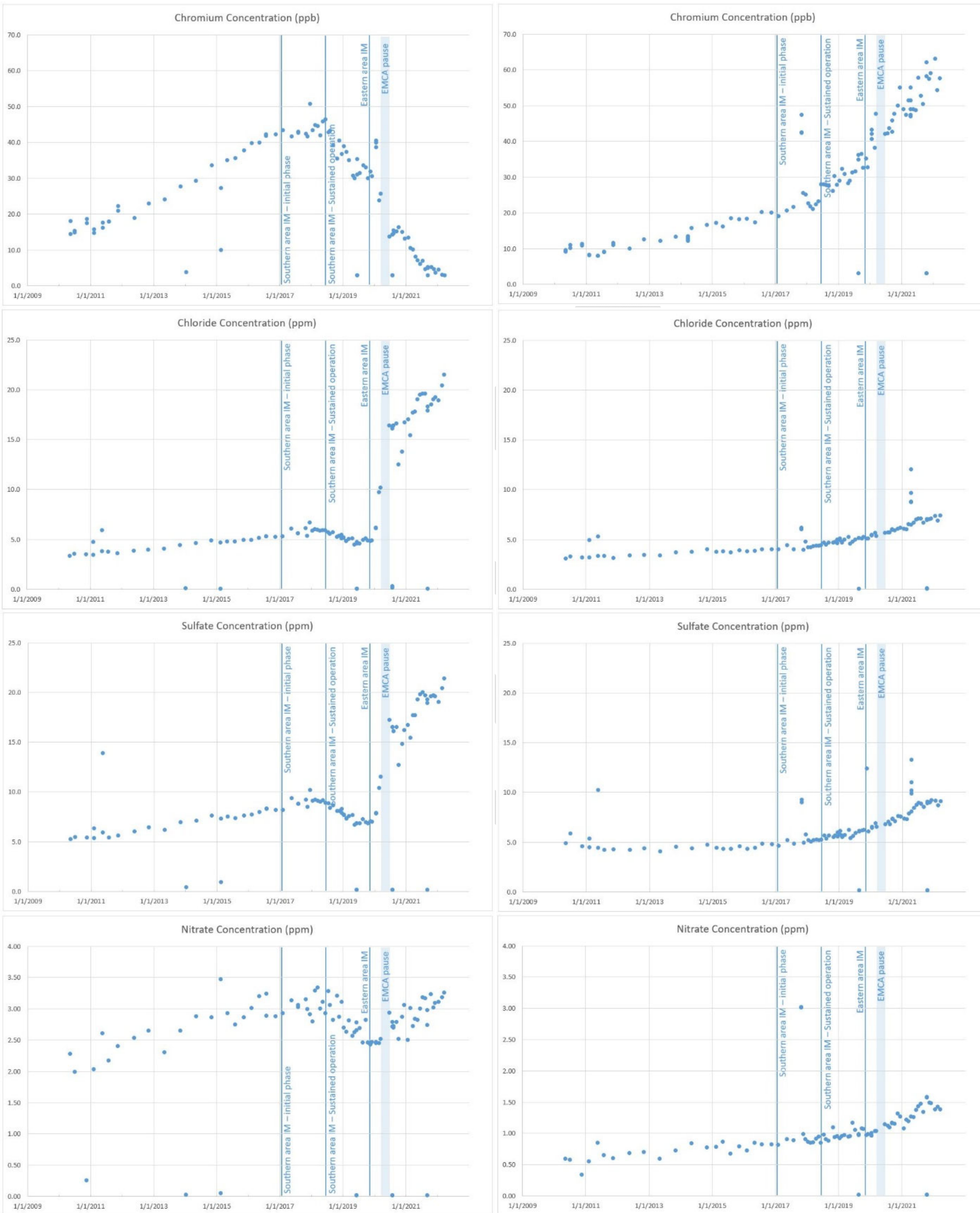


Figure 3. Chromium and anion concentrations at R-45. Left panels: Screen 1. Right panels: Screen 2.

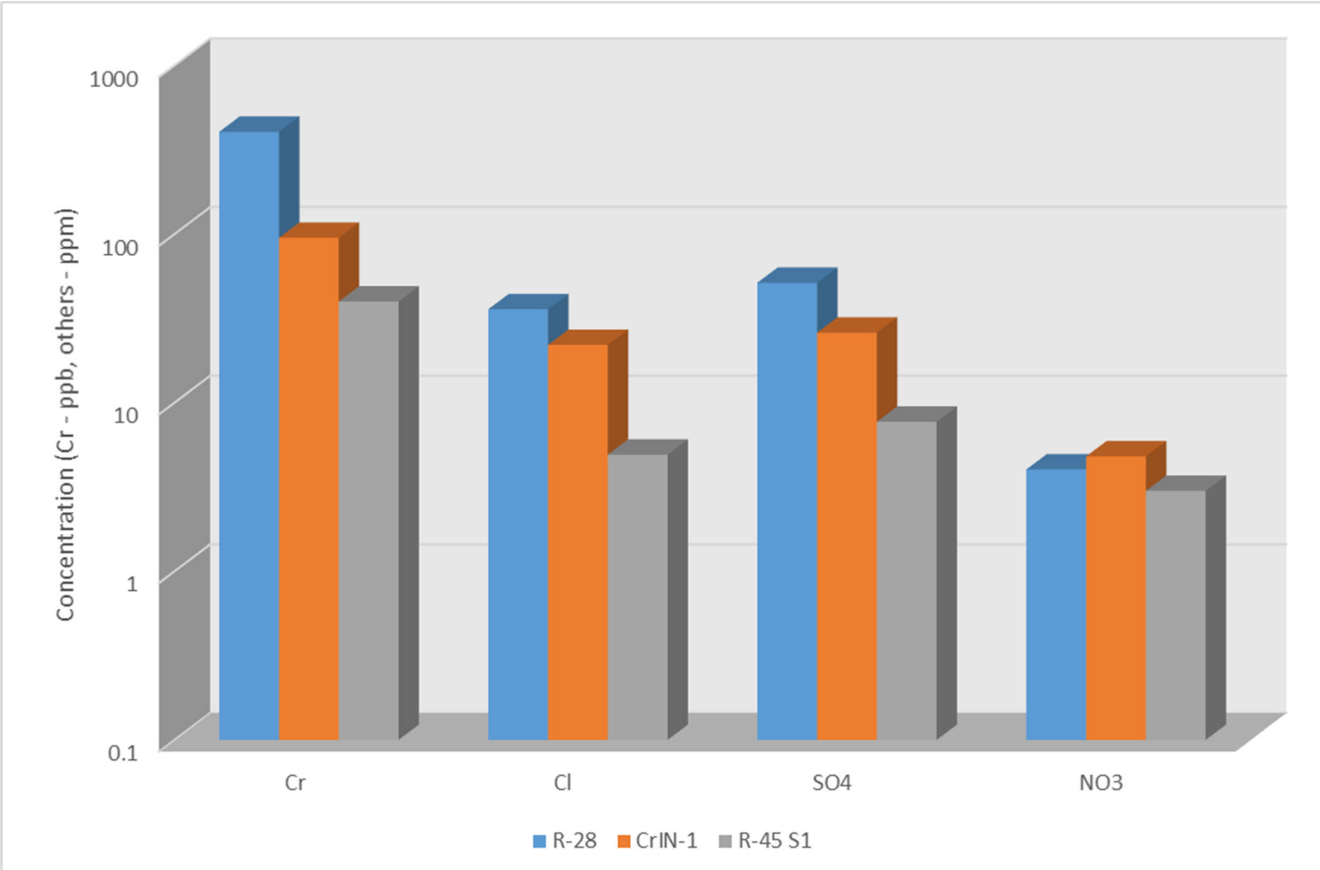


Figure 4. Geochemistry along flow path: Concentrations of species at R-28 and down-gradient locations CrIN-1 and R-45 S1 before amendments and initiation of IM (data from 2016).

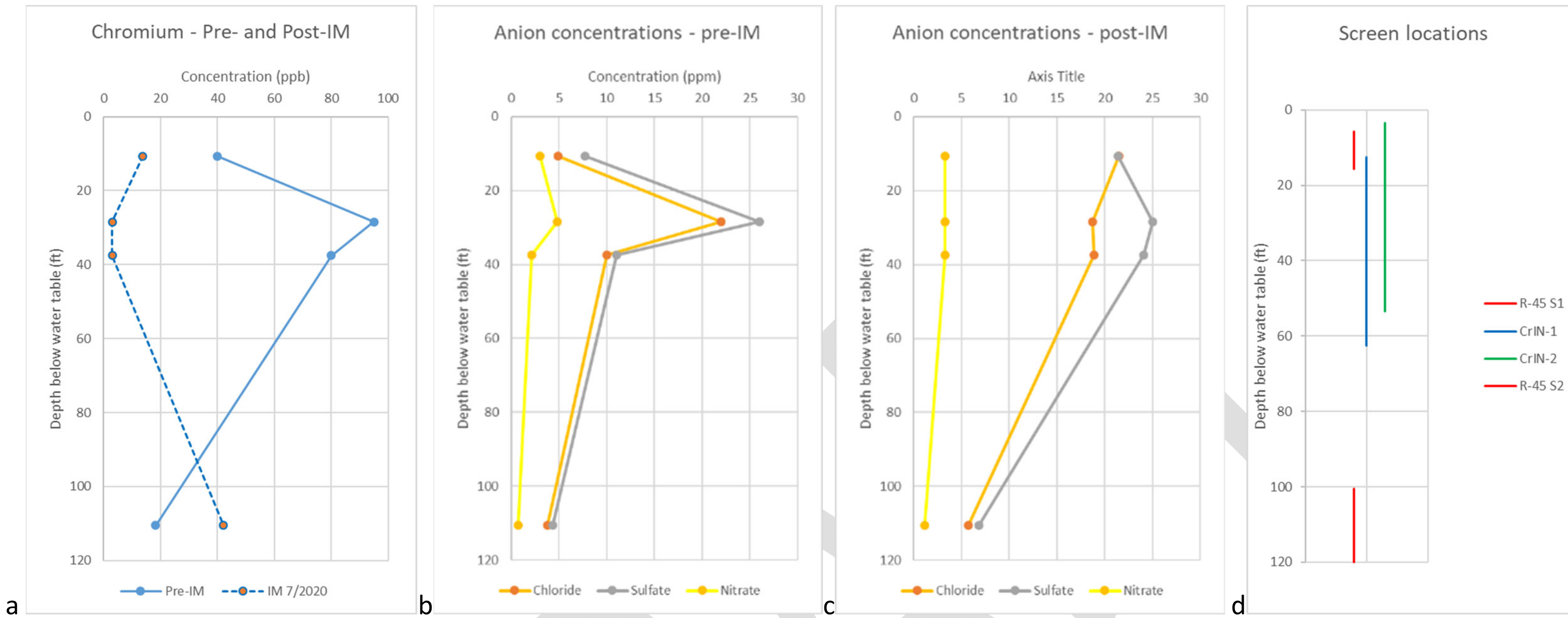


Figure 5. Concentration profiles in the vicinity of R-45, CrIN-1, and CrIN-2. a) Cr Pre- and post-IM concentrations; b) Anion pre-IM concentrations; c) Anion post-IM concentrations; d) Screened intervals of R-45 S1, CrIN-1, CrIN-2, and R-45 S2.

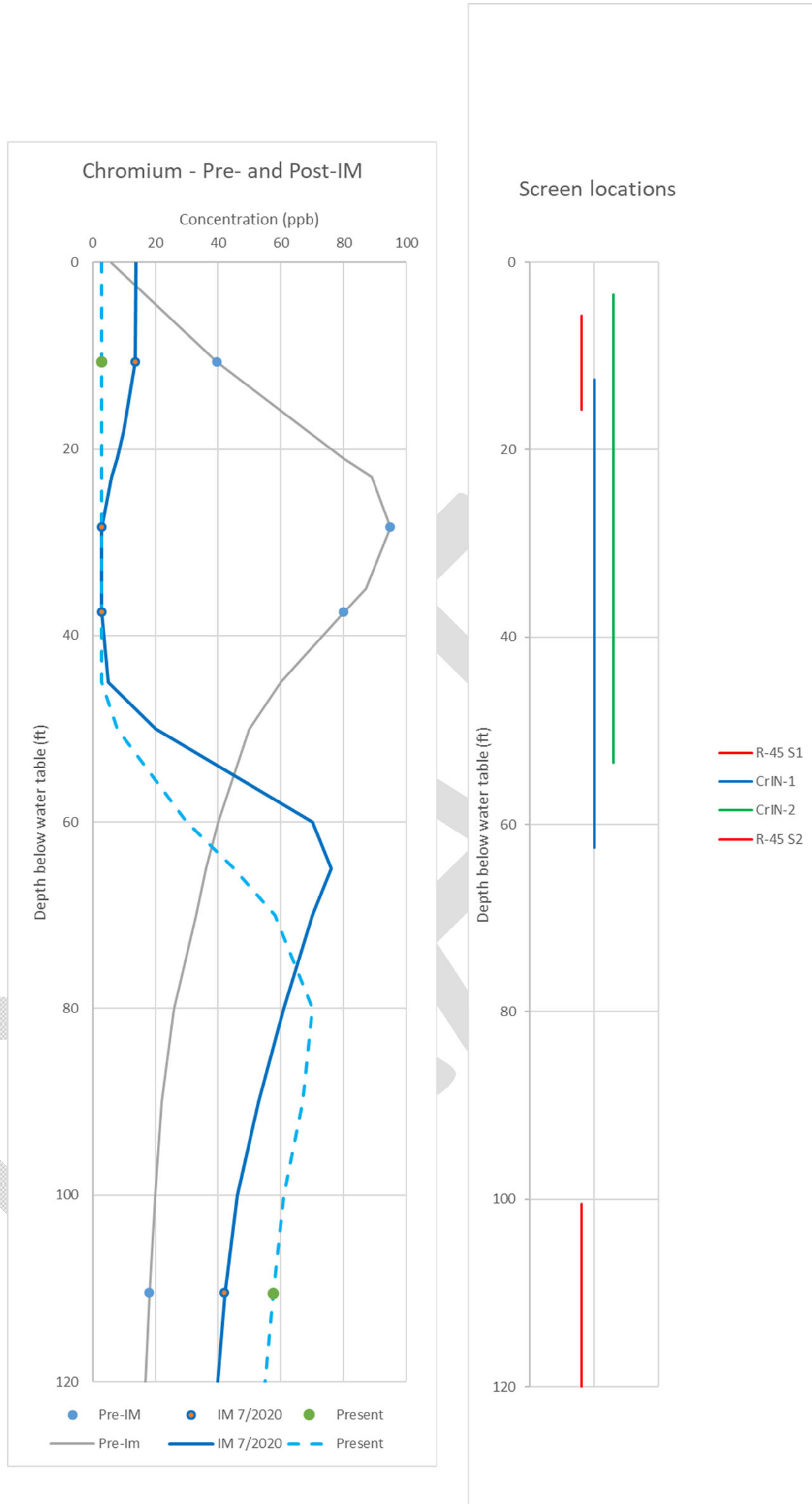


Figure 6. Conceptual depiction of Cr concentration profiles pre-IM (spring/summer 2016), post-IM (July 2020), and present day (dashed line). Points represent measured concentrations, and the screen lengths and depths are depicted on the right panel.