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Date: February 28, 2023
Refer To: N3B-2023-0067

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

Subject: Submittal of Initial Five-Year Evaluation of the Interim Measures for Chromium Plume Control with an Assessment of Potential Modifications to Operations

Reference: 1. New Mexico Environment Department Hazardous Waste Bureau email, N. Dhawan to A.Q. Duran, "RE: Notification of Cr Extraction/Injection Well Shutdown," dated November 21, 2022.

Dear Mr. Ball:

On June 6, 2022, the New Mexico Environment Department Groundwater Quality Bureau (NMED-GWQB) issued "Notice of Violation, Los Alamos National Laboratory Underground Injection Control Wells, DP-1835" to the U.S. Department of Energy Environmental Management Los Alamos Field Office (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.

On September 30, 2022, EM-LA submitted the "Regional Aquifer Monitoring Well R-45 Action Plan," (R-45 Action Plan) providing activities that EM-LA proposed for addressing chromium in the regional aquifer. On December 12, 2022, NMED-GWQB provided a review of the R-45 Action Plan and direction to cease all injection of treated water authorized under Discharge Permit 1835 by April 1, 2023, "until the Permittees complete the proposed corrective actions and can definitively prove through qualitative and quantitative analyses, simulations, monitoring well installation, and continued monitoring that further migration is not occurring." Although the installation of the two new monitoring wells described in the R-45 Action Plan cannot reasonably be completed by April 1, 2023, monitoring of the chromium project area is ongoing and will continue to contribute to the evaluation of the interim measures (IM) system.

To address NMED-GWQB concerns associated with the IM influence on the regional aquifer and chromium plume migration, EM-LA has prepared an initial assessment of the IM. Two hard copies with electronic files of the document entitled "Initial Five-Year Evaluation of the Interim Measures for Chromium Plume Control with an Assessment of Potential Modifications to Operations" are enclosed for NMED-GWQB review and evaluation.

This document presents an analysis of the IM influence on the regional aquifer system in the vicinity of the chromium plume, along with a predictive assessment of potential impacts associated with modifying IM operations. The analysis of the IM influence on the regional aquifer examined potentiometric surfaces, chromium concentrations, and concentrations of injected tracers and natural tracers resulting from groundwater treatment. In addition, a calibrated numerical model of the chromium plume area has been used to supplement the assessment of chromium plume migration, specifically by supporting the evaluation of extraction well capture and examining IM performance under different operational scenarios. The analyses in this document also address the NMED-GWQB direction in a letter dated December 12, 2002, "…to control the cause of the contamination migration and prevent further migration of the contamination plume." Results of the data-driven and numerical modeling analyses support the conclusion that groundwater located at R-45 screen 2 is captured by the extraction wells. The cause for an increase in chromium concentrations at this location is the migration of a zone of chromium concentrations that existed between the two well screens at R-45 before the commencement of IM operations. Hence, planned monitoring well R-80 is needed on a priority basis to either confirm or refute this conclusion and provide additional performance monitoring data downgradient of R-45.

EM-LA notes that cessation of injection into existing injection wells will severely hamper the ability to operate the IM system because of the need to disposition treated groundwater. While land application is a possible option, there are several limitations on the conditions under which land application can occur. The most significant restrictions are the prohibition of land application under freezing conditions, during precipitation events, and under ponding conditions. Land application can occur only during daylight hours for a maximum of 10 hours per day. This means that land application can occur for a maximum of 7 months per year, and only during daylight hours, with the monsoon season further restricting the number of hours that land application can occur. Apart from weather restrictions, land application of treated water requires that the water be treated to 90% of the numeric standards for chromium and other analytes. Currently, a nominal 10-day turnaround time exists with a state-certified analytical laboratory to verify that the treated water can be land-applied.

Streamlined implementation of land application as an alternative method of dispositioning treated wastewater will require additional actions, including potential modifications of Discharge Permit 1793 to address logistical bottlenecks (e.g., Conditions #4 and #7). Without these modifications, land application can accommodate only about 1% of the extraction system capacity. Additionally, land application will require obtaining water rights for consumptive use associated with the IM, which requires (1) reapplication to the New Mexico Office of the State Engineer for change in use of water and additional points of diversion and (2) a request for emergency authorization to include consumptive use of water rights for the IM.

Numerical modeling predictions are presented on concentration changes at monitoring wells under different operational scenarios: (1) full operations, (2) current reduced operations consistent with the NMED Hazardous Waste Bureau direction of November 21, 2022 (Reference 1), (3) land-application only, and (4) no operations. These simulations are an initial evaluation to be used as a basis for further optimization of potential IM operational changes. Modeling results demonstrate that given the wait time required for dispositioning the treated water, and logistics associated with the land application of the treated water, IM operations under a land-application only scenario is functionally equivalent to a complete cessation of IM operations with respect to control of the chromium plume.

Of the four operational scenarios, the full-IM operational scenario is predicted to be the most successful at maintaining hydraulic plume control and reducing concentrations at monitoring and extraction wells. The full-IM operations scenario is the only scenario that predicts a concentration reduction at R-45 screen 2 to below the New Mexico Administrative Code standard of 0.050 mg/L within the approximate 4-year simulation timeframe.

Based on this assessment, EM-LA recommends the following:

- The IM system should continue to be operated at full capacity to maximize hydraulic plume control and chromium concentration reduction.
- The installation of R-79 and R-80, as recommended in the R-45 Action Plan, should be a priority.
- Continued extraction at CrEX-5 should be a priority for the IM going forward.

Deep extraction does not appear to be necessary at this time to continue to achieve IM objectives but may emerge as a priority, pending analyses that will become available when deeper monitoring wells (R-76 and R-77) are installed.

EM-LA invites NMED-GWQB input in the continued evaluation of the IM and further input on optimizing potential modifications to IM operations.

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

1. Initial Five-Year Evaluation of the Interim Measures for Chromium Plume Control with an Assessment of Potential Modifications to Operations (EM2023-0067)

cc (letter with CD/DVD enclosure[s]):
Laurie King, EPA Region 6, Dallas, TX
Jason Herman, NMED-GWQB
Pat Longmire, NMED-GWQB
Neelam Dhawan, NMED-HWB
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cc (letter and enclosure[s] emailed):
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M. Lee Bishop, DOE EM-LA
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February 2023
EM2023-0067

Initial Five-Year Evaluation of the Interim Measures for Chromium Plume Control with an Assessment of Potential Modifications to Operations

EXECUTIVE SUMMARY

This document presents an analysis of the interim measures (IM) for chromium plume control influence on the regional aquifer system in the vicinity of the chromium plume, along with a predictive assessment of potential impacts associated with modifying IM operations. This document also provides recommendations on the future operation of the IM, based on the examination of past behavior and the use of a numerical model to predict future behavior under different operational scenarios. These simulations are considered to be an initial evaluation and are to be used as a basis for further optimization of potential IM operational changes.

The analyses in this document also address the New Mexico Environment Department Ground Water Quality Bureau (NMED-GWQB) direction in a letter dated December 12, 2022, "…to control the cause of the contamination migration and prevent further migration of the contamination plume." In that letter, NMED-GWQB directed the U.S. Department of Energy Environmental Management Los Alamos Field Office to cease "…all injection activities until the Permittees complete the proposed corrective actions and can definitively prove through qualitative and quantitative analyses, simulations, monitoring well installation, and continued monitoring that further migration is not occurring." This document provides the requested analyses and information to meet the specified April 1, 2023, date for completing these actions. Although the installation of two new monitoring wells cannot be completed by April 1, monitoring of the chromium project area is ongoing and will continue to contribute to the evaluation of the IM system provided in this document.

The NMED-GWQB letter states, "cessation of all injection activities does not inhibit the Permittee from the continued operation of the ion exchange treatment system by utilizing a different treated groundwater disposal option." With the only other permitted means to discharge treated groundwater being Discharge Permit (DP) 1793, the letter implies land application of treated water as a viable option for disposition of treated water. However, given the current system configuration and limitations associated with lagoon capacity and turnaround times on water quality sampling, dispositioning treated water reduces IM operations by nearly 99% relative to full IM operations which extracts, treats, and injects at a nominal rate of 280 gallons per minute (gpm). This reduction is due to the restrictions associated with land application, including the inability to land-apply water when temperatures are below freezing, during precipitation events, and under ponding conditions. Due to turnaround times associated with water quality sampling before land application of water and the requirement that all land-application activities be supervised and occur during daylight hours for no more than 10 hr per day, the IM could effectively extract for only 3 days at 140 gpm, 8-hr per day, filling each lagoon to capacity (200,000-gal. capacity each for a total of 600,000 gal. for all three lagoons). This results in a nominal 2-week period needed to sample and disposition the treated water following the 3 days of treatment. These activities could be executed only 6–7 months per year to meet the terms and conditions of the permit.

Given the limitations associated with land application, engineering changes to the IM system as well as changes to conditions for land application will likely be needed to maximize the disposition of water through land application if it becomes the only option for dispositioning treated water. Although the engineering changes could be accomplished in approximately 1 year, any modifications to Discharge Permit 1793 needed to maximize land application are estimated to require at least 2 years 8 months, based on historical timeframes needed for writing, reviewing, and approving changes.

The evidence at the time the IM system was designed suggested that the chromium plume was located predominantly in the upper 50 ft of the aquifer, and the IM injection and extraction wells were designed accordingly. Assessment of the system response after more than 5 years of sustained operations and the installation of additional monitoring wells indicates that while the conceptual site model (CSM) for

chromium at shallow depths has been confirmed for the southern plume area, chromium plume concentrations in the eastern plume area have shown an opposite trend, with relatively high chromium concentrations at depths greater than 50 ft below the water table. This shift in the CSM plays an important role in conclusions and recommendations.

The analysis of the IM influence on the regional aquifer examined potentiometric surfaces, chromium concentrations, and concentrations of injected tracers and natural tracers resulting from groundwater treatment (e.g., chloride and sulfate). The results of these analyses demonstrate that changes in the water table configuration responded slowly to each phase of the IM system, requiring approximately 1 year to achieve equilibrium from sustained operations, given the relatively high hydraulic conductivity of basin sediments and the low gradient in the chromium investigation area. At the water table, once full operations were achieved and the system achieved equilibrium, a groundwater divide had formed between the cone of depression formed by extraction wells near the centroid of the plume and the five injection wells positioned along the plume periphery. Because of the flat hydraulic gradients and relatively high hydraulic conductivities in the regional aquifer, a distinct mound from injection has not formed. However, the impacts from injection can be identified along the area of the divide, indicating in general, there is effective hydraulic containment of the plume over a broad area.

Natural and injected tracers also elucidate the influence of IM operations on flow patterns in the plume area. To date, tracers introduced in injection wells and the distinct geochemical signature of injection water are present only in the shallow upper 50 ft of the aquifer in only the upper screens at wells R-44, R-45, and R-50. There is no evidence to date of injection water migration below depths of the lower screens.

Since the initiation of IM operations, chromium concentrations have decreased in all five extraction wells, as well as at R-50 screen 1 and several other monitoring locations (e.g., R-11, R-15, R-44 screen 1, R-45 screen 1, and R-70 screens 1 and 2). The R-50 result indicates that the principal objective of the IM has been met, namely to reduce chromium concentrations and to shift the 50-ppb chromium concentration contour north of the Los Alamos National Laboratory boundary. A significantly sized “clean zone” of chromium-free water is now present along the line of injection wells, including the region between R-50 and CrEX-1. Furthermore, there is no evidence that the effects of IM operation have forced chromium concentrations as deep as R-50 screen 2, situated approximately 110 ft below the water table. Thus, the IM has been successful in reducing concentrations along the southern boundary of the plume and creating a hydraulic barrier to flow in the southern plume area.

Although chromium concentrations were increasing before IM operations, notable increases in chromium concentration have occurred at two locations: R-45 screen 2 and R-61 screen 1. Currently, chromium concentrations at R-61 are below the New Mexico Administrative Code (NMAC) groundwater standard (except for a single measurement of 51 ppb), and the cause for the increasing trend is under investigation by means of data analyses and numerical modeling. For R-45, it is likely that a zone of chromium concentrations higher than in either screen existed between the two well screens at R-45 before IM operations. Once sustained eastern area operations commenced, injection water caused the moderate concentration zone to migrate to the depth of the bottom of the lower well screen (~120 ft below the water table). Capture zone analyses, however, indicate that in the south and southeastern regions of the plume, specifically at the depth of R-45 screen 2, the IM extraction wells (e.g., CrEX-5 and CrEX-3) capture groundwater. In addition, decreasing concentration trends at R-70 screen 2 and CrEX-5 indicate that CrEX-5 extracts chromium concentrations at depth, potentially capturing groundwater from R-45 screen 2 as well.

As specified by one of the actions identified in the R-45 Action Plan, well R-80 will be located 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. The upper screen will be located at an equivalent depth to that of R-45 screen 2. 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. If chromium concentration data are below the NMAC standard at R-80 at both screen locations, these data will confirm that the IM is capturing chromium at the depth of R-45 screen 2. However, this result is dependent on continued IM operations.

The capture zone analysis also identified that the northwest plume area, north of R-70, is a region where the IM may be unsuccessful in maintaining hydraulic control of the plume. This result is based on numerical modeling that explores uncertainty in potential chromium migration pathways, with 25% of the simulations resulting in a potential northern migration pathway. Hence, another action identified in the R-45 Action Plan specified that well R-79 will further delineate the lateral and vertical extents of chromium concentrations in this area. Given high chromium concentrations at depth identified with R-70 (e.g., 200 ppb), and the similar decline in concentration at both R-70 screen 2 and CrEX-5, continued operation of extraction well CrEX-5 is critical for continued hydraulic plume control in this region of the plume.

The second objective of numerical simulations is to provide a basis for decision-making on potential modifications to IM operations. The operational scenarios include full operations, reduced operations as the system is currently configured (CrEX-4, CrEX-5, CrIN-4, and CrIN-5), extraction with land application instead of injection, and no operations. The current system configuration operates at half capacity (140 gpm) due to maintenance issues that have resulted in the shutdown of three extraction wells, with three injection wells also shut down to load-balance the system. Of the four operational scenarios, the full IM operational scenario is predicted to be the most successful at maintaining hydraulic plume control and reducing concentrations at monitoring and extraction wells. The full IM operations scenario is the only scenario that reduces concentrations at R-45 screen 2 to below the NMAC standard of 0.050 mg/L (50 ppb) within the simulation timeframe of present day through the end of calendar year 2026. At the other extreme, the complete shutdown and land-application-only scenarios allow for rebound of the system and an eventual loss of plume containment achieved by the IM to date. The highest risk to ceasing IM operations is in the northeastern region of the plume, near CrEX-5 and R-70.

The following recommendations are based on the results of the analyses presented in this study:

- The IM system should continue to be operated at full capacity to maximize hydraulic plume control and chromium concentration reduction.
- Continued extraction at CrEX-5 should be a priority for the IM going forward.
- Planned monitoring wells R-79 and R-80 are needed on a priority basis to reduce uncertainties and to provide additional performance monitoring.

Deep extraction does not appear to be necessary at this time to continue to achieve IM objectives but may emerge as a priority, pending analyses that will become available when deeper monitoring wells (R-76 and R-77) are installed.

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1.0 INTRODUCTION

On June 6, 2022, the New Mexico Environment Department Ground Water Quality Bureau (NMED-GWQB) issued a notice of violation to the U.S. Department of Energy (DOE) Environmental Management Los Alamos Field Office (EM-LA) under Underground Injection Control Wells, Discharge Permit 1835 (DP-1835) based on measured concentrations of total dissolved chromium in the regional aquifer at well R-45 screen 2 (Figure 1.0-1) that exceeded the 20.6.2.3103 New Mexico Administrative Code (NMAC) groundwater standard of 0.050 mg/L (50 ppb) (NMED 2022, 702153). On September 30, 2022, EM-LA submitted the “Regional Aquifer Monitoring Well R-45 Action Plan” (R-45 Action Plan), which included a description of four proposed actions to address NMED-GWQB expectations for addressing chromium in the regional aquifer at regional aquifer monitoring well R-45 screen 2 as directed (N3B 2022, 702350). These four actions included

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 50-ppb 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.

NMED-GWQB responded that these actions were acceptable in a letter dated December 12, 2022 (NMED 2022, 702464). However, NMED-GWQB requested additional actions “…to control the cause of the contamination migration and prevent further migration of the contamination plume.” The letter also directed EM-LA that by “April 1, 2023, the Permittees shall cease all injections authorized under DP-1835 to prevent any potential further migration of chromium contamination. Cessation shall include all injection activities until the Permittees complete the proposed corrective actions and can definitively prove through qualitative and quantitative analyses, simulations, monitoring well installation, and continued monitoring that further migration is not occurring.”

Although some of the accepted actions can be completed by April 1, 2023, Action 3, monitoring well installation and collection of representative samples from wells R-79 and R-80, will not be completed for at least 1.5 to 2 years. Current target dates for first samples collected are January 31, 2024, at R-80 and September 30, 2024, at R-79. However, completion of other activities is possible by April 1, 2023. Concerning Action 1, a semi-quantitative analysis of concentration increases at R-45 screen 2 was submitted to NMED as part of the R-45 Action Plan (N3B 2022, 702350). A simulation plan to further identify the interim measure (IM) influence on the aquifer and concentration trends at R-45 will be completed by April 1, 2023 (Action 2). Action 4 is an ongoing activity that will continue to be executed beyond the deadline and will be enhanced by the incorporation of the new wells into the monitoring network.

To address the NMED concerns associated with chromium movement in the regional aquifer, this document provides an initial 5-year analysis of the IM influence on chromium migration and evaluates the impacts of modifying IM operations. To this end, this document provides background information on the IM hydraulic control design basis through pump-and-treat (P&T) and injection, water rights, and permitting, followed by a description of the current chromium plume conceptual site model (CSM) and more detailed information on IM design and operations. Collectively, this information provides the context for the primary goal of this document, to provide an initial 5-year assessment of the IM. This evaluation will fundamentally address chromium movement in groundwater and the influence of the IM on the regional aquifer to date. The impact of adjusting extraction and injection rates, including the reduced operations associated with the land-application-only approach for treated extraction water, is also provided as part of the IM assessment.

2.0 BACKGROUND

In the sections that follow, a brief description of the chromium plume control IM is provided, followed by information associated with water rights and permits associated with its operation. This provides important context for potential changes in IM operations.

2.1 Chromium Interim Measure

The IM consists of five extraction wells, an ion-exchange treatment, and five injection wells, with the latter component located along the downgradient portion of the plume to hydraulically control plume migration (see Figure 1.0-1). Pilot testing and characterization activities to support the successful installation and monitoring of the IM were outlined in a series of work plans spanning a timeframe from 2013 to 2018 (LANL 2013, 241096; LANL 2014, 254824; LANL 2015, 600458; LANL 2015, 600615; LANL 2018, 603010). The 2015 Interim Measures Work Plan for Chromium Plume Control proposed the IM to control chromium migration in groundwater while long-term corrective action remedies were being evaluated; with the principal objective of achieving and maintaining the 50-ppb New Mexico groundwater standard for chromium at the plume edge within the Los Alamos National Laboratory (LANL or the Laboratory) boundary (LANL 2015, 600458). The 2015 IM work plan for chromium plume control also identified a secondary objective as hydraulically controlling plume migration in the eastern downgradient portion of the plume near well R-45. Therefore, the objectives for the IM were twofold: (1) effectively establish a 50-ppb plume edge within the Laboratory boundary and away from nearby water-supply wells through groundwater extraction, treatment, and injection and (2) reduce the footprint of the chromium plume for the final remedy.

2.1.1 Critical Role of Injection for Hydraulic Control

A critical component of hydraulic plume control is the injection of treated water into wells located on the downgradient regions of the plume. Modeling analyses performed as part of the 2015 Work Plan for Chromium Plume Center Characterization (LANL 2015, 600615) indicated that extraction to remove chromium within the plume centroid did not appreciably affect the concentration of chromium at the southern plume edge in the near term and thus did not meet the primary objective of the IM (to maintain the 50-ppb plume edge within the Laboratory boundary [LANL, 2015, 600458]). Analyses indicated that only a combination of extraction and injection along the downgradient plume edge would have a rapid effect on stabilizing the plume edge (as defined by the 50-ppb New Mexico groundwater standard) well within the Laboratory boundary in less than 3 years of operation.

Disposition options, other than injection of treated groundwater via injection wells, were considered, including land application and piping and discharge of treated groundwater via an existing outfall that would release water into the same pathway that the chromium source initially followed. There is a potential risk associated with the outfall option if implemented in Sandia Canyon, with accelerating the release of chromium that may reside in the vadose and perched water zones between the approximate 1000 ft between the ground surface and the regional aquifer. Moreover, In addition, dispositioning treated water via a pipeline and existing outfall would not have provided the benefit of hydraulic control that injection wells provide. Relatively small volumes of treated groundwater can be land-applied in accordance with approved permits, but limitations on the amount of water that can be land-applied and the logistics associated with continuous operations would not have resulted in sufficient extraction rates (see sections 4.5 and 6.1).

Hence, the injection of treated water was established as a critical component of the IM. However, the injection of clean water requires a discharge permit from GWQB for Class V underground injection control wells.

2.2 Water Rights and Permits to Support IM Operations

In Los Alamos County (LAC), there is a total of 5547.1 acre feet per year water rights for municipal, industrial, and related purposes. These rights are jointly owned by DOE and the LAC, with a 30/70 split, respectively. LAC leased the 30% DOE-owned water rights from 2001 to 2011 and once again in 2020.

To support the chromium IM, DOE and LAC submitted a joint application to the New Mexico Office of State Engineer (NMOSE) in May 2016 to change the existing right (DOE 2016, 702319). A request for emergency authorization also accompanied the application, which was granted in September 2016 (DOE 2016, 702319; DOE 2016, 702320; NMOSE 2016, 702329). The application requested a change in purpose of use for groundwater to add groundwater remediation and additional groundwater points of diversion (PODs) to be used for control and future characterization of chromium-containing groundwater. The application requested 24 additional PODs (3 extraction wells, 6 injection wells, and 15 monitoring wells). The total volume of water for the application was 679 acre-ft/yr with non-consumptive use of the water (DOE 2016, 702319). NMOSE approved the emergency authorization request in 2016 (NMOSE 2016, 702329), allowing for extraction from the wells identified in the application until the permit was issued under the application. The emergency authorization allowed for the extraction of water of up to 648,000 gallons per day, or up to a maximum diversion of groundwater of 679 acre-ft/yr. This translates into maximum extraction and injection rates of approximately 450 gallons per minute (gpm) for the IM system. As of 2019, the permit had not been issued, prompting DOE to submit an updated joint application and request for emergency authorization in September 2019 (DOE 2019, 700203; DOE 2019, 700204). The 2019 request for emergency authorization was approved in that same month (NMOSE 2019, 702321). To date, the IM continues to operate under the 2019 emergency authorization (NMOSE 2019, 702321).

2.3 Discharge Permit

Injection of treated water is allowed under the Underground Injection Control Wells, Discharge Permit 1835 (DP-1835) granted by NMED-GWQB. An application to discharge treated water into the regional aquifer through up to six Class V Underground Injection Control (UIC) wells was submitted in April 2015. DP-1835 was granted on August 31, 2016 (NMED 2016, 702584). As stated in the permit, “NMED's purpose in issuing this Discharge Permit, and in imposing the requirements and conditions specified herein, is to control the discharge of water contaminants from the injection of treated groundwater (effluent) into the regional aquifer beneath LANL, so as to protect and preserve ground and surface waters for present and future uses and to protect human health.”, The permit contains a requirement that all groundwater is to be treated to achieve numeric standards equal to less than 90% of the standards set forth in 20.6.2.3103 NMAC (i.e., 50 ppb) and less than 90% of the numeric standards established for tap water for seven analytes, including chromium.

The DP-1835 permit also has a provision that reserves the right to require a discharge permit modification in the event NMED determines that the requirements may be violated and that management actions are needed to be protective of groundwater quality: “Pursuant to Section 20.6.2.3109 NMAC, NMED reserves the right to require a Discharge Permit Modification in the event NMED determines that the requirements of 20.6.2 NMAC are being or may be violated or the standards of Section 20.6.2.3103 NMAC are being or may be violated. This may include a determination that structural controls and/or management practices approved under this Discharge Permit are not protective of groundwater quality and that more stringent requirements to protect groundwater quality may be required by NMED. The permittees may be required to implement abatement of water pollution and remediate groundwater contamination."

3.0 CONCEPTUAL SITE MODEL

This section provides a brief overview of the hydrologic CSM for the Laboratory based on Katzman et al. (N3B 2018, 702317), which broadly describes the main features of the hydrogeologic environment beneath the Pajarito Plateau where the 36 mi^2 of Laboratory property is located. The plateau hosts a series of fingerlike mesas separated by deep narrow canyons. The canyons are mostly dry, but some reaches have supported ephemeral and perennial flows from natural runoff, spring discharge, or permitted effluent sources. If surface water does not infiltrate through the alluvium, it can continue to the canyons.

There are three types of saturated systems beneath the plateau, two within the vadose zone, which is approximately 600–1230 ft thick beneath mesas of the plateau (Broxton and Vaniman 2005, 090038; Robinson et al. 2005, 091682). Shallow groundwater occurs in alluvial systems beneath canyon sections with ephemeral and perennial flows. Under portions of Pueblo, Los Alamos, Mortandad, and Sandia Canyons, intermediate-perched groundwater occurs in the lower part of the Bandelier Tuff and within the underlying Puye Formation and Cerros del Rio basalt.

The third saturated system is the laterally continuous aquifer that exists at 900 ft or more below ground surface, referred to as the regional aquifer. The Puye Formation often hosts the top of the regional aquifer, but the aquifer at depth can also reside in the underlying pumiceous Puye and the lithologic units of the Santa Fe Group. Beneath Mortandad Canyon, the Chamita Formation is a member of the Santa Fe Group, also known as Tcar, and consists of axial-river deposits deposited by the ancestral Rio Grande. Figure 3.0-1 shows a depiction of the groundwater setting at Los Alamos.

3.1 Chromium Migration to the Regional Aquifer

The hexavalent chromium plume originated from releases of up to 160,000 lb of potassium dichromate—a corrosion inhibitor for a power plant—from cooling towers from 1956 to 1972 (N3B 2018, 702317). The CSM for chromium transport is that hydraulic head from the outfall discharge was present for enough time to move the contaminants through hydraulically conductive geologic strata. Initially, hexavalent chromium traveled rapidly on the surface via an effluent-supported stream for approximately 2.5 miles. In Sandia Canyon, a wetland has flourished downstream of the cooling tower discharge and likely retains a sizeable amount of reduced trivalent chromium in the sediments due to persistent reducing conditions associated with the abundance of decaying organic matter. Some portion of the effluent passed through the wetland with little infiltration or residence time, infiltrating through a stratigraphically complex 900–1000-ft-thick vadose zone to arrive in the deep regional aquifer. Geologic contacts and internal bedding features have the potential to influence groundwater pathways and flow directions in the vadose zone. As a consequence, chromium-contaminated surface water that began an infiltration pathway in Sandia Canyon likely percolated vertically through the vadose zone to the regional aquifer and migrated southward in the vadose zone before entering the regional aquifer beneath Mortandad Canyon.

The thick vadose zone has been historically viewed as protecting the regional aquifer from contamination at the surface. Away from wet canyons, infiltration rates on the Pajarito Plateau are small, and travel times to the regional aquifer are long. However, the current CSM for chromium transport is that effluent-enhanced recharge from the bottom of Sandia Canyon leads to a combination of downward percolation through the tuff layers, feeding an array of circuitous saturated contaminant pathways that lead to the regional aquifer. Infiltration beneath dry canyons and mesa tops is estimated to be very low, resulting in travel times to the regional aquifer of several hundred to thousands of years (Birdsell et al. 2005, 092048). Fracture flow through fractured tuffs or basalts, however, is comparatively rapid. Travel times as short as 5 to 10 years to the regional aquifer are likely, and the presence of multiple pathways means that several chromium "source terms" are likely to exist at the water table of the regional aquifer in Sandia and Mortandad Canyons.

3.2 Chromium Migration within the Regional Aquifer

Chromium concentrations within the groundwater system beneath Sandia and Mortandad Canyons are strongly influenced by the complex hydrogeologic setting. Differences in permeability amongst cooling units within the tuff, lateral and vertical extent of facies within an alluvial fan depositional environment (Puye Formation), and interflow zones between sequential basalt flows all control vertical and horizontal movement of groundwater (N3B 2018, 702317). Different geologic units at the water table and structural dip of depositional bedding appear to have little effect on chromium migration and plume shape and thickness in the regional aquifer. Instead, chromium transport is a function of multiple breakthrough locations and interconnectedness of preferential hydraulic strata under small vertical gradients.

Hexavalent chromium travels through the regional aquifer in a direction consistent with the hydraulic gradient, generally west to east in the chromium plume area. Chromium is not observed to undergo reduction under the oxidizing conditions in the upper portion of the regional aquifer (LANL 2018, 602964), nor does sorption appear to be a significant factor. A reasonable assumption is that chromium travels as a nonsorbing, nonreactive species under these geochemical conditions.

Transport velocities are highly variable throughout the plateau due to heterogeneity of the basin fill sediments, which in addition to sources entering the regional aquifer, contributes to the spatial variability of chromium in the regional aquifer. Although spatially variable, groundwater velocities are approximately 30 ft/year (Birdsell et al. 2005, 092048).

3.3 Chromium Concentrations Before IM Operations

From 2009 to 2016, before IM operations and pilot testing of in situ amendments, regional wells R-28 and R-42 were identified as wells with the highest measured concentrations of chromium; 400–1000 ppb, with highest concentrations measured at well R-42. These wells are located at the centroid of the plume, with R-50 and R-61 along the southern plume boundaries and R-45 to the east, as defined by the 50-ppb contour interval (shown in Figure 3.3-1, 2015 plume map). Since the deployment of amendments at wells R-42 and R-28 in 2017, groundwater samples from these wells have not been considered representative of aquifer conditions (LANL 2018, 602862; LANL 2018, 603031; N3B 2018, 700032; N3B 2018, 700108; N3B 2019, 700214; N3B 2019, 700420; N3B 2019, 700723). However, recent hydraulic and geochemical testing at R-42 has indicated a recovery to pre-amendment geochemical conditions (N3B 2022, 702099).

A schematic of an idealized groundwater plume is shown in Figure 3.3-2. Three zones are shown: (1) the source/high concentration zone; (2) mid-plume area; and (3) the leading edge of the plume. Although there are likely multiple source zones within the chromium investigation area, R-28 and R-42 are likely located within the highest concentration source zone (LANL 2012, 228624). Elevated concentration of chloride and sulfate have also been measured in the central area of the chromium plume. At well R-45, concentrations of chromium and chloride and sulfate have been gradually increasing at both screens (Figures 3.3-3 and 3.3-4), suggesting that the high concentration area is moving downgradient.

Figure 3.3-5 shows the 2016 average concentrations of chromium (Cr) and the anionic species, chloride (Cl^-) and sulfate (SO_4^{2-}) along a flow path from west to east (illustrated in Figure 3.3.6) at R-28, CrIN-1, and R-45 screen 1. CrIN-2 is not shown to simplify the analysis, but pre-IM concentrations were of similar magnitude to those of CrIN-1. Data before 2017 in CrIN-1 correspond to pre-IM conditions, and thus represent concentrations unaffected by fluid injection. The relatively constant, higher concentrations exhibited at R-28 represent a source for downgradient locations. All concentrations at CrIN-1 and R-45 screen 1 suggest that by 2016, the plume front had reached R-45 at levels approaching 10% of the upgradient zone of high concentrations.

Regional well R-50 is located along the southern boundary of the chromium plume (Figure 3.3-6). The chromium concentration in the upper screen increased to approximately 140 ppb before the start of sustained IM operations (2018). The concentration in the lower screen (R-50 screen 2) has historically remained at background concentrations (6–10 ppb). Regional well R-61 is located along the southwestern portion of the chromium plume, forming the basis of the depiction of the 50-ppb extent of plume in this region. Chromium concentrations at R-61 have been historically above background but below the 50-ppb standard before IM operations (see section 5.3.3). Concentration trends are presented in more detail in section 5.3 and in Appendix A.

3.4 Vertical and Eastern Chromium Concentration Distributions

Stratified sampling in 2017 during the drilling of CrEX-2 demonstrated that chromium concentrations exceeding the standard extended to an approximate depth of 60 ft below the water table, with low concentrations measured below that depth (LANL 2017, 602595). Thus, in the periphery of the plume extending from the CrEX-2 location to the south to R-50 and R-44, concentrations are relatively shallow, probably not extending much below 50–75 ft below the water table but not as deep as R-50 screen 2.

Extraction well CrEX-4, also drilled in 2017, was completed as a two-screen well with the screens separated by 10 ft of blank casing. Individual samples from these two screens, collected before operation as an extraction well, revealed high chromium concentrations in both screens, the lower of which extended to approximately 75 ft below the water table. The CrEX-4 finding provided a definitive indication of chromium located at depth near R-28 and R-42. The depth of the plume near the plume centroid has not yet been determined. Proposed wells R-76 and R-77 will investigate plume depth in this region.

In the northeastern region of the plume, CrIN-6 chromium concentrations were anticipated to measure below the groundwater standard, but were significantly higher, at 250–300 ppb. This outcome indicated that the plume extended further to the east than the CSM had quantified to date, which prompted changing CrIN-6 to extraction well, CrEX-5 (see Figure 1.0-1). In response to concentrations at CrEX-5, well R-70 was installed in mid-2019. Samples collected from R-70 screen 1 and screen 2 further confirmed that concentrations in excess of 200 ppb extend significantly farther east (Figure 3.4-1), 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). The data at CrEX-5 and R-70 have contributed to the current interpretation of the plume horizontal extents, with both shallow and deep plume footprints (Figure 1.0-1).

The concentrations at individual wells are translated to a depiction of the chromium plume based on the knowledge available before IM operations (Figure 3.4-2) and present day (Figure 3.4-3). The pre-IM plume (Figure 3.4-2) is based on the state of knowledge presented in the 2015 “Interim Measures Work Plan for Chromium Plume Control” (LANL, 2015, 600458). The southern edge of the plume extended to the boundary of LANL and Pueblo de San Ildefonso, and the eastern area was represented at the time as extending only as far east as CrIN-1, although uncertainties of the eastern extent were acknowledged.

Comparison of the pre-IM and present-day plume depictions reveals both changes in the plume itself along with changes in the plume representation gained through a more complete understanding of nature and extent than was available at the initiation of the IM. The largest beneficial change occurred on the southern plume region, where the combination of extraction and injection resulted in a retreat of the 50-ppb plume line a significant distance north of the boundary with Pueblo de San Ildefonso between R-50 and CrEX-1. This change constitutes a success of the primary IM objective as stated in the 2015 IM chromium plume control work plan (LANL, 2015, 600458).

In contrast, data from new wells R-70 and CrEX-5, along with recent trends at R-45, have led to a new plume depiction in the eastern plume area, with a deep component of the plume extending further east than was originally thought. Other new wells and measurements to the west (wells CrEX-2 and CrEX-4) have led to a more complete picture of the presence or absence of deep contamination—deeper contamination likely extends from the centroid of the plume to at least as far east as R-70 but does not appear to be present in the southern plume area, as evidenced by the low concentrations in the deep screens of R-50 and R-44. Residual uncertainties on the nature and extent of chromium remain and can be closed either by the drilling of additional monitoring wells or with extraction wells to greater depths as part of a final remedy. Uncertainties in chromium concentrations based on depth (greater than or less than 50 ft below the water table) are depicted in Figure 3.4-2 and Figure 3.4-3 and demonstrate the evolving CSM and progress toward data gap closure.

4.0 GROUNDWATER TREATMENT AND HYDRAULIC CONTROL SYSTEMS

Groundwater P&T systems are operated to achieve control of contaminated groundwater migration, contaminant mass removal, or to accomplish both purposes. If mass removal is the primary goal, P&T systems are designed so that contaminated water from zones of highest concentrations is pumped to the surface through one or more extraction wells and treated in an aboveground facility. Treated groundwater can be returned to the subsurface through injection wells, discharged to a publicly owned treatment works, discharged to a surface water body, or beneficially reused (e.g., as irrigation water). Restoration of groundwater to meet cleanup standards requires that sufficient groundwater be flushed through the contaminated zone to remove dissolved contaminants and those that will continue to desorb from porous media, dissolve from precipitates, or diffuse from low-permeability zones (https://semspub.epa.gov/work/HQ/174486.pdf). The sum of these processes and dilution in the contaminated zone are required until acceptable groundwater quality standards are met. P&T designed for aquifer restoration generally combines hydraulic containment with higher pumping rates or pulsed rates to attain groundwater cleanup goals (https://semspub.epa.gov/work/HQ/174486.pdf).

If containment is the primary goal, effective hydraulic containment can be achieved using extraction and injection wells that control the direction of groundwater flow with pumping, pressure ridges, or physical barriers. The hydraulic control can be used to help contain the impact of an ongoing source of contamination or prevent the plume from migrating further, even though overall contaminant mass reduction within the source or plume may not be efficient. Hydraulic manipulation includes the effects of groundwater extraction and injection of treated water on the hydraulic gradients in the aquifer.

When groundwater enters a well for aboveground treatment, a cone of depression is created around the well, creating a zone of influence where the potentiometric surface has been modified. The capture zone is the portion of the zone of influence where groundwater flows to the extraction well because of horizontal and vertical capture. The well capture zone is defined as the region from which water is withdrawn from one or more extraction wells. Conversely, a flood zone is the portion of the zone of influence where groundwater flows laterally and vertically away from the injection well. After extraction and injection are initiated, the capture and flood zones grow with time and reach a maximum at steady state (i.e., equilibrium). Capture zones are generally parabolic in shape, but the exact size and shape of the capture zone is dependent on (1) the hydraulic gradient and hydraulic conductivity of the aquifer; (2) subsurface heterogeneity and anisotropic extent; (3) pumping rate and the existence of other extraction and injection wells; and (4) extent of the well screen within the aquifer (e.g., reduced or fully penetrating). Capture zones can also be designed such that one or more extraction and injection wells provide a barrier to contaminated groundwater flow, preventing contaminant migration beyond the downgradient influence of the capture zone.

4.1 Extraction and Injection Influence on Concentrations

P&T systems involve extraction of groundwater from an aquifer as a mechanism for both contaminant mass removal and hydraulic gradient manipulation. During extraction, concentrations at monitoring wells are generally expected to decrease over time because of ongoing mass removal. However, concentrations may show varying trends over time. For example, Figure 4.1-1 shows the location of an extraction well in the mid-plume area of the idealized plume configuration, with one monitoring well located within the source/high concentration zone, and the other monitoring well located at the leading edge of the plume. White arrows indicate the direction of groundwater flow under pumping conditions. Assuming all the well screens are located at a similar depth, the monitoring well located upgradient of the extraction well will likely show a concentration increase once pumping is initiated because it is sampling water from a high concentration zone that is migrating through the well due to extraction. By contrast, the monitoring well located downgradient of the extraction well will likely show a concentration decrease over time because it is sampling water from a lower concentration zone downgradient of the extraction well.

Another cause for concentration increase may be due to variations in the vertical distribution of contaminated groundwater. If a vertical gradient is created, either with an extraction well, injection well, or a combination of both, concentrations at a monitoring well location could increase. For example, Figure 4.1-2 shows that concentrations at a monitoring well could increase under a vertical gradient induced by an injection well if a high concentration zone is initially located above the monitoring well screen. The top panel in this figure shows a plan view of a plume located at depth and the locations of an extraction, monitoring, and injection well. In the second panel, a cross-sectional view shows injection water mixing with the higher concentration zone, causing it to dilute and vertically migrate deeper into the aquifer where it is measured at the deeper monitoring well screen location. The third panel, also a cross-sectional view, shows that the extraction well is capturing the plume. If the extraction well is unable to capture the contaminated water at that depth, then adjustments to the P&T and injection system may be needed to ensure capture.

Once treated water has received aboveground treatment, injection water will likely have a distinct geochemical signature and be dependent on the treatment system. Injection water will have low concentrations of the targeted contaminant(s), and if treated via ion exchange, it may also have higher than background concentrations of the anion being exchanged (e.g., Cl^- or SO_4^{2-}). If co-located contaminants (that are above background but below the water quality standard) are not treated in the aboveground system, then they can also be used as tracers as the water is transferred from extraction locations to points of injection.

4.2 IM Design for Hydraulic Control

As stated in section 2.1, injection of treated water was determined to be a time-critical component to achieve effective hydraulic control of the chromium plume. At the time of that determination, groundwater modeling had indicated that extraction alone within the plume centroid required at least 10 years of operation to hydraulically control the plume and reduce chromium concentrations at well R-50 in the southern edge of the plume (LANL 2015, 600615). Groundwater modeling had demonstrated that a combination of extraction and injection along the downgradient plume edge would have a rapid effect on stabilizing the plume edge (as defined by the 50-ppb New Mexico groundwater standard) well within the Laboratory boundary in less than 3 years of operation.

The IM was designed for plume containment based on increasing trends in chromium concentrations at wells R-50 and R-45 (LANL 2015, 600458). By locating injection wells at the downgradient plume boundaries that had been identified at that time (CrIN-1, CrIN-2, CrIN-3, CrIN-4, CrIN-5, and CrIN-6), and locating extraction wells (CrEX-1, CrEX-2, and CrEX-3) upgradient of the injection wells (Figure 1.0-1), the system was to be primarily operated to achieve hydraulic plume control. The priority injection well locations were those situated along the Laboratory boundary west (CrIN-5) and east (CrIN-4) of R-50 because of their specific role in helping to control off-site chromium plume migration to the south. CrEX-4 was installed to provide additional water (anticipated to be between 60–80 gpm) for distribution to injection wells. Another key purpose that drove the proposed location of CrEX-4 was to provide additional plume-center characterization data because the well will be located near the highest concentrations of chromium known in the plume and likely screened largely within the Miocene pumiceous unit where well R-42 (highest chromium in the plume) is screened (LANL 2017, 602594). CrEX-4 is the only well located in the interior of the plume and also supports an increase in total drawdown, a steeper gradient, and an integrated area of groundwater capture.

CrEX-1 was the first extraction well installed to test the concept of hydraulic capture. Aquifer testing indicated that CrEX-1 would perform effectively and would be capable of sustaining an extraction rate of approximately 80–100 gpm (LANL 2015, 600170). Chromium extraction well CrEX-3 was originally installed as part of 2015 plume center characterization work and was later integrated into the IM as part of the hydraulic control system. Extraction well CrEX-3 and chromium injection wells CrIN-1, CrIN-2, CrIN-3, CrIN-4, and CrIN-5 were completed in 2016. Chromium extraction wells CrEX-2 and CrEX-4 and chromium injection well CrIN-6 were completed in 2017.

When the IM was designed, data from existing monitoring dual-screened monitoring wells had indicated that chromium was predominantly located within the upper 50 ft, with elevated chromium concentrations in shallow screens and below 50-ppb in deeper screens (~100 ft below the water table). Consequently, extraction and injection well screens were targeted for that interval (see well screen locations shown conceptually in Figure 4.2-1 relative to other monitoring wells). Well screen locations for extraction, injection, and monitoring wells are provided in Table 4.2-1. Although potential variation in hydraulic performance between injection wells was acknowledged, based on variations in the local-scale hydraulic properties, it was assumed that injection wells could accept injection rates comparable with the rates of extraction.

Two assumptions were not realized in specific regions of the plume. In the central area of the plume, CrEX-3 is located near R-28 (Figure 1.0-1), where a pilot-scale amendment test was conducted to evaluate the feasibility of molasses for in situ treatment of hexavalent chromium [Cr(VI)] (LANL 2017, 602505). The introduction of molasses into the regional aquifer caused an increase in microbial activity, which may have contributed to a lower sustained extraction rate (30–35 gpm) and frequent maintenance at CrEX-3 relative to other extraction wells (N3B 2021, 702318). In the northeastern region of the plume, initial CrIN-6 chromium concentrations of 250–300 ppb indicated that the plume extended further east. In response to this finding, CrIN-6 and associated surface infrastructure was converted to a fifth extraction well, CrEX-5 (see Figure 1.0-1).

4.3 IM Operations

Operations in the southern plume area were initiated in January 2017, with only CrEX-1, CrIN-4, and CrIN-5 in operation. The full water-distribution system used to pipe water between extraction wells, treatment system, and injection wells was completed in January 2018. The piping network included approximately 3.1 miles of double- and single-wall high-density polyethylene (HDPE) pipe. Pipelines were trenched, tested, and installed underground along pre-existing roads in Mortandad Canyon. The central treatment unit consisting of ion exchange treatment, finished water holding tanks, and booster pumps, was constructed on the well pad near monitoring well R-28. Figure 4.3-1 shows the treatment system infrastructure and the area approved for land application.

Sustained operations in the southern plume area began a year and a half later (May 2018) and included CrEX-1, CrEX-2, CrEX-3, CrIN-3, CrIN-4, and CrIN-5. Sustained eastern area operations began in November 2019, with all five extraction wells and five injection wells operational when available. Currently, untreated groundwater is pumped from the extraction wells through double-walled HDPE pipe to central treatment, treated via ion exchange, held in tanks, and then pumped and distributed through single-walled HDPE pipe to the injection wells by the booster pumps. Figure 4.3-2 summarizes the cumulative extraction and injection volumes of water over time. The entire operation is controlled and monitored by a programmable SCADA (supervisory control and data acquisition) system.

4.4 IM Operational Constraints

Apart from the extraction and injection wells, the current IM system consists of two treatment train units, chromium treatment unit A (CTUA) and chromium treatment unit C (CTUC), containing three and two treatment trains, respectively. Each treatment train consists of a primary ion exchange (IX) column (lead) and a secondary IX column (lag). The primary IX column in the lead/lag configuration is responsible for the majority of chromium removal. The secondary IX column is the polisher vessel, acting as a safeguard against exhaustion of the primary vessel.

Figure 4.4-1 shows a conceptual diagram of the lead/lag configuration and the location of bag filters. Water from all five extraction wells is combined in the pipeline before reaching CTUA and CTUC. Water is then diverted to each chromium treatment unit, passing through one of three lead/lag treatment trains in CTUA, and one of two lead/lag treatment trains in CTUC. Currently, sampling is performed in the first sample valve location shown in Figure 4.4-1 to calculate mass removed by the treatment system. Total flow rates from all five extraction wells are used to determine the mass removed during treatment.

Each of the five ion exchange treatment units has a maximum treatment capacity of 60 gpm, yielding a maximum total rate of approximately 300 gpm. With all wells operational, the system nominally operates at 280 gpm, just under the maximum capacity to allow for potential variations in individual extraction and injection flow rates. The current system design requires that CrEX-1 and CrEX-2 be operated in tandem, and CrIN-4 and CrIN-5 also perform best when operating together. Historically, CrEX-3 flow rates are usually at least 50% (30–35 gpm) of the other extraction well rates because of residual biological mass that likely remains from molasses injection at R-28 (N3B 2021, 702318).

If injection rates are reduced (or ceased) in one or more injection wells, extraction rates also need to be reduced unless the deficit can be made up by increasing injection in the other wells. Any modifications to the existing pumping rates need to include an evaluation of the impact on chromium plume control as discussed in section 6.

4.5 Land Application of Treated Groundwater

The chromium IM treatment system also includes a third treatment train, CTUB, which is designed to treat water generated from activities such as water from routine groundwater sampling purges, well development, and aquifer testing. In brief, the workflow consists of supervised activities, beginning with the transfer of water destined for treatment at CTUB to frac tanks. There are currently 11 frac tanks on-site that together hold a capacity of 220,000 gal. of storage capacity. Frac tank water is first transferred to CTUB at a nominal rate of 80 gpm. Once treated, water is then transferred to synthetically lined lagoons. Currently, there are three lagoons on-site, each with a total capacity of approximately 200,000 gal.

Groundwater is treated to less than 90% of the New Mexico Water Quality Control Commission (NMWQCC) groundwater standard for chromium of 50 ppb. Before water can be discharged by land application in accordance with Work Plan #5 under Discharge Permit 1793 (DP-1793), water quality sampling is required before land-application execution to verify the treated water is below standards (NMED 2015, 600632; LANL 2017, 702583). Once a lagoon is filled to the desired capacity, water quality samples are taken, with a 10-day turnaround time on analytical results.

Once analytical results confirm that groundwater has been treated to less than 90% of the NMWQCC groundwater standard for chromium, land application can occur by means of (1) water trucks (3000–10,000-gal. capacity) equipped with both standard rear-mounted dust control sprayers and multiple high-pressure water sprayers, and/or (2) irrigation-type sprinklers at the designated irrigation site.

The following terms and conditions associated with land application of treated water must be met:

1. Land application is prohibited at the following locations:
    - Watercourses,
    - Water bodies,
    - Wetlands,
    - Areas of concern (AOCs) (with the exception of the following canyon-bottom AOCs: C-00-001 through C-00-019 and C-00-021),
    - Solid waste management units,
    - Slopes greater than 2% if the site is poorly vegetated (<50% ground cover), and
    - Slopes greater than 5% if the site is well vegetated (>50% ground cover).
2. Land application cannot result in water flow from an approved land application site.
3. Land application cannot create ponds or pools or standing water.
4. Land application must be conducted in a manner that maximizes infiltration and evaporation.
5. Land application is restricted to daylight hours for a maximum of 10 hr/day.
6. Land application must be supervised.
7. Land application cannot extend off LANL property without written permission from the land owner.
8. Land application will be terminated if leaks in the application system are detected.
9. Land application is prohibited while precipitation is occurring or when temperatures are below freezing.

Given the current system configuration and limitations associated with lagoon capacity and turnaround times on water quality sampling, dispositioning treated water from the IM through land application only (no injection), severely reduces IM operations. If treated water can be applied only when temperatures are above freezing and intermittently during the monsoon season, the IM would effectively operate for 3 days at 140 gpm, 8 hr per day, filling each lagoon to capacity (200,000-gal. capacity each for a total of 600,000 gal. for all three lagoons). Since CTUB operations require supervision, extraction operations would be conducted only during daylight hours, followed by a 10-day hold time for water quality analyses. Land application is assumed to be irrigation only, since 60 truckloads (10,000-gal. capacity) would be needed to transport the treated water to approved land-application areas or off-site locations, which would create a significant disturbance. Land-applying one lagoon (200,000 gal. at ~100 gpm) is anticipated to take 5 days. To land-apply all three lagoons, 15 days are required. Since supervised treatment can resume once the first lagoon is emptied, this means that nominally 2 weeks are required before the treatment cycle can be repeated, accounting for the hold time on lagoon water quality.

4.5.1 Potential Land-Application Modifications

The IM is currently configured for extraction and injection with treatment through treatment units CTUA and CTUC. If land application becomes the only option for dispositioning treated water, then the IM system may need to be updated to streamline operations and to address potential issues associated with water storage and transfer. While running the P&T system intermittently is feasible, equipment adjustments may be needed to reduce the risk of downtimes associated with infrastructure designed to run continuously. Equipment winterization will be an important element of system maintenance if the P&T system is not operational when temperatures are below freezing. Any water rights issues would also need to be resolved, as land-applying all treated water would result in a consumptive water use (approximately 7.4 acre-ft/year).

Given the limitations associated with land application, engineering changes to the IM system will likely be needed to maximize the disposition of water through land application. If changes are warranted, a new work plan would need to be submitted to NMED-GWQB for public review and approval. The new work plan would likely include the use of CTUA and CTUC for land application and incorporate engineering changes to pipe CTUA and CTUC to the existing lagoons, specifying sampling frequencies for contaminants of concern. The estimated time to complete the work plan and submit to NMED is 4 months. After submittal, NMED has a 60-day review cycle, which also includes a public comment period, followed by either NMED approval or denial of the work plan.

To further maximize land application of treated water, modifications to the conditions of DP-1793 may also be required. Historical durations are used as a basis for estimating the time needed to complete the following list of activities:

- DOE rewrite, review, and submittal of revised permit application (6 months)
- NMED review and public notification (2 months)
- NMED draft permit (6 months)
- Public notice on draft permit (1 month)
- NMED scheduling of public hearing (2 months)
- NMED hearing (1–3 years)
- NMED rules on hearing and issues permit (3 months)

Although engineering changes could be accomplished in approximately 1 year, any modifications to the DP-1793 permit needed to maximize land application will require at least 2 years 8 months, if the NMED hearing is completed within 1 year.

5.0 IM EVALUATION

Since IM operations were initiated in 2018, changes have occurred both in water levels and chromium concentration trends in monitoring wells. Concentration trends have also been observed both in extraction and injection wells, with the latter showing a distinct geochemical signature associated with the ion exchange treatment. These data, as well as modeling analyses, are presented in this section to provide an initial assessment of IM operations, including

- an evaluation of the potentiometric surface at the water table,
- an analysis of concentration trends based on location and response to different phases of the IM (both planned and unplanned operational changes),
- an analysis of field-scale tracer studies and injection fluid geochemical signatures,
- a qualitative analysis of the downgradient impacts of injection,
- a qualitative and quantitative assessment of IM capture,
- the effectiveness of the integrated capture and flood zones created by extraction and injection wells, and
- the translation of all of these elements into an overall assessment of plume behavior and hydraulic plume control.

5.1 Potentiometric Surface Evaluation

Changes in the potentiometric surface were evaluated by reviewing potentiometric surface maps that have supported the quarterly DP-1835 reporting. In addition, vertical hydraulic gradient information generated from water-level data has been used in this evaluation since data are too sparse to generate a meaningful water table map at depth.

As described in the DP-1835 reports, simple interpolation methods for water table data from a complex heterogeneous site could produce maps that do not represent physically realistic hydrological systems. These water table maps were contoured by incorporating process knowledge of groundwater hydraulics (e.g., flownet conformity rules) as well as conceptual models of groundwater flow in the project area. Key inputs to the CSM include knowledge of long-term operations of extraction and injection wells, water-level elevations in monitoring wells near extraction and injection points, and cross-hole tracer data between injection wells and monitoring wells. Because of the spatial coverage of wells and piezometers and the regional structure of significantly steeper gradients to the east and west of the chromium plume area, surrounding wells (e.g., R-21, R-31, R-32, R-37, and R-40) and control points based on expert opinion are used to provide estimated water-level elevations in areas that do not have sufficient data to provide constraints.

The effects of the chromium IM operation were identified by reviewing annual changes observed in the potentiometric surface maps from the calendar year fourth quarter for the years 2016 through 2021 (Figures 5.1-1–5.1-6). The Quarter 4 maps were chosen for this evaluation to help minimize the observed water-level response due to seasonal increases in groundwater withdrawal rates by LAC production wells.

5.1.1 Pre-IM Conditions

The approximate pre-stress condition in the regional aquifer is represented by the Quarter 4 2016 potentiometric surface map (Figure 5.1-1 [LANL 2017, 602199]). Although CrEX-3 extraction (e.g., development and testing) occurred during this period, the Quarter 4 2016 potentiometric surface map is still considered to be representative of a pre-IM condition because only a small fraction of the total volume extracted from CrEX-3 had been extracted by that time (~8%).The hydraulic gradient and groundwater flow direction are predominately from west to east/southeast in the chromium plume area. The regional-aquifer groundwater flow direction mirrors the land surface topographic relief with higher elevations to the west and lower elevations to the east and southeast. The groundwater flow direction is also reflected in the shape of observed chromium plume with a narrower cross-sectional area on the west side of the plume near the source area and a wider cross-sectional area downgradient to the east and southeast.

The hydraulic gradient measured on the west side upgradient of the chromium plume is steep, 0.01 ft/ft, indicating a groundwater recharge area, likely from the mountain block, that influences groundwater flow in the regional aquifer. A mound at well R-15 also exists upgradient of the 2016 depiction of the chromium plume. The hydraulic gradient flattens in the central plume area in the vicinity of monitoring wells R-42 and CrPZ-3 to approximately 0.002 ft/ft. The cone of depression shown on the 2016 potentiometric surface map in the vicinity of CrEX-3 is likely associated with the development and testing of CrEX-3 and use of the CrEX-3 water level in the generation of the Quarter 4 2016 potentiometric surface map.

5.1.2 Southern IM Operations

Chromium IM operations were implemented in a phased approach beginning on the southern edge of the plume. Groundwater extraction was initiated in the second half of 2016 at extraction wells CrEX-1 and CrEX-3. Treated effluent from the chromium IM system was initially discharged into injection wells CrIN-4 and CrIN-5. The potentiometric surface conditions after the first year of operation (Quarter 4 2017) are shown in Figure 5.1-2 (LANL 2018, 602911). Overall, groundwater flow direction and hydraulic gradients are similar to those observed from the pre-stress condition, with a predominant flow direction from west to east and a dissipation of the mound at R-15. Steep hydraulic gradients were still present to the west of the plume (0.01 ft/ft) and then flattened in the center plume area (0.001 ft/ft), which continued towards the eastern edge of the plume. Directional changes in the hydraulic gradient in response to extraction from CrEX-1 and CrEX-3 and injection in CrIN-4 and CrIN-5 are not evident after the first year of operations.

The chromium IM operations were expanded in 2018 to include groundwater extraction at CrEX-2 and CrEX-4 and injection of treated effluent at CrIN-3. The primary objective of the system expansion was to provide hydraulic control of the plume southern boundary and prevent migration of the plume off LANL property. The Quarter 4 2018 potentiometric surface map illustrates the development of a cone of depression between extraction wells CrEX-2 and CrEX-4 within the 50-ppb boundary of the chromium plume (Figure 5.1-3 [N3B 2019, 700304]). The diameter of the cone of depression in the vicinity of CrEX-1, CrEX-2, CrEX-3, and CrEX-4 continues to expand in 2019 (Figure 5.1-4 [N3B 2020, 700779]). The hydraulic gradient is altered on the southern plume boundary with groundwater flow from south to north towards the four active extraction wells and away from the LANL property boundary. The hydraulic gradient on the north side of the plume is also altered with groundwater flow from north to south towards the cone of depression.

5.1.3 Eastern IM Operations

Chromium IM operations were expanded on the east side of the plume in late 2019, with the conversion of CrIN-6 to CrEX-5. Groundwater extraction was initiated at CrEX-4 and CrEX-5 and injection of treated groundwater was initiated at CrIN-1 and CrIN-2 to address the eastern plume area. The operations of CrEX-4, CrEX-5, CrIN-1, and CrIN-2 on the east side of the plume significantly altered the hydraulic gradient in the vicinity of extraction well CrEX-5 and injection wells CrIN-1 and CrIN-2 relative to those observed previously (Figure 5.1-3; Figure 5.1-4; Figure 5.1-5 [N3B 2021, 701249]; Figure 5.1-6 [N3B 2022, 701904]). The previously identified flat hydraulic gradient and corresponding groundwater flow direction of west to east shown in Figure 5.1-2 is no longer observed on the eastern side of the plume. Although a distinct mound has not formed from injection, the injection of treated groundwater into CrIN-1 and CrIN-2 appears to have created a groundwater divide between the cone of depression observed in the vicinity of CrEX-1, CrEX-2, CrEX-3, and CrEX-4 and the eastern edge of the plume (see Figure 5.1-6). Separate flow paths are created towards the northeast and the southeast.

5.1.4 Hydraulic Gradient Evaluation

Review of the vertical component of the hydraulic gradient provides insight into the plume migration within the regional aquifer. Vertical gradient density plots for select dual-screened monitoring wells and piezometer are shown in Figure 5.1-7. Separate gradient density plots were created for IM operational and non-operational periods, controlling for nearby LAC water supply well PM-4 operations, with extended periods of several weeks included in each category. PM-4 was selected for this analysis because it is the PM well that has the greatest influence on water levels in the chromium plume area. The various plots allow comparison of the IM influence on hydraulic gradients relative to extraction from PM-4. However, hydraulic gradients within the chromium plume area are more significantly influenced by the IM than by PM-4 operations.

Upgradient on the west side of the plume, outside of the 50-ppb plume boundary, the hydraulic gradient at monitoring well R-33 exhibits a strong vertical downward component with the greatest density occurring at approximately −0.3 ft/ft. The gradient density plots are very similar for the operational and non-operational periods of the chromium IM; however, a large shift is seen in the vertical gradient as a result of PM-4 pumping. This indicates that the R-33 well location is outside of the hydraulically affected area of the chromium IM but in an area of the aquifer that is impacted by PM-4 pumping.

In the center of the plume area, as characterized by piezometers CrPZ-2a and CrPZ-2b (located in the same borehole), the ambient vertical gradient is downward with the greatest density of measurements observed at approximately 0.005 ft/ft during periods when the IM is not operating. The density plots show a shift to approximately −0.015 ft/ft under IM operational conditions. In the center of the plume, the vertical gradient component is always downward or negative, under both operational and non-operational conditions, indicating that groundwater moves deeper into the regional aquifer as it migrates downgradient.

Similar increases in downward vertical gradient magnitude as a result of IM operations are observed along the plume edge at wells R-44, R-45, R-50, R-61, and R-70. The largest impact on vertical gradients is observed at monitoring wells R-50 and R-45. At R-50, the vertical gradient during non-operational periods is slightly downward with the greatest density of measurements observed at −0.002 ft/ft. During operational periods, the vertical gradient becomes increasingly negative, with the greatest density of measurements at −0.011 ft/ft. The injection of treated groundwater at CrIN-4 and CrIN-5 likely affects the vertical gradient in the vicinity of R-50.

Monitoring well R-45 is located immediately downgradient of and between injection wells CrIN-1 and CrIN-2. At R-45, the vertical gradient component during non-operational periods is minimal with the greatest density of measurements observed at approximately −0.001 ft/ft. During IM operations, the vertical gradient component becomes more negative or downward with the greatest density of measurements observed at −0.009 ft/ft. The injection of treated groundwater at CrIN-1 and CrIN-2 likely affects the vertical gradient in the vicinity of R-45.

At wells R-44, R-61, and R-70, the impact of IM operations on vertical gradients is also evident, but to a lesser extent. At R-44, located southeast of the chromium plume, and downgradient of CrIN-3, an ambient downward vertical gradient is observed with the greatest density around 0.004 ft/ft. This shifts downward to densities between −0.006 and −0.008 ft/ft as a result of IM operations. At R-61, located southwest of the chromium plume, measurements range between 0 and 0.001 ft/ft, indicating a slightly upward ambient vertical gradient at this location. The gradient is reversed to a slightly downward gradient, with measurements between −0.001 and −0.002 ft/ft as a result of IM operations. At R-70, located in the northeast portion of the chromium plume, a slightly upward ambient vertical gradient appears to flatten to zero as a result of IM operations.

5.2 Potentiometric Surface Evaluation and Capture Zone Analysis

The combined extraction at CrEX-1, CrEX-2, CrEX-3, and CrEX-4 has resulted in an integrated area of groundwater capture in the upper portions of the aquifer, likely at depths to at least 60 ft below the water table, based on the depths and lengths of extraction-well and injection-well screens. This integrated capture zone provides for plume control through beneficial capture of chromium mass flux in the upper portions of the plume within the general centroid of the plume. Because of the lack of deeper monitoring points in the centroid of the plume, the depth of groundwater capture is unknown. Also unknown is whether chromium mass escapes the capture zones of the extraction wells and flood zones of the injection wells.

5.2.1 Capture Zone Approach

To assess the IM ability to achieve capture, hydraulic head and gradient data are interpreted within the context of a capture zone analysis. Capture zones for extraction wells and flood zones for injection wells at the chromium plume have been initially assessed based on the methodology described in the U.S. Environmental Protection Agency (EPA) sentinel document, “A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems” (https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=187788). This document describes the following six steps:

1. Assessing site data and formulating a CSM,
2. Defining targeted capture zones,
3. Interpreting water levels by developing potentiometric surface maps and hydraulic gradients,
4. Calculating flow rates and tracking particles by means of analytical and numerical modeling to identify capture zones,
5. Evaluating concentration trends, and
6. Interpreting final capture zones based on steps 1–5.

Step 4 emphasizes using numerical modeling to identify capture zones. A common approach is to track many particles from different regions of the aquifer, including injection wells, and examine visualizations of particle traces to determine the boundaries between assemblages of particles that end up in extraction wells. However, the capture zone identified with particle tracking is only as accurate as the underlying head predictions from the numerical model. The numerical model of the chromium project area, referenced here as the chromium model (CM), has been applied to field data and is fit for use for this purpose as documented in a presentation (Appendix B) and will be described in greater detail in a report to be published in March 2023. The results of the capture zone analysis are described below and documented in a presentation as well (Appendix C). A more detailed description of the capture zone analysis will be published in March 2023.

5.2.2 Numerical Chromium Model

A numerical model of the chromium plume area has been built using the code, Finite Element Heat and Mass Transfer (FEHM) (https://fehm.lanl.gov/). FEHM can account for complexities associated with partially penetrating wells, aquifer heterogeneity, and complex boundary conditions and has been benchmarked against MODFLOW https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs. This section provides a brief description of the CM, with more detailed description of the model build and calibration to be published in March 2023.

A first step in the construction of a groundwater model is to identify the domain extents. In the CM the upper surface is the regional aquifer water table, which is approximately 900–1000 ft below the land surface. Water table elevations range from 6300 ft above mean sea level (ft amsl) near the western edge of the domain, which approaches the mountain block, to approximately 5300 ft amsl near the Rio Grande. The model is designed to represent the regional aquifer and covers an area of 137 mi^2, with a depth that extends from the top of water table down to 3280 ft amsl. The model domain is discretized into an unstructured tetrahedral mesh. Variable grid sizes are used based on the distance from the chromium plume area and the proximity to injection and extraction wells, with the latter requiring a more refined grid.

Hydrologic and transport parameters include advective porosity, dispersivity, lateral and vertical hydraulic conductivity, and specific storage. Some parameters are assigned to individual cells within the model grid following the pilot point approach (Doherty 2003, 700894), while others are homogeneous throughout the domain. Given the heterogeneity of the sediments in the regional aquifer, a unique value of hydraulic conductivity is assigned to each cell in the model domain. The final parameter values are based on model calibration, which is achieved by changing the values of model input parameters to match field data.

All boundary conditions, like other model parameters, use input distributions that limit parameters to plausible values. The hydraulic gradient in the model is set by assigning constant head conditions to the western (mountain block) and eastern (Rio Grande) boundaries. No-flow boundaries are set approximately parallel to regional flow (north and south model edges) and the base of the model, which is sufficiently deep (1300–1970 ft) so that it does not impact plume transport behavior in the upper region of the regional aquifer.

On the surface of the CM, elliptical hydraulic windows are used to represent sources of chromium and water entering the regional aquifer from the vadose zone. These pathways are referred to as “hydraulic windows” or “drip points.” During model calibration, the spatial extent of the ellipses, as controlled by the center coordinates and *x* and *y* radii, are allowed to vary as shown in Figure 5.2-1. Temporal variations in chromium concentrations are also allowed to occur within any given drip point. Currently, five hydraulic windows are used to represent continuing sources to the regional aquifer. These locations have been inferred from groundwater concentrations of chromium and other analytes (e.g., perchlorate, nitrate, tritium).

The CM has been calibrated to available field data through October 22, 2022 (e.g., heads, hydraulic gradients, and chromium concentrations) to support decision-making associated with the IM. Uncertainty in parameter estimates, including hydrologic and transport properties, boundary conditions, and sources, is considered in the calibration approach. This means that there is variability in model predictions, which can be expressed as a range in concentration estimates or plume configurations.

5.2.3 Capture Zone Analysis

EPA emphasizes the need to use multiple lines of evidence to effectively understand capture zones for complex groundwater P&T systems including potentiometric surface mapping, analytical calculations, and numerical modeling that brings together data and physical equations of flow (https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=187788). Two analytical methods were executed to determine the lateral extent of integrated capture when all five extraction wells are operational. These approaches assume a homogeneous subsurface geology and a flow system that has achieved equilibrium (i.e., steady state). Three numerical methods were also executed to determine the lateral and vertical extent of capture. Although the analytical and numerical approach both assume a steady state, i.e., the capture zones have achieved complete development and have reached a maximum size, the numerical methods can account for geologic heterogeneity within the regional aquifer. Five methods, two analytical and three numerical, were executed to provide multiple lines of evidence for hydraulic capture, as recommended in the guidance document cited above.

Capture zone estimates from each line of evidence are shown in Figure 5.2-2 for when all five extraction wells are operational. The approximate plume extent (defined by the 50-ppb contour) is shown as a shaded contour for context and is equivalent to the deep and shallow plumes depicted in Figure 1.0-1. Each method used to determine lateral capture is shown with a distinct color. The orange line corresponds to an analytical potentiometric surface mapping method, which involves mapping the contours of a water table surface using temporal hydraulic head measurements. The capture zone estimate is generated by identifying key synoptic periods, after equilibrium is established either during full IM operations or during periods with no IM operations, and then comparing the resulting maps for when the IM is fully operational and when it is completely off, using closed contours and flow vectors to determine capture. The analytical width, shown in Figure 5.2-2 in black, is an analytical flow solution estimating the width of capture used for screening a target capture zone (https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=187788) but cannot be used to determine capture zone depth.

Three numerical methods are also shown in Figure 5.2-2, including streamlines, solute transport, and particle tracking approaches. All the methods leverage the calibrated CM, which is run to a steady-state equilibrium condition with all extraction and injection wells operational to perform the capture zone analysis. All three of these methods account for the heterogeneous spatial distribution of hydraulic conductivity within the regional aquifer and permit the exploration of parametric uncertainty. Although only one simulation is presented in this section for simplicity, multiple simulations were executed to determine lateral and vertical capture with modeling.

The streamlines method (shown in yellow in Figure 5.2-2) is similar to the analytical potentiometric surface mapping described above, but modeling can explicitly account for geologic heterogeneity and resultant groundwater flow behavior. The solute transport method (as indicated with the brown outline), accounts for both advective and dispersive processes. In this method, the release of a hypothetical conservative tracer occurs upgradient to determine the zone of capture at the extraction wells. A third numerical method, particle tracking (shown in green), is similar to the solute transport method, except that instead of simulating the release of a hypothetical conservative tracer upgradient, particles are released upgradient and traced to their exit points at extraction wells. Particles that terminate in extraction wells determine the zone of capture.

Figure 5.2-2 depicts lateral capture near the water table, but the extent of vertical capture is shown in Figure 5.2-3 based on particle tracking results for one simulation of the calibrated model. Three cross-sections depicting the vertical extent are shown, representing the north (corresponding to CrEX-5 y-coordinate), center (corresponding to CrEX-4 y-coordinate), and south (corresponding to CrEX-2 y-coordinate) areas of the plume. Depth of capture is up to 250 ft below the water table across the lateral extent of the capture zone.

As described in section 5.2.2, the calibration of the numerical CM accounts for uncertainty in parameter estimates that can result in differences in the estimate of plume capture. For example, Figure 5.2-4 (top panel) shows the complete capture of particles. For 75% of the simulations executed to account for uncertainty, the IM extraction wells were successful in capturing all particles, which is equivalent to creating a successful capture zone for chromium. Figure 5.2-4 (bottom panel) shows the depth below the water table where capture occurs. However, in 25% of the simulations executed, the potential for uncaptured chromium pathways was identified. These pathways begin upgradient of the IM system from the northern part of the estimated plume area, bypassing CrEX-5 to the north and passing through the vicinity of R-70, where there is uncertainty in the plume extent and depth. These results are shown in Figure 5.2-5 (panel a), with captured particle pathways depicted in blue and uncaptured particle pathways in red. The depth of capture is depicted in Figure 5.2-5 panels (c) and (d) and demonstrates that shallow particles released upgradient move deeper into the profile as they travel downgradient. Concentrations shown in panel b demonstrate that although particles may bypass IM capture, concentrations are below the groundwater standard (as indicated by gray pathways) before exiting the Laboratory property. With respect to all of the simulations executed to explore parameter uncertainty, the particle tracks depicted in Figure 5.2-3 are from the simulation that shows the greatest potential for incomplete capture in the northeastern region of the plume.

According to the capture zone analysis, the IM system meets the goal of maintaining the 50-ppb plume edge within the LANL boundary on the southern edge of the chromium plume and is additionally reducing the plume footprint to the east. The only region that may be escaping capture by the IM is in the northern part of the plume near R-70, where there is uncertainty in the plume extent and plume depth. Capture is complete at depth in the plume southern, central, and southeastern regions for all simulation approaches. All simulations indicate that operating all of the injection and extraction wells results in complete capture, both laterally and vertically, in the plume southern, central, and southeastern regions.

5.3 Chromium Concentration Trends Post Start of IM Operations

Since the start of the IM, trends in concentrations at monitoring wells within the chromium investigation area have been influenced by IM operations. To examine the IM influence, monitoring wells have been grouped into three different regions as shown in Figure 5.3-1: (1) plume centroid, (2) southern plume area, and (3) northeastern plume area. In the sections that follow, concentration trends for chromium and other geochemical constituents are examined for statistical significant trends based on different phases of the IM. Mann-Kendall (M-K) testing has been performed to detect the presence of linear trends in the concentration time series data. Appendix A provides the results of the M-K test results. The M-K test assesses if a series is steadily increasing, decreasing, or has no trend at all. The M-K testing has been performed in segments that correspond to the times of key IM operational phases:

- Initial operations in the southern plume area (January 2017), with only CrEX-1, CrIN-4, and CrIN-5 in operation
- Sustained initiation of operations in the southern plume area (May 2018); CrEX-1, CrEX-2, CrEX-3 (when available) and CrEX-4, CrIN-3, CrIN-4, and CrIN-5 in operation
- Initiation of eastern area operations (November 2019); all wells operational when available, including wells CrIN-1, CrIN-2, and CrEX-5 in the eastern plume area

- Extended pause in operation for COVID-19-related reasons (essential mission critical activities [EMCA] pause). Because of data sparsity during the EMCA pause, M-K testing was not performed for this period.

5.3.1 IM Injection Water Signature

In addition to observing tracer responses (see section 5.4), the influence of the IM on aquifer flow patterns can be evaluated by observing changes in chloride, sulfate, and Cr[VI] concentrations in the monitoring wells. Chloride and sulfate both have significantly higher concentrations in extraction wells than at the plume periphery (see Appendix D), and most of the time these anions pass through the anion exchange resin in the chromium treatment system with little or no change in concentration. For example, the extremely low molar concentration of chromate (CrO_4^{2-}) compared with the chloride concentrations that chromate displaces suggests that ion exchange has a very small effect on chloride as water passes through the resin. Thus, both chloride and sulfate serve as excellent geochemical markers to indicate where treated water injected into CrIN wells is appearing in monitoring wells near the plume periphery. Similarly, decreases in chromium concentrations can also be attributed to the appearance of treated water in monitoring wells.

5.3.2 Concentration Trends by Plume Area

Results of the M-K testing at the 95% confidence level are provided in Appendix A and visually summarized in Table 5.3-1 with arrows showing the direction of the chromium concentration trends before IM operations, after sustained southern IM operations, and after sustained eastern area IM operations. If no statistically significant trend exists, then the em-dash (—) symbol is shown. All symbols are color-coded, with decreasing trends shown in green and increasing trends shown in red. Trends that are below the 50-ppb standard are shown in gray. To simplify the presentation, the wells chosen for analysis were only those monitoring and extraction wells thought to be potentially influenced by IM injection or extraction operations. On this basis, wells R-43 and R-62 were excluded—they exhibit concentration trends but are relatively distant from the IM infrastructure wells, and the trends predate the start of IM operations. Furthermore, piezometers CrPZ-1, -2a, -2b, -3, -4, and -5 are omitted for simplicity.

For the discussion that follows, well screen depths are shown conceptually in Figure 4.2-1 and locations are provided in Table 4.2-1. Only chromium concentrations are provided in the main text of this document. Plots of chloride and sulfate concentrations are provided in Appendix D.

5.3.3 Southern Plume Area Concentration Trends

There are six monitoring wells (R-15, R-61, R-50, R-44, SIMR-2 and R-13) and two extraction wells (CrEX-1 and CrEX-2) located in the southern plume area (see Figure 5.3-1). Before IM operations, chromium concentrations in four of the monitoring wells showed increasing trends (R-15, R-61 screen 1, R-50 screen 1, and R-44 screen 1), but only R-50 screen 1 was above the 50-ppb groundwater standard.

Concentrations at well R-15, located near the southern Laboratory boundary upgradient of the chromium plume, had measured approximately 1.5 times background concentrations (~12 ppb) by the time sustained southern plume area operations had commenced, whereas well R-44 screen 1 and R-61 screen 1 concentration trends peaked at approximately twice the background concentration. Chromium concentrations in the R-44 lower screen (screen 2) have always remained below the upper limit for the background concentration for chromium, specifically below 7.48 ppb.

Before IM operations, SIMR-2 and R-13 were at background concentrations and have remained unaffected by sustained extraction and injection.

5.3.3.1 Concentrations at R-50

Performance of the IM in the southern plume area along the Laboratory boundary with the Pueblo de San Ildefonso is manifested largely by chromium concentrations at monitoring well R-50. That well is situated approximately 375 ft north of the Laboratory boundary.

Before initiation of IM operations in the southern plume area, chromium concentrations had reached approximately 140 ppb in the upper screen (screen 1) in R-50 (Figure 5.3-2). R-50 screen 1 is near the water table and screen 2 is centered at approximately 110 ft below the water table, thus providing the basis for the assumption that the chromium plume had a thickness within the regional aquifer of less than about 100 ft. Upon initiation of sustained operations in the southern plume area, chromium concentrations dropped precipitously and are currently at levels below background. There is also an injection water geochemical signature at R-50 screen 1, with chloride and sulfate concentrations reaching a value that is 4 times greater than pre-IM conditions (~20 mg/L).

The decreasing chromium concentrations at R-50 screen 1 provide the basis for changes (retreat) in the plume edge (as defined by the 50-ppb groundwater standard) over time. However, the 111-day COVID-19-pandemic-driven EMCA pause when IM operations ceased in 2020 caused chromium concentrations to increase by approximately 75%, remaining just below the 50-ppb groundwater standard. Once IM operations resumed, chromium concentrations returned to pre-EMCA values within a few months and have continued to decrease to background concentrations measured present day. This rise in concentrations upon shutting down the injection and extraction wells can be compared with a later situation in which extraction well CrEX-1 was not operational while injection continued at CrIN-4 and CrIN-5. During a 251-day shutdown of CrEX-1 beginning on July 22, 2021, concentrations at R-50 screen 1 did not increase. A comparison of this behavior with the EMCA pause result demonstrates that injection, rather than extraction, plays the predominant role in keeping concentrations low at the periphery of the plume (Figure 5.3-2). As shown in shown in Figure 5.1-6, the water level contours near well R-50 show that groundwater is flowing toward CrEX-1, due solely to injection at CrIN-4 and CrIN-5.

5.3.3.2 Concentrations at R-61

Monitoring well R-61, located to the southeast of the chromium plume area, has shown consistent increases in chromium concentrations in screen 1 (located approximately 20 ft below the water table), coincident with initiation of the IM (Figure 5.3-3). Water-level data in R-61 indicate a response to IM pumping, presumably from the nearest extraction well (CrEX-2) and injection well (CrIN-5). However, no injection water signature is evident at R-61 screen 1, as concentrations of chloride and sulfate remain around background (~5 mg/L). It is possible that the combined effect of extraction from CrEX-2 and injection from CrIN-5 could be altering groundwater flow directions. The cause for the increasing trend is currently unknown but could be the result of CrEX-2 drawing water from a high concentration zone (as shown in Figure 4.1-1).

5.3.3.3 Concentrations at Extraction Wells CrEX-1 and CrEX-2

Extraction well CrEX-1 is located approximately 1000 ft north of the Laboratory boundary. CrEX-1 chromium concentrations at the well screen located at the water table were approximately 150 ppb before IM operations but have now decreased to concentrations that are approximately at the 50-ppb groundwater standard (Figure 5.3-4). In a similar manner to R-50 screen 1, the geochemical signature of injection water is evident, with chloride and sulfate concentrations that are approximately 2 times higher than background (see Appendix D).

CrEX-2, with the center of well screen located approximately 35 ft below the water table, exhibits chloride and sulfate concentrations nearly 2 times greater than those in CrEX-1. Although this could be due to a signal from CrIN-5 injection water, the more likely explanation is that higher concentrations of these species are present within the chromium plume and are produced along with chromium. Tracers injected in CrIN-5 have not been detected at CrEX-2, and the trends over time are inconsistent with the arrival of injection water from CrIN-5 or any other injection well. CrEX-2 is located to the west of CrEX-1, and approximately 1400 ft north of the Laboratory boundary. Chromium concentrations are higher at CrEX-2 but have been decreasing monotonically from approximately 250 ppb at the start of the IM to approximately 200 ppb present day (Figure 5.3-5).

5.3.4 Eastern Plume Area Concentration Trends

There are five monitoring wells (R-11, R-45, R-70, R-35a, and R-35b) and one extraction well (CrEX-5) located in the eastern plume area (see Figure 5.3-1). Although well R-70 was not installed before IM operations, wells R-35a and R-35b, with well screen depths of 213 and 62 ft below the water table to the tops of the screens, respectively, have been at background since the start of the IM to present day. Chromium concentrations at R-11, with a depth to the top of the screen of 12 ft below the water table, continue to measure below the 50-ppb groundwater standard, with variations in concentrations that are not likely related to IM operations (Table 5.3-1).

Well R-45 is located southwest of R-70 and flanked by injection wells CrIN-1 and CrIN-2 to the west. Pre-IM concentrations in screen 1 and screen 2 were below 50 ppb but above background and rising since the well was first sampled in 2009, climbing to about 40 ppb in screen 1 and 20 ppb in screen 2 (Figure 5.3-6).

5.3.4.1 Concentrations at R-45

Chromium concentrations at R-45 screen 1 demonstrate a trend reversal after the start of sustained injection in the southern region of the plume. The monotonic decrease in concentrations continued after eastern area operations commenced (Figure 5.3-6). Since there is a concomitant increase in chloride and sulfate concentrations (Figure 5.3-7), this is indicative of injection water entering the screen 1 interval. These concentration trends suggest that dilution is occurring at this location due to injection.

By contrast, chromium concentrations in R-45 screen 2 have increased after sustained IM operations (Figure 5.3-6), but the geochemical signature of injection water is absent at this screened interval location. Given the proximity of CrIN-1 and CrIN-2 to R-45, and the definitive impact of that injection on screen 1, it is likely that eastern area injection has had some impact on R-45 screen 2 concentrations as well.

Data from CrIN-1 and CrIN-2, before initiation of the IM, indicate a chromium front has been migrating from the core of the plume into this region of the aquifer since at least the early 2000s and was present in concentrations as high as 100 ppb (see Figure 3.3-5). This portion of the plume resides at an intermediate depth between screen 1 and screen 2, similar to what is shown in Figure 4.1-2. Upon initiation of the IM in the eastern plume area in late 2019, the geochemical signature from injection was detected at R-45 screen 1 but has not been detected at screen 2. Hence, the moderate concentration increases observed at R-45 screen 2 since late 2019 are likely due to injection water influencing the vertical migration of higher chromium concentrations that was already present between the screens into the R-45 screen 2 interval. 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 chromium concentrations above the 50-ppb groundwater standard at these depths.

5.3.4.2 Concentrations at CrEX-5

The unexpected high chromium concentrations (approximately 300 ppb) found when drilling the well, which was originally designated as injection well CrIN-6, prompted a design change, converting CrIN-6 to CrEX-5, with the center of the well screen located approximately 40 ft below the water table. Since operating CrEX-5 in late 2019, chromium concentrations have steadily decreased to less than 150 ppb as shown in Figure 5.3-8. There is no evidence of an injection water geochemical signature from CrIN-1 at CrEX-5 (see plots of chloride and sulfate concentrations provided in Appendix D). Additional information on water flow to CrEX-5, including a broader discussion that includes chloride and sulfate concentration trends, is provided in section 5.4.

5.3.4.3 Concentrations at R-70

R-70 is a dual-screened well located approximately 1900 ft north of the southern Laboratory boundary, approximately 1800 ft southwest of the LAC water supply well PM-3. The vertical concentration distribution at R-70 is the reverse of what is found at the southern boundary, with concentrations greater than 250 ppb (Figure 3.4-1) in the lower screen 2 at approximately 90 ft below the water table. Conversely, the screen located approximately 35 ft below the water table, screen 1, measures chromium concentrations below the 50-ppb groundwater standard. As indicated in Table 5.3-1, since initiation of sustained operations of CrEX-5, chromium concentrations at R-70 screen 2 have decreased to about 150 ppb. There is currently no evidence of injection water mixing with groundwater at either screen location (see section 5.4 for further analysis).

5.3.5 Plume Centroid Concentration Trends

Since chromium concentrations have not been considered representative at wells R-28 and R-42 because of pilot studies investigating the potential to immobilize chromium via amendment injection, the only wells located in the centroid area of the plume to represent current chromium concentrations are CrEX-3, centered approximately 30 ft below the water table, and CrEX-4, with the shallow and deep screens centered approximately 30 ft and 65 ft below the water table, respectively. Both wells have demonstrated monotonic decreases in chromium concentrations with the sustained eastern IM operations (Table 5.3-1). As shown in Figures 5.3-9 and 5.3-10, chromium concentrations at both wells have steadily declined since sustained eastern area operations. Whereas CrEX-4 has shown a steady decline in concentration from nearly 500 ppb to approximately 250 ppb, CrEX-3 concentrations varied as the well operated intermittently once sustained southern operations commenced. As a result, the concentration decline is slower, with recent chromium concentrations measuring at approximately 120 ppb.

5.4 Analysis of Tracers

In this section, flows induced by the IM are analyzed based on both tracer and injection well geochemical signatures arriving at monitoring and extraction wells. Collectively, this information is used to bound injection water migration, as well as identify extraction well source locations. Tracer injections and IM inflows and outflows are first summarized; then key observations in various monitoring or extraction wells are presented. Finally, a summary of IM flow inferences, including a map depicting these flow inferences, is provided.

5.4.1 Injection Well Tracers and Geochemical Signatures

Tracers have been deployed into each of the five injection wells to allow observations of tracer arrivals at monitoring wells and extraction wells as summarized in Table 5.4-1 and previously documented in Reimus et al. (2021, 701331) and (LANL 2018, 602964). Naphthalene sulfonate tracers were used for all injection wells because they are highly soluble, nontoxic, and nonsorbing; have very low detection limits; and are relatively inexpensive for the large injection masses necessary for detection at monitoring and extraction wells (Rose et al. 2001, 232203).

Since concentrations of chloride and sulfate are unaffected by the treatment process, their concentrations in injection water are largely a continuous, flow-weighted average of extraction well concentrations. Therefore, treated water arrivals cannot be traced to a particular injection well. By contrast, naphthalene sulfonate tracers were introduced as a concentrated slug of short duration. Hence, tracers can indicate an unequivocal arrival of treated water from an injection to an extraction well. By combining tracer data with geochemical responses due to injection water signals, important information on flow patterns and mixing associated with IM operation can be discerned. Since chloride has the least potential reactivity and cleanest signal, it is used in this analysis to indicate treated water arrivals.

5.4.1.1 CrIN-4 and CrIN-5 Tracers

Figure 5.4-1 shows the responses of chloride, sulfate, chromium and the 1,5-naphthalenedisulfonic (1,5-NDS) tracer (injected into CrIN-4) at R-50 screen 1, centered approximately 10 ft below the water table. Not long after the arrival of the injection water in R-50 screen 1, the chloride concentration in R-50 screen 1 reached 20 ppb, which is approximately the injection water concentration, suggesting that the aquifer water originally present in R-50 screen 1 was essentially completely replaced by the injection water. Chloride trends in R-44 screen 1 and R-45 screen 1 were similar, rapidly approaching injection water concentrations.

The R-50 screen 1 response of the 2,6-NDS tracer that was injected into CrIN-4 over a year after the 1,5-NDS tracer is not shown in Figure 5.4-1 because there was only one sample with a detectable concentration at R-50 screen 1 on January 15, 2019. This tracer apparently biodegraded in the aquifer soon after it arrived at R-50 screen 1, an unexpected outcome given that naphthalene sulfonate tracers are known to have lifetimes of many years in geothermal reservoirs (Rose et al., 2001, 232203).

Figure 5.4-2 shows the 1,5-NDS tracer response in CrEX-1 along with the response of this tracer in R-50 screen 1. The tracer arrivals at both locations had similar arrival times, despite CrEX-1 being located at nearly twice the distance from CrIN-4 as R-50 screen 1. Unlike R-50 screen 1, the tracer concentration at CrEX-1 has not dropped off significantly and remains relatively high to the present day. Because CrEX-1 has been pumped (as opposed to just being a passive monitoring location like R-50 screen 1), it is possible to estimate the fraction of tracer recovered at this extraction well. Approximately 16.5% of the 1,5-NDS tracer mass has been recovered to date, implying that at least 16.5% of the water injected into CrIN-4 since the tracer was injected has been drawn into CrEX-1. Given the current trend shown in Figure 5.4-2, the tracer recovery will continue to increase, and the estimated fraction of water injected into CrIN-4 reaching CrEX-1 will likely continue to increase. As this occurs, it is likely that this tracer will pass through the ion exchange system and be reinjected into all CrIN wells. However, this secondary signal would be much lower than the original tracer injection and thus would likely be too weak to detect. Although the major contribution of injected water in CrEX-1 is from CrIN-4, with the apparent susceptibility of some of these tracers to biodegradation, it is possible that some injection water from CrIN-5 may also be reaching CrEX-1. However, CrIN-5 tracers have not been detected at CrEX-1 or at any monitoring well.

Finally, chloride, sulfate, and chromium concentration histories in R-50 screen 2, as well as lack of tracer arrivals, indicate that injection fluid has not arrived in the deeper screen. There has also been no evidence of tracer or injection water arrivals at SIMR-2, despite its relatively close proximity to CrIN-4 and CrIN-5, approximately 1100 and 2000 ft to the southeast, respectively.

5.4.1.2 CrIN-3 Tracers

R-44 screen 1, centered approximately 15 ft below the water table, has shown a definitive response to the injection water and the 1,3,6-napthalenetrisulfonic (1,3,6-NTS) tracer injected into CrIN-3 (Figure 5.4-3). Also as with R-50, no tracer or injection water signal has been detected in the lower screen, R-44 screen 2, approximately 100 ft below the water table. Thus, the CrIN-3 injection water seems to remain relatively shallow, similar to the injection water from CrIN-4. The CrIN-3 tracer and injection water signatures have also not been detected at R-13 or SIMR-2.

5.4.1.3 CrIN-1 and CrIN-2 Tracers

Tracers were not injected into either CrIN-1 or CrIN-2 until March 2021, so it was not immediately known whether CrIN-1 or CrIN-2 (or both) was responsible for the arrival of injection water at R-45 screen 1. To date, neither CrIN-1 nor CrIN-2 tracers have been detected in R-45 screen 1, which again suggests that at least one of the tracers biodegraded before arriving at R-45 screen 1.

Figure 5.4-4 shows that in early 2022, the 1,3,5-NTS tracer injected into CrIN-2 started arriving at CrEX-3. The total tracer mass recovery to date in CrEX-3 has been about 1% of the injection mass, but it is clearly increasing with no indication of biodegradation. This result suggests that the injection water arriving in R-45 screen 1 came from CrIN-1 rather than CrIN-2, and that the 2,6-NDS tracer injected into CrIN-1 inexplicably biodegraded before it could be detected in any monitoring or extraction well. If the 2,6-NDS tracer had a similar longevity in the aquifer as the CrIN-4 injection, it should have at least been measured in R-45 screen 1 or possibly CrEX-5. The reason the 2,6-NDS tracer had greater longevity in the aquifer after its injection into CrIN-4 (relative to CrIN-1) has not yet been determined.

Figure 5.4-5 shows the chloride, sulfate, and chromium concentration histories in CrEX-5, which, in lieu of a tracer response, can be used to look for evidence of treated water arrival from CrIN-1. While the trends in sulfate and chromium are consistent with the possibility of a treated water arrival, it is clear that the concentrations of all constituents have been decreasing since CrEX-5 began operations. Hence, the lower concentrations may be due to a concentration decrease in groundwater drawn into CrEX-5, treated water arrival, or both. Since the chloride concentration in CrEX-5 has dropped below the average concentration in injection water, then at least some of the observed decrease is from groundwater being treated at CrEX-5, presumably from locations within or at the edge of the plume where concentrations are lower.

Figure 5.4-6 shows chloride, sulfate, and chromium trends in R-70 screen 2, which has higher concentrations relative to R-70 screen 1 (see Figure 3.4-1) and appears to be better connected to the plume centroid than the upper screen at R-70. Chloride, sulfate, and chromium trends at R-70 screen 2 are similar to those at CrEX-5, although the chloride concentration at R-70 screen 2 has dropped to even lower levels than in CrEX-5. These results suggest that treated injection water has not yet arrived at R-70 screen 2, given the continuously declining concentrations of chloride and sulfate to levels lower than the injection fluid concentrations. Furthermore, there are no signs of injection water reaching R-70 screen 1. Instead, a reasonable assumption is that CrEX-5 is, at least in part, pulling groundwater from R-70 preferentially from the depths of R-70 screen 2 and perhaps from R-70 screen 1 as well.

5.4.2 IM Flow Inferences from Tracers

Collectively, the tracer and injection water geochemistry observations discussed in the previous section provide a qualitative description of IM injection well flow footprints. They also provide a description of groundwater flow toward IM extraction wells, particularly CrEX-1 and CrEX-3. An annotated depiction is shown in Figure 5.4-7, which not only integrates information provided in this document, but also with previous tracer studies documented in Reimus et al. (Reimus et al. 2021, 701331) and the absence of a cross-hole response with the R-28 amendment injection. Inferences from injection water tracers and geochemistry are as follows:

- Injection flow into CrIN-4 reached both R-50 screen 1 and CrEX-1, with about 17% of the injection flow (likely more) being drawn into CrEX-1. CrIN-4 injection water has not reached other observation locations, including R-50 screen 2 and SIMR-2. The injection water appears to remain shallow, at least in the vicinity of R-50.
- Injection flow into CrIN-5 has not been definitively observed at any location, possibly due to the biodegradation of the CrIN-5 tracer.
- Injection flow into CrIN-2 reached CrEX-3, with about a 1% tracer recovery at CrEX-3 to date. CrIN-2 injection water has not reached either R-45 screen 1 or R-45 screen 2 or any other locations.
- Injection flow into CrIN-1 reached R-45 screen 1 very rapidly, but the rapid degradation of the tracer injected into CrIN-1 has prevented a positive detection of arrival at CrEX-5. CrIN-1 injection flow does not appear to be reaching R-45 screen 2, R-70 screen 1, or R-70 screen 2.
- CrEX-3 is extracting groundwater from CrIN-2, with an exact percentage of the injected water currently unknown, but likely to be significantly higher than the 1% of CrIN-2 tracer mass already recovered.

This information has also been summarized in the final column of Table 5.3.1.

5.5 Injection at Plume Boundaries

Chromium-free groundwater has been injected at the periphery of the plume after aboveground treatment since the initiation of the IM, beginning with CrIN-4 and CrIN-5 in early 2017, followed by CrIN-3 in 2019, and CrIN-1 and CrIN-2 in late 2019 (Figure 1.0-1). Measurements of chromium concentrations before these wells had received clean injection water indicated that the wells were located at the periphery of the chromium plume. Figure 5.5-1 shows a 2017 plume map with chromium concentration values in ppb (red font) at each injection well and in nearby monitoring wells in 2017, along with interpreted contours of chromium concentrations in the vicinity of CrINs -3, -4, and -5. Pre-injection CrIN concentrations ranged from 50 ppb (CrIN-3) to 95 ppb (CrIN-5), or about 5-10% of the maximum concentrations near the 1000-ppb levels measured in the plume centroid.

5.5.1 Approach

An important factor influencing chromium mass movement and concentrations is the extent to which injection water attenuates the plume. In lieu of detailed information on these dynamics, an order-of-magnitude approach is employed in this analysis where the total volume of water injected into each injection well is hypothesized to mix and ultimately displace groundwater with chromium-free water. Assuming a cylinder centered at the well with height equal to the screen length, and assuming a porosity of 0.25, the radius of fluid displacement around each injection well was calculated. Figure 5.5-2 shows the radii of the calculated cylinders in plan view. Similarly, computed radii around the extraction wells are also included for reference in this qualitative analysis.

There are several simplifying assumptions that make this analysis approximate, including the potential effects of a natural gradient superimposed on the system, heterogeneous aquifer properties, potential vertical flow above and below the screen horizon, flow interactions between the wells, and uncertain values for porosity. These effects would either shrink or enlarge the radius, result in a non-circular shape, or result in merged zones of influence. Nevertheless, this approximate method shows that the radius of influence at each well is large enough to create an extensive zone between the extraction and injection wells that is strongly influenced by injection of chromium-free water and capture of chromium by the group of extraction wells CrEX-1, -2, -3, and -4 (CrEX-5 is too distant from the other extraction wells) This description is corroborated by the analysis of potentiometric surface changes during the IM presented in section 5.1.

5.5.2 Chromium Fate at the Plume Periphery

Figure 5.5-3 superimposes on the injection well zones of influence the present-day chromium concentration measurements (red font) at monitoring wells, along with inferred low concentrations (<3 ppb) at the injection wells. Concentrations at injection wells were last measured during the EMCA pause in 2020 and were shown to be below detection. Therefore, concentrations are expected to be above 3 ppb after an additional 2.5 years of operation. Also included in the figure are inferred concentration contours representing the present-day condition in this portion of the plume. A significant region of low concentration has been created by the combination of extraction of mass to the north and attenuation of the plume due to injection. Some chromium mass was likely present to the south of CrIN-4 and CrIN-5 before IM operation began, and it has probably transported away from the zone of influence to the south towards SIMR-2. Chromium mass near CrIN-5 and to the north and west is also likely being driven away from CrIN-5 and toward CrEX-2, which may explain, in part, the rise in concentration at R-61 screen 1 during the IM.

Regarding the chromium mass south of the injection wells, there is uncertainty in concentrations because of the unknown amount of attenuation due to injection relative to the amount of mass captured by extraction wells. Given the sparse well network, the 50-ppb contour drawn is notional and could be an overestimate or underestimate of the actual concentrations at that location. What is known is that there is no evidence of migration as far as SIMR-2 or R-13. Furthermore, chromium mass in this region has not been driven by injection to below 100 ft below the water table, as evidenced by the lack of perceptible increases in either R-50 screen 2 or R-44 screen 2. The plume appears to be relatively shallow in the southern area, and whatever mass is now south of CrINs -3, -4, and -5 should be detected eventually at SIMR-2 or R-13, if it has not already been dispersed and diluted to concentrations near background.

The lateral influence of injection in the eastern plume area is likely similar to that in the southern plume area, as any chromium mass present in the vicinity of CrIN-1 and CrIN-2 in the upper 50 ft of the aquifer has either been captured by CrEX-3 or possibly CrEX-5 (see tracer analysis presented in section 5.4) or transported downgradient toward R-36, where chromium concentrations are at background levels. The vertical influence of injection is also likely similar to that of the southern plume area, with the difference being the existence of a high concentration zone located between the two well screens at R-45 (see conceptual diagram in Figure 4.1-2). This conceptual model for chromium migration is further supported by the absence of injection water detection in the lower screens at R-45 and R-70 (Table 5.3-1).

5.6 IM Influence

Before IM operations, the chromium plume was conceptualized as shallow, located within the upper 50 ft of the regional aquifer based on the data available at that time. This conceptualization remains true for the southern plume area, as there is no evidence to date of chromium migration with depth, nor has there been any detection of tracers or injection water geochemical signatures at depth. These tracer data, along with the decreasing chromium concentrations at R-50, provide the basis for changes (retreat) in the plume edge as defined by the 50-ppb NMED groundwater standard over time.

The IM was designed for hydraulic plume control at depths of approximately 50 ft below the water table. The combined extraction at CrEX-1, CrEX-2, CrEX-3, and CrEX-4 has resulted in an integrated area of groundwater capture in the aquifer, likely at depths to at least 75 ft below the water table, based on the depths and lengths of extraction-well and injection-well screens. This integrated capture zone provides for plume control through beneficial capture of chromium mass flux in the upper portions of the plume within the general centroid of the plume.

With the drilling of well R-70, a deeper plume has been identified in the northeastern region of the plume. However, there still lacks any evidence of the injection water geochemical signatures or tracers arriving at lower well screens (located 100 to 120 ft below the water table), such as R-45. It is likely that injection water is mixing with a zone of higher concentration located between the lower and upper screens at R-45, causing the vertical migration of the shallower plume to at least the depth of the lower screen. Tracer results suggest that injection water arriving at R-45 screen 1 originated from CrIN-1 rather than CrIN-2. However, it is also possible that both CrEX-3 and CrEX-5 are pulling water from R-45. Since chromium concentrations are decreasing at CrEX-5 and R-70 screen 2, CrEX-5 seems to be hydraulically connected at depth to R-70, which may also extend to R-45 screen 2. It is also possible that the CrEX-3 capture zone is pulling water through R-45 from the south, in addition to CrIN-2.

The capture zone analysis has shown that vertical capture extends up to approximately 250 ft below the water table, including the southern, central, and southeastern regions (including R-45) of the plume. All simulations indicate that operating all the injection and extraction wells results in complete capture in these regions. Although modeling has indicated that R-45 screen 2 is within the integrated capture zone, there are no measured data to support this result because of the lack of monitoring wells downgradient of R-45. Well R-80 (see Figure 1.0-1), specified as Action 3 in the R-45 Action Plan (N3B 2022, 702350), is a monitoring point needed to confirm this analysis, but monitoring data will not likely be available for 1.5 years or more at this location. R-80 represents a downgradient response to R-45, with an upper screen located at an equivalent depth to R-45 screen 2 and a lower screen depth at approximately 150 ft below the water table. Data from R-80 will help determine if deep migration is occurring beneath the depth of R-45 screen 2. If chromium concentration data are below the groundwater standard at R-80 at both screen locations, these data will confirm that the IM is capturing chromium at the depth of R-45 screen 2. However, this result is dependent on continued IM operations.

The only region where uncaptured pathways are identified (in 25% of the simulations) is in the northeastern area of the plume, north of R-70, where there is uncertainty in the plume extent and plume depth. Given the zone of high concentrations at depth, and the decreasing concentration trends at both CrEX-5 and R-70 screen 2, continued operation of CrEX-5 is critical for continued hydraulic plume control in this region of the plume.

6.0 ANALYSIS OF DIFFERENT IM OPERATIONAL SCENARIOS

Simulations are used to demonstrate concentration changes at sentinel locations under four different operational scenarios, including

- Full operations (all five extraction and all five injection wells operating 24 hr per day, 7 days per week, at a nominal total of 285 gpm)
- Continuation of current system configuration operations (CrEX-4 and CrEX-5, CrIN-4 and CrIN-5 operating only, 24 hr per day, 7 days per week, at a nominal total of 140 gpm). This scenario is referred to as the “reduced IM” and resulted from maintenance activities.
- Land application of extraction water, (CrEX-4 and CrEX-5 operating only at nominal rate of 140 gpm, 8 hr per day for 3 days, followed by a 2-week period with no extraction, while water is land-applied from April to November [when freezing conditions are absent and not during precipitation])
- No operations (0 gpm for all extraction and injection wells)

The starting point for all four simulations assumes the historical pumping record through October 2022. In November 2022, because of maintenance issues, CrEX-1, CrEX-2, and CrEX-3 were turned off, resulting in a concomitant shutdown of injection wells CrIN-1, CrIN-2, and CrIN-3 to balance water flow in the IM system. The simulations assumed that this reduced operational scenario extends to April 1, 2023, based on the date given in the NMED-GWQB letter (NMED 2022, 702464) to complete the actions described in section 1. Using a start date of April 1, 2023, the four different operational scenarios described above were simulated until January 1, 2027 (i.e., through the end of calendar year 2026). This period was selected assuming that any operational changes would be relatively short term, but long enough to observe changes in chromium concentrations due to the modifications in operations. Table 6.1.1 presents IM extraction and injection well rates for the four operational scenarios.

6.1 Chromium Concentration Impacts

To evaluate the impacts associated with modifications to the IM system, concentration trends were evaluated at several existing wells, including R-35a, R-35b, R-44, R-45, R-50, R-61, and R-70 (Figure 6.1-1). Since R-80 is a future well that is part of the R-45 Action Plan (N3B 2022, 702350), simulated concentrations at its proposed location are also evaluated (Figure 6.1-2), with the upper screen located 100 ft below the water table and an equivalent depth of R-45 screen 2, and the lower screen located at 150 ft below the water table.

The concentration time series shown in Figure 6.1-1 reveal that concentration trends with land-application-only and no-operations scenarios are nearly identical. Concentration differences are difficult to discern, and where visibly different, differences are insignificant. The logistical challenges and regulatory constraints for land application severely limit extraction operations. For example, an average extraction rate of 8 gpm can be executed over a 7-month period, reducing IM operations by 97% relative to reduced operations (140 gpm year round), and nearly 99% relative to full IM operations (nominally 285 gpm year round). However, for all four scenarios through the end of calendar year 2026, wells R-35a and R-35b remain at background concentrations.

Chromium concentrations at both screens R-50 remain below the groundwater standard, demonstrating that rebound in well R-50 screen 1 is not expected to occur if the IM system remains off over the next 3 years and 9 months This simulated result is in contrast to the actual rebound that occurred at R-50 screen 1 during the 111-day EMCA pause, when concentrations increased by approximately 75%. This implies that the 50-ppb plume boundary has moved far enough away from the Laboratory boundary that

IM operations over the next 3.75 years will not cause chromium concentrations to rise significantly at R-50. Though not entirely analogous because injection at CrIN-4 and CrIN-5 occurred, the lack of rebound in the July 2021 to March 2022 period of the CrEX-1 shutdown supports this model result. However, as indicated in Figure 6.1-1, under the land-application and no-operations scenarios, rebound does begin to occur at the end of 2026.

Full IM operations is the most effective scenario for reducing concentrations at R-45 and R-70. Although both screen locations at these wells show concentration increases under land-application and no-operations scenarios, the lower screens are more significantly impacted because these concentrations are above the groundwater 50-ppb standard. Under full operations, chromium concentrations are reduced below the groundwater standard before 2026, whereas concentrations begin increasing at R-45 screen 2 after an initial decline by 2025 under all operational scenarios except full operations. At R-70 screen 2, reduced operations is unable to reduce concentrations below the groundwater standard, and land-application and no-operations scenarios result in concentration increases effective in 2023. Concentrations at the planned location for R-80 are near background concentrations at both proposed screen locations, with full IM operations resulting in the lowest concentrations.

6.2 Uncertainty Considerations

Ribbon plots of concentration time series in Figure 6.2-1 depict uncertainty at R-45 and R-70 for both screen locations for full, reduced, and no operations (since land-application results are nearly identical to no operations, land application is not shown). Despite a wide range in potential concentrations, full IM operations is the only scenario that demonstrates a definitive decrease in concentration at R-45 screen 2 to background chromium concentrations. The decrease in concentration to below the groundwater standard under the reduced-operations scenario is also likely, but concentrations do not significantly decrease below the 50-ppb standard and will likely rebound by 2026. A similar result is anticipated under no operations, although chromium concentrations may never decrease to below the groundwater standard.

At R-70 screens 1 and 2, uncertainty bounds clearly demonstrate concentration increases under a no-operations scenario, although concentrations in the upper screen will remain above background but below the groundwater standard. The most significant concentration reduction in screen 2 will be achieved under full operations, but under reduced operations CrEX-5 still operates in a high-concentration region of the plume. The benefit of full operations is realized with injection, possibly due to a steepening of the hydraulic gradient to allow more flow to extraction wells or dilution of nearby groundwater.

Simulated concentrations at R-61 demonstrate concentration increases under all four operational scenarios. However, when accounting for model uncertainty, there is a wide range of potential outcomes, and the concentration under the full IM scenario could increase, level off, or decline. This result implies that the concentration at R-61 is more dependent on the source-term representation in the model rather than on IM operations. The reduced-operational scenario has a limited ability to reduce concentrations at R-61.

6.3 Chromium Inventory

Although regulatory compliance is based on concentrations, the total mass within the modeling domain (i.e., inventory) can also be used as a metric to evaluate the impact of different operational scenarios. Note that because of the uncertainty associated with continuing sources to the regional aquifer, the current model conservatively assumes that chromium mass continues to enter groundwater at a constant mass flux through January 1, 2027. Figure 6.3-1 shows that the full-operations scenario decreases the total mass of chromium in the regional aquifer, reduced IM operations remains largely unchanged, and a no-operations scenario increases the total inventory (because of continuing sources of chromium entering the regional aquifer). From April 1, 2023, when the operational scenarios diverge, to January 1, 2027, when the simulations end, the full IM can reduce the mass in the aquifer by 75 to 196 lb, the reduced IM could lead to changes from −51 lb to +102 lb in the aquifer, and turning the IM off leads to increases of 326 to 485 lb. Ranges of inventory are provided because the simulations account for uncertainty. The volume of water treated, estimated mass removal, and changes in inventory from April 1, 2023, to Jan 1, 2027, are also shown in Table 6.1-1.Since land application is functionally equivalent to no operations, it would also have an increase in mass occurrence similar to the no-operations scenario.

6.4 Summary of Simulation Results

Simulations have been used to evaluate the effect of four operational scenarios, including full operations, reduced operations, land-application only, and no operations. By comparing concentration changes at monitoring wells and total mass within the aquifer, the analysis demonstrated the following distinctions among the four different operational scenarios:

- Land application results in a significant reduction in operations (nearly 99% relative to full IM operations) and is functionally equivalent to no-IM-operations.
- If IM operations cease, chromium mass in the regional aquifer increases because of continuing sources of chromium entering the regional aquifer; estimated range of increase of 326 lb to 485 lb.
- No-IM-operations and land-application scenarios result in an increase in chromium mass.
- Reduced IM operations results in no significant changes in chromium mass; estimated removal from 51 lb to potential increase of 102 lb (based on modeled source scenario).
- The full-IM-operations scenario results in the lowest predicted concentrations in both screens at wells R-45 and R-70 and reduces the total chromium mass.
- Continued operation of CrEX-5 under the reduced-IM-operations scenario also results in beneficial reduction in concentration at R-70 screen 2.
- Full IM operations is the only operational scenario that reduces concentrations at R-42 screen 2 to below the 50-ppb groundwater standard without a possible increase in concentration at a later time.

These simulations are considered to be an initial evaluation and will be used as a basis for further optimization of potential IM operational changes.

7.0 SUMMARY AND CONCLUSIONS

Two principal lines of inquiry were presented in this document. The first was an analysis of the IM influence on the regional aquifer system, and the second was a predictive assessment of potential impacts associated with modifying IM operations. For the latter, the modifications were the result of maintenance issues that led to the shutdown of three extraction wells (CrEX-1, CrEX-2, and CrEX-3). To load-balance the system, three injection wells were also shut down (CrIN-1, CrIN-2, and CrIN-3), which resulted in reduced operations at 140 gpm, rather than the full 280 gpm that is typical with all five extraction and five injection wells in operation. The land application of treated water was also evaluated, but because of logistics associated with land application, this resulted in a functional reduction in operations (nearly 99%) that is functionally equivalent to ceasing IM operations completely.

The evidence at the time the IM system was designed suggested that the chromium plume was located predominantly in the upper 50 ft of the aquifer. As a result, the IM was designed with extraction and injection well screens located approximately 50–75 ft below the water table. While the CSM for chromium at shallow depths continues to apply for the southern plume area, chromium plume concentrations in the eastern plume area have shown opposite trends, with high chromium concentrations at depth and concentrations below the groundwater standard in the upper region of the aquifer. In this region, higher concentrations are correlated with the high concentration zone in the plume centroid. The vertical concentration distribution in the plume centroid will be better defined with the installation of wells R-76 and R-77 (see Figure 1.0-1). This shift in the CSM plays an important role in the conclusions and recommendations that follow.

7.1 IM Influence on the Regional Aquifer

The analysis of the IM influence on the regional aquifer examined potentiometric surfaces, chromium concentrations, and concentrations of injected tracers and natural tracers resulting from groundwater treatment (e.g., chloride and sulfate). The results of these analyses demonstrated that changes in the water table configuration responded slowly to each phase of the IM system, requiring approximately 1 year to achieve equilibrium from sustained operations, given the relatively high hydraulic conductivity of basin sediments and the low gradient in the chromium investigation area. Although a distinct mound is difficult to discern given the flat gradients in the chromium plume area, once full operations were achieved and the system achieved equilibrium, a groundwater divide had formed between the cone of depression formed by extraction wells near the centroid of the plume and the five injection wells positioned along the plume periphery.

Natural and injected tracers also elucidate the influence of IM operations on flow patterns in the plume area. To date, the geochemical signature of injection water is present only in the shallow upper 50 ft of the aquifer (the upper screens in R-44, R-45, and R-50; see Table 5.3-1). Tracers originating from injection wells also demonstrate arrivals at extraction wells, providing additional evidence that injection water migration occurs in the upper region of the aquifer (50–60 ft).

Since the initiation of IM operations, chromium concentrations have decreased in all five extraction wells. M-K analyses have also confirmed a decrease in chromium concentrations in key monitoring well locations, most significantly in R-50 screen 1. The R-50 result indicates that the principal objective of the IM was met, namely to reduce chromium concentrations and to shift the 50-ppb chromium concentration contour well north of the Laboratory boundary. A “clean zone” of chromium-free water of significant size is now present along the line of injection wells. Furthermore, there is no evidence that the effects of IM operation have forced the chromium concentrations as deep as R-50 screen 2, situated about 110 ft below the water table. Thus, the IM has been successful in reducing concentrations along the southern boundary of the plume and creating a hydraulic barrier to flow in the southern plume area.

M-K analyses have also demonstrated monotonic increases in concentrations at two well locations: R-45 screen 2 and R-61 screen 1. Currently, chromium concentrations at R-61 are below the groundwater standard (except for a single measurement of 51 ppb) and the cause for the increasing trend is unknown. One hypothesis is that R-61 is positioned between a high concentration zone and extraction well CrEX-2 (see Figure 4.1-1), which is drawing higher concentrations into the R-61 region. If the trend continues and reaches concentrations above the groundwater standard, then additional investigation or further modifications to the IM may be necessary.

The cause for increased concentrations at R-45 screen 2 has been demonstrated by analyzing upgradient chromium concentration trends (e.g., R-28, CrIN-1, and CrIN-2) and geochemical signatures at both screens at R-45. The geochemical signature of injection water is present only in the upper screen (~60 ft below the water table). Therefore, it is likely that a zone of chromium concentrations higher than in either screen existed between the two well screens at R-45 before IM operations, as evidenced by chromium, chloride, and sulfate concentrations upgradient at R-28, CrIN-1, and CrIN-2. Once sustained eastern area operations commenced, injection water caused the moderate concentration zone to migrate to the depth of the lower well screen (~120 ft below the water table), as shown conceptually in Figure 4.1-2. The vertical and horizontal migration of the high-concentration zone is a risk only if extraction wells are unable to capture the plume migration.

7.2 IM Capture Zone Analysis

Multiple approaches were used to assess IM capture, with modeling as the only method that can assess capture at depth (analytical methods can only evaluate lateral capture). In the plume southern and centroid areas, modeling analyses demonstrated that the IM extraction wells capture the plume lateral and vertical extents. In the eastern plume area, the capture zone analysis has identified a region where the IM may be unsuccessful in maintaining hydraulic control of the plume north of well R-70. However, there is uncertainty in the plume lateral extent and depth in this area. The installation of well R-79, to be sited in the northern region of the plume, as specified in another action identified in the R-45 Action Plan (N3B 2022, 702350), will further delineate the lateral and vertical extents of chromium concentrations in this area. Given high chromium concentrations at depth identified with R-70 (e.g., 200 ppb), continued operation of extraction well CrEX-5 is critical for continued hydraulic plume control in this region of the plume because CrEX-5 appears to be connected hydraulically to R-70 screen 2.

The hydraulic connection of R-70 screen 2 is indicative of deep extraction at CrEX-5 (approximately 100 ft below the water table). As shown in Figure 5.5-2, the combined impact of injection water from both CrIN-1 and CrIN-2 and extraction from CrEX-5 can result in complete capture of groundwater at R-45 screen 2. This interpretation is also supported by the capture zone analysis and simulations that predict that full IM operations result in concentration reductions at R-45 screen 2. Currently, there are no measured data to support this result at R-45 because of the lack of monitoring wells downgradient of this well. Well R-80, which was specified in one of the actions identified in the R-45 Action Plan (N3B 2022, 702350), will provide the data needed to either confirm or refute this assessment.

7.3 IM Operational Modifications Based on Simulation Results

Simulation results have been presented to provide a basis for decision-making on potential modifications to IM operations. Of the four operational scenarios investigated (full operations, reduced operations, land-application only, and no operations) the full IM operational scenario is predicted to be the most successful at maintaining hydraulic plume control and reducing concentrations at monitoring and extraction wells. Because of land-application logistics and restrictions, land-applying treated water is essentially equivalent to a complete shutdown of the IM system (operation goes to 1% of full IM). Since the model assumes that chromium sources continue to enter the aquifer, no-operations/land-application-only scenarios result in a chromium mass increase to the regional aquifer in the future.

The full IM operations scenario is the only scenario that reduces concentrations at R-45 screen 2 to below the NMAC standard of 50 ppb within the simulation timeframe of present day through end of calendar year 2026. All other scenarios show that concentrations will decrease to just above the groundwater standard within the next few years and then increase in concentration by 2027. This is due to the absence of mass extraction, as well as impacts of injection water dilution. Although concentration increases are expected to occur if IM operations cease, they are expected to occur slowly (e.g., on the order of years, not months). The highest risk to ceasing IM operations is in the northeastern region of the plume, near CrEX-5 and R-70.

7.4 Recommendations

Although there is still uncertainty with respect to the vertical distribution of the chromium plume in the plume centroid and northeastern region of the plume, the evidence to date indicates that IM operations have effectively contained the plume. **Therefore, the IM system should continue to be operated at full capacity to maximize the benefits of the IM.** While the concentration increases at R-45 screen 2 can be interpreted as a detrimental trend caused by the IM, the concentrations are expected to decrease as the IM extraction wells capture the chromium located at this depth **and** attenuation of the plume continues due to clean water injection. Simulations predict that full IM operations is the only scenario that reduces chromium concentrations to below the NMAC standard of 50 ppb. **Reverting to full IM operation will confirm or refute this result and provide important new information on plume behavior that will aid in final remedy design.**

The principal objective of the IM has been to hydraulically control the plume. To date, the IM has been successful in controlling the lateral extent of the plume in the south and southeastern regions of the plume. Concentration decreases at CrEX-5 and R-70 screen 2 indicate that extraction has played a role in the hydraulic control of the plume. Capture zone analyses indicate that further hydraulic control may be needed in the region near CrEX-5. **Ensuring continued extraction at CrEX-5 should be a priority for the IM going forward. Planned monitoring wells R-79 and R-80 are also needed on a priority basis to reduce uncertainties and to provide additional performance monitoring.**

Chromium concentrations at R-61 screen 1 are currently below the (NMAC groundwater standard (except for a single measurement of 51 ppb). Water-level data in R-61 indicate a response to IM pumping, presumably from the nearest extraction well (CrEX-2) and injection well (CrIN-5). The cause for the increasing trend is currently unknown but could be the result of CrEX-2 drawing water from a high concentration zone. **Additional investigation into the cause for the increasing trend at R-61 screen 1 is recommended.**

The concentration profile is uncertain at depth in the plume centroid and in the northeastern plume area. If the chromium plume is located at depths below the current capture of the IM system, then deeper extraction will likely be required as part of a final remedy. Additional monitoring wells are planned to reduce this uncertainty. Nevertheless, **deep extraction does not appear to be necessary at this time to continue to achieve IM objectives.**

8.0 REFERENCES AND PRESENTATIONS

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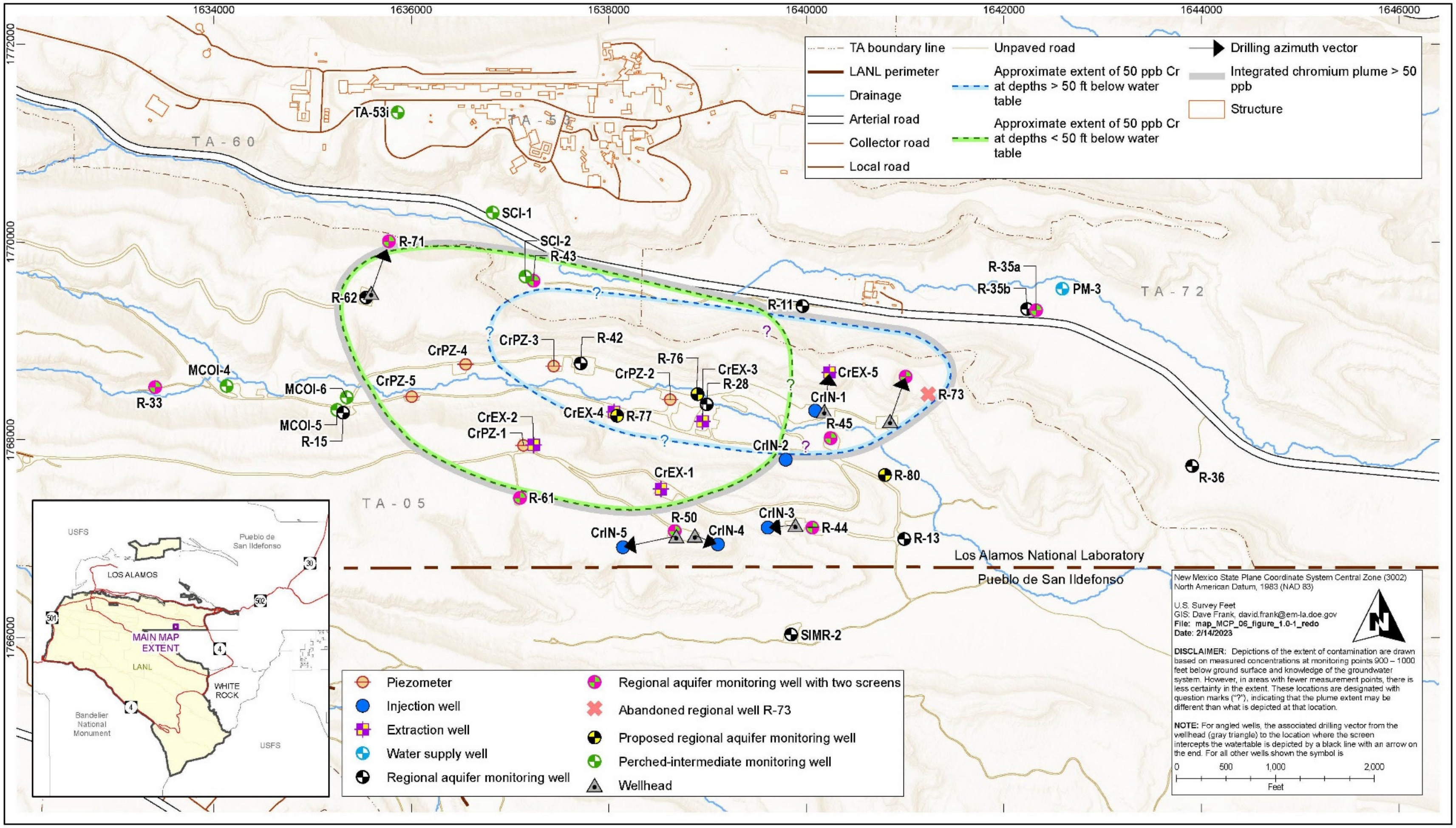


Figure 1.0-1 **Present-day chromium plume depiction showing both a deep (blue) and shallow (green) plume footprint. R-45 is located on the eastern plume edge. Well R-45 is located to the north and east of injection well CrIN-2, where the deep and shallow plumes meet on the eastern edge of the plume.**

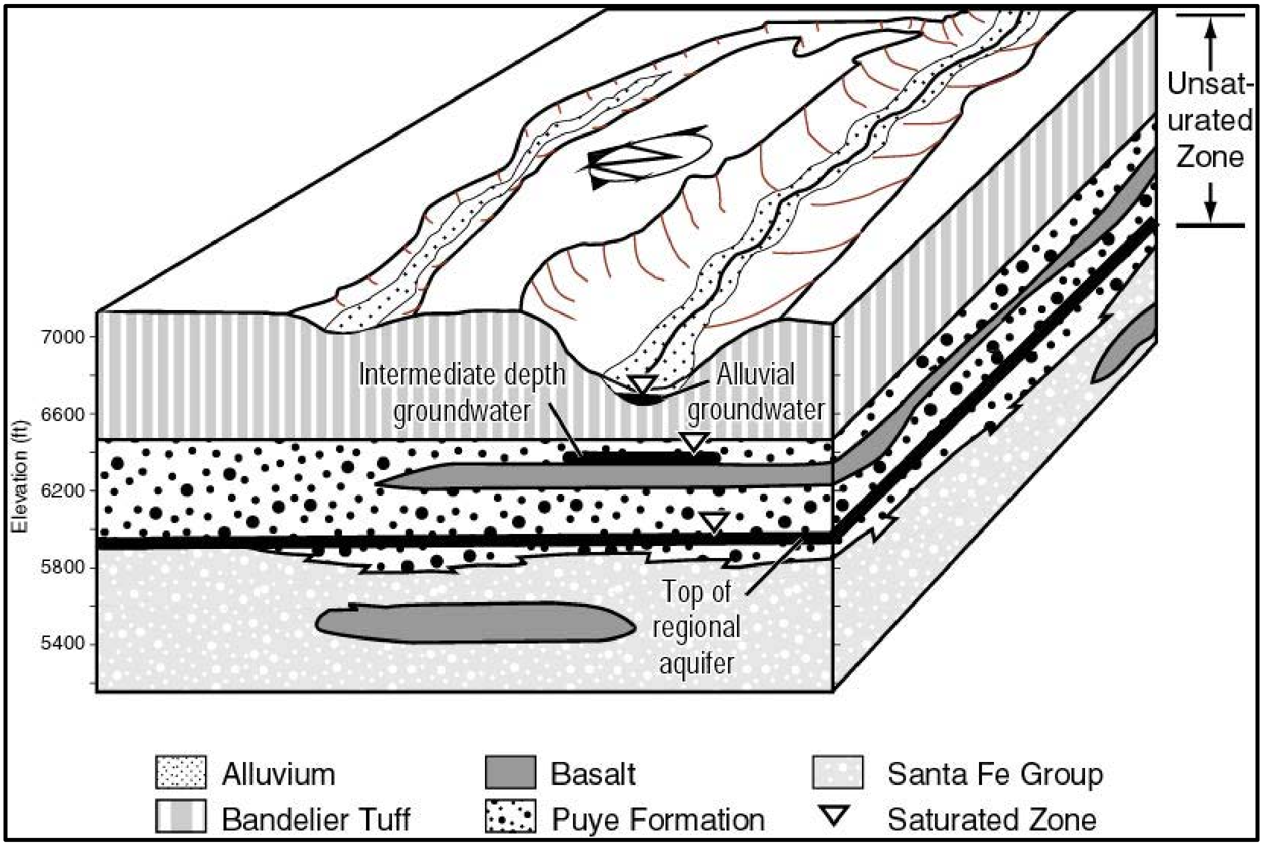


Figure 3.0-1 Depiction of groundwater at Los Alamos

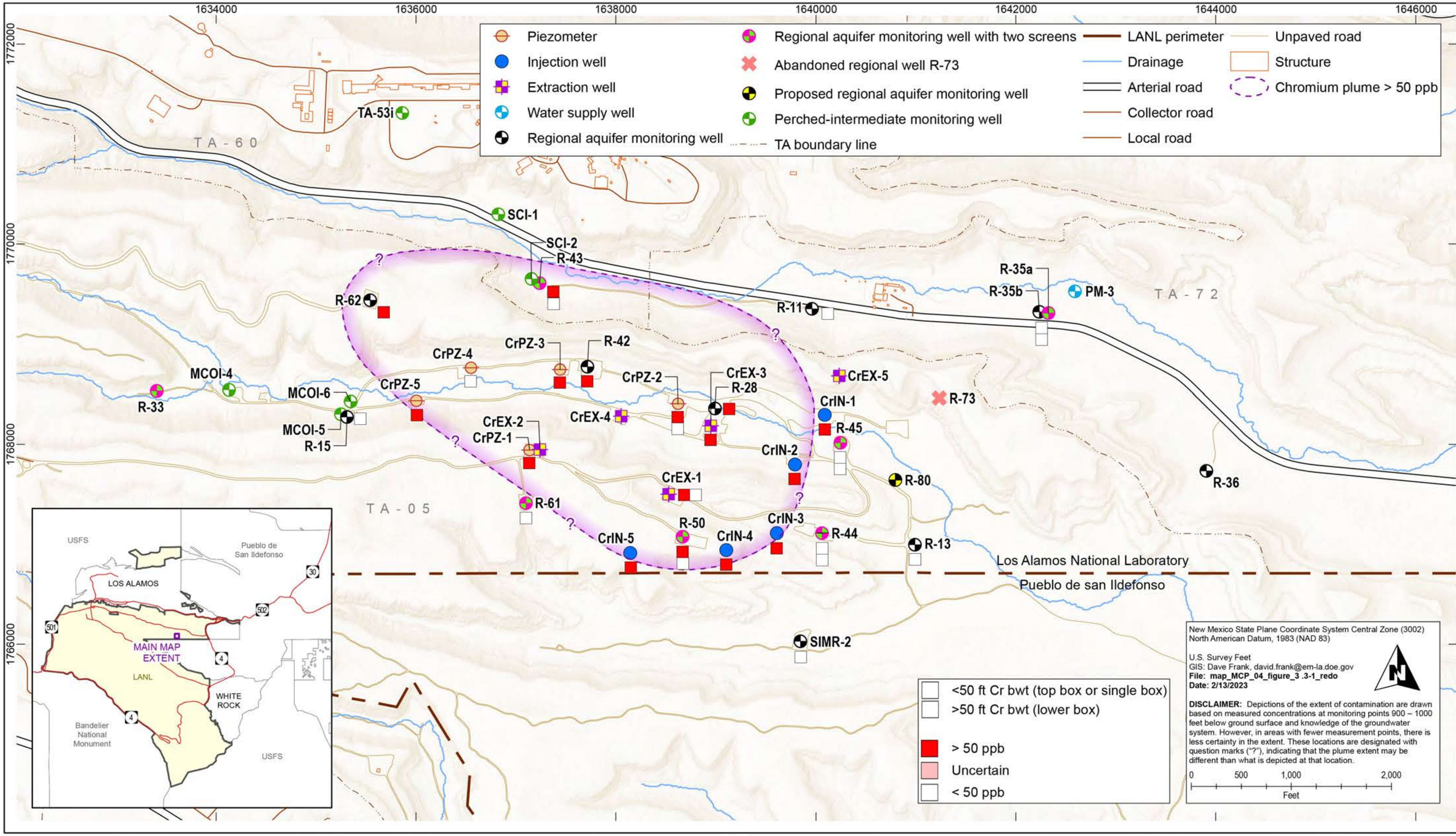


Figure 3.3-1 2015 chromium plume depiction

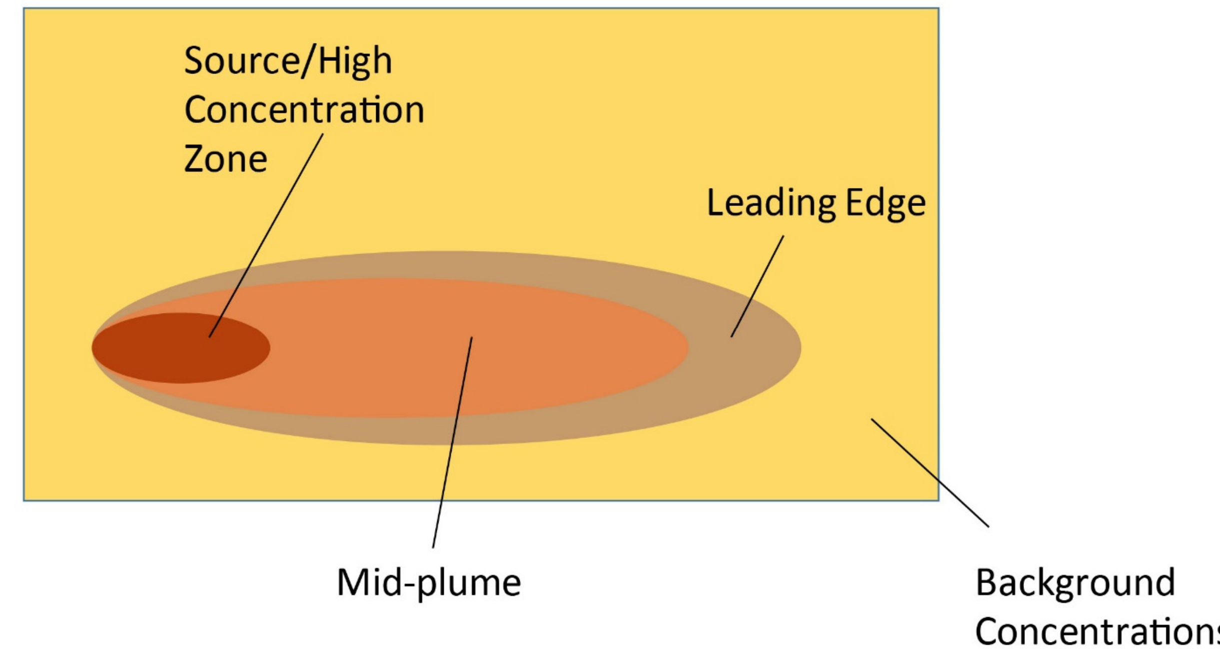


Figure 3.3-2 Idealized plume spatial distribution

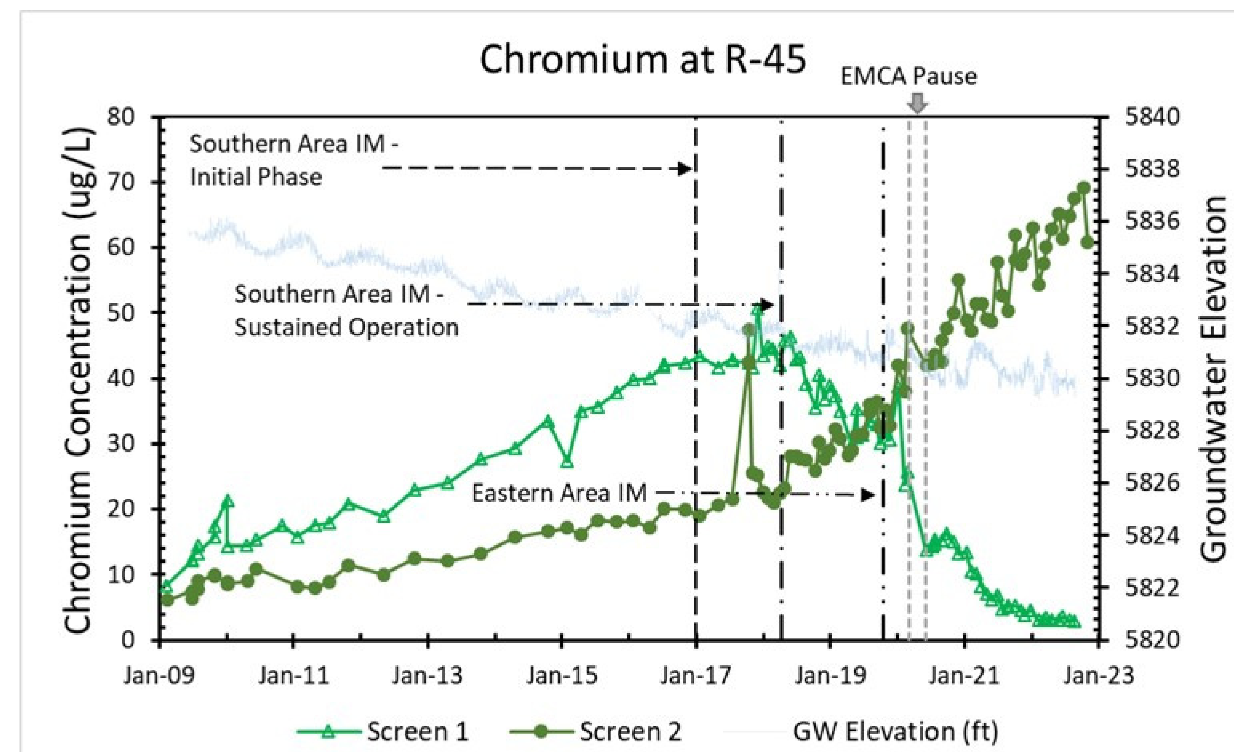


Figure 3.3-3 Chromium concentrations at R-45

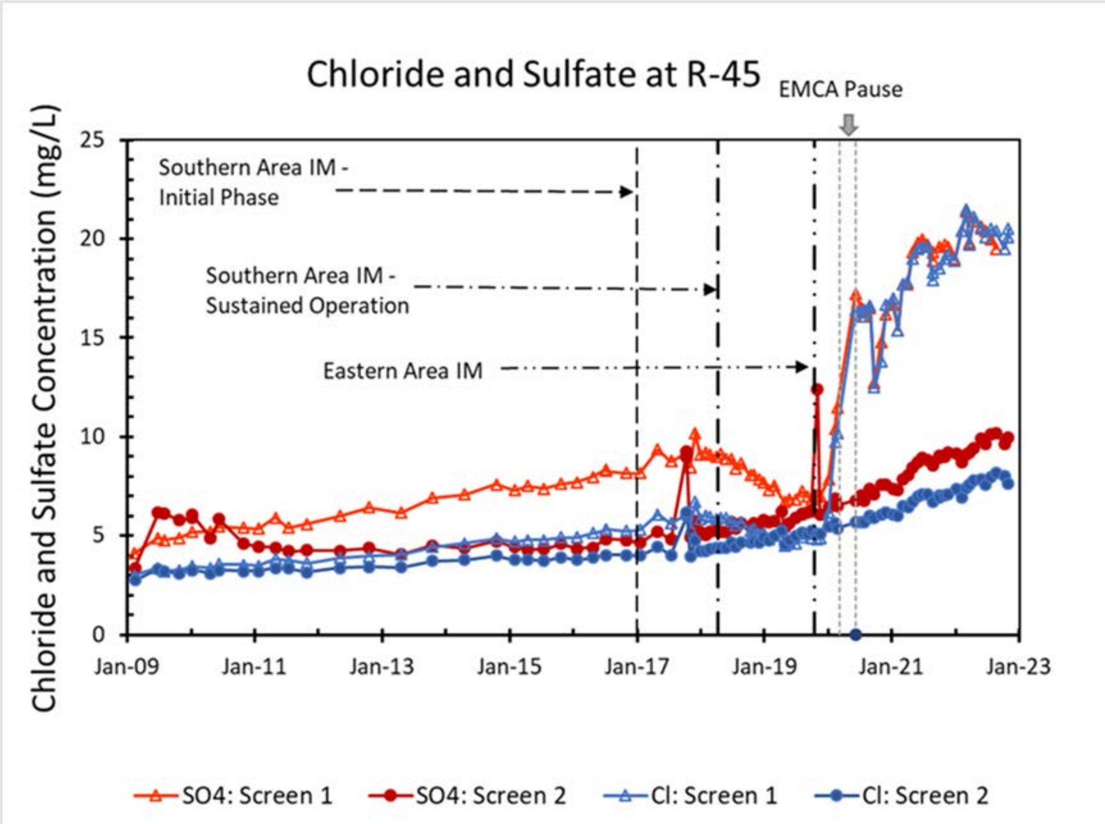


Figure 3.3-4 Chloride and sulfate concentrations at R-45

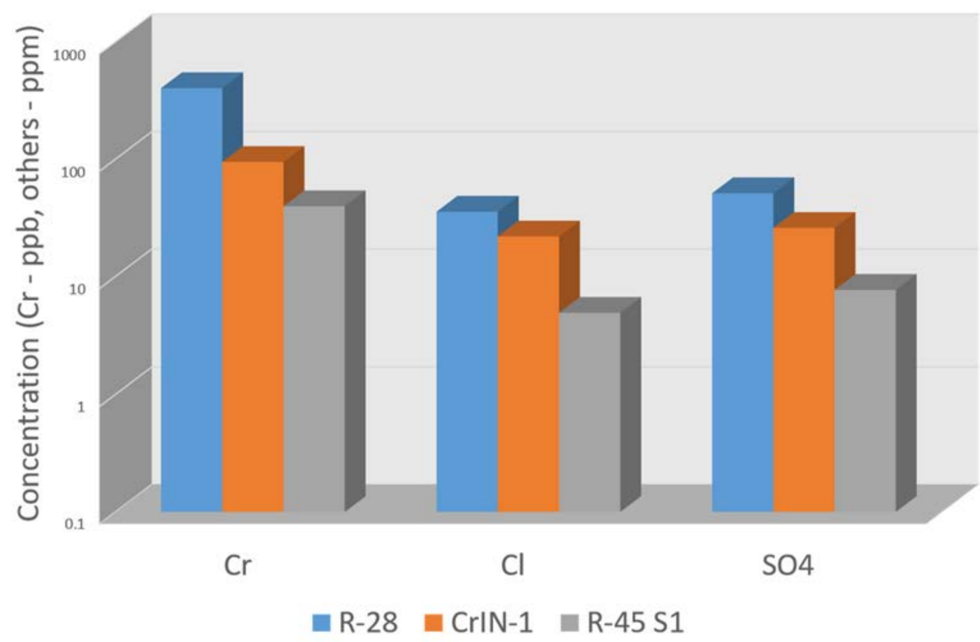


Figure 3.3-5 Geochemistry along flow path: Concentrations of species at R-28 and downgradient locations CrIN-1 and R-45 screen 1 (S1) before amendments and initiation of IM (data from 2016).

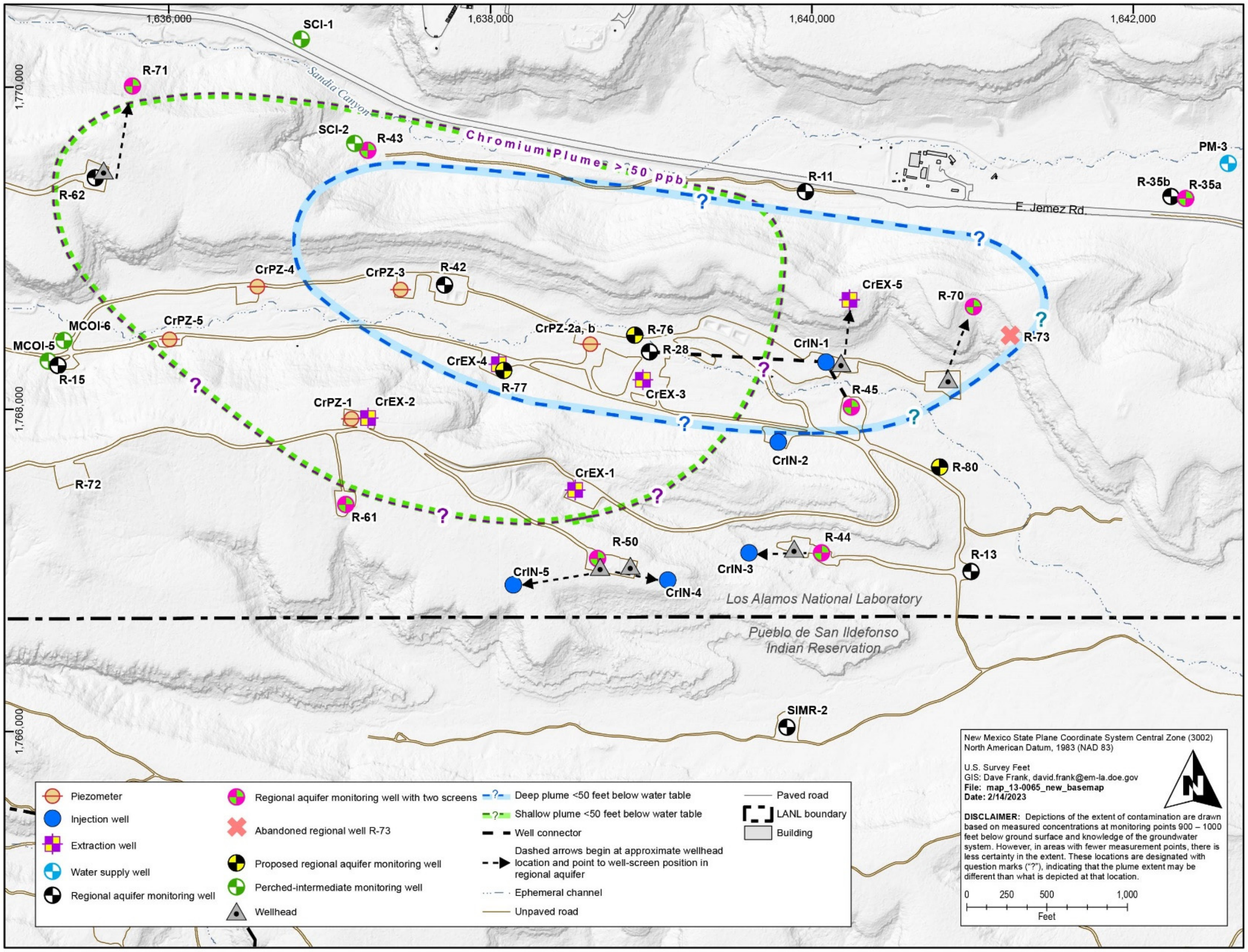


Figure 3.3-6 **Location map and depiction of shallow and deep plumes at the chromium plume. Dashed black line shows a "fenceline" from R-28 to CrIN-1 to R-45, used to illustrate the concentration profiles along the plume transport pathway.**

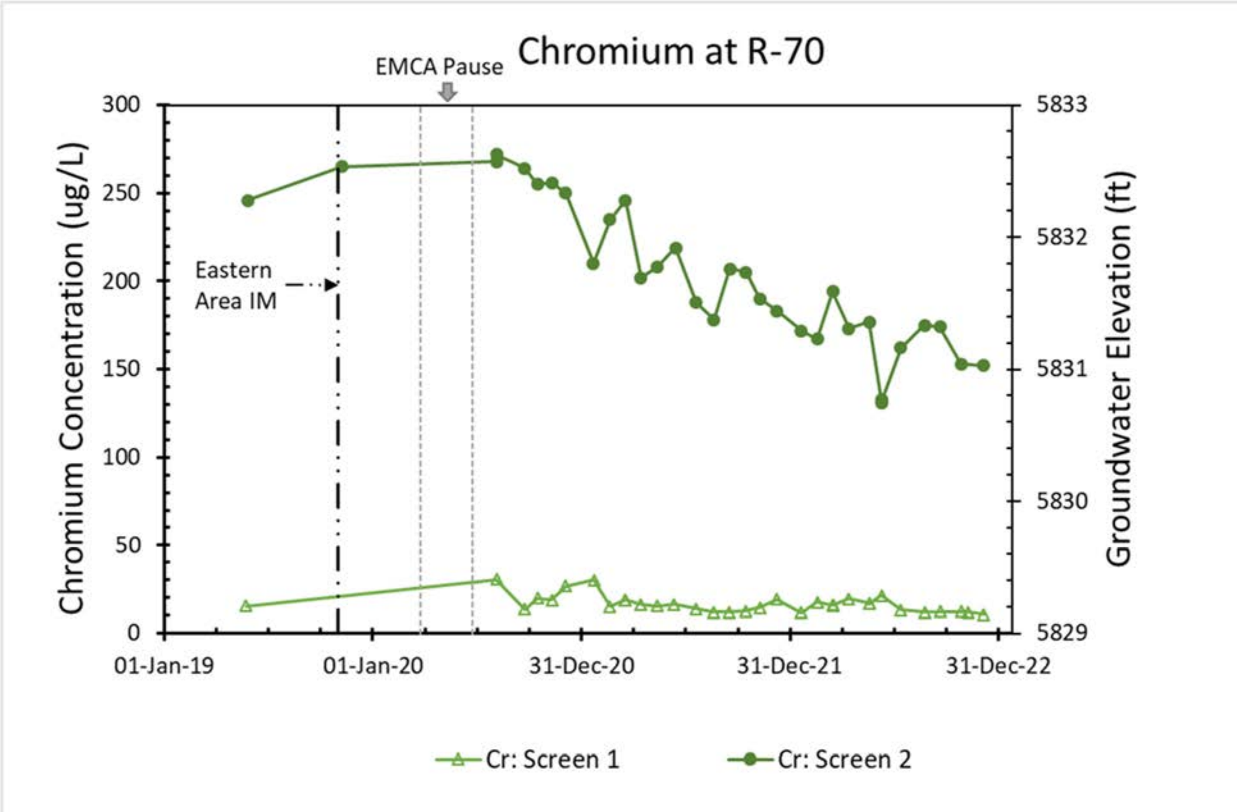


Figure 3.4-1 Chromium concentrations at R-70 screens 1 and 2

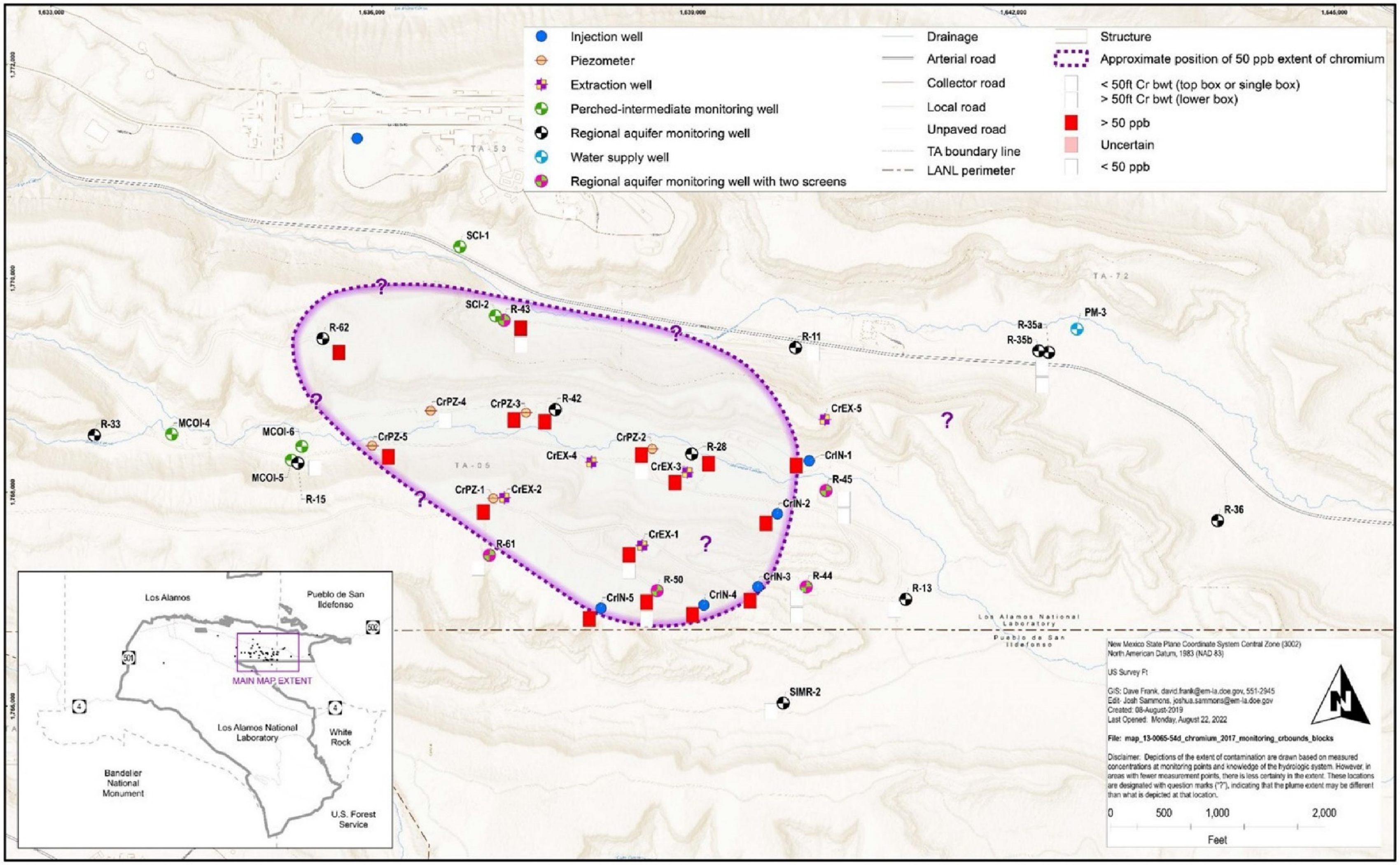


Figure 3.4-2 **Plume depiction published in the 2015 IM work plan for chromium plume control, along with symbols depicting the level of chromium concentrations (>50 or <50 ppb) at sampling locations**

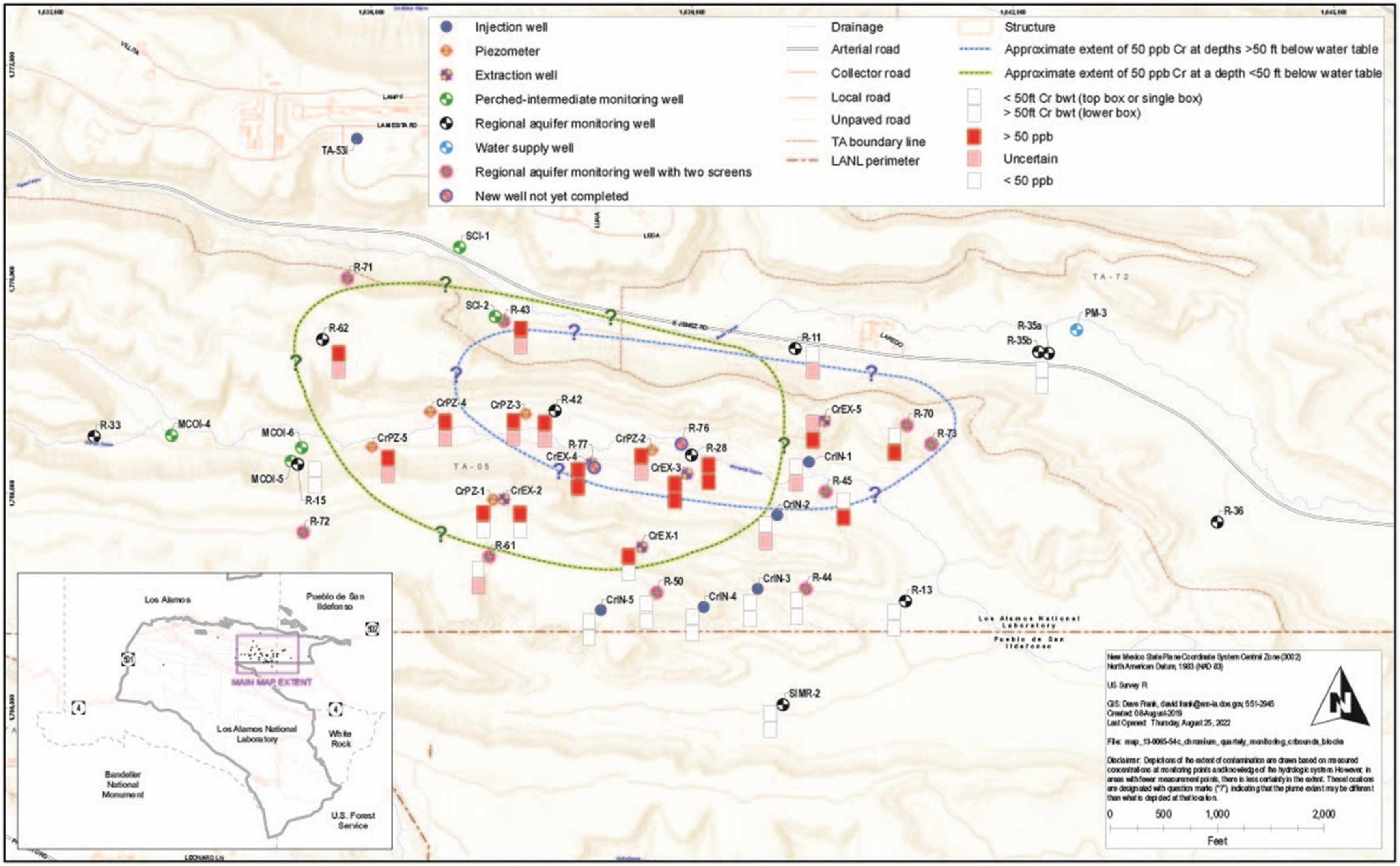


Figure 3.4-3 **Present-day plume depiction, along with symbols depicting the level of chromium concentrations (>50 or <50 ppb) at sampling locations**

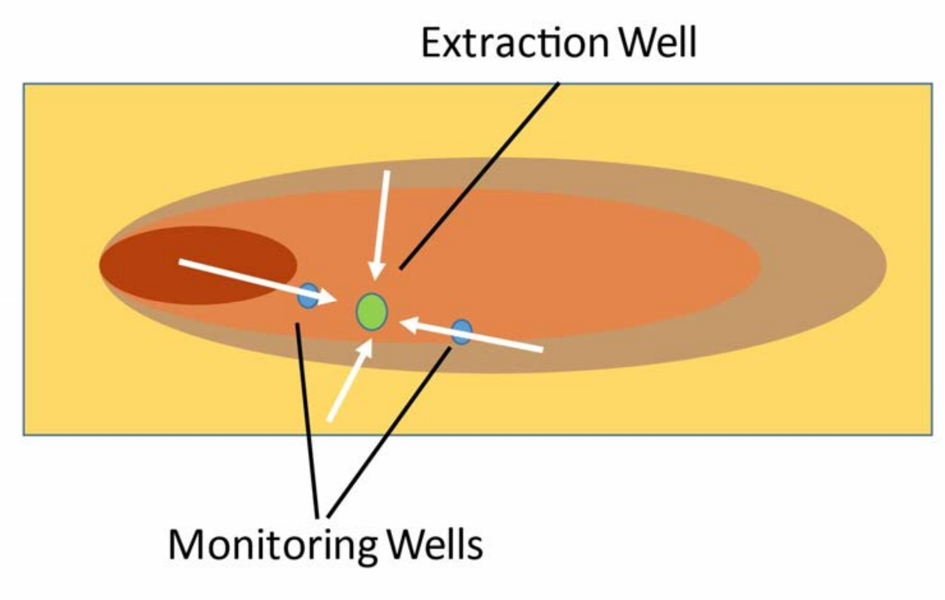


Figure 4.1-1 Monitoring well located between a high concentration zone and an extraction well

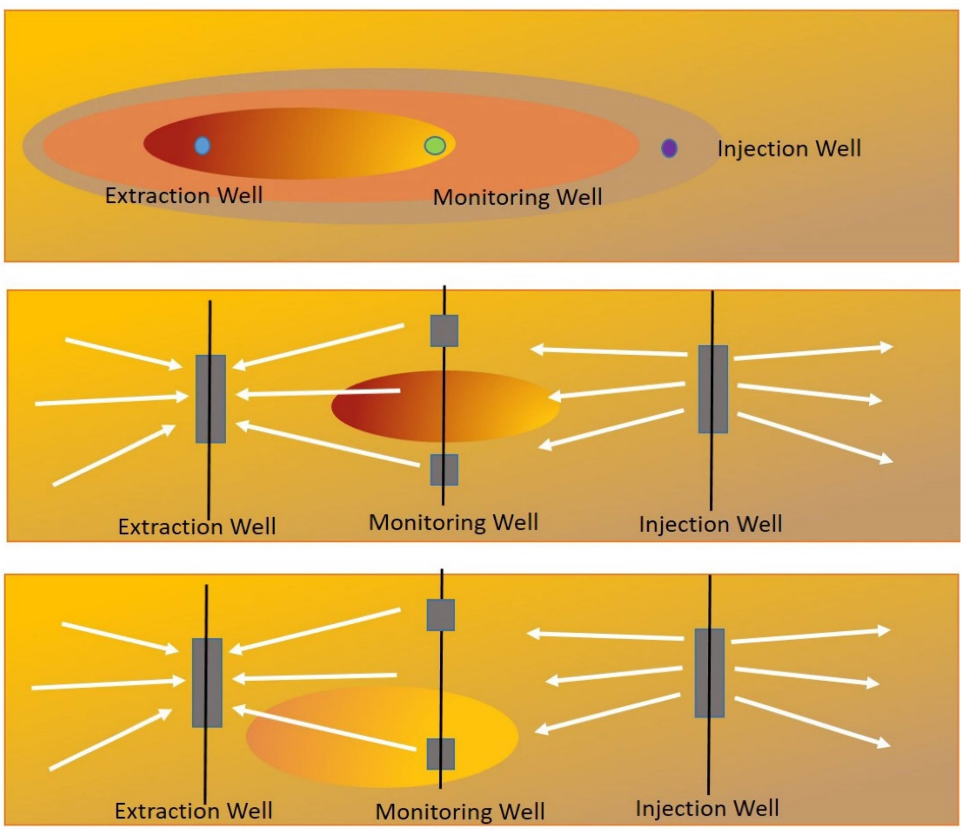


Figure 4.1-2 Depiction of a high concentration zone that could migrate with depth under the influence of an injection well, causing concentrations to increase at a monitoring well screen at depth. A nearby extraction well may still be able to capture the higher concentration zone even though it has migrated to a deeper location within the aquifer.

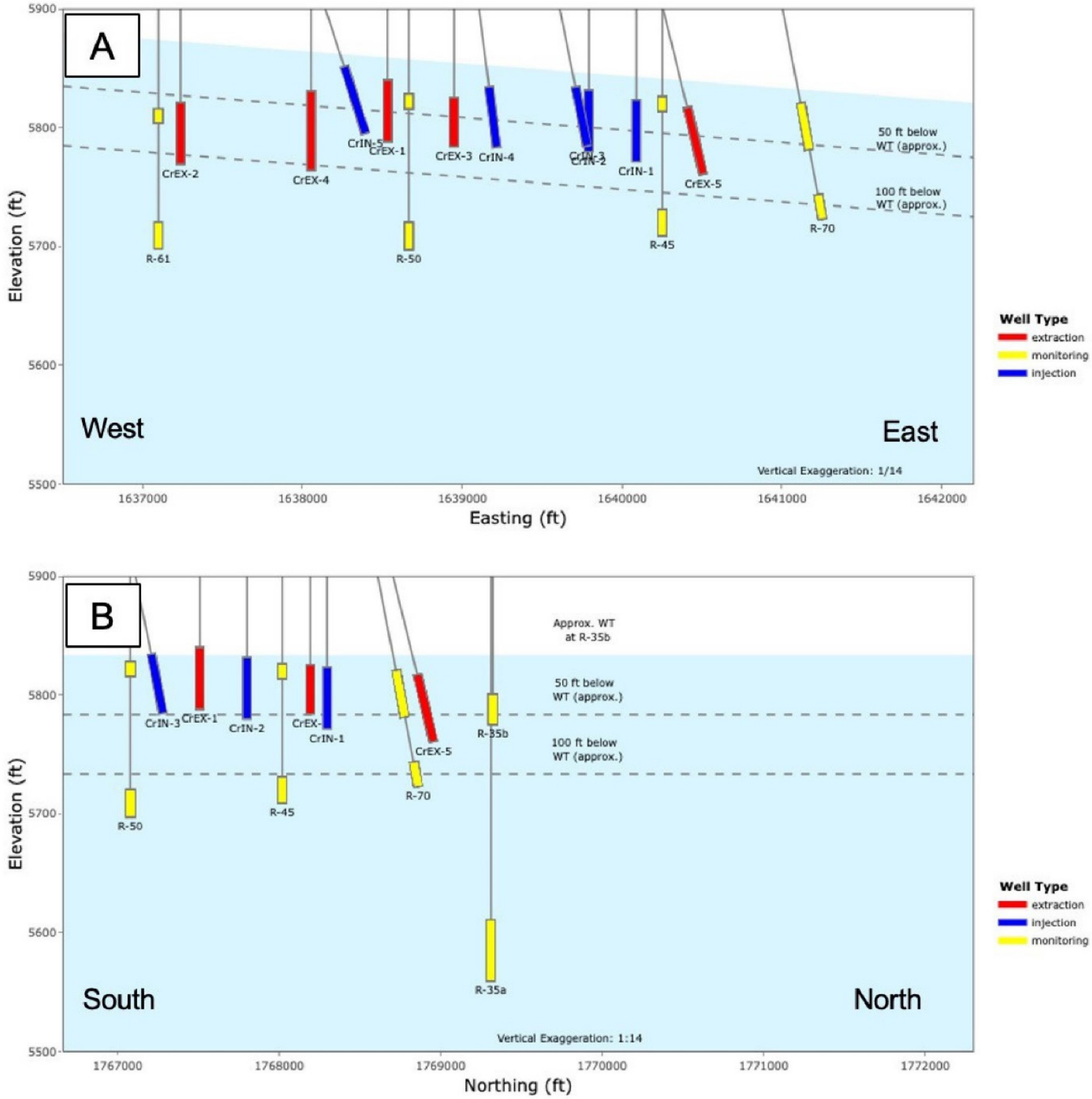


Figure 4.2-1 **Conceptual well screen locations for extraction, injection, and key monitoring well locations from (a) west to east with an approximate water table location, and (b) south to north, with a water table location approximated by well R-35b.**

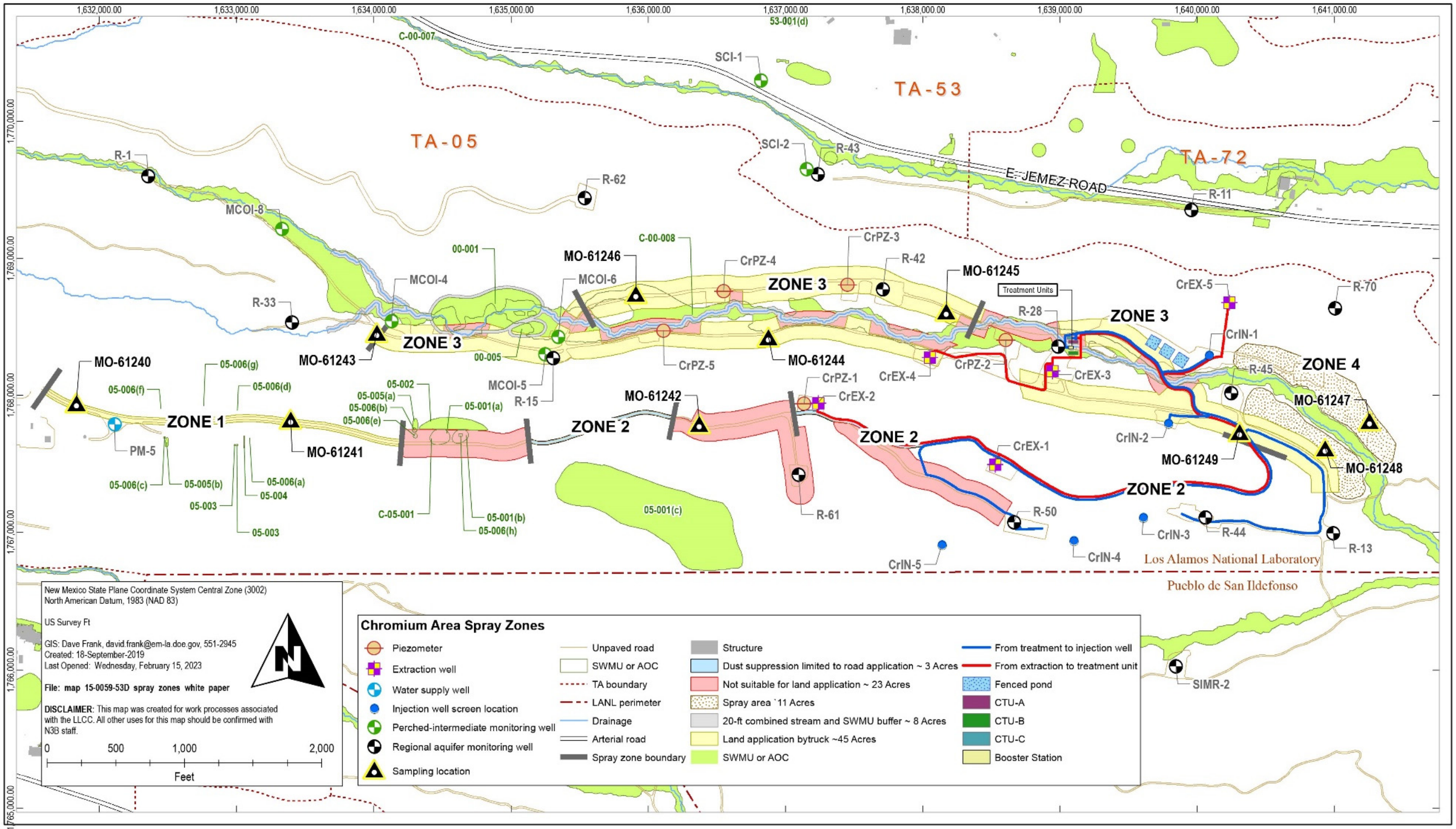


Figure 4.3-1 Treatment system infrastructure and the area approved for land application

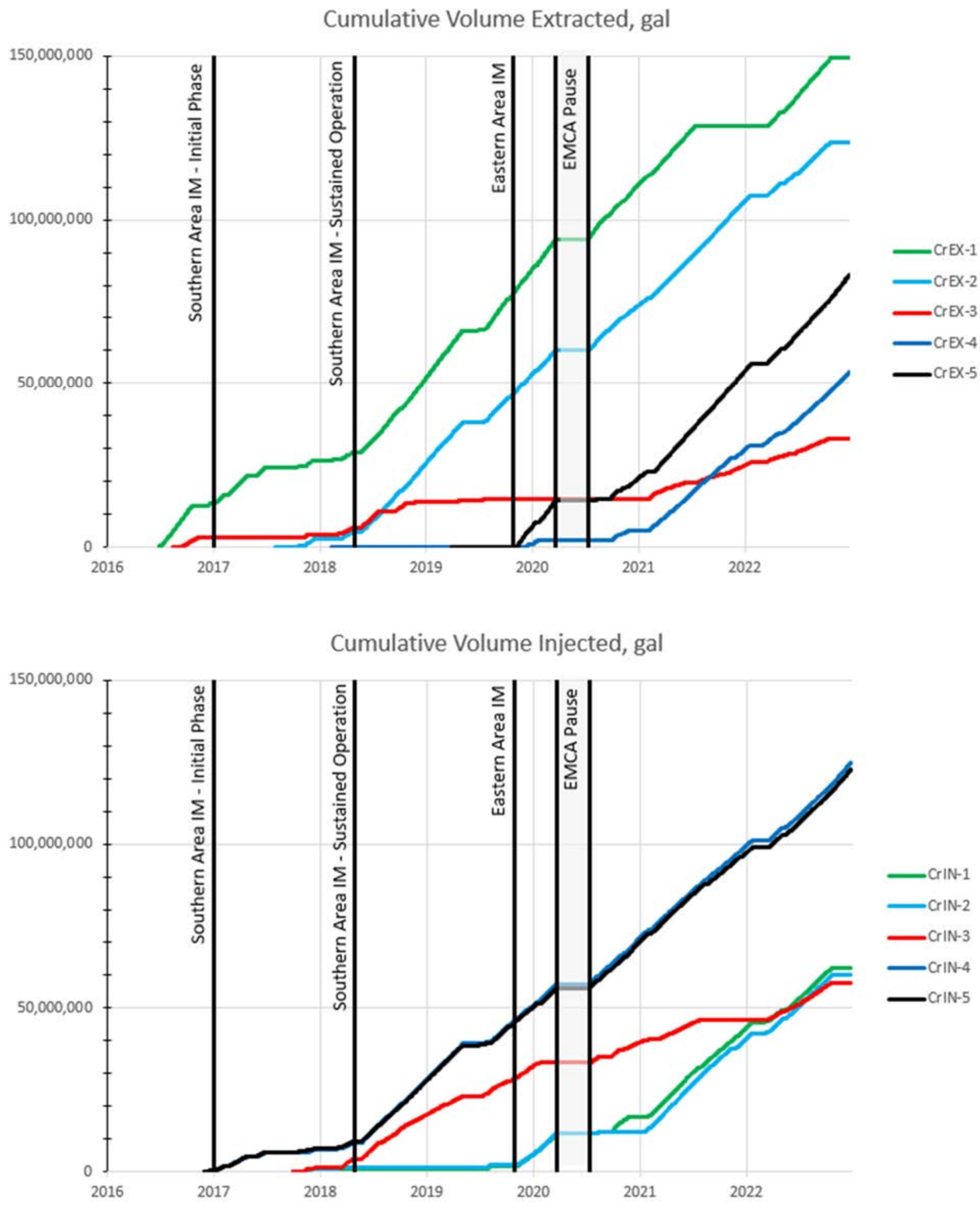


Figure 4.3-2 Cumulative extraction volumes (upper panel) and injection volumes (lower panel) throughout the operation of the IM. Vertical lines represent time markers for key changes in IM operations.

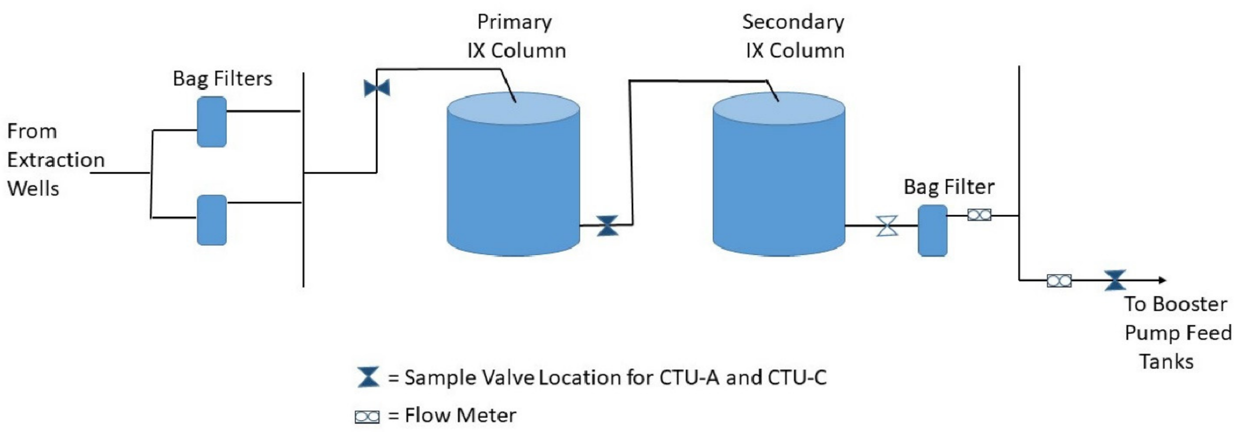


Figure 4.4-1 Conceptual design of P&T system

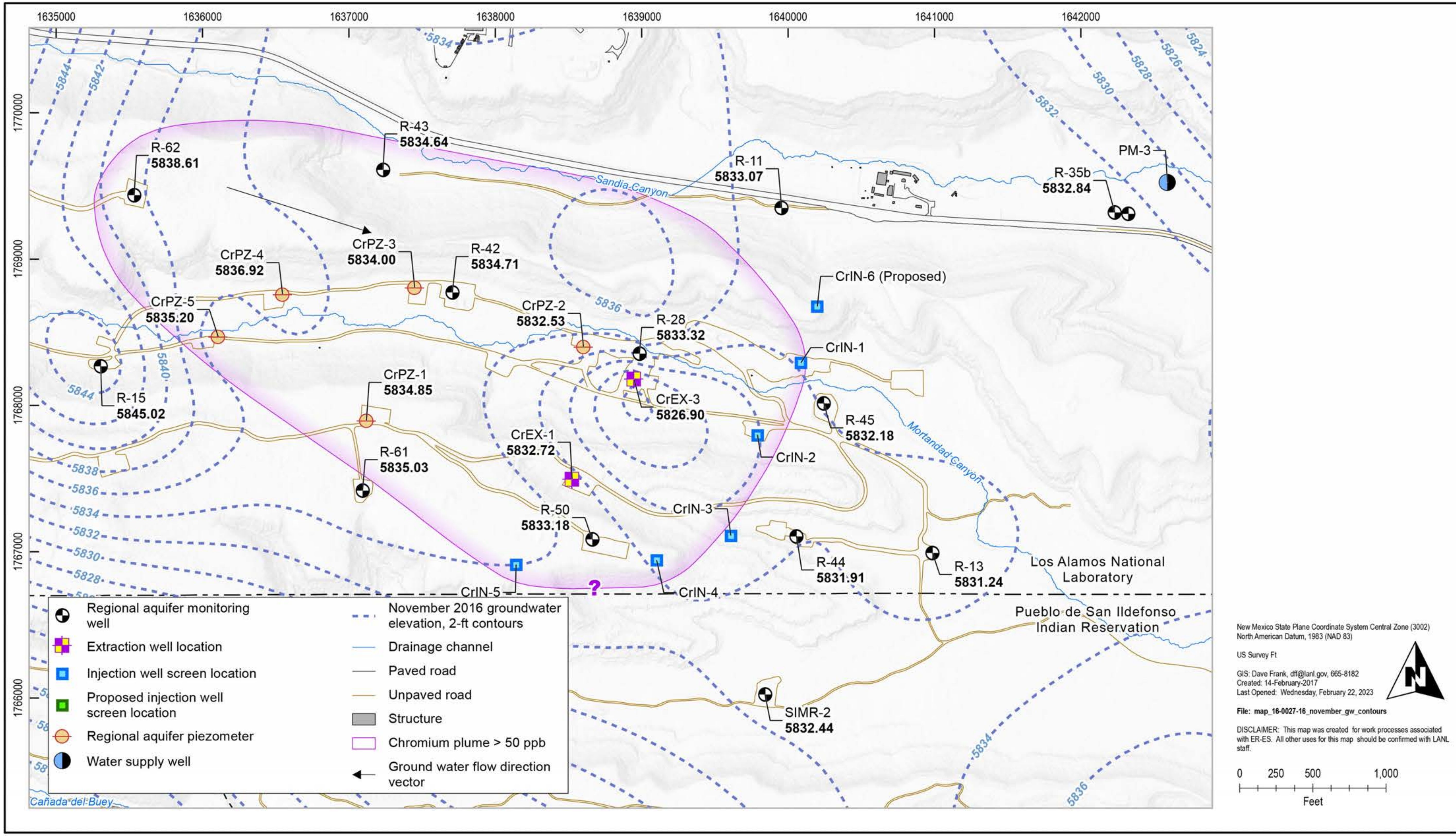


Figure 5.1-1 Potentiometric surface map to support DP-1835 for Quarter 4 2016

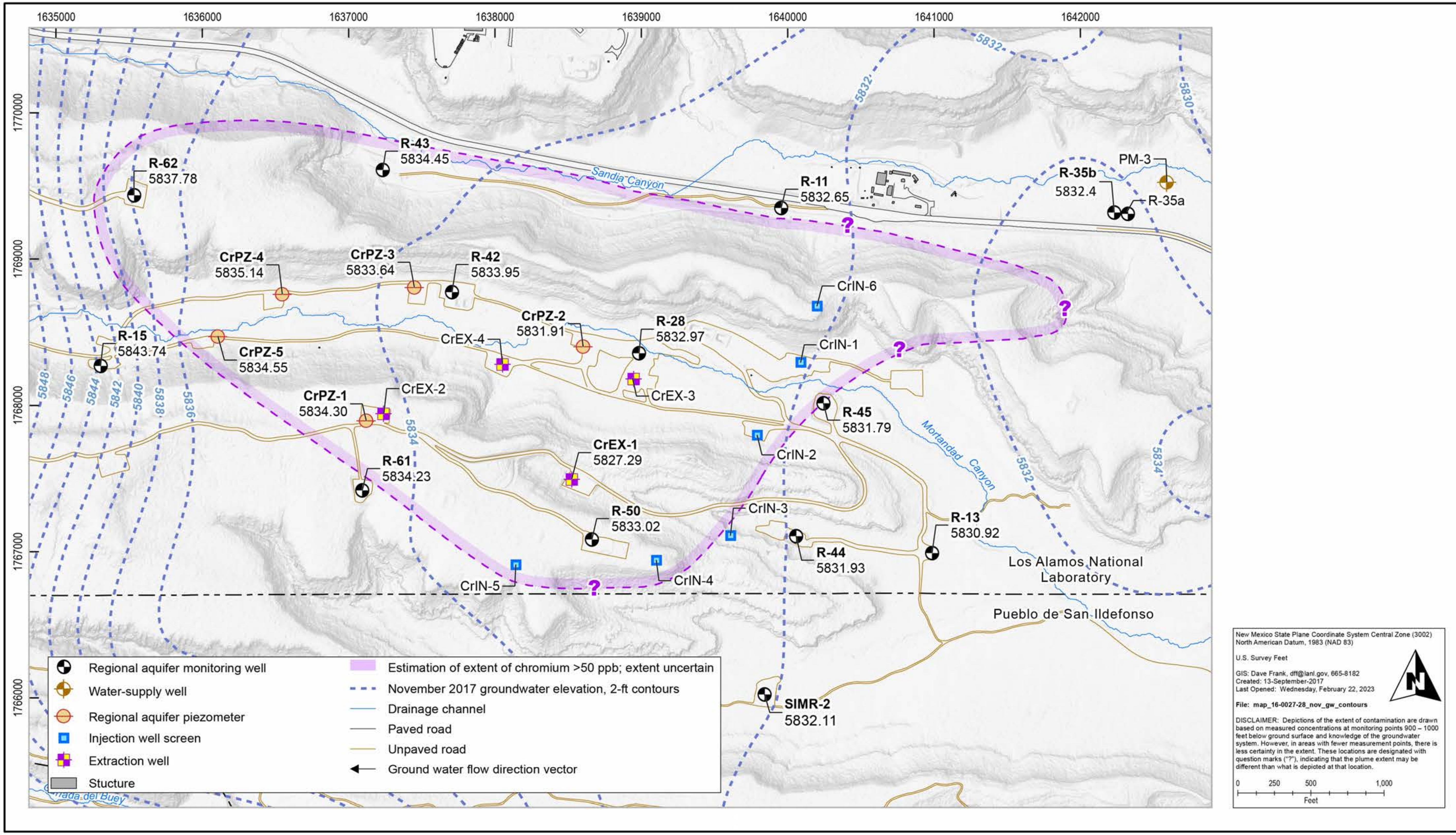


Figure 5.1-2 Potentiometric surface map to support DP-1835 for Quarter 4 2017

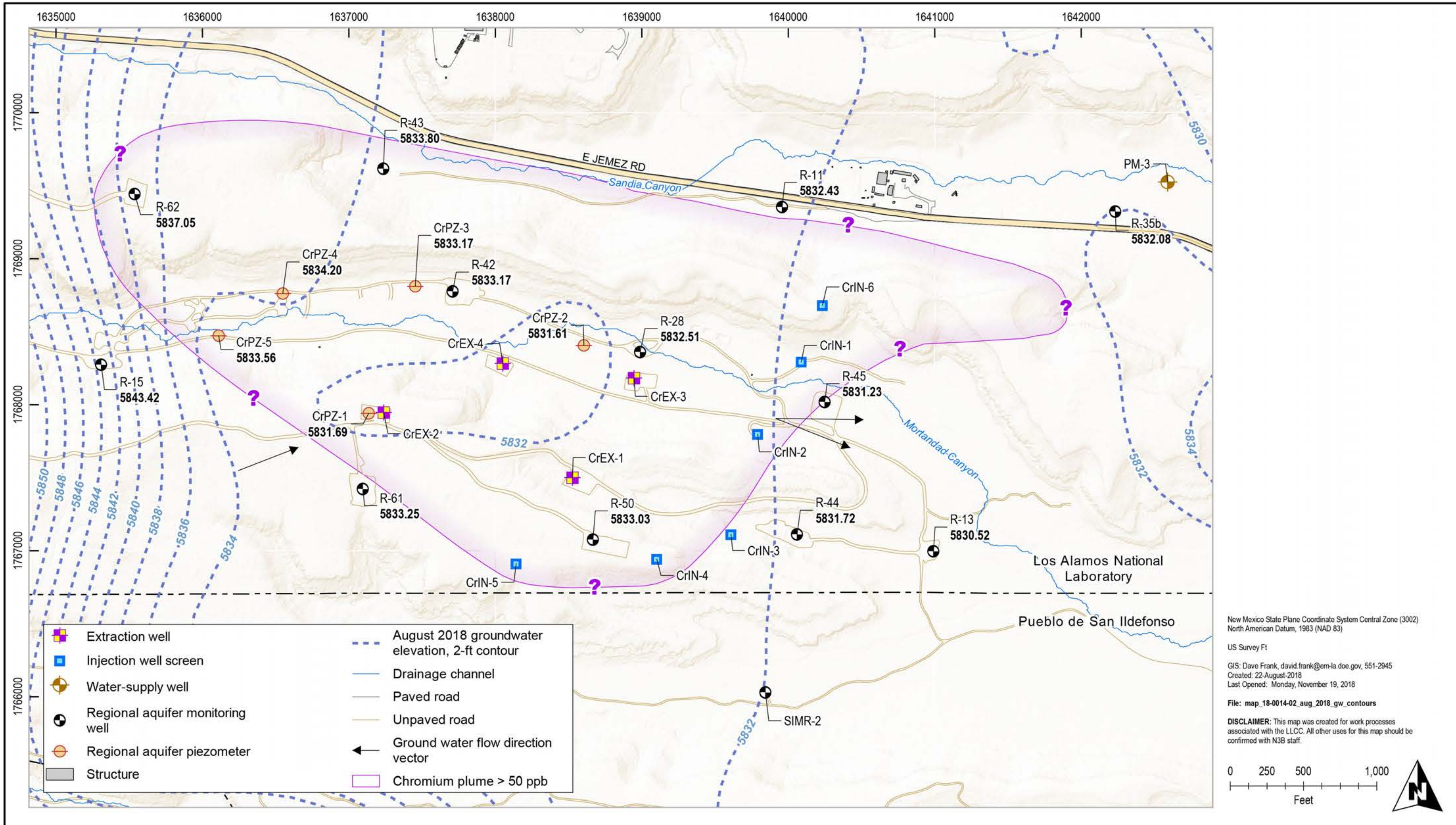


Figure 5.1-3 Potentiometric surface map to support DP-1835 for Quarter 4 2018

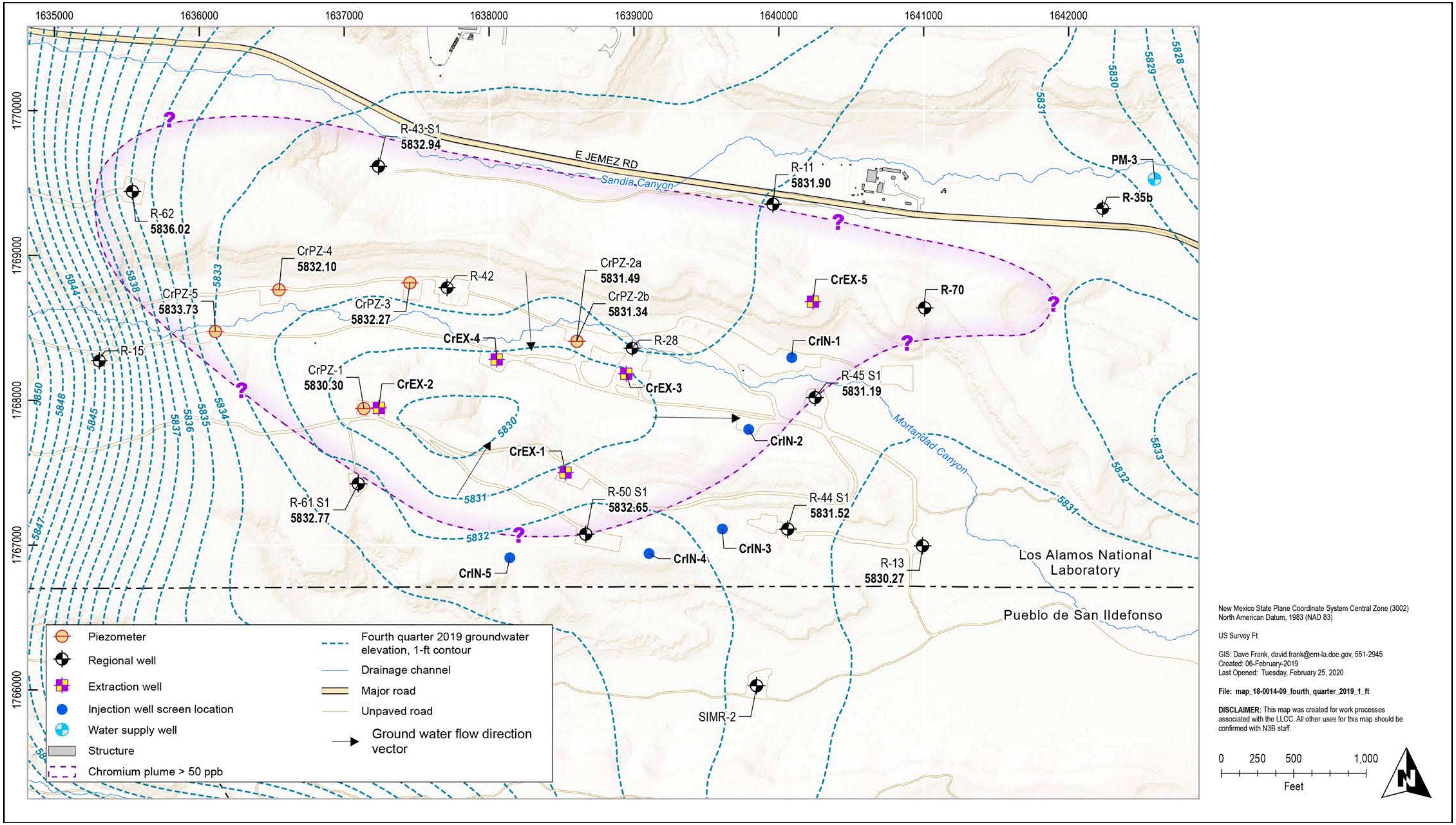


Figure 5.1-4 Potentiometric surface map to support DP-1835 for Quarter 4 2019

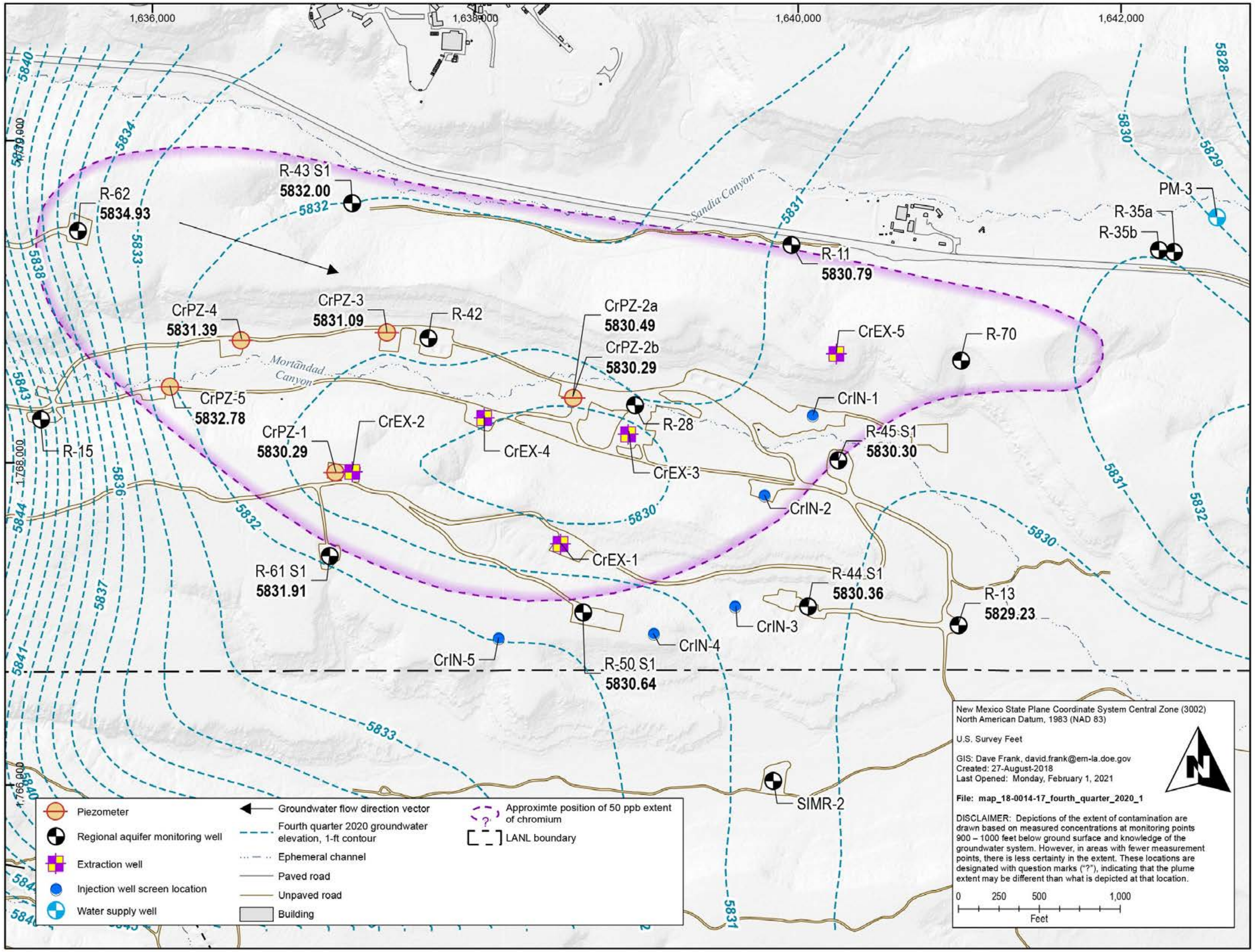


Figure 5.1-5 Potentiometric surface map to support DP-1835 for Quarter 4 2020

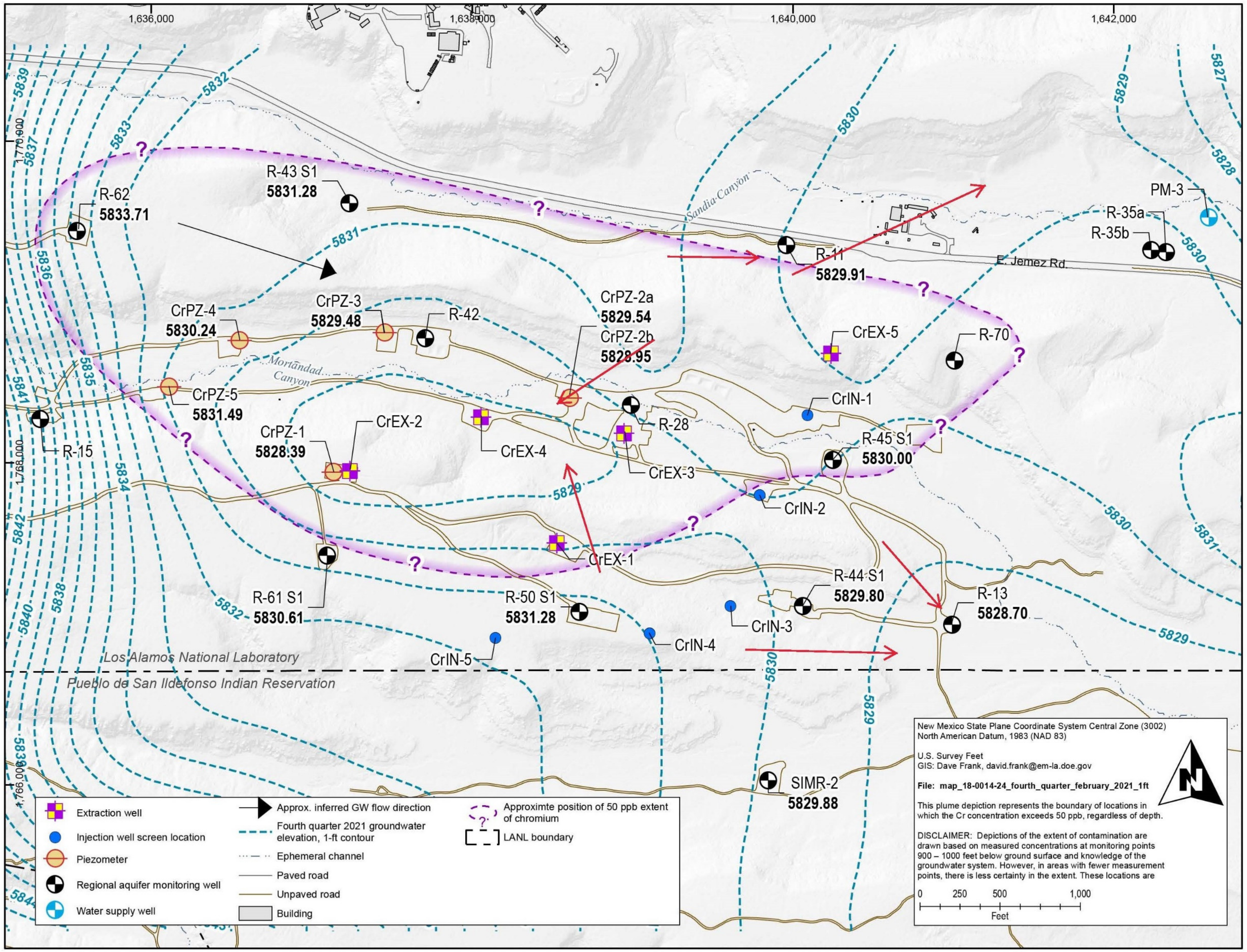


Figure 5.1-6 Potentiometric surface map to support DP-1835 for Quarter 4 2021. Red arrows are indicators of groundwater flow divide.

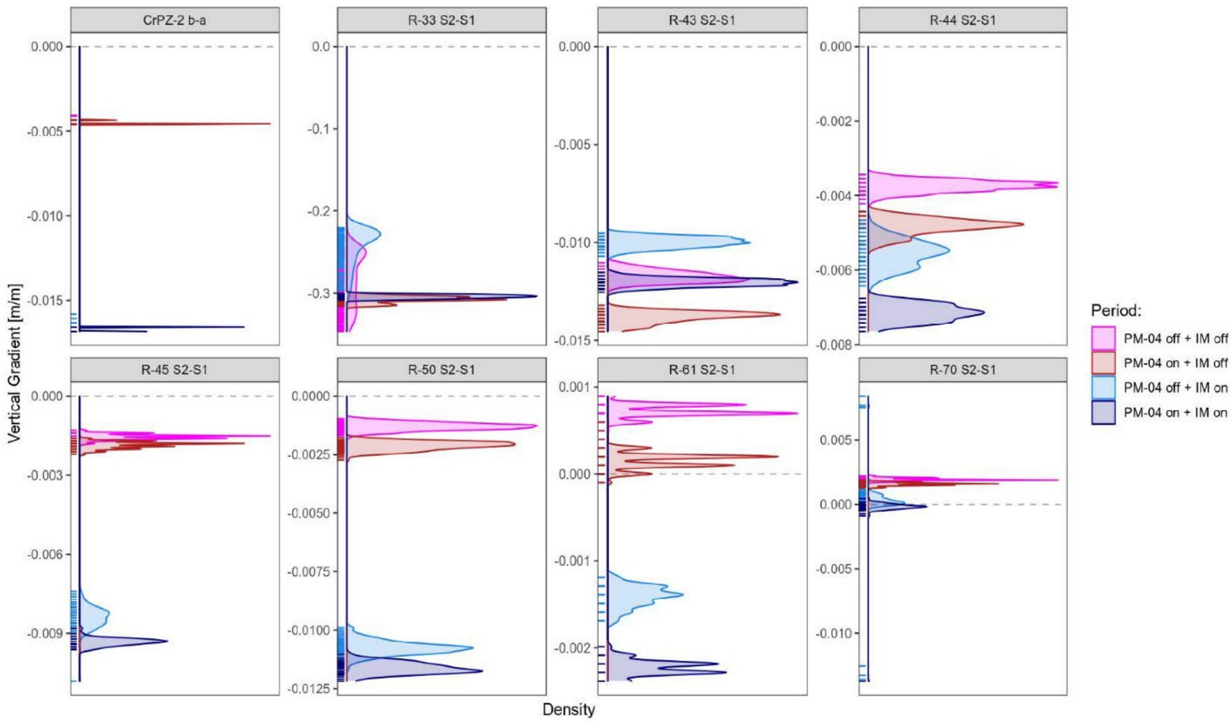


Figure 5.1-7 Temporal hydraulic gradients (hourly averages) at dual-screened wells from 2020 through 2021

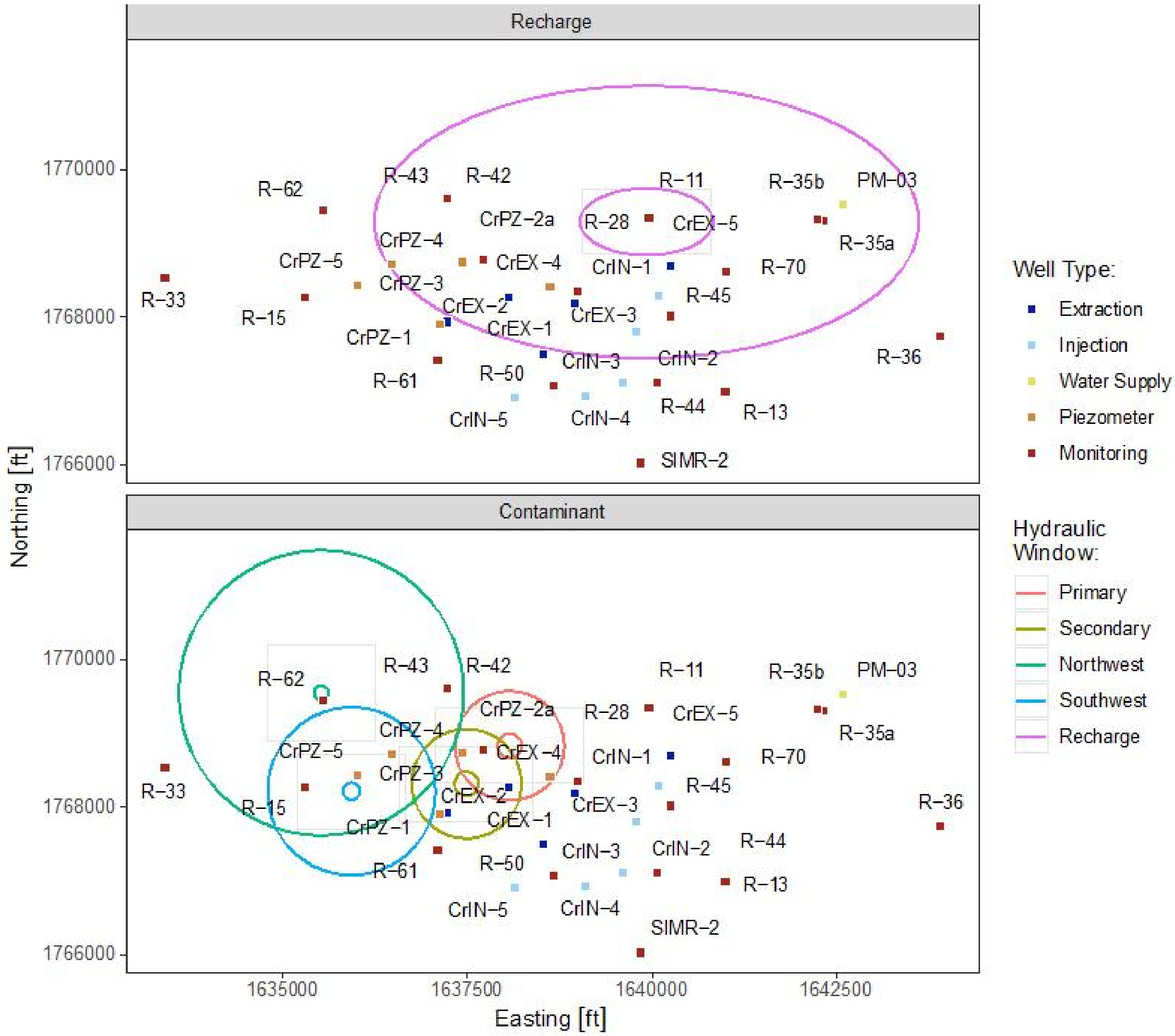


Figure 5.2-1 **Chromium-free recharge (top), and chromium source (bottom) locations. The shaded rectangle shows the range of allowed center coordinate locations, and the darker ellipses show the allowed range of *x* and *y* radii.**

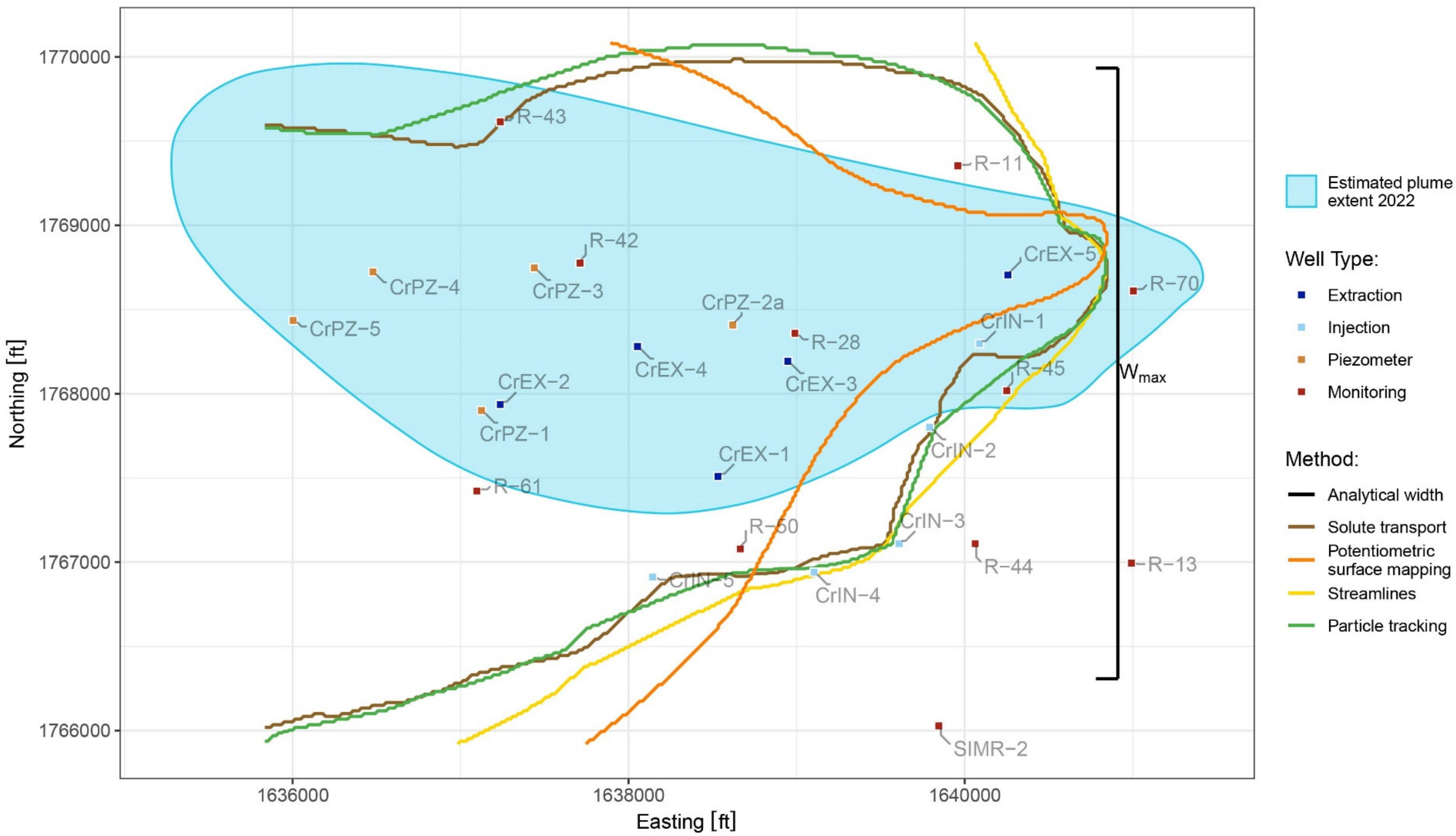


Figure 5.2-2 **Capture zone of IM during full operation estimated using potentiometric surface mapping (orange), analytical width estimates (black), and three modeling approaches. All three modeling approaches—streamlines (yellow), solute transport (brown), and particle tracking (green)—use the same calibrated fate and transport model and explore uncertainty; the mean result is shown.**

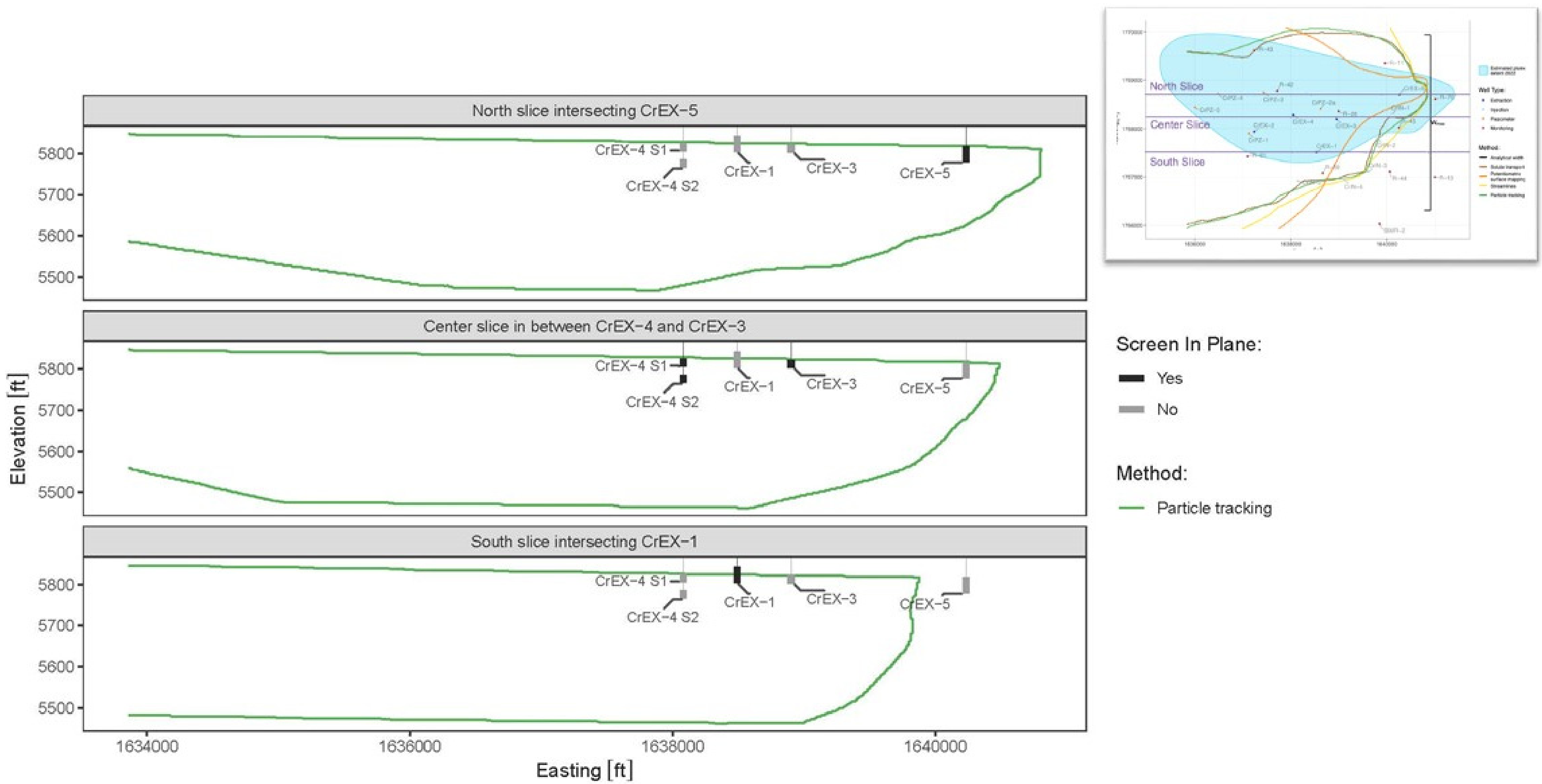


Figure 5.2-3 Capture zone estimates in the vertical dimension at three y-coordinates corresponding to northern, central, and southern portions of the plume

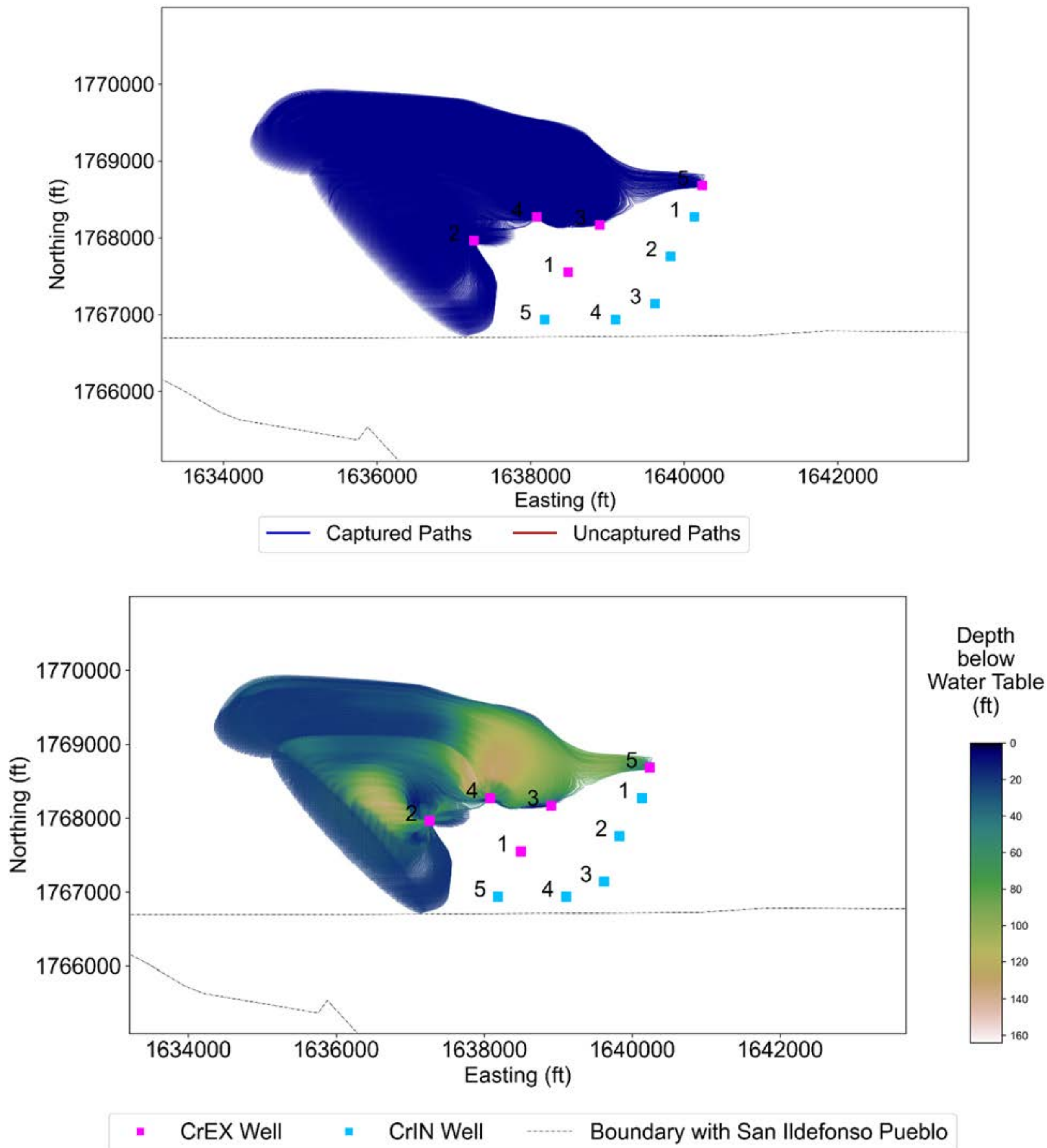


Figure 5.2-4 Plan view figures of captured particle pathways, where (a [upper panel]) shows the location (at any depth) of captured particle and uncaptured particle pathways relative to the injection and extraction wells; (b [lower panel]) shows particle pathways depth of capture

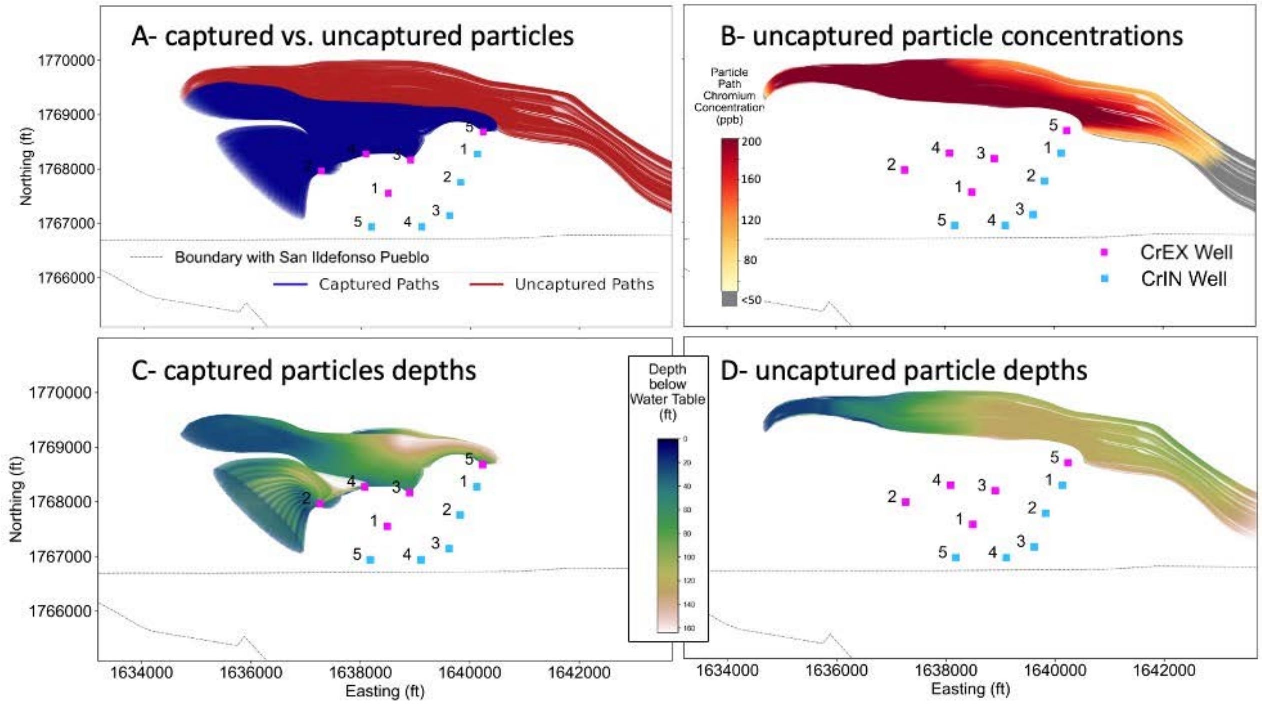


Figure 5.2-5 **Plan view figures of captured and uncaptured particle pathways, where (a) shows the location (at any depth) of captured particle and uncaptured particle pathways relative to the injection and extraction wells; (b) shows particle pathways not captured by the IM (north of both the extraction and injection wells); (c) shows particle pathways captured by extraction wells; and (d) shows the concentration of particle pathways that are not captured by the IM, with the gray tracers as indicators of chromium concentrations below the 50-ppb groundwater standard**

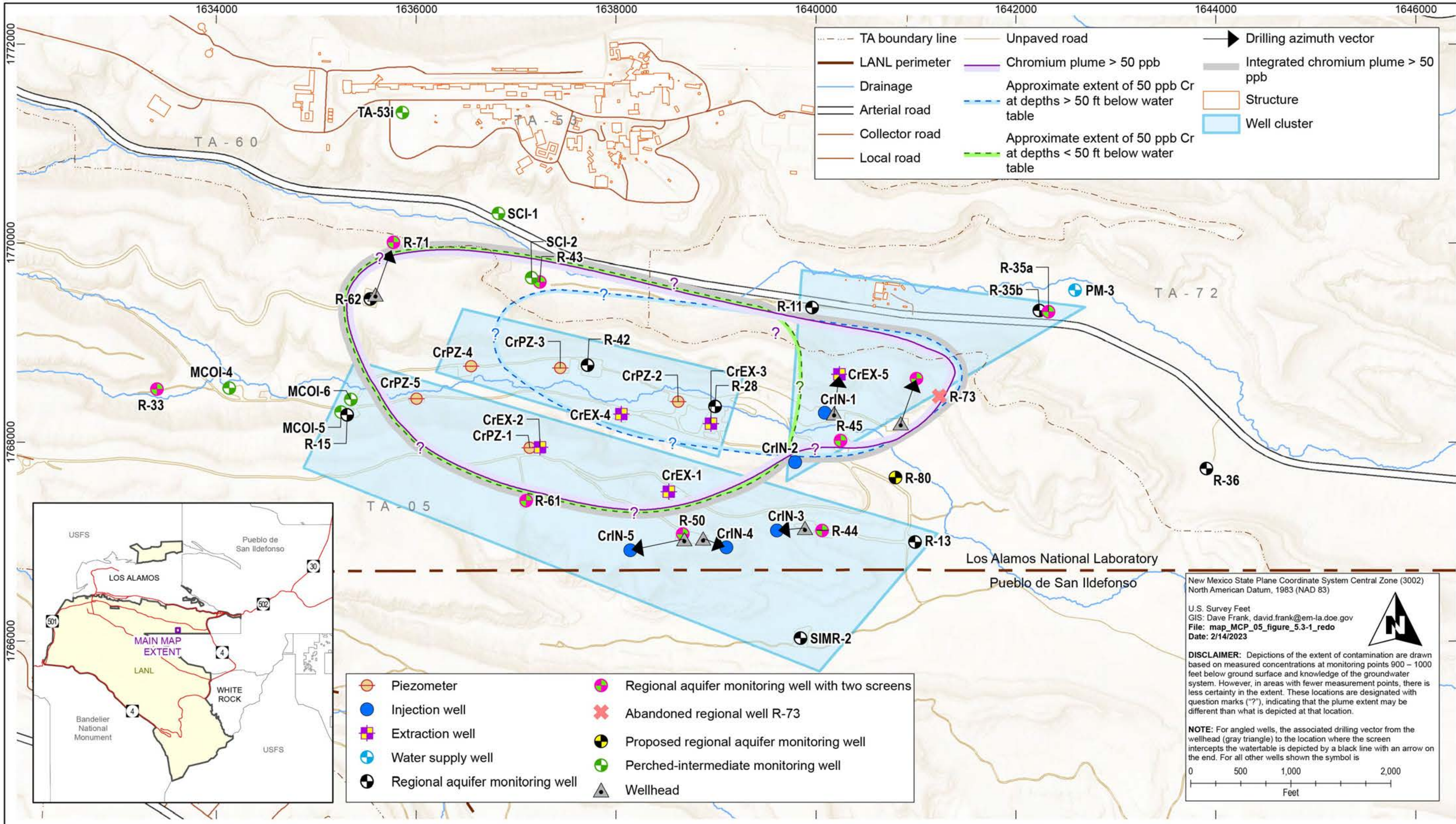


Figure 5.3-1 Groups of monitoring wells: (1) plume centroid, (2) southern area of the plume, and (3) northeastern area of the plume

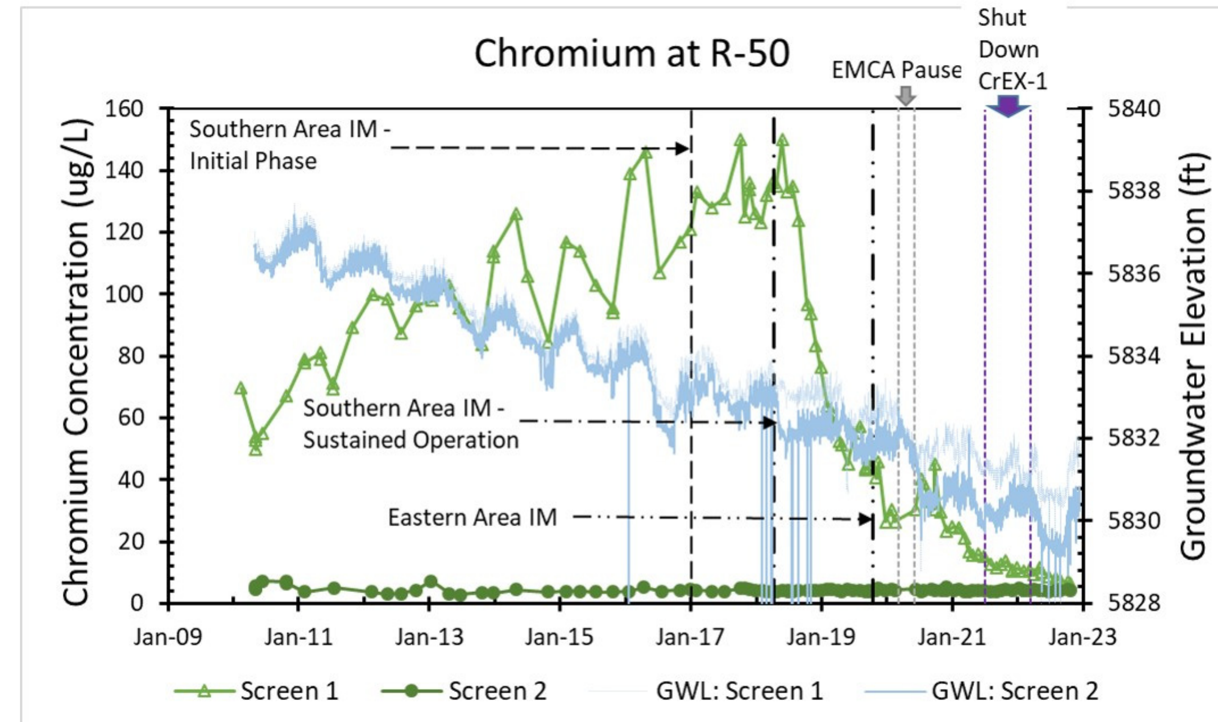


Figure 5.3-2 Chromium concentrations and water levels at R-50 screens 1 and 2

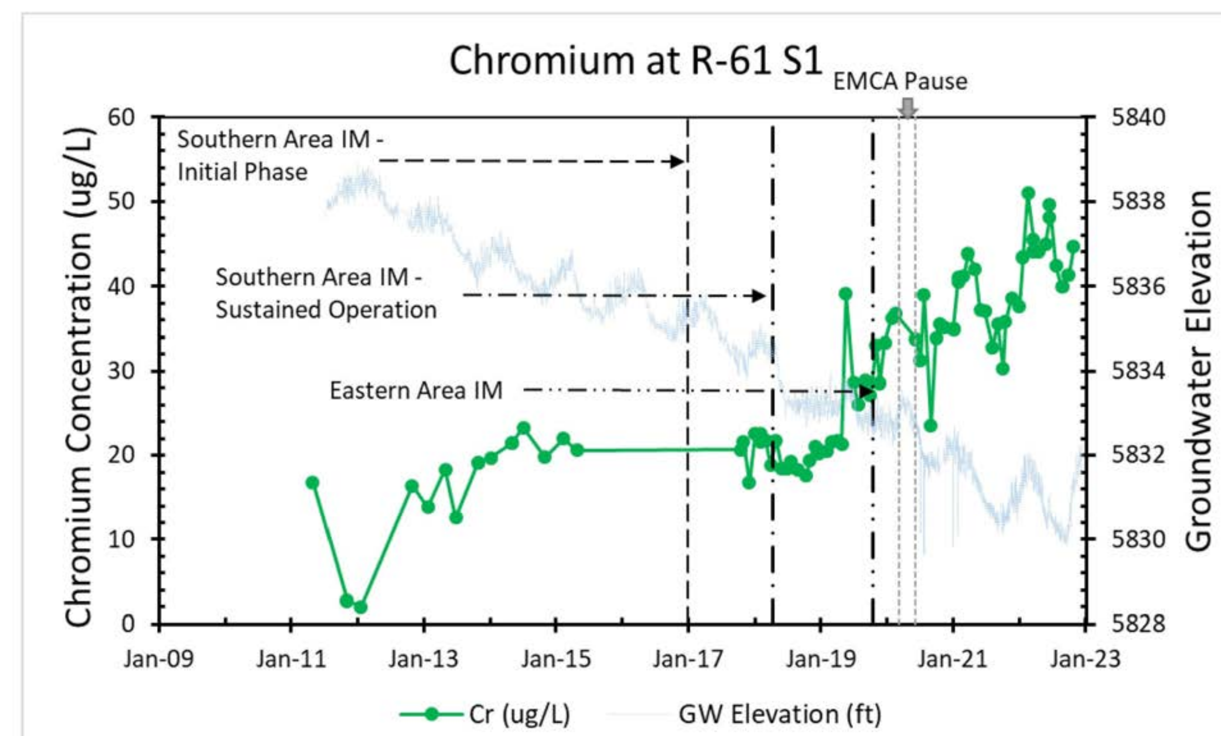


Figure 5.3-3 Chromium concentrations and water levels at R-61 screen 1

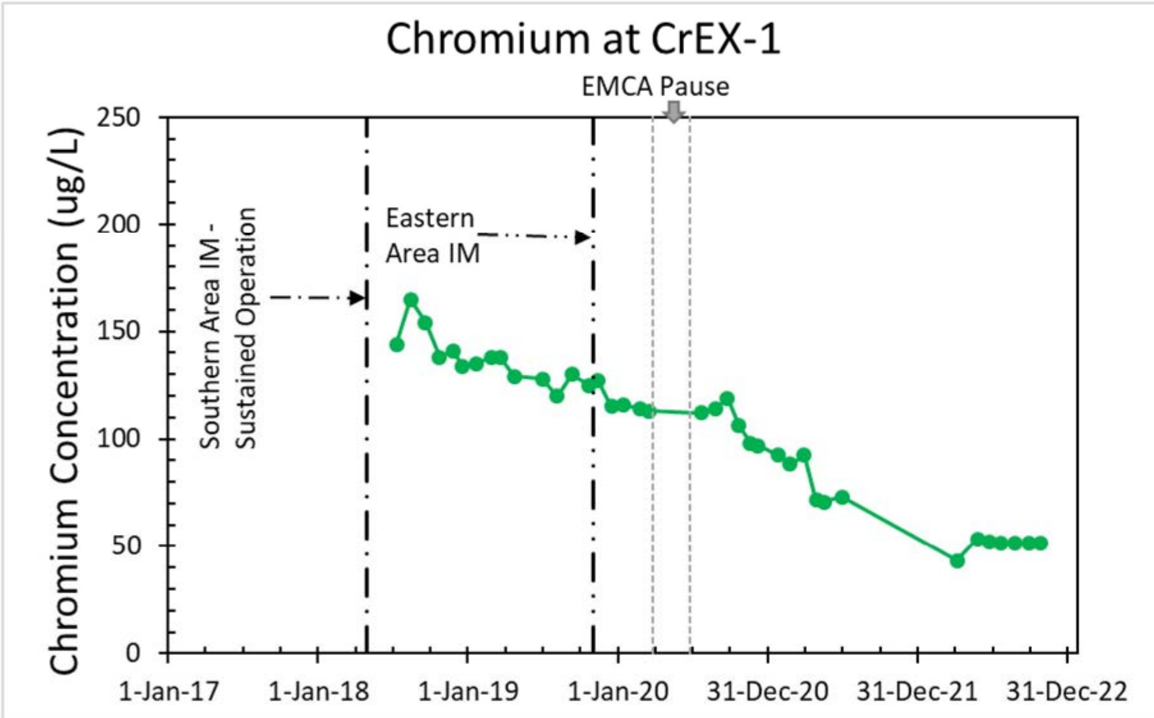


Figure 5.3-4 Chromium concentrations at CrEX-1

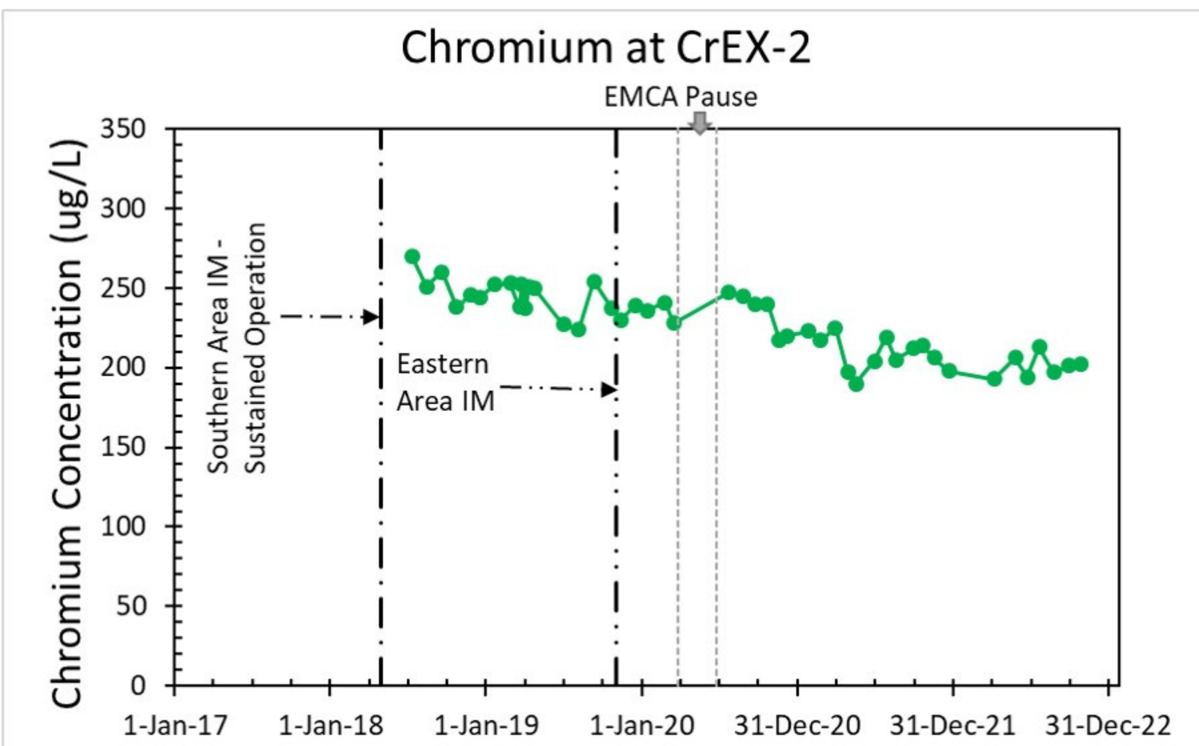


Figure 5.3-5 Chromium concentrations at CrEX-2

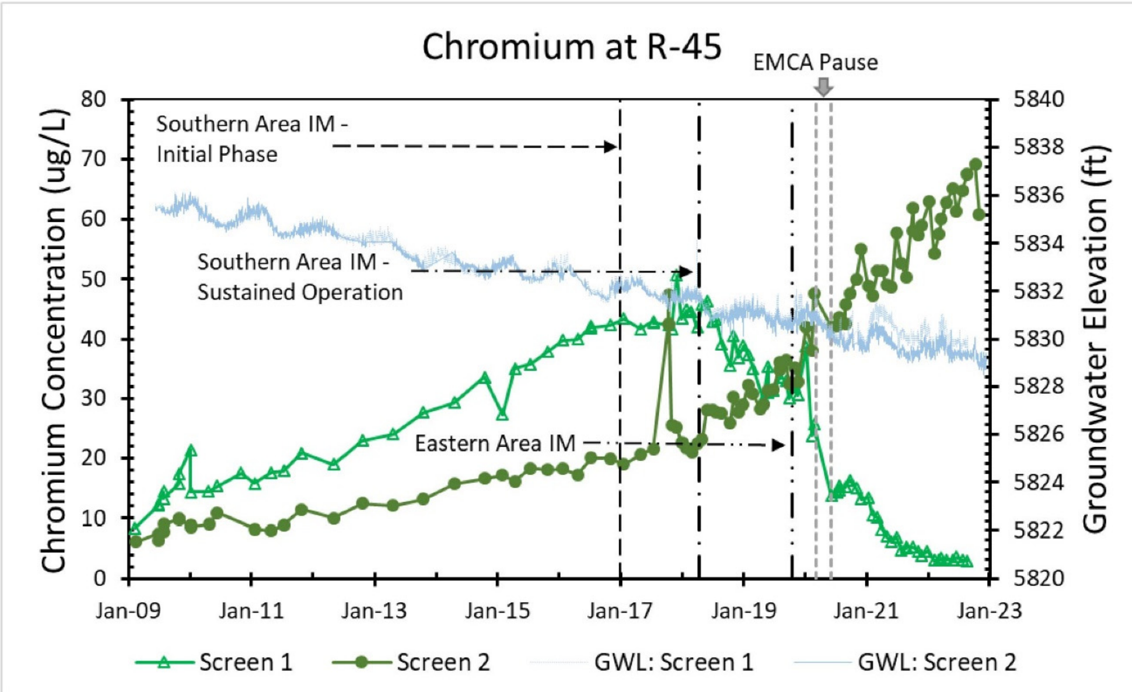


Figure 5.3-6 Chromium concentrations at R-45

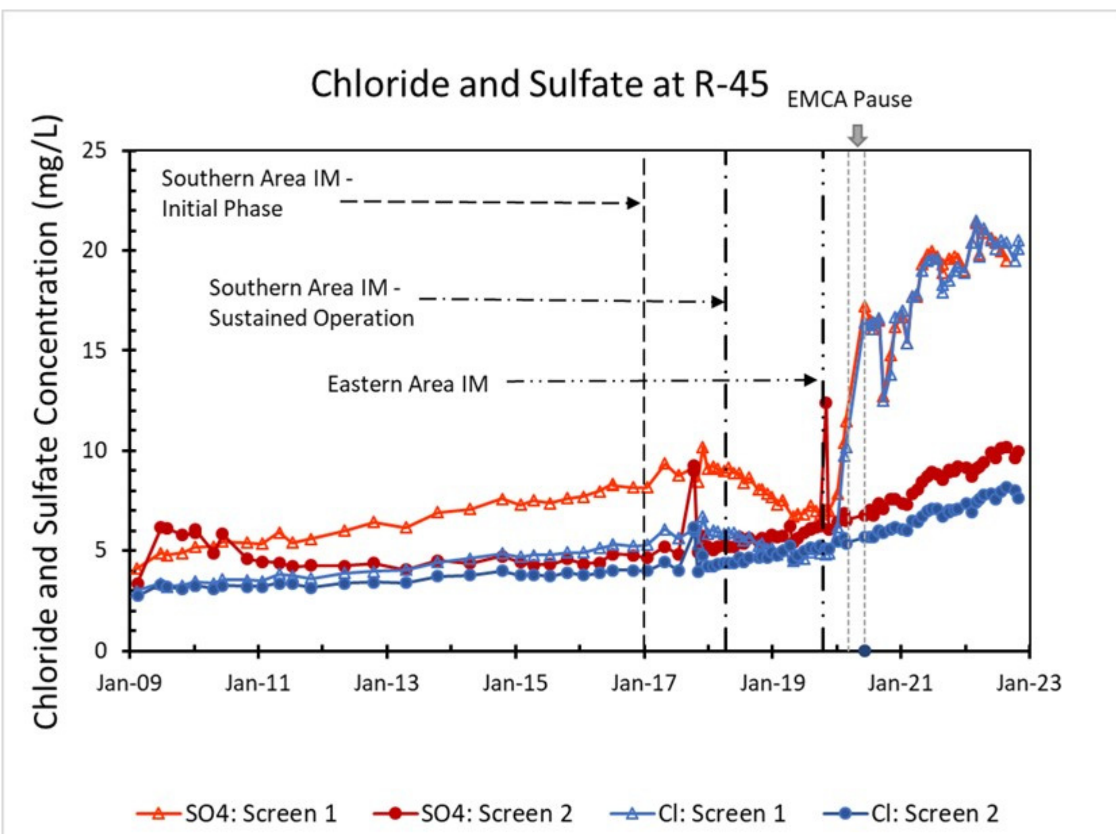


Figure 5.3-7 Chloride and sulfate concentrations at R-45

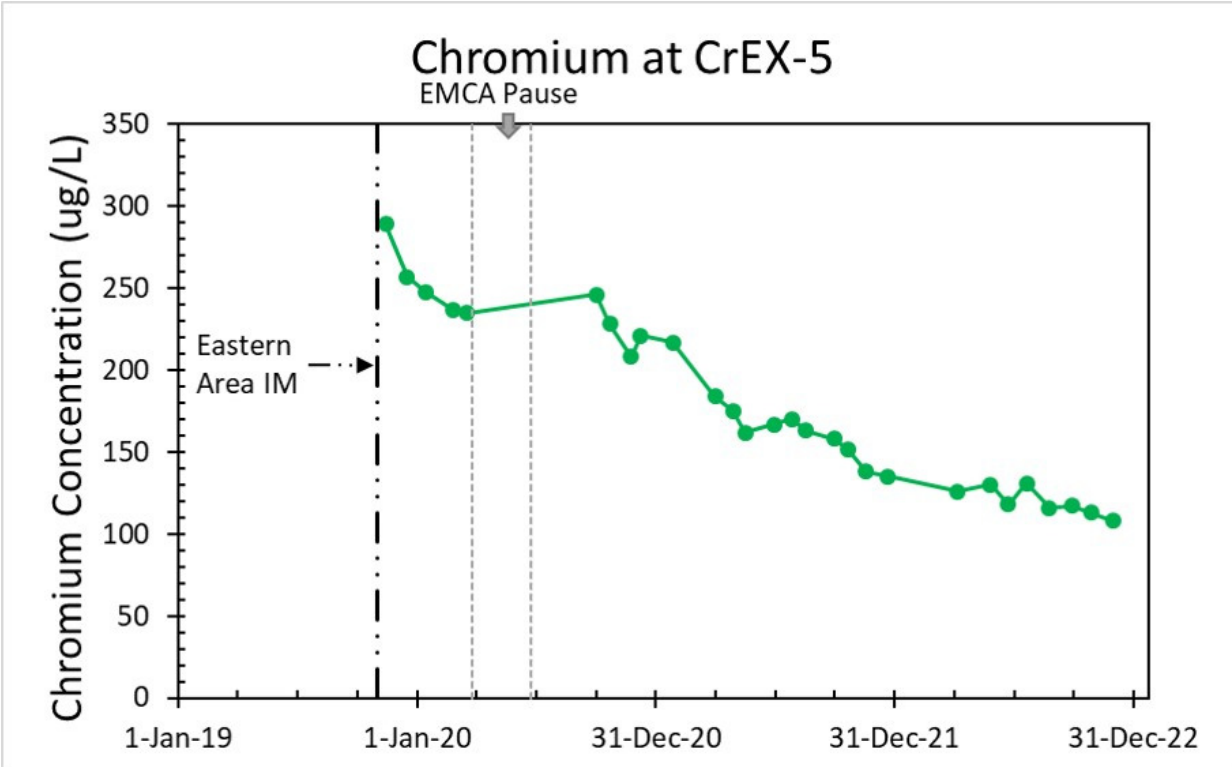


Figure 5.3-8 Chromium concentrations at CrEX-5

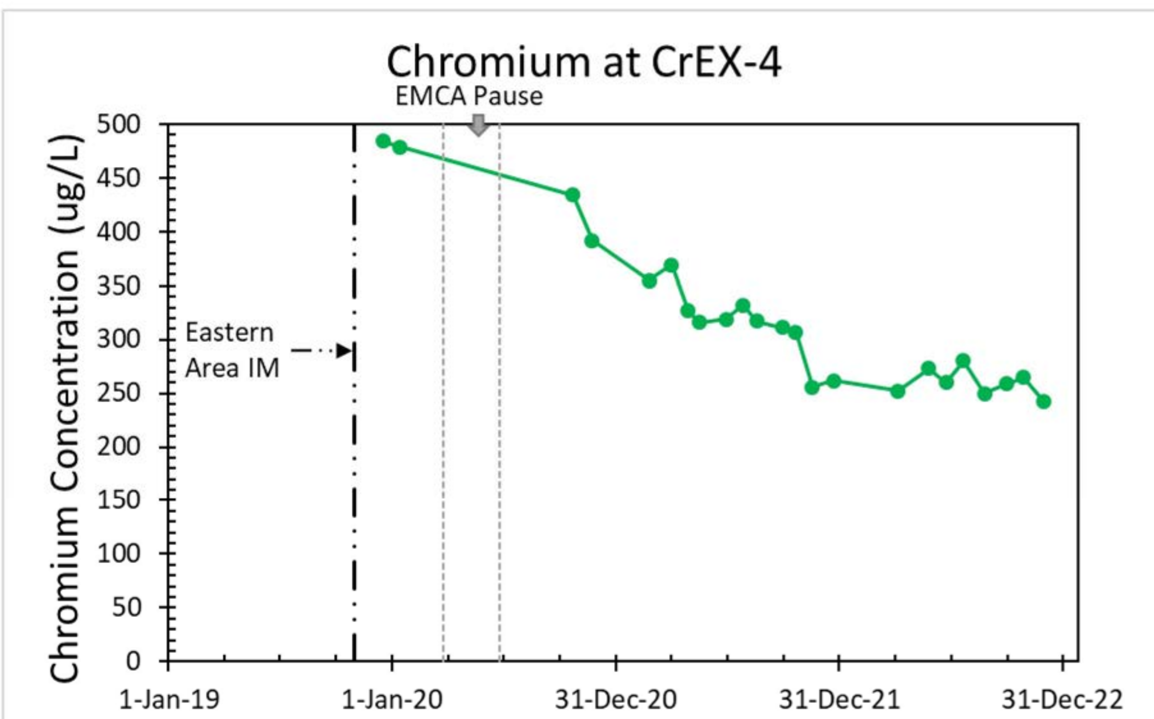


Figure 5.3-9 Chromium concentrations at CrEX-4

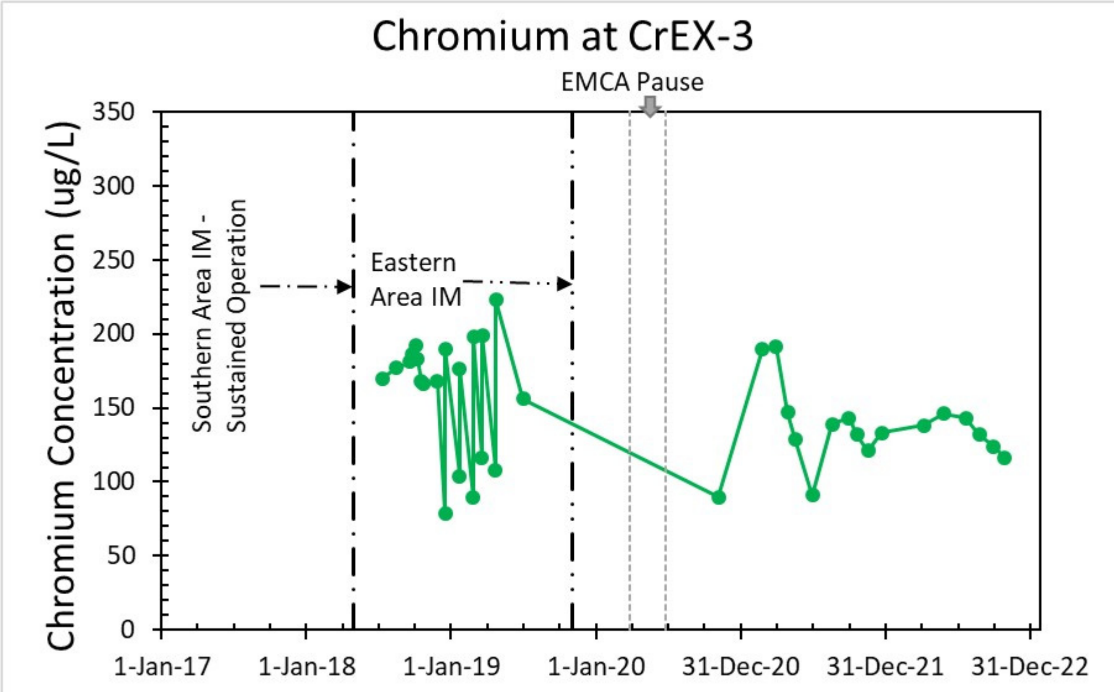
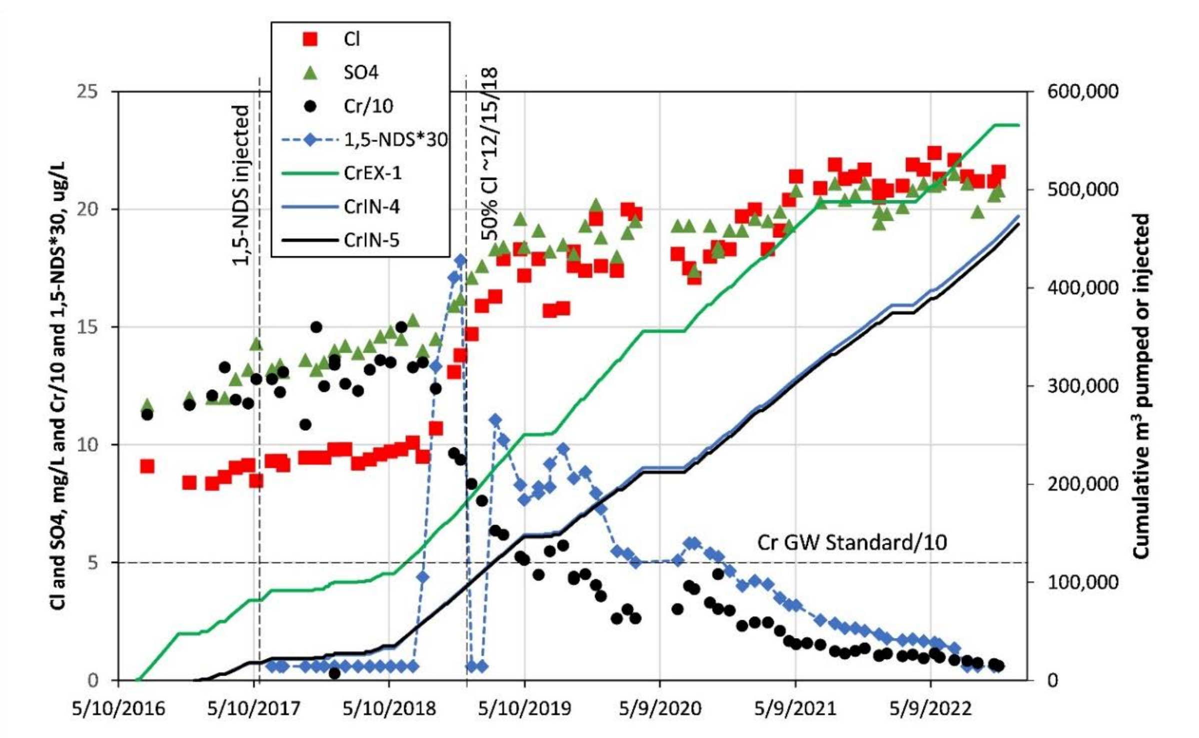


Figure 5.3-10 Chromium concentrations at CrEX-3



Note: Cr concentration is divided by 10, and 1,5-NDS concentration is multiplied by 30. Vertical dashed lines show time of tracer injection and approximate time of 50% Cl- arrival.

Figure 5.4-1 Concentrations of Cl^-; $SO4^{2-}$; chromium; and the 1,5-NDS tracer in R-50 screen 1 shown with cumulative extraction or injection volumes in nearby IM wells

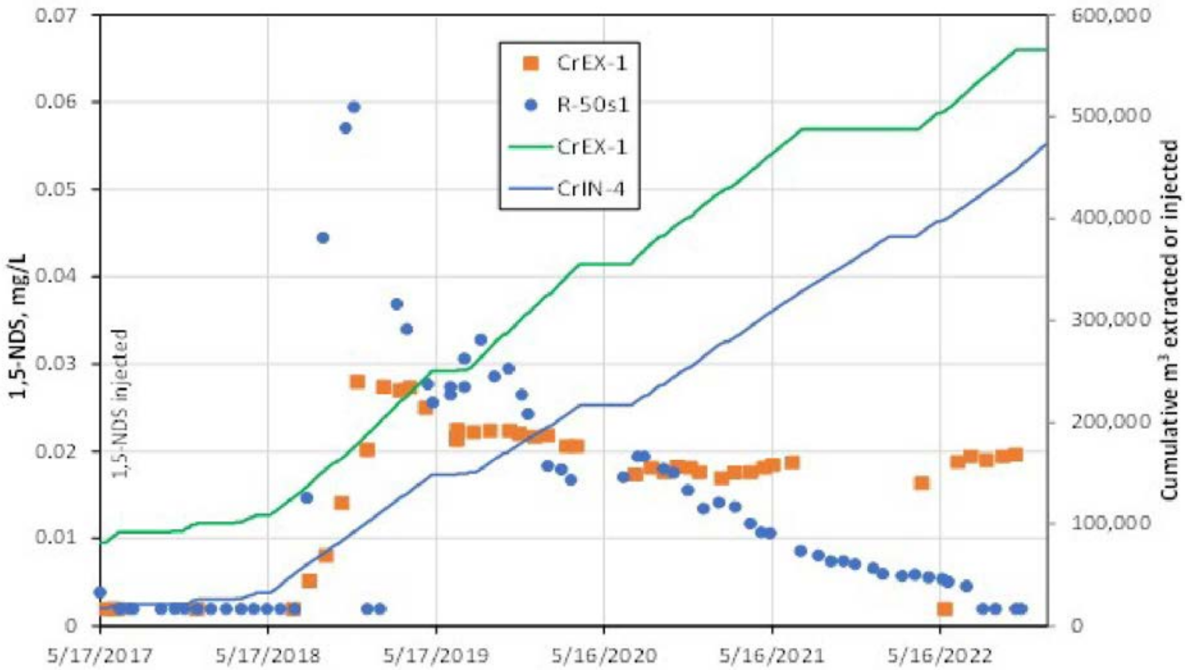
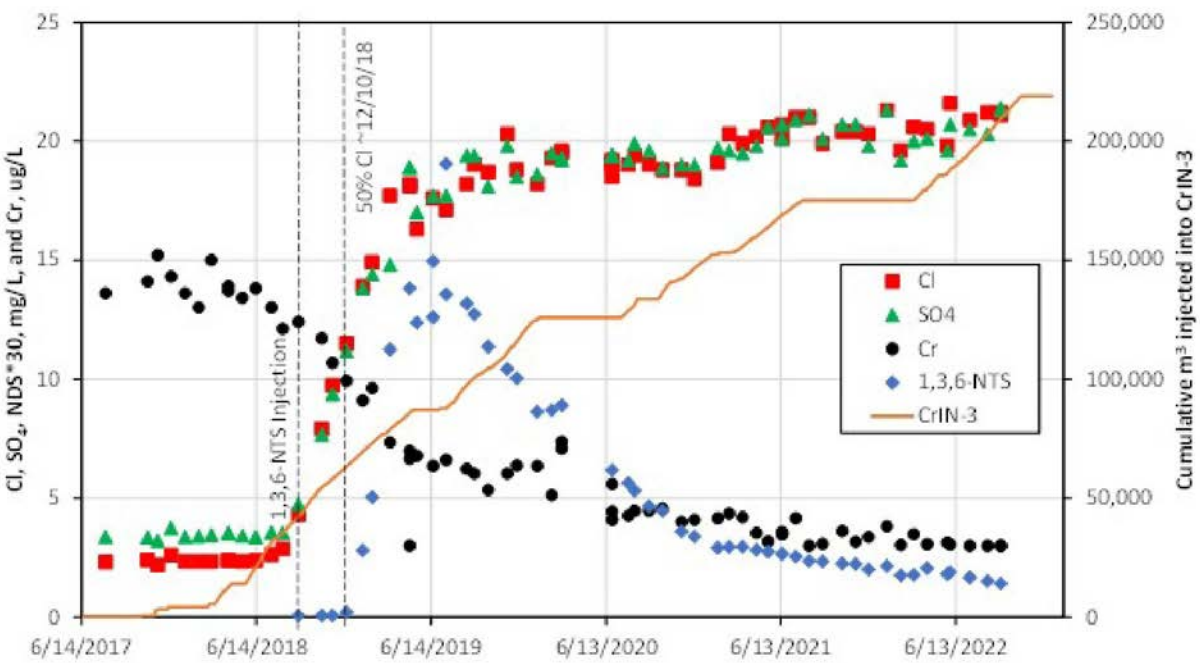
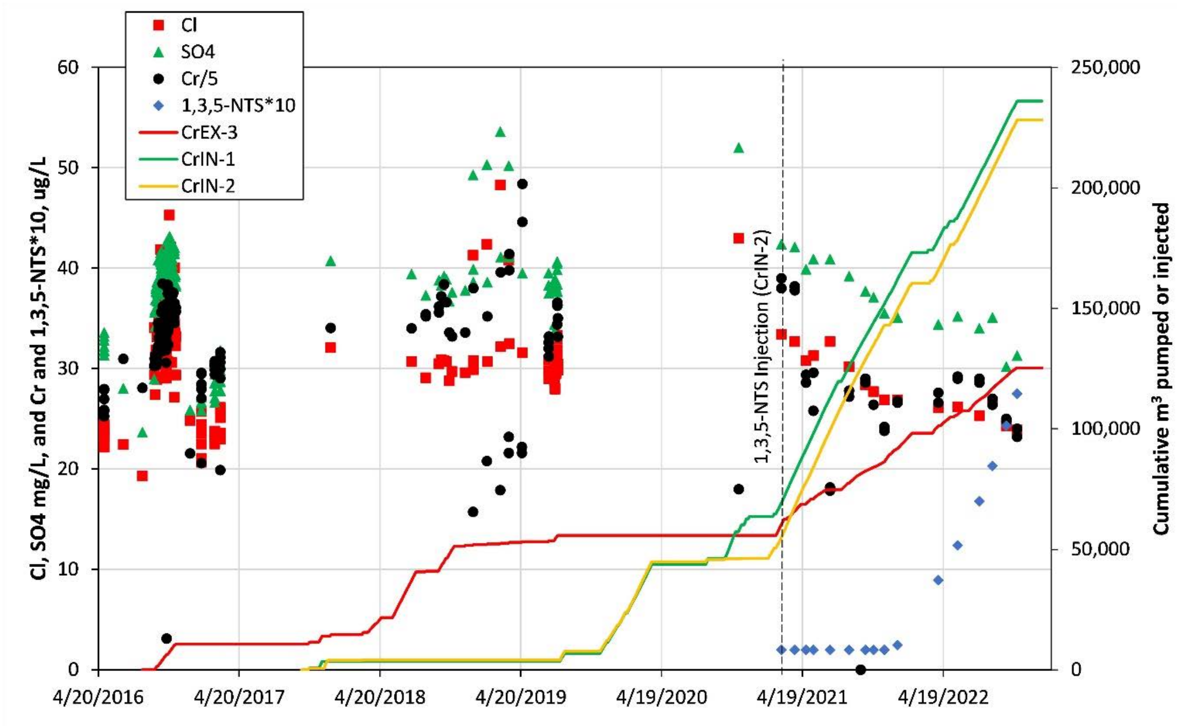


Figure 5.4-2 Concentrations of 1,5-NDS in R-50 screen 1 and CrEX-1 over time



Note: 1,3,6-NTS concentration is multiplied by 30. Vertical dashed lines show time of tracer injection and approximate time of 50% Cl- arrival.

Figure 5.4-3 Concentrations of Cl-; $SO4^{2-}$; chromium; and the 1,3,6-NTS tracer in R-44 screen 1 shown with cumulative injection volume into CrIN-3



Note: 1,3,6-NTS concentration is multiplied by 10. Vertical dashed line shows time of CrIN-2 tracer injection.

Figure 5.4-4 Concentrations of Cl-; SO4^{2-}; chromium; and the 1,3,5-NTS tracer in CrEX-3 shown with cumulative extraction and injection volumes in nearby IM wells

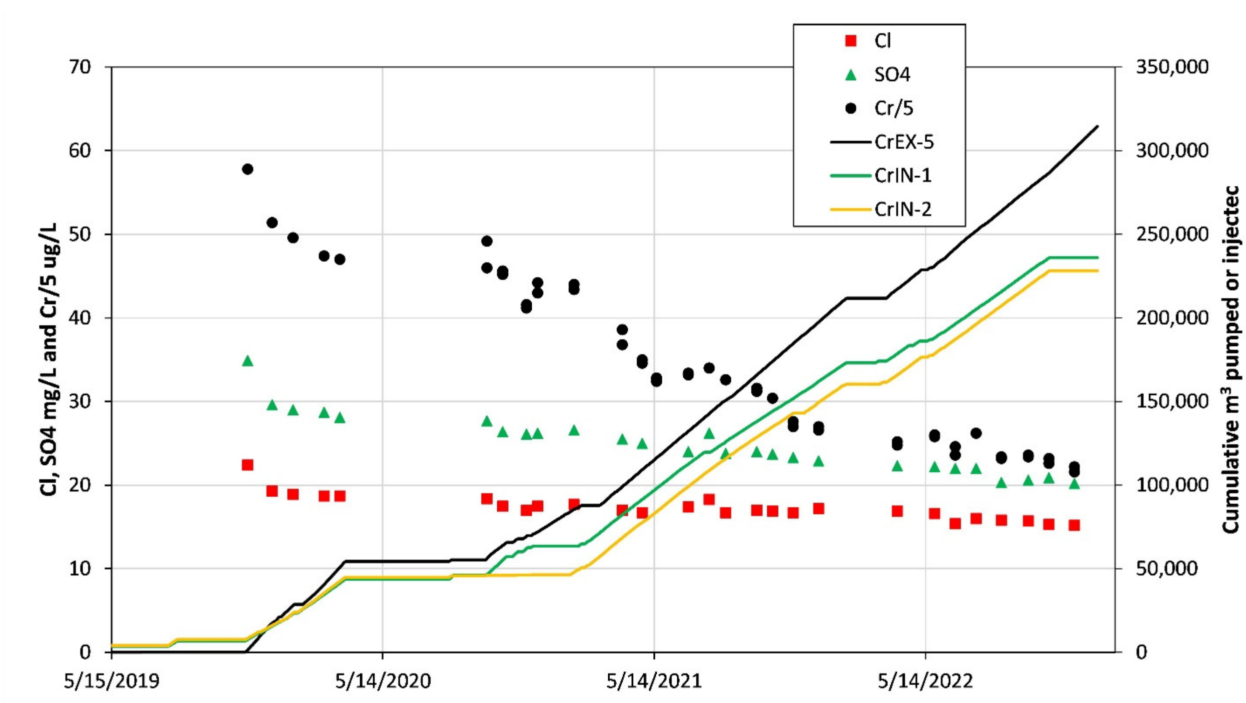


Figure 5.4-5 Concentrations of Cl-, SO4^{2}, and chromium in CrEX-5 shown with cumulative extraction and injection volumes in nearby IM wells

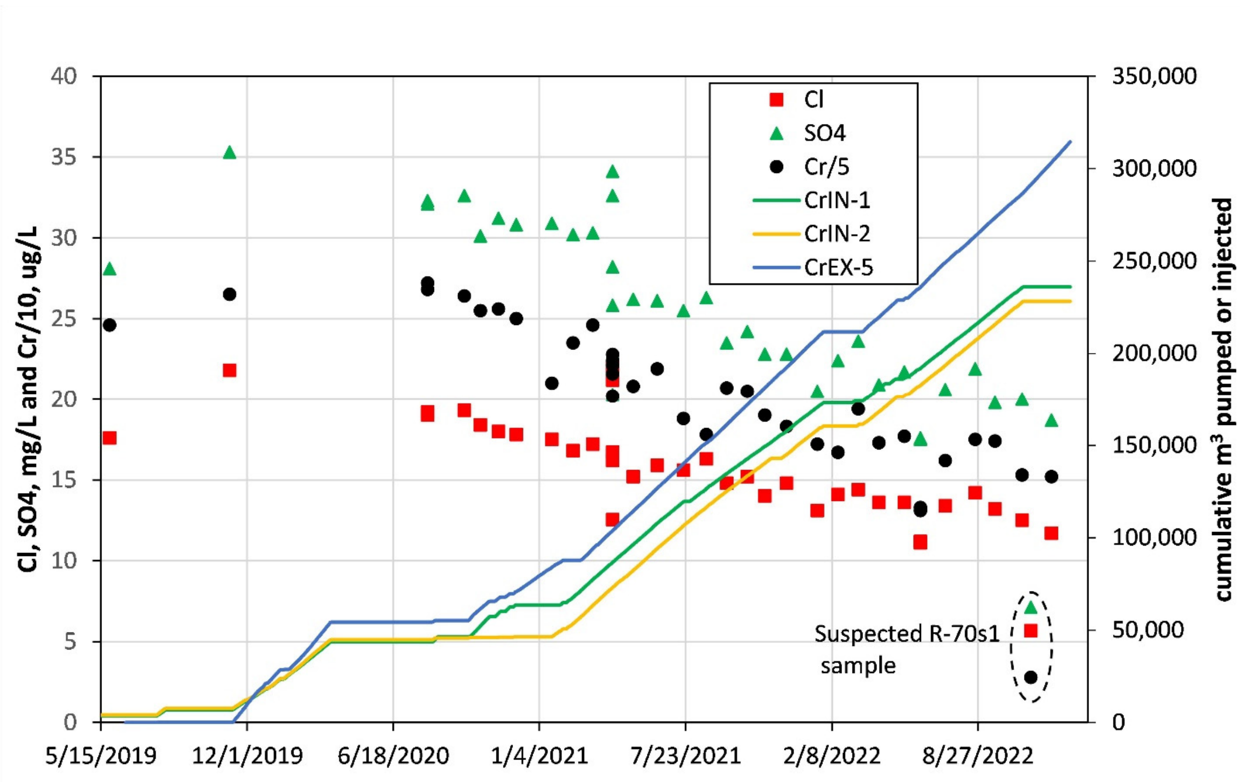


Figure 5.4-6 Concentrations of Cl-, SO4^{2}, and chromium in R-70 screen 2 shown with cumulative extraction and injection volumes in nearby IM wells

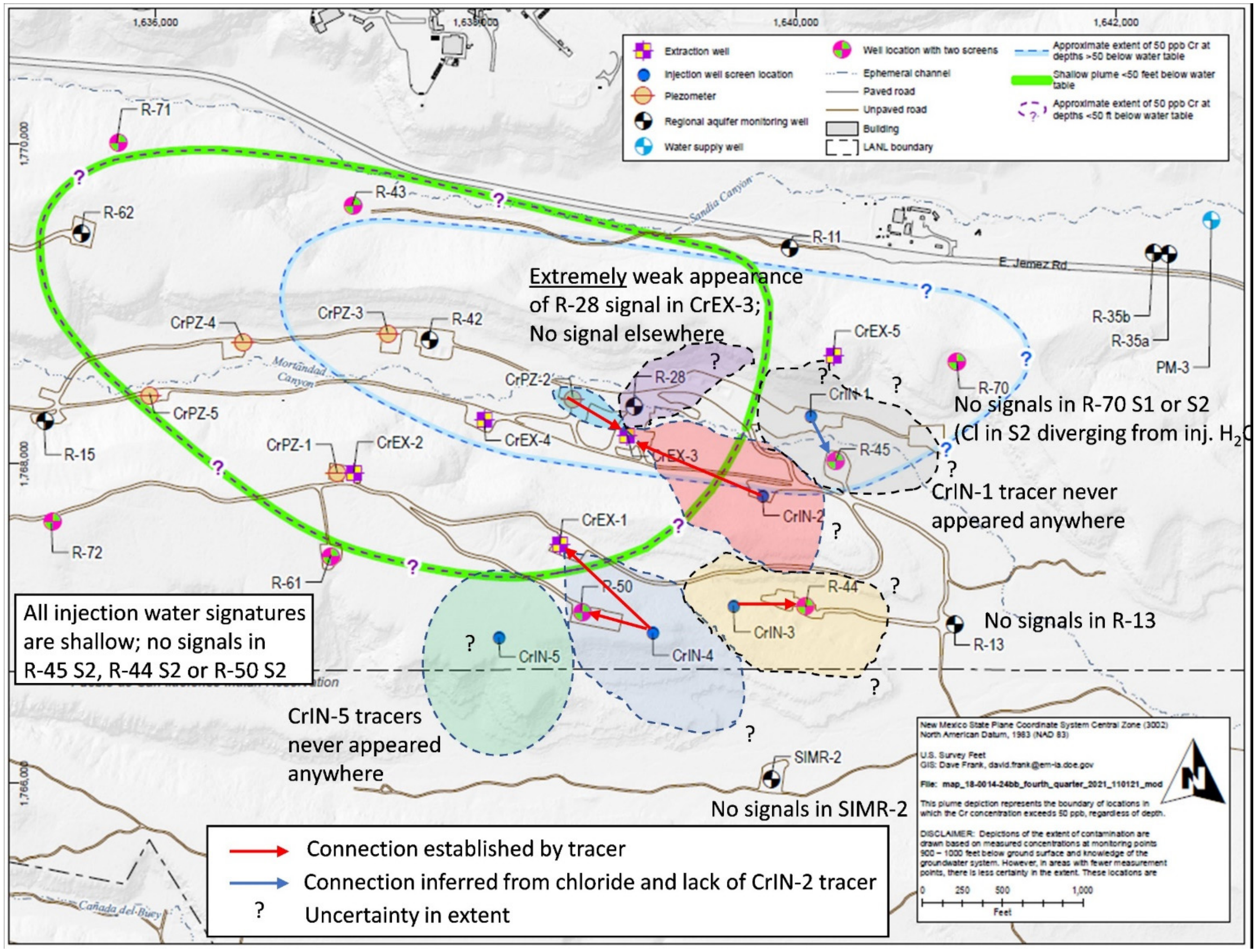


Figure 5.4-7 Depiction of IM injection flows and summary of other inferences from tracer and geochemical signatures

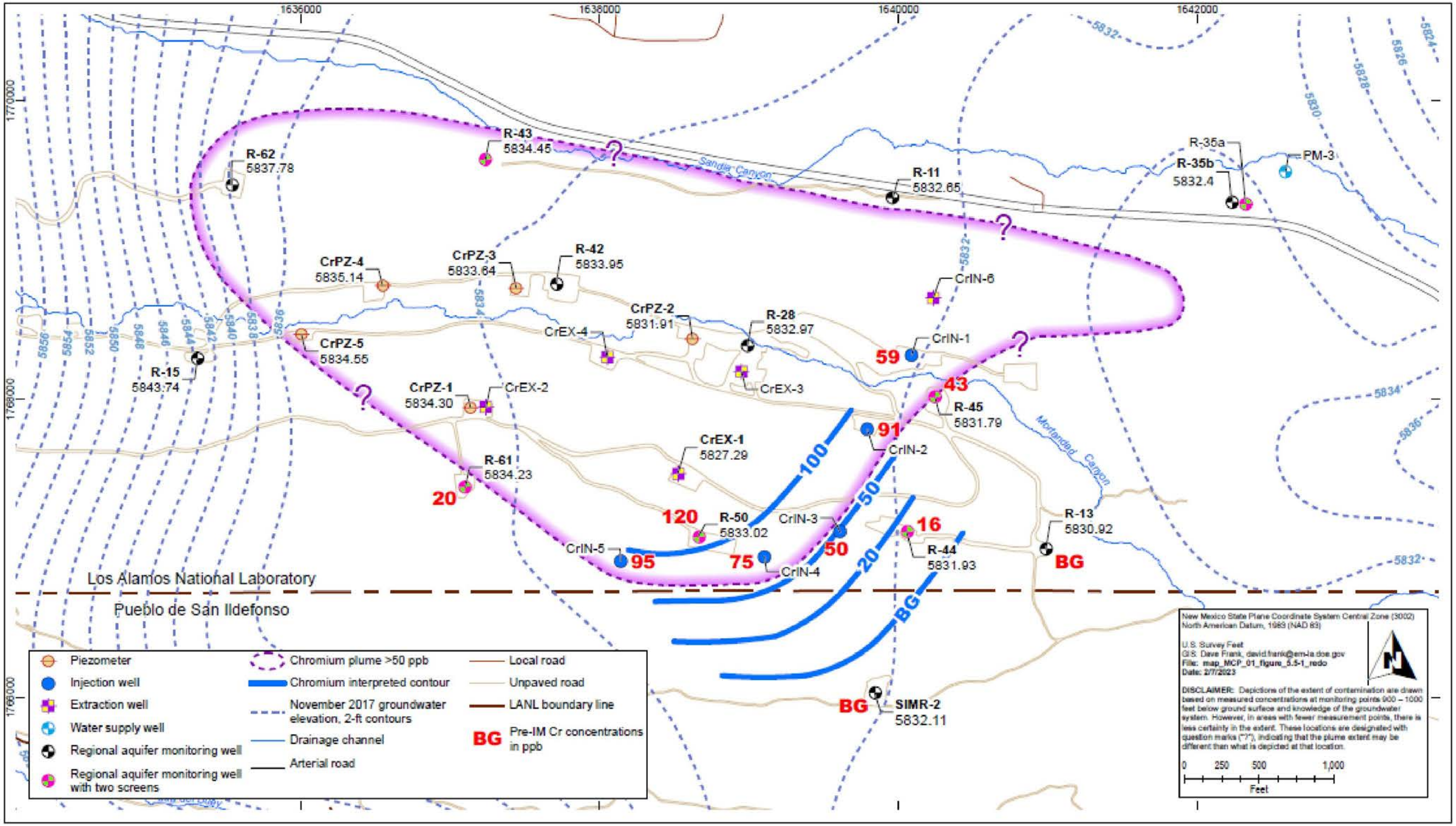


Figure 5.5-1 Chromium concentration values in μg/L (red font) at each injection well and in nearby monitoring wells in 2017, along with interpreted contours of chromium concentrations in the vicinity of CrINs -3, -4, and -5

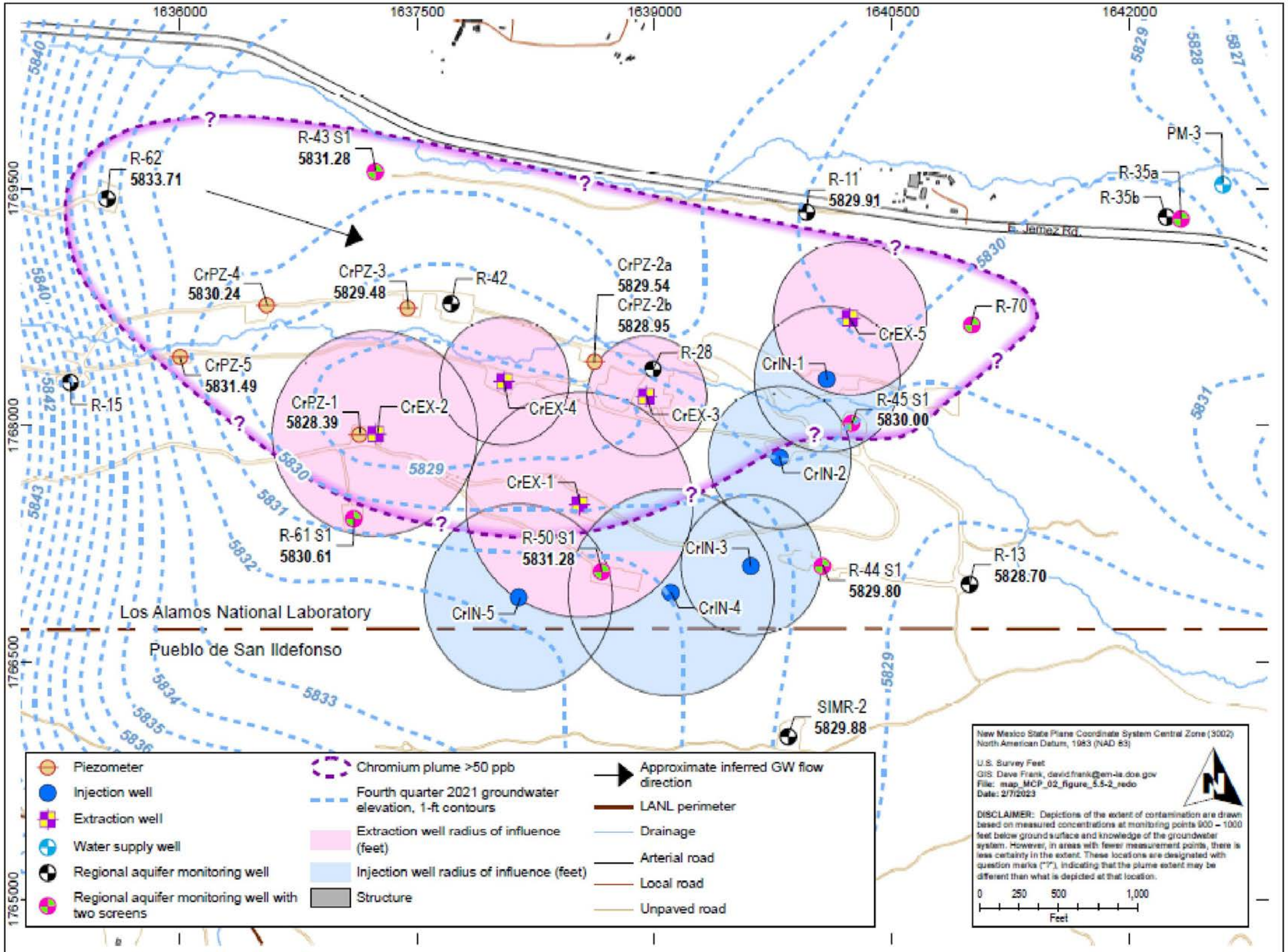


Figure 5.5-2 Radii of fluid displacement based on cylindrical analysis of zones of influence for injection (blue) and extraction (pink) wells

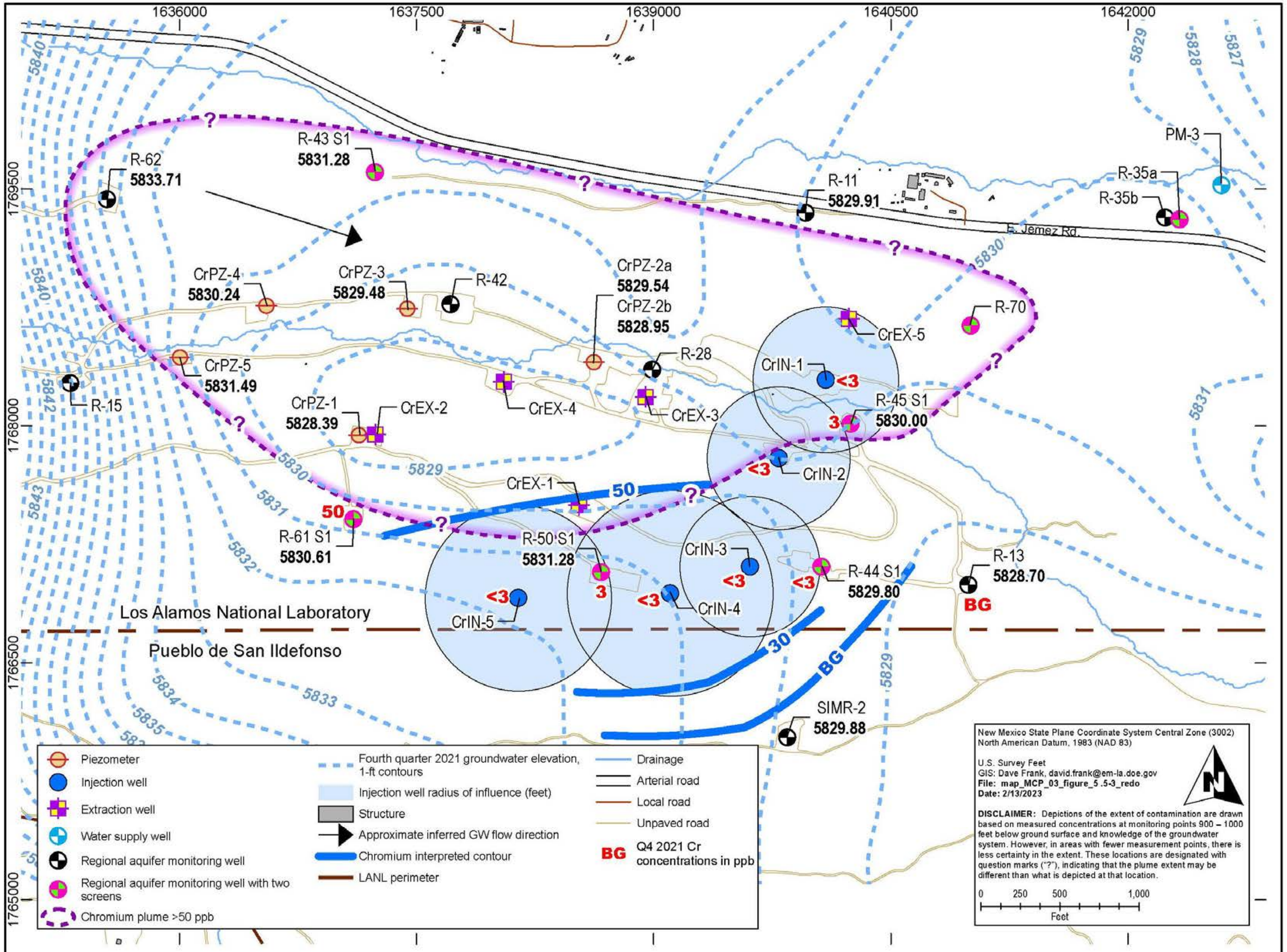


Figure 5.5-3 **Superimposition of injection well zones of influence on present-day chromium concentration measurements (red font) at monitoring wells, with inferred low concentrations (<3 ppb) at the injection wells (BG = background concentration)**

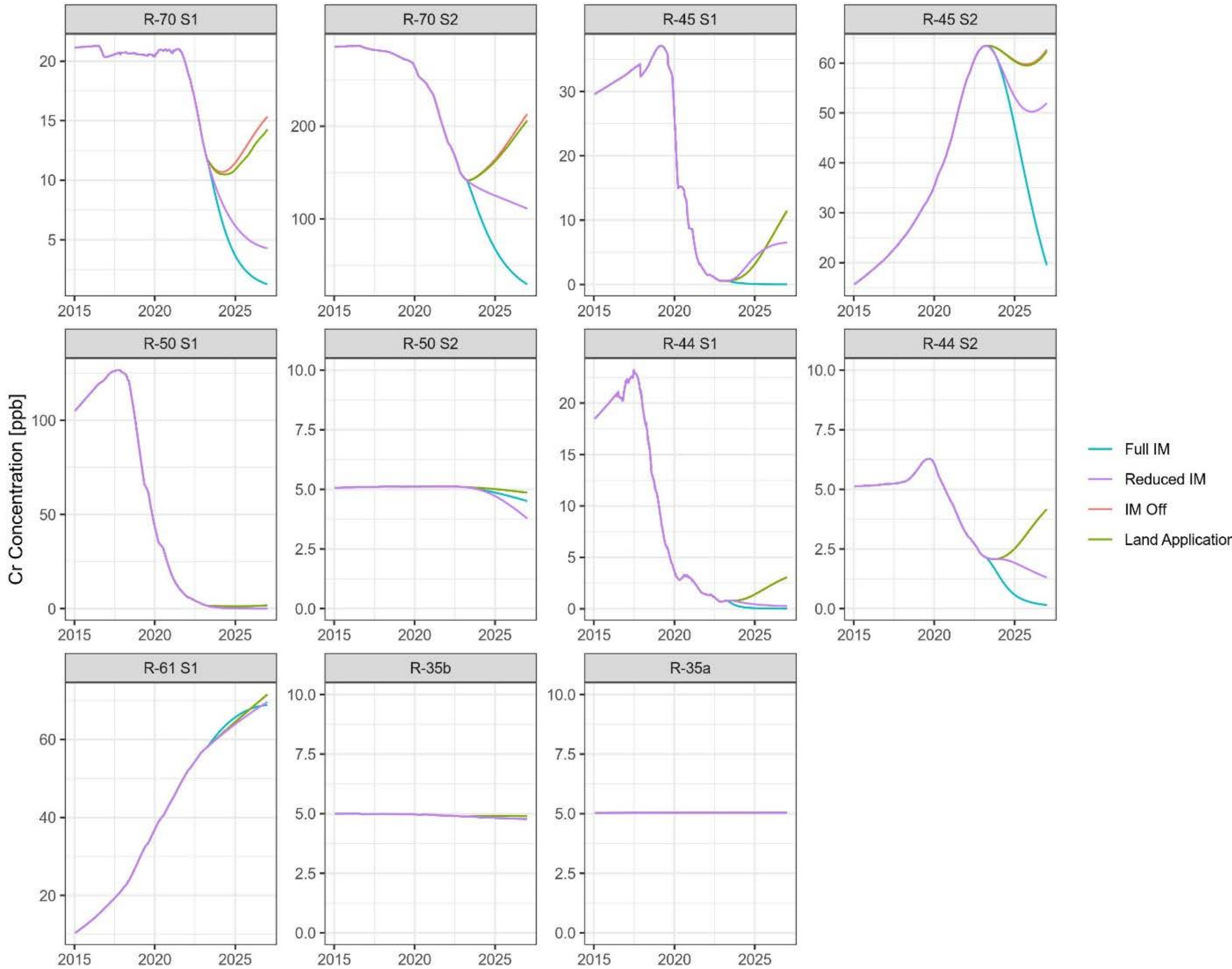


Figure 6.1-1 Modeled concentration trends at existing wells for the four pumping scenarios

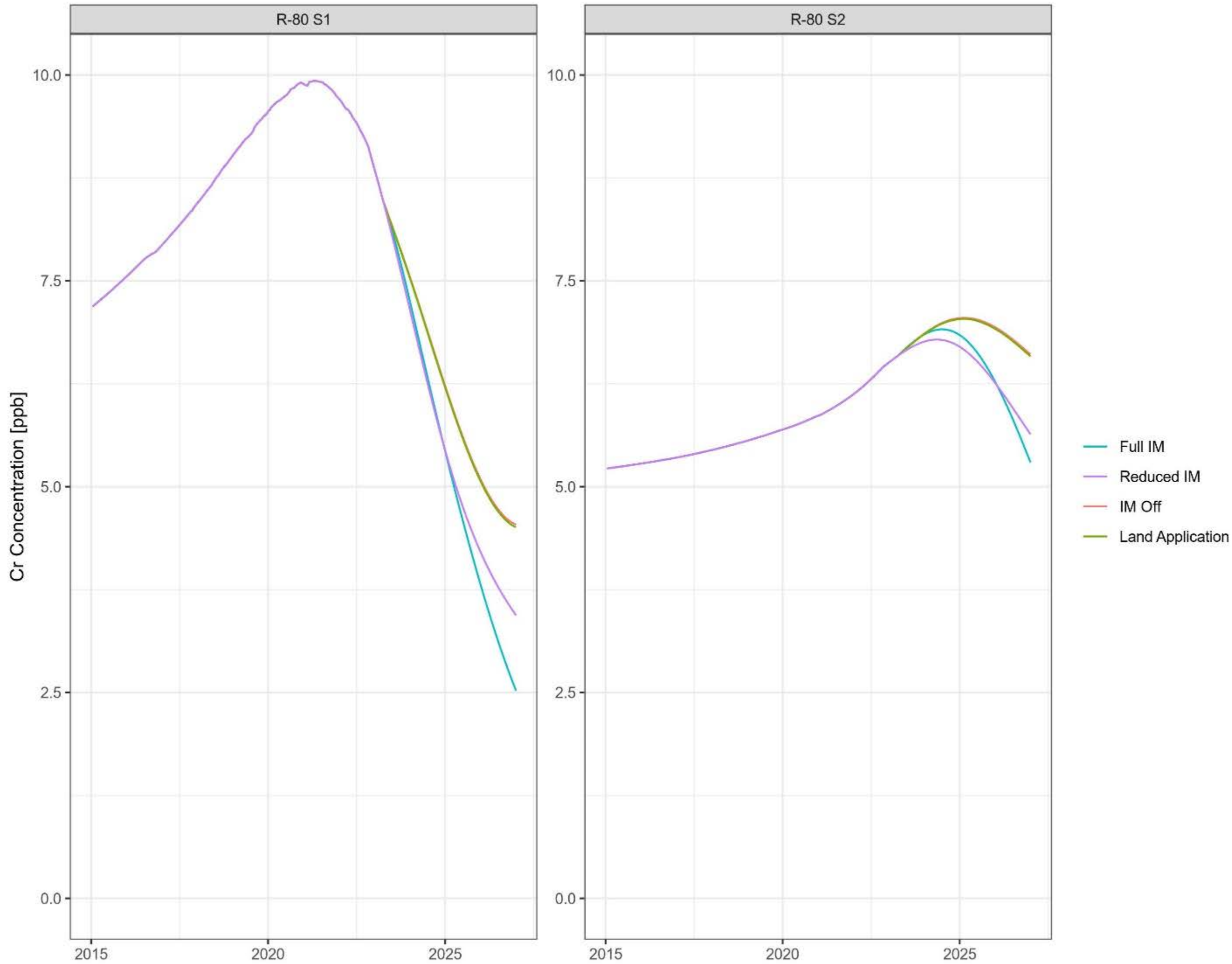


Figure 6.1-2 Modeled concentration trends at planned well R-80

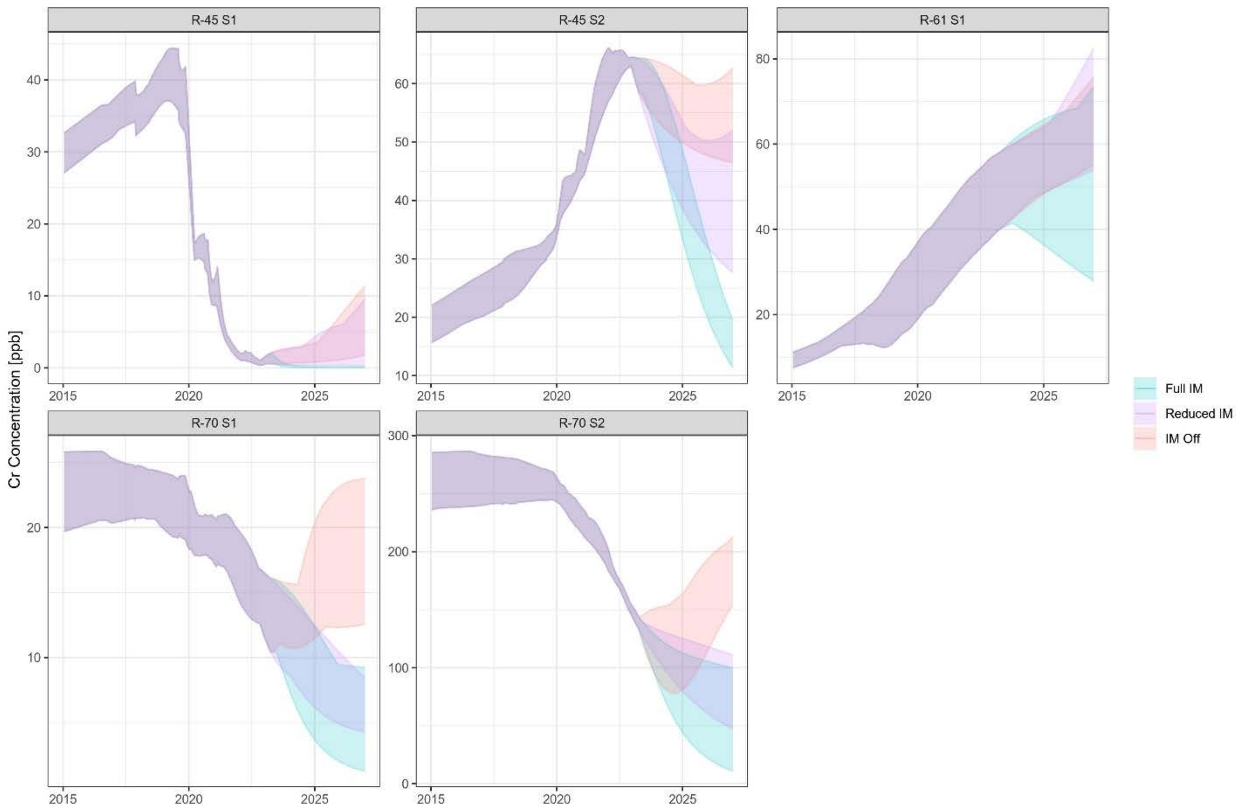


Figure 6.2-1 Concentration versus time with bands showing the range of model uncertainty for each operational scenario

Figure 6.3-1 The modeled total inventory of chromium in the regional aquifer for three pumping scenarios at the beginning of each year

Table 4.2-1
Screen Length and Depths below the Water Table
for Monitoring Wells, Piezometers, and Infrastructure Wells

Well Screen		Screen Length (ft)	Current Depth from Water Table to Top of Screen (ft)[a,b]	Current Depth from Water Table to Bottom of Screen (ft)[a]
Monitoring Wells				
R-11		22.8	11.7	34.5
R-13		60.4	113.9	174.3
R-15		61.7	−20.7	41.0
R-28		23.8	36.2	60.0
R-35a		49.1	218.1	267.2
R-35b		23.1	31.2	54.3
R-36		23.0	14.9	37.9
R-42		21.1	3.5	24.7
R-43	Screen 1	20.7	2.9	23.6
	Screen 2	10.0	67.9	77.9
R-44	Screen 1	10.0	9.7	19.7
	Screen 2	9.9	100.0	109.9
R-45	Screen 1	10.0	5.7	15.7
	Screen 2	20.0	100.5	120.5
R-50	Screen 1	10.0	4.0	14.0
	Screen 2	20.6	111.6	132.2
R-61	Screen 1	10.0	16.7	26.7
	Screen 2[c]	20.6	111.1	131.7
R-62		20.7	7.9	28.6
R-70[d]	Screen 1	41.0	11.3	48.5
	Screen 2	20.5	88.6	107.2
R-71[d]	Screen 1	20.0	12.2	30.4
	Screen 2	10.3	70.9	80.2
R-72	Screen 1	20.0	31.3	51.3
	Screen 2	20.0	101.3	121.3
SIMR-2		20.4	12.8	33.2
Piezometers				
CrPZ-1		10.0	3.7	13.7
CrPZ-2a		10.0	1.9	11.9
CrPZ-2b[e]		20.0	35.3	55.3
CrPZ-3		20.0	3.7	23.7
CrPZ-4		20.0	−0.6	19.4
CrPZ-5		20.0	5.3	25.3

Table 4.2-1 (continued)

Well Screen		Screen Length (ft)	Current Depth from Water Table to Top of Screen (ft)[a,b]	Current Depth from Water Table to Bottom of Screen (ft)[a]
Extraction Wells				
CrEX-1	Shallow	50.0	−7.2	42.8
	Deep[f]	20.0	72.8	92.8
CrEX-2		50.0	16.2	66.2
CrEX-3		39.2	11.1	50.3
CrEX-4[g]	Shallow	35.0	9.9	44.9
	Deep	20.0	54.9	74.9
CrEX-5[d]		60.0	12.2	66.6
Injection Wells				
CrIN-1		50.0	12.5	62.5
CrIN-2		50.0	3.4	53.4
CrIN-3[d]		50.0	1.5	49.3
CrIN-4[d]		50.0	4.0	53.1
CrIN-5[d]		60.0	2.6	57.0

[a] Recent water table depth is used, which may be significantly lower than the depth when the well was drilled because of long-term water table decline.

[b] Negative depth to top of screen indicates the water table is now below the top of the screen by that amount.

[c] R-61 screen 2 is not sampled because of persistent reducing conditions.

[d] Angled well. Vertical depths to top and bottom of screen are calculated based on the average angle from vertical.

[e] Water samples are no longer collected at CrPZ-2b because of difficulties accessing the screened interval.

[f] CrEX-1 Deep screen is isolated using a packer. Water is not extracted from this screen.

[g] CrEX-4 Shallow and deep screens are open to the well. Water is extracted from both screens.

Table 5.3-1
Concentration Trends at Chromium Area Monitoring and Extraction Wells Based on Mann-Kendall Trend Analysis at the 95% Confidence Level

Monitoring Well	Screen	Pre-IM Operations	Sustained Southern IM Operations	Sustained Eastern IM Operations	Injection Water Signature (Cl^- and SO_4^{2-})	Tracer Injection
Southern Plume Area						
R-15		↑	↓	↓		
R-61	S1[a]	↑	↑	↑		
	S2[b]	—	—	—		
CrEX-2				↓		
CrEX-1				↓	✔	CrIN-4
R-50	S1	↑	↓	↓	✔	CrIN-4
	S2	—	—	—		
R-44	S1	↑	↓	↓	✔	CrIN-3
	S2	—	↓	↑		
SIMR-2		—	—	—		
R-13		—	—	—		
Eastern Plume Area						
R-11		↑	↓	—		
CrEX-5				↓		
R-45	S1	↑	↓	↓	✔	
	S2	↑	↑	↑		
R-70	S1			↓		
	S2			↓		
R-35a		—	—	—		
R-35b		—	—	—		
Plume Centroid						
CrEX-3				↓		CrIN-2
CrEx-4				↓		

Notes: Arrows pointing up indicate an increasing concentration trend, whereas arrows pointing down indicate a decreasing concentration trend. If no statistically significant trend exists, then the em-dash (—) symbol is used. Trends that are below the 50 µg/L standard are shown in grey. Arrows in red indicate unfavorable (increasing) trends in concentration and arrows in green indicate favorable (decreasing) trends in concentration. Tracers injected at injection wells that have been detected at extraction and monitoring wells are listed in the final column of the table. Note that tracers from CrIN-5 have not been detected at any location, possibly due to its biodegradation.

[a] S1 = Screen 1.

[b] S2 = Screen 2.

Table 5.4-1
Summary of Naphthalene Sulfonate Tracer Injections into CrIN Wells

CrIN Well	Tracer[a]	Injection Date(s)	Injection Mass[b] (g)	Injection Vol. (gal.)
CrIN-4	1,5-NDS	5/17–18/2017	50,000	15,000
CrIN-5	1,6-NDS	5/22–23/2017	50,000	15,000
CrIN-3	1,3,6-NTS	9/10/2018	50,000	15,000
CrIN-4	2,6-NDS	9/17/2018	50,000	15,000
CrIN-5	2,7-NDS	9/18/2018	50,000	15,000
CrIN-2	1,3,5-NTS	3/30/2021	50,000	12,000 + 3000[c]
CrIN-1	2,6-NDS	3/31/2021	50,000	12,000 + 3000[c]

[a] All tracers injected as sodium salts. NDS = naphthalene disulfonate; NTS = naphthalene trisulfonate.

[b] Masses are those of disodium or trisodium salts.

[c] Tracer was injected in 12,000 gal. followed by 3000 gal. of untraced chase water.

Table 6.1-1
IM Extraction and Injection Well Rates for Four Different Operational Scenarios and Estimated Mass Removal for Each Scenario

Well	Full IM	Reduced IM	Land-Application Only	No Operations
CrEX-1	75	0	0	0
CrEX-2	65	0	0	0
CrEX-3	30	0	0	0
CrEX-4	50	65	3.8	0
CrEX-5	65	75	4.4	0
CrIN-1	60	0	0	0
CrIN-2	60	0	0	0
CrIN-3	45	0	0	0
CrIN-4	60	75	0	0
CrIN-5	60	65	0	0
Effective Total	**285**	**140**	**8**	**0**
Volume treated from April 1, 2023, to January 1, 2027 (millions of gallons)	562	276	9	0
Chromium removed from April 1, 2023, to January 1, 2027 (lb)	471–577	340–429	21–24	0
Chromium added from April 1, 2023, to January 1, 2027 (lb)	326–485	326–485	326–485	326–485
Net Change in chromium Inventory (lb)	−196–−75	−51–102	302–464	326–485

Notes: Rates are for (1) full operations, (2) partial operations, (3) land-application only, and (4) no operations. Whereas full and partial operational scenarios operate continuously, the land-application scenario operates only for 3 days per month, 8 hours per day, 7 months per year to yield that which is equivalent to operating at 5 gpm during a calendar year.

Appendix A

Mann-Kendall Test Results

R-15 Mann-Kendall Test Results

Test	Pre-IM[a]		Southern Area IM		Eastern Area IM	
	Screen 1	Screen 2	Screen 1	Screen 2	Screen 1	Screen 2
Chromium Concentration at R-15 Mann-Kendall Test						
M-K Test Value (S)	630	n/a[b]	-56	n/a	34	n/a
Critical Value (0.05)	1.645	n/a	n/a	n/a	n/a	n/a
Standard Deviation of S	105.5	n/a	18.17	n/a	24.14	n/a
Standardized Value of S	5.96	n/a	-3.028	n/a	1.367	n/a
Approximate p-value	1.263E-9	n/a	0.00123	n/a	0.0858	n/a
Concentration Trend	**Increasing**	n/a	**Decreasing**	n/a	**None**	n/a
Chloride Concentration at R-15 Mann-Kendall Test						
M-K Test Value (S)	-151	n/a	3	n/a	-33	n/a
Critical Value (0.05)	-1.645	n/a	n/a	n/a	n/a	n/a
Standard Deviation of S	102.1	n/a	18.27	n/a	24.21	n/a
Standardized Value of S	-1.47	n/a	0.109	n/a	-1.322	n/a
Approximate p-value	0.071	n/a	0.456	n/a	0.0932	n/a
Concentration Trend	**None**	n/a	**None**	n/a	**None**	n/a
Sulfate Concentration at R-15 Mann-Kendall Test						
M-K Test Value (S)	278	n/a	-20	n/a	-28	n/a
Critical Value (0.05)	1.645	n/a	n/a	n/a	n/a	n/a
Standard Deviation of S	105.6	n/a	18.24	n/a	24.18	n/a
Standardized Value of S	2.624	n/a	-1.042	n/a	-1.117	n/a
Approximate p-value	0.00434	n/a	0.149	n/a	0.132	n/a
Concentration Trend	**Increasing**	n/a	**None**	n/a	**None**	n/a

R-61 Mann-Kendall Test Results

Test	Pre-IM		Southern Area IM		Eastern Area IM	
	Screen 1	Screen 2	Screen 1	Screen 2	Screen 1	Screen 2
Chromium Concentration at R-61 Screen 1 Mann-Kendall Test						
M-K Test Value (S)	94	n/a	116	n/a	434	n/a
Critical Value (0.05)	n/a	n/a	1.645	n/a	1.645	n/a
Standard Deviation of S	24.23	n/a	50.55	n/a	85.82	n/a
Standardized Value of S	3.837	n/a	2.275	n/a	5.046	n/a
Approximate p-value	6.216E-5	n/a	0.0115	n/a	2.261E-7	n/a
Concentration Trend	**Increasing**	n/a	**Increasing**	n/a	**Increasing**	n/a
Chloride Concentration at R-61 Screen 1 Mann-Kendall Test						
M-K Test Value (S)	-13	n/a	212	n/a	445	n/a
Critical Value (0.05)	0.327	n/a	1.654	n/a	1.645	n/a
Standard Deviation of S	26.22	n/a	50.5	n/a	85.8	n/a
Standardized Value of S	-0.458	n/a	4.178	n/a	5.175	n/a
Approximate p-value	0.324	n/a	1.468E-5	n/a	1.141E-7	n/a
Concentration Trend	**None**	n/a	**Increasing**	n/a	**Increasing**	n/a
Sulfate Concentration at R-61 Screen 1 Mann-Kendall Test						
M-K Test Value (S)	43	n/a	240	n/a	495	n/a
Critical Value (0.05)	0.056	n/a	1.645	n/a	1.645	n/a
Standard Deviation of S	26.36	n/a	50.6	n/a	85.8	n/a
Standardized Value of S	1.593	n/a	4.724	n/a	5.758	n/a
Approximate p-value	0.0556	n/a	1.158E-6	n/a	4.267E-9	n/a
Concentration Trend	**None**	n/a	**Increasing**	n/a	**Increasing**	n/a

CrEX-2 Mann-Kendall Test Results

Mann-Kendall Test	Chromium		Chloride		Sulfate	
	Pre-IM	**Post-IM**	**Pre-IM**	**Post-IM**	**Pre-IM**	**Post-IM**
M-K Test Value (S)	n/a	-717	n/a	-743	n/a	-805
Critical Value (0.05)	n/a	-1.645	n/a	-1.645	n/a	-1.645
Standard Deviation of S	n/a	109	n/a	105.6	n/a	109
Standardized Value of S	n/a	-6.568	n/a	-7.03	n/a	-7.378
Approximate p-value	n/a	2.545E-11	n/a	1.036E-12	n/a	8.021E-14
Concentration Trend	n/a	**Decreasing**	n/a	**Decreasing**	n/a	**Decreasing**

CrEX-1 Mann-Kendall Test Results

Mann-Kendall Test	Chromium		Chloride		Sulfate	
	Pre-IM	**Post-IM**	**Pre-IM**	**Post-IM**	**Pre-IM**	**Post-IM**
M-K Test Value (S)	n/a	-626	n/a	275	n/a	-585
Critical Value (0.05)	n/a	-1.645	n/a	1.645	n/a	-1.645
Standard Deviation of S	n/a	79.51	n/a	88.8	n/a	88.93
Standardized Value of S	n/a	-7.861	n/a	3.086	n/a	-6.567
Approximate p-value	n/a	1.906E-15	n/a	0.00102	n/a	2.571E-11
Concentration Trend	n/a	**Decreasing**	n/a	**Increasing**	n/a	**Decreasing**

R-50 Mann-Kendall Test Results

Test	Pre-IM		Southern Area IM		Eastern Area IM	
	Screen 1	Screen 2	Screen 1	Screen 2	Screen 1	Screen 2
Chromium Concentration at R-50 Mann-Kendall Test						
M-K Test Value (S)	433	-57	-285	-21	-556	-57
Critical Value (0.05)	1.645	-1.645	-1.645	-1.645	-1.645	-1.645
Standard Deviation of S	73.4	47.95	56.01	55.99	76.46	76.4
Standardized Value of S	5.886	-1.168	-5.07	-0.357	-7.259	-0.733
Approximate p-value	1.98E-9	0.121	1.99E-7	0.36	1.95E-13	0.232
Concentration Trend	**Increasing**	**None**	**Decreasing**	**None**	**Decreasing**	**None**
Chloride Concentration at R-50 Mann-Kendall Test						
M-K Test Value (S)	299	-112	478	174	382	-88
Critical Value (0.05)	1.645	-1.645	1.645	1.645	1.645	-1.645
Standard Deviation of S	67.46	52.92	70.38	55.77	73.33	70.19
Standardized Value of S	4.418	-2.097	6.778	3.102	5.196	-1.24
Approximate p-value	4.988E-6	0.018	6.094E-12	9.616E-4	1.018E-7	0.108
Concentration Trend	**Increasing**	**Decreasing**	**Increasing**	**Increasing**	**Increasing**	**None**
Sulfate Concentration at R-50 Mann-Kendall Test						
M-K Test Value (S)	212	-216	334	-100	353	52
Critical Value (0.05)	1.645	-1.645	1.645	-1.645	1.645	1.645
Standard Deviation of S	67.3	53.19	55.98	55.81	73.17	70.28
Standardized Value of S	3.135	-4.042	5.948	-1.774	4.81	0.726
Approximate p-value	8.58E-4	2.65E-5	1.355E-9	0.038	7.528E-7	0.234
Concentration Trend	**Increasing**	**Decreasing**	**Increasing**	**Decreasing**	**Increasing**	**None**

R-44 Mann-Kendall Test Results

Test	Pre-IM		Southern Area IM		Eastern Area IM	
	Screen 1	Screen 2	Screen 1	Screen 2	Screen 1	Screen 2
Chromium Concentration at R-44 Mann-Kendall Test						
M-K Test Value (S)	302	33	-319	-194	-468	245
Critical Value (0.05)	1.645	1.645	-1.645	-1.645	-1.645	1.645
Standard Deviation of S	61.63	70.42	53.28	53.31	73.29	70.38
Standardized Value of S	4.884	0.454	-5.968	-3.62	-6.372	3.467
Approximate p-value	5.205E-7	0.325	1.199E-9	1.47E-4	9.329E-11	2.634E-4
Concentration Trend	**Increasing**	**None**	**Decreasing**	**Decreasing**	**Decreasing**	**Increasing**
Chloride Concentration at R-44 Mann-Kendall Test						
M-K Test Value (S)	212	213	320	-168	349	390
Critical Value (0.05)	1.645	1.645	1.645	-1.645	1.645	1.645
Standard Deviation of S	50.55	58.76	53.27	53.17	73.32	70.38
Standardized Value of S	4.174	3.608	5.988	-3.141	4.746	5.527
Approximate p-value	1.496E-5	1.544E-4	1.062E-9	8.43E-4	1.035E-6	1.627E-8
Concentration Trend	**Increasing**	**Increasing**	**Increasing**	**Decreasing**	**Increasing**	**Increasing**
Sulfate Concentration at R-44 Mann-Kendall Test						
M-K Test Value (S)	152	-130	309	-244	329	344
Critical Value (0.05)	1.645	-1.645	1.645	-1.645	1.645	1.645
Standard Deviation of S	50.6	58.81	53.26	55.99	73.24	70.36
Standardized Value of S	2.984	-2.193	5.783	-4.34	4.479	4.875
Approximate p-value	0.00142	0.0141	3.678E-9	7.117E-6	3.757E-6	5.444E-7
Concentration Trend	**Increasing**	**Decreasing**	**Increasing**	**Decreasing**	**Increasing**	**Increasing**

R-11 Mann-Kendall Test Results

Test	Pre-IM		Southern Area IM		Eastern Area IM	
	Screen 1	Screen 2	Screen 1	Screen 2	Screen 1	Screen 2
Chromium Concentration at R-11 Mann-Kendall Test						
M-K Test Value (S)	200	n/a	-143	n/a	-31	n/a
Critical Value (0.05)	1.645	n/a	n/a	n/a	-1.645	n/a
Standard Deviation of S	70.41	n/a	35.46	n/a	98.79	n/a
Standardized Value of S	2.826	n/a	-4.004	n/a	-0.304	n/a
Approximate p-value	0.00235	n/a	3.113E-5	n/a	0.381	n/a
Concentration Trend	**Increasing**	n/a	**Decreasing**	n/a	None	n/a
Chloride Concentration at R-11 Mann-Kendall Test						
M-K Test Value (S)	200	n/a	-58	n/a	-137	n/a
Critical Value (0.05)	1.645	n/a	n/a	n/a	-1.645	n/a
Standard Deviation of S	67.43	n/a	35.42	n/a	98.79	n/a
Standardized Value of S	2.951	n/a	-1.609	n/a	-1.377	n/a
Approximate p-value	0.00158	n/a	0.0538	n/a	0.0843	n/a
Concentration Trend	**Increasing**	n/a	**None**	n/a	**None**	n/a
Sulfate Concentration at R-11 Mann-Kendall Test						
M-K Test Value (S)	215	n/a	-4	n/a	-73	n/a
Critical Value (0.05)	1.645	n/a	n/a	n/a	-1.645	n/a
Standard Deviation of S	67.43	n/a	35.16	n/a	98.81	n/a
Standardized Value of S	3.174	n/a	-0.0853	n/a	-0.729	n/a
Approximate p-value	7.522E-4	n/a	0.466	n/a	0.233	n/a
Concentration Trend	**Increasing**	n/a	**None**	n/a	**None**	n/a

CrEX-5 Mann-Kendall Test Results

Mann-Kendall Test	Chromium		Chloride		Sulfate	
	Pre-IM	Post-IM	Pre-IM	Post-IM	Pre-IM	Post-IM
M-K Test Value (S)	n/a	-352	n/a	-280	n/a	-324
Critical Value (0.05)	n/a	-1.645	n/a	-1.645	n/a	-1.645
Standard Deviation of S	n/a	50.62	n/a	47.86	n/a	47.94
Standardized Value of S	n/a	-6.935	n/a	-5.829	n/a	-6.738
Approximate p-value	n/a	2.038E-12	n/a	2.872E-9	n/a	8.032E-12
Concentration Trend	n/a	**Decreasing**	n/a	**Decreasing**	n/a	**Decreasing**

R-45 Mann-Kendall Test Results

Test	Pre-IM		Southern Area IM		Eastern Area IM	
	Screen 1	Screen 2	Screen 1	Screen 2	Screen 1	Screen 2
Chromium Concentration at R-45 Mann-Kendall Test						
M-K Test Value (S)	418	347	-237	228	-639	531
Critical Value (0.05)	1.645	1.645	-1.645	1.645	-1.645	1.645
Standard Deviation of S	58.79	56.05	53.28	58.81	82.61	76.44
Standardized Value of S	7.093	6.173	-4.429	3.86	-7.723	6.934
Approximate p-value	6.58E-13	3.35E-10	4.73E-6	5.67E-06	5.69E-15	2.05E-12
Concentration Trend	**Increasing**	**Increasing**	**Decreasing**	**Increasing**	**Decreasing**	**Increasing**

R-45 Mann-Kendall Test Results (continued)

Chloride Concentration at R-45 Mann-Kendall Test						
M-K Test Value (S)	320	262	-242	232	572	581
Critical Value (0.05)	1.645	1.645	-1.645	1.645	1.645	1.645
Standard Deviation of S	47.96	47.94	53.31	56.04	82.59	76.45
Standardized Value of S	6.652	5.445	-4.521	4.122	6.914	7.586
Approximate p-value	1.45E-11	2.60E-8	3.08E-6	1.88E-05	2.36E-12	1.64E-14
Concentration Trend	**Increasing**	**Increasing**	**Decreasing**	**Increasing**	**Increasing**	**Increasing**
Sulfate Concentration at R-45 Mann-Kendall Test						
M-K Test Value (S)	321	-80	-271	214	496	518
Critical Value (0.05)	1.645	-1.645	-1.645	1.645	1.645	1.645
Standard Deviation of S	47.95	47.96	53.28	56.04	82.56	76.45
Standardized Value of S	6.674	-1.647	-5.067	3.801	5.995	6.763
Approximate p-value	1.25E-11	0.05	2.02E-7	7.21E-05	1.01E-9	6.76E-12
Concentration Trend	**Increasing**	**Decreasing**	**Decreasing**	**Increasing**	**Increasing**	**Increasing**

R-70 Mann-Kendall Test Results

	Chromium		Chloride		Sulfate	
Mann-Kendall Test	**Post-IM**		**Post-IM**		**Post-IM**	
	Screen 1	**Screen 2**	**Screen 1**	**Screen 2**	**Screen 1**	**Screen 2**
M-K Test Value (S)	-180	-339	-246	-356	-324	-354
Critical Value (0.05)	-1.645	-1.645	-1.645	-1.645	-1.645	-1.645
Standard Deviation of S	61.65	56.05	61.67	56.02	61.65	56.04
Standardized Value of S	-2.904	-6.03	-3.973	-6.337	-5.239	-6.299
Approximate p-value	0.00185	8.184E-10	3.548E-5	1.175E-10	8.059E-8	1.499E-10
Concentration Trend	**Decreasing**	**Decreasing**	**Decreasing**	**Decreasing**	**Decreasing**	**Decreasing**

CrEX-3 Mann-Kendall Test Results

Mann-Kendall Test	Chromium		Chloride		Sulfate	
	Pre-IM	Post-IM	Pre-IM	Post-IM	Pre-IM	Post-IM
M-K Test Value (S)	n/a	-173	n/a	-236	n/a	-209
Critical Value (0.05)	n/a	-1.645	n/a	-1.645	n/a	-1.645
Standard Deviation of S	n/a	76.43	n/a	82.6	n/a	82.62
Standardized Value of S	n/a	-2.251	n/a	-2.845	n/a	-2.518
Approximate p-value	n/a	0.0122	n/a	0.002	n/a	0.00591
Concentration Trend	n/a	**Decreasing**	n/a	**Decreasing**	n/a	**Decreasing**

CrEX-4 Mann-Kendall Test Results

Mann-Kendall Test	Chromium		Chloride		Sulfate	
	Pre-IM	Post-IM	Pre-IM	Post-IM	Pre-IM	Post-IM
M-K Test Value (S)	n/a	-201	n/a	-131	n/a	-168
Critical Value (0.05)	n/a	-1.645	n/a	-1.645	n/a	-1.645
Standard Deviation of S	n/a	37.86	n/a	37.78	n/a	37.85
Standardized Value of S	n/a	-5.282	n/a	-3.441	n/a	-4.412
Approximate p-value	n/a	6.386E-8	n/a	2.894E-4	n/a	5.119E-6
Concentration Trend	n/a	**Decreasing**	n/a	**Decreasing**	n/a	**Decreasing**

[a] IM = Interim measures.
[b] n/a = Not applicable.

Appendix B

Chromium Regional Calibrated Model

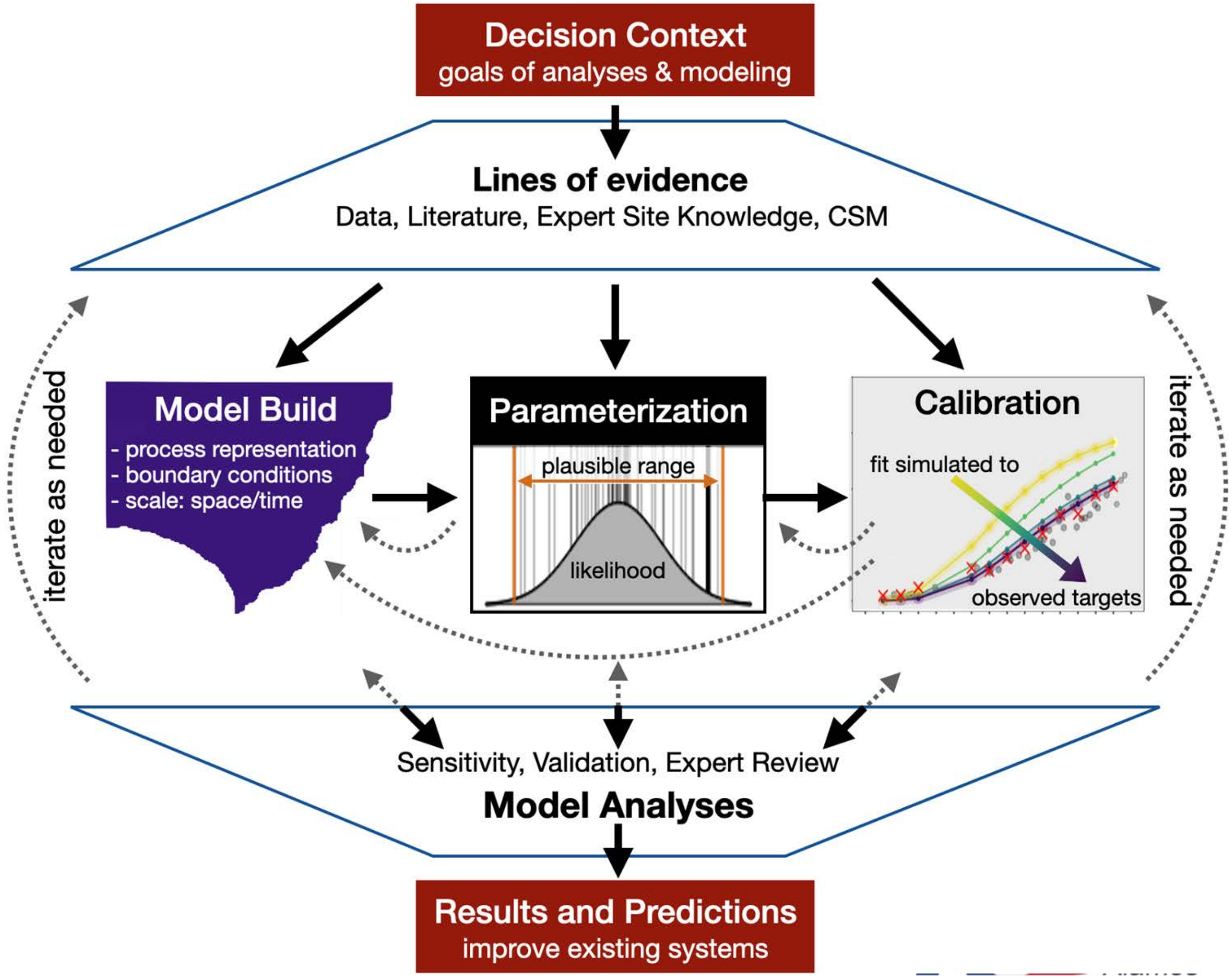
Chromium Regional Calibrated Model

Forthcoming report (Spring 2023) will provide full details

Outline of modeling framework

“Mathematical modeling may be used to organize vast amounts of disparate data into a sensible framework”

– EPA on evaluating pump and treat systems

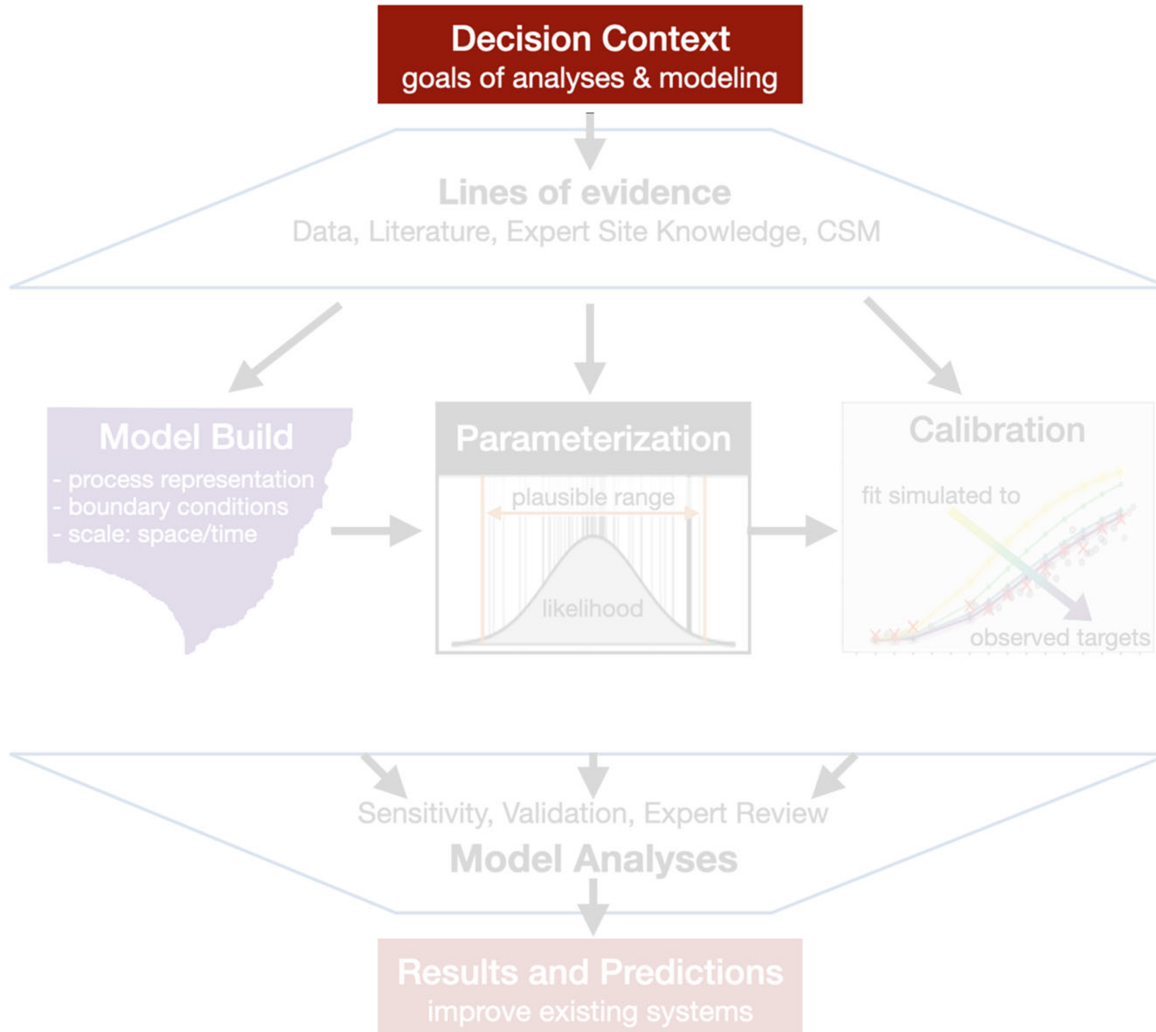


THE WHY MATTERS "all models are wrong and some are useful"

The decision context is critical for any model.

Context for the CRM "Chromium Regional Model" at present – why is it useful?

- Evaluate the efficacy of the IM network in meeting its goals (capture zone analysis)
- Identify modifications to IM operations and network
- Estimate plume extent, support data gap analysis (identify regions of high uncertainty), and improve plume understanding with physical constraints
- Future analyses and new decision contexts: re-evaluate appropriateness of model for new decision contexts



Models are not separate from data, they INTEGRATE data

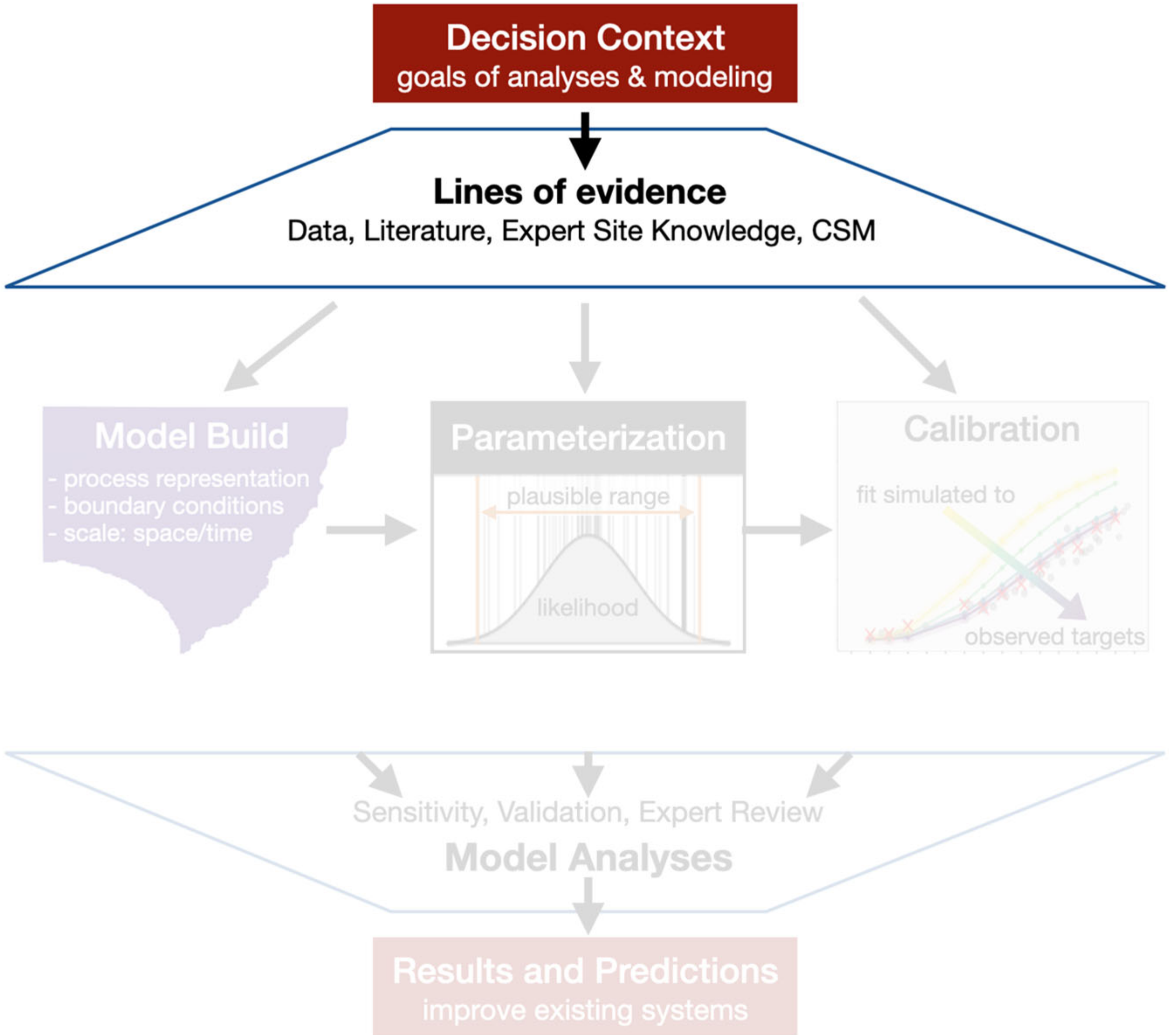
Lines of evidence inform every aspect of the modeling:

1. Site-specific data

2. Literature and generic data (where site-specific unavailable)

3. Expert knowledge

4. Conceptual Site Model



We will discuss all of these items in detail today

Model Build

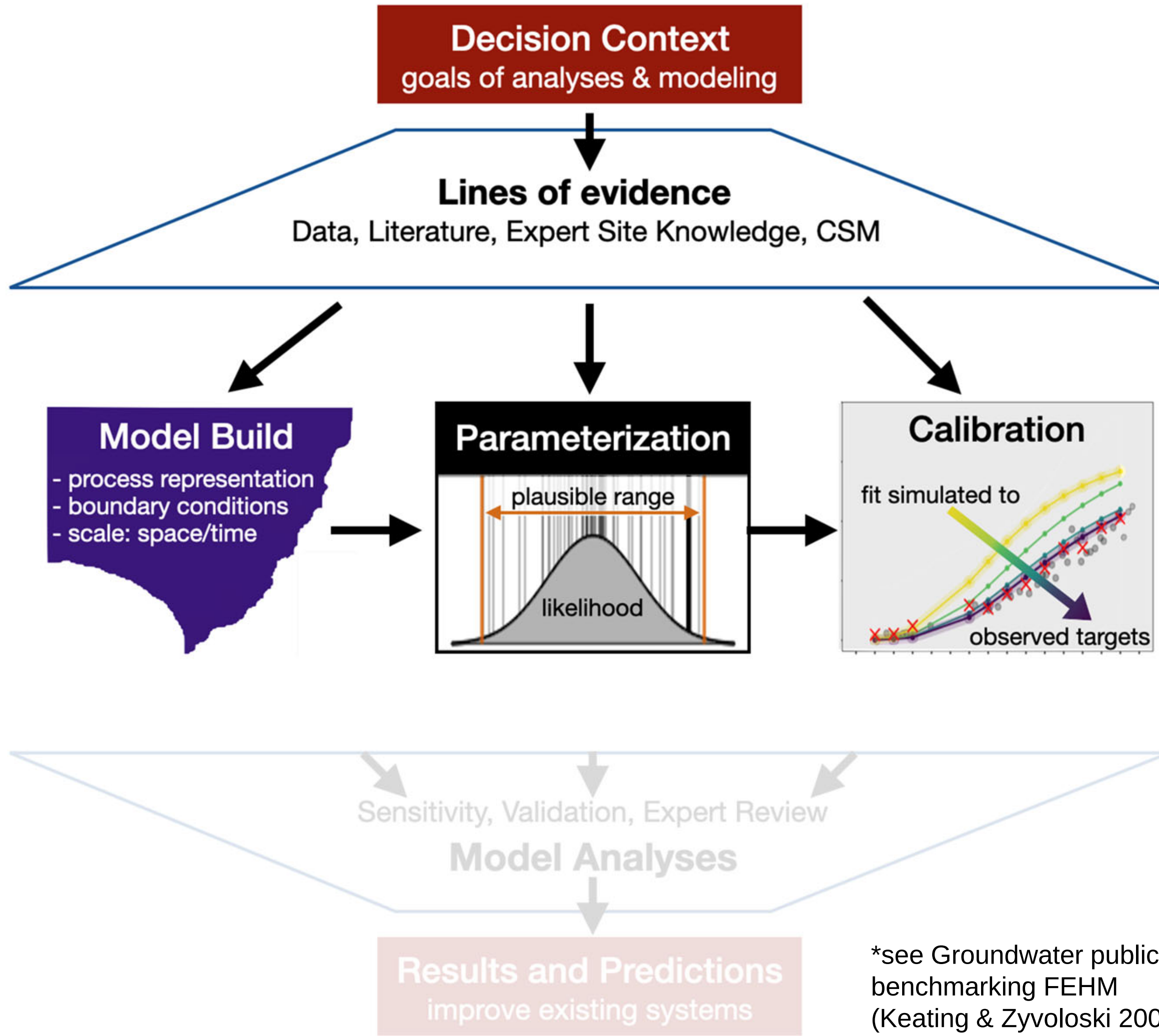
- Boundary/initial conditions
- Scale in space and time
- Code – FEHM (flow and transport, vetted in literature, benchmarked with other codes)*
- Assumptions

Parameterization

- All inputs should be physically reasonable based on available information
- Distribution development

Calibration

- Sweeps of parameter space
- Close investigation by hydrologists/experts for reasonableness
- Computational tools to improve fit

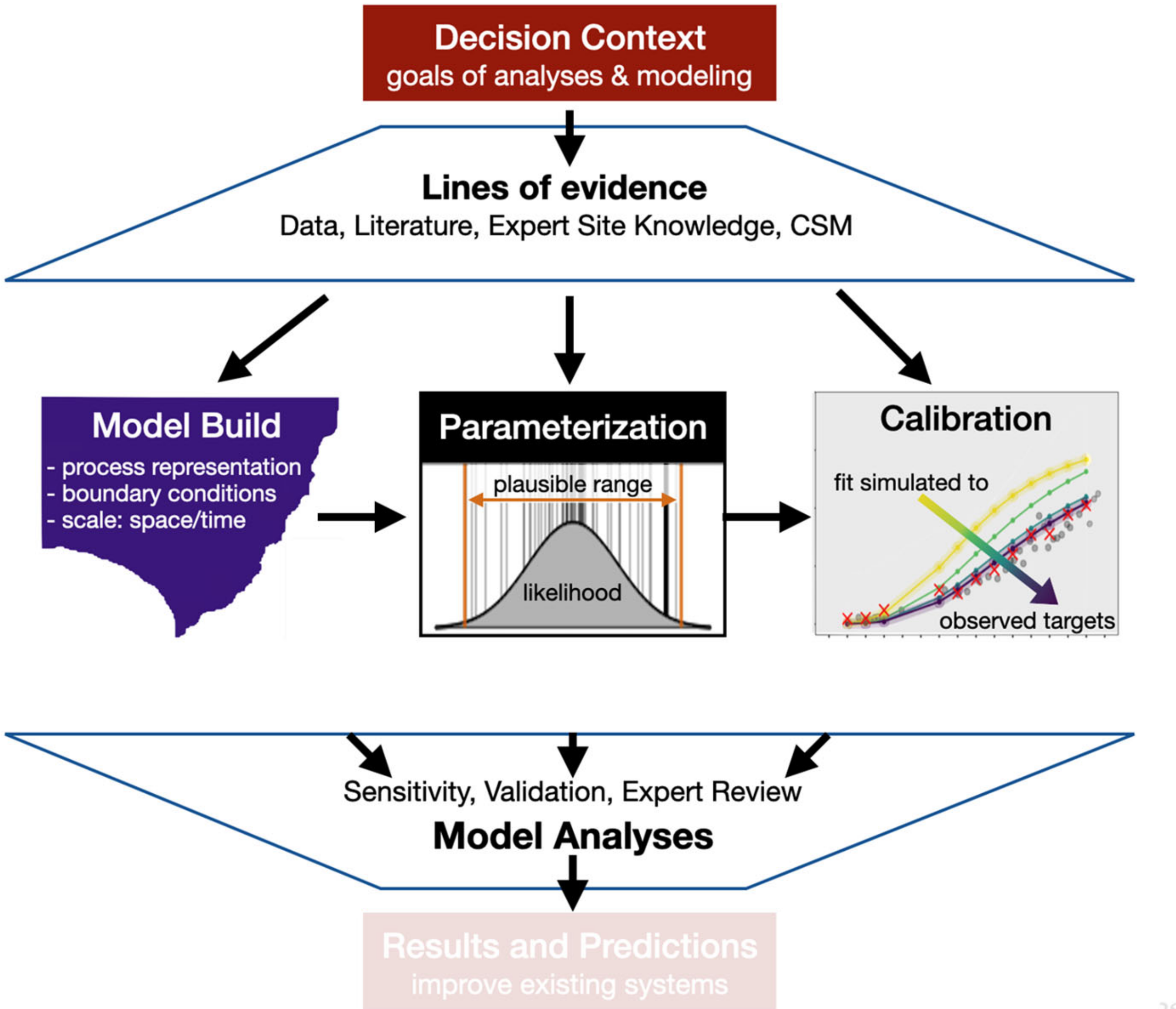


*see Groundwater publication benchmarking FEHM (Keating & Zyvoloski 2009)

Model results are analyzed, validated, and scrutinized closely

Model analyses include:

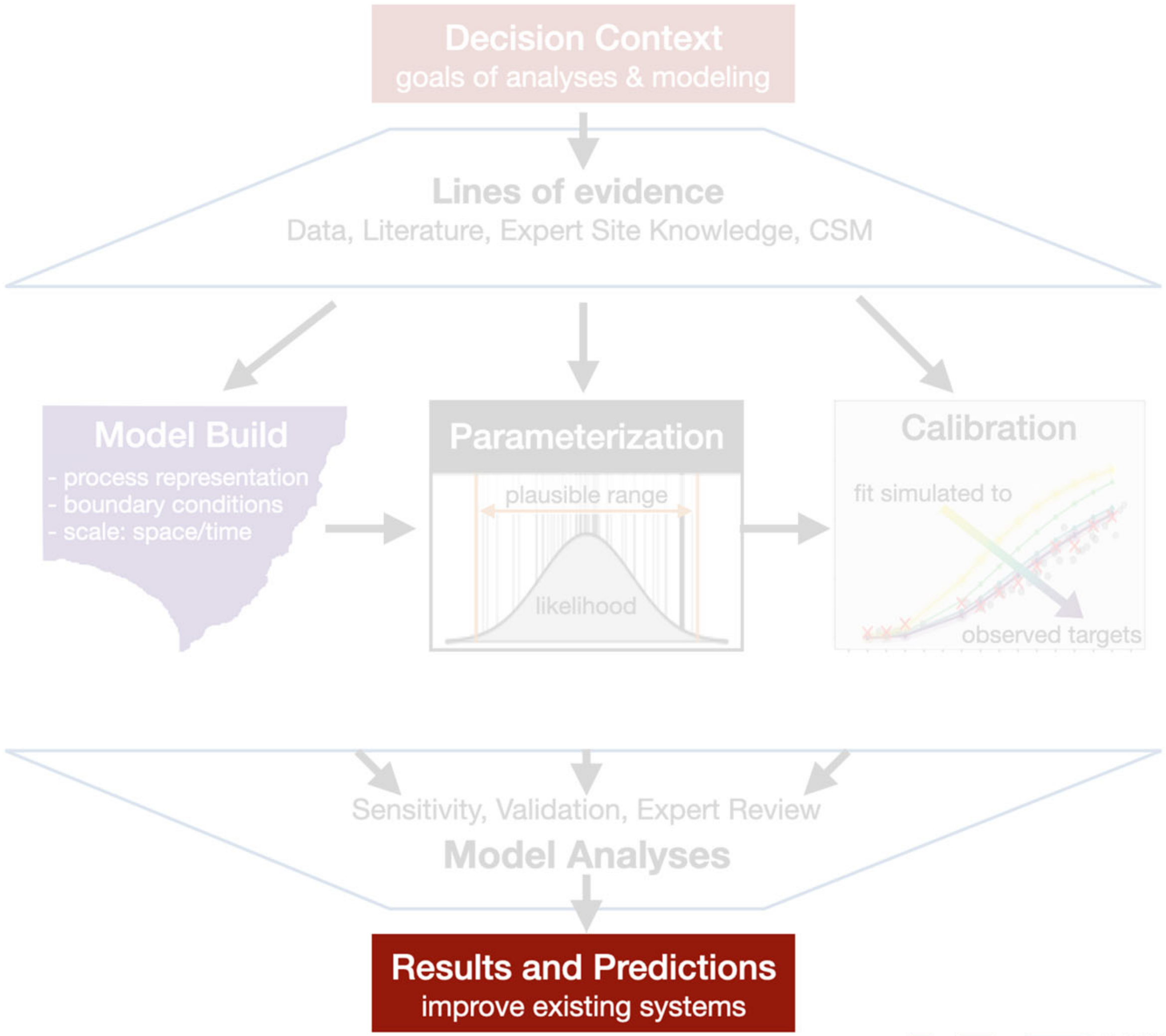
- Statistical analyses
- Hydrogeological analyses
- Discussion with experts outside the modeling workflow to verify conceptual information
- Sensitivity analyses (both by hand and larger, robust sweeps)
- Uncertainty analysis



Ultimately, the CRM informs decision makers and data collection

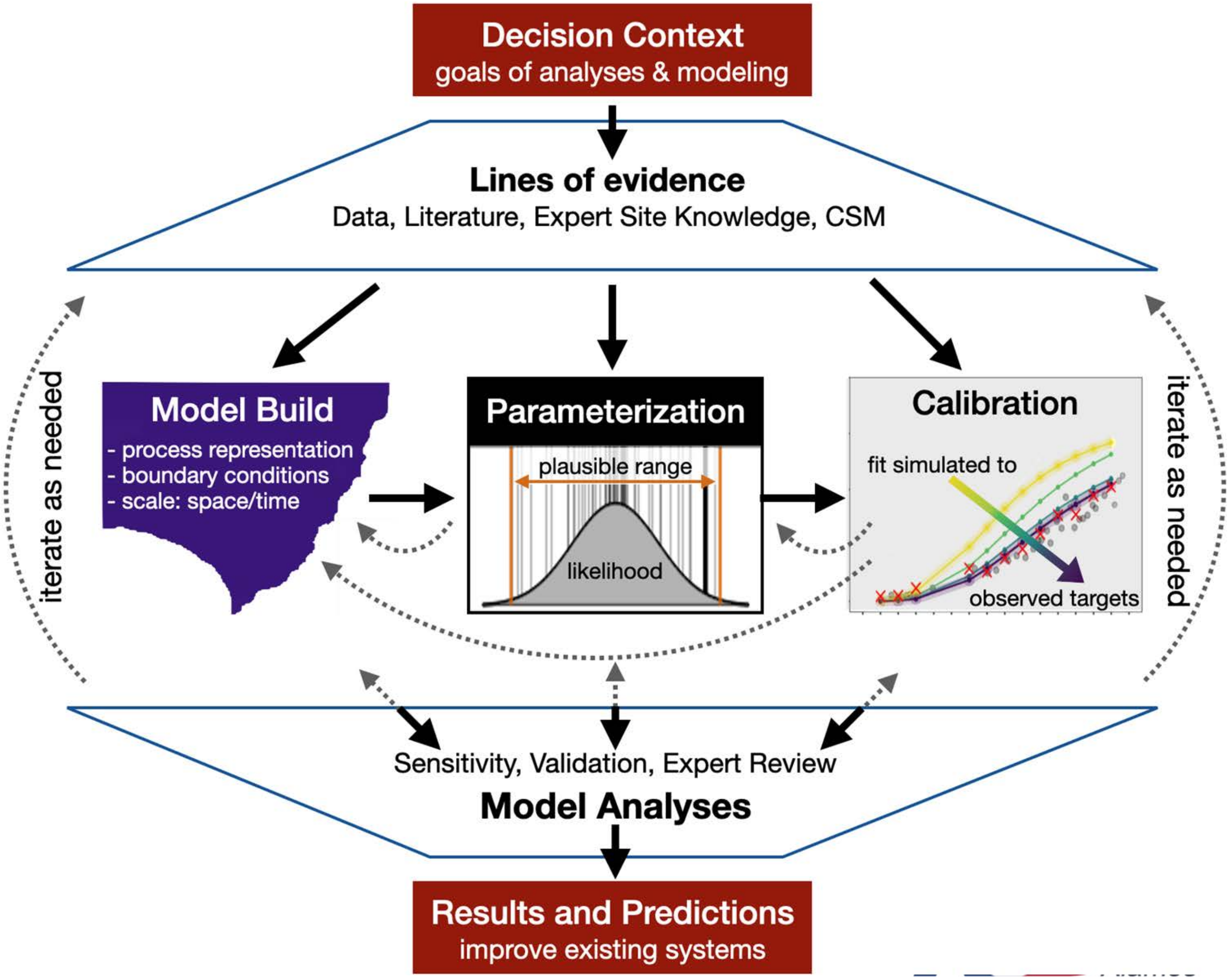
A model should be used as a tool to:

- Better understand groundwater flow and chromium transport
- Integrate available lines of evidence, and further constrain predictions with physics
- Identify data gaps and regions of high uncertainty
- Decision-making



Modeling is iterative – information in the workflow can update previous steps

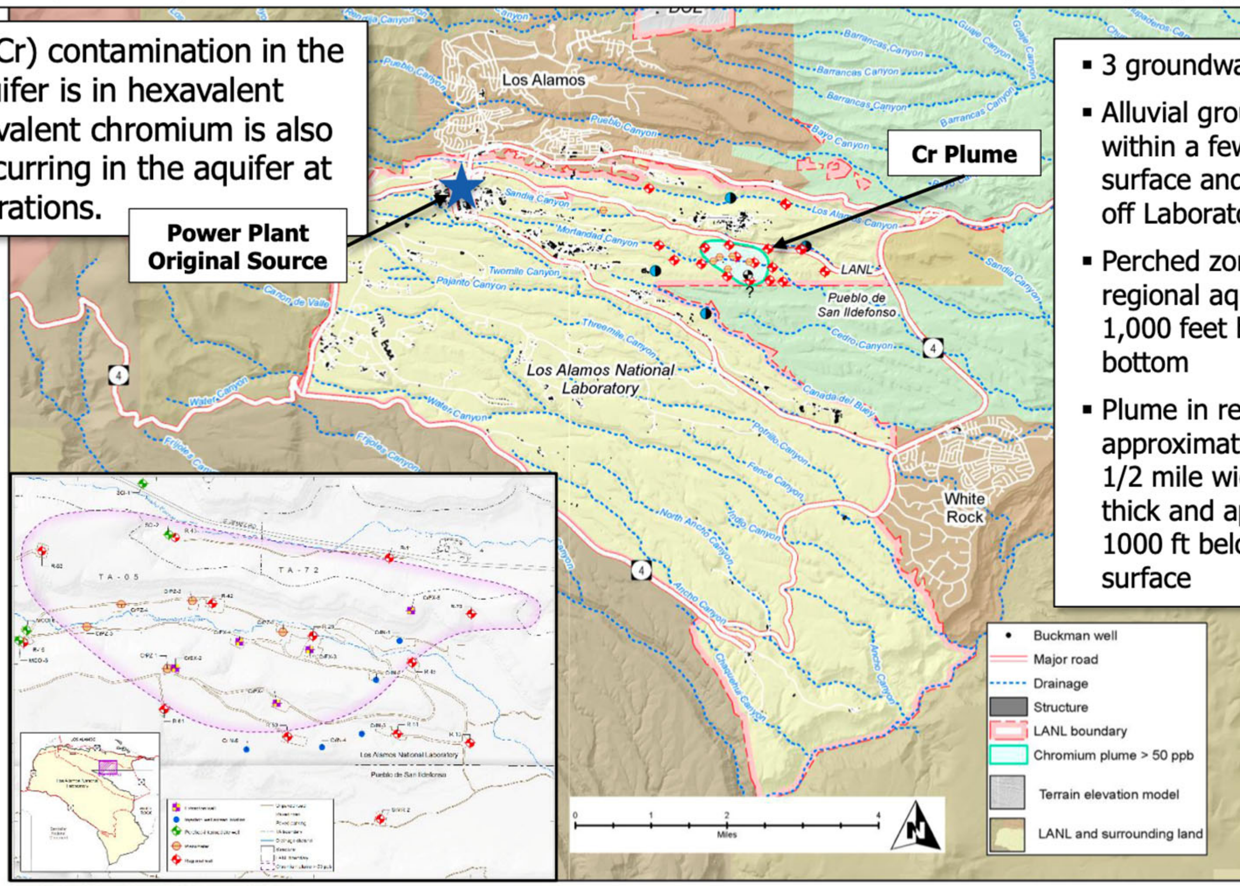
- Adaptive management – improve model and improve understanding as new information becomes available
- "New information" includes things learned within the modeling process, which can improve/inform previous steps
- *"The approach presented here should be considered iterative since few sites, if any, begin the process with sufficient field data to evaluate and confirm hydraulic containment"* - EPA



Background and Conceptual Site Model (CSM)

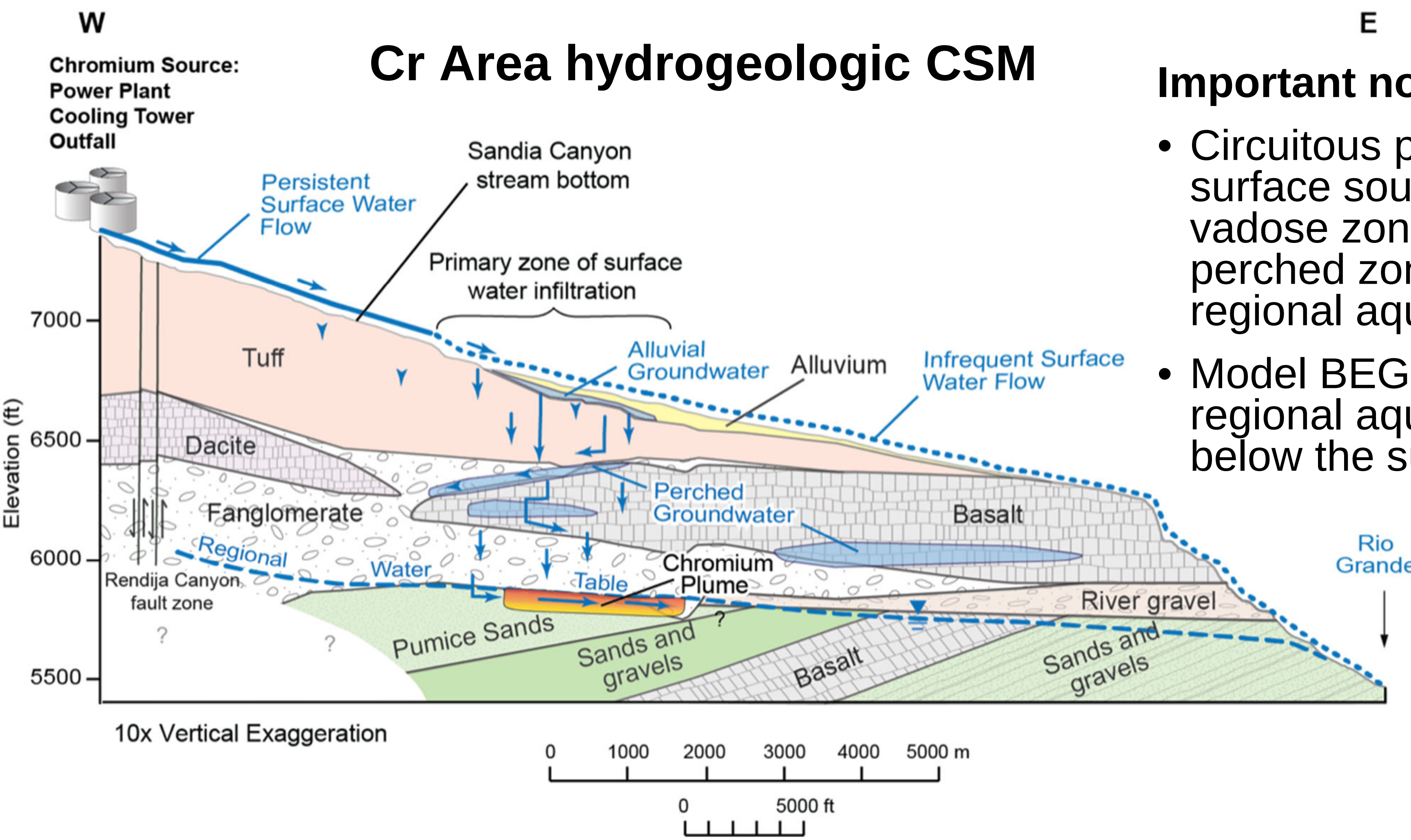
- Potassium dichromate used in cooling towers at a Laboratory power plant
- Up to 160,000 lb released from 1956-72 in hexavalent chromium form [Cr(VI)]

Chromium (Cr) contamination in the regional aquifer is in hexavalent form. Hexavalent chromium is also naturally occurring in the aquifer at low concentrations.



- 3 groundwater zones
- Alluvial groundwater is within a few feet of ground surface and does not extend off Laboratory property
- Perched zone is ~550 ft, regional aquifer is 900–1,000 feet below canyon bottom
- Plume in regional aquifer is approximately 1 mile long x 1/2 mile wide x ~100 ft thick and approximately 1000 ft below ground surface

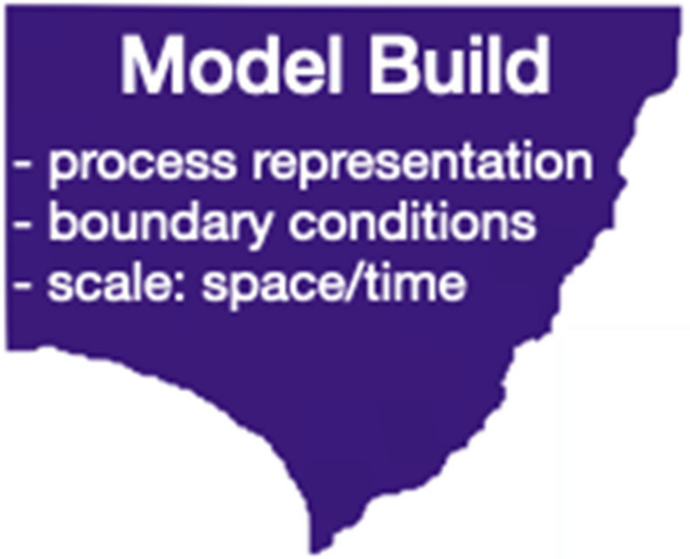
Background and Conceptual Site Model (CSM)

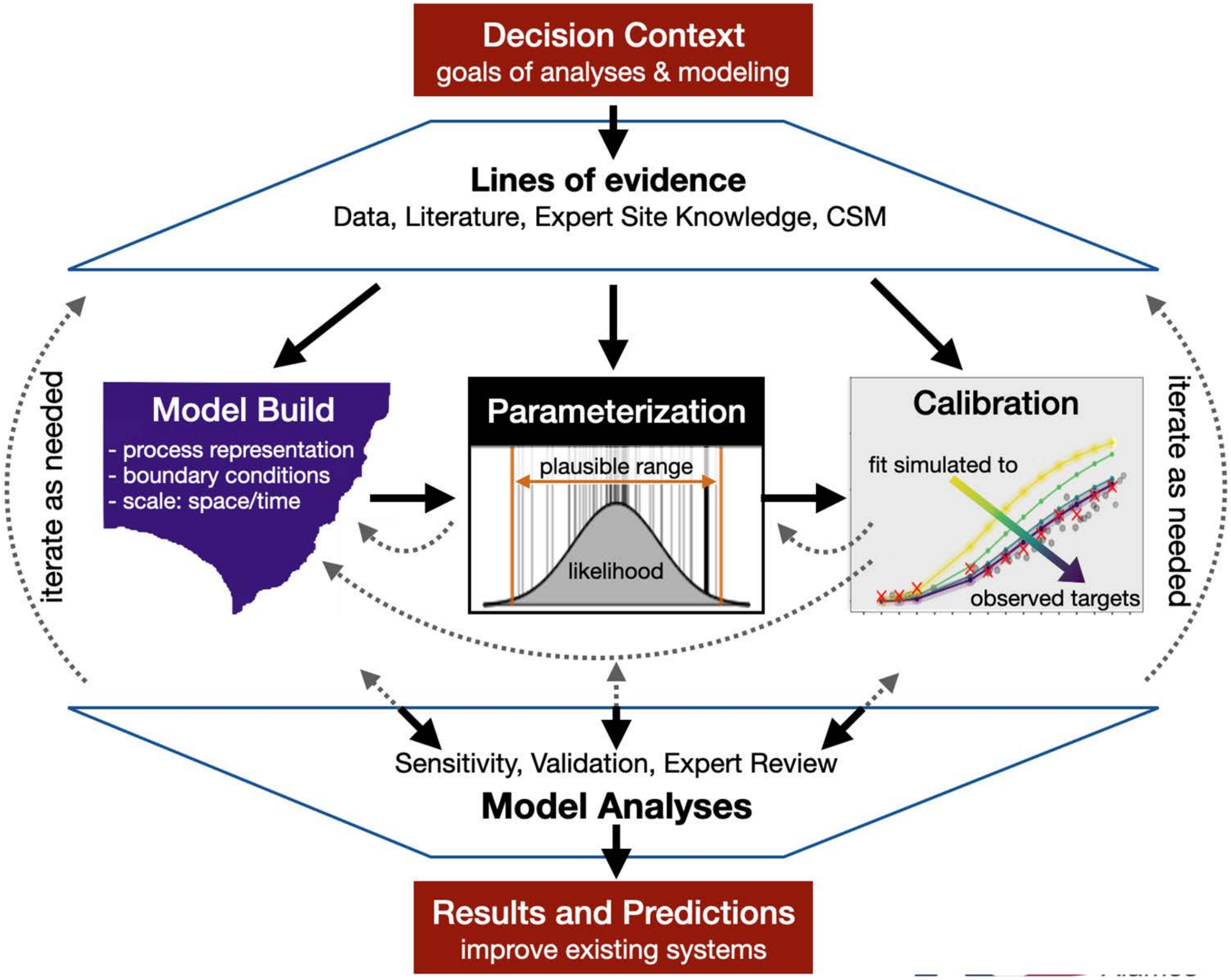


Important notes:

- Circuitous pathway from surface source through vadose zone (and perched zones) to the regional aquifer
- Model BEGINS at regional aquifer, ~1000 ft. below the surface

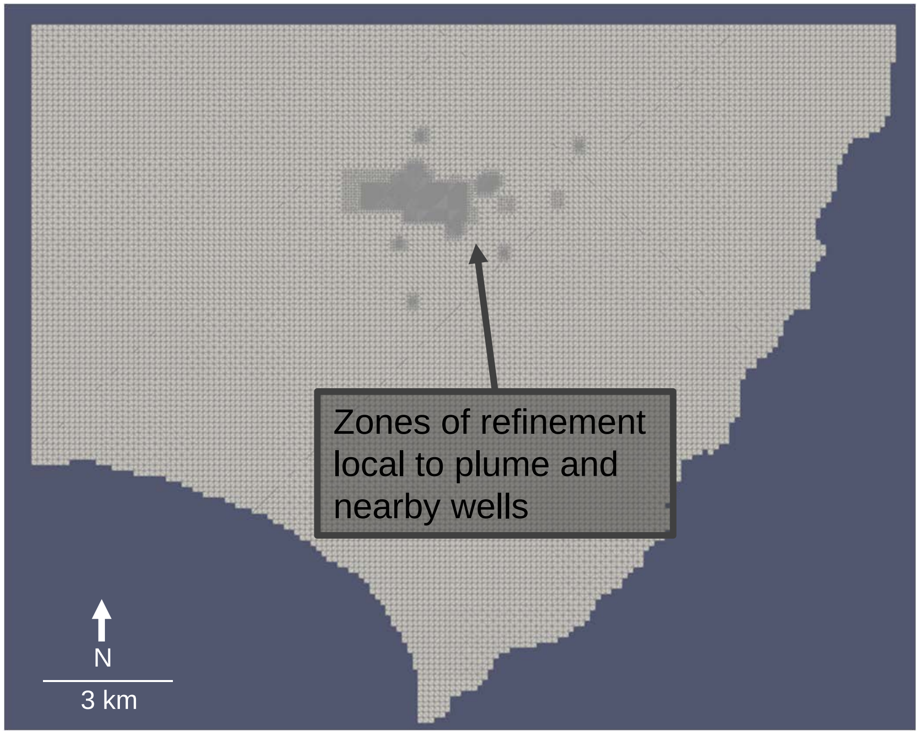
MODEL BUILD STEP





Scale and Initial Condition

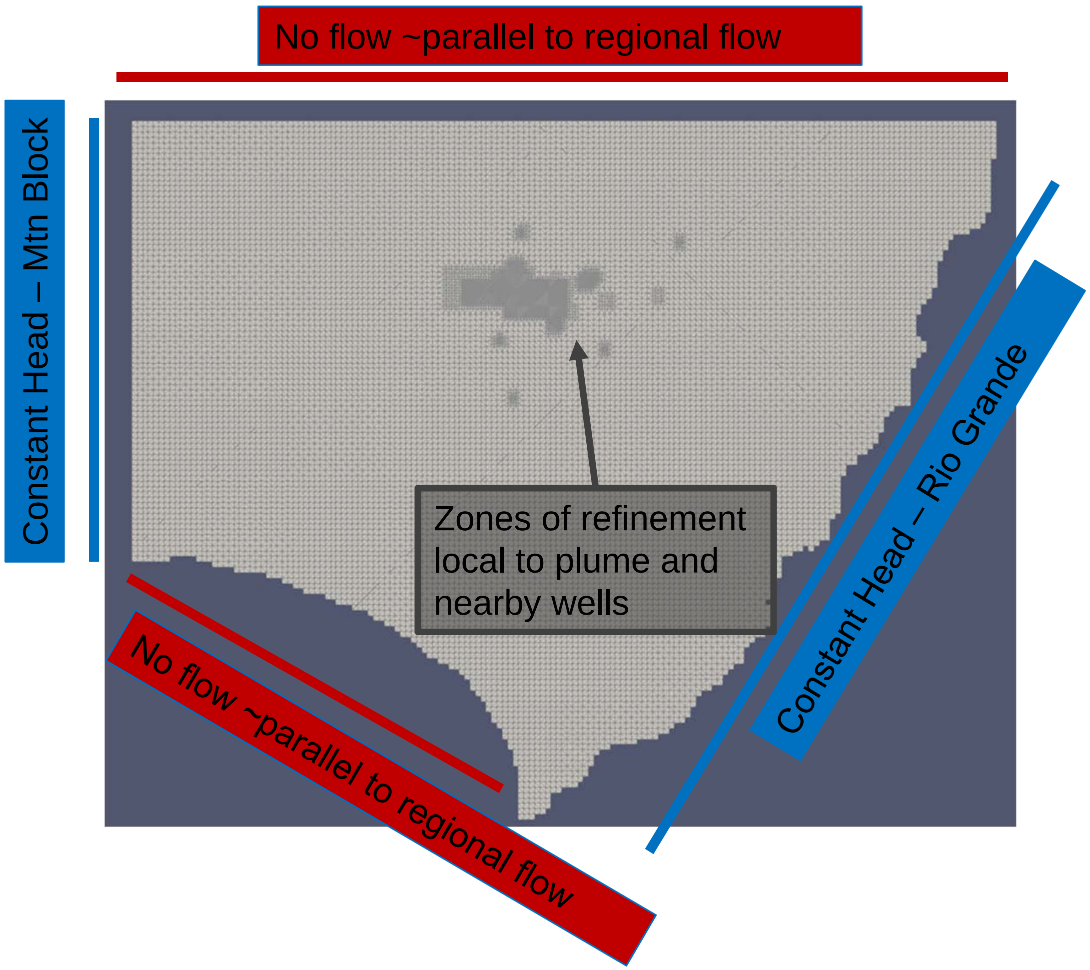
Model Build
- process representation
- boundary conditions
- scale: space/time

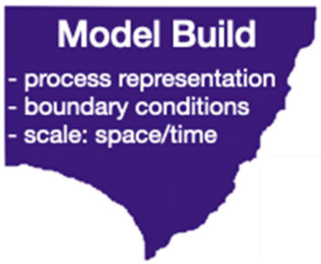


- **Grid:**
  - 31.25 m in x-y at highest resolution, decreasing to 125 m regionally
  - 6-m at WT decreasing to 24 m
  - Water Table (1616 m amsl to 1920 m) down to 1000 m amsl: up to 920 m thick

- **Initial Condition**
  - Flow field is first initialized to steady-state, matching overall head conditions
  - Once the steady-state flow field converges, the transient simulations with pumping, sources of Chromium, etc. begin in 1964

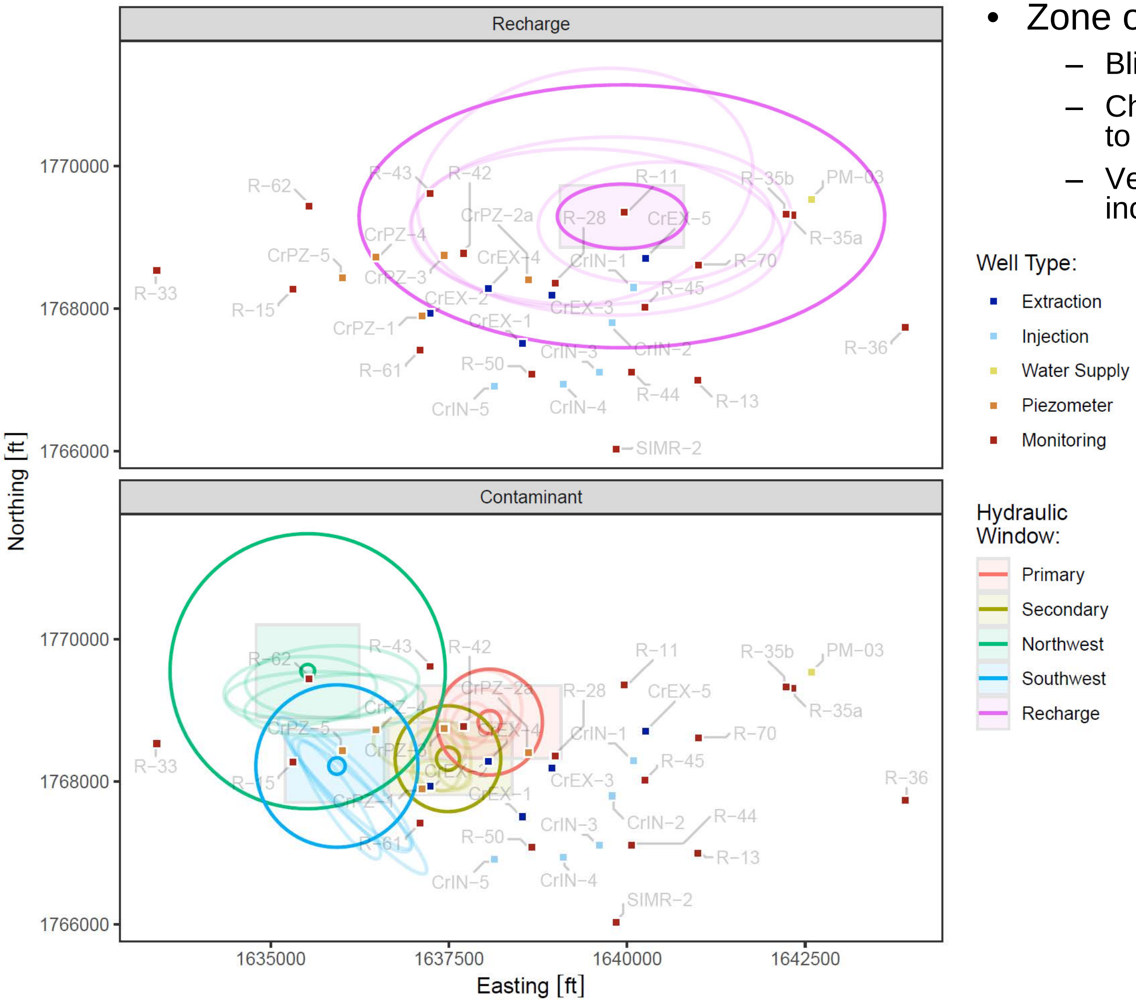
Boundary Conditions





- **Calibrated western (mtn block) and eastern (Rio Grande) constant heads**
- **Bottom of the model/N/S – no flow**
- **Top of the model – hydraulic windows from the Vadose Zone (VZ)** (next slides)
- **IM pumping boundary conditions** (next slides)
- All boundary condition parameters receive distribution development to define the range and likelihood of plausible values given existing site data

Boundary Conditions – Hydraulic Windows (clean and Cr sources)



Model Build
- process representation
- boundary conditions
- scale: space/time

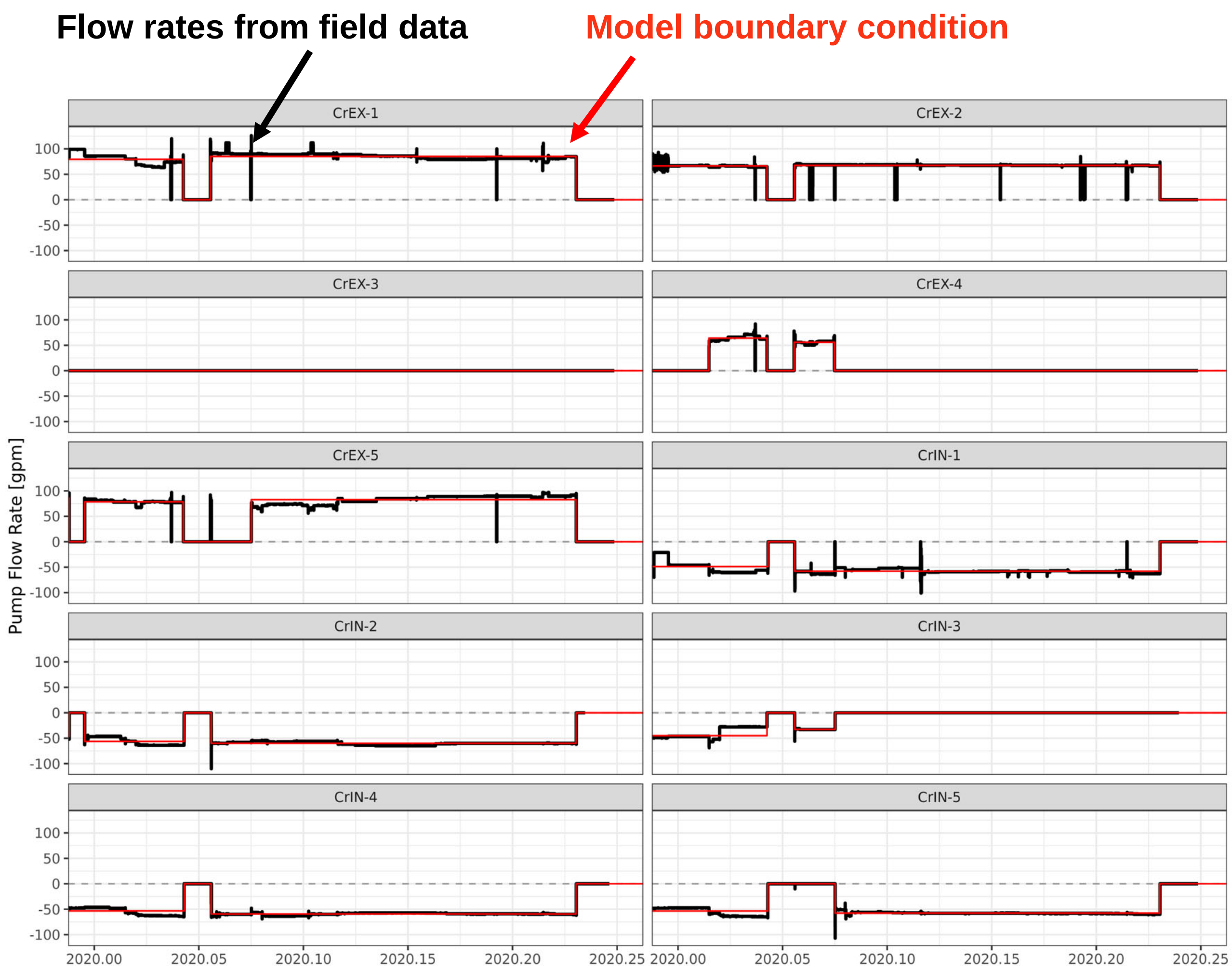
- Zone of **preferential clean recharge**
  - Blind source separation study
  - Chemical makeup of wells from R-43 to R-35 to R-45
  - Vertical differences in Cr concentrations, including inverted gradient

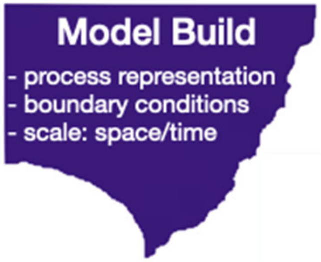
- **Primary** and **secondary** windows comprise main flux of Cr
  - Somewhat near R-42 (highest observed Cr)
  - Large differences in concentrations in north/south portions of plume necessitate two sources (no geochemical distinction)

- **Northwestern** source
  - Increasing trends at R-62/R-43

- **Southwestern** source
  - Unique geochemical signature and GW flow direction

Boundary Conditions – Pumping at extraction and injection wells

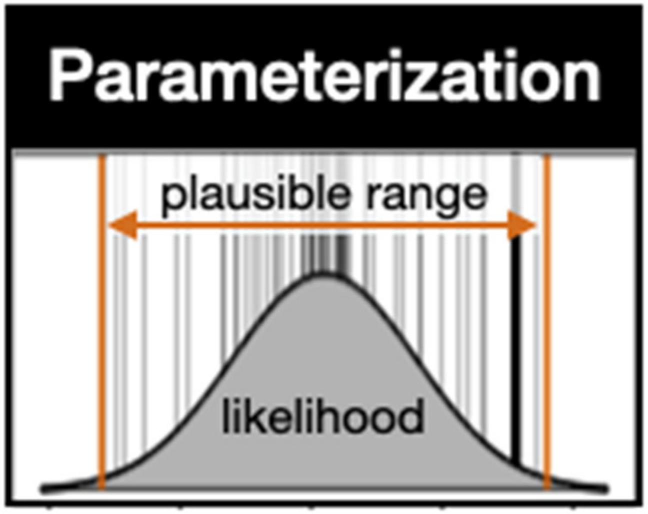


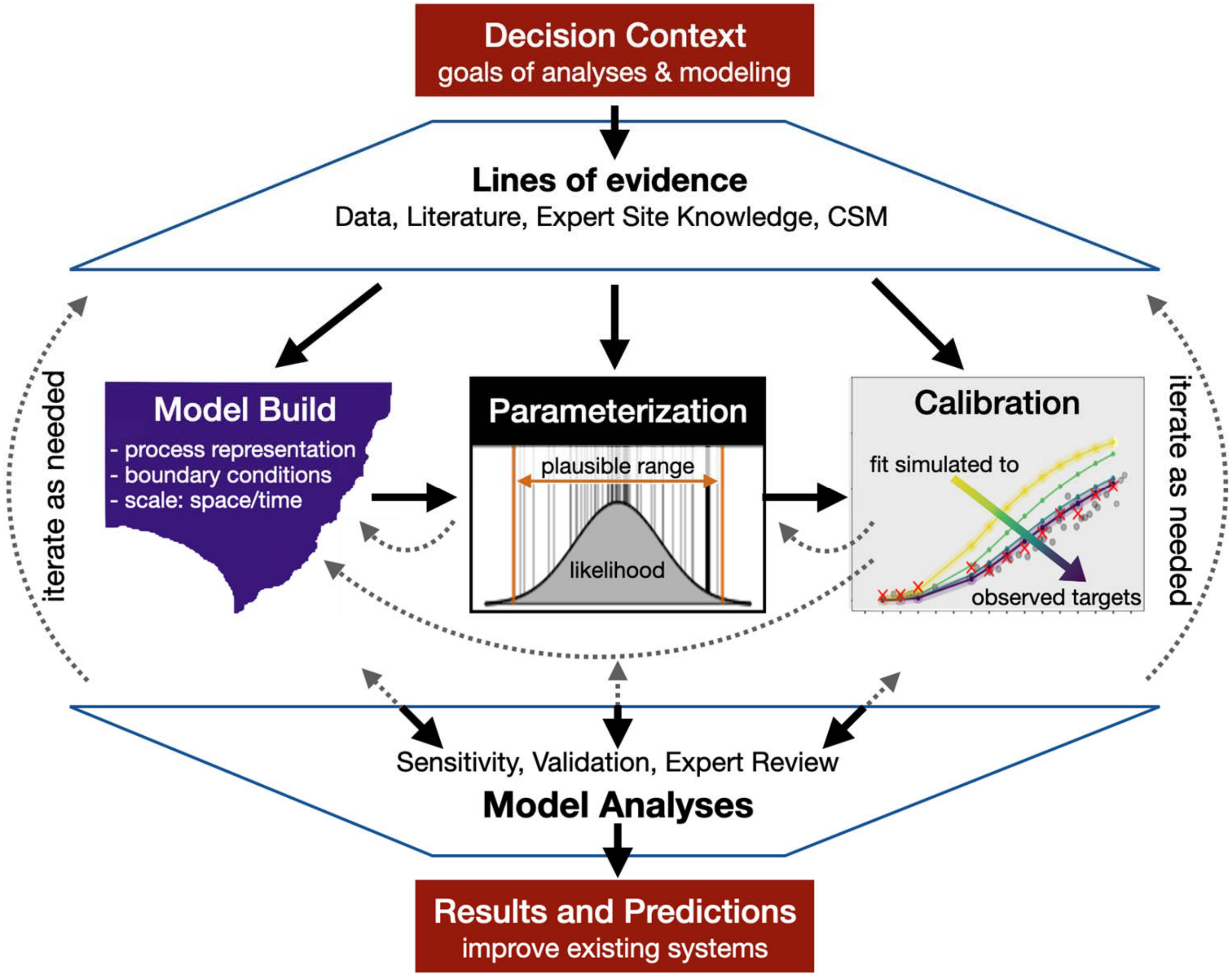


- Smoothing of the **boundary conditions** is required to limit the number of time steps and prevent numerical instability

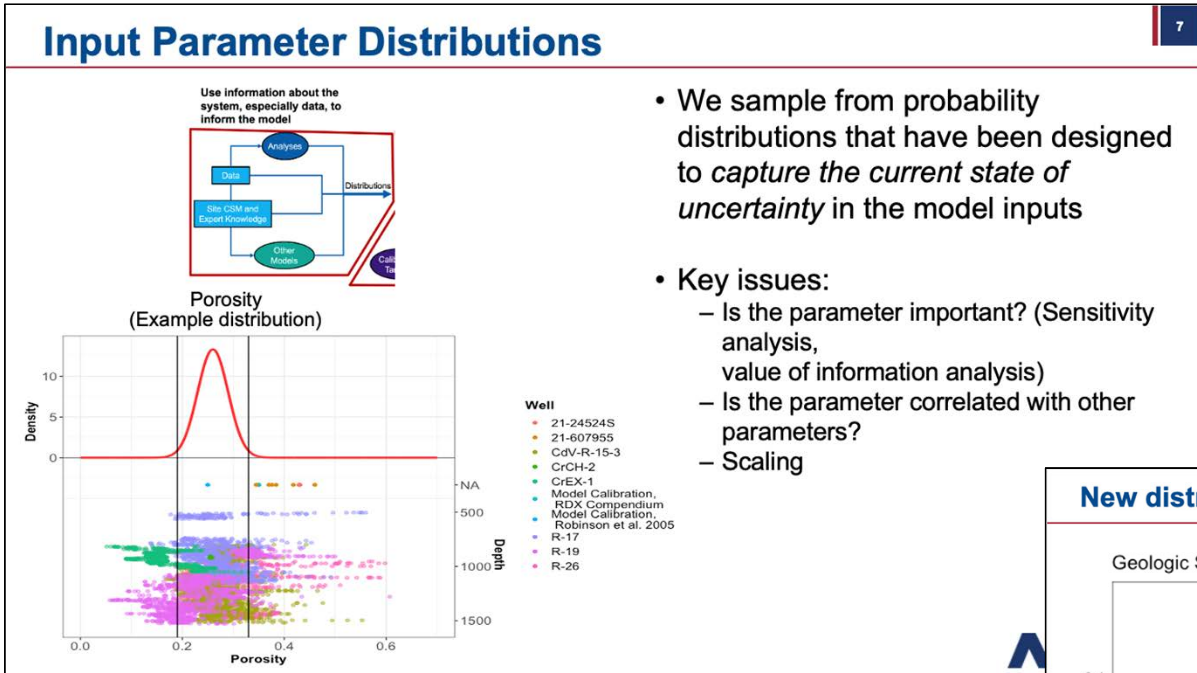
- Smoothed CrEX and CrIN flow rate **boundary condition** closely follows **field data**

INPUT PARAMETERIZATION STEP





Distribution Development – plausible range and likelihood for inputs

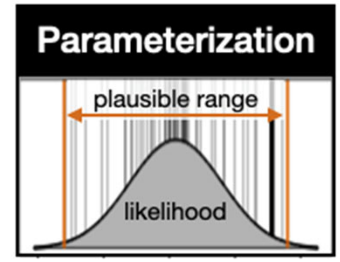


> Rigorous process to gather all available sources of information

> Scale (model vs. data)

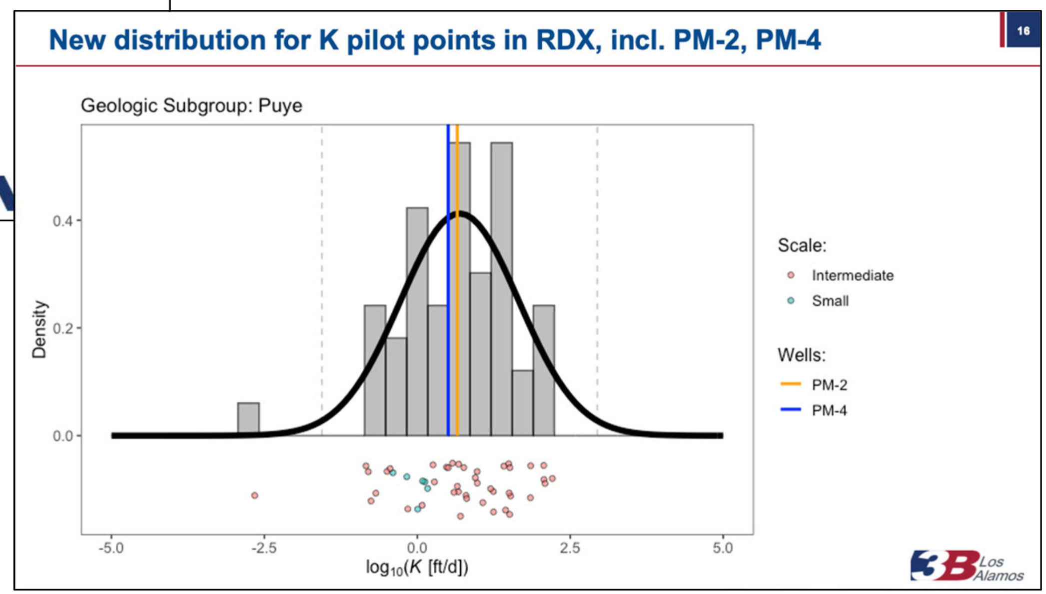
> Weighting (reliability of data)

> All of the above in the site-specific context of the CSM

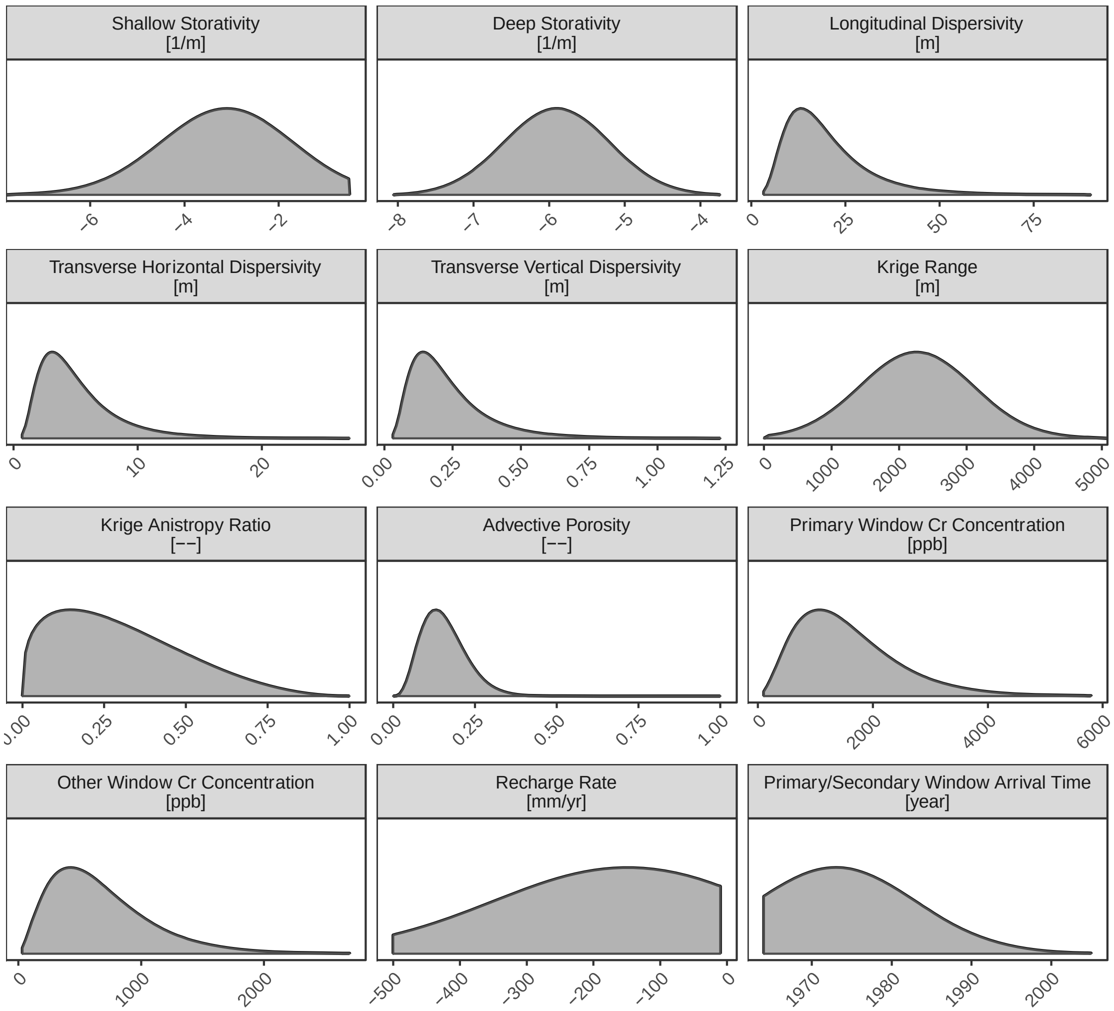


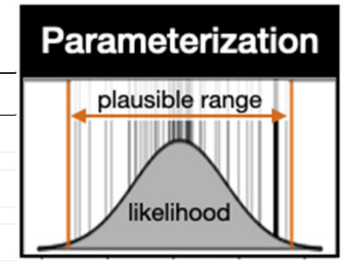
ABOVE: nuances of distribution development have been discussed previously with NMED

RIGHT: example of K distribution addressing NMED concern as to PM-2/PM-4 test data (NOTE: all NMED recommendations on K distributions have been included)



418 unique parameters constrained by 74 unique distributions





Material Properties Parameters

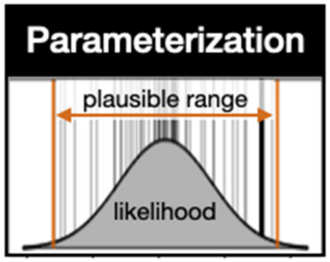
Parameter	Model Notation	Median	1st, 99th %		
Hydraulic Conductivity[1]	-	-	-		
Puye Formation (pilot points)	(kx, ky)(pp#)	12	0.2, 685		
Anchor points	(kx, ky)(ap#)	2.51E-04 - 7.76E-09			
Specific Storage	-	-	-		
Shallow (unconfined to semi-confined)[3]	s(pp#)	-3.7	-7.5, -0.7		
Deep (confined to semi-confined)	s(pp#)	-5.9	-4.2, -7.6		
Dispersivity[1]	-	-	-		
Longitudinal	disp_long	17.5	5.1, 60.1		
Transverse Horizontal	disp_trans_hor	4.4	1.1, 17.3	m	Literature
Transverse Vertical	disp_trans_vert	0.2	0.1, 0.8	m	Literature
Other	-	-	-	-	-
Krige Scale[3]	krige_range(K,S)	2264	410, 4204	m	Literature, Modeling
Krige Anisotrophy Ratio[5]	krige_v(K,S)_semiaxis	0.27	0.01, 0.8	m/s	Literature, Modeling
Advective porosity[5]	adv_por	0.15	0.04, 0.35	-	Well Data, Literature

Boundary Condition Parameters

Long name	Parameter name	Median	1st, 99th %	Unit	Sources of Information
Primary window centroid coordinates[3]	s2(x,y)0	(499284, 539141)	x(498979,499589) y(538986,539295)	State Plane NAD83	CSM, Modeling, Geochemistry
Secondary window centroid coordinates[3]	s1(x,y)0	(499106, 538984)	x(498832,499380) y(538830,539139)	State Plane NAD83	CSM, Modeling, Geochemistry
Northwest window centroid coordinates[3]	s3(x,y)0	(498506, 539359)	x(498285,498727) y(539160,539558)	State Plane NAD83	CSM, Modeling, Geochemistry
Southwest window centroid coordinates[3]	s4(x,y)0	(498631, 538953)	x(498410,498852) y(538798,539108)	State Plane NAD83	CSM, Modeling, Geochemistry
Primary/secondary window elipse radii[3]	s(1-2)r(x,y)	138	49, 226	m	CSM, Modeling, Geochemistry
Northwest window elipse radii[3]	s3r(x,y)	288	29, 589	m	CSM, Modeling, Geochemistry
Southwest window elipse radii[3]	s4r(x,y)	188	35, 347	m	CSM, Modeling, Geochemistry
Primary window Cr concentration[4]	s2c	1408	239, 4353	ppb	CSM, Modeling
Other window Cr concentration[4]	s(1,3,4)c	597	83, 1995	ppb	CSM, Modeling
Hydraulic window recharge rate[3]	infils(1-5)	201	10, 500	mm/yr	CSM, Modeling
Preferential recharge centroid coordinates[3]	s5(x,y)0	(499850, 539281)	x(499585,500115) y(539149,539414)	State Plane NAD83	CSM, Modeling, Geochemistry
Preferential recharge window x radius[3]	s5rx	700	276, 1124	m	CSM, Modeling, Geochemistry, Data
Preferential recharge window y radius[3]	s5ry	350	138, 562	m	CSM, Modeling, Geochemistry, Data
Primary/secondary window arrival time	t0s(1-2)	1975	1964, 2005	year	CSM, Modeling
Northwest/sourthwest window arrival time	t0s(3-4)	2000	1990, 2009	year	CSM, Modeling
Window eccentricity (tilt)[3]	s(1-5)corr	0	-1, 1	-	CSM, Modeling
Eastern constant head[2]	easthead	1745	1715, 1775	m	Data, Literature, Modeling
Western constant head[2]	westhead	1830	1800, 1860	m	Data, Literature, Modeling

NOTE: Parameter distributions are normal unless marked superscripts: (1) lognormal, (2) uniform, (3) truncnormal, (4) gamma, (5) beta

Key aspect of CSM that informs model assumptions

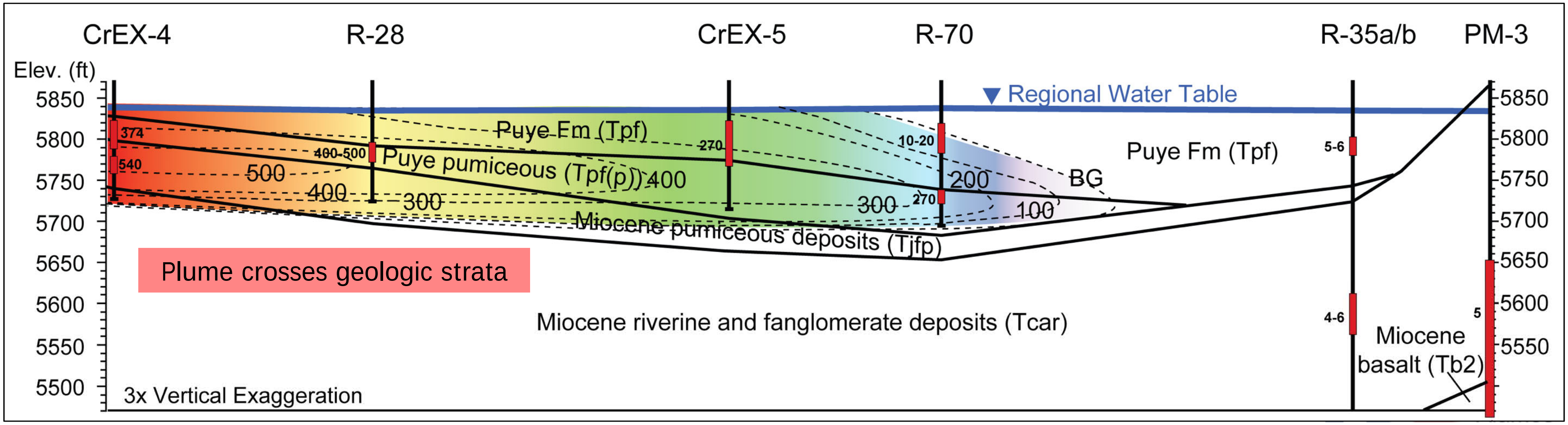


Aspect of CSM:

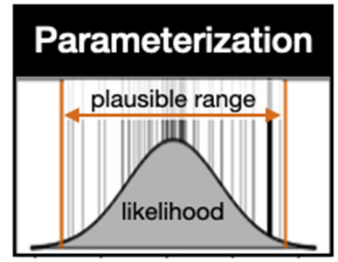
- Several geologic strata behave similarly and have similar K estimates from pump tests; less is known about impact of Tcar boundary
- Strong anisotropy, non-continuous layering
- Unconfined near surface, leaky-confined at depth

Model Assumptions

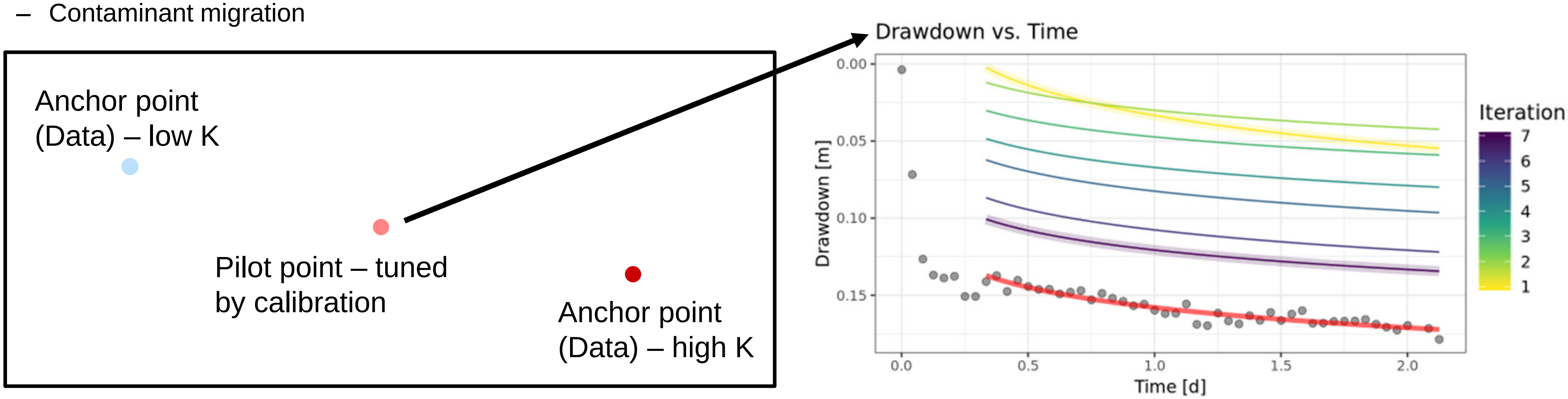
- Consider Tpf, Tpf(p), Tjfp, and Tcar to be the same hydrostratigraphic unit
- Use pilot point approach for K field



Pilot point approach balances flexibility and physical properties

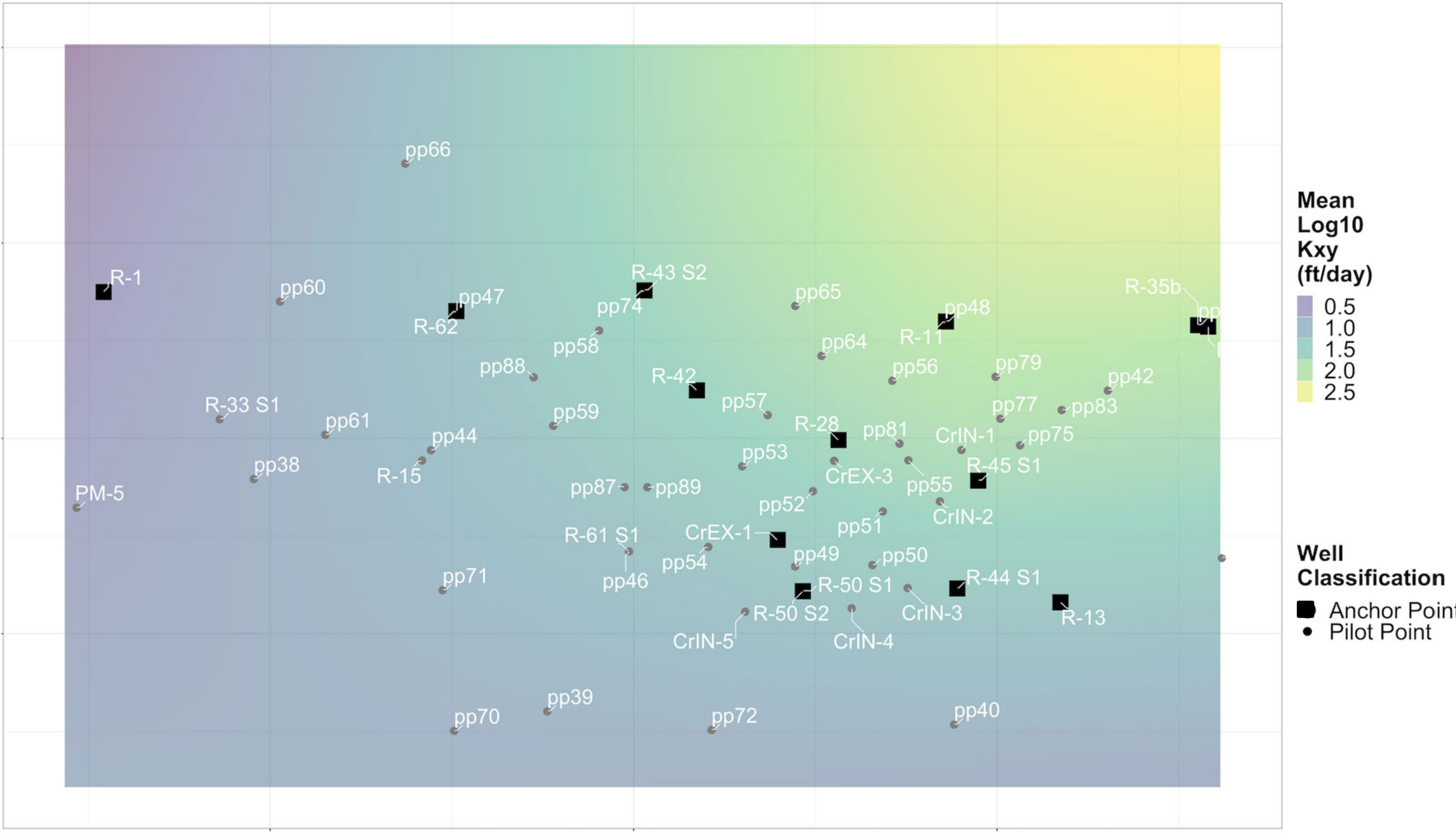


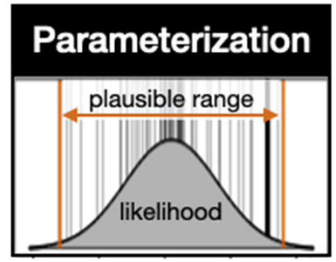
- Explicitly locate data in space (i.e. well locations)
- Locating pilot points between anchor points allows the calibration to link data points (anchor) based on the modeled physics
- Links observations by varying spatially-explicit properties that drive hydraulic response
  - Groundwater flow (water levels, 3-point generated flow gradients, drawdown responses)
  - Contaminant migration



- Honors the principle of parsimony – “as simple as possible but no simpler”

Spatial interpolation of median anchor point data at all wells





- 92 pilot and anchor points
- 4 values at each of these:
- kx, ky, kz, and specific storage

- **Amounts to 368 of the 418 input parameters!**

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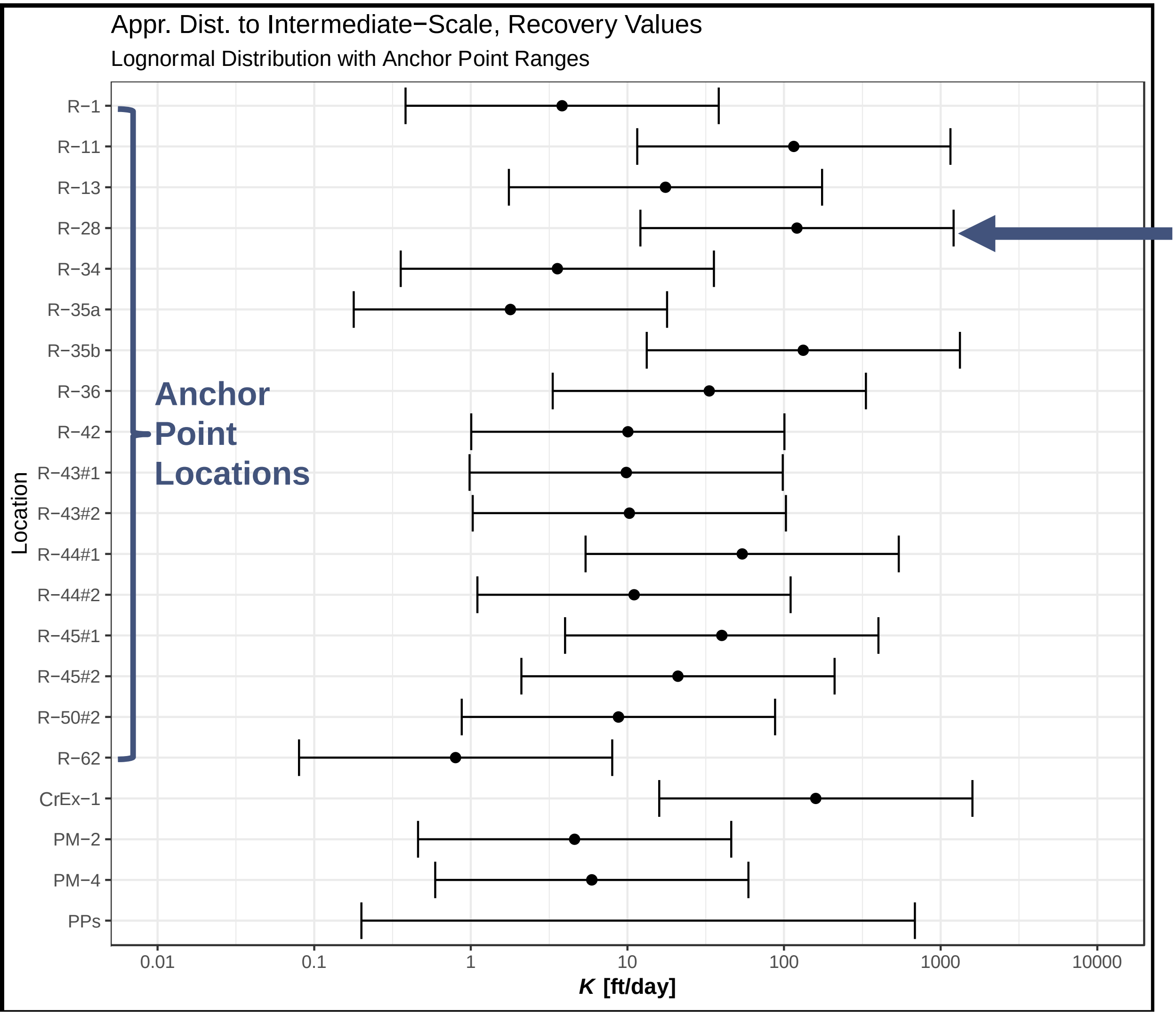
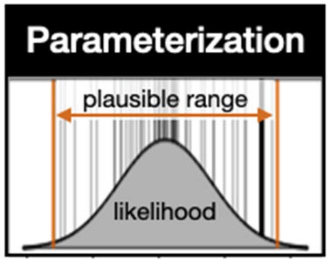
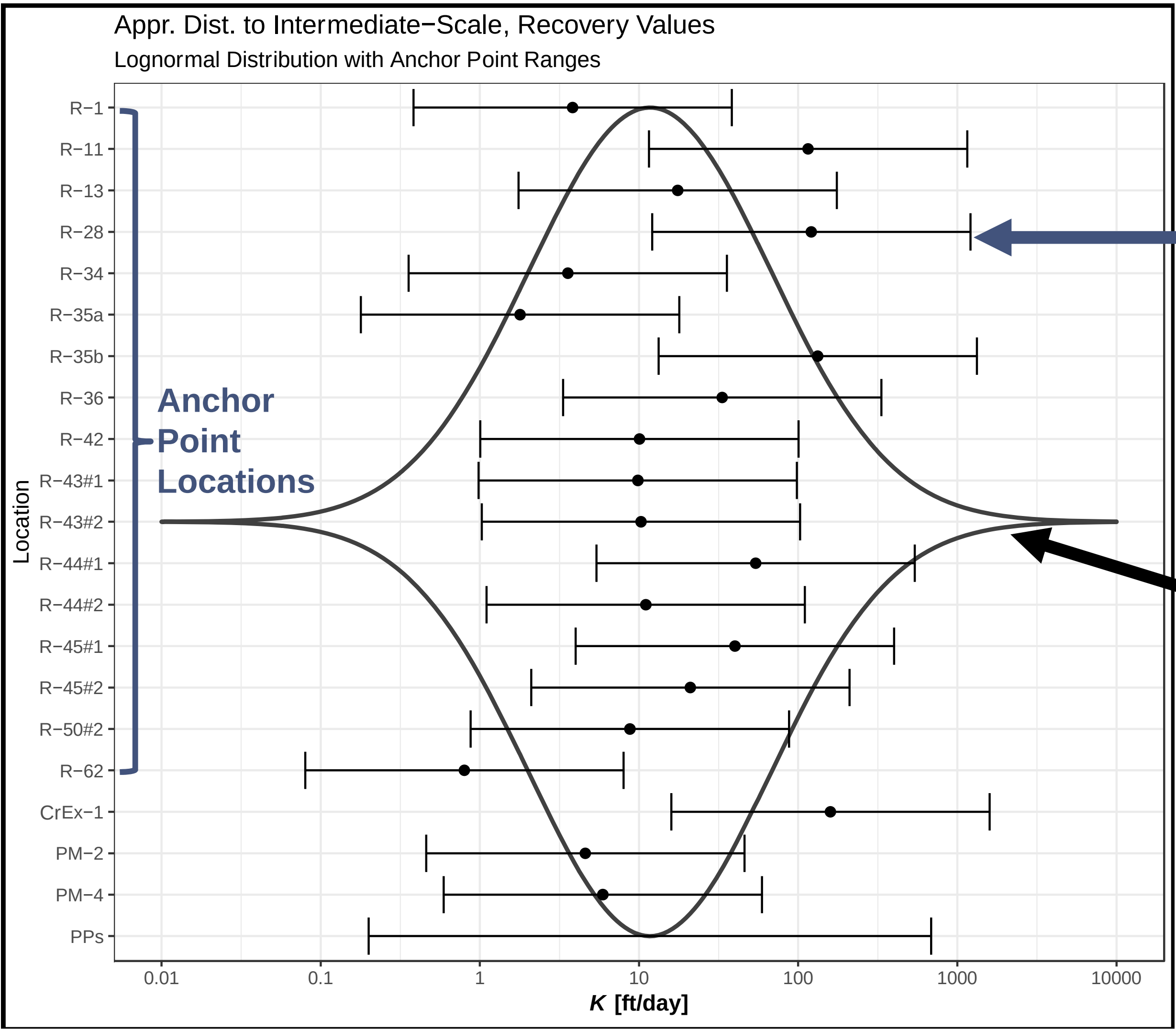
Distribution of pilot points informed by ALL anchor data



Anchor Point Distribution
Plausible range set to 1 OM around median of well recovery data

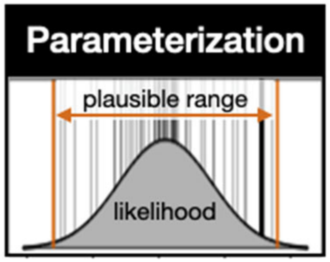


Distribution of pilot points informed by ALL anchor data

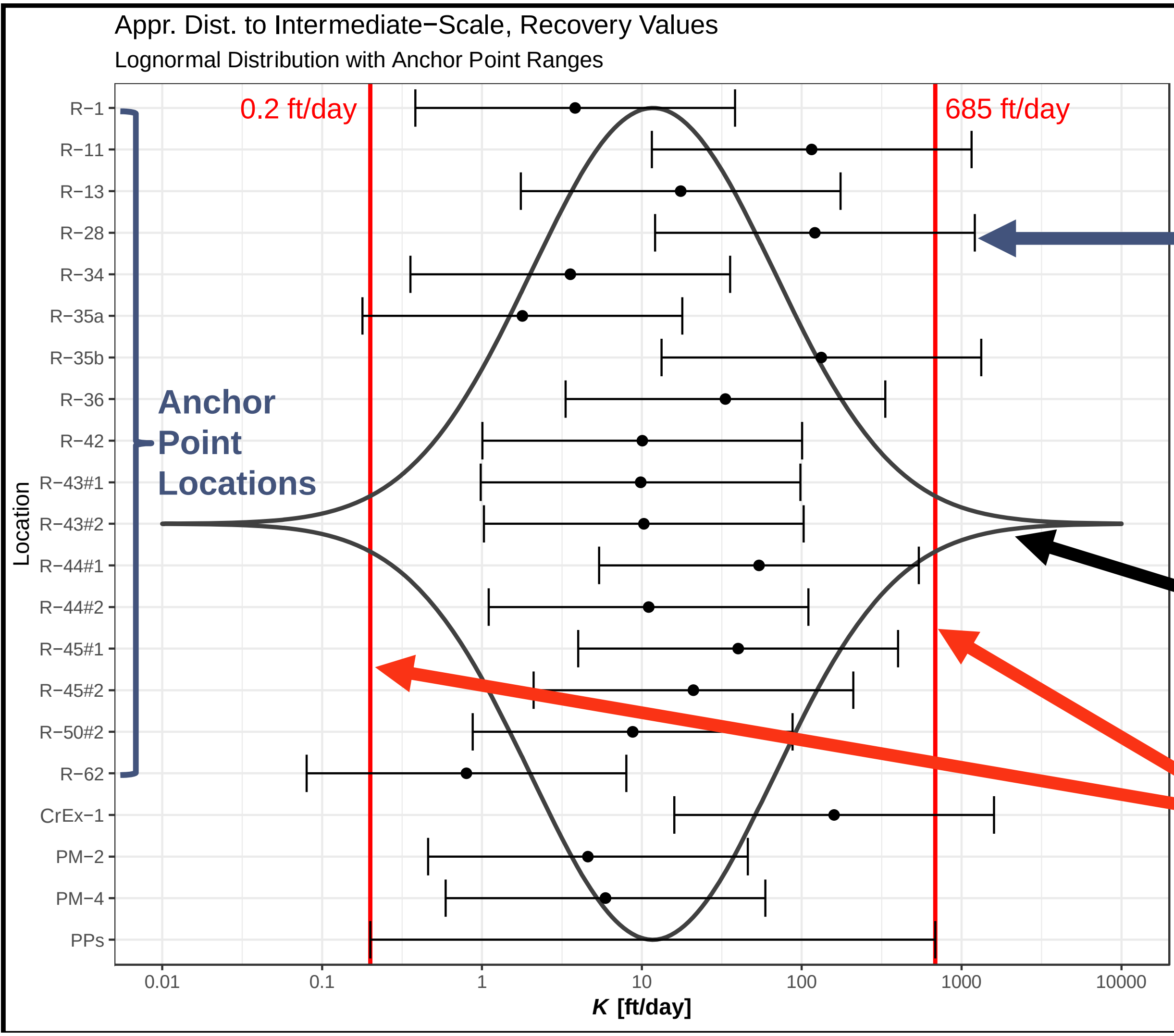


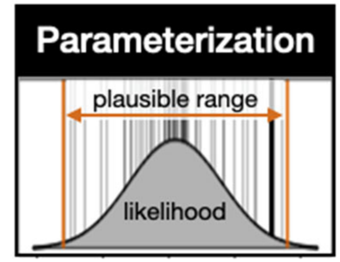
Anchor Point Distribution
Plausible range set to 1 OM around median of well recovery data

Pilot point distribution (likelihood) uses ALL anchor points as input dataset.



Distribution of pilot points informed by ALL anchor data





Anchor Point Distribution
Plausible range set to 1 OM around median of well recovery data

Pilot point distribution (likelihood) uses ALL anchor points as input dataset.

Plausible range

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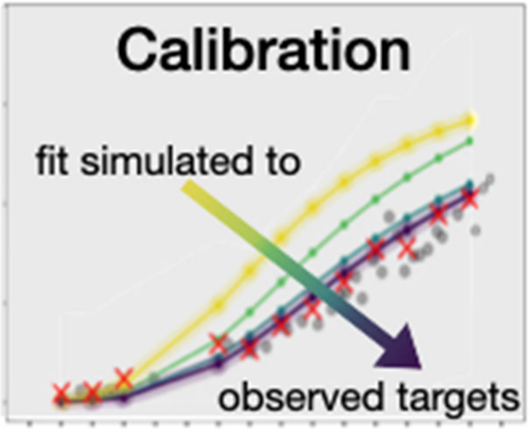
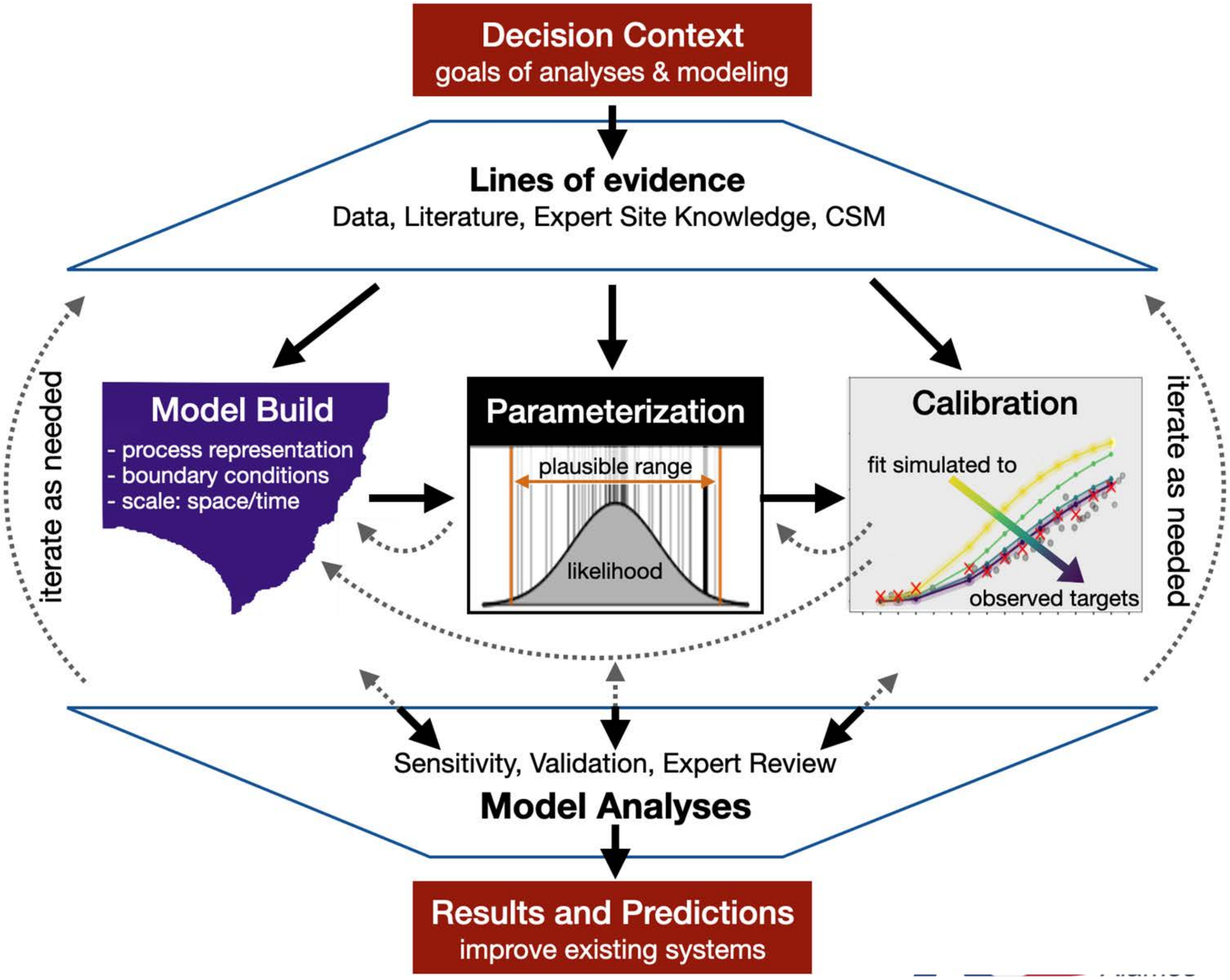
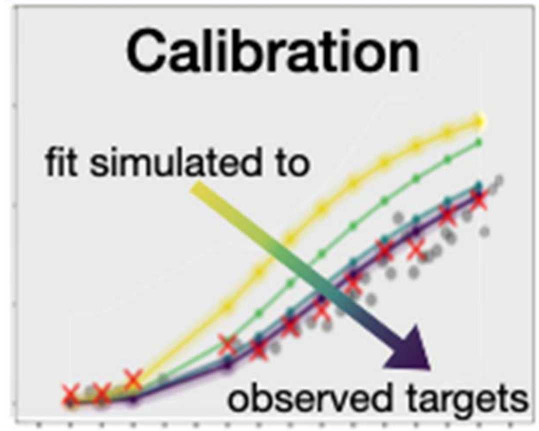
CALIBRATION STEP





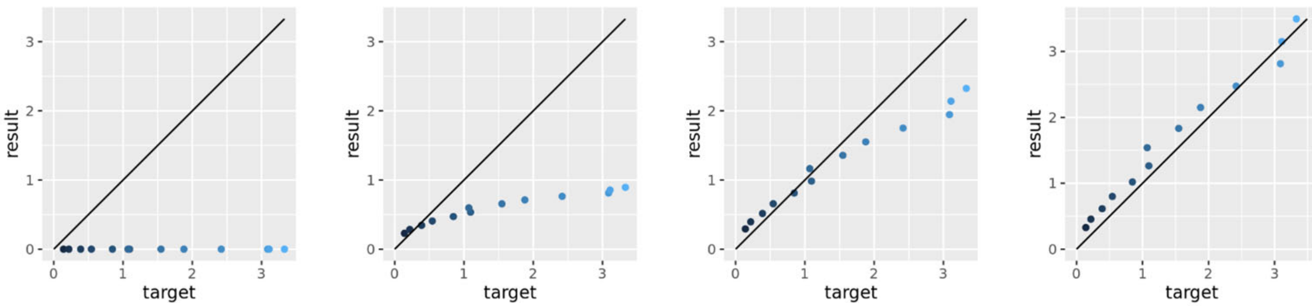
Targets are critical to an effective calibration

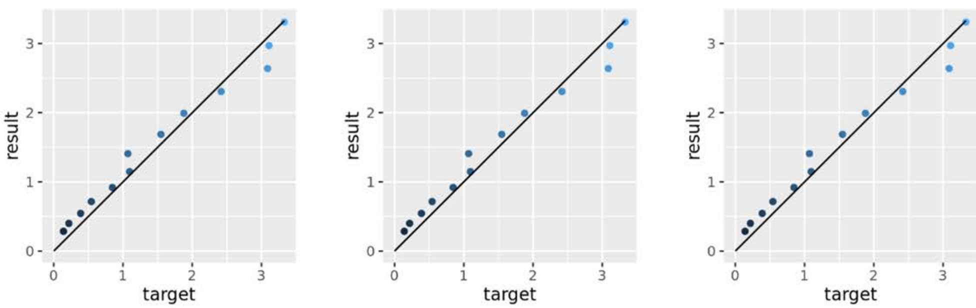


- Model constrains possible pathways using all available data (input distributions) and groundwater flow physics

- Targets guide the model in finding solutions
  - Numerical rewards for simulations matching target data

- The computer adjusts parameters (inputs) to match data (targets)



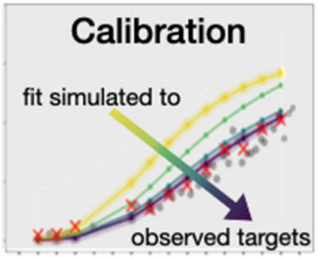


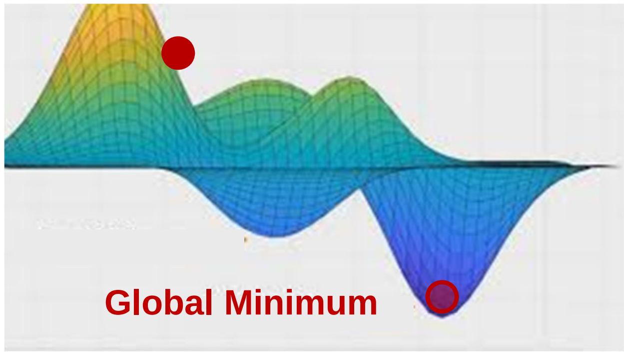
- Matching a single point is much easier than matching many points

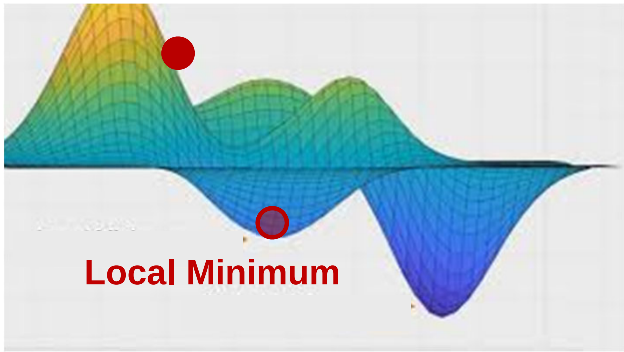
- Prioritizing targets helps to direct time and effort at finding solutions that are relevant to decisions

N3B Los Alamos

Solutions in 400+ dimensional space are challenging

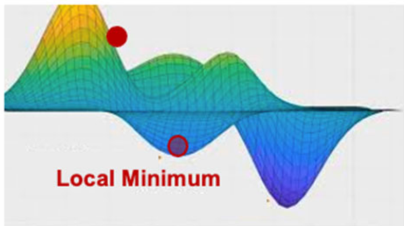


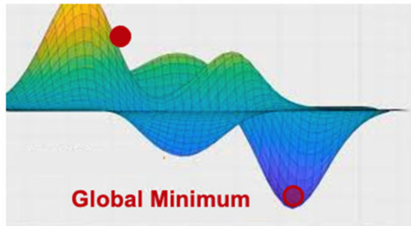


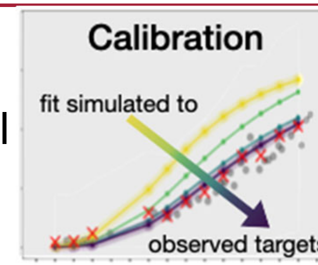


- Model is trying to find minima (where the target data and simulation match as closely as possible)
- The computer adjusts parameters (inputs) to match targets, but there may be many local minima that are not as good a solution as the global minimum.
- Many trials are needed to explore a 400+ dimensional parameter (input) space.
- Constraining solutions with conceptual understanding is also necessary.

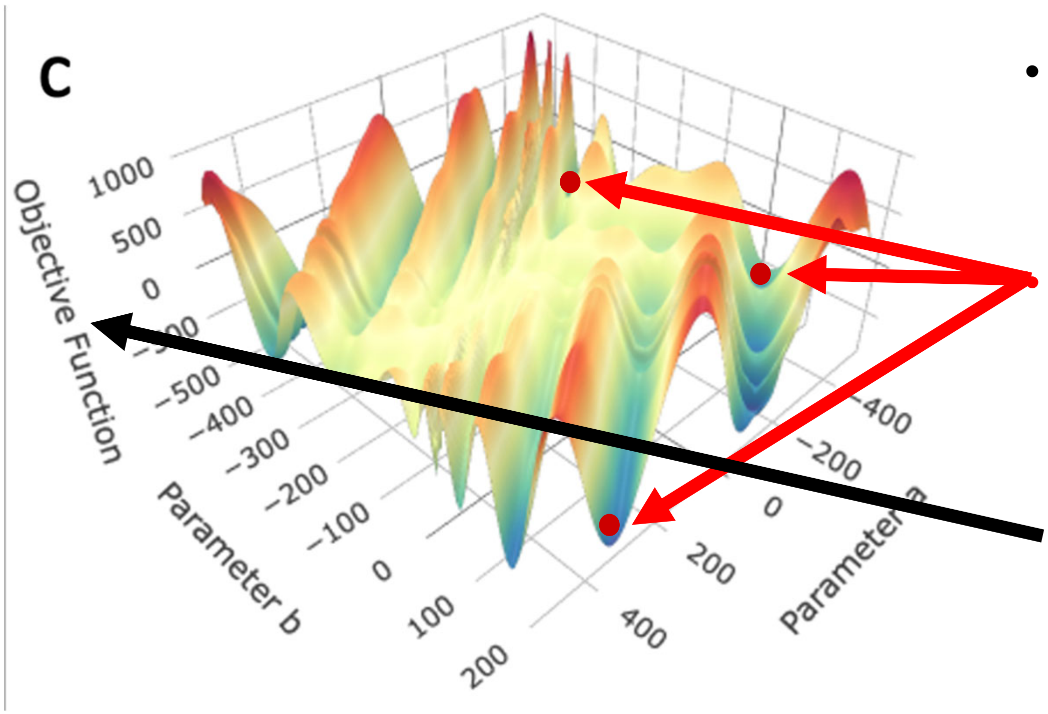
Conceptual uncertainty – identifying promising local minima







- A global minimum is not identifiable in an 400-dimensional space, so we find multiple sets of very good local minima

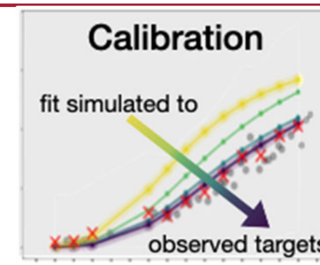


- The complexity of these 2-dimensional (parameter a vs. parameter b) spaces is already complex, imagine 400+ dimensions!

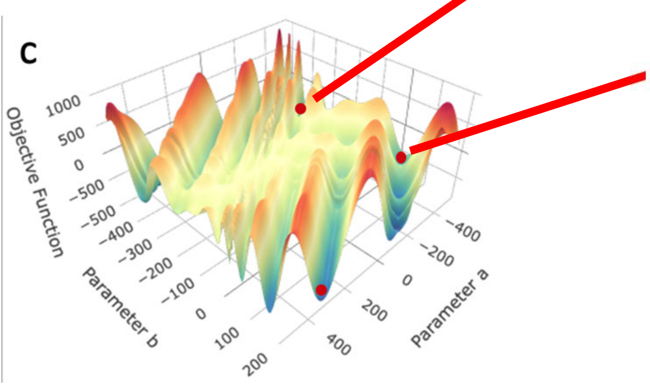
- **These local minima** represent a range of conceptualizations of the sources and flow fields, they are promising points within parameter space (ALL of which effectively minimize the **Objective Function**)

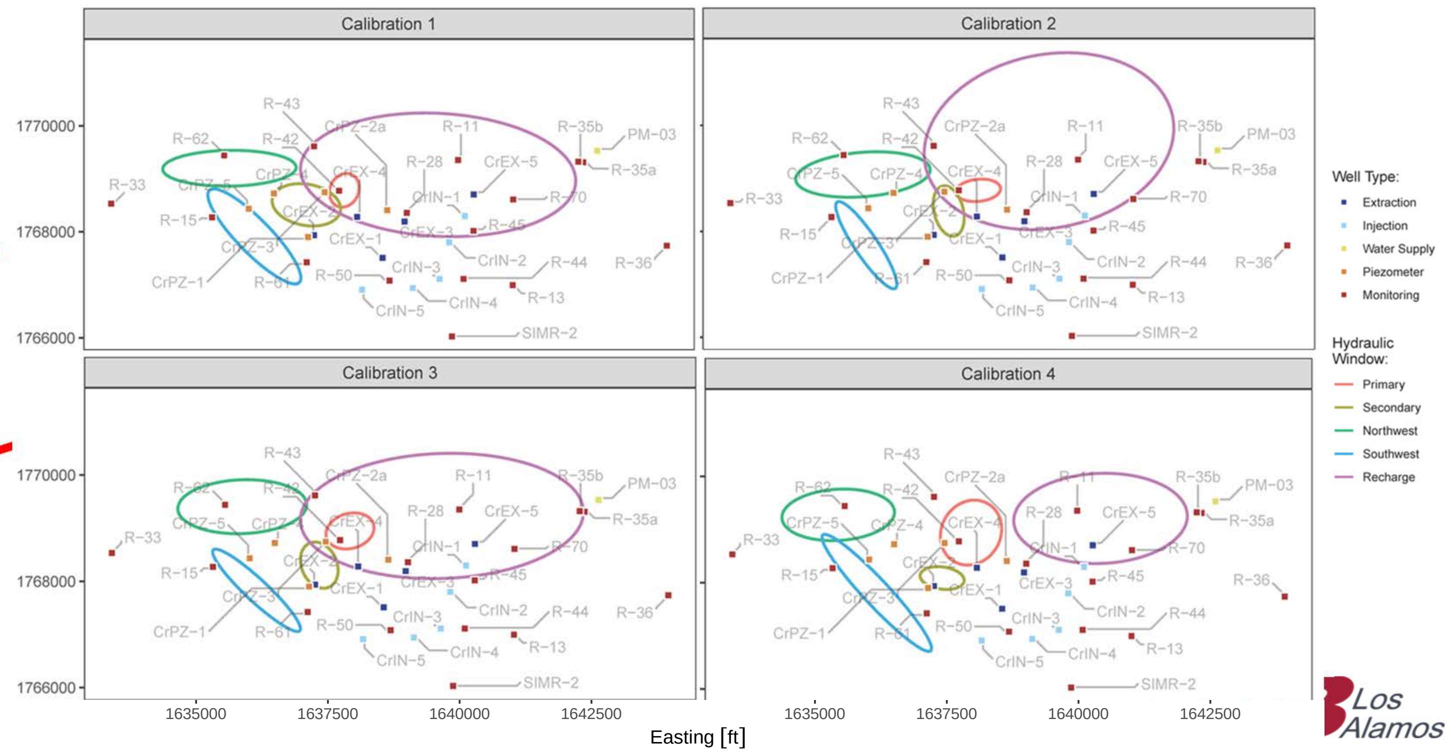
Four conceptualizations instead of one deterministic simulation

- Four promising combinations of sources and flow field parameters are identified
- Informed by input distributions and constrained by matches to target datasets



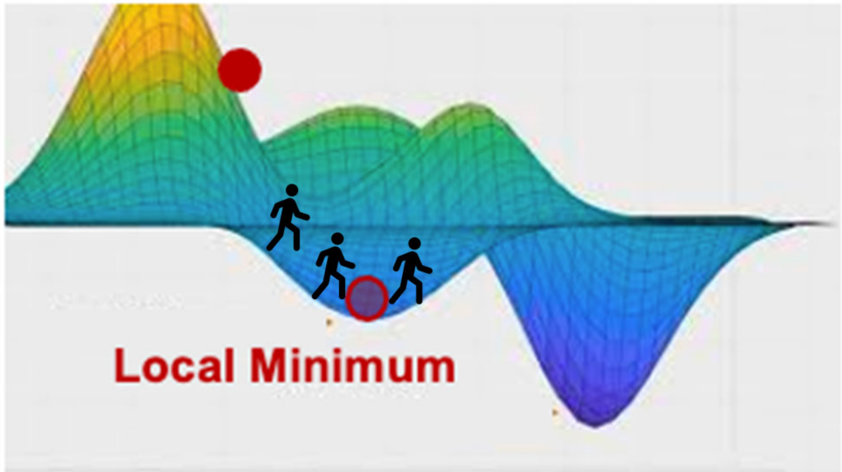
- ALL calibrations match the target data (see later slides for results)
- Numbering is random (Calibration “1” is not the best match)

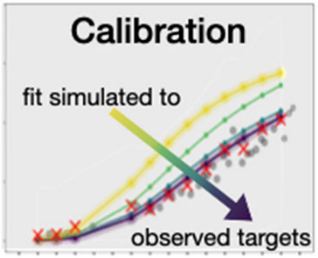




Los Alamos

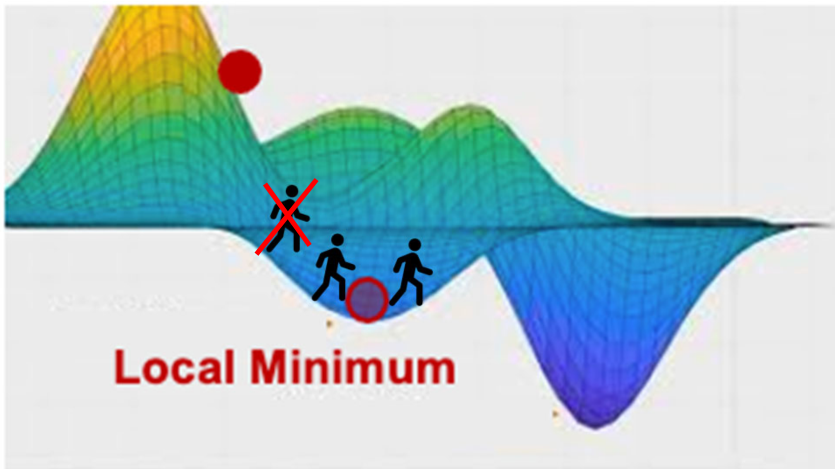
Markov Chain Monte Carlo – sensitivity around transport parameters

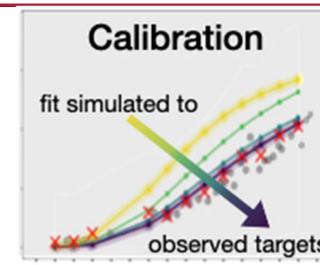




- Each calibration (local minimum) represents a unique conceptualization of the sources and flow field
- Within each calibration, transport parameters are varied with Markov chain Monte Carlo “walkers” to assess sensitivity

MCMC – explain sensitivity around transport + match OF





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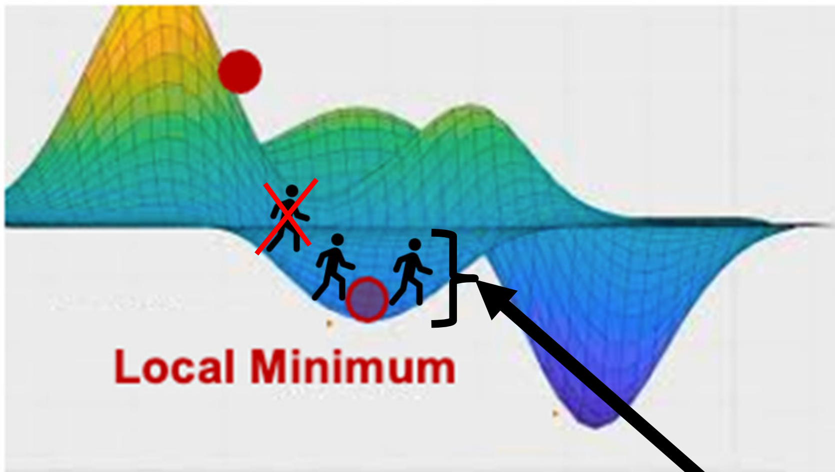
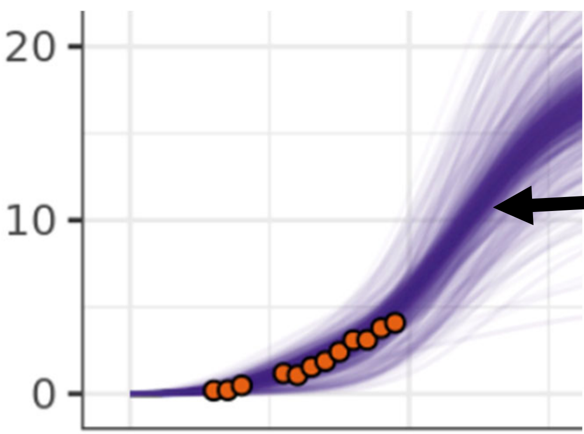
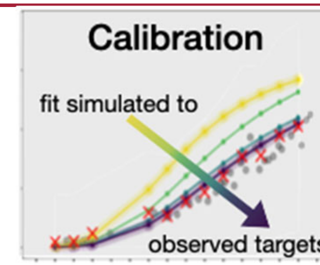
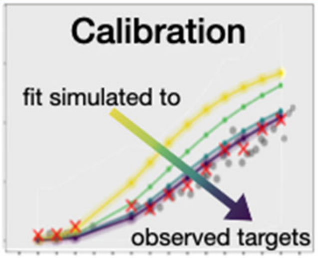






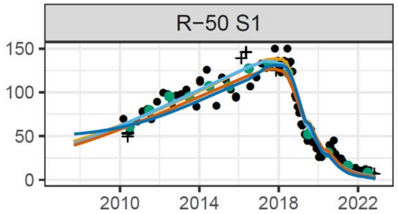
- Each calibration (local minimum) represents a unique conceptualization of the sources and flow field
- Within each calibration, transport parameters are varied with Markov chain Monte Carlo “walkers” to assess sensitivity
- Parameter sets (walkers) that perform poorly in the objective function are discarded, whereas those that perform well are accepted
- The collection of accepted walkers agree with the data and provide thousands of runs for a smoother and more robust estimate of uncertainty

Model targets are weighted to prioritize important components of CSM

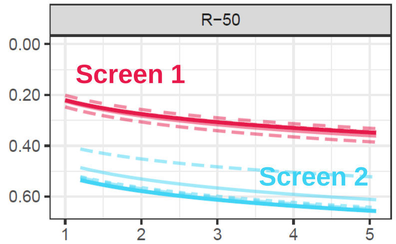


Target group prioritization

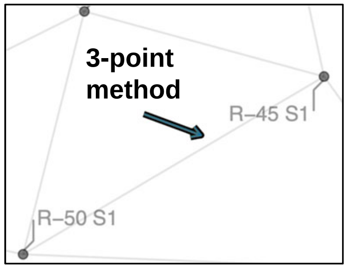
(1) Concentration (yearly avg)



(2) Drawdown response

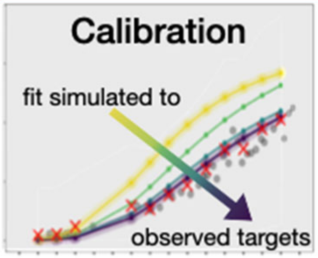


(3) Hydraulic gradient



(4) Hydraulic head

Model targets are weighted to prioritize important components of CSM



Target group prioritization

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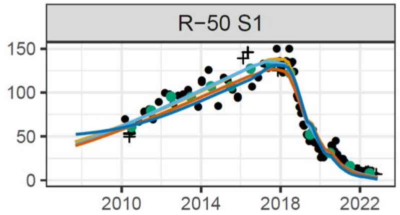
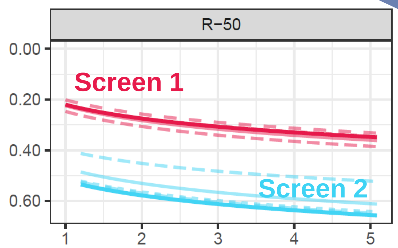
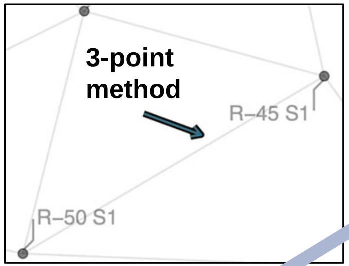


(2) Drawdown response



(3) Hydraulic gradient



(4) Hydraulic head

Within group preference weighting
*prioritize key behaviors

Well priorities:

1. *Sentinel wells* (R-35a/b, SIMR-2),
   CSM critical wells R-70, R-45 S2,
   CrEX-4 (dual screen measurement)
2. *Response to IM:*
   R-50 S1, R-45 S1, R-44 S1
   CrEX wells, CrPZ-1
3. *Plume centroid of mass* R-28, R-42 (pre-amendments)
   CrIN wells (pre-IM), CrPZ-2a

drawdowns prioritized here because critical to evaluating pump and treat system

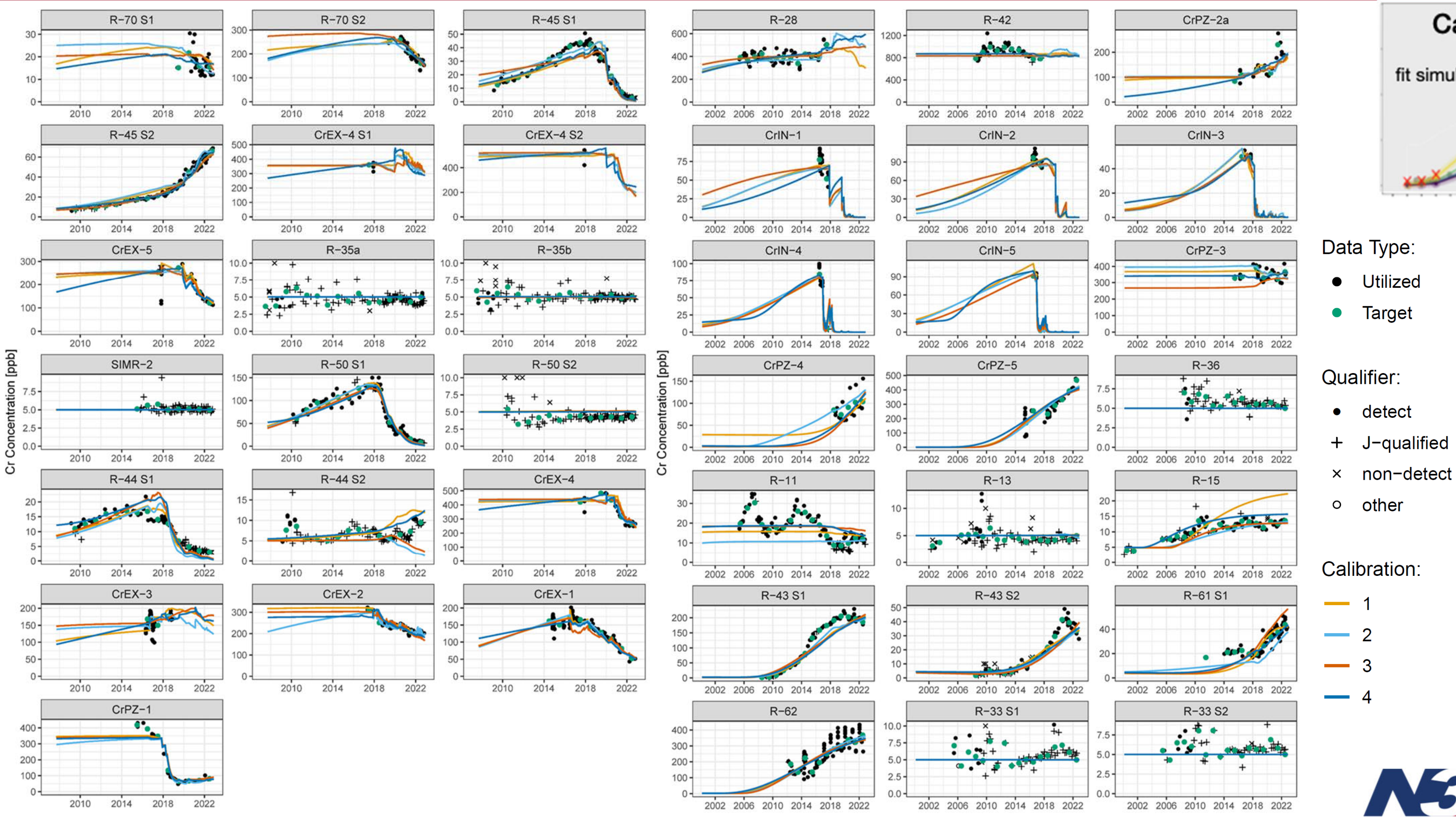
4. All remaining wells

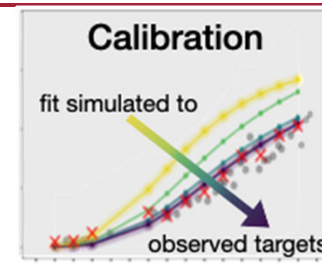
getting **regional flow** patterns accurate (**hydraulic gradients**) is prioritized here
water table estimates before pumping help establish broad patterns in flow

These weights create an **Objective Function**
a grouped, weighted average of residuals that measures how closely the simulation matches the observations.

N3B Los Alamos

Calibration matches concentrations at 40 wells over 20 years



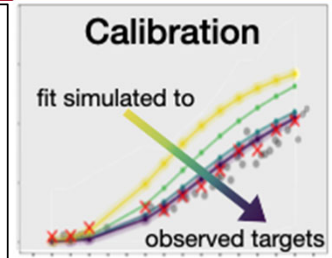


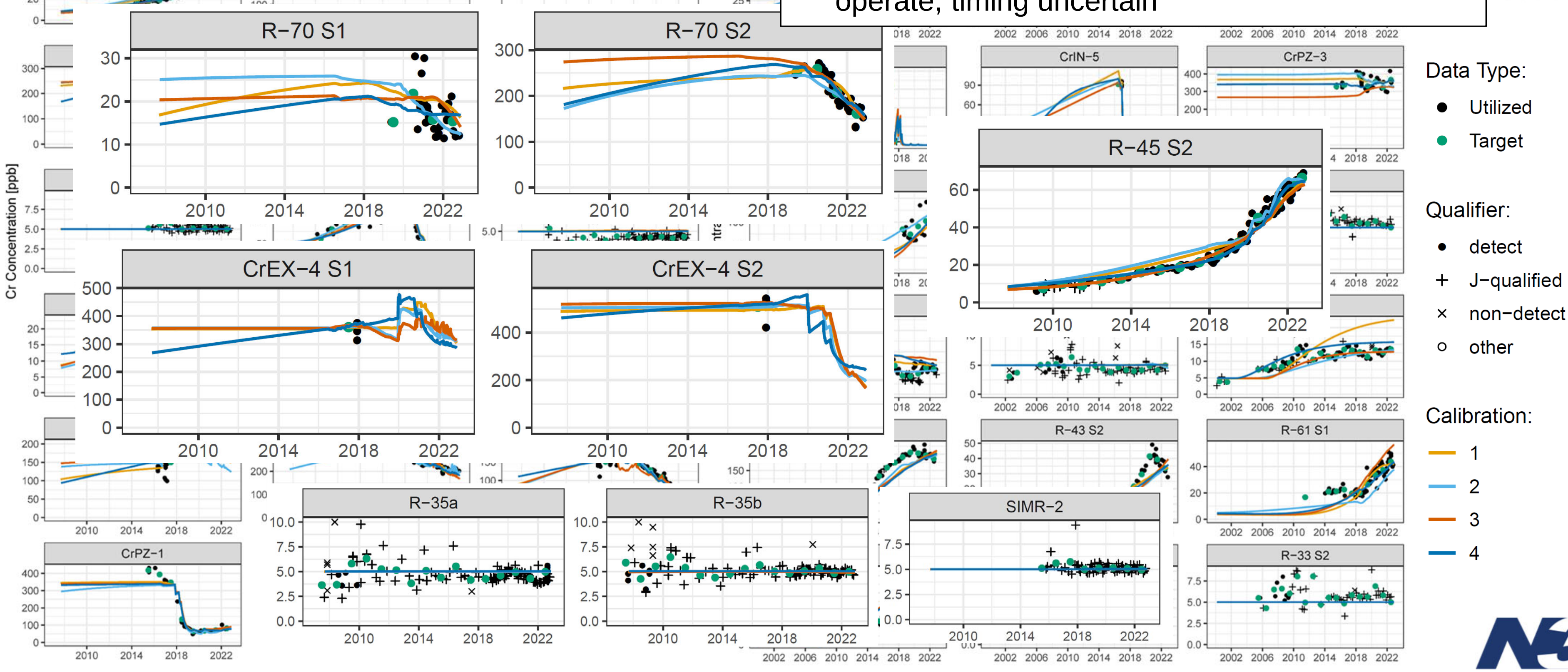
Calibration matches inverted concentration gradient

Well priorities:

1. *Sentinel wells* (R-35a/b, SIMR-2), *CSM critical wells* R-70, R-45 S2, CrEX-4 (dual screen measurement)

- Close matches of inverted concentration gradient at CrEX-4, R-70, AND at validation data for R-70
- R-45 S2 target data is matched in all models, one of the four hits the validation data as well NOTE: all four predict turnover if IM continues to operate, timing uncertain

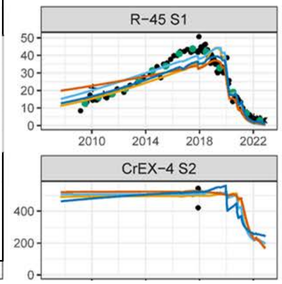




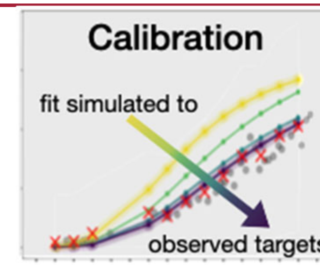
Calibration reproduces strong responses to IM pumping

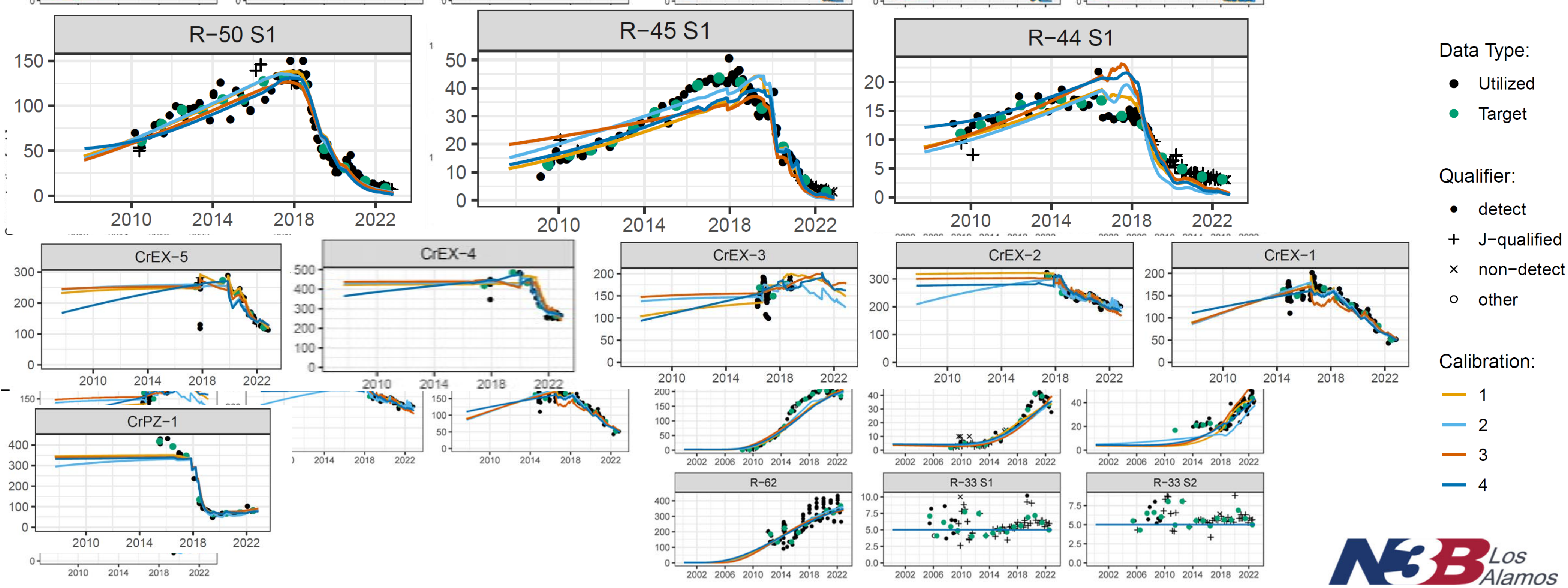
Well priorities:

1. *Sentinel wells* (R-35a/b, SIMR-2), *CSM critical wells* R-70, R-45 S2, CrEX-4 (dual screen measurement)
2. *Response to IM:* R-50 S1, R-45 S1, R-44 S1 CrEX wells, CrPZ-1



- Response to IM pumping matched at multiple magnitudes (150 ppb – R-50, 50 ppb – R-45, 25 ppb – R-44)
- Extraction wells and the abrupt drop at CrPZ-1 from over 400 ppb at IM initiation matched



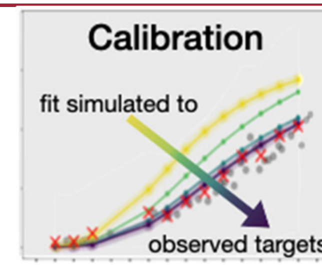


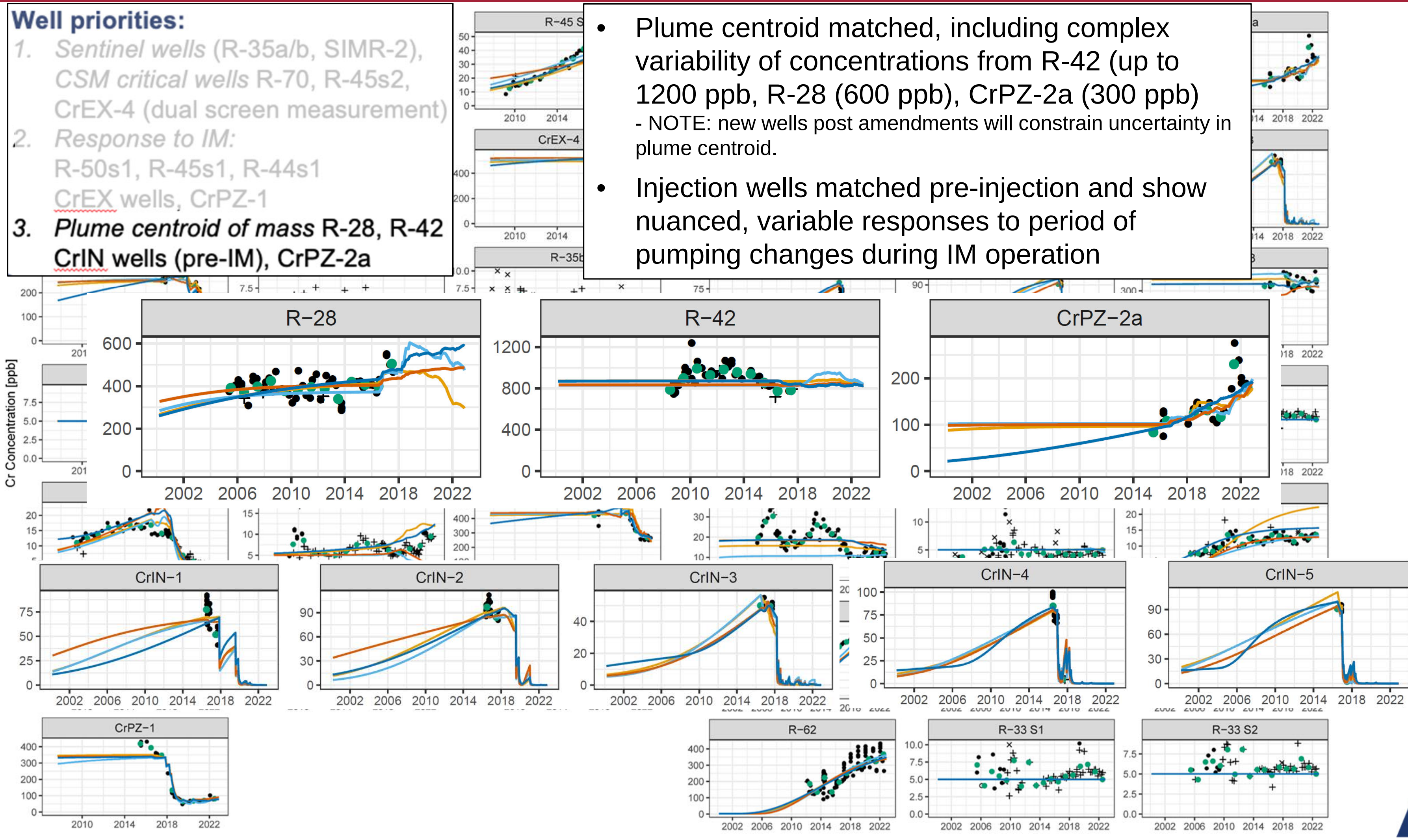
Calibration matches variable concentrations in plume centroid

Well priorities:

1. *Sentinel wells* (R-35a/b, SIMR-2), *CSM critical wells* R-70, R-45s2, CrEX-4 (dual screen measurement)
2. *Response to IM:* R-50s1, R-45s1, R-44s1 CrEX wells, CrPZ-1
3. *Plume centroid of mass* R-28, R-42 CrIN wells (pre-IM), CrPZ-2a

- Plume centroid matched, including complex variability of concentrations from R-42 (up to 1200 ppb, R-28 (600 ppb), CrPZ-2a (300 ppb)
  - NOTE: new wells post amendments will constrain uncertainty in plume centroid.
- Injection wells matched pre-injection and show nuanced, variable responses to period of pumping changes during IM operation

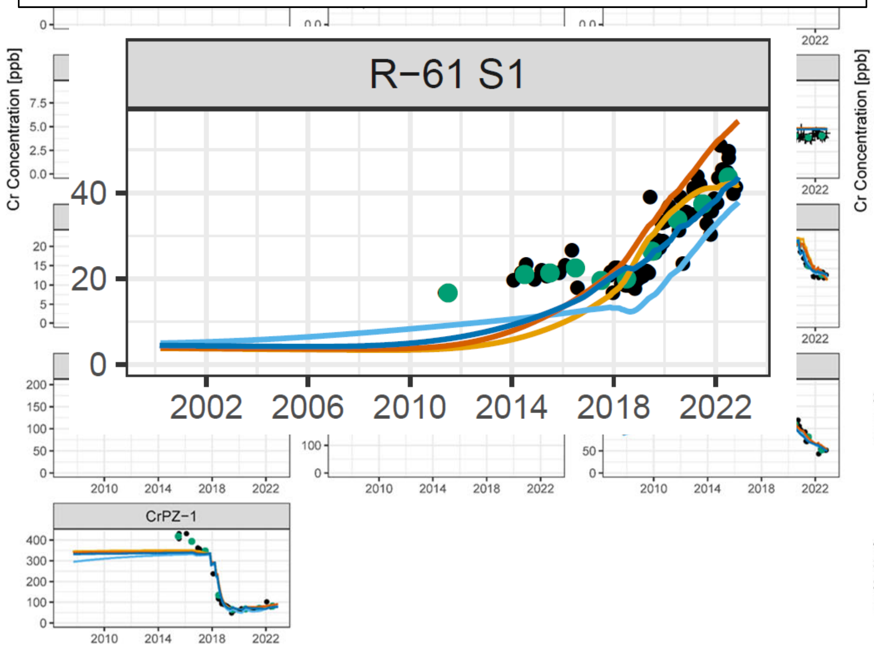


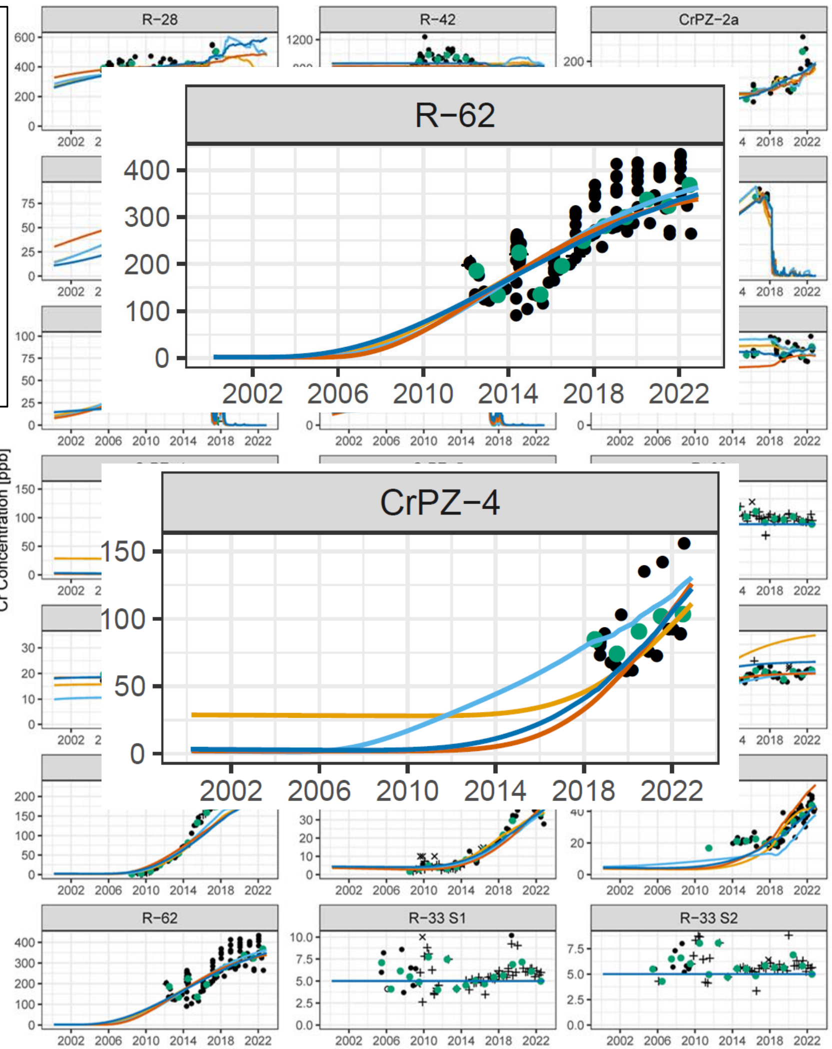


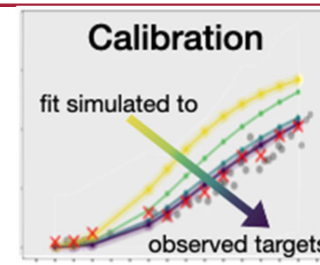
N3B Los Alamos

CRM is able to predict validation points well at many locations

- Generally validation data is quite well matched.
- At these locations we build confidence in the model because the newer data, which was excluded from the calibration, is reproduced accurately.
- An exceptional calibration rule of thumb in industry is being within 10% of most target data, this calibration well exceeds that metric at all wells







Data Type:
- ● Utilized
- ● Target

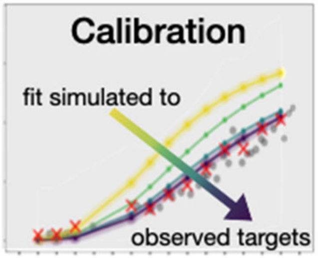
Qualifier:
- ● detect
- + J−qualified
- × non−detect
- ○ other

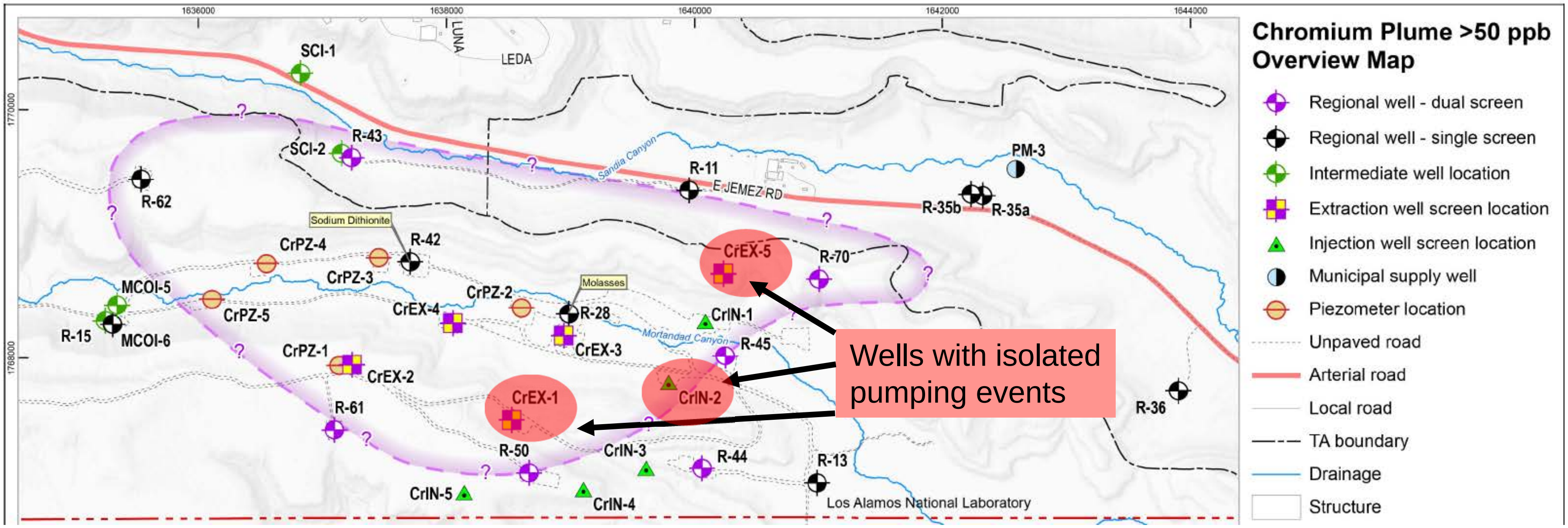
Calibration:
- 1
- 2
- 3
- 4

N3B Los Alamos

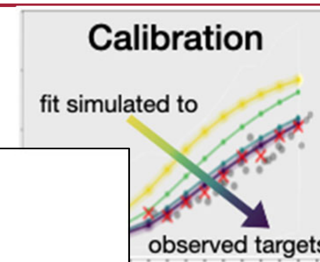
Calibration matches drawdowns at 13 screens across site

- Isolated pumping events are identified (no other well is pumping at that same time)
- Allows for clean responses from other wells to help calibrate the flow field
- Especially want to calibrate, where possible, to dual screened responses

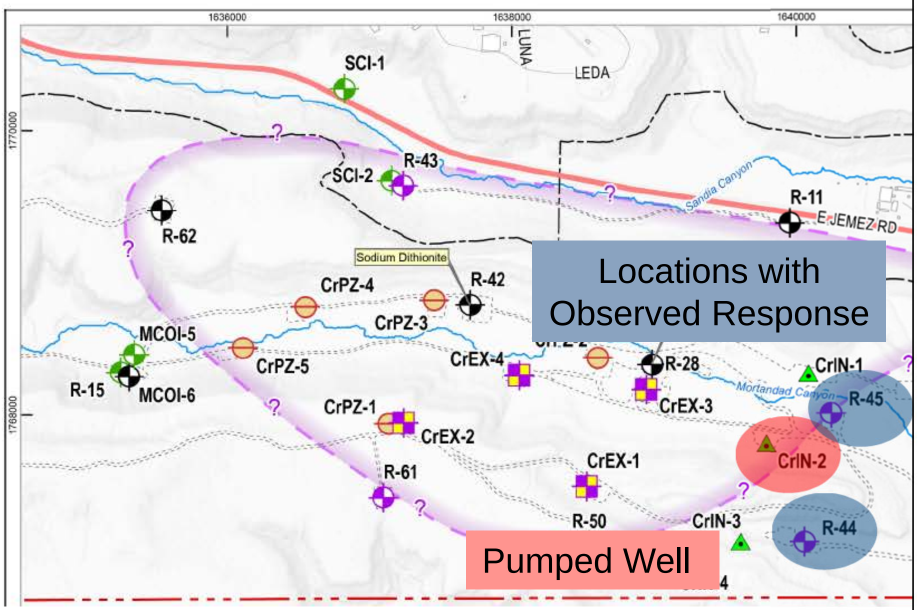


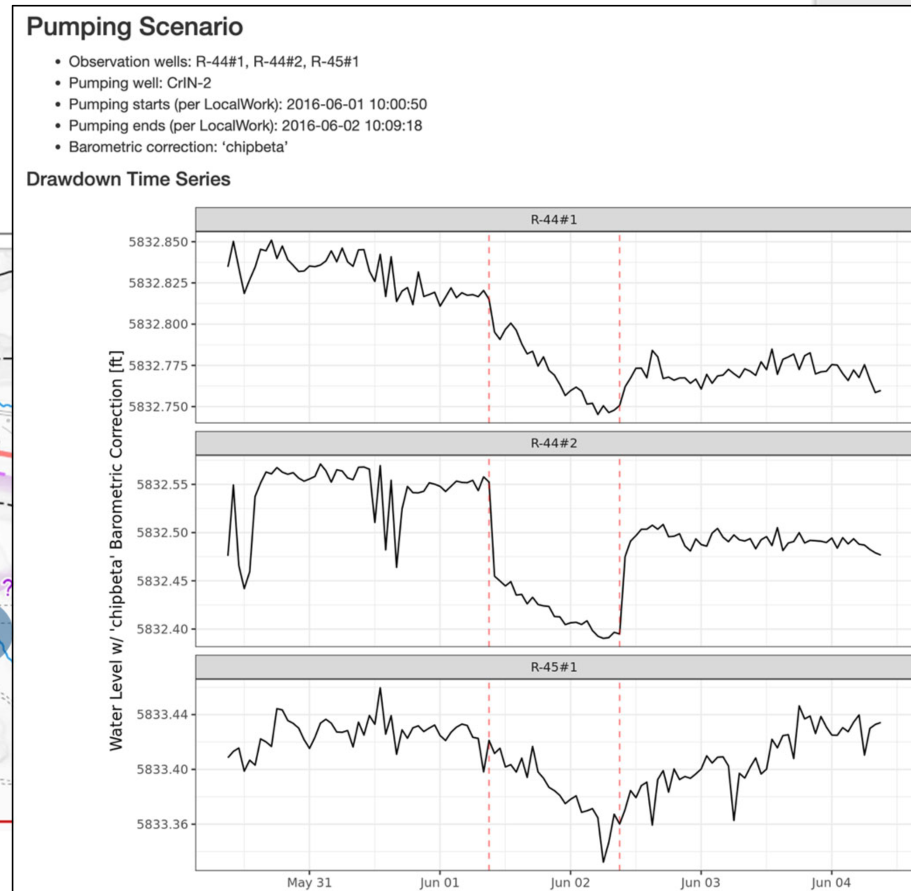


Calibration matches drawdowns at 13 screens across site

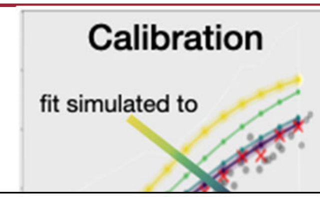


- CrIN-2 pumping event in 2016 *aquifer test with EXTRACTION, not injection
  - Responses observed at 3 screens:
    - R-44 Screen 1
    - R-44 Screen 2
    - R-45

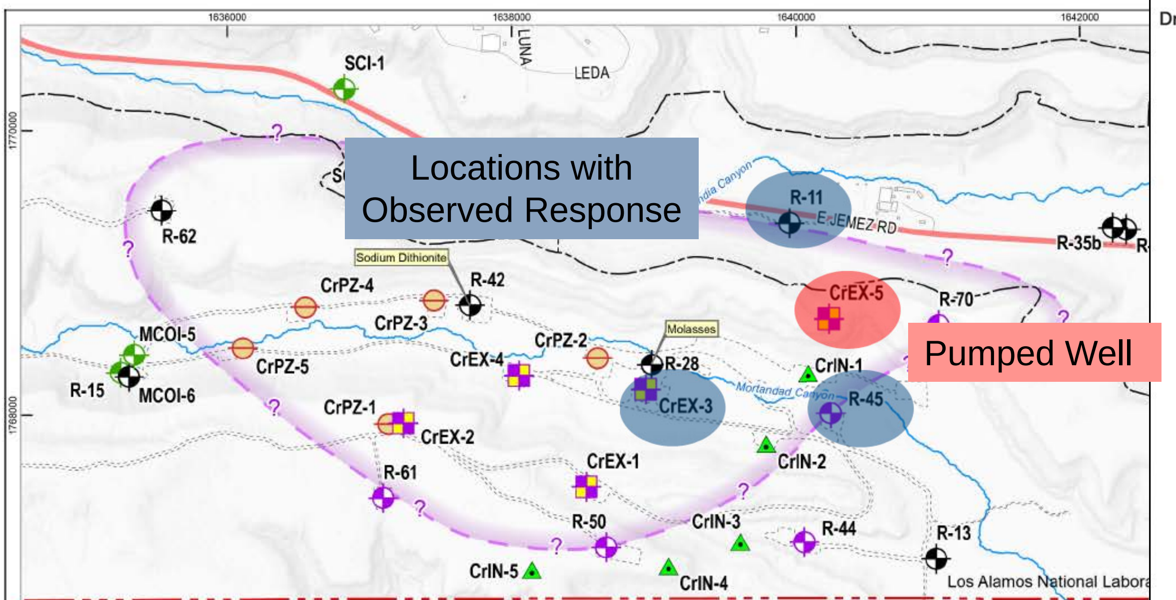


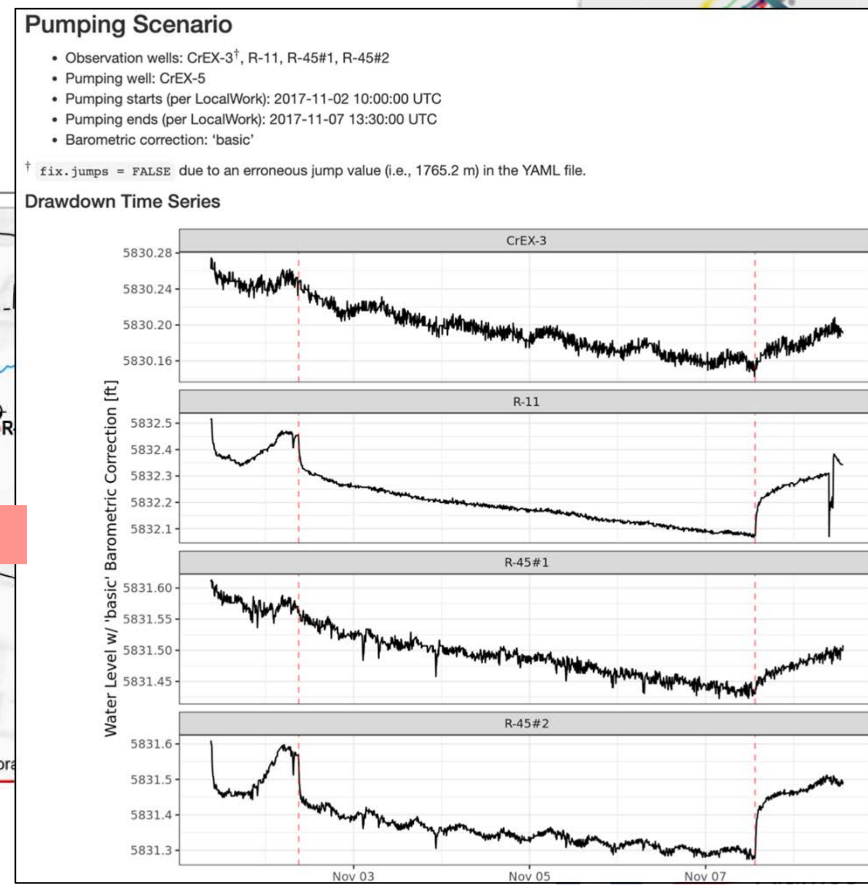


Calibration matches drawdowns at 13 screens across site



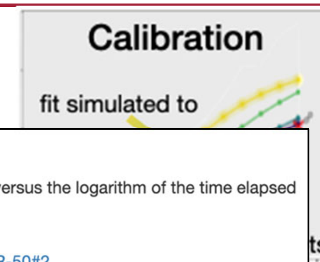
- CrEX-5 pumping event in 2017
  - Responses observed at four screens:
    - CrEX-3
    - R-11
    - R-45 screen 1
    - R-45 screen 2

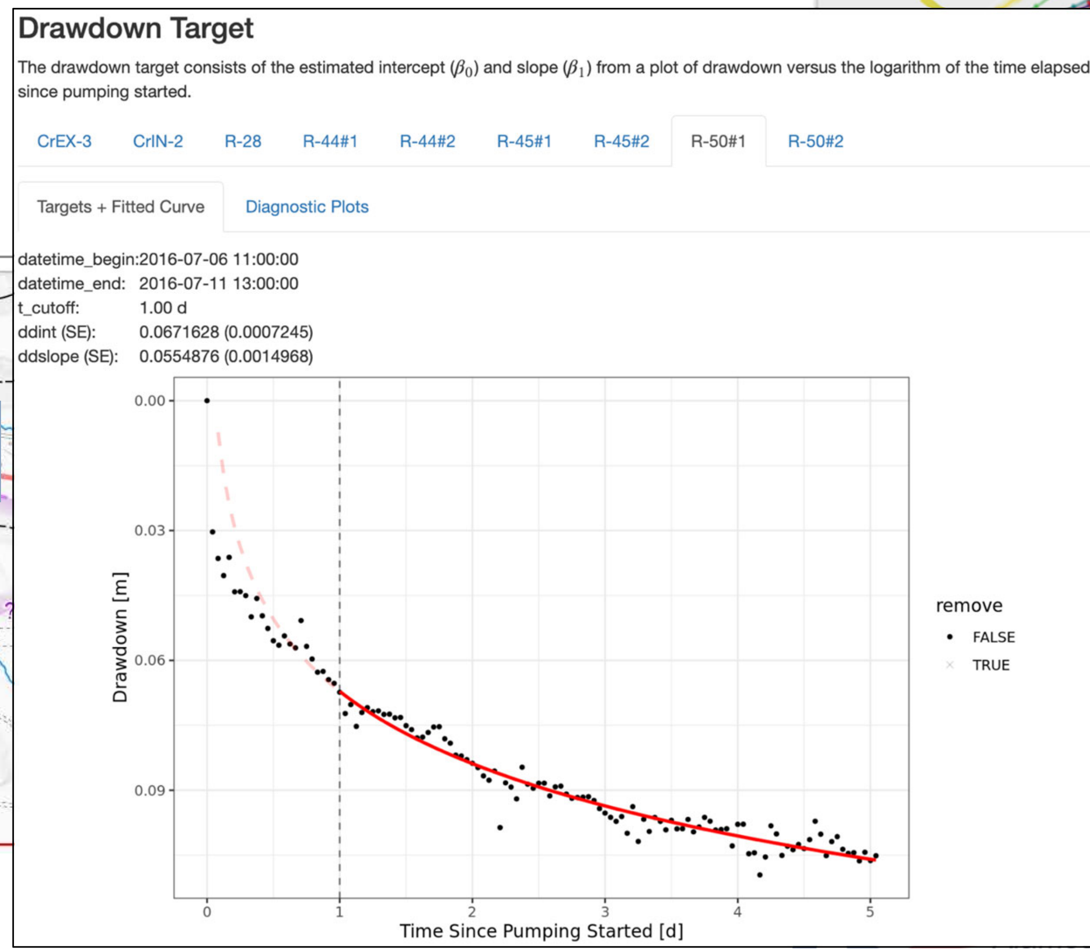


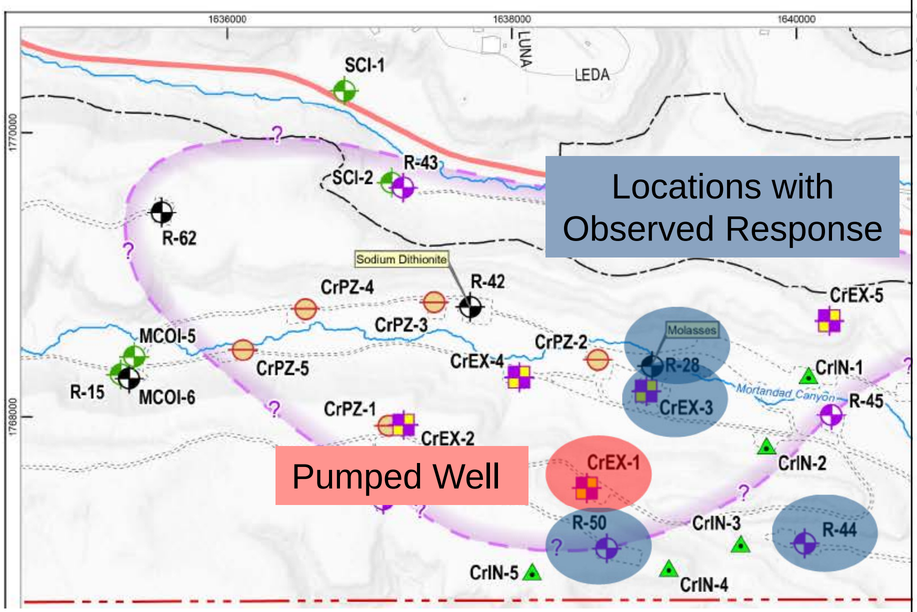


Calibration matches drawdowns at 13 screens across site

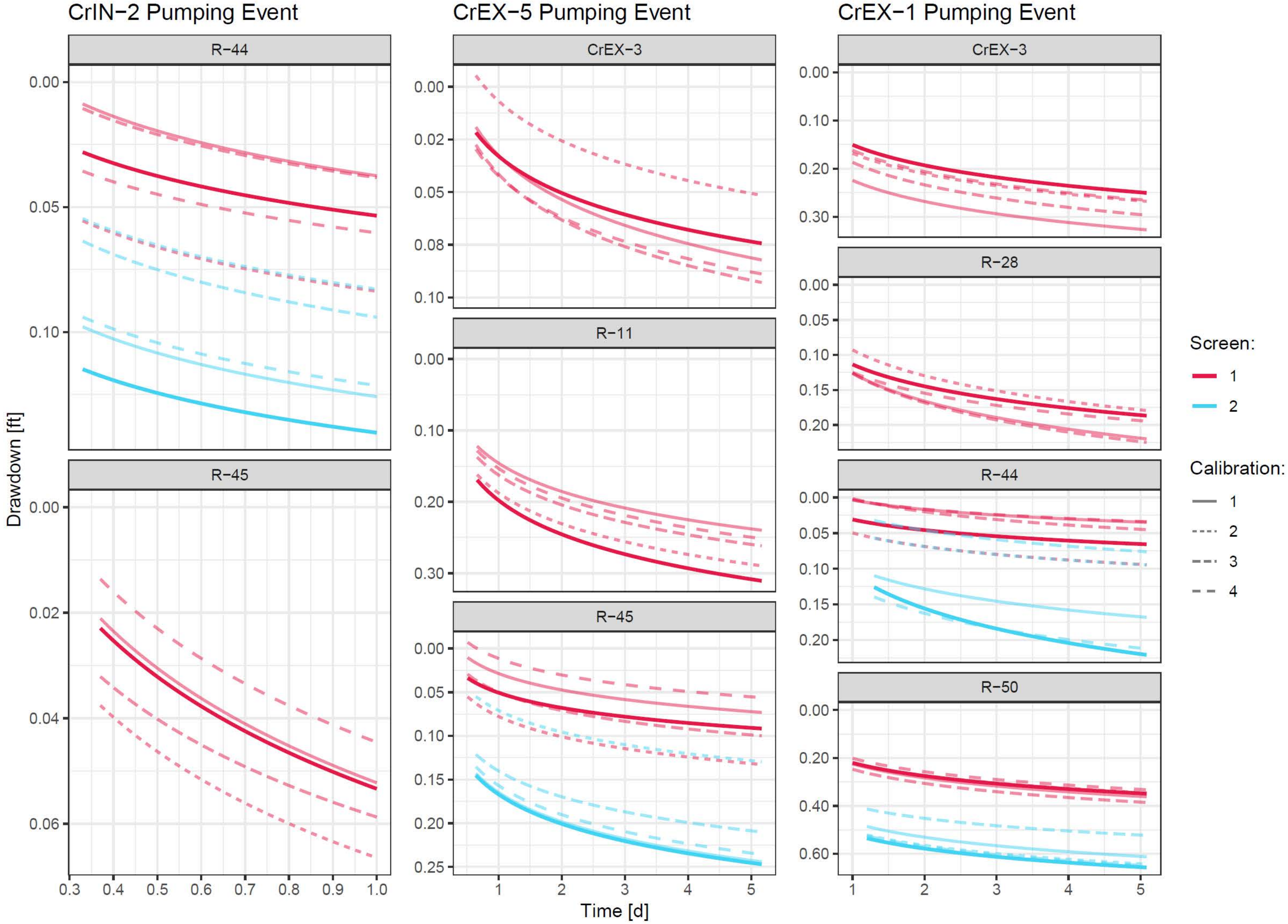
- CrEX-1 pumping event in 2016
  - Responses observed at:
    - CrEX-3
    - R-28
    - R-44 screen 1
    - R-44 screen 2
    - R-50 screen 1
    - R-50 screen 2

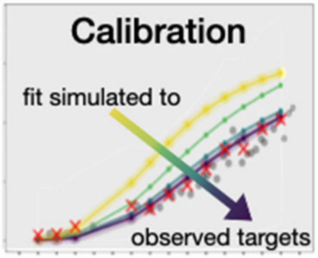






Calibration matches drawdowns at 13 screens across site

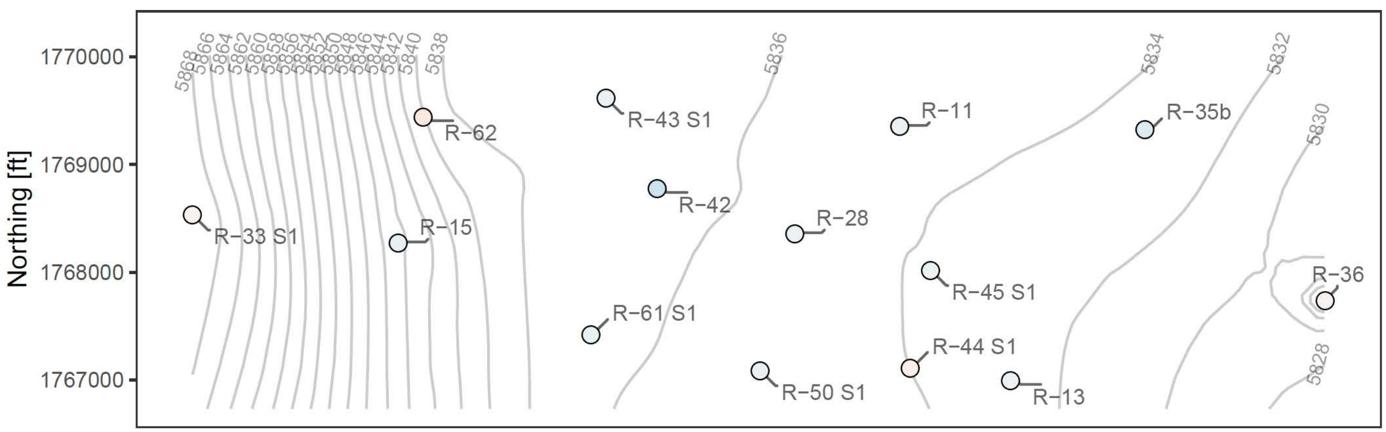


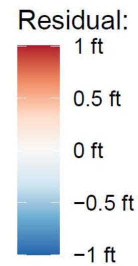


- Drawdowns are closely matched in single screen responses
- Drawdowns at dual screens show a distinct separation in response magnitude in most calibrations, with some overlap in R-44 responses (and one in R-45 for calibration 2)

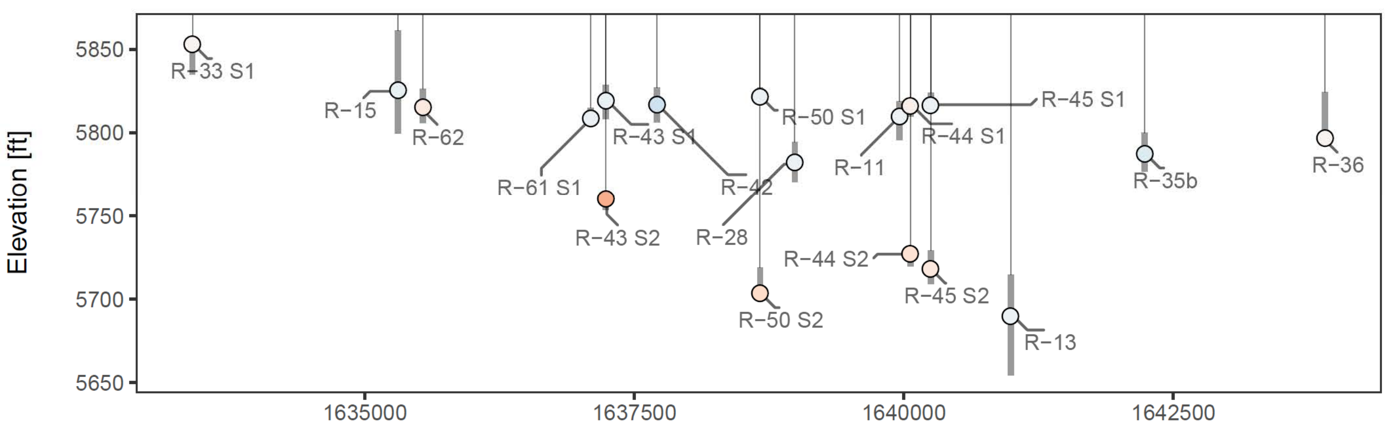
Calibration matches flow field (hydraulic gradients and heads)

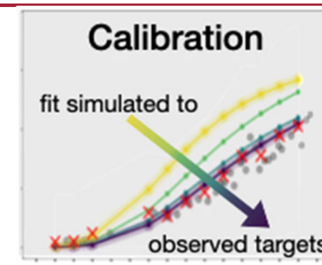
Plan view head matches with water table contours





Cross-sectional view of screens with depth





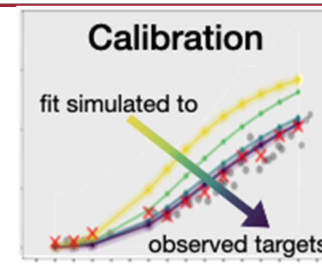
- All heads in all calibrations are matched within ≈ 1 ft

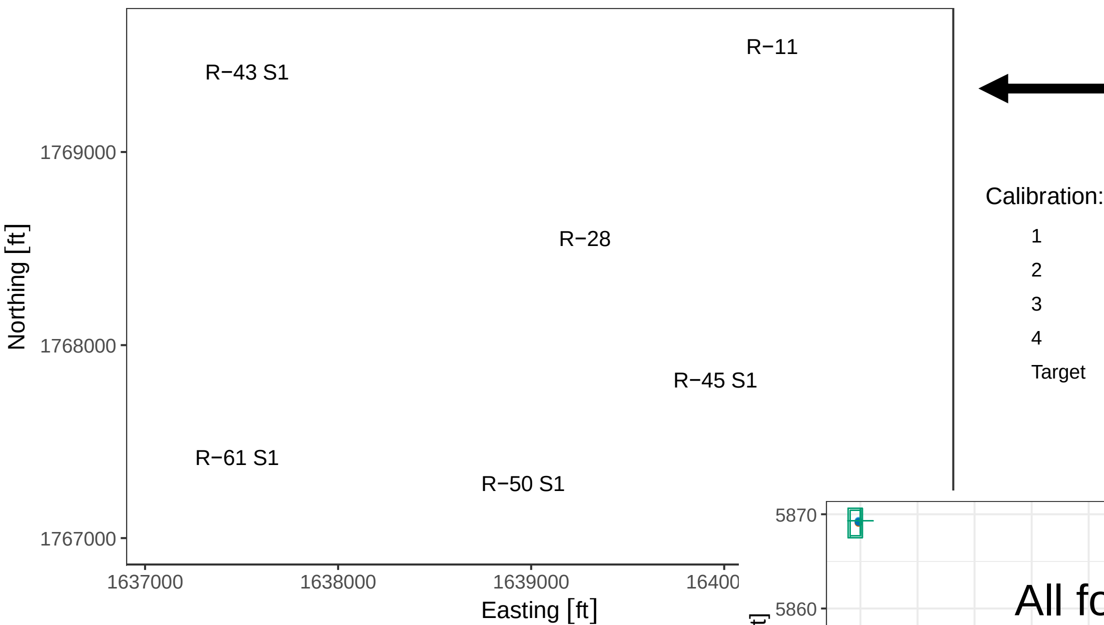
- Most matches, however, are within inches

- NOTE: only a single, deterministic calibration is shown at right

N3B Los Alamos

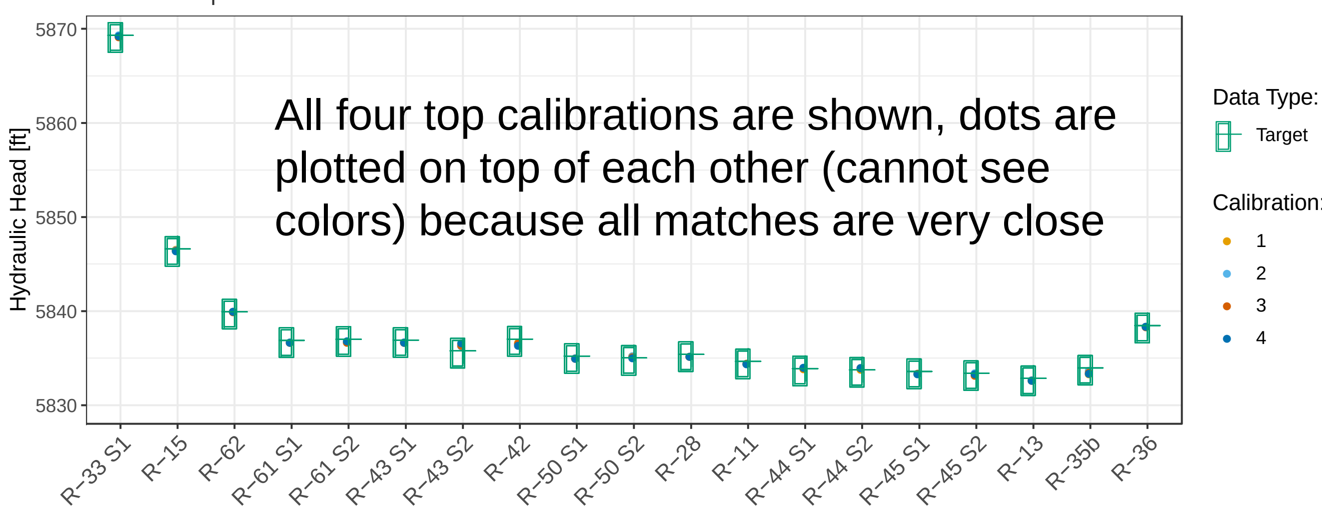
Calibration matches flow field (hydraulic gradients and heads)





Matches to gradients are so accurate that it is impossible to distinguish the individual arrows

Similarly, heads when viewed across the full site gradient (west to east) match targets closely

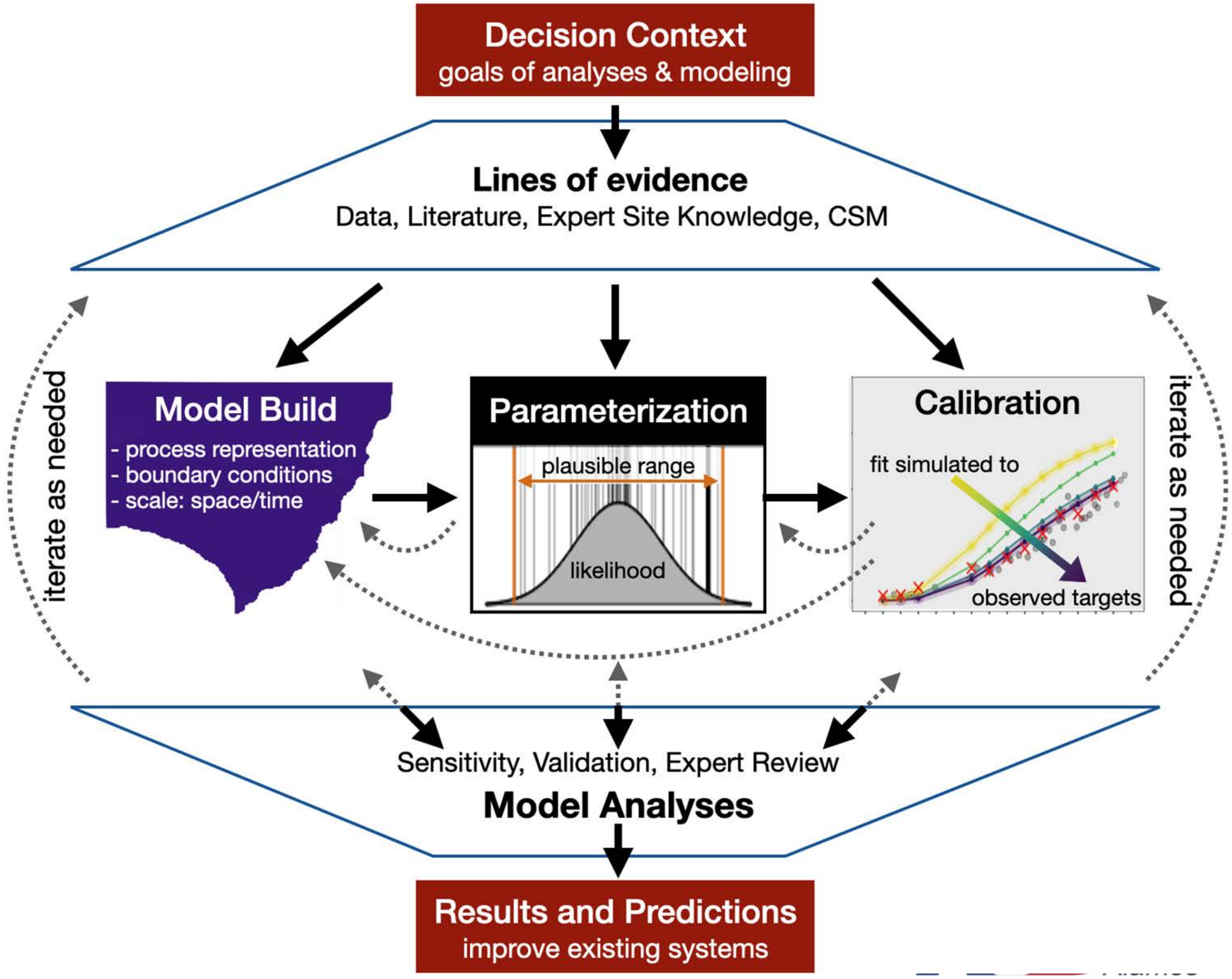


All four top calibrations are shown, dots are plotted on top of each other (cannot see colors) because all matches are very close

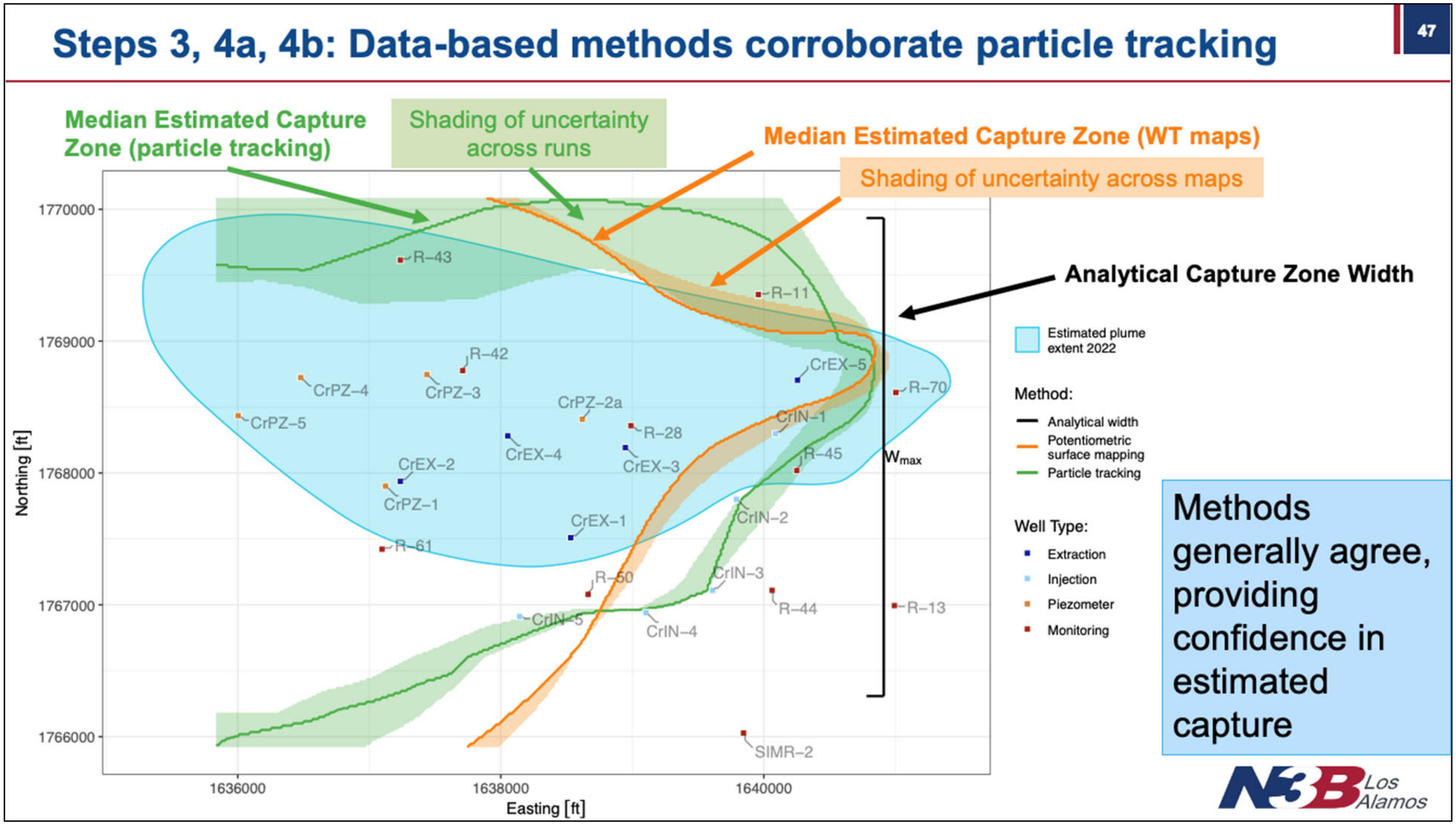
Outline of modeling framework

"Mathematical modeling may be used to organize vast amounts of disparate data into a sensible framework"

– EPA on evaluating pump and treat systems



Results: CZ agree across methods and is effective in South / SE



Discussion and Next Steps

- ITERATIVE: As new data and information becomes available the model will be improved, recalibrated, and analyses can be re-run
- Address uncertainties: use the model to help identify new datapoints (well locations) that reduce uncertainty and improve understanding
- Scenarios:
  - Understand and explore uncertainty with depth (especially using new data from R-76 and R-77)
  - Optimize the system towards decision endpoints
- Additional analyses:
  - Run hypothetical/intentional experiments (from realistic to extreme conditions) to better understand mechanism for observations. What are the MECHANISMS for the OBSERVED BEHAVIOR (i.e. better understand the reason for increasing concentrations at R-45 screen 2)

Appendix C

Cr IM Capture/Flood Zone Analysis
(on CD included with this document)

Cr IM Capture/Flood Zone Analysis

Forthcoming report (Spring 2023) will provide full details

Outline

- Following EPA (2008) to the letter:

Six Steps for Systematic Evaluation of Capture Zones

Step 1: ***Review site data, site conceptual model, and remedy objectives***

Step 2: ***Define site-specific Target Capture Zone(s)***

Step 3: ***Interpret water levels***
- potentiometric surface maps (horizontal) and water level difference maps (vertical)
- water level pairs (gradient control points)

Step 4: ***Perform calculations***
- estimated flow rate calculation
- capture zone width calculation (can include drawdown calculation)
- modeling (analytical or numerical) to simulate water levels, in conjunction with particle tracking and/or transport modeling

Step 5: ***Evaluate concentration trends***

Step 6: ***Interpret actual capture based on Steps 1-5, compare to Target Capture Zone(s), assess uncertainties and data gaps***

Step 1: Review Site Data, Conceptual Model, and Remedy Objectives

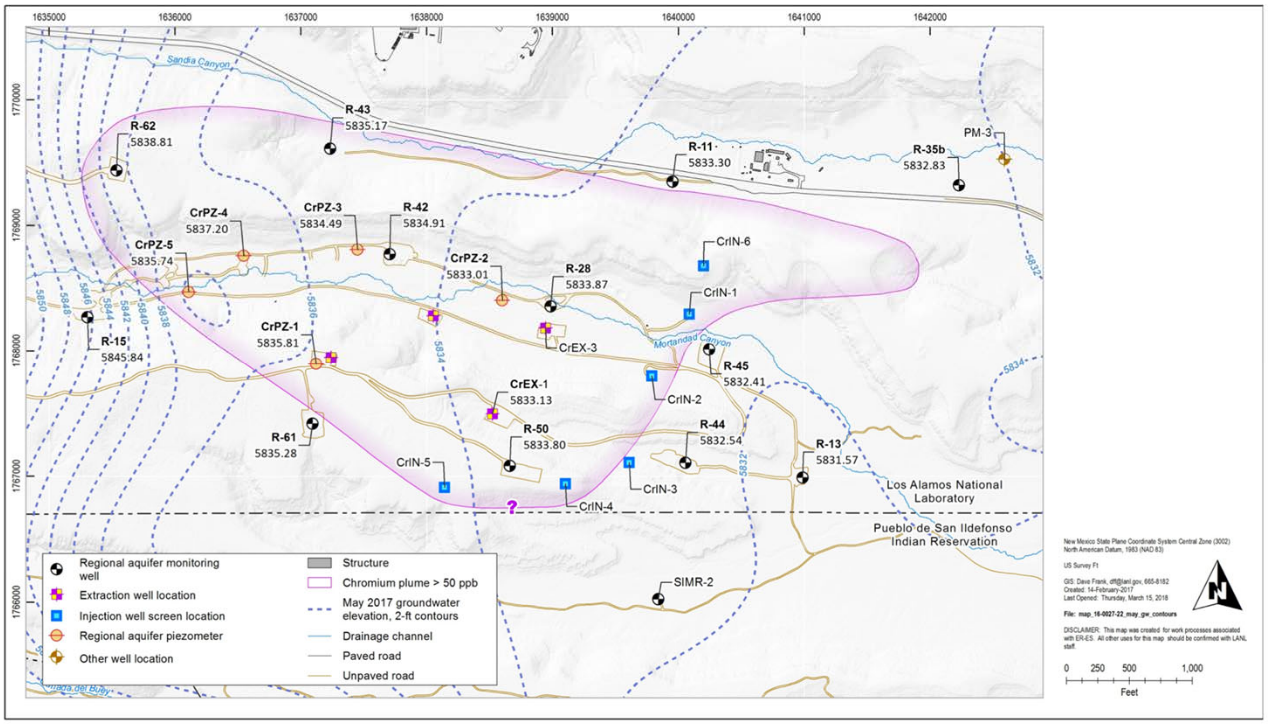
- Monitoring well network data:
  - Stratigraphy [once]
  - Aquifer testing [typically, once]: *K*, storativity, anisotropy
  - Hydraulic head [every ~1 hour]
  - Chemical sampling [every ~1 month] (in the immediate Cr plume area)

- Approach is iterative, as described by EPA and analyses should be revisited and improved as new data (R-76, R-77 soon) become available
  - Adaptive management as new information becomes available
  - Data Quality Objectives (DQO) process for future well site selection

- Conceptual Site Model
  - Key aspects that lead to modeling assumptions will be revisited in the presentation (slides sent to NMED) on the Cr Regional Model
  - Additional detail is provided in previous reporting and could schedule an entire presentation in future on this topic if desired

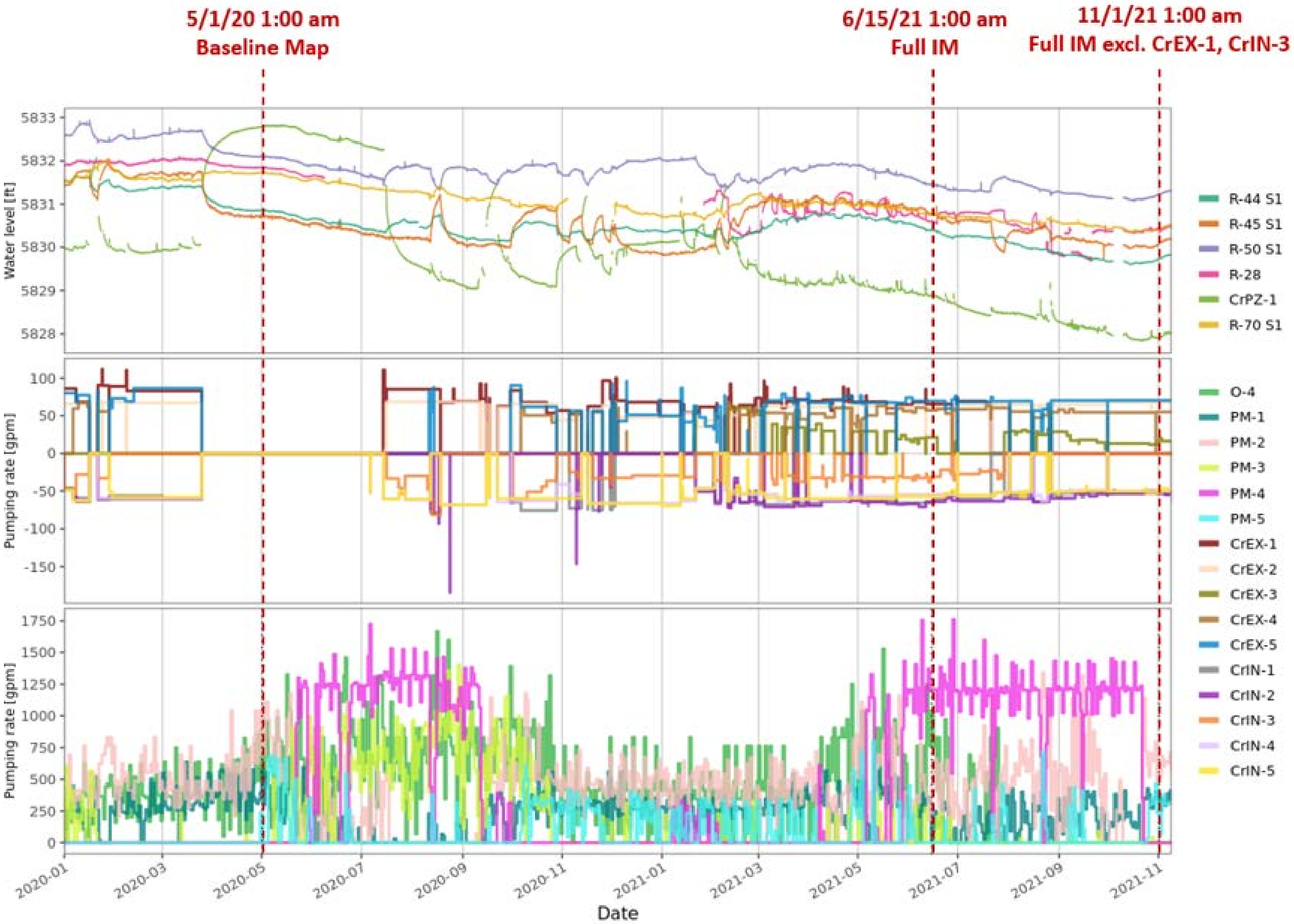
Step 2: Define Target Capture Zone

- IM objectives (LANL 2015, map from 2017 Work Plan):
  - To achieve and **maintain the 50-ppb downgradient plume edge within the laboratory** boundary
    - Metric: reduction of Cr at R-50 to under 50 ppb within 3 yr
  - **Hydraulically control plume migration** in the eastern, downgradient portion of the plume
  - Utilize information obtained from the IM to refine the hydrogeologic understanding of the site



Step 3: Interpret Water Levels | Water Table Maps – Data Processing

- Synoptic times selected based on activity of interest:



Step 3: Interpret Water Levels | Water Table Maps – Data Processing

- Wells used:
  - R-13 used for both shallow & deep
  - R-35a heavily impacted by PM-3, not used
  - R-36 excluded
  - R-33 S2 heavily impacted by PM-4, not used when PM-4 is operational
  - No infrastructure wells (CrEX/CrIN)
  - Newer wells not available at the time of this analysis will be included in future analyses
- List agreed upon with NMED

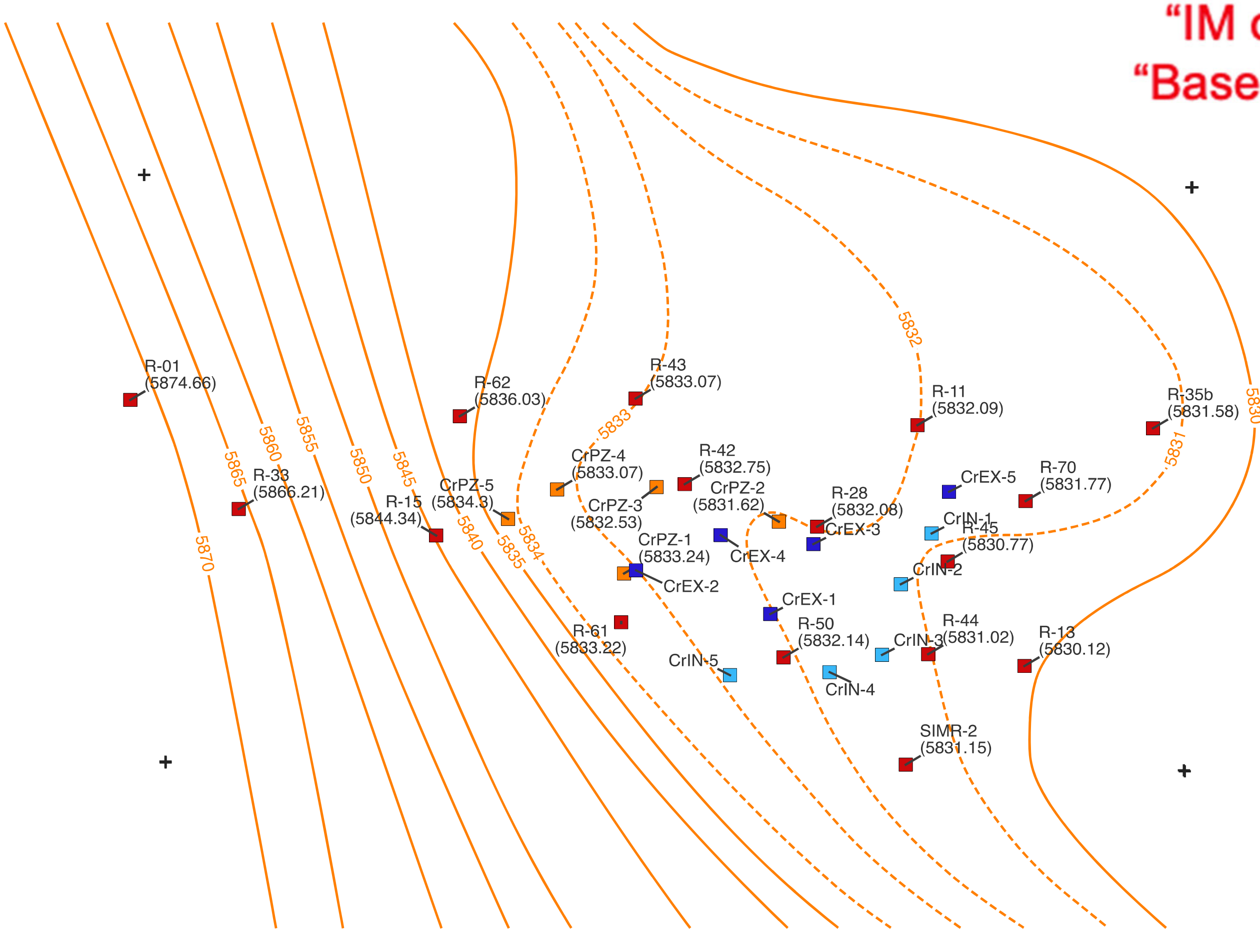
Well locations used for water-table maps

Shallow Screens	Comments	Deep Screens	Comments
CrPZ-1		CrPZ-2b	Shallower than other S2's
CrPZ-2a		R-13	Crosses Tpf/Tpf(p)/Tjfp
CrPZ-3		R-33 S2	Excluded when PM-4 is pumping
CrPZ-4		R-43 S2	Entirely in Tcar
CrPZ-5		R-44 S2	
SIMR-2		R-50 S2	
R-1		R-61 S2	
R-11		R-70 S2	
R-13	Deeper than other "shallow" screens; crosses Tpf/Tpf(p)/Tjfp		
R-15	Longer than most shallow screens, crosses Tpf/Tpf(p)/Tjfp		
R-28			
R-33 S1			
R-35b			
R-42	In Tjfp		
R-43 S1	Straddles Tjfp/Tcar, mostly in Tcar		
R-44 S1			
R-45 S1			
R-50 S1			
R-61 S1			
R-62	In Tjfp		
R-70 S1			

Step 3: Interpret Water Levels | Water Table Maps – Shallow Comparisons

- **Baseline**: flow generally west to east, southeast

5/1/20
“IM off”
“Baseline”



IM Well	Pumping Rate (gpm)	
CrEX-1	0	66
CrEX-2	0	61
CrEX-3	0	22
CrEX-4	0	57
CrEX-5	0	70
CrIN-1	0	-65
CrIN-2	0	-64
CrIN-3	0	-31
CrIN-4	0	-55
CrIN-5	0	-57

Regional Monitoring Well
Regional Piezometer
Extraction Well
Injection Well
Ambient Contours
IM On Contours

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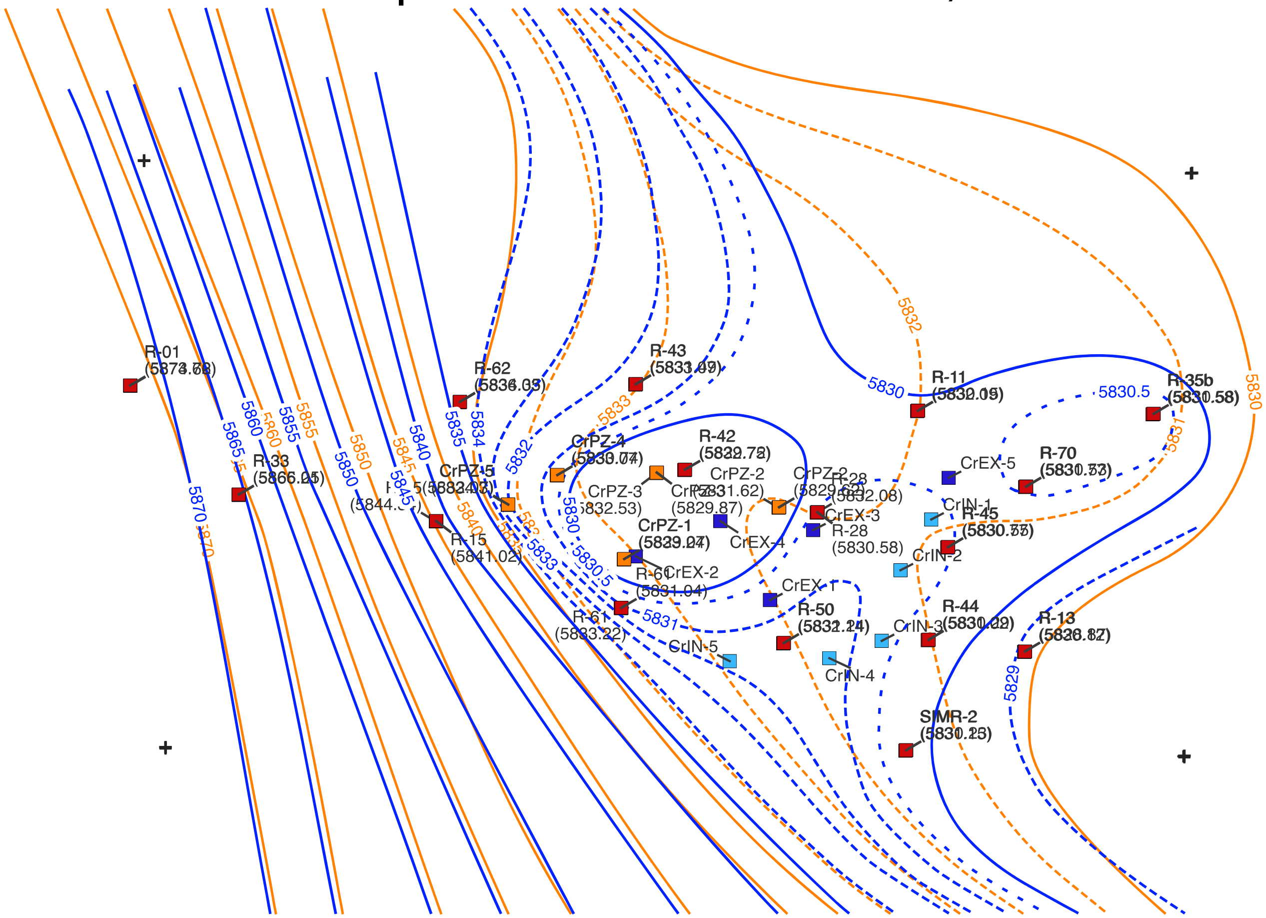
Step 3: Interpret Water Levels | Water Table Maps – Shallow Comparisons

- **Baseline** versus **IM on**: Cone of depression in central area, ridging coincident with CrINs, CrEX-5 breaks up an otherwise flat area, flow now West to East/Northeast



IM Well	Pumping Rate (gpm)	
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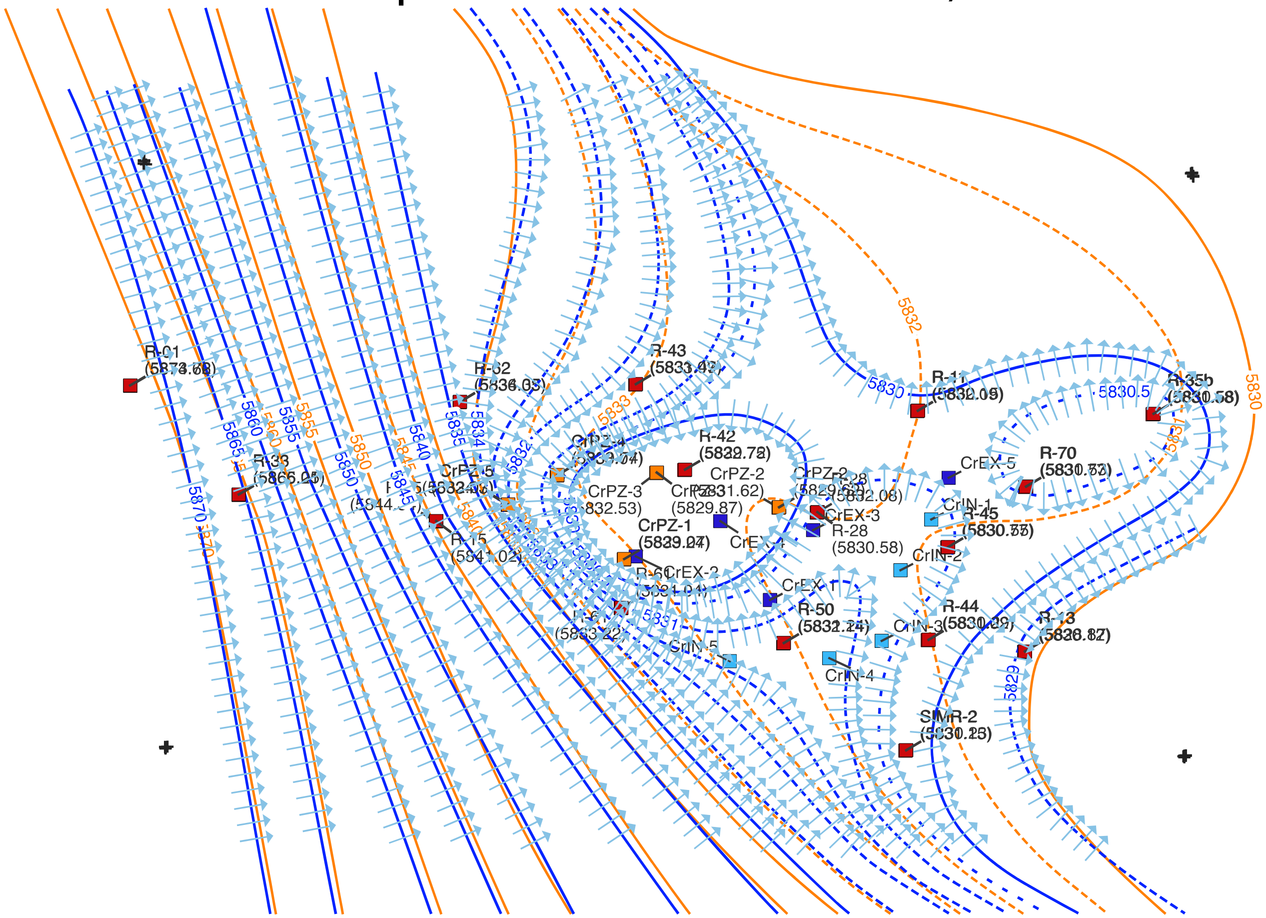
CrEX-2	0	61
CrEX-3	0	22
CrEX-4	0	57
CrEX-5	0	70
CrIN-1	0	-65
CrIN-2	0	-64
CrIN-3	0	-31
CrIN-4	0	-55
CrIN-5	0	-57

Regional Monitoring Well
Regional Piezometer
Extraction Well
Injection Well
Ambient Contours
IM On Contours

Step 3: Interpret Water Levels | Water Table Maps – Shallow Comparisons

- **Baseline** versus **IM on**: Cone of depression in central area, ridging coincident with CrINs, CrEX-5 breaks up an otherwise flat area, flow now West to East/Northeast



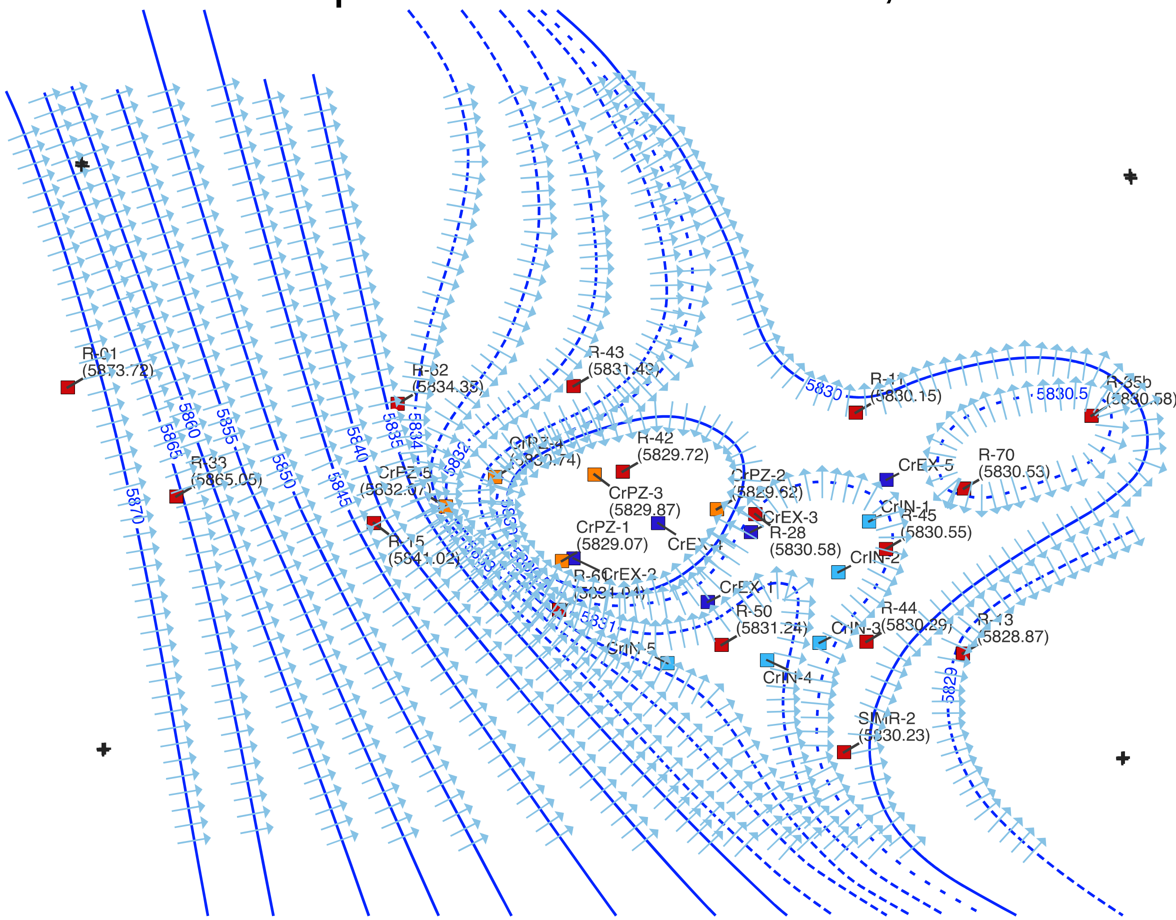
IM Well	Pumping Rate (gpm)	
CrEX-1	0	66
CrEX-2	0	61
CrEX-3	0	22
CrEX-4	0	57
CrEX-5	0	70
CrIN-1	0	-65
CrIN-2	0	-64
CrIN-3	0	-31
CrIN-4	0	-55
CrIN-5	0	-57

Regional Monitoring Well
Regional Piezometer
Extraction Well
Injection Well
Ambient Contours
IM On Contours

Los Alamos

Step 3: Interpret Water Levels | Water Table Maps – Shallow Comparisons

- **Baseline** versus **IM on**: Cone of depression in central area, ridging coincident with CrINs, CrEX-5 breaks up an otherwise flat area, flow now West to East/Northeast



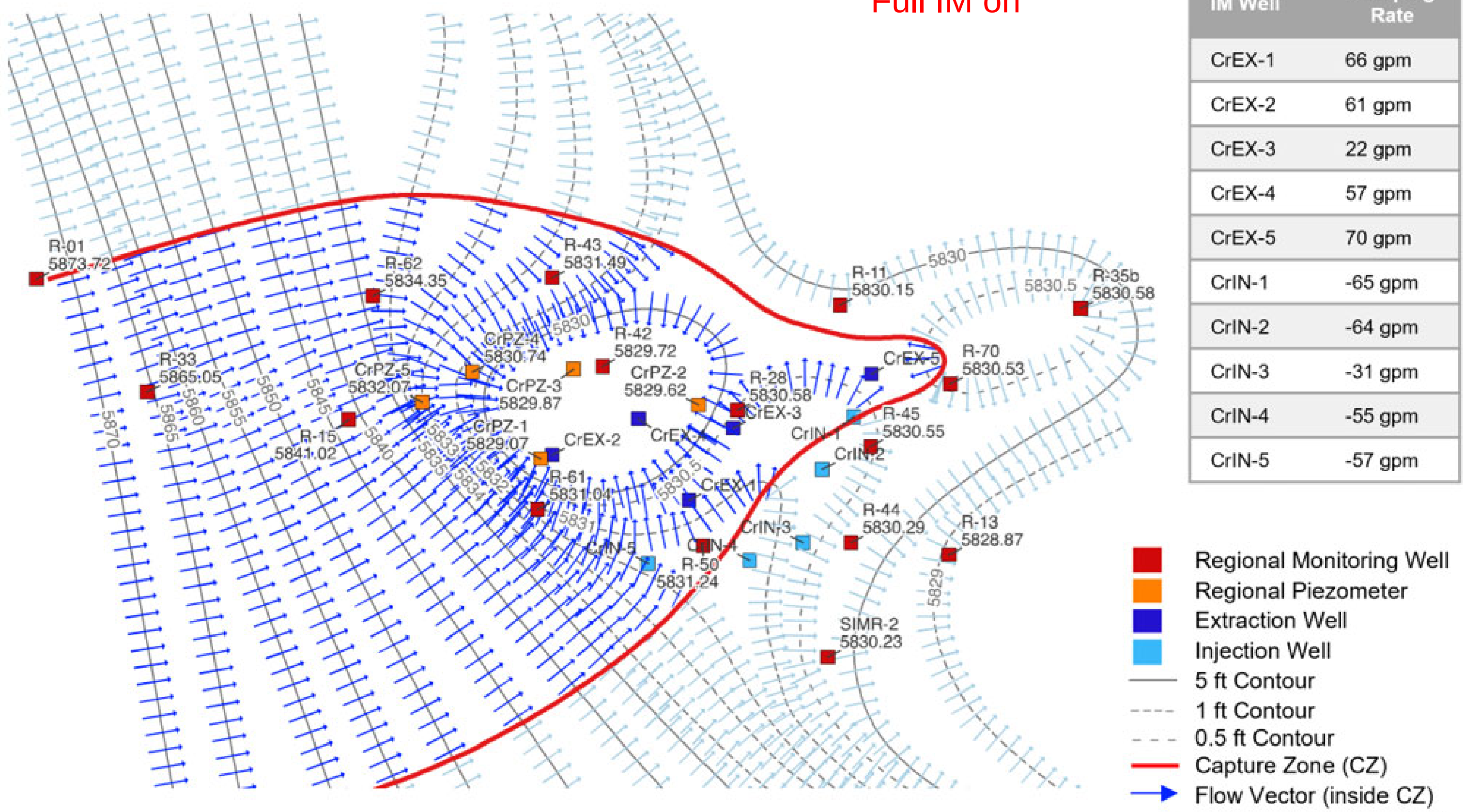
IM Well	Pumping Rate (gpm)	
CrEX-1	0	66
CrEX-2	0	61
CrEX-3	0	22
CrEX-4	0	57
CrEX-5	0	70
CrIN-1	0	-65
CrIN-2	0	-64
CrIN-3	0	-31
CrIN-4	0	-55
CrIN-5	0	-57

- Regional Monitoring Well
- Regional Piezometer
- Extraction Well
- Injection Well
- Ambient Contours
- IM On Contours

Step 3: Interpret Water Levels | Water Table Maps – Shallow

- Perpendicular vectors define approximate capture zone:

6/15/21
"Full IM on"



IM Well	Pumping Rate
CrEX-1	66 gpm
CrEX-2	61 gpm
CrEX-3	22 gpm
CrEX-4	57 gpm
CrEX-5	70 gpm
CrIN-1	-65 gpm
CrIN-2	-64 gpm
CrIN-3	-31 gpm
CrIN-4	-55 gpm
CrIN-5	-57 gpm

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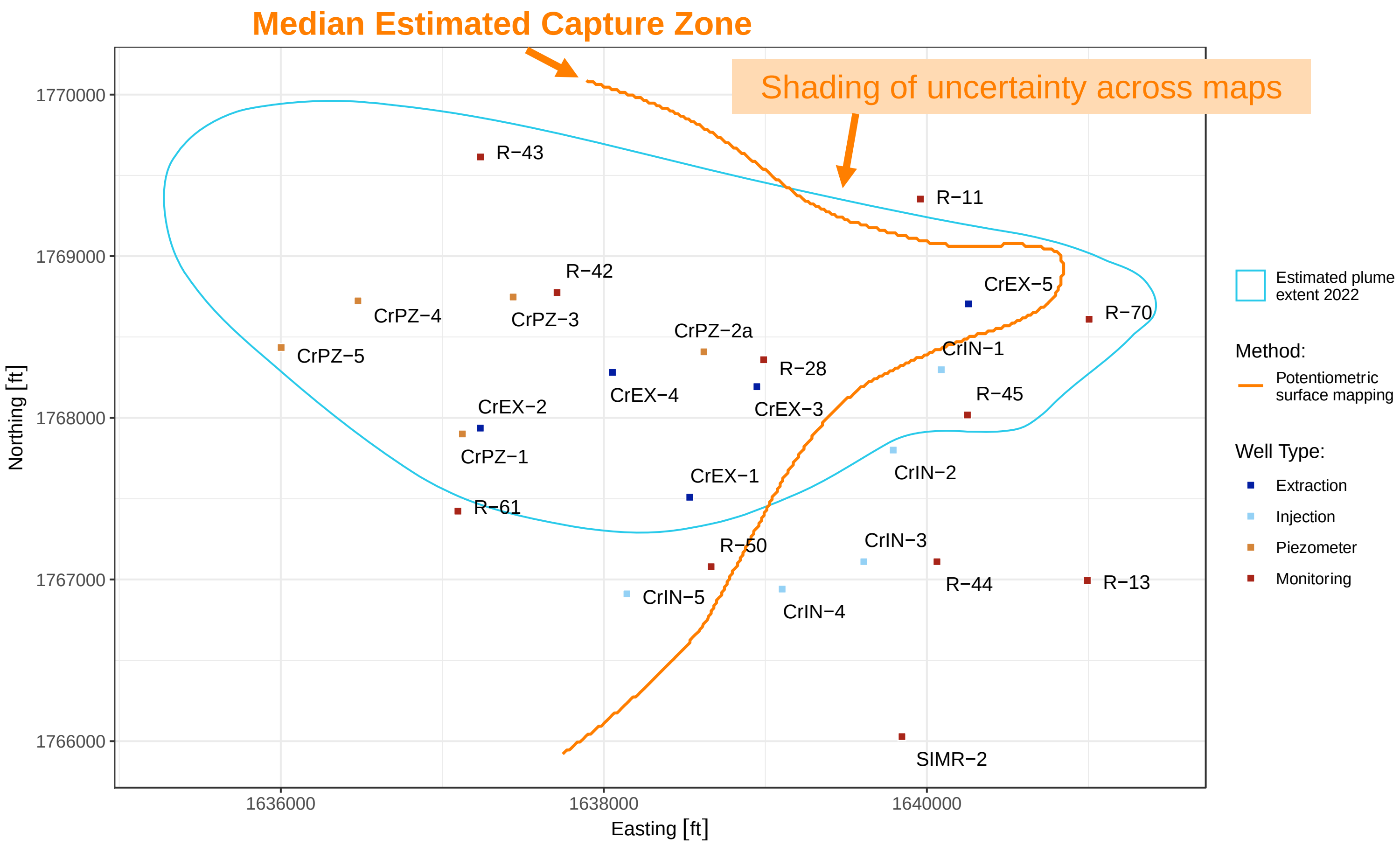
Step 3: Interpret Water Levels | Water Table Maps – Shallow



- Multiple dates of mapping allow for shading of uncertainty

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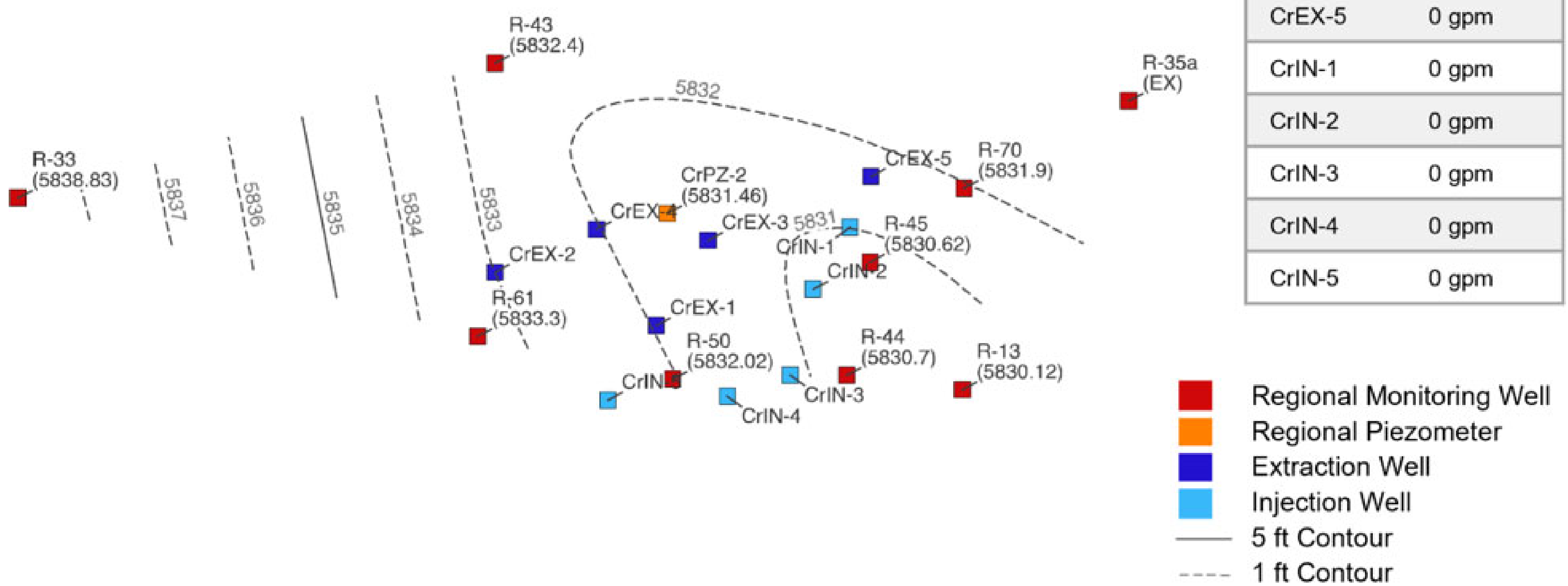
Step 3: Water Table Maps – Deep

5/1/20
"IM off"
"Baseline"

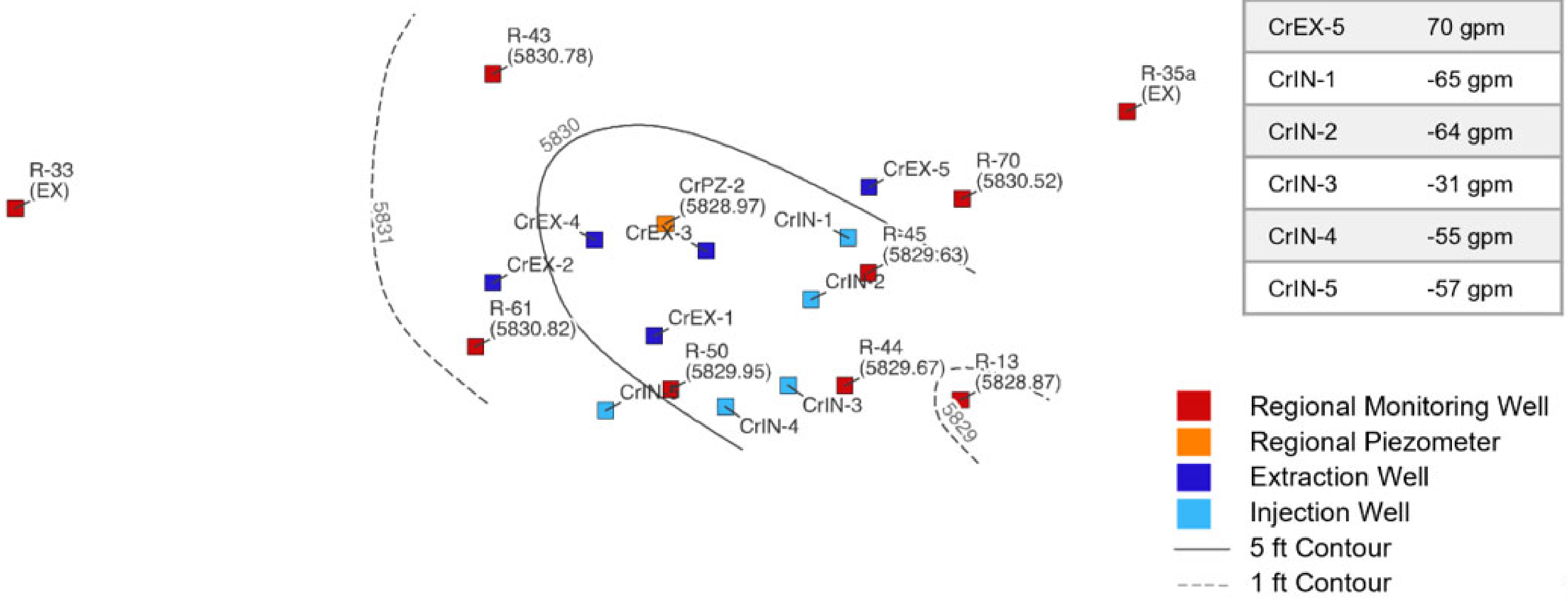


IM Well	Pumping Rate
CrEX-1	0 gpm
CrEX-2	0 gpm
CrEX-3	0 gpm
CrEX-4	0 gpm
CrEX-5	0 gpm
CrIN-1	0 gpm
CrIN-2	0 gpm
CrIN-3	0 gpm
CrIN-4	0 gpm
CrIN-5	0 gpm

Step 3: Water Table Maps – Deep

6/15/21
"Full IM on"

IM Well	Pumping Rate
CrEX-1	66 gpm
CrEX-2	61 gpm
CrEX-3	22 gpm
CrEX-4	57 gpm
CrEX-5	70 gpm
CrIN-1	-65 gpm
CrIN-2	-64 gpm
CrIN-3	-31 gpm
CrIN-4	-55 gpm
CrIN-5	-57 gpm



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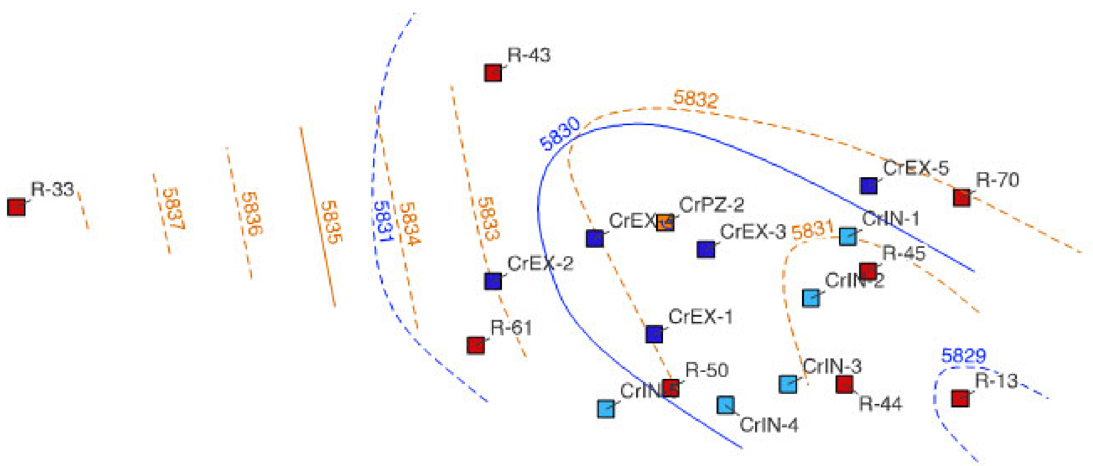
Step 3: Water Table Maps – Deep Comparisons

- **Baseline** versus **IM on**: Shallower hydraulic gradient… IM slows down deep flow
- Not enough data to estimate capture zone

IM Well	Pumping Rate (gpm)	
CrEX-1	0	66
CrEX-2	0	61
CrEX-3	0	22
CrEX-4	0	57
CrEX-5	0	70
CrIN-1	0	-65
CrIN-2	0	-64
CrIN-3	0	-31
CrIN-4	0	-55
CrIN-5	0	-57



Regional Monitoring Well
Regional Piezometer
Extraction Well
Injection Well
Ambient Contours
IM On Contours

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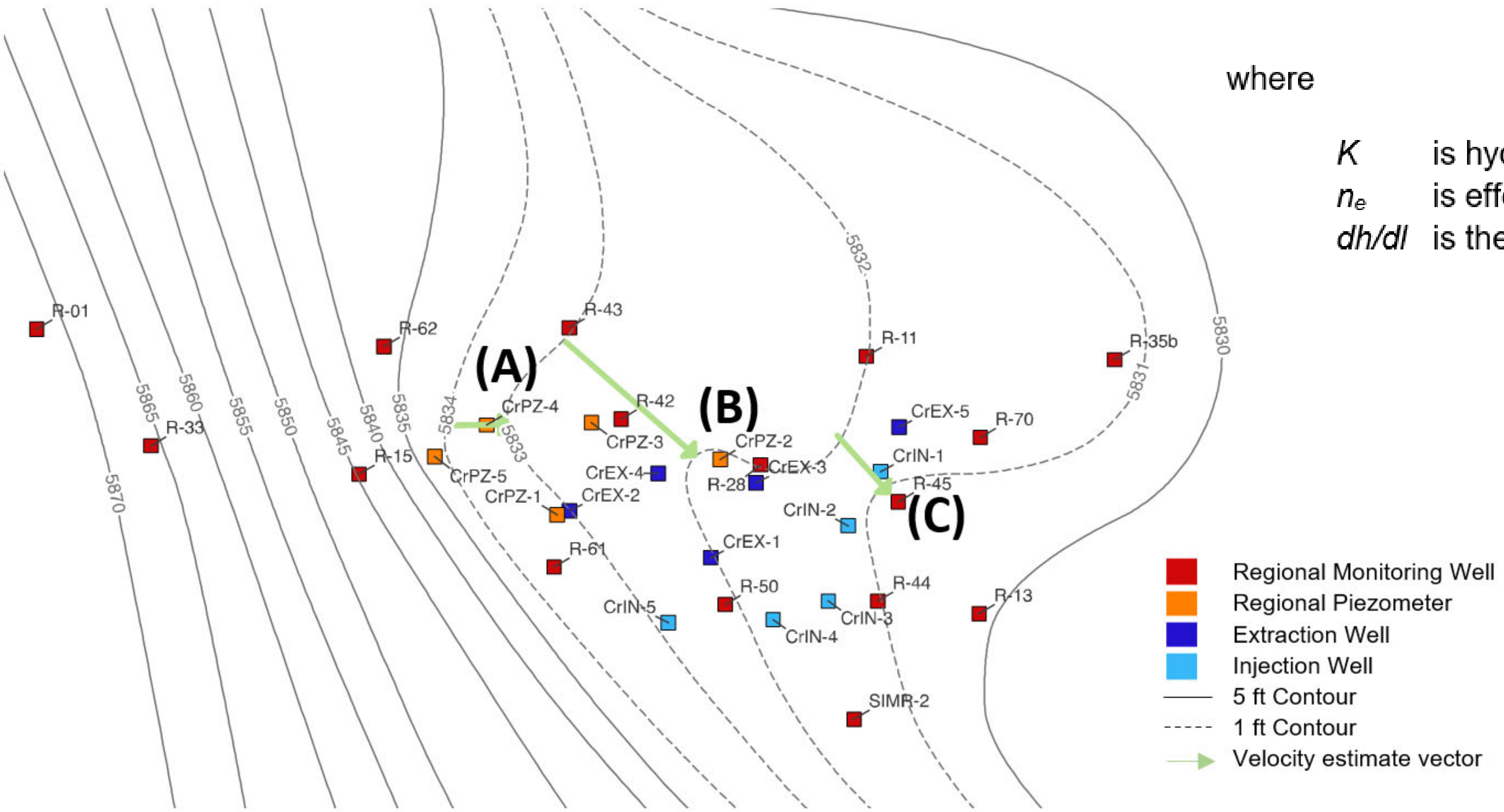
Additional (not EPA step): Velocities estimated from hydraulic data

- Need: estimated gradient, hydraulic conductivity, effective porosity

$$v = \frac{K}{n_e}\frac{dh}{dl},$$

where

K	is hydraulic conductivity [ft d^{-1}],
n_e	is effective (advective) porosity [–], and
dh/dl	is the local hydraulic gradient [–].



Additional (not EPA step): Velocities estimated from hydraulic data

Date	IM Status	Loc.	Hydraulic gradient[1] (ft/ft)	Nearest *K* estimate[2] (ft/d)	*K* range, 1/99th percent[3]	n_e range, 1/99th percent[4]	Velocity, closest *K* (ft/d)	Velocity range[5] (ft/d)	
5/1/2020	OFF	A	2E-03	3.42	(0.2, 685)	(0.06, 0.26)	0.036	1E-03	19
5/1/2020	OFF	B	6E-04	144	(0.2, 685)	(0.06, 0.26)	0.562	5E-04	6.9
5/1/2020	OFF	C	1E-03	42.5	(0.2, 685)	(0.06, 0.26)	0.364	1E-03	15
6/15/2021	Full	A	3E-03	3.42	(0.2, 685)	(0.06, 0.26)	0.062	2E-03	32
6/15/2021	Full	B	3E-03	144	(0.2, 685)	(0.06, 0.26)	2.588	2E-03	32
6/15/2021	Full	C	1E-04	42.5	(0.2, 685)	(0.06, 0.26)	0.029	9E-05	1.2
11/1/2021	CrEX-1 Off	A	2E-03	3.42	(0.2, 685)	(0.06, 0.26)	0.042	2E-03	22
11/1/2021	CrEX-1 Off	B	3E-03	144	(0.2, 685)	(0.06, 0.26)	2.684	2E-03	33
11/1/2021	CrEX-1 Off	C	1E-04	42.5	(0.2, 685)	(0.06, 0.26)	0.026	8E-05	1.1

1. Estimated from water table maps.
2. Mean hydraulic conductivity based on pumping tests at nearby wells.
3. Neptune (2022) – hydraulic conductivity development.
4. Porosity and advective porosity estimates from N3B (2020a).
5. Uncertainty in velocity with variable *K* and total porosity; hydraulic gradient and advective porosity fraction fixed.

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Step 4a: Analytical Estimates

- Estimated CZ width (full IM pumping at center location):

- Confined aquifer (EPA, 2008) for CrEX-1 at 65 gpm, w_{max} = 1708 ft, w_{well} = 854 ft

$$w_{well} = \frac{Q}{2Kbi} \qquad w_{max} = \frac{Q}{Kbi}$$

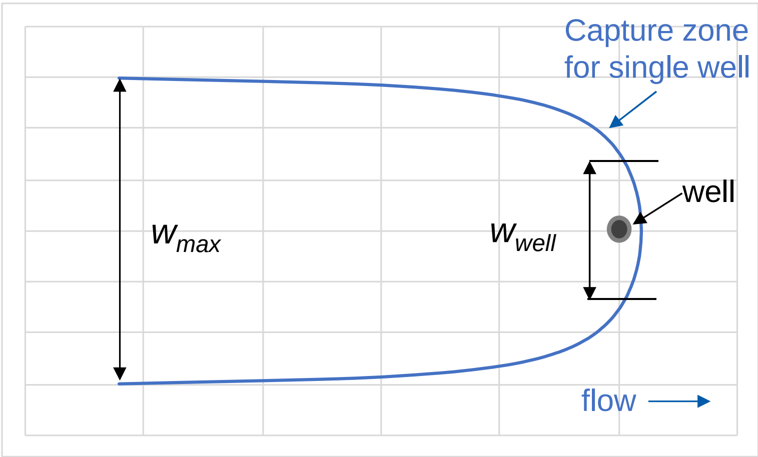
- Unconfined aquifer (Grubb, 1993) for CrEX-1 yields

  w_{max} = 1681 ft (similar)

$$w_{max} = \frac{QL}{K(h_1^2 - h_2^2)}$$

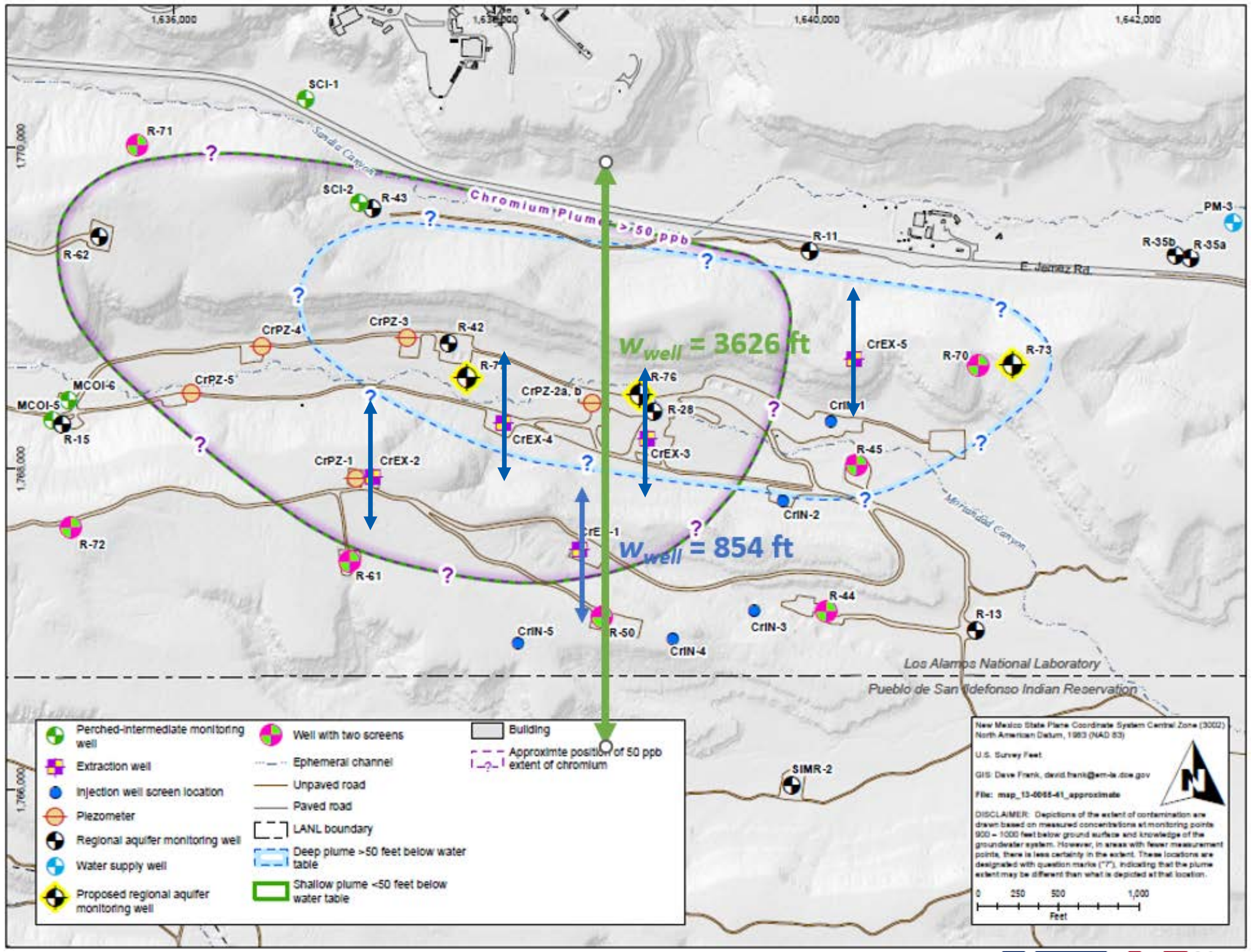
Variables:
Q – flow rate out of well [ft³/d]
K – hydraulic conductivity [ft/d]
b – aquifer thickness [ft]
i – horizontal hydraulic gradient [-]
h_1 – head at upgradient well (R-61) [ft]
h_2 – head at downgradient well (R-44) [ft]
L – Distance between down/upgradient wells

- Many assumptions including:
  - Homogeneous, isotropic, uniform-thickness aquifer
  - Fully-penetrating well
  - Steady-state flow
  - Negligible vertical gradients, no net recharge, no sources of water



Step 4a: Analytical Estimates

- For CrEX-1 at 65 gpm, w_{max} = 1708 ft, w_{well} = 854 ft
- For full IM at 276 gpm, w_{max} = 7252 ft, w_{well} = 3626 ft
- w_{max} is located at the limit where x reaches infinity… all interpretations of capture beyond these lines depend on subjective/approximate placement of w_{max}



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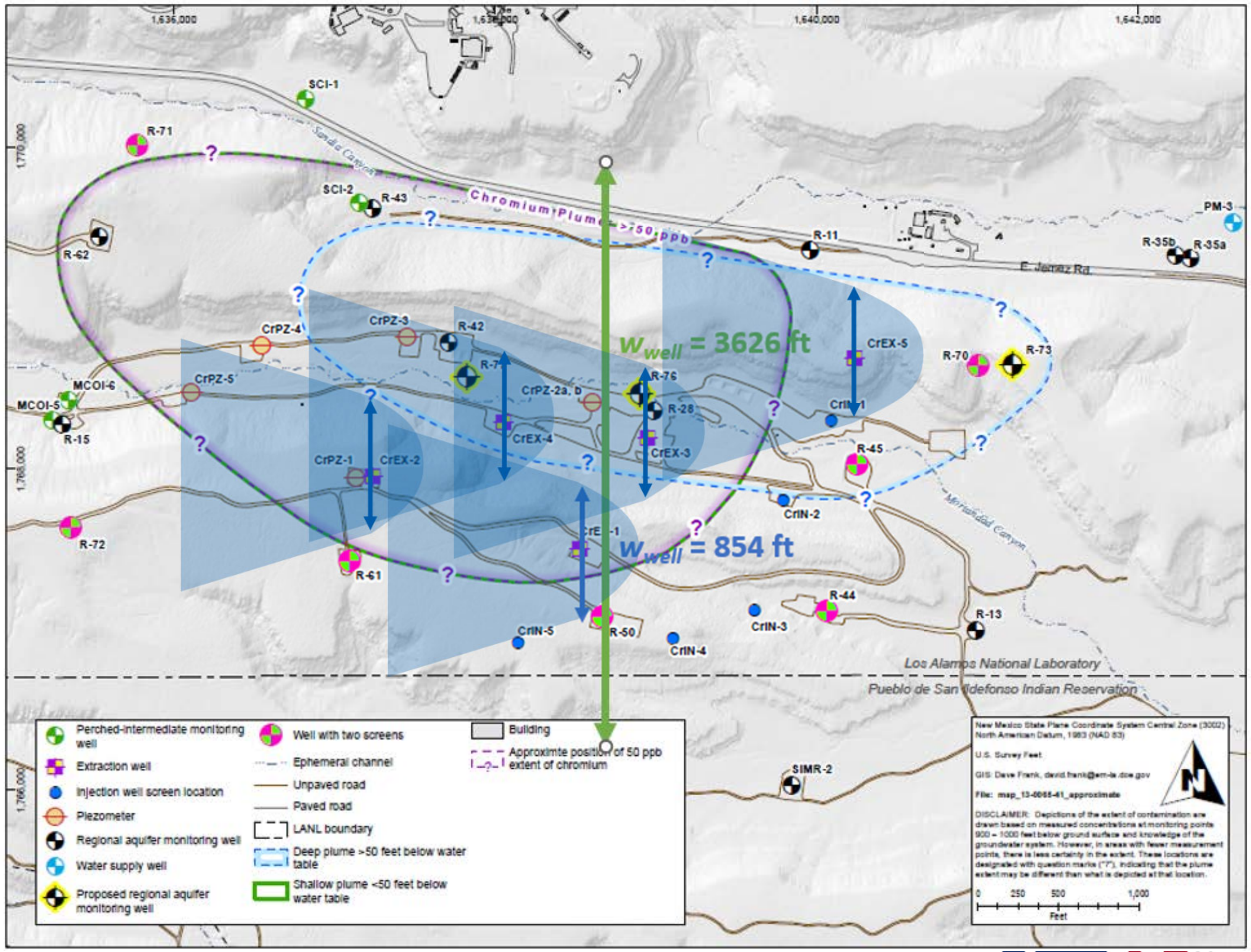

Step 4a: Analytical Estimates

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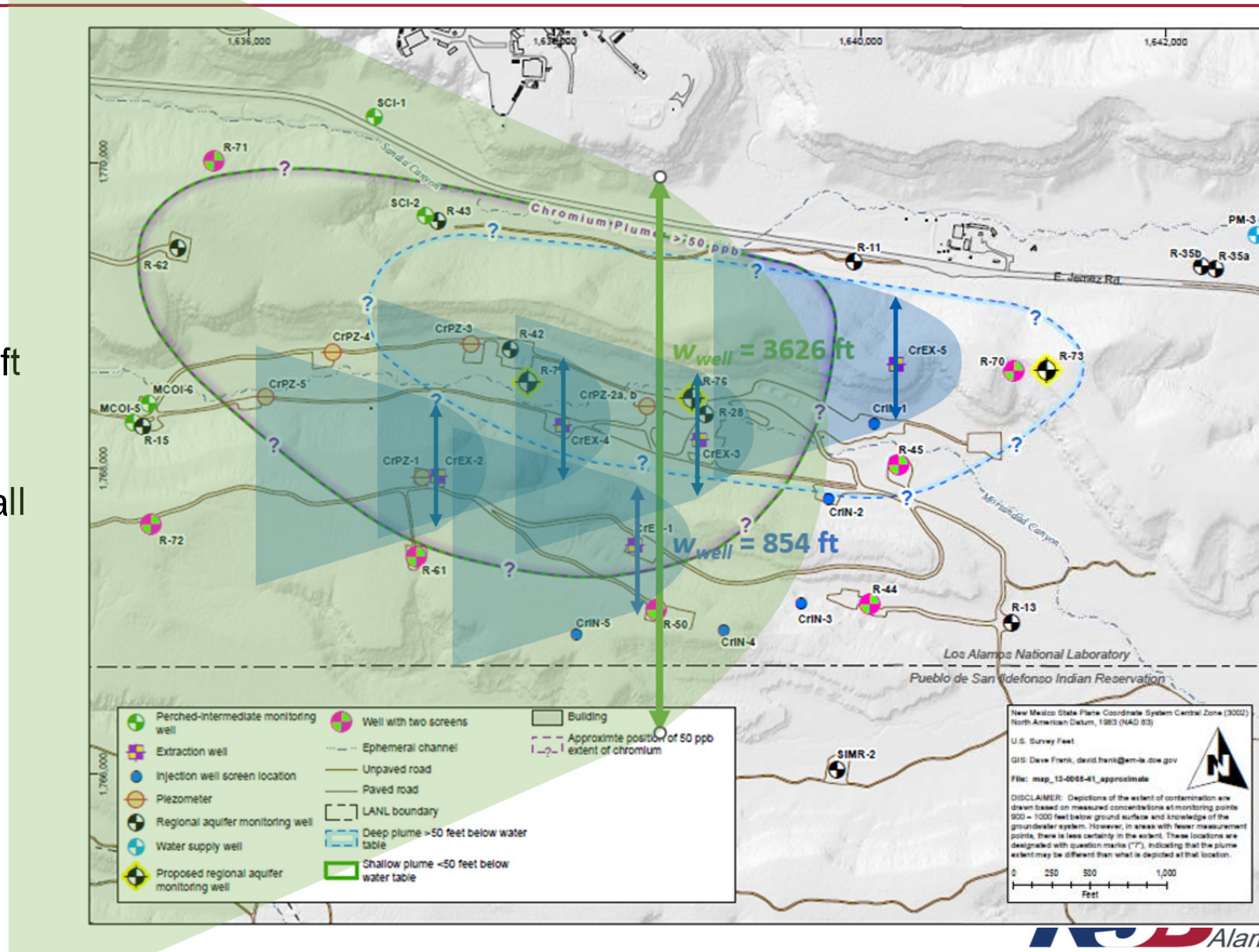
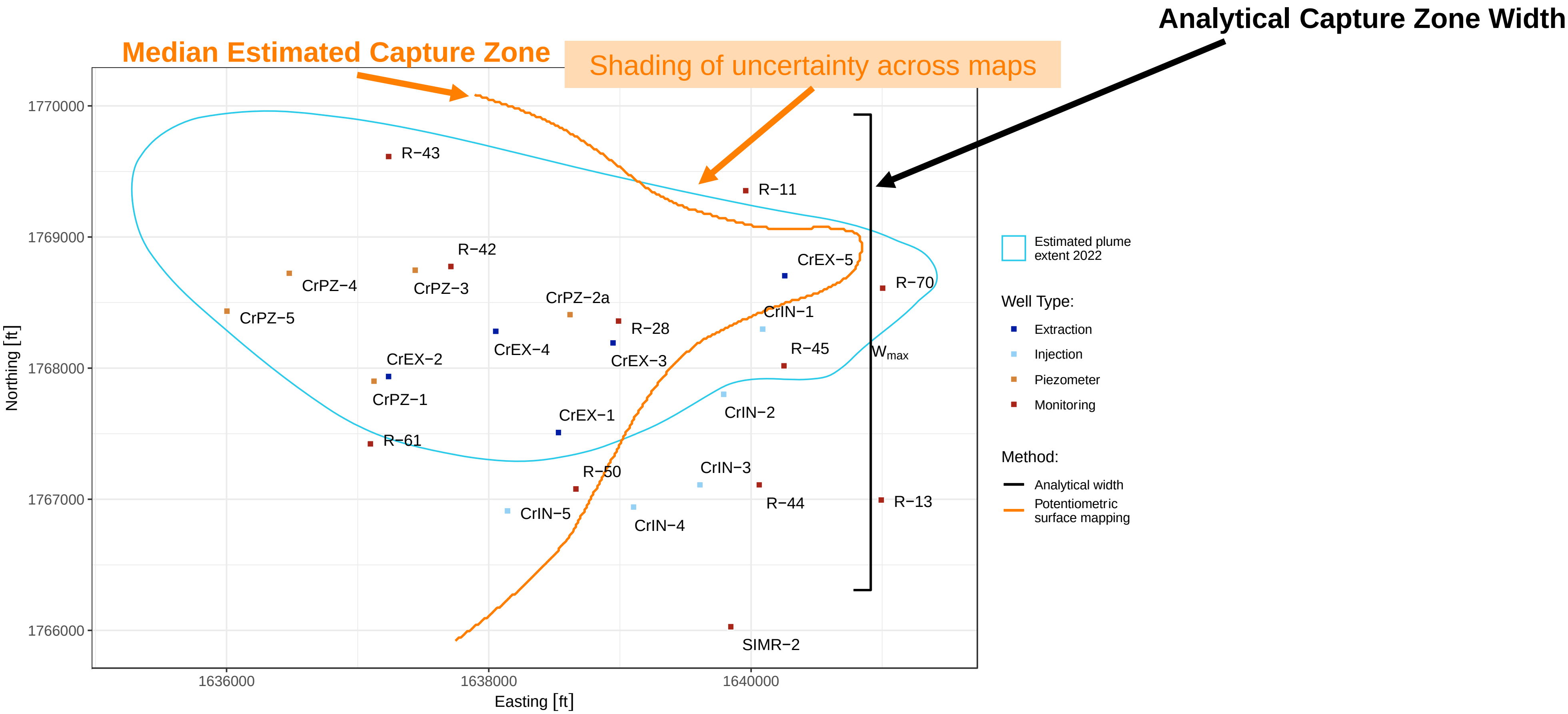


Step 3 and 4a: two lines of evidence

- Multiple dates of mapping allow for shading of uncertainty

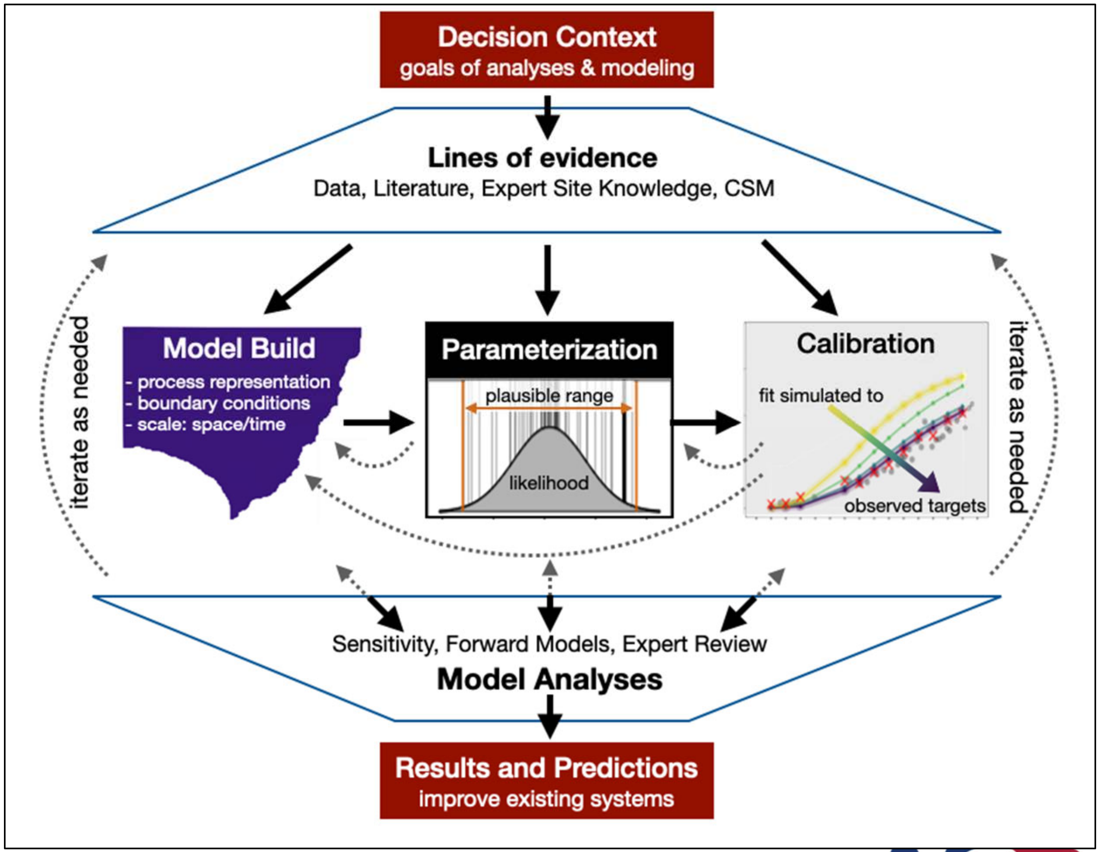


Step 4b: Numerical Calculations – Calibrated Model with Uncertainty

“Mathematical modeling may be used to organize vast amounts of disparate data into a sensible framework”

– EPA on evaluating pump and treat systems

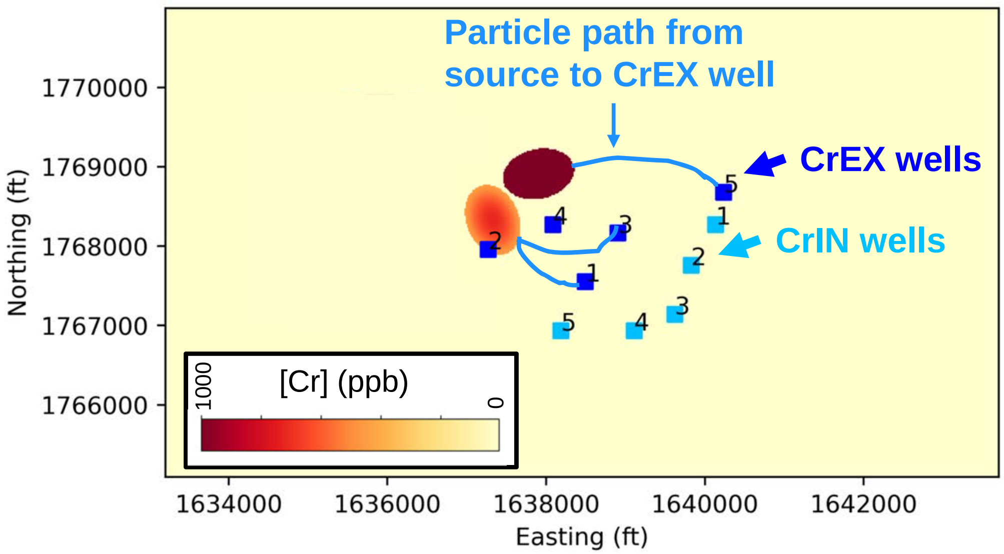
The Chromium Regional Model (framework shown below), will be discussed in detail at our next meeting. You already have the slides.



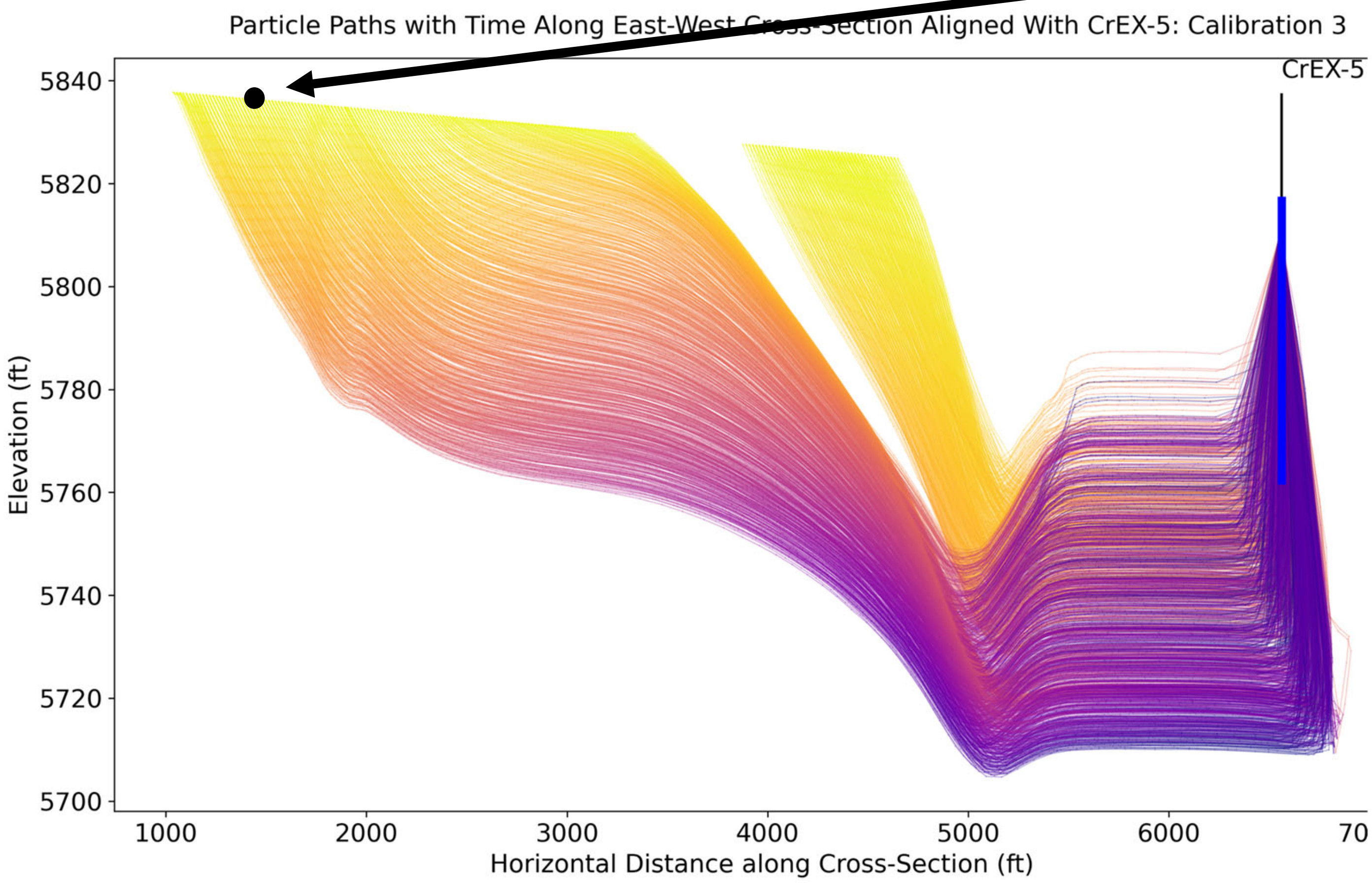
Step 4b: Numerical Calculations – Particle Tracking

- Particles are initialized at Cr sources on the water table and follow flow pathways

- Three particles are shown below, which arrive at CrEX wells and are captured

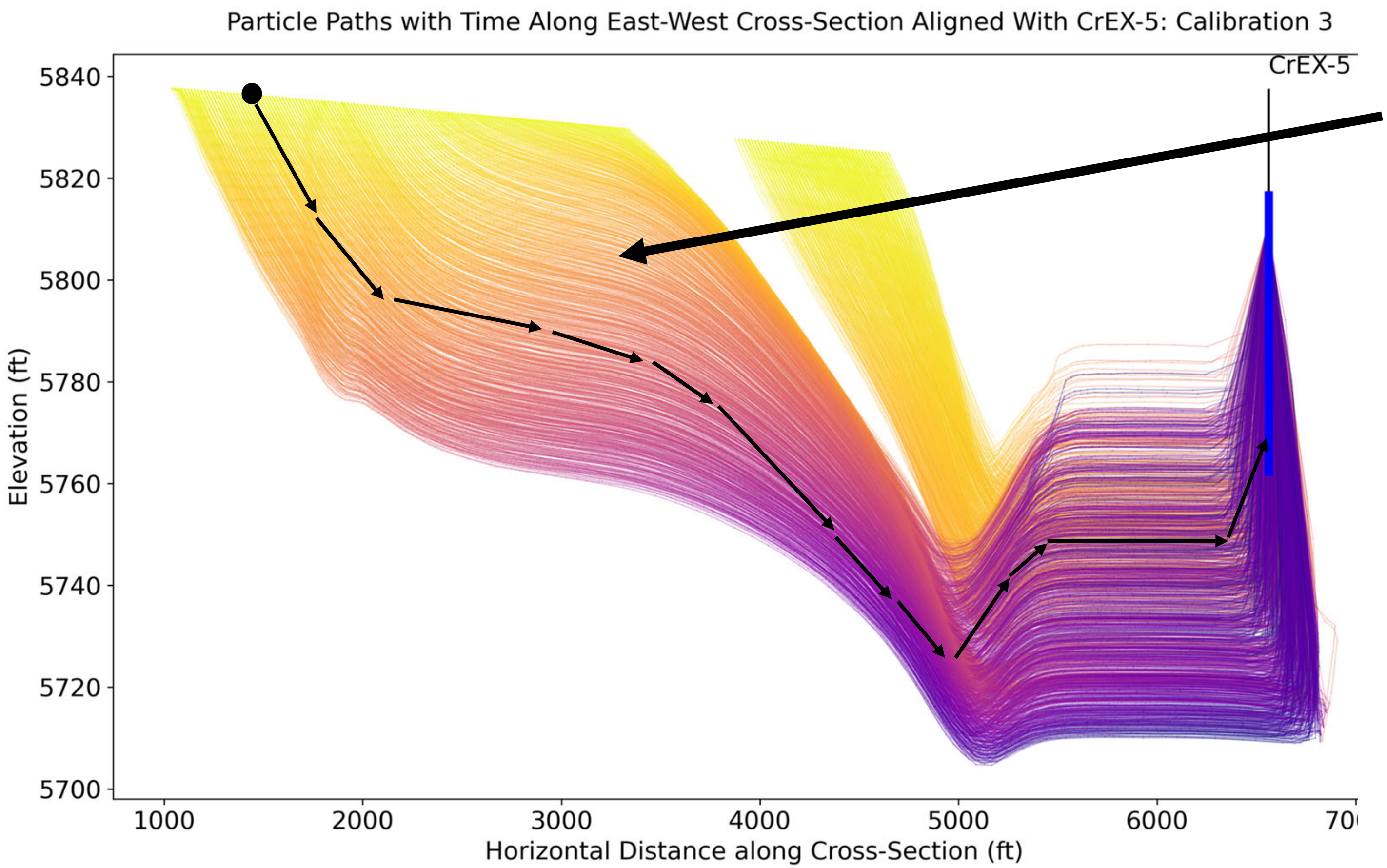


Step 4b: Numerical Calculations – Particle Tracking



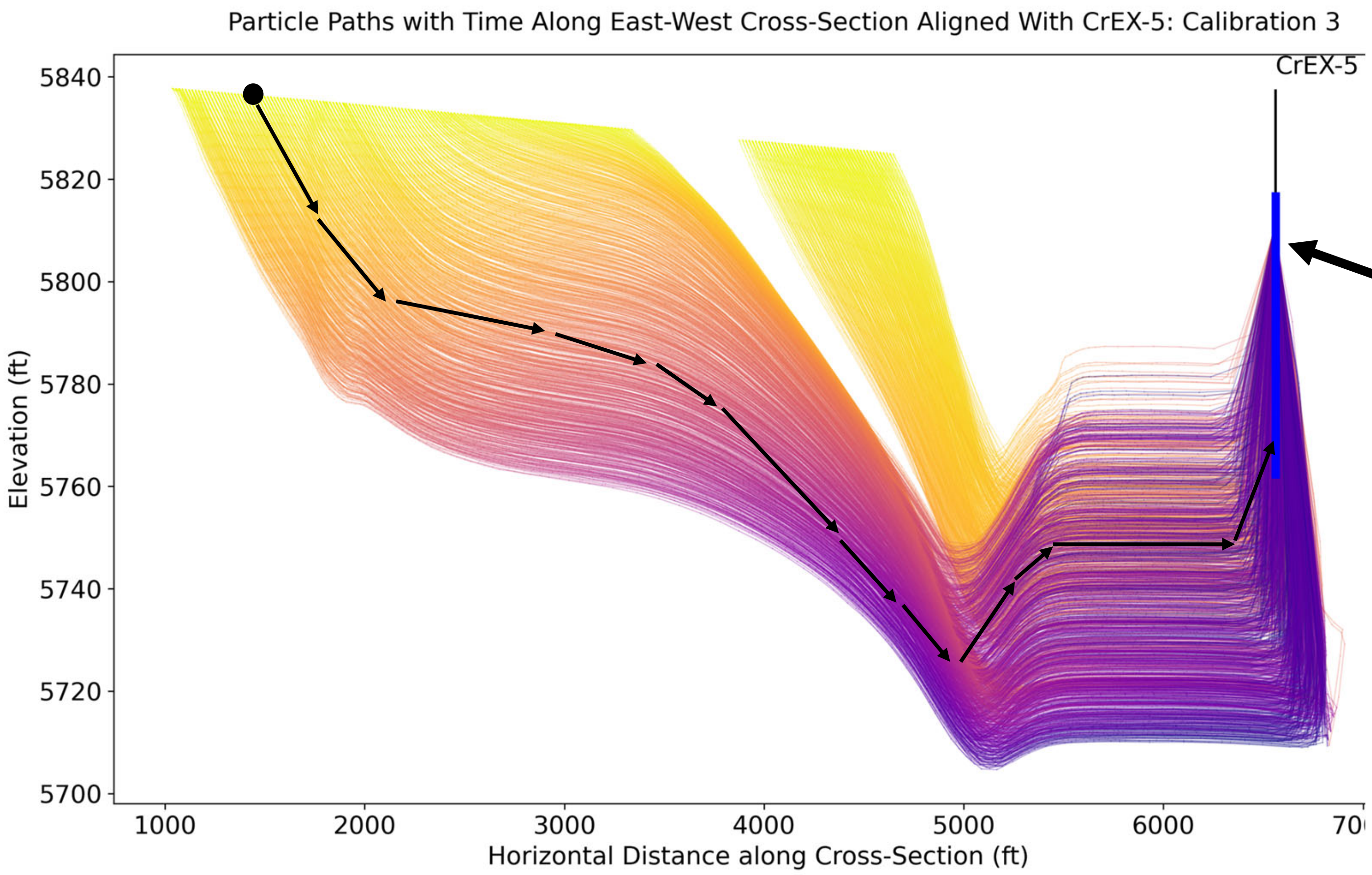
1. Release particles into the calibrated numerical model

Step 4b: Numerical Calculations – Particle Tracking



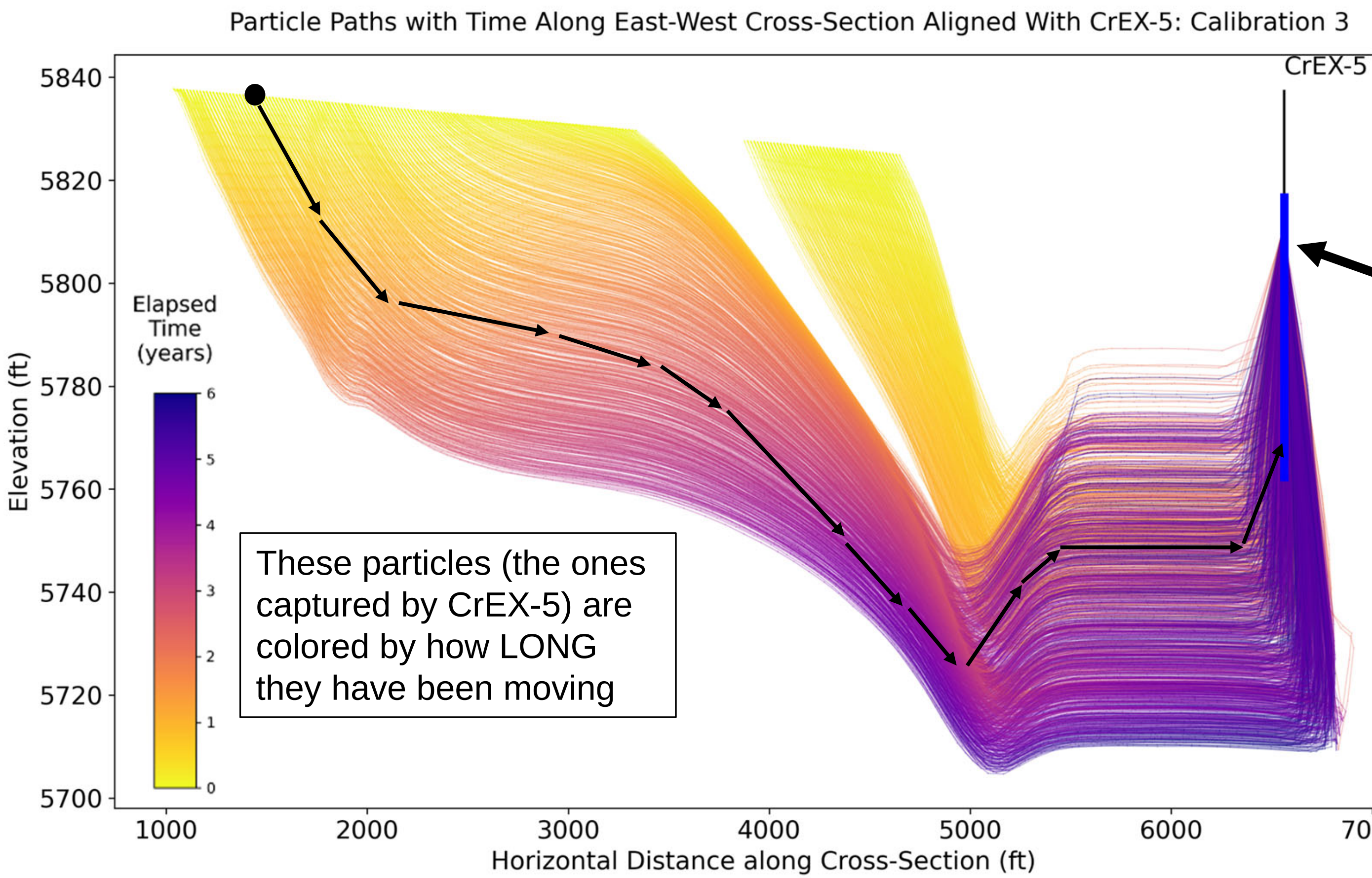
1. Release particles into the calibrated numerical model
2. The particles follow the hydraulic gradients/flow field

Step 4b: Numerical Calculations – Particle Tracking



1. Release particles into the calibrated numerical model
2. The particles follow the hydraulic gradients/flow field
3. If they encounter an extraction well screen they are removed from the model

Step 4b: Numerical Calculations – Particle Tracking



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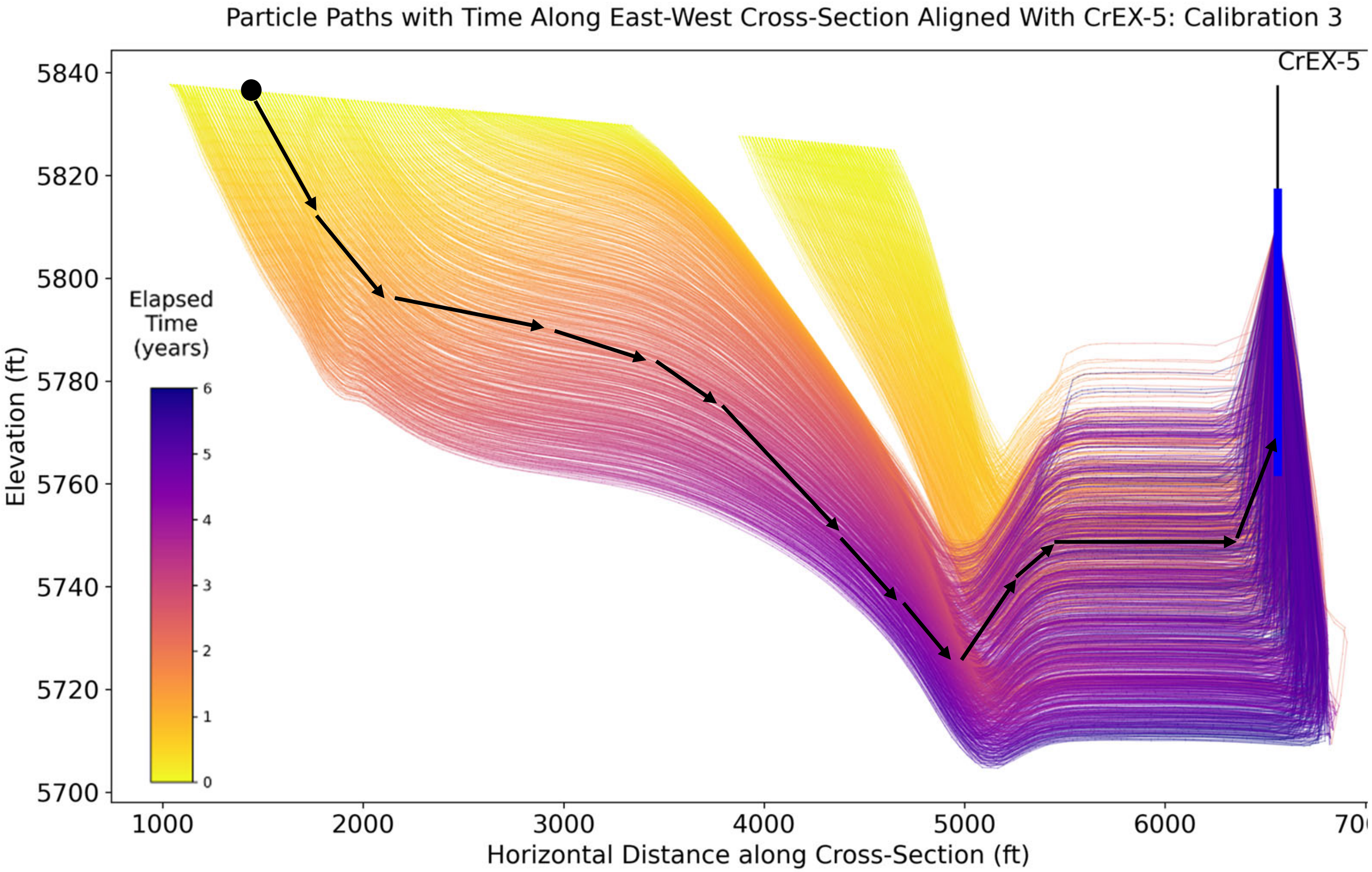


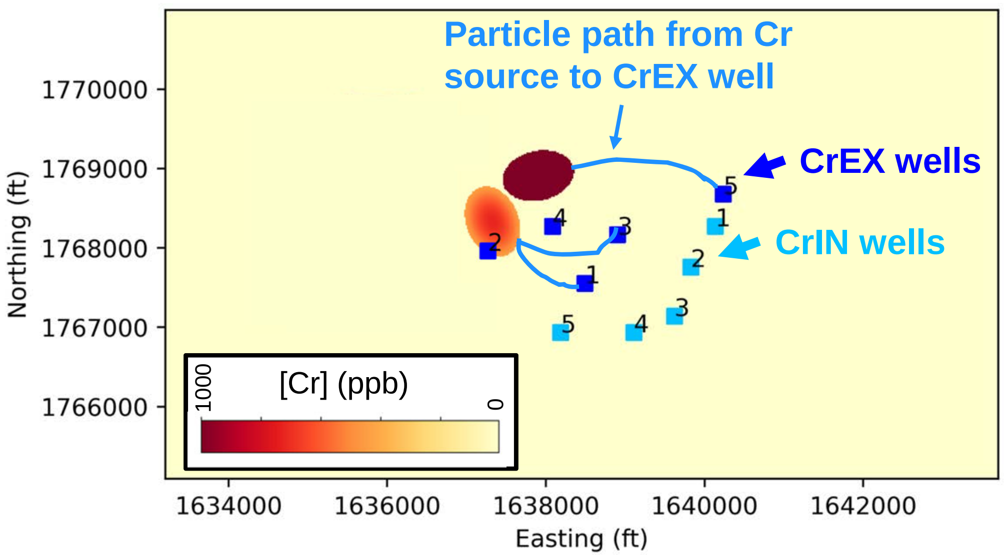
1. Release particles into the calibrated numerical model
2. The particles follow the hydraulic gradients/flow field
3. If they encounter an extraction well screen they are removed from the model
4. We can use this to estimate the “capture zone” by highlighting which particles are captured and which are uncaptured

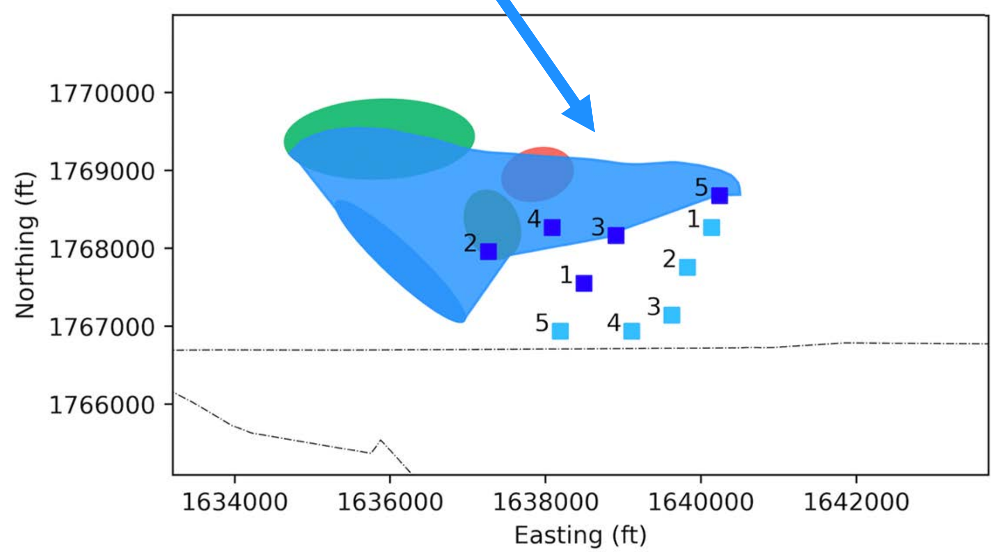
Step 4b: Numerical Calculations – Particle Tracking

- Particles are initialized at Cr sources on the water table and follow flow pathways

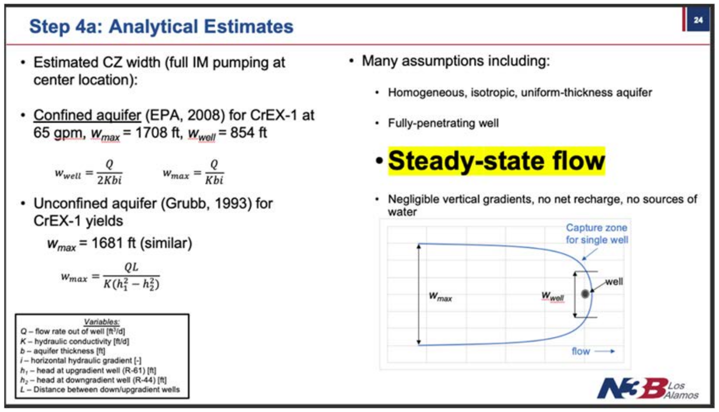
- Three particles are shown below, which arrive at CrEX wells and are captured

- Many particles are released, and the full region of particles that arrive at CrEX wells delineate the **capture zone**





Step 4b: Numerical Calculations – What is “steady-state”?



Step 4a: Analytical Estimates

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$$w_{well} = \frac{Q}{2Kbi} \qquad w_{max} = \frac{Q}{Kbi}$$

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  w_{max} = 1681 ft (similar)

$$w_{max} = \frac{QL}{K(h_1^2 - h_2^2)}$$

Variables:
Q – flow rate out of well [ft^3/d]
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h_1 – head at upgradient well (R-61) [ft]
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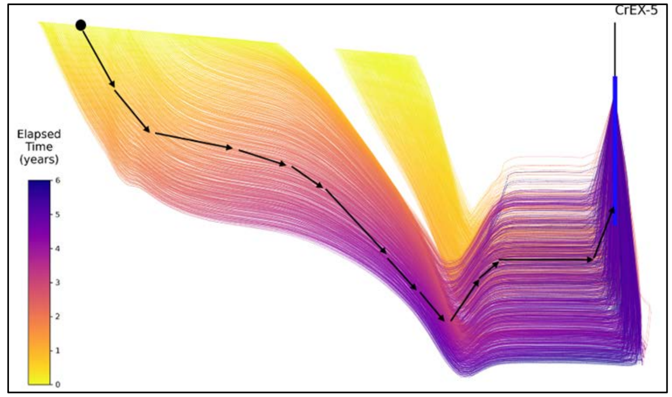
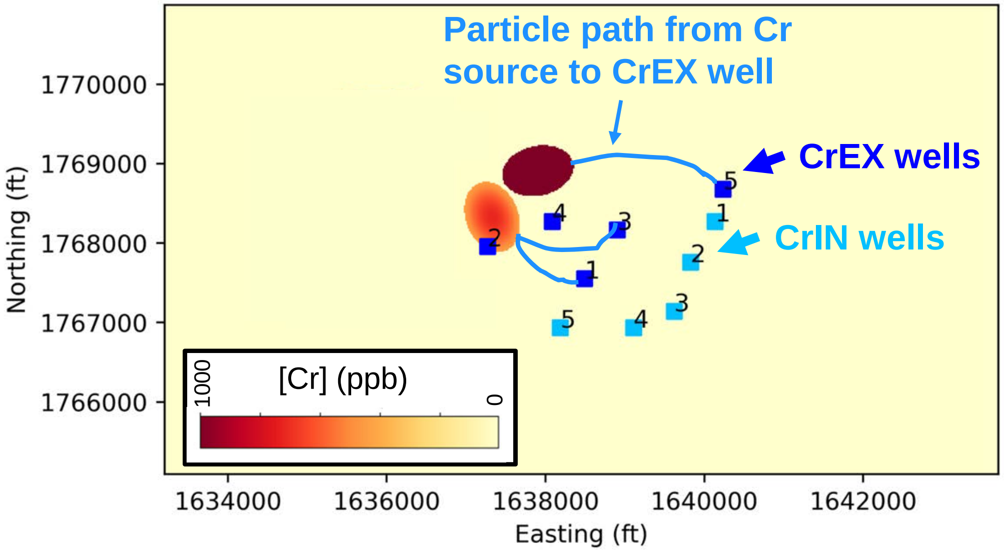
L – Distance between down/upgradient wells

- Many assumptions including:
  - Homogeneous, isotropic, uniform-thickness aquifer
  - Fully-penetrating well
  - **Steady-state flow**
  - Negligible vertical gradients, no net recharge, no sources of water

For a CAPTURE ZONE analysis we want to understand capture of both **LONG** and **SHORT** flow pathways (particles)



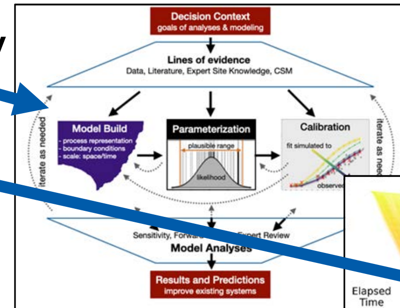


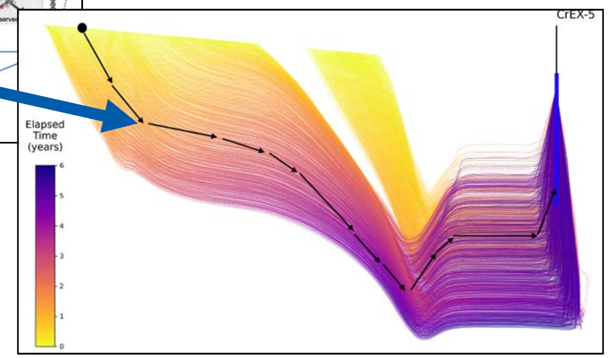
We need EQUILIBRIUM / STEADY-STATE to get to COMPLETE CAPTURE:

- If you only looked at a short time period you would not include particles traveling longer pathways
- Complete capture estimates require equilibrium

Step 4b: Numerical Calculations – Particle Tracking

- Calibrated model that incorporates uncertainty
- Particle tracking follows Cr particles as they moves through the subsurface





- Capture AND flood zones are evaluated
  > **Capture**: the region where particles are EXTRACTED
  > **Flood**: the area clean particles cover after INJECTION

- Simulations are run to **steady-state** before particles are released
  - Cr particles are CONTINUOUSLY added for hundreds of years
    > no constraints on total inventory, we are trying to understand CAPTURE
  - IM is operational CONTINUOUSLY for hundreds of years
    > no changes so the flow field can reach EQUILIBRIUM
  - We want to understand how well this system performs, if it is allowed to continue to run so we can delineate what is captured (Particles shouldn't be dropped into a changing flow field where the capture zone is still expanding, which is why a steady-state initialization is used)

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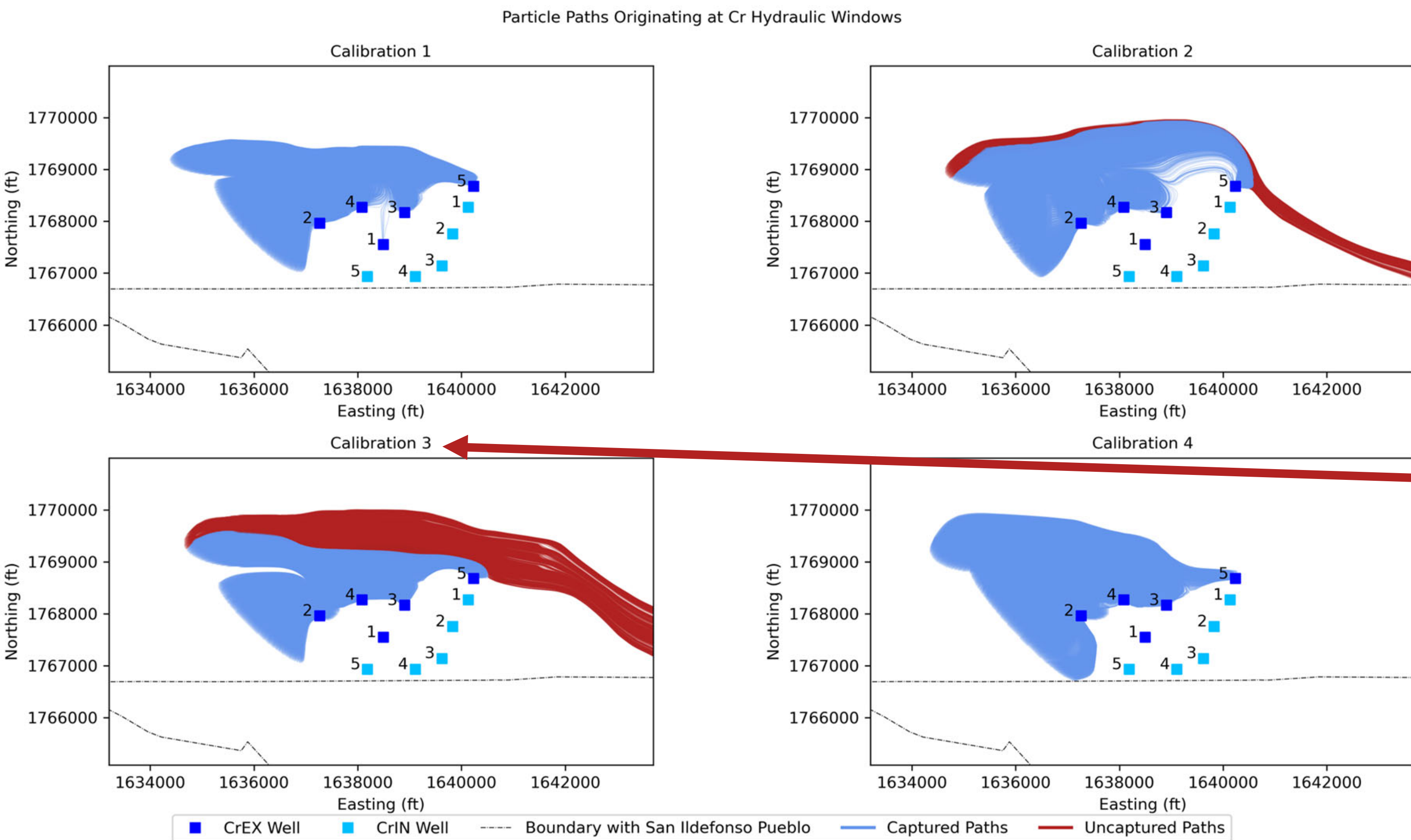
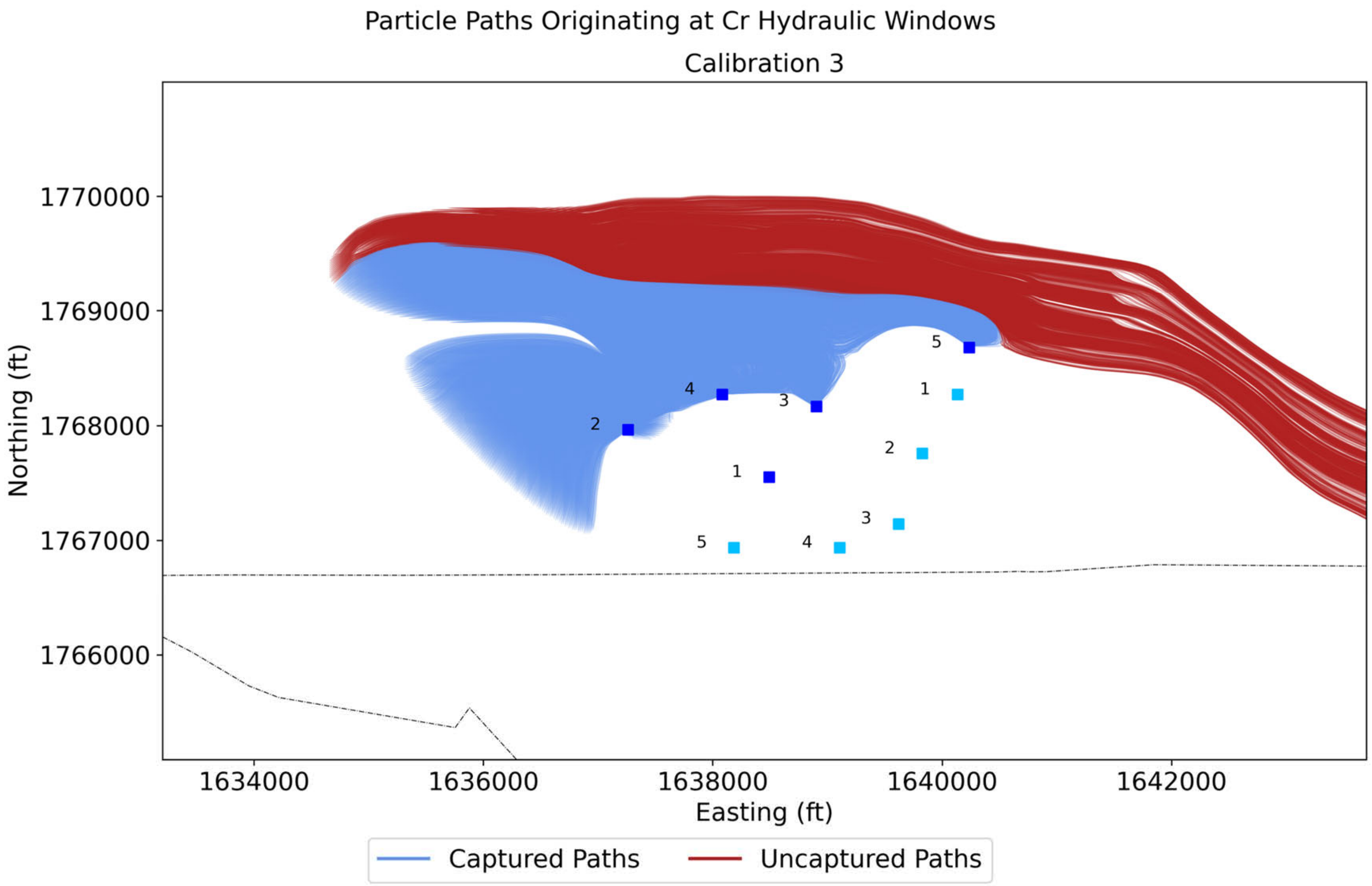
All capture zone work includes uncertainty estimates



- All simulations show full capture to the south and southeast
- 50% of simulations show full capture of all Cr sources
- Focus examples today on Calibration 3, the worst case in terms of total capture, to look at results

Cr source particles: which are captured which are uncaptured?



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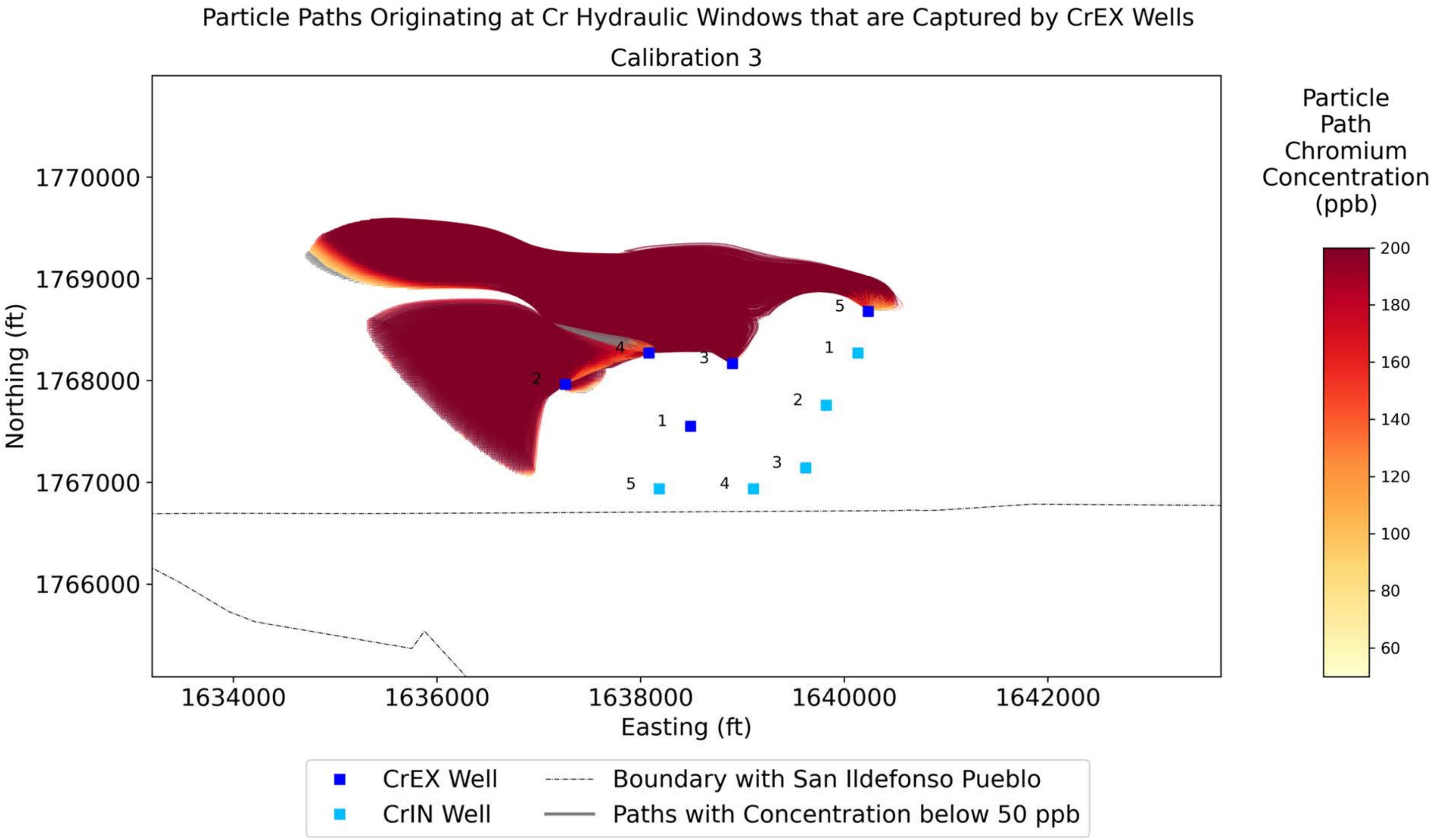
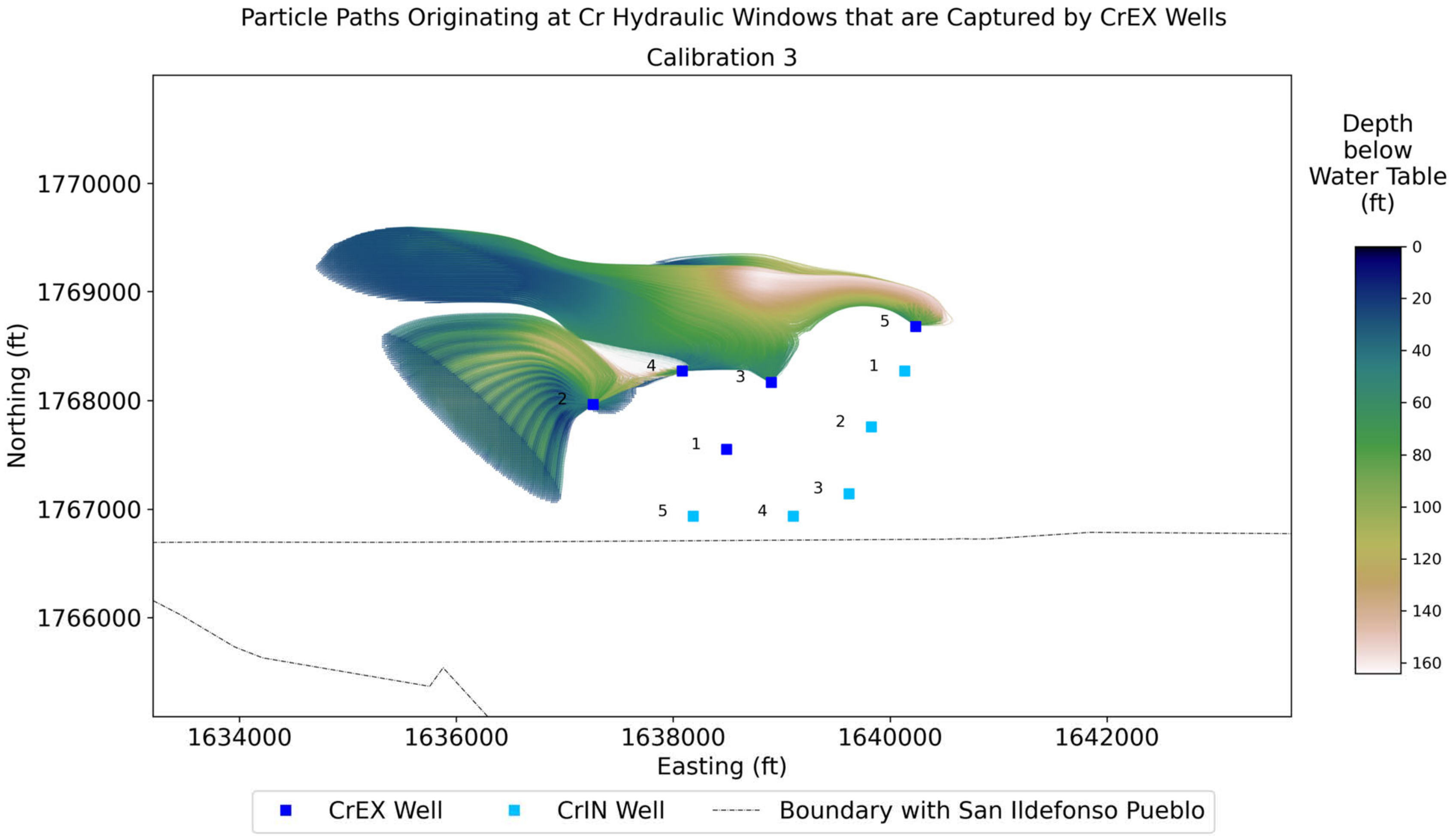
Step 4b: Particle Tracking Method

- Tracing the paths of particles –where are captured particles and at what concentrations?



Step 4b: Particle Tracking Method

- Tracing the paths of particles –where are captured particles and at what depth?



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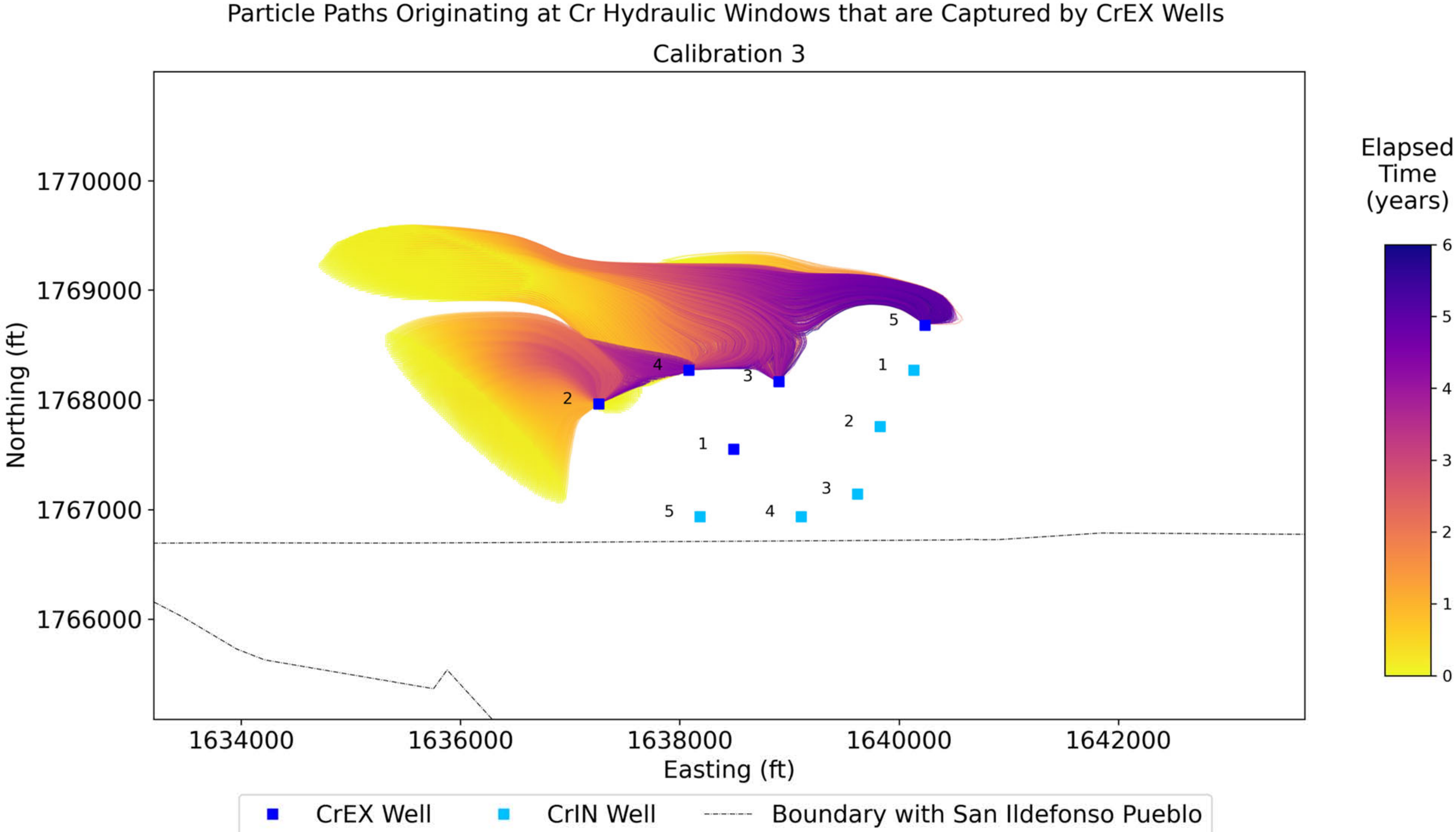
Step 4b: Particle Tracking Method

- Tracing the paths of particles –where are captured particles and how long does capture take?



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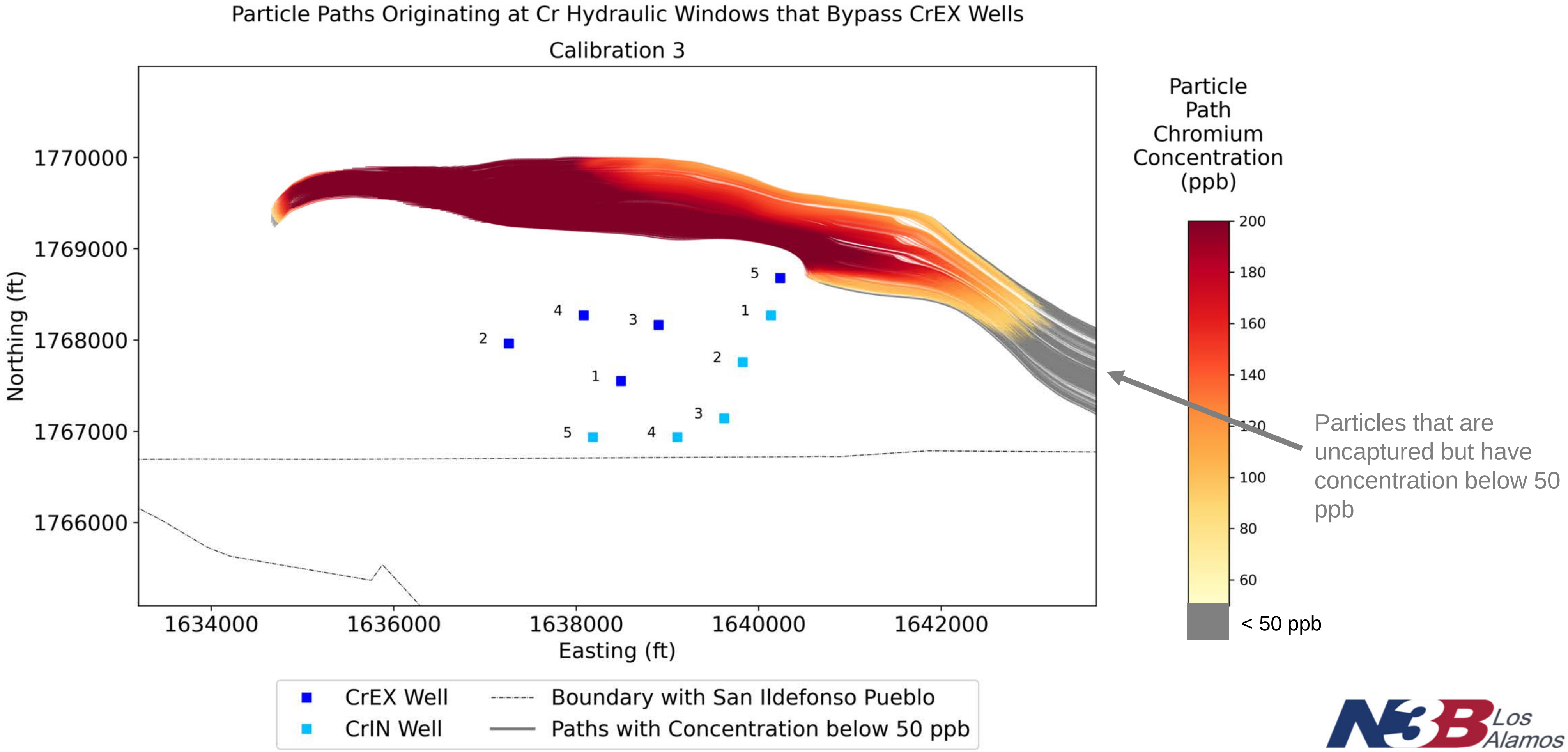
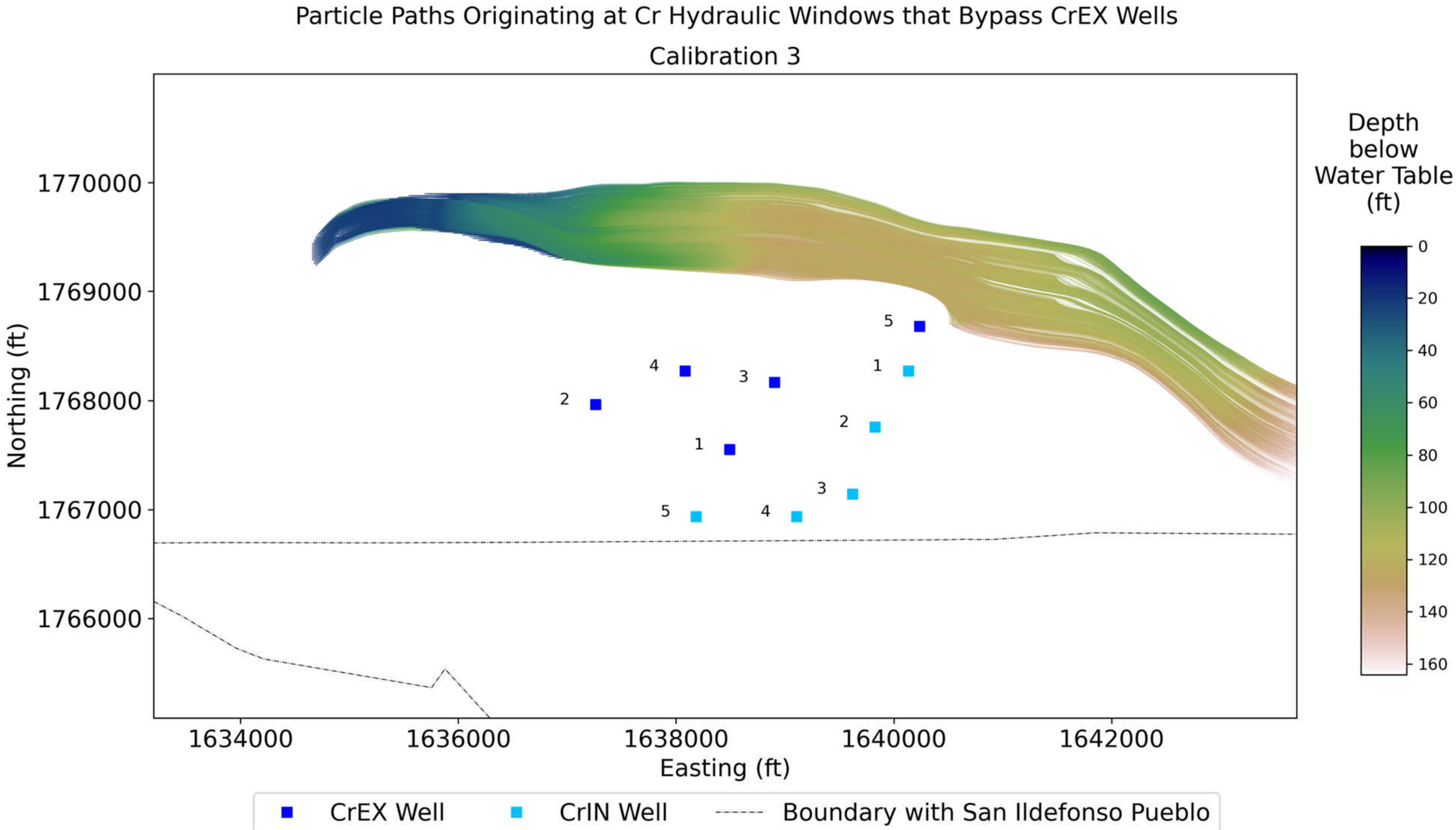
Step 4b: Particle Tracking Method

- Tracing the paths of particles –where are uncaptured particles and at what concentrations?



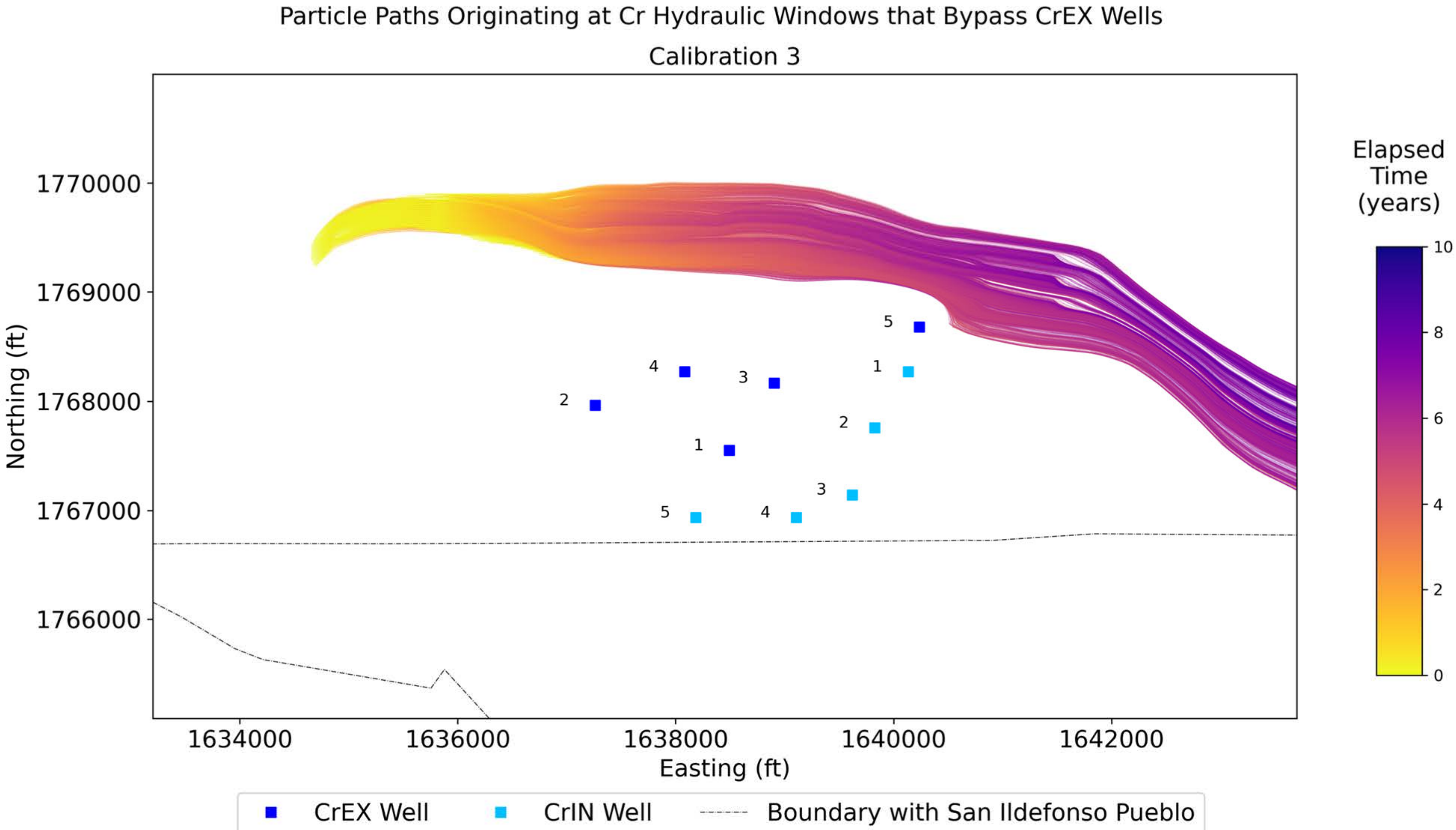
Step 4b: Particle Tracking Method

- Tracing the paths of particles –where are uncaptured particles and at what depth?



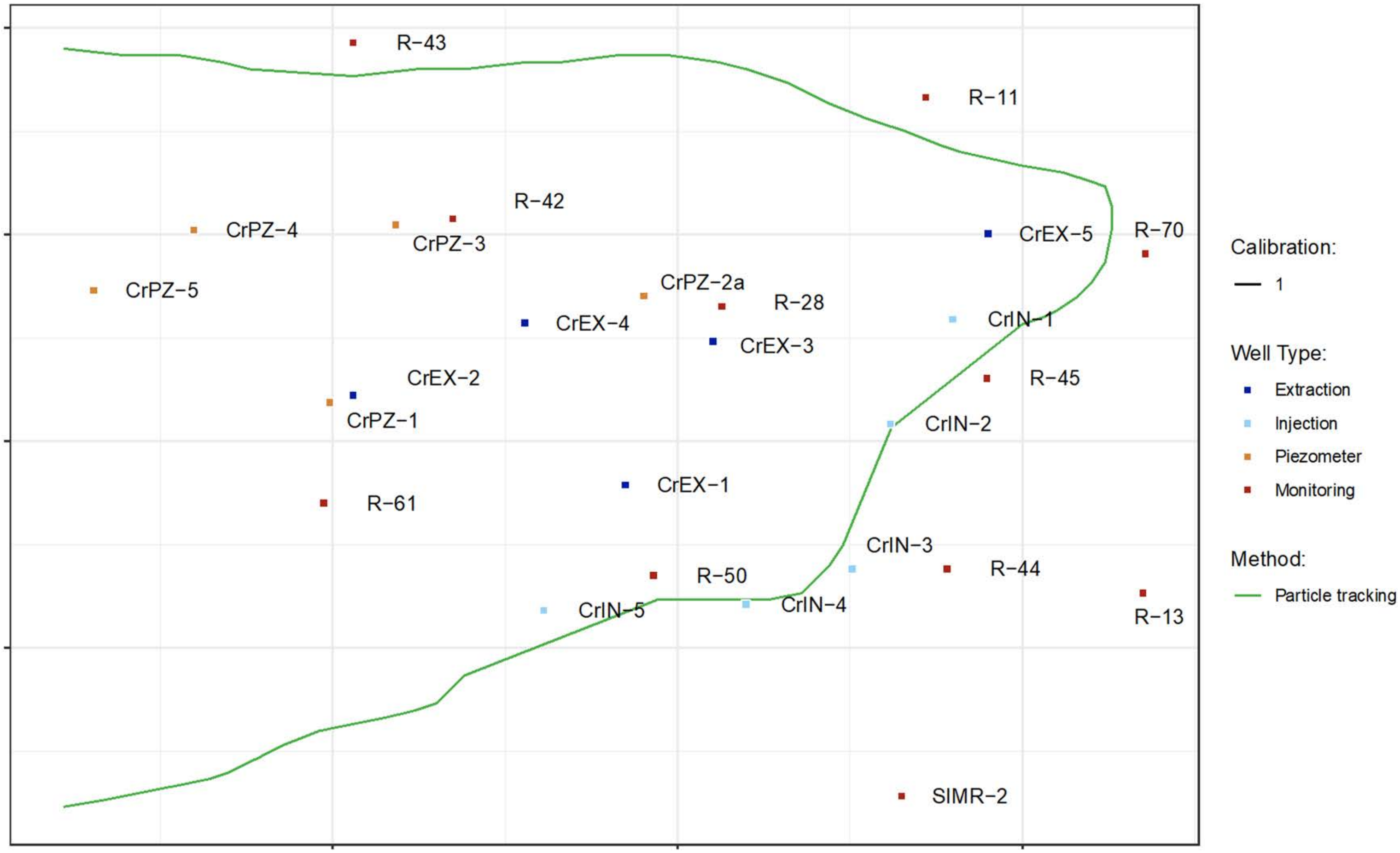
Step 4b: Particle Tracking Method

- Tracing the paths of particles –where are uncaptured particles and how long does transport take?

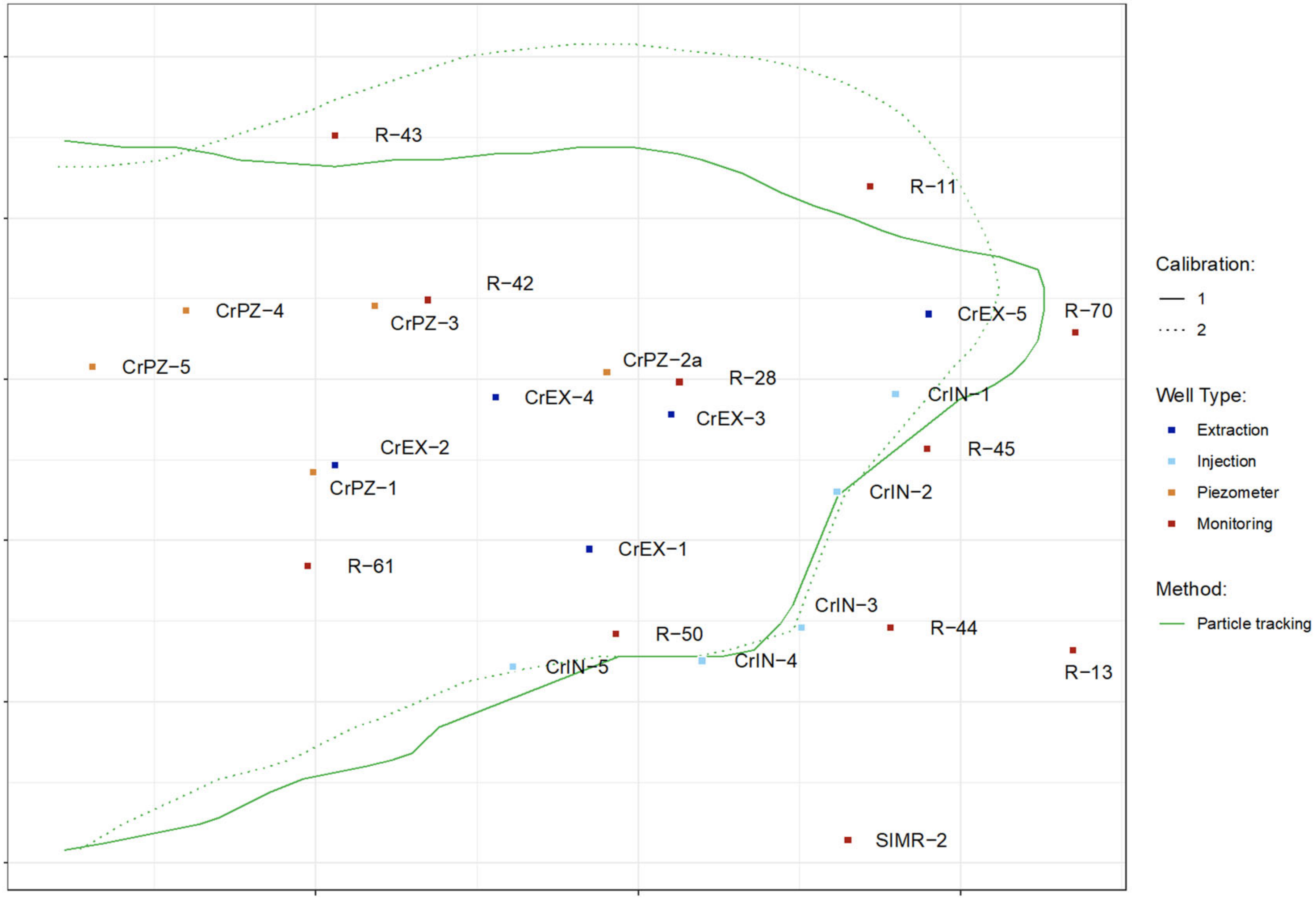


Step 4b: Particle Tracking Method

Estimating capture zone for a single (deterministic) calibration



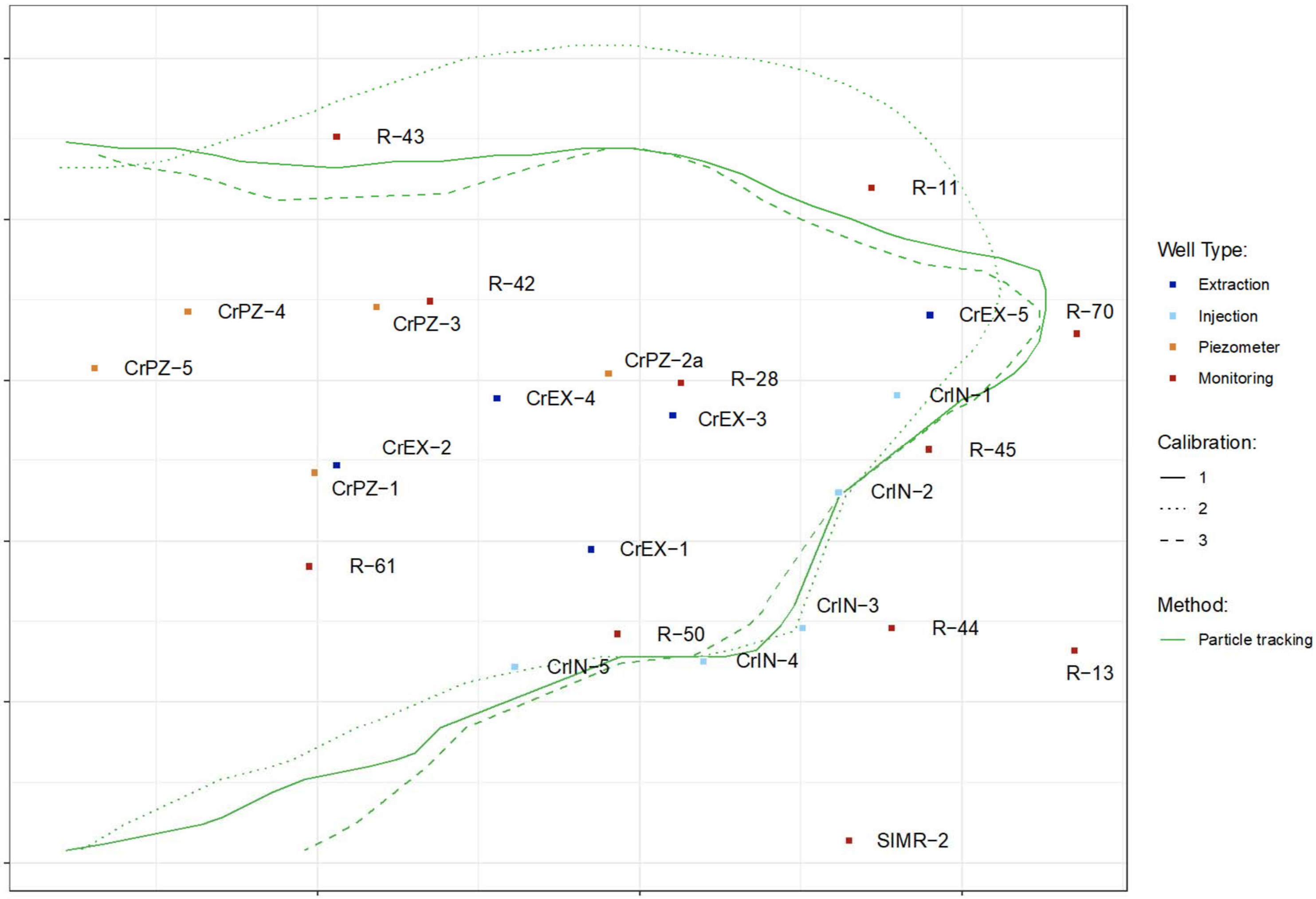
Step 4b: Particle Tracking Method



Estimating capture zone for a single (deterministic) calibration

Expanding across many simulations (all match calibration data) to quantify uncertainty

Step 4b: Particle Tracking Method



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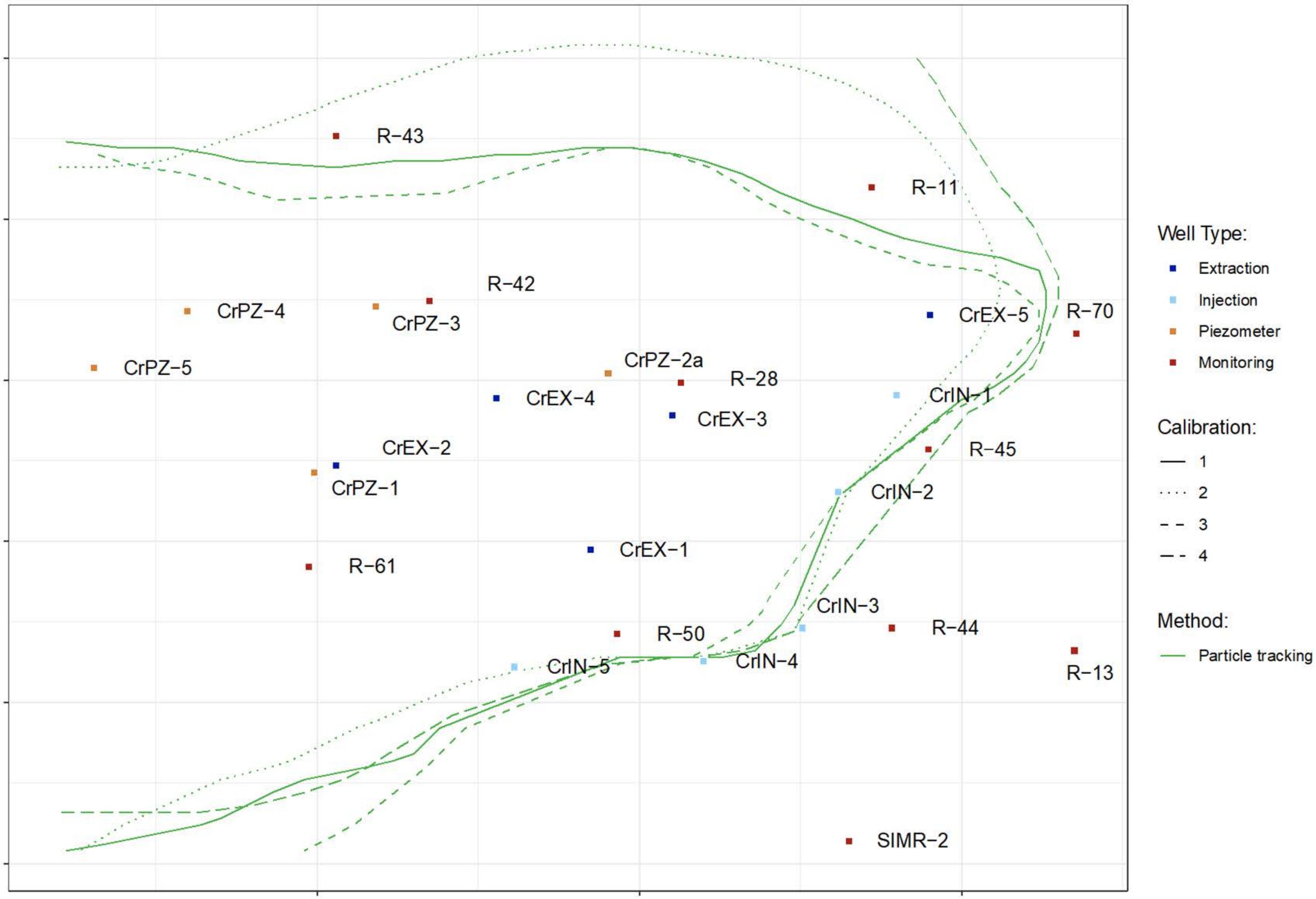

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Expanding across many simulations (all match calibration data) to quantify uncertainty

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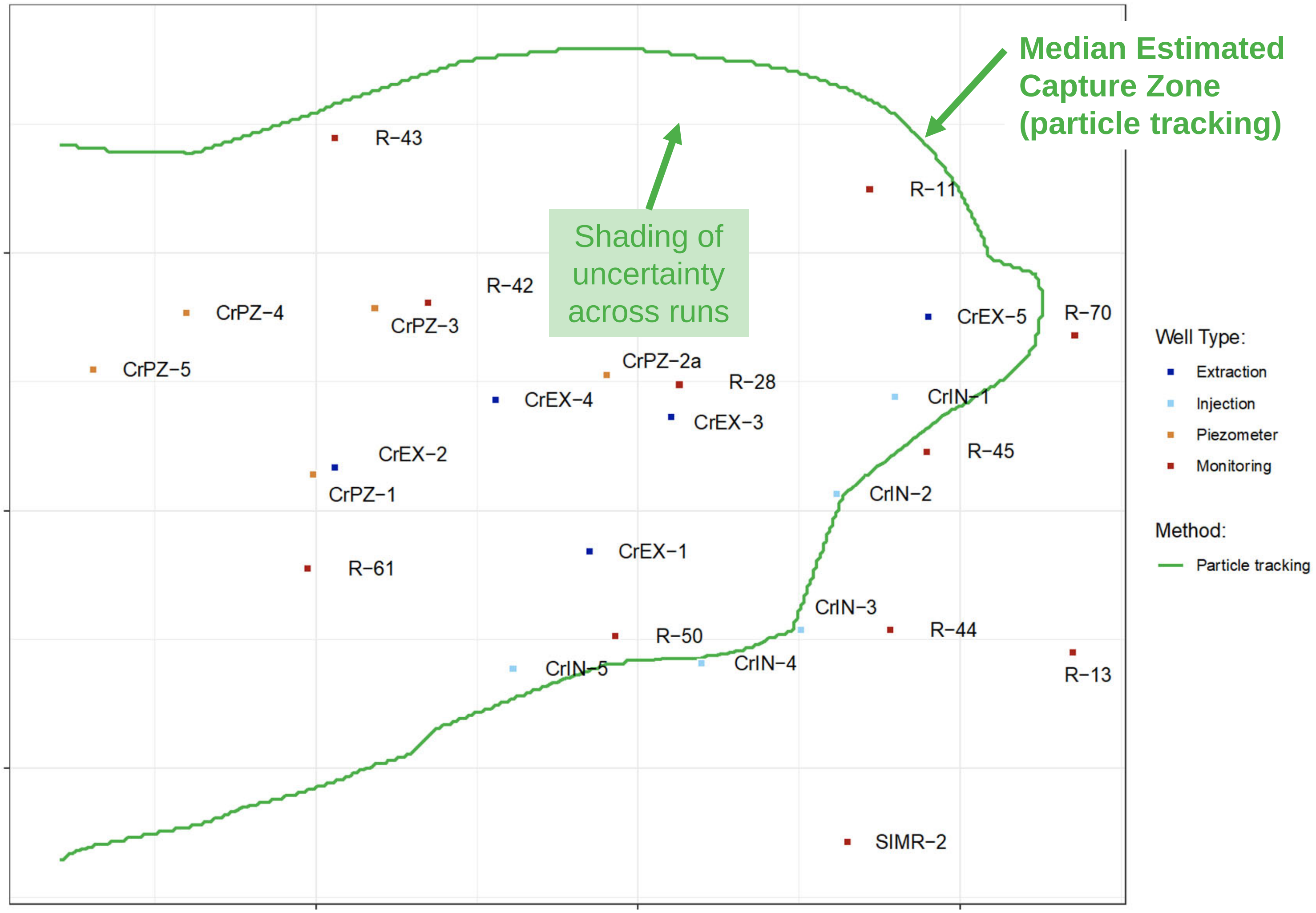
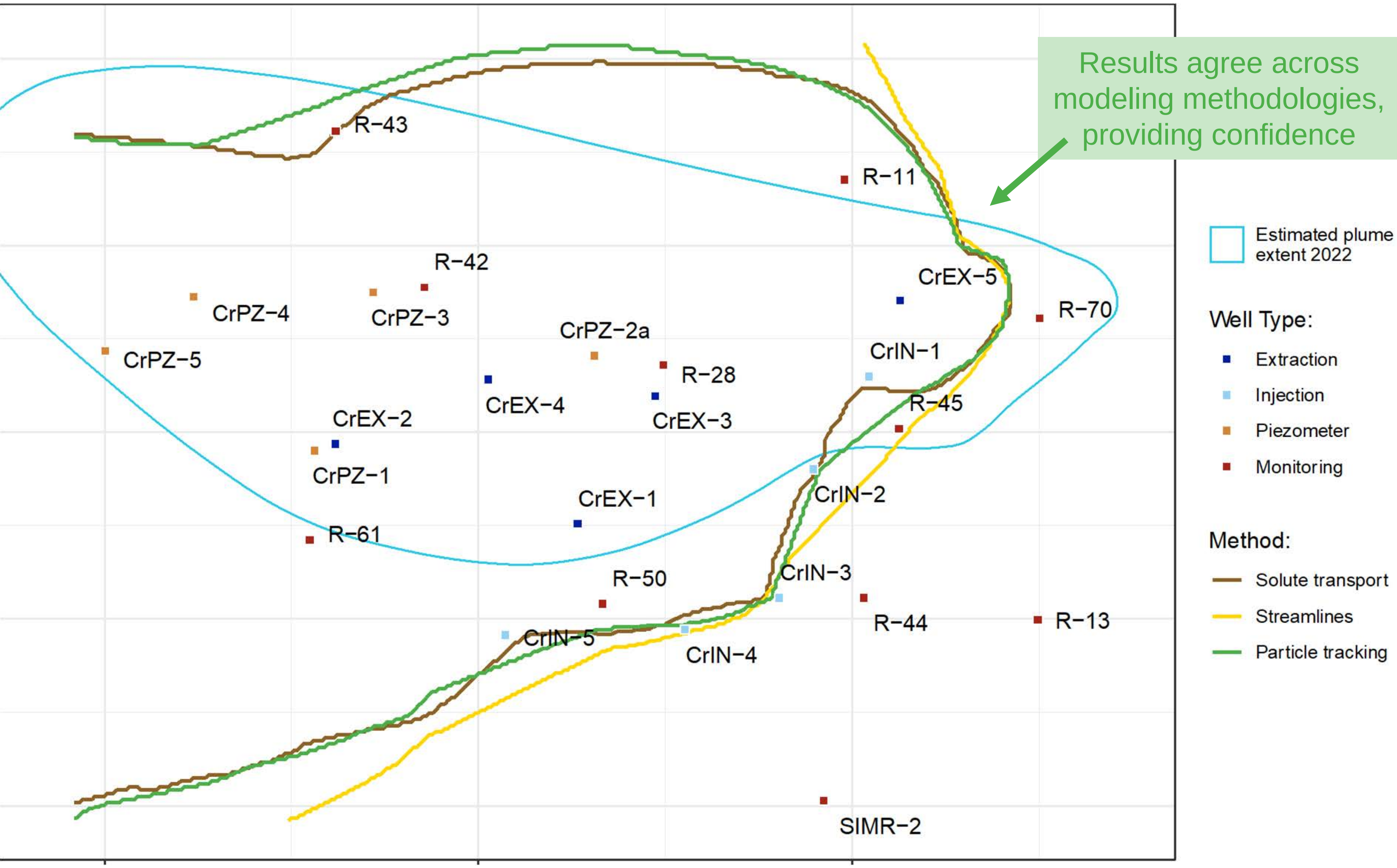
Step 4b: Particle Tracking Method



Estimating capture zone for a single (deterministic) calibration

Expanding across many simulations (all match calibration data) to quantify uncertainty

Step 4b: Other modeling methods corroborate particle tracking



Solute Transport Method includes dispersion and tracers instead of particles

Streamlines Method uses only the flow field and is much like the Potentiometric Surface Mapping, but with a heterogeneous flow field

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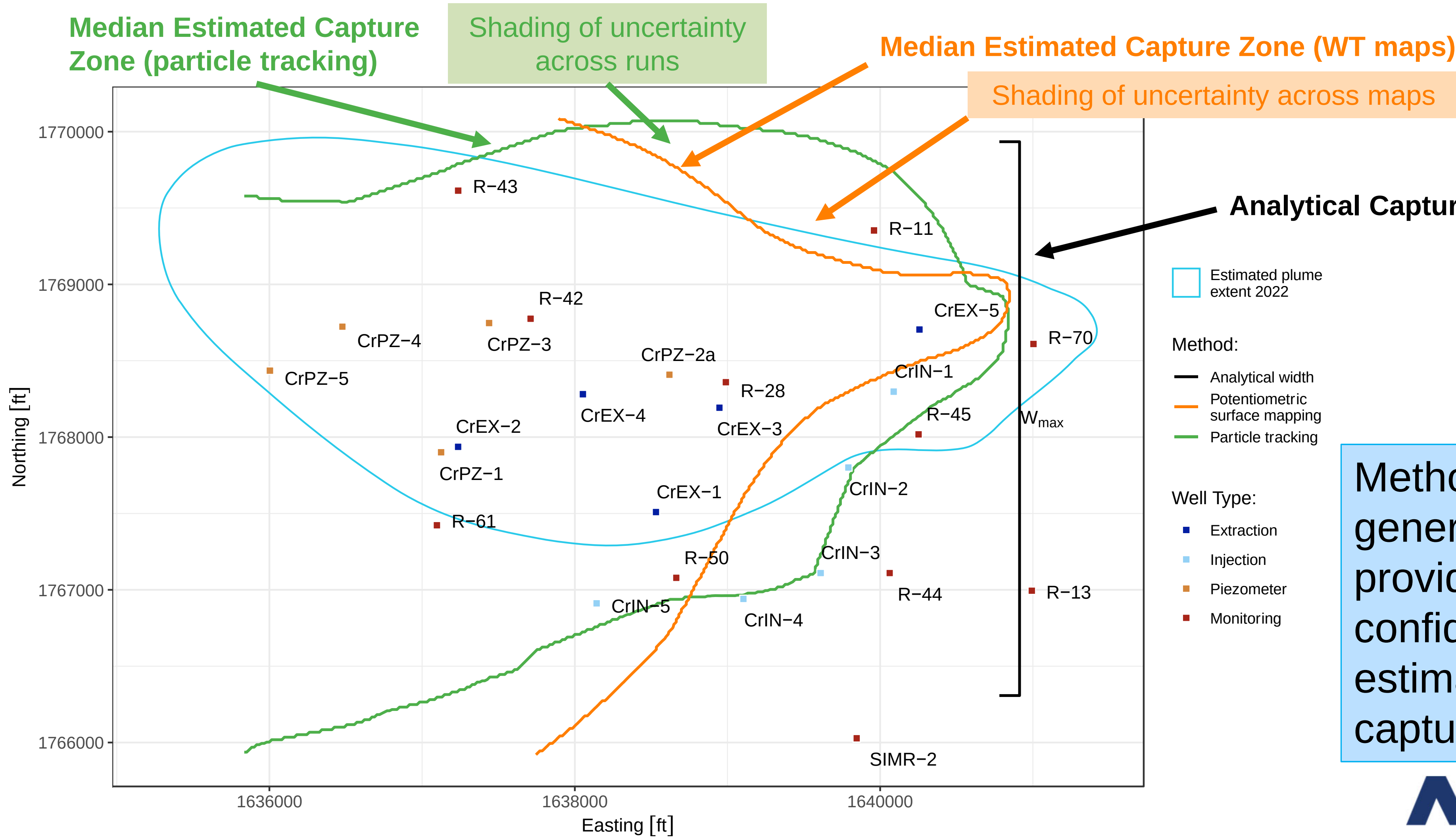
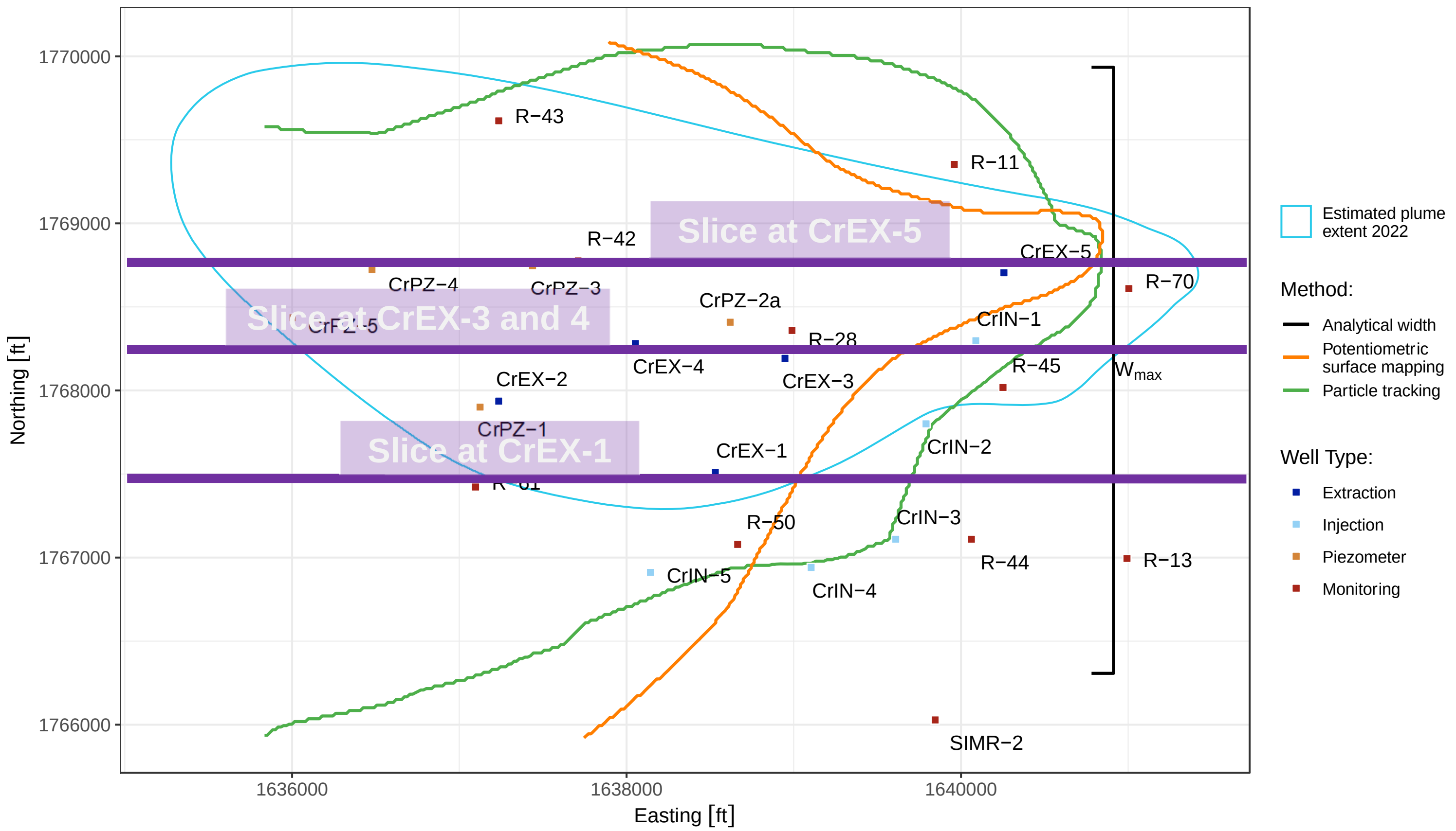
Steps 3, 4a, 4b: Data-based methods corroborate particle tracking



Methods generally agree, providing confidence in estimated capture

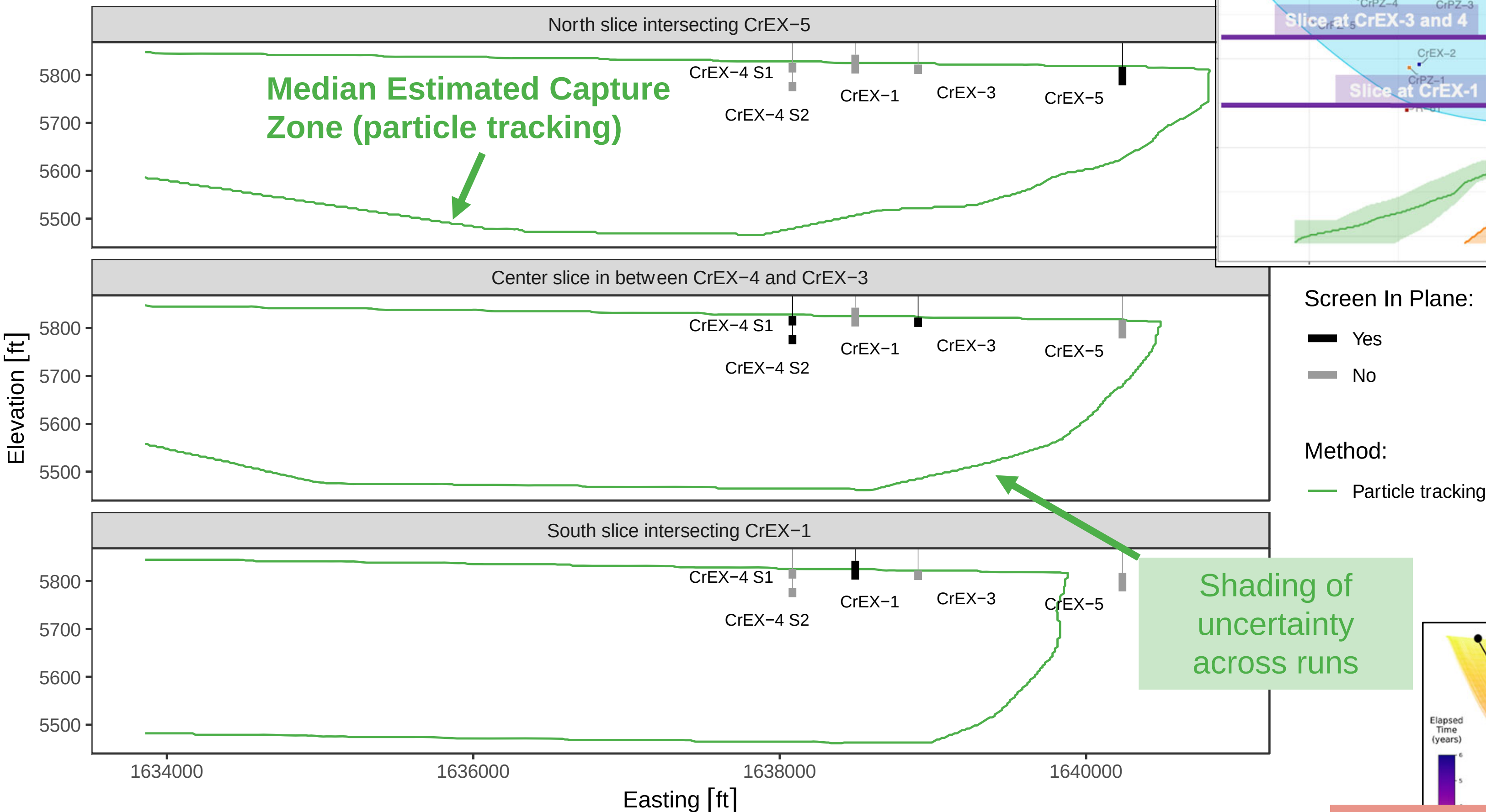
Capture zone in z-dimension (only numerical model)

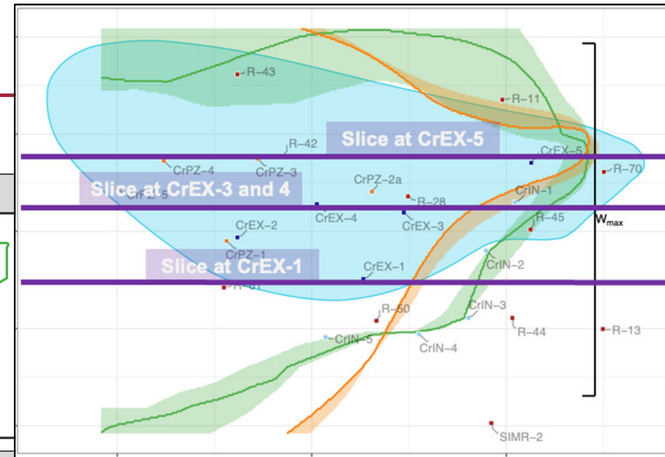


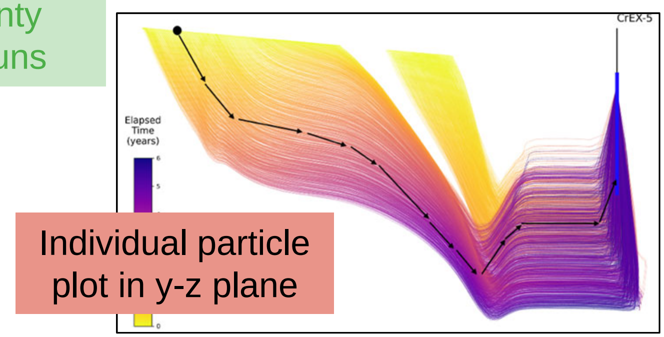
Cannot use the water table mapping methods or the analytical methods for a 3D estimate of capture

To look at the vertical dimension we need to use numerical modeling

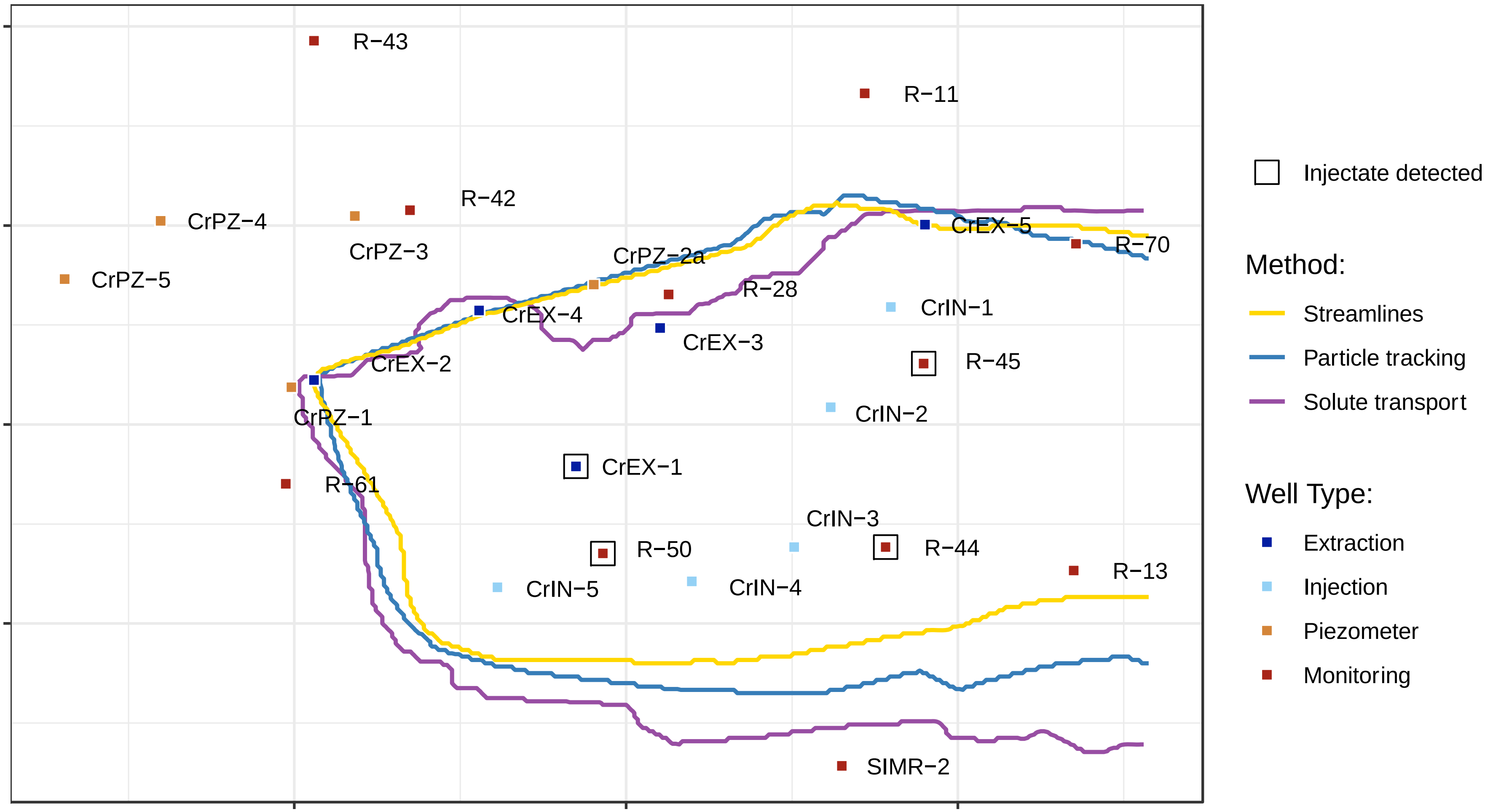
Capture zone depth slices







Flood zone – i.e. the influence of clean injected water



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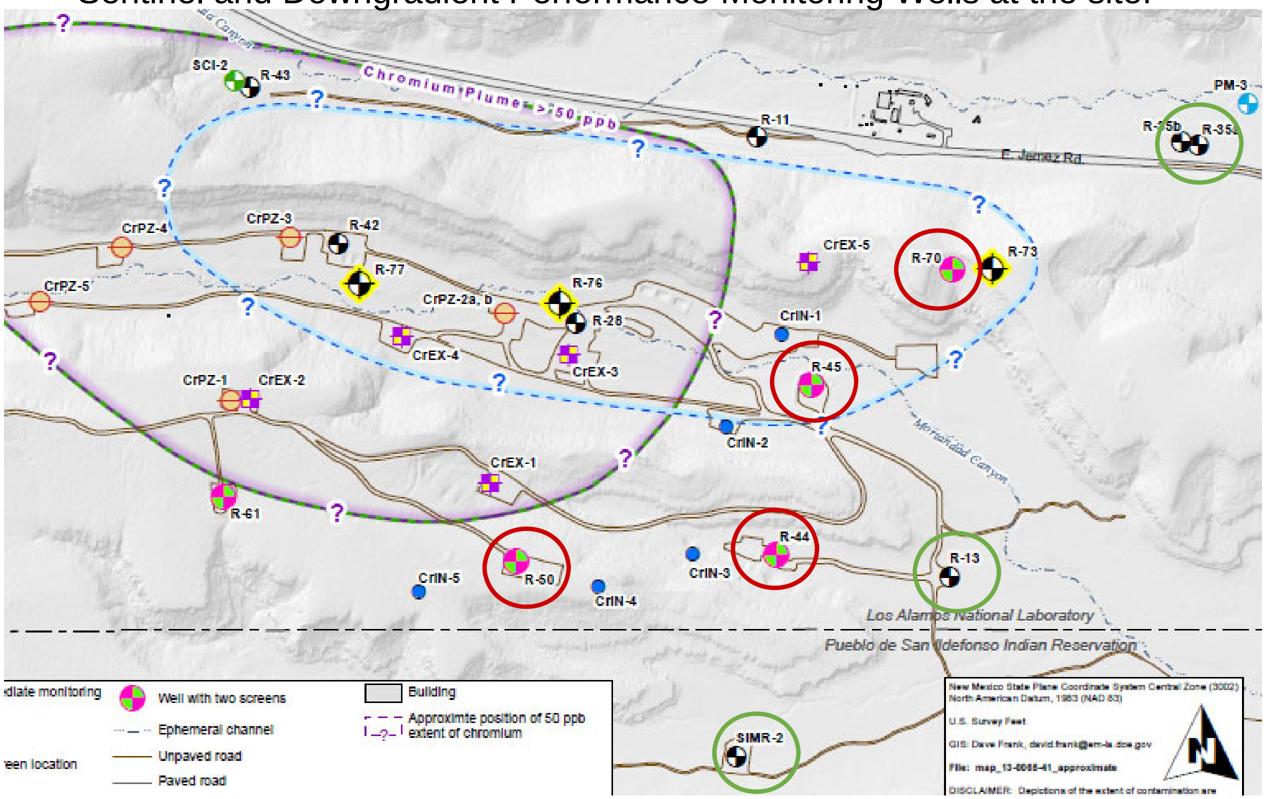
Step 5: Evaluate Concentration Trends

Definitions (EPA 2008)**:**

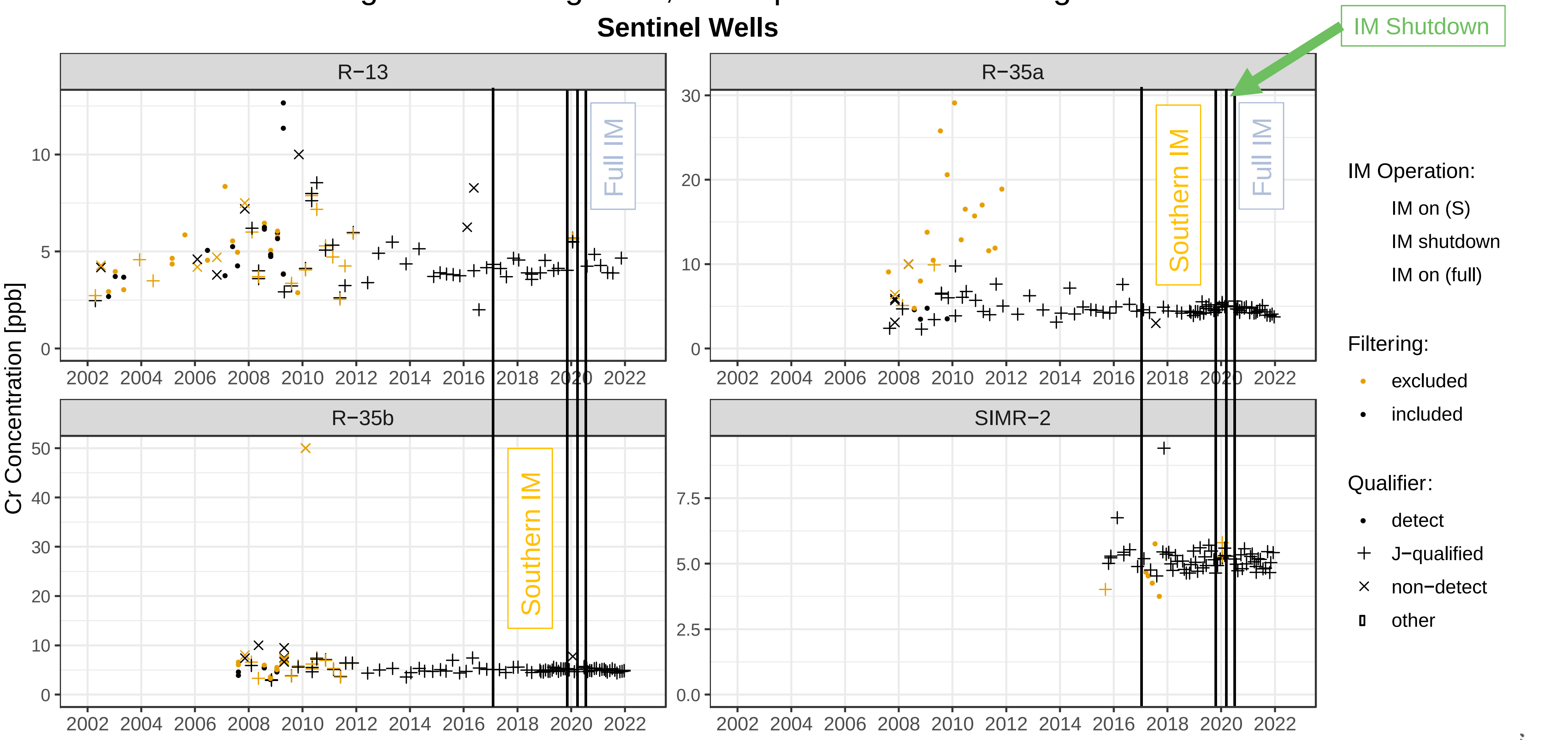
- **Sentinel Wells**: downgradient of target CZ, not impacted above background
- **Downgradient Performance Monitoring Wells**: impacted, downgradient of target CZ

Sentinel and Downgradient Performance Monitoring Wells at the site:



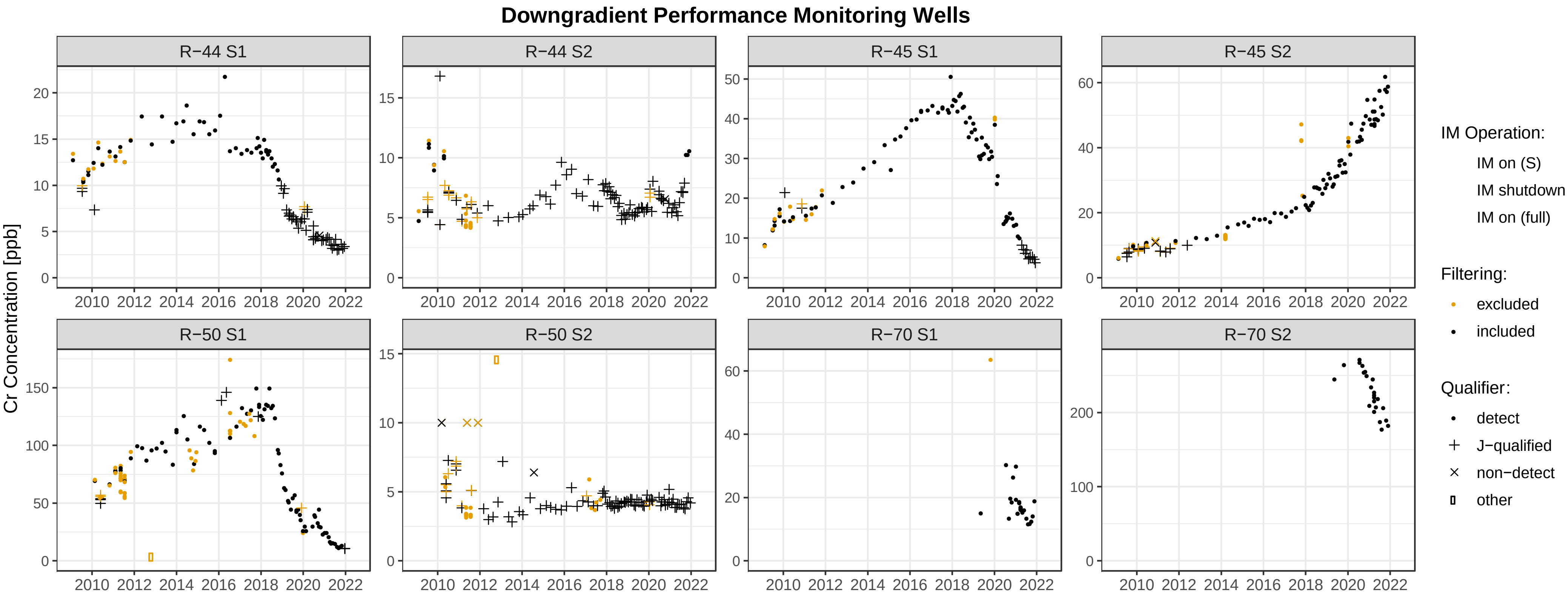
Step 5: Evaluate Concentration Trends

- **Sentinel Wells**: downgradient of target CZ, not impacted above background



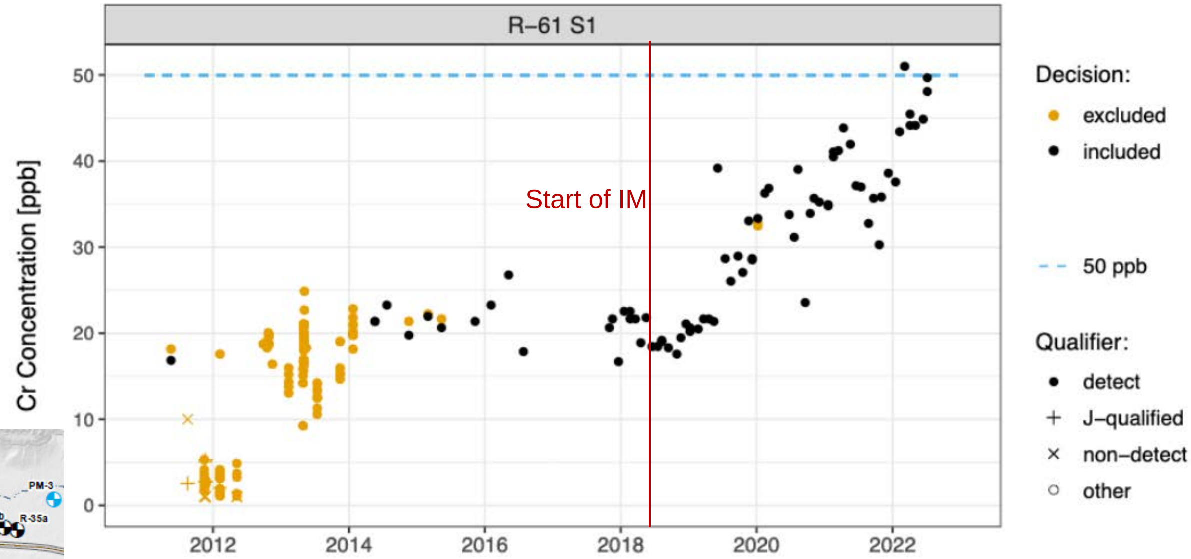
Step 5: Evaluate Concentration Trends

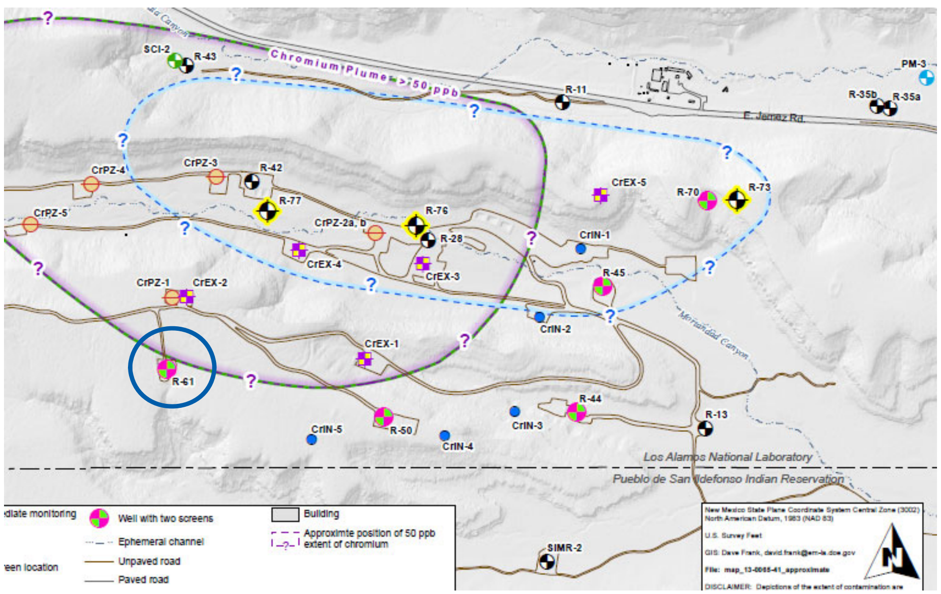
- **Downgradient Performance Monitoring Wells**



Step 5: Evaluate Concentration Trends

- R-61 is **UPGRADIENT** of the capture zone/majority of the plume.
  - Flow direction during pumping points TOWARDS plume
- Concentrations appear to be increasing because of pulling from extraction





Step 6: Discussion

- Synthesis of all of the above

Possible Format for Presenting Results of a Capture Zone Evaluation

Line of Evidence	Is Capture Sufficient? IM Objectives Met?	Comments
Water Levels • Potentiometric surface maps • Vertical head difference maps • Water level pairs		
Calculations • Estimated flow rate calculations • Capture zone width calculations • Ground-water flow modeling with particle tracking		
Concentration Trends • Sentinel wells • Downgradient performance monitoring wells		
Overall Conclusion • Is capture sufficient, based on "converging lines of evidence"? • Key uncertainties/data gaps • Recommendations to collect additional data, install new monitoring wells, change current extraction rates, change number/location of extraction wells, etc.		

IM objectives (LANL 2015):

- To achieve and maintain the 50-ppb downgradient plume edge within the laboratory boundary
  - Metric: reduction of Cr at R-50 to under 50 ppb within 3 yr
- **Hydraulically control plume migration in the eastern, downgradient portion of the plume**
- Utilize information obtained from the IM to refine the hydrogeologic understanding of the site

Step 6: Discussion

Type of Analysis	Line of Evidence	IM Objectives Met?	Comments
Water Level Data	Potentiometric surface maps	Yes	The capture zone area estimated by streamlines perpendicular to contours is wide enough to encompass the target capture zone in the central and southern areas. The hydraulic control created by injection wells along the southern boundary is evident when comparing water table maps with and without IM operation.
	Water level gradient triples (horizontal)	Yes	Analysis of the hydraulic gradients suggests hydraulic control along the southern boundary of the plume. In the northeast, downgradient of CrEX-5, a probable reversal in flow direction is observed, consistent with the results of other analyses. Observed gradient changes are consistent with the expected behavior during IM operations. I thought this was removed?
Analytical Calculation	Estimated flow rate calculations	Yes	The calculation suggests that IM pumping rates are sufficient to encompass the target capture area.
	Capture zone width calculations	Yes	The capture zone estimated by an analytical method suggests that the IM system's capture zone is sufficiently large to meet IM objectives. The estimated maximum capture zone width is 7252 ft. As with all simple analytical techniques employed in complicated settings, this calculation is highly uncertain. Is this the number on the map?

Step 6: Discussion

Type of Analysis	Line of Evidence	IM Objectives Met?	Comments
MODELING	Particle tracking method	Area of Concern in Northeast portion of plume	Particle tracking suggests that the IM system is sufficiently large to meet IM objectives in the south and southeastern portions of the site. Uncaptured pathways are identified north of R-70, especially at depth, in half of the simulations modeled. This indicates uncertainty in the extent of the Cr plume and the extent of capture in this region.
	Streamline method	Yes	Streamline analysis of the four model calibrations suggests that the capture zone of the IM in sufficient to encompass the known plume area.
	Solute transport method	Area of Concern in Northeast portion of plume	Steady-state solute transport analysis using the four model calibrations suggests that the 50 ppb contour is contained within LANL property and does not reach downgradient or south of the IM area.

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Step 6: Discussion

Type of Analysis	Line of Evidence	IM Objectives Met?	Comments
MONITORING WELL DATA	Concentration trends at downgradient performance monitoring wells	Yes	At R-45 S2, an increasing trend is observed. At this location all capture methods estimate that R-45 S2 is within the capture zone, suggesting that this rise is related to temporary movement of the existing plume and not indicative of failed capture. Cr concentration data from all other downgradient performance monitoring wells – R-44 (S1/S2), R-45 S1, R-50 (S1/S2) and R-70 (S1/S2) – do not show concerning trends, although the record at R-70 is comparatively short and will be monitored carefully due to high concentrations at depth.
	Concentration trends at sentinel wells	Yes	Sentinel wells R-35a, R-35b, R-13, and SIMR-2 remain at background levels for Cr.

Discussion and Next Steps

- Capture zones agree broadly across lines of evidence, providing confidence in results
  - Capture is consistently predicted at southern and south-eastern portion of the plume. Some uncaptured Chromium is predicted at the northern portion of the plume, especially at depth
- The capture zone analysis (and model) are iterative. As new data and information becomes available the model can be improved, and the analyses can be re-run
- Address uncertainties – are there new data points that would improve understanding?
- Scenarios:
  - Understand and explore uncertainty with depth (especially using new data from R-76 and R-77)
  - Optimize the system towards decision endpoints
- Additional analyses:
  - Run hypothetical/intentional experiments (they do not have to be realistic) to better understand mechanism for observations. What are the MECHANISMS for the OBSERVED BEHAVIOR (i.e. better understand the reason for increasing concentrations at R-45 screen 2)

Appendix D

Chloride and Sulfate Concentrations
at Extraction Wells and Select Monitoring Wells

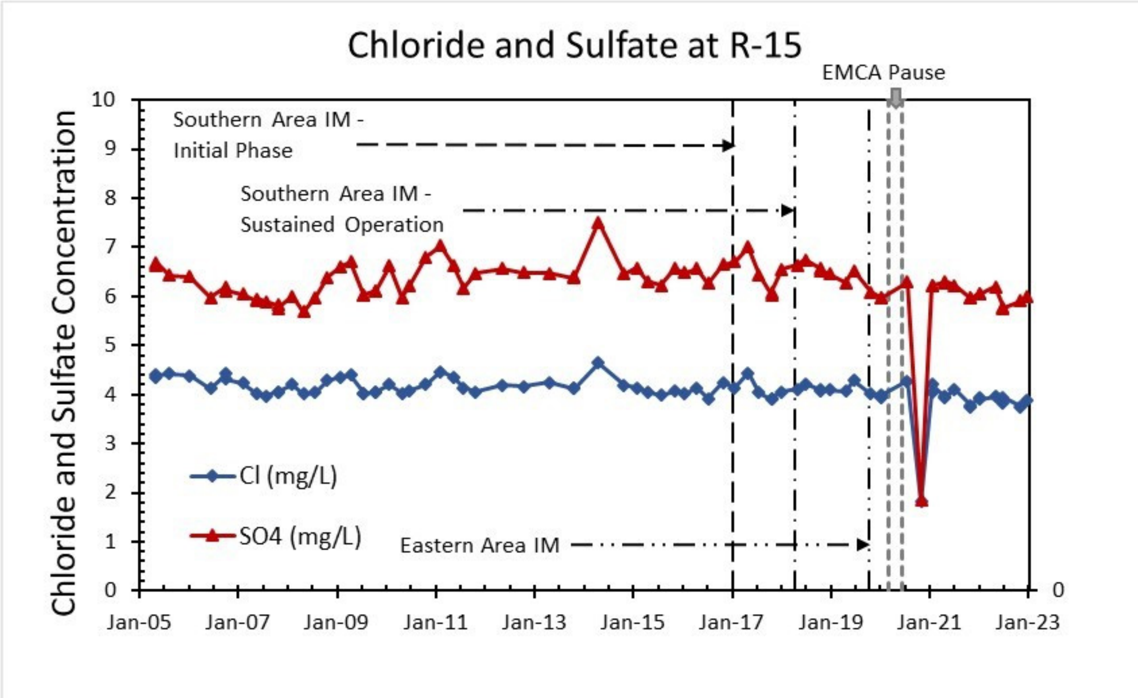

Figure D-1 Chloride and sulfate concentrations at monitoring well R-15

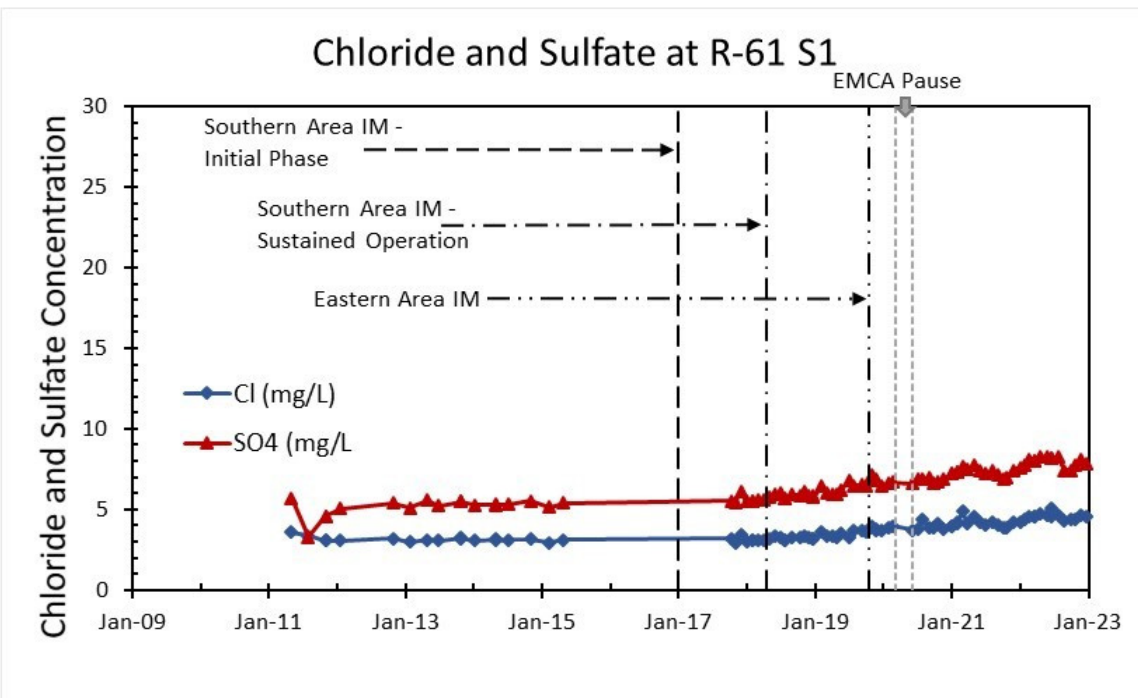

Figure D-2 Chloride and sulfate concentrations at monitoring well R-61

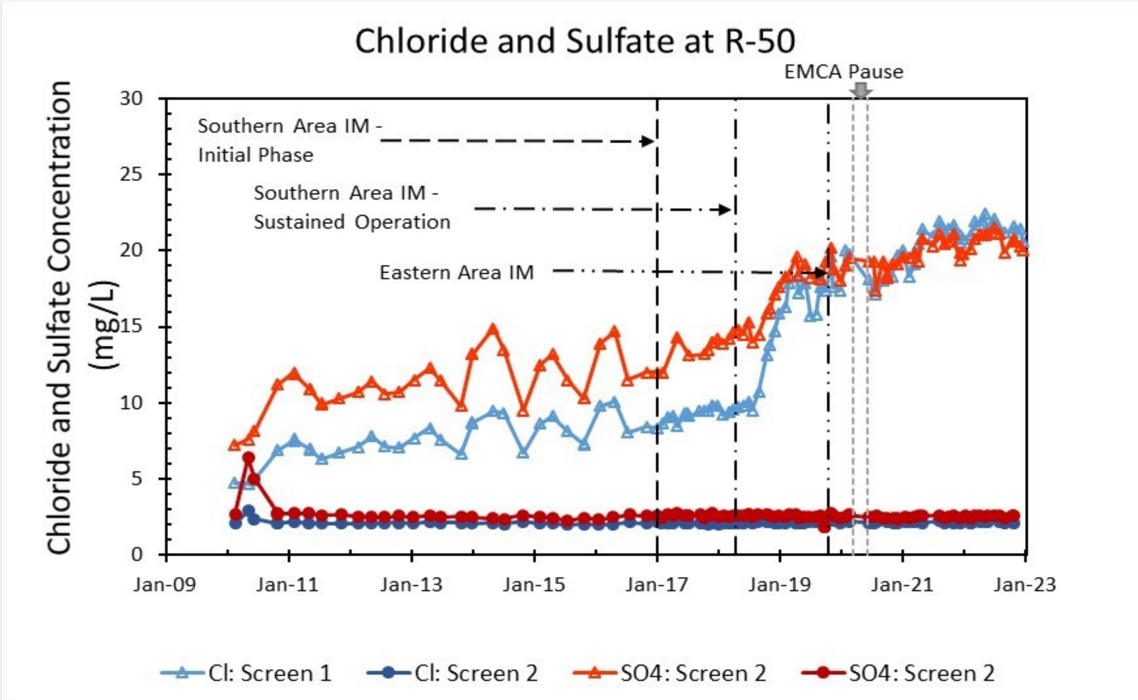

Figure D-3 **Chloride and sulfate concentrations at monitoring well R-50**

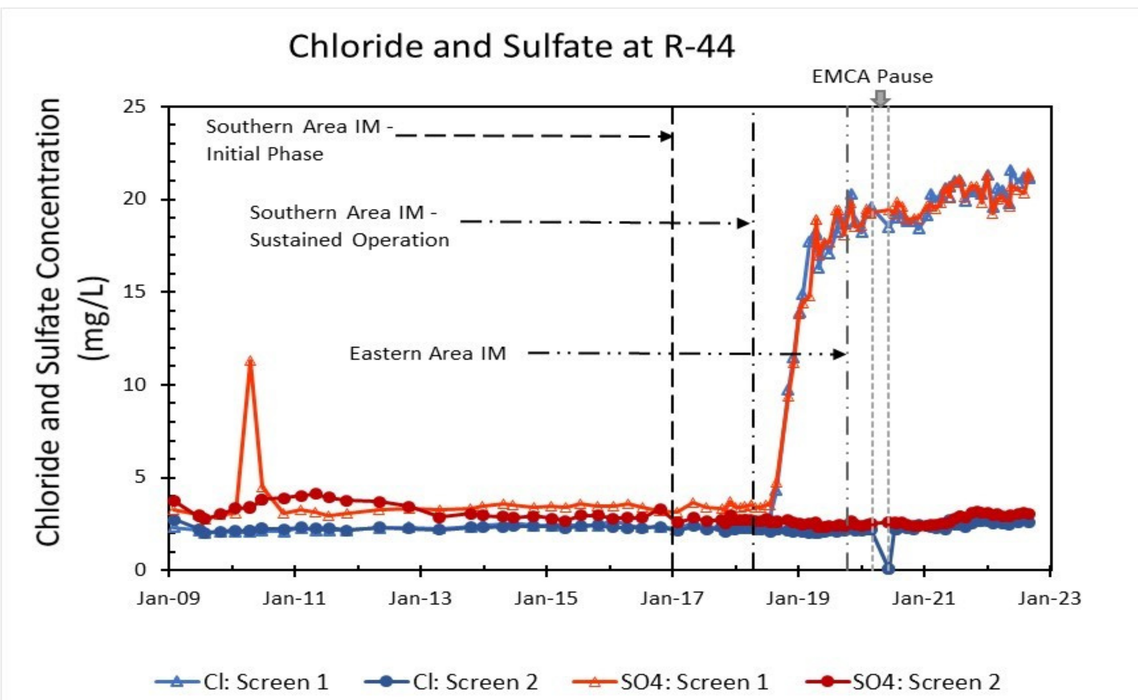

Figure D-4 **Chloride and sulfate concentrations at monitoring well R-44**

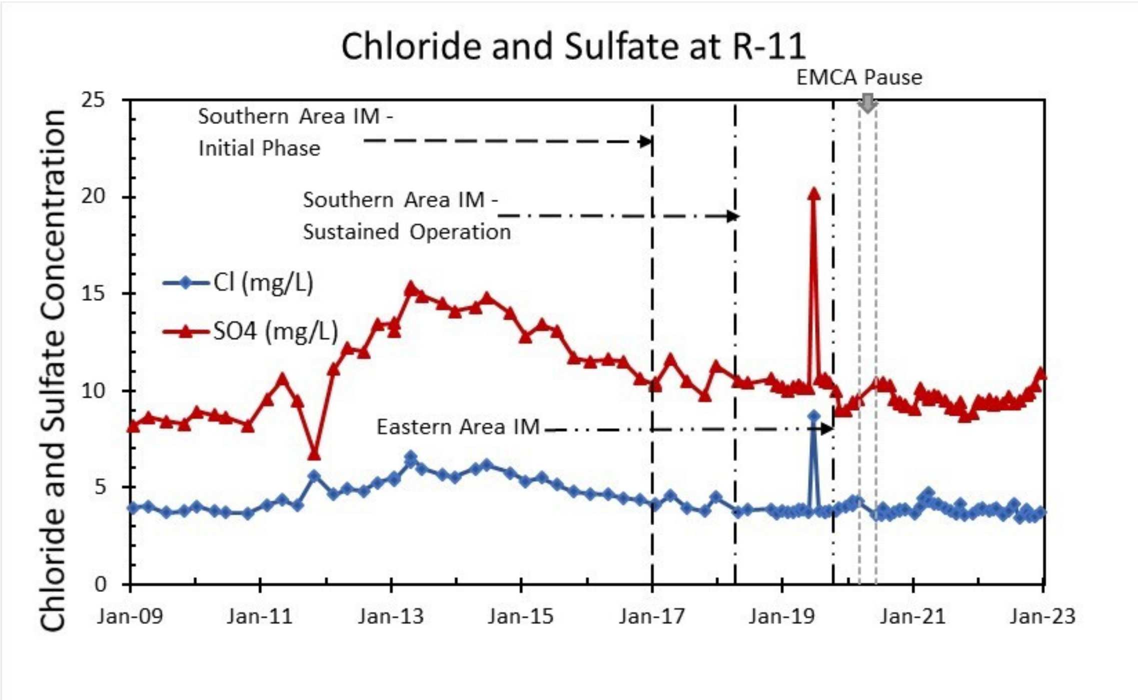

Figure D-5 Chloride and sulfate concentrations at monitoring well R-11

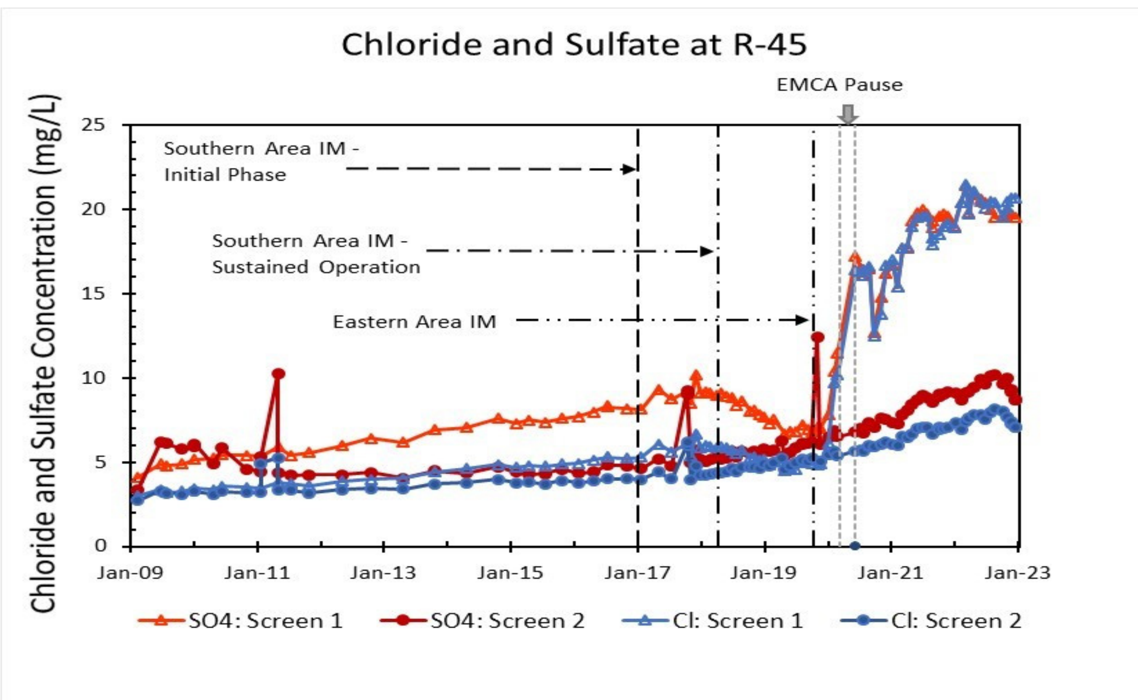

Figure D-6 Chloride and sulfate concentrations at monitoring well R-45

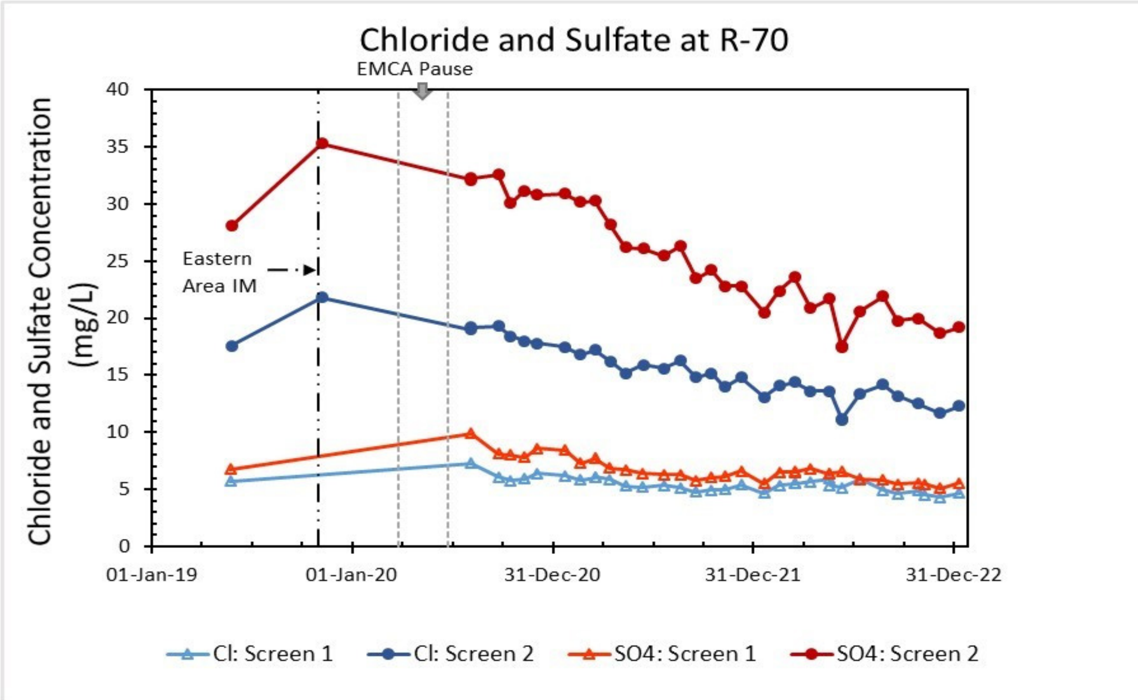

Figure D-7 **Chloride and sulfate concentrations at monitoring well R-70**

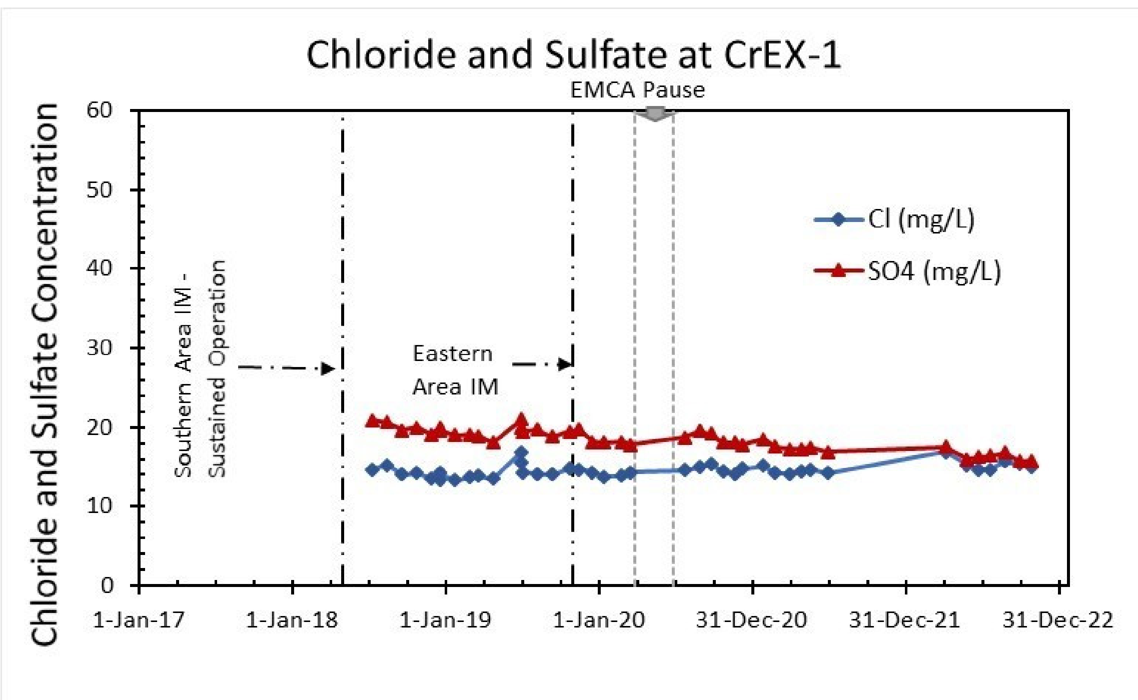

Figure D-8 **Chloride and sulfate concentrations at extraction well CrEX-1**

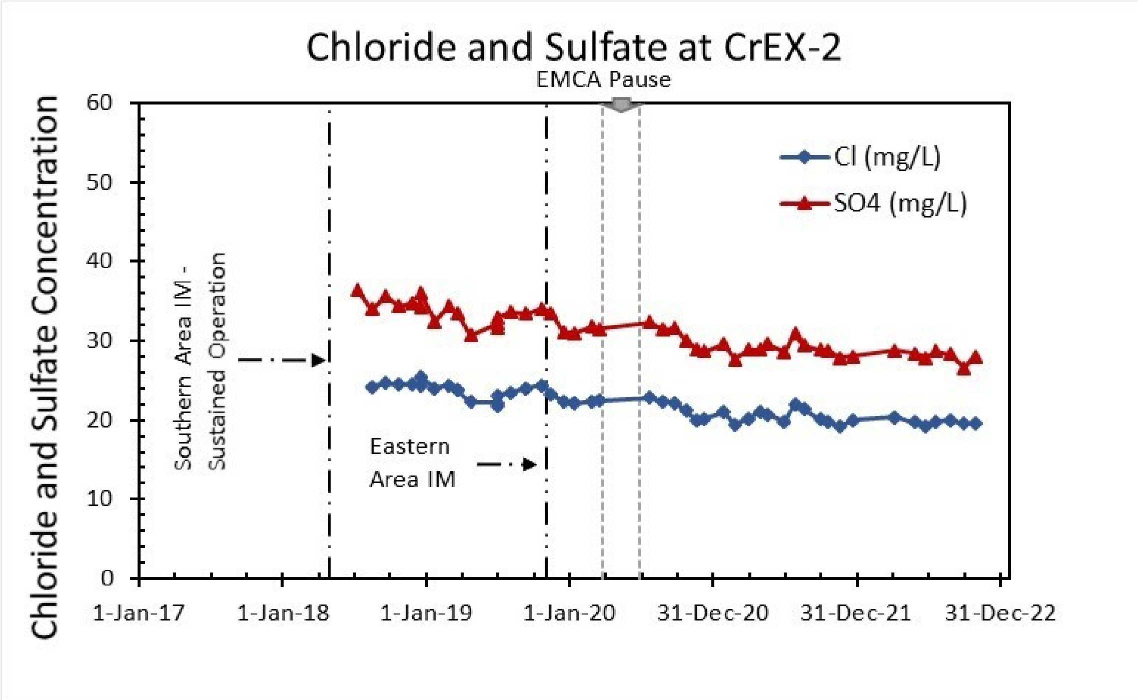

Figure D-9 **Chloride and sulfate concentrations at extraction well CrEX-2**

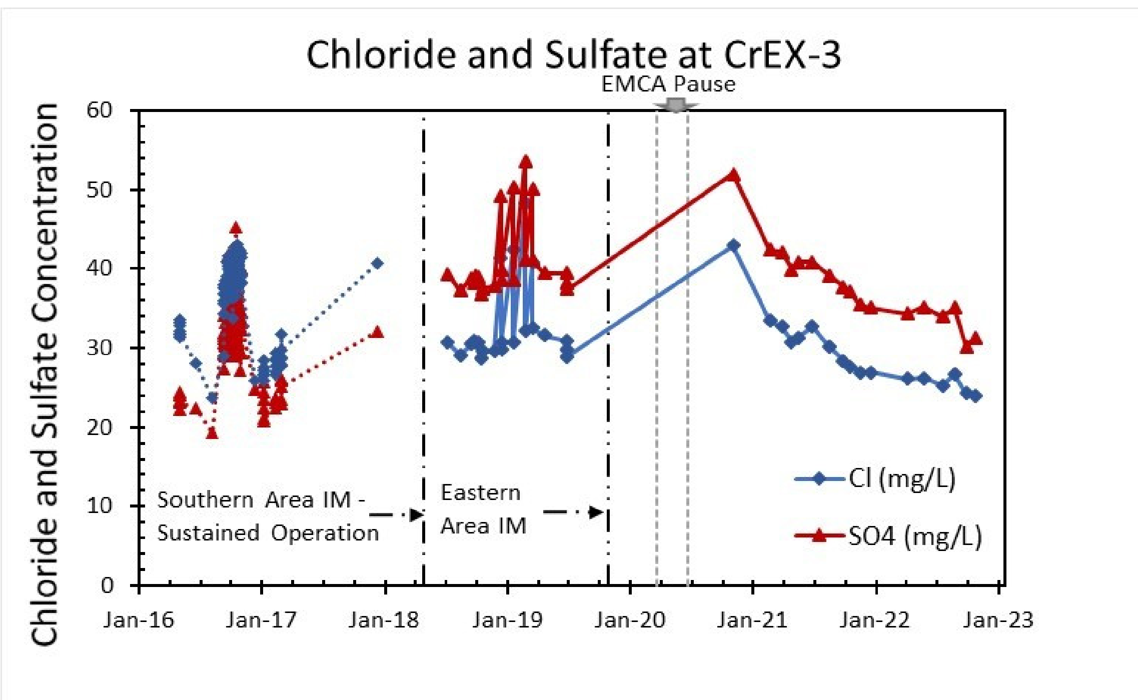

Figure D-10 **Chloride and sulfate concentrations at extraction well CrEX-3**

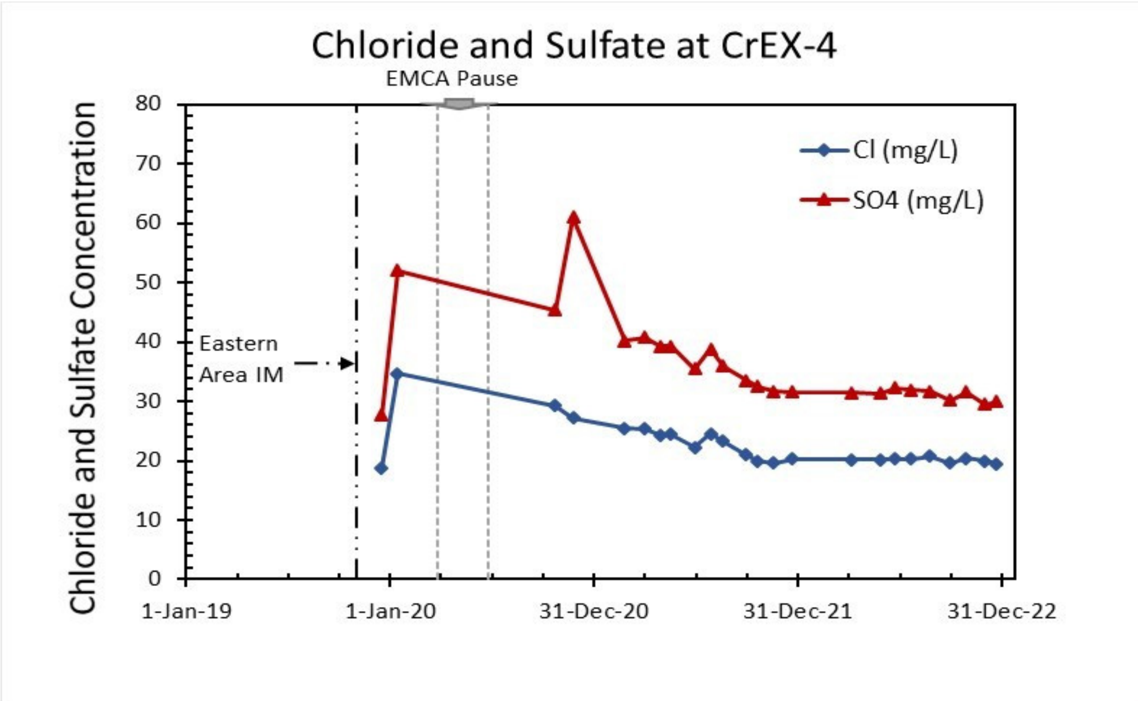

Figure D-11 Chloride and sulfate concentrations at extraction well CrEX-4

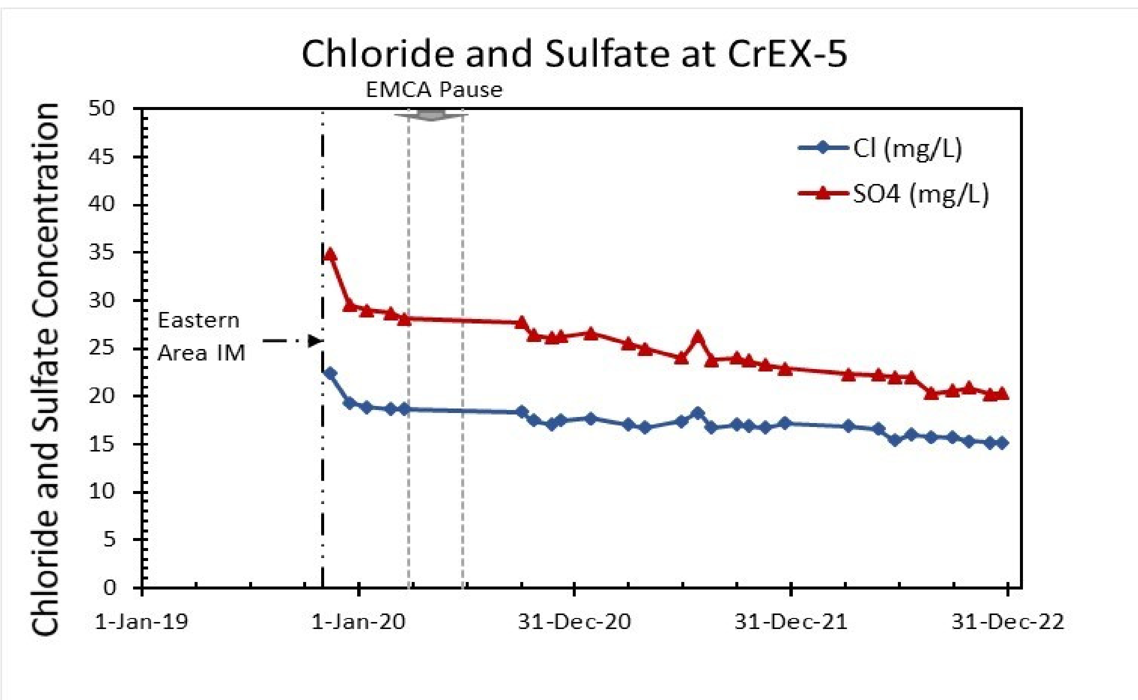

Figure D-12 Chloride and sulfate concentrations at extraction well CrEX-5