LM National Laboratory Network Collaboration Report Weldon Spring, Missouri, Site

May 2022

Revised August 2023

U.S. DEPARTMENT OF ENERGY | Legacy Management

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Abbreviations

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DOE	U.S. Department of Energy
EE/CA	Engineering Evaluation/Cost Analysis
EPA	U.S. Environmental Protection Agency
ESD	Explanation of Significant Differences
ft	feet
GWOU	Groundwater Operable Unit
IC	institutional control
LM	Office of Legacy Management
LMS	Legacy Management Support
LTS&M	Long-Term Surveillance and Maintenance
MCL	maximum contaminant level
MDC	Missouri Department of Conservation
MDNR	Missouri Department of Natural Resources
MNA	monitored natural attenuation
MoDOT	Missouri Department of Transportation
NLN	National Laboratory Network
NPL	National Priorities List
ORD	Office of Research and Development
OU	operable unit
pCi/L	picocuries per liter
QROU	Quarry Residuals Operable Unit
RD/RA	Remedial Design/Remedial Action
ROD	Record of Decision
TCE	trichloroethene
TI	Technical Impracticability

Executive Summary

This report presents recommendations to reduce risk involved with the Comprehensive Environmental Response, Compensation, and Liability Act (also called CERCLA) monitored natural attenuation (MNA) remedy issues at the Weldon Spring, Missouri, Site. The recommendations are the result of a collaborative effort between the U.S. Department of Energy (DOE) Office of Legacy Management (LM), the Legacy Management Support contractor, and the DOE National Laboratory Network (NLN) from September 15, 2021, to November 17, 2021. U.S. Environmental Protection Agency (EPA) Region 7, the EPA Office of Research and Development, and the Missouri Department of Natural Resources (MDNR) also participated in the collaboration as observers. Participation by EPA and MDNR was with the understanding that any official input or endorsement for any of the recommendations would be reserved for if and when DOE decides to pursue implementation of a recommendation at the site. The phrase "LM/NLN collaboration" refers to the joint effort of all the participants mentioned above.

The collaboration focused on two focus areas related to the Groundwater Operable Unit at the site. Both focus areas are identified in the Weldon Spring Site Sixth Five-Year Review. The issues and recommendations identified are described below.

Issue 1: The current monitoring network may not be adequate to meet the MNA remedy objectives. (This was first raised as an issue in 2004 when results of recently installed wells into the unweathered zone indicated higher levels of contamination than anticipated. The sampling results of these wells were not available until after DOE and regulators had established trigger levels for MNA earlier that year.)

Recommendation 1: LM will initiate a working group in collaboration with the NLN to evaluate the need and location(s) for additional monitoring wells to further delineate the uranium plume in the unweathered unit. The recommendations identified in the July 2020 EPA Office of Research and Development Memorandum will be evaluated during this working group. The results of this evaluation will be presented as a written summary and an implementation strategy will be discussed with EPA.

Issue 2: The remedy is not projected to return groundwater to its beneficial use within a reasonable time frame.

Recommendation 2: LM will evaluate alternative solutions for removing residual uranium sources and restoring groundwater. If this evaluation finds no viable alternative remedies, and after issue 1 has been resolved, evaluate justification for a Technical Impracticability waiver. The results of this evaluation will be presented as a written summary.

Two focus areas were identified for the LM/NLN collaboration.

Focus Area 1: Benefit of Additional Characterization

- **Additional wells in the unweathered unit:** Examine how or if additional wells would enhance the remedy (impacted area and downgradient).
- **Justification:** Include a description of goals, number and locations of wells, supplemental characterization methods to optimally locate the wells, and how each well would advance environmental management and regulatory objectives.

- Include practical considerations (e.g., the expectation that it will take 3–5 years before well concentrations stabilize, inherent uncertainties in complex heterogeneous systems like karsts).
- Assess and recommend alternative characterization methods.

Focus Area 2: Alternative Strategies to MNA

- Examine the technical basis for *alternative strategies* to MNA. Examples are enhanced attenuation or a Technical Impracticability for the impacted area.
- Evaluate current and additional characterization to address regulatory requirements for each alternative, focusing on the persistence of elevated unweathered unit uranium concentrations in the Raffinate Pits area.
- Develop an objectives list to augment current monitoring with additional characterization for each regulatory alternative.
- Outline the process and the advantages and disadvantages for each alternative.

Evaluation of MNA Remedy Progress

A short summary of the progress achieved by the MNA remedy on reducing the site's environmental impact on surface water and groundwater is presented below.

Springs and surface water locations: MNA is progressing as expected with yearly maximum uranium concentrations continuing their long-term decreasing trend at Burgermeister Spring and at Southeast Drainage springs. Maximum concentrations are occasionally over 50 picocuries per liter (pCi/L) during dry periods, varying as much as an order of magnitude during the year in response to dilution from runoff in wet periods. Uranium concentrations at surface ponds and streams are at or near background levels.

Weathered unit: MNA is working as expected with yearly average uranium concentrations below trigger levels at all locations and only slightly above the 20 pCi/L maximum contaminant level (MCL) at MW-3030 in the footprint of Raffinate Pit 4 (22 pCi/L and a long-term decreasing trend). Downgradient weathered unit uranium concentrations are low and typically at background levels.

Unweathered unit: MNA has not progressed as expected at all locations. This condition is the driver for the LM/NLN collaboration. At far downgradient locations, uranium concentrations are at background levels. At one near-downgradient well in the western paleochannel (MW-4043), uranium concentrations are elevated (40 pCi/L) but steadily decreasing and should be below the 20 pCi/L MCL in 15–20 years.

Elevated uranium concentrations have been identified in the upper part of the unweathered unit at two locations adjacent to the former raffinate pits. Concentrations increased for several years and have been stable for the last 10 years, neither increasing nor decreasing. Uranium concentrations are low in deeper unweathered unit wells both downgradient and near the raffinate pits (MW-4042). Until uranium concentrations begin to decline in the upper unweathered unit wells, a time for final cleanup to be achieved through the MNA remedy cannot be projected.

Recommendations from the LM/NLN Initiative

The Weldon Spring Site LM/NLN collaboration team's goal was to develop recommendations to help resolve the issues identified in the Sixth Five-Year Review, with a special focus on evaluating (1) the need and location(s) for additional monitoring wells to further delineate the uranium plume in the unweathered unit and (2) to evaluate alternative solutions for removing residual uranium sources and restoring groundwater at the site.

The following recommendations resulted from the collaboration and are actionable within the next 1 to 5 years. Narratives for each of these recommendations and actions are provided in Attachment A. LM/NLN collaboration team documentation (i.e., schedule and working group meeting agendas and notes) is provided in Attachment B.

1. Evaluate trends in existing wells using statistical methods such as Mann-Kendall using data from longer time periods (Narrative 2).
   - The Weldon team has used the Mann-Kendall test to predict trends since the MNA remedy began but have been constrained formally to a 5-year analysis window by regulatory agreement. The Weldon team has been showing longer time frames for some locations and analytes in recent annual reports to show long-term trends.
   - Work with regulators to formally allow extending the current 5-year trending period when appropriate (i.e., when needed for locations with highly variable concentrations).
2. Assess connectivity of the upper unweathered unit with the surrounding formation to determine if the persistent elevated uranium concentrations are restricted to isolated areas (Narrative 1).
   - Perform high-flow sampling of certain unweathered unit wells.
   - Perform tracer testing on certain unweathered unit wells.
   - Based on the above results, conduct borehole dilution testing of certain unweathered unit wells.
3. Develop uranium mass balance and mass flux estimate at the site (i.e., determining where the uranium is and where it is going) (Narrative 1).
   - Use remediation evaluation modeling (REMChlor-MD) to assess recalcitrant source removal and subsequent plume attenuation.
4. Assess the potential for uranium attenuation mechanisms in the weathered karst aquifer not related to dilution and dispersion (Narratives 4, 5, and 6).
   - Look at fractures of existing core (and those from future wells or boreholes) for sorption and precipitation.
   - Consider using matrix diffusion as a nonconventional attenuating mechanism.
   - Use geochemical modeling to evaluate the probability that alternative natural attenuations mechanisms, such as precipitation of uranium-rich minerals on fracture faces, could be occurring at the site.

5. Refine estimates of the vertical and lateral extent of uranium at the site, focusing on the upper part of the unweathered unit near the raffinate pits and downgradient in the western paleochannel (Narratives 3 and 4).
    - Use the geophysical survey results to optimally position future wells.
    - Use the geophysical survey results as a surrogate/supplement for lateral plume delineation where warranted.
    - Use targeted geophysical surveys to image lateral and vertical fracture networks and the boundaries and structure of the more highly fractured “paleochannel.”
6. In addition to geophysical logging, conduct FLUTe transmissivity profiling on future wells to identify preferential flow zones. Use targeted flow meter testing on high transmissivity zones to quantify flow (Narrative 1).

1.0 Introduction

1.1 Purpose and Scope

The U.S. Department of Energy (DOE) Office of Legacy Management (LM) is responsible for the stewardship of a growing portfolio of over 100 sites formerly used for defense-related mining, milling, processing, disposal, and program management. LM recently undertook a major effort to rank each site in its portfolio by relative risks related to human health, regulatory compliance, institutional controls (ICs), and stakeholder concerns. The ranking of sites within the four risk categories is a relative ranking (within LM) of potential future risks. A site with a "high" ranking in a given category does not pose an immediate threat; rather, relative to sites ranked "low," it has a greater potential to pose a problem in the future.

The Weldon Spring, Missouri, Site's overall and Groundwater Operable Unit (GWOU) risk indexes for 2021 are presented in Table 1.

Table 1. 2021 Site Risk Index Results for the Weldon Spring Site

LM Site Information		Site Risk Factor Inputs					Risk Index
Site Name	**Regulatory Driver/ Programmatic Framework**	**Human Health Risk**	**Stakeholder Risk**	**Regulatory Risk**	**Institutional Controls Risk**	**Site Complexity Factor**	
Weldon Spring, Missouri, Site	CERCLA/RCRA	Medium	Medium	High	Low	Category 3	0.78
Weldon Spring, Missouri, Site GWOU	CERCLA/RCRA	Medium	Medium	High	Low	Category 2	0.74

Abbreviations:
CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act
RCRA = Resource Conservation and Recovery Act

The risk categories are defined as follows:

- **Human Health Risk:** The possibility that human receptors could be exposed to unacceptable levels of site-related contamination
- **Stakeholder Risk:** The likelihood that protectiveness of a given site could be affected or questioned in some way based on input from stakeholders (individuals or organizations)
- **Regulatory Risk:** The likelihood that a site will not attain compliance goals (e.g., groundwater cleanup is ongoing) or that compliance will not be maintained in the future
- **IC Risk:** An assessment of the effectiveness of an IC to maintain protectiveness of human health and the environment

The director of LM envisioned a partnership—a collaboration among LM, the Legacy Management Support (LMS) contractor, and DOE's National Laboratory Network (NLN)—working together to help DOE reduce risks at the highest ranked sites, reduce uncertainty, and improve efficiency by strategically leveraging and applying innovative technically based solutions. LM focused the participants toward developing actionable (i.e., implementable in the 1–5-year time frame), consensus-driven (i.e., lacking dissent among the NLN, the LMS contractor, LM, and other invited participants) recommendations that directly reduce identified risks. For the Weldon Spring Site, the U.S. Environmental Protection Agency (EPA) and the Missouri Department of Natural Resources (MDNR) were invited to participate. Participation by EPA and MDNR was with the understanding that any official input or endorsement for any of the recommendations would be reserved for if and when DOE decides to pursue implementation of a recommendation at the site. The phrase "LM/NLN collaboration" refers to the joint effort of all the participants mentioned above.

1.1.1 Human Health Risk

According to the LM risk ranking system, the Weldon Spring Site human health risk is categorized as medium. The only identified location that could be considered a point of exposure—5-year average uranium levels (24 picocuries per liter [pCi/L]) above the drinking water standard (20 pCi/L)—is Burgermeister Spring, where concentrations are steadily decreasing. Other downgradient wells and surface water locations have consistently low uranium levels.

1.1.2 Stakeholder Risk

According to the LM risk-ranking system, the Weldon Spring Site stakeholder risk is categorized as medium. Medium risk sites are defined as those that had active stakeholder interest or were in an area that had received attention; while interest may have waned, the potential exists for renewed public attention.

Engaging with stakeholders has been a long-term process at the Weldon Spring Site. The St. Charles Countians Against Hazardous Waste formed in the early days of remediation, and the organization continued advocating for the community through site closure. During the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process, the Weldon Spring Citizens Commission played a central role in crafting decisions regarding final land use. Stakeholder engagement continues through ongoing community engagement via Weldon Spring Site Interpretive Center activities.

1.1.3 Regulatory Risk

According to the LM risk ranking system, the Weldon Spring Site regulatory risk is categorized as high. The Weldon Spring Site has been addressing an issue regarding the groundwater remedy since the *Record of Decision for the Final Remedial Action for the Groundwater Operable Unit at the Chemical Plant Area of the Weldon Spring Site* (DOE 2004a), also called the GWOU ROD, was issued in January 2004. The issue of the extent of uranium impact at the site arose when monitoring wells MW-3040 and MW-4040 were installed to delineate the vertical extent of uranium in the Raffinate Pits area. Elevated concentrations of uranium were unexpectedly discovered in the upper portion of the unweathered unit. Before this, the unweathered unit was not believed to be impacted. Wells MW-3040 and MW-4040 were drilled in May 2004 as the monitored natural attenuation (MNA) fixed trigger values were being established in the *Remedial Design/Remedial Action Work Plan for the Final Remedial Action for the Groundwater Operable Unit at the Weldon Spring Site* (RD/RA Work Plan) in July 2004 (DOE 2004b).

Sample results for these wells were not available until August 2004. The result from the first sample collected June 30, 2004, at well MW-4040 was 178 pCi/L, exceeding the 100 pCi/L trigger value agreed to in the RD/RA Work Plan. The trigger level became a concern for EPA and MDNR because this indicated that the nature and extent of contamination in the unweathered Burlington-Keokuk Limestone bedrock below the Chemical Plant area had not been fully characterized. Uranium concentrations in wells MW-3040 and MW-4040 trended upward for the next 5 to 10 years before stabilizing. DOE believes the impacted area fixed uranium trigger value was set prematurely, before an adequate dataset had been collected after remediation activities ended. Concentrations are expected to be decreasing or stable for an MNA remedy. Trigger levels are indicators of MNA progress and are established to alert of increasing concentrations.

At the request of EPA Region 7, the scientific research arm of the EPA, the Office of Research and Development (ORD), performed an evaluation of the site in 2020. This evaluation resulted in the development of a 2020 ORD memorandum (EPA 2020) that concluded that additional characterization of the site was needed. The LM/NLN collaboration team reviewed and evaluated the ORD observations and incorporated their recommendations for additional data collection with the LM/NLN collaboration recommendations of potential activities to improve site characterization.

The Sixth Five-Year Review report (DOE 2021) was finalized on September 30, 2021. The issues and recommendations identified in the report are as follows:

Issue 1: The current monitoring network may not be adequate to meet the MNA remedy objectives.

Recommendation 1: LM will initiate a working group in collaboration with the DOE NLN to evaluate the need and location(s) for additional monitoring wells to further delineate the uranium plume in the unweathered unit. The recommendations identified in the July 2020 EPA Office of Research and Development Memorandum will be evaluated during this working group. The results of this evaluation will be presented as a written summary and an implementation strategy will be discussed with EPA.

Issue 2: The remedy is not projected to return groundwater to its beneficial use within a reasonable time frame.

Recommendation 2: LM will evaluate alternative solutions for removing residual uranium sources and restoring groundwater. If this evaluation finds no viable alternative remedies, and after issue 1 has been resolved, evaluate justification for a Technical Impracticability (TI) waiver. The results of this evaluation will be presented as a written summary.

This report is intended to act as the written summary to fulfill the first recommendation. To resolve these issues, further discussion on the implementation strategy will occur between DOE and EPA if and when DOE decides to pursue implementation of any recommendations.

1.1.4 IC Risk

According to the LM risk ranking system, the Weldon Spring Site's IC risk is categorized as low. The definition of low risk applies to property under other government ownership with ICs that do not explicitly address residual contamination or to property under private or tribal ownership with ICs explicitly addressing residual contamination.

The Weldon Spring Site ICs are in place as described in Section 2.2 and include easements on offsite properties that restrict the use of groundwater. Restrictions against soil excavation and land use are in place.

1.2 Collaboration Process

The LM/NLN collaboration at the Weldon Spring Site was conducted as follows:

- A kickoff meeting to orient participants to the site and the collaboration objectives was held on September 15, 2021
- Two full team (moderated) meetings were held on September 22 and November 3, 2021
- Three working team meetings (unmoderated) were held on October 6, October 13, and November 10, 2021
- A wrap up meeting was held on November 17, 2021
- This report summarizes the risk reduction recommendations made by the group

At the recommendation of the Weldon Spring Site LM site manager, site regulators were invited and encouraged to participate in the collaboration process. For the Weldon Spring Site, this included EPA and MDNR. Both EPA and MDNR participated in the kickoff meeting and the working group and focus meetings by sharing impressions and thoughts about the topics being discussed. For the kickoff meeting, ORD representatives gave a presentation regarding the 2020 ORD memorandum (EPA 2020) that was issued to the Weldon Spring Site. Both EPA and MDNR made it clear that any official input by them would be reserved for if and when any of the recommendations coming out of the collaboration were presented to them as something the site had selected to implement.

The organizations invited to participate included the following:

- LM
- LMS contractor
- NLN:
  - Savannah River National Laboratory
  - Pacific Northwest National Laboratory
  - National Energy Technology Laboratory
  - Los Alamos National Laboratory
- MDNR
- EPA Region 7
- EPA ORD

The names and affiliations of those invited are noted on the meeting agendas in Attachment B.

This multiorganizational LM/NLN collaboration led to a broad range of topics covered and brought many voices together to formulate the risk reduction recommendations that are detailed in this report.

As discussed in more detail in Section 3.0, one team was organized to provide input for both focus areas for the Weldon Spring Site LM/NLN collaboration. The team designated both an NLN and an LMS lead. The NLN lead was primarily responsible for coordinating discussions and for compiling the tabulation of recommendations and the implementation details. The LMS lead was primarily responsible for focusing the discussion and ensuring that the recommendations were actionable within the context of the Weldon Spring Site project, weighed against work done to date and work already planned. Incremental documentation to support recommendation development was made available to all participants for input and comment.

2.0 Site Background

2.1 Brief Site History

The Weldon Spring Site (approximately 228 acres) is in St. Charles County, Missouri, approximately 30 miles west of St. Louis. It is a Category 3 LM site with an onsite staff. The Weldon Spring Site is a Category 3 site due to the operation and maintenance of an active remedial system, routine inspections to verify the integrity of engineered facilities and ICs, groundwater and surface water monitoring, and records-related activities. The Weldon Spring Site is one of nine CERCLA sites managed by LM.

The site comprises two geographically distinct, DOE-owned properties: the former Weldon Spring Chemical Plant and Raffinate Pit areas (Chemical Plant) and the former Weldon Spring Quarry (Quarry). The Chemical Plant is about 2 miles southwest of the junction of Missouri State Route 94 and Interstate 64. The Quarry is about 4 miles southwest of the Chemical Plant. Both sites are accessible from Missouri State Route 94.

During the early 1940s, the U.S. Department of the Army (Army) acquired 17,232 acres of private land in St. Charles County to construct the Weldon Spring Ordnance Works facility. The former Ordnance Works site has since been divided into several contiguous areas under different ownership. Land use of the Ordnance Works site includes the Chemical Plant and Quarry, the U.S. Army Reserve Weldon Spring Training Area, the Missouri Department of Conservation (MDC), the MDNR Division of State Parks (MDNR-Parks), Francis Howell High School, a St. Charles County highway maintenance (formerly Missouri Department of Transportation [MoDOT]) facility, the Public Water Supply District No. 2 water supply facility, the St. Charles County law enforcement training center, the village of Weldon Spring Heights, and the University of Missouri research park.

The Chemical Plant and Quarry areas total 228.16 acres. The Chemical Plant occupies 219.50 acres, and the Quarry occupies 8.66 acres.

EPA placed the Quarry and Chemical Plant areas on the National Priorities List (NPL) in 1987 and 1989, respectively. Initial remedial activities at the Chemical Plant (a series of Interim

Response Actions authorized through the Engineering Evaluation/Cost Analysis [EE/CA] process) included:

- Removal of electrical transformers, electrical poles and lines, and overhead piping and asbestos that presented an immediate threat to workers and the environment.
- Construction of an isolation dike to divert runoff around the Ash Pond area to reduce the concentration of contaminants going offsite in surface water.
- A detailed characterization of onsite debris, the separation of radiological and nonradiological debris, and the transport of materials to designated staging areas for interim storage.
- Dismantling of 44 Chemical Plant buildings under four separate Interim Response Actions.
- Treatment of contaminated water at the Chemical Plant and the Quarry.

Remediation of the Weldon Spring Site was administratively divided into four operable units (OUs): the Chemical Plant OU, the Quarry Bulk Waste OU, the Quarry Residuals OU (QROU), and the GWOU. The Southeast Drainage was remediated under a CERCLA removal action and documented through the *Engineering Evaluation/Cost Analysis for the Proposed Removal Action at the Southeast Drainage near the Weldon Spring Site, Weldon Spring, Missouri* (DOE 1996b), hereafter referred to as the EE/CA Report, and the *Decision Document for the Southeast Drainage* (DOE 1996a). The selected remedies are summarized in the following sections.

2.1.1 Chemical Plant OU

In the *Record of Decision for Remedial Action at the Chemical Plant Area of the Weldon Spring Site* (DOE 1993), also called the Chemical Plant ROD, DOE established the remedy for controlling contaminant sources at the Chemical Plant (except groundwater) and disposing of contaminated materials in an onsite disposal cell. The remedy included remediation of 17 offsite vicinity properties affected by Chemical Plant operations. The vicinity properties were remediated in accordance with Chemical Plant ROD cleanup criteria. The *Chemical Plant Operable Unit Remedial Action Report* (DOE 2004c) was finalized in January 2004.

The selected remedy included:

- Removal of contaminated soils, sludge, and sediment.
- Treatment of wastes by chemical stabilization or solidification, as appropriate.
- Disposal of wastes removed from the Chemical Plant and stored Quarry bulk wastes in an engineered onsite disposal facility.

2.1.2 Quarry Bulk Waste OU

DOE implemented remedial activities for the Quarry Bulk Waste OU set forth in the *Record of Decision for the Management of the Bulk Wastes at the Weldon Spring Quarry* (DOE 1990).

The selected remedy included:

- Excavation and removal of bulk waste (i.e., structural debris, drummed and unconfined waste, process equipment, sludge, and soil).
- Transportation of waste along a dedicated haul road to a temporary storage area at the Chemical Plant.
- Staging of bulk wastes at the temporary storage area.

2.1.3 Quarry Residuals OU

The QROU remedy was described in the *Record of Decision for the Remedial Action for the Quarry Residuals Operable Unit at the Weldon Spring Site, Weldon Spring, Missouri* (DOE 1998). The QROU ROD addressed residual soil contamination in the Quarry, surface water and sediments in the Femme Osage Slough and nearby creeks, and contaminated groundwater. The *Quarry Residuals Operable Unit Interim Remedial Action Report* (DOE 2003) was finalized in November 2003.

The selected remedy included:

- Long-term monitoring and ICs to prevent exposure to contaminated groundwater north of the Femme Osage Slough.
- Long-term monitoring and ICs to protect the quality of the public water supply in the Missouri River alluvium and the implementation of a well field contingency plan.
- Confirming the ongoing presence of reducing conditions in the slough area that prevents uranium migration to the alluvium south of the slough.

2.1.4 Groundwater OU

DOE implemented the *Interim Record of Decision for Remedial Action for the Groundwater Operable Unit at the Chemical Plant Area of the Weldon Spring Site* (DOE 2000), which was approved on September 29, 2000, to investigate the practicability of remediating trichloroethene (TCE) contamination in Chemical Plant groundwater using in situ chemical oxidation. Based on extensive monitoring, it was determined that in situ oxidation did not perform adequately under field conditions; therefore, the remediation of TCE was reevaluated, along with the remaining contaminants of concern.

In the GWOU ROD (DOE 2004a), DOE established the MNA remedy to address contaminated groundwater and springs. The *Interim Remedial Action Report for the Groundwater Operable Unit of the Weldon Spring Site* (DOE 2005a) was finalized in March 2005.

The selected remedy included:

- Sampling of groundwater and surface water, including springs, to verify the effectiveness of naturally occurring processes (dilution and dispersion) to reduce contaminant concentrations over time.
- ICs to prevent exposure to contaminated groundwater at the Chemical Plant and to the north toward Burgermeister Spring.

2.1.5 Southeast Drainage

Remedial action for the Southeast Drainage was addressed as a separate action under CERCLA. The EE/CA Report (DOE 1996b) was prepared in August 1996 to evaluate the human and ecological health risks within the drainage. The EE/CA Report recommended that selected sediment in accessible areas of the drainage should be removed with track-mounted equipment and transported by off-road haul trucks to the Chemical Plant. Soil removal occurred in two phases: from 1997 to 1998 and in 1999. More details are included in the *Southeast Drainage Closeout Report Vicinity Properties DA4 and MDC7* (DOE 1999).

2.2 Current Compliance Strategy

The Weldon Spring Site is listed on the NPL and is therefore governed by the CERCLA process. The site reached construction completion under CERCLA on August 22, 2005. The site also received the EPA Superfund Sitewide Ready for Anticipated Use (SWRAU) designation from EPA in a letter dated March 20, 2013. The SWRAU performance measure applies to sites documented as ready for reuse when the entire construction-completed NPL site meets the following requirements:

- All cleanup goals in the RODs or other remedy decision documents have been achieved for media that could affect current and reasonably anticipated future land uses of the site, so that there are no unacceptable risks
- All ICs or other controls required in the RODs or other remedy decision documents have been put in place

After a review of all relevant site documents, including the RODs; the *Long-Term Surveillance and Maintenance Plan for the U.S. Department of Energy Weldon Spring, Missouri, Site* (DOE 2008a), also called the LTS&M Plan; Five-Year Reviews; annual inspections and monitoring data; and ICs documentation, EPA determined that DOE has achieved the SWRAU performance measure for all DOE-owned land at the site. This includes the Chemical Plant and Quarry areas and totals approximately 228 acres. The SWRAU measure was recorded as completed in the EPA Comprehensive Environmental Response, Compensation, and Liability Information System database on February 13, 2013.

Because some areas of the site are still contaminated beyond levels that would allow unlimited use and unrestricted exposure, CERCLA requires that the remedial actions be reviewed at least every 5 years. These reviews are commonly called Five-Year Reviews. DOE completed the sixth Five-Year Review report for the site in September 2021 (DOE 2021).

DOE issued the *Explanation of Significant Differences, Weldon Spring Site* (DOE 2005b) in accordance with CERCLA in February 2005. That Explanation of Significant Differences (ESD) clarified the use restrictions for the separate OUs that are necessary for the remedial actions specified in the RODs to remain protective over the long term. The ESD clarified specific requirements for each site area that needed use restrictions, and it established how DOE would implement, maintain, and monitor the specific requirements.

DOE developed the LTS&M Plan, which addressed the full scope of the site management activities necessary to ensure that conditions at the Weldon Spring Site remain protective over the long term. In addition to addressing such activities as long-term groundwater monitoring and disposal cell maintenance, the LTS&M Plan was developed and issued to ensure that the use restrictions identified in the ESD were properly imposed and maintained. The LTS&M Plan included a detailed IC implementation plan, which includes a process for evaluating and identifying specific IC mechanisms that best accomplish the objectives set out in the ESD. Consistent with EPA guidance on selecting ICs, various IC mechanisms were evaluated, including government controls, proprietary controls, enforcement tools, and informational devices. Redundant mechanisms were employed to increase the effectiveness of the ICs.

The additional ICs discussed in the ESD and LTS&M Plan have been completed as presented below:

- **Special Use Area designation under the State Well Drillers Act:** The "Special Use Area" under the Missouri well code was finalized in the Missouri regulations and became effective August 2007 as Title 10 *Code of State Regulations* 23-3.100(8) (10 CSR 23-3.100[8]). This is a special regulation that DOE and the Army pursued with MDNR that requires additional drilling protocols and construction procedures to be implemented by regulations on any well construction within the restriction boundaries. This regulation has since been updated in January 2019, and the new citation is 10 CSR 23-3.090(13).
- **Memorandum of Understanding with the Army:** The Army and DOE signed the memorandum in September and October 2009, respectively.
- **Easements with surrounding affected state agency landowners (MDC, MDNR-Parks, MoDOT) for implementing the use restrictions required on state properties:** DOE established easements to restrict use of the contaminated groundwater in the area of the hydraulic buffer zone, to restrict land use in the Southeast Drainage, and to restrict land use at the Quarry reduction zone. DOE and MDNR-Parks finalized and signed the easement regarding the MDNR-Parks property in September 2009. The easement with MDC was finalized in July 2011, and the easement with MoDOT was finalized in June 2012. The MoDOT property was transferred to St. Charles County, and the restrictive easement was conveyed with the land transfer and is still in effect.

2.3 Weldon Spring Site GWOU Background Information

EPA signed the GWOU ROD (DOE 2004a) on February 20, 2004. The final GWOU ROD specified a remedy of MNA with ICs to limit groundwater use during the period of remediation. MNA relies on the effectiveness of naturally occurring processes to reduce contaminant concentrations over time. The GWOU ROD establishes remedial goals and performance standards for MNA.

In July 2004, DOE initiated monitoring for MNA as outlined in the RD/RA Work Plan (DOE 2004b). The monitoring network as presented in the *Interim Remedial Action Report for the Groundwater Operable Unit of the Weldon Spring Site* (DOE 2005a) has been modified over time as wells are added to and dropped from the network. Figure 1 shows the current monitoring well network.

2.3.1 Chemical Plant (GWOU) Monitoring Program

Monitoring at the Chemical Plant was changed in July 2004 to focus on MNA, the selected remedy. Under the monitoring program, total uranium, nitroaromatic compounds, TCE, and nitrate are monitored at selected locations throughout the Chemical Plant area. The sampling locations target areas of highest impact in the shallow aquifer and migration pathways associated with paleochannels in the Burlington-Keokuk Limestone. Deeper wells are sampled to assess potential vertical migration.

There were 48 wells (Figure 1), five springs, and one surface water location sampled at the Chemical Plant during 2020 to assess the progress of the MNA remedy. Each well was selected to fulfill objectives specified in the GWOU ROD (DOE 2004a) for the MNA monitoring network.

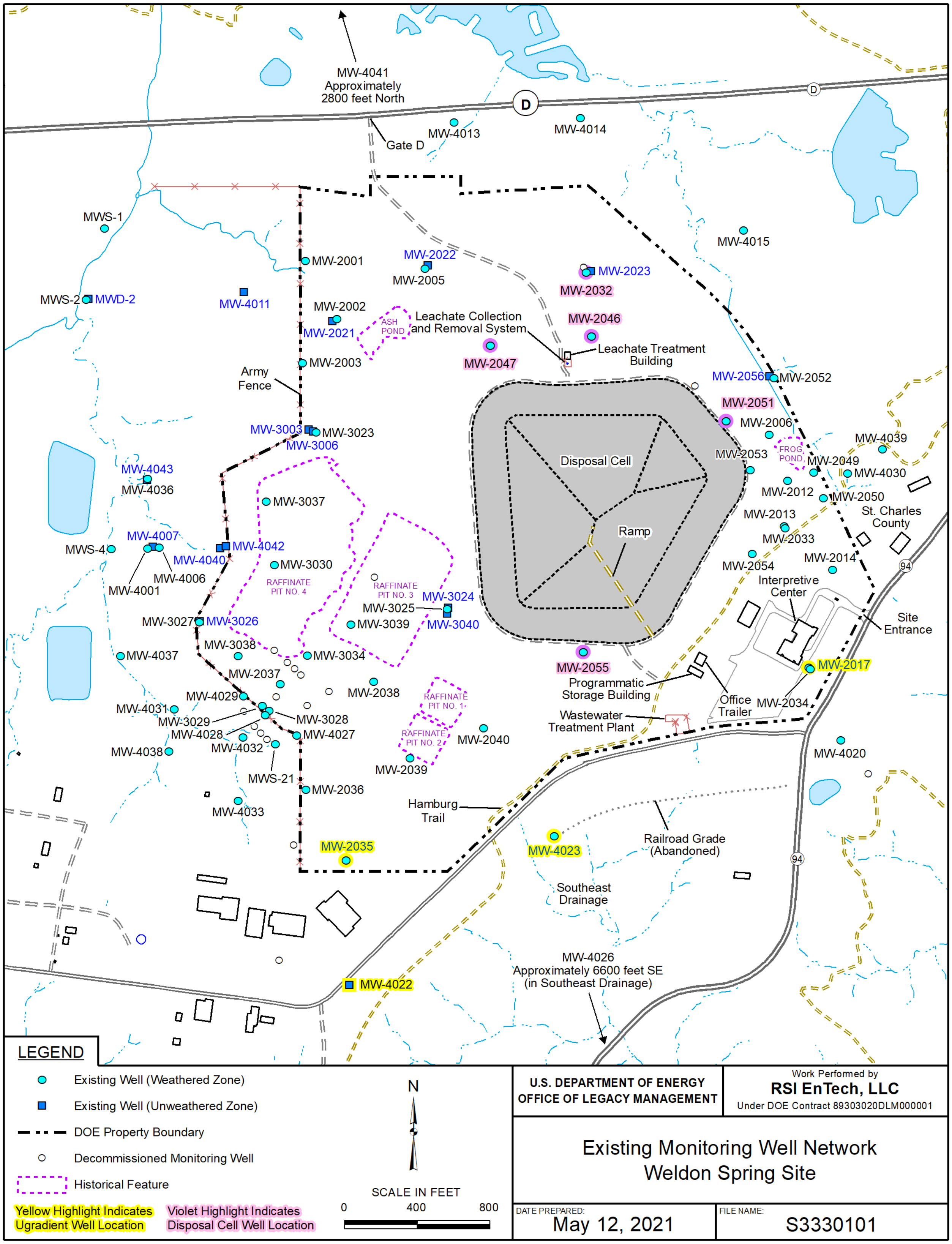
The monitoring network is designed to provide data either to show that natural attenuation processes are acting as predicted or to trigger the implementation of contingencies when these processes are not acting as predicted (e.g., unexpected expansion of the plume or sustained increases in concentrations within the area of impact). The data analysis and interpretation will satisfy the following monitoring objectives:

- **Objective 1:** Upgradient locations to monitor background levels
- **Objective 2:** Locations that monitor concentrations within the area of impact (source zone)
- **Objectives 3, 4, and 5 (lateral, vertical, and springs):** Downgradient locations to monitor for contaminant migration
- **Objective 6:** Water levels are measured at all monitoring network wells, even those that are not routinely sampled, to evaluate groundwater flow directions at the site

Data are evaluated as outlined in *Baseline Concentrations of the Chemical Plant Operable Unit Monitored Natural Attenuation Network at the Weldon Spring Site* (DOE 2008b). The evaluation of data was established to satisfy the monitoring objectives for the MNA remedy.

2.3.1.1 Trigger Levels

Trigger level indicators were set for each contaminant at the performance and detection monitoring locations in the event of unexpected increases. There are two trigger level types for each contaminant, the first of which is independent of the specific contaminant. The primary trigger level is set at what would be considered a statistically significant increase of a contaminant concentration at a location and is defined as the mean of the previous eight data points plus three standard deviations. This trigger is most useful for downgradient wells with relatively low and stable concentrations. It is less useful for higher-concentration wells adjacent to an impacted area where results are typically more variable. Higher-concentration zones where contamination was previously stable could be subject to a period of unstable, increasing concentrations after remediation. Removal of the source eventually leads to decreasing trends.



Abbreviation: SE = southeast

Figure 1. Monitoring Well Network at the Weldon Spring Site

The secondary trigger levels are fixed concentrations, for each objective area and analyte, that were established as a level above which concentration increases would be considered unacceptable from an MNA perspective (Table 2). The fixed trigger levels were based on a review of data collected before 2004 and were set at roughly 2 times the typical results with consideration for variability. They are typically set at higher levels near impacted areas and at lower levels, such as the maximum contaminant level (MCL), in downgradient, nonimpacted areas. The fixed trigger levels were formalized in the RD/RA Workplan (DOE 2004b). The trigger levels, both the primary and secondary, are used to evaluate MNA performance.

Table 2. Secondary (Fixed) Trigger Levels for Performance and Detection Monitoring for the GWOU

Analyte	Cleanup Standard	Objective 2	Objective 3 (near)	Objective 3 (far)	Objective 4	Objective 5
Nitrate (mg/L)	10	1350	30	10	20	20
Uranium (pCi/L)	20	100	50	20	40	150
TCE (μg/L)	5	1000	15	5	10	5
2,4-DNT (μg/L)—FP	0.11	2300	1.1	0.11	0.22	0.22
2,4-DNT (μg/L)—RP		5	0.55			
2,6-DNT (μg/L)	1.3	2000	13	1.3	2.6	1.3
2,4,6-TNT (μg/L)	2.8	500	11.2	2.8	5.6	2.8
1,3-DNB (μg/L)	1.0	20	4	1	2	1
NB (μg/L)	17	50	34	17	17	17

Note:
Cleanup standards from the "National Primary Drinking Water Regulations" (40 CFR 141) and Missouri "Water Quality Standards" (10 CSR 20-7.031).

Abbreviations:
DNB = dinitrobenzene
DNT = dinitrotoluene
FP = Frog Pond
mg/L = milligrams per liter
μg/L = micrograms per liter
NB = nitrobenzene
RP = raffinate pits
TNT = trinitrotoluene

Data collected since 2004 indicate that the fixed trigger for uranium in the impacted area was set prematurely. The 2004 to 2006 baseline study (DOE 2008b) did not include the new wells in the reevaluation of initial concentrations and suggested that additional data were needed to better establish baseline concentrations. Uranium levels in the three wells that exceed the fixed trigger value have stabilized; the 2020 average uranium concentrations are almost the same as the 2015 through 2020 average.

2.3.2 Hydrogeologic Description

Subsurface flow and transport in the Chemical Plant area occurs primarily in the carbonate bedrock. The overlying unconsolidated surficial materials are clay-rich, mostly glacially derived units, which are generally unsaturated beneath the site. These materials become saturated to the north and influence groundwater flow. The thickness of the unconsolidated materials ranges from 20 to 50 feet (ft) (DOE 1992).

A groundwater divide along the southern boundary of the site can be seen on potentiometric maps of both the weathered and unweathered units (Figure 2 and Figure 3). Groundwater north of the divide flows north toward Dardenne Creek and ultimately to the Mississippi River, and groundwater south of the divide flows south to the Missouri River. Localized flow is controlled largely by bedrock topography. Groundwater movement is generally by diffuse flow through an equivalent porous media until reaching localized zones of discrete flow through secondary porosity features such as fractures and solution channels. Dashed contours are used on the maps in areas where data are less abundant.

The aquifer of concern beneath the Chemical Plant is the shallow bedrock aquifer in the Mississippian Burlington-Keokuk Limestone (the uppermost bedrock unit) and the underlying Fern Glen Formation. The Burlington-Keokuk Limestone has two different lithologic zones—a shallow, weathered zone and an underlying unweathered zone. The weathered portion of this formation is highly fractured and exhibits solution voids and enlarged fractures. These features may also be present on a limited scale in the unweathered zone, particularly near buried preglacial stream channels (paleochannels). Localized aquifer properties are controlled by fracture spacing, solution voids, and preglacial weathering, including structural troughs along the bedrock-overburden interface.

All monitoring wells at the Chemical Plant are completed in the Burlington-Keokuk Limestone. Most of the wells are completed in the weathered zone of the bedrock where groundwater has the greatest potential to be contaminated. Wells screened in the underlying unweathered zone of the Burlington-Keokuk Limestone are used to assess the vertical migration of contaminants and to monitor for any horizontal migration in this zone. Preferential flow zones have been inferred from bedrock topography, groundwater surface maps, hydraulic conductivity data, and subsurface tracer results (DOE 2005a). The irregular contact between the weathered and unweathered units is lower, and hydraulic conductivities are typically higher, in the paleochannel areas. This provides preferential flow paths that coincide with the north-trending bedrock lows that are indicated on the groundwater elevation maps of both the weathered (Figure 2) and unweathered (Figure 3) units.

Numerous springs, a common feature in carbonate terrains, are present near the site. Five springs that are monitored routinely have been historically influenced by Chemical Plant discharge water or by groundwater that contained one or more contaminants of concern.

The presence of elevated total uranium and nitrate levels at Burgermeister Spring (SP-6301), approximately 1.2 miles north of the site, indicates that discrete subsurface flow paths are present near the site. Groundwater tracer tests performed in 1995 (DOE 1997) confirmed that a discrete and rapid subsurface hydraulic connection exists between the northern portion of the Chemical Plant and Burgermeister Spring.

2.3.2.1 Chemical Plant Hydrogeologic Data Analysis

Groundwater levels in monitoring network wells are measured quarterly to evaluate site groundwater flow directions at different times of the year. The configuration of the potentiometric surfaces is similar throughout the year and has remained relatively unchanged from previous years. Troughs in the groundwater surfaces coincide with the location of paleochannels. The potentiometric head levels also vary somewhat from the upper, middle, to lower portions of each unit.

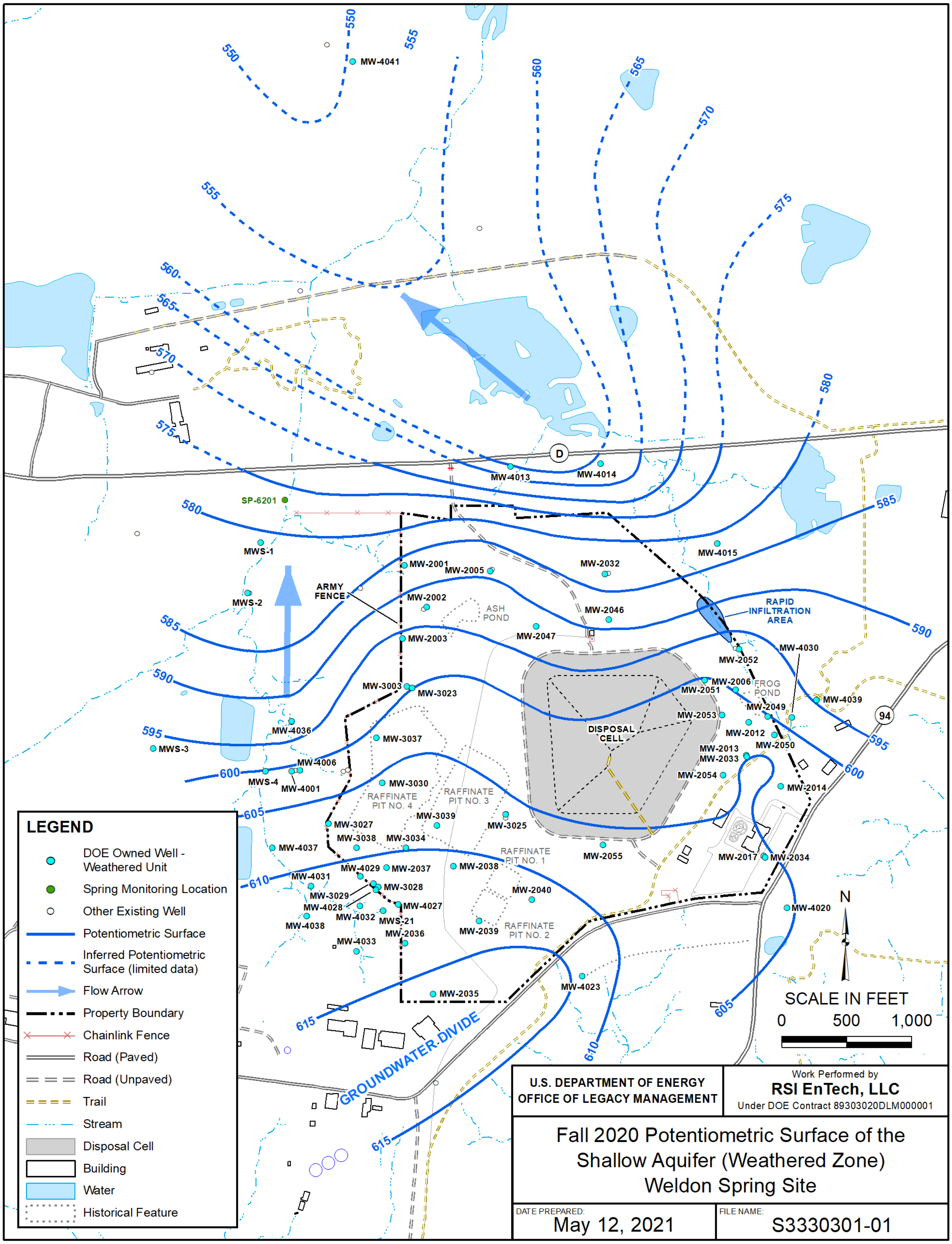


Figure 2. Weathered Unit Groundwater Surface at the Chemical Plant

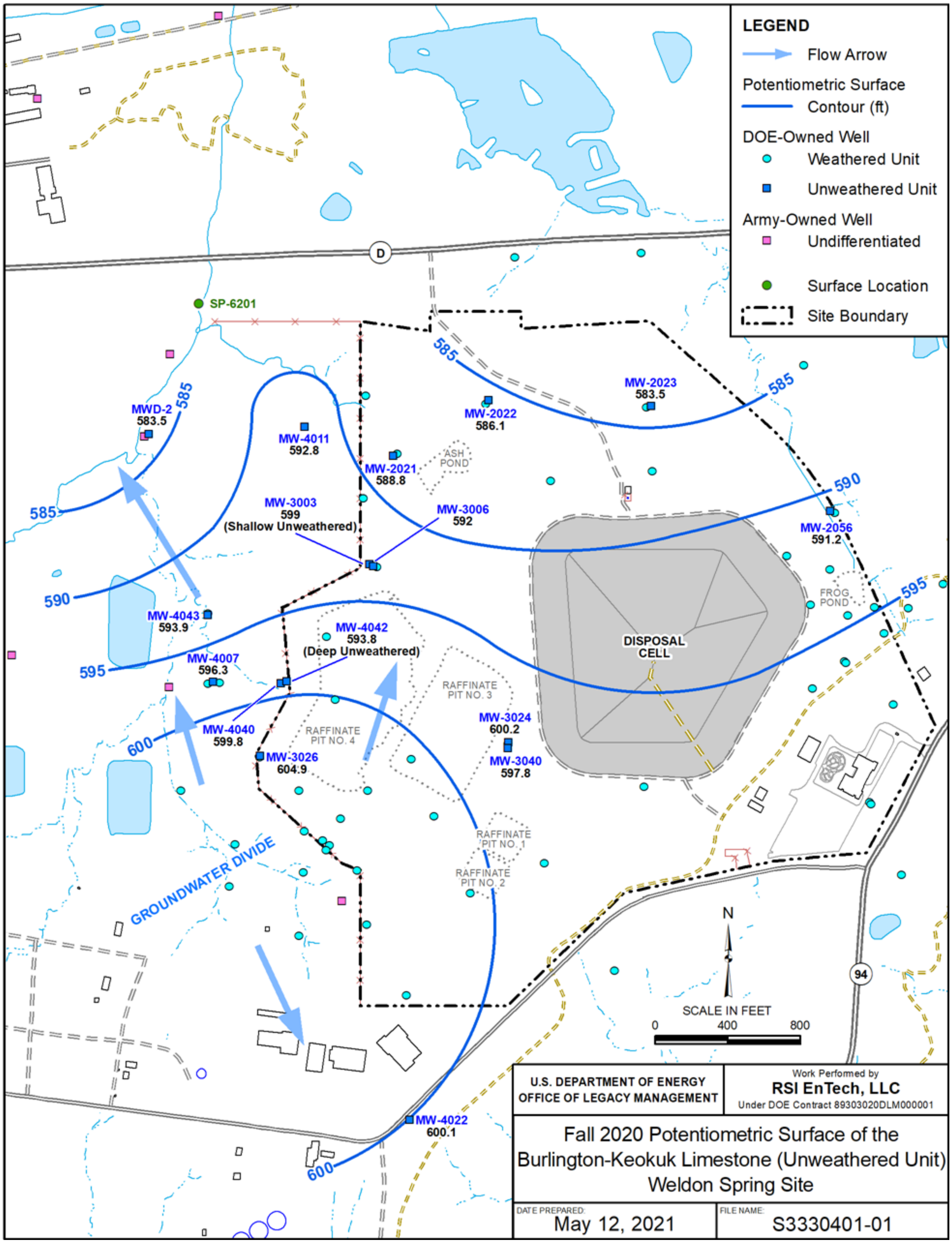


Figure 3. Unweathered Unit Groundwater Surface at the Chemical Plant

2.3.2.2 *Frequently Collected Water-Level Data*

Pressure transducers record groundwater elevations every hour at selected wells, focusing on locations with both a weathered and unweathered unit well. This allows vertical gradients to be evaluated along with the effects of seasonal changes. There is a downward vertical gradient near the former raffinate pits (Figure 4). West of the raffinate pits, water elevations in upper unweathered unit well MW-4040 (light red line) are higher than those in deeper unweathered unit well MW-4042 (dark red line). Immediately north of the raffinate pits, water elevations in MW-3003 (light green line, screened across the transition from weathered to unweathered unit) are higher than those in MW-3006 (dark green line, screened in the deeper unweathered unit). This area is on a topographic high where groundwater recharge and a downward gradient are expected.

The groundwater system transitions from recharging to discharging (i.e., the deeper well of the paired wells has a higher head) as the surface topography slopes to the north from a relative high near the former raffinate pits to a relative low in the August Busch Preserve, a groundwater discharge area with many lakes. The transition from downward to upward gradient is seen in water elevations at the MW-4036/MW-4043 and MWS-2/MWD-2 well clusters. The water elevations in the shallow well (MW-4036, light blue line) are below those in the deeper well (MW-4043, dark blue line). The persistent upward gradient at this location is maximized during wet periods, typically in the spring. As described under *Performance Monitoring Results for the GWOU*, higher uranium concentrations in the unweathered unit (MW-4043) appear to be pushed upward, causing a seasonal uranium to increase in the overlying weathered unit (MW-4036). The water elevations in the shallow well (MWS-2, gray line) are below those in the deeper well (MWD-2, black line), indicating an upward vertical gradient, except during the spring wet season when the water elevations are about the same (Figure 4).

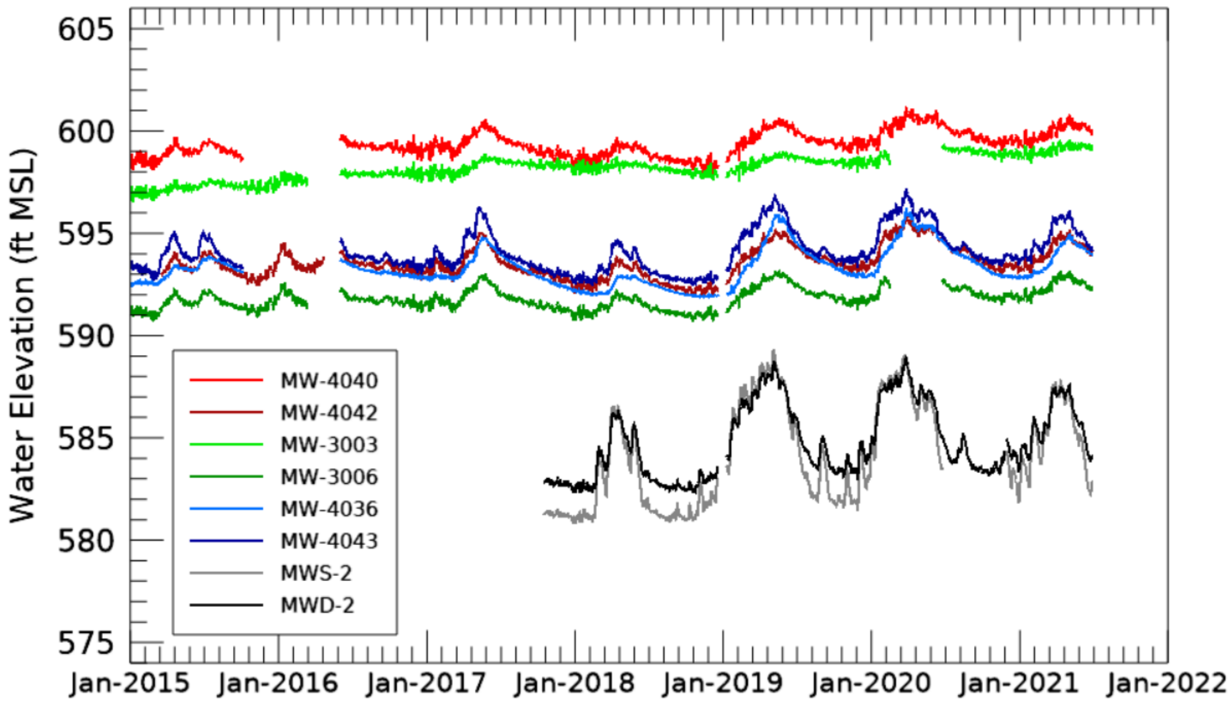
Groundwater discharges in the low area north of the site, replenishing surface water bodies in dry periods and contributing additional water during wet periods. Groundwater levels in this area are more variable, with water levels in MW-4041 (about 1 mile north of the site) varying by as much as 10 ft during the year. The steady discharge of groundwater is what keeps Burgermeister Spring (about a third of a mile north of MW-4041) flowing year-round.

2.3.2.3 *Nonparametric Trend Analysis*

Trending of time series concentrations is performed using uranium, nitrate, TCE, and nitroaromatic compound data for the previous 5 years in accordance with the RD/RA Workplan (DOE 2004b). Results for the trending analysis are reported for the Objective 2 (impacted area) wells and the Objective 5 springs. The trend analysis is conducted using the Mann-Kendall test described in Helsel and Hirsch (2002).

2.3.3 Uranium GWOU Monitoring–Impacted Area

The area of uranium impact is in the former Raffinate Pits area in the western portion of the site. Uranium levels exceed the 20 pCi/L MCL in both the weathered and unweathered units of the Burlington-Keokuk Limestone. Figure 5 shows performance (red) and detection (blue) monitoring locations with 2020 uranium averages. Weathered unit wells are round symbols and unweathered unit well symbols are square.



Abbreviation: MSL = mean sea level

Figure 4. Transducer Water Elevations in Wells West of the Disposal Cell

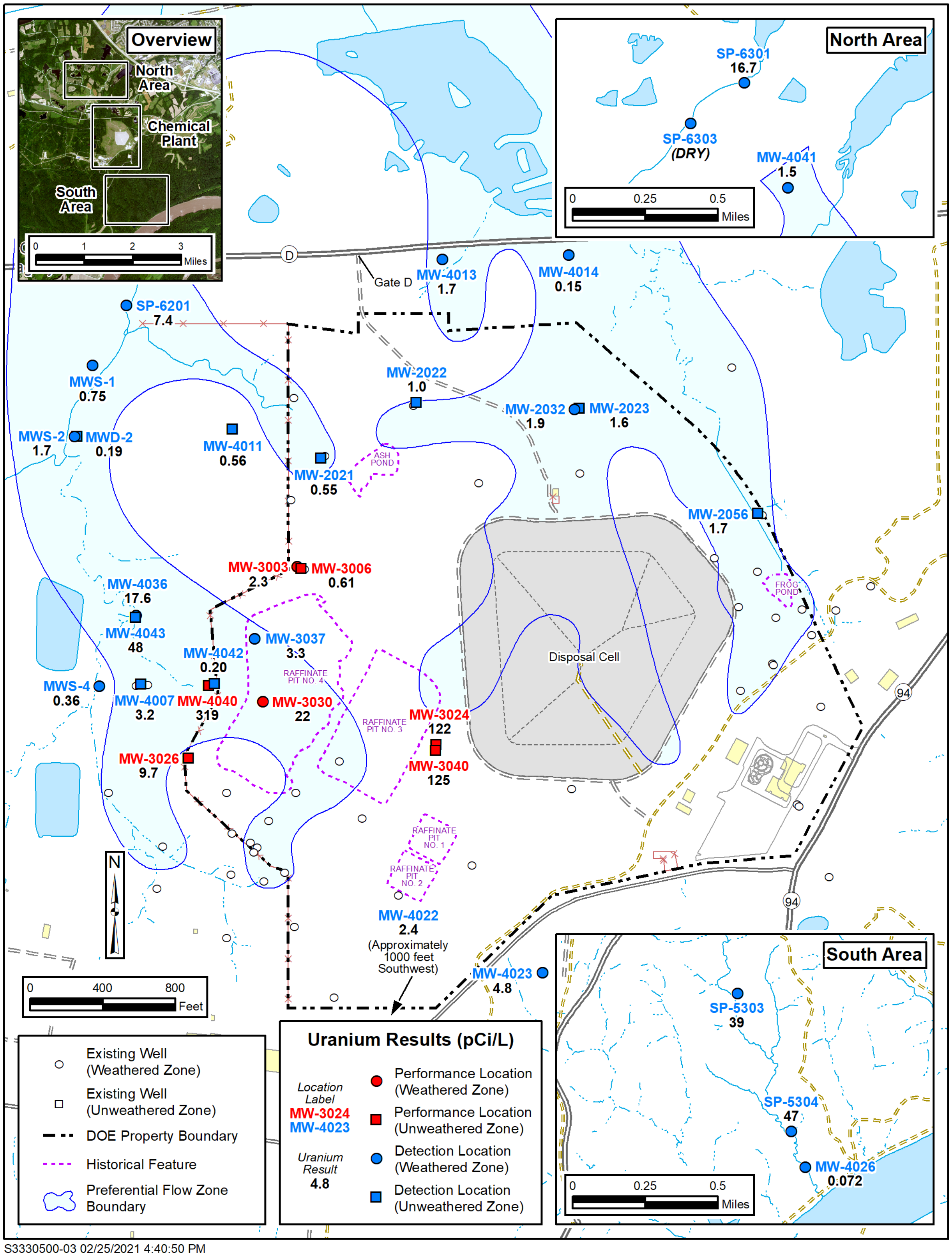


Figure 5. Uranium Monitoring Locations with 2020 Average Concentrations

2.3.3.1 Weathered Unit

Uranium impact in the weathered unit is monitored in two wells. The highest uranium levels in this unit are measured in MW-3030 (Figure 6), which is installed beneath the former raffinate pits. The Objective 2 wells screened in the weathered unit have shown gradually decreasing uranium levels since removal of the pits. The levels in MW-3003 (north of Raffinate Pit 4) have consistently been less than the MCL since 2000. Well MW-3003 is screened where the weathered unit transitions to the unweathered unit. Uranium levels in MW-3003 have declined to low levels and are beginning to stabilize near background levels, approximately 1–3 pCi/L for the weathered unit based on 10-year averages from unimpacted weathered unit wells.

Uranium levels in wells screened in the weathered unit have continued to decrease over the past 5 years. A Mann-Kendall downward trend is indicated for MW-3003. The rate of decline appears to be slowing (Figure 6), but uranium levels in MW-3030 should be consistently below the 20 pCi/L uranium MCL by 2025 to 2030.

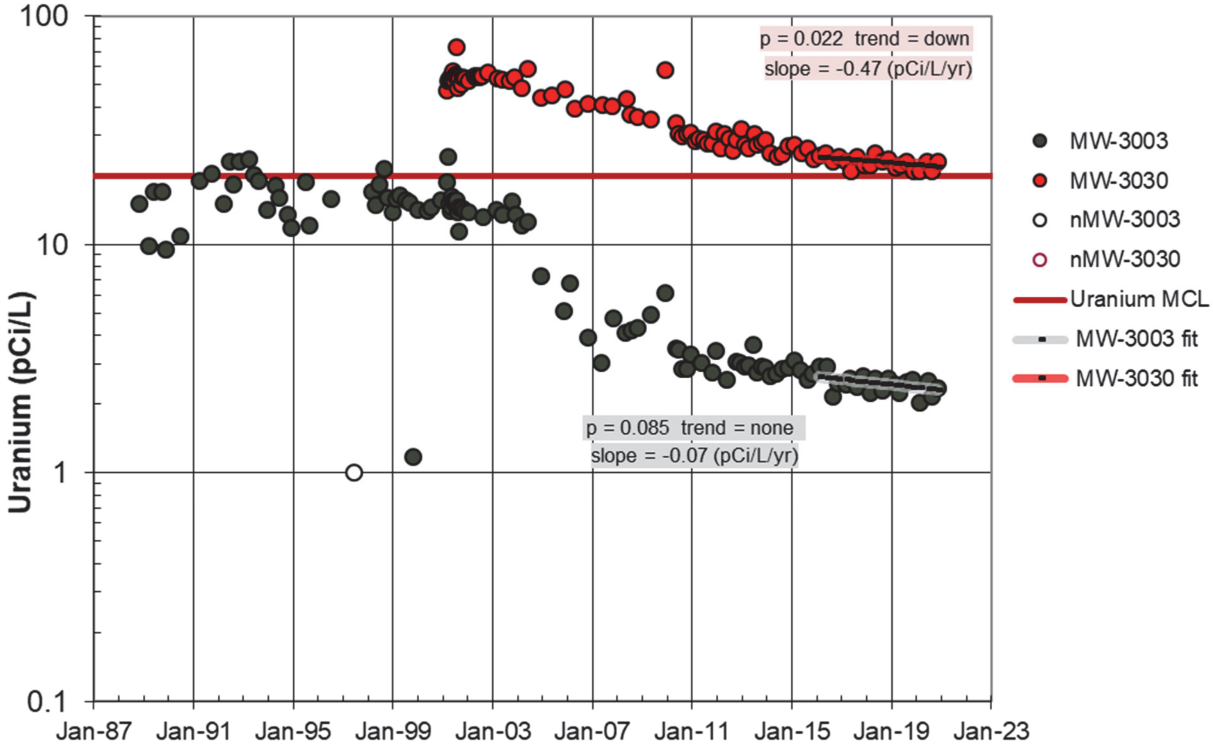
2.3.3.2 Unweathered Unit

Uranium impact is greatest in the wells that are screened in the upper part of the unweathered unit beneath and immediately downgradient of the former raffinate pits (Figure 7). Remediation and removal of the raffinate pits were completed in 2000. Wells MW-3040 and MW-4040 were installed in 2004 to provide uranium data for the unweathered unit in this area. Uranium results in wells MW-4040, MW-3040, and MW-3024 were consistently above the 100 pCi/L Objective 2 trigger level during the previous 5 years. However, the uranium concentrations in these wells have stabilized in that results since 2013 have been within a relatively narrow range that is neither increasing nor decreasing.

Well MW-4040 was installed in the upper part of the unweathered unit in the paleochannel area west of the raffinate pits in May 2004 as an Objective 4 well to delineate the vertical extent of uranium in the impacted area and to monitor for potential downward migration. Elevated uranium levels above the recently set trigger value of 100 pCi/L (178 pCi/L for the June 2004 sample and generally increasing thereafter for a few years) were encountered at MW-4040. Well MW-3040 was installed at the same time for the same purpose east of the raffinate pits. It is adjacent to well MW-3024, which is screened in the upper 20 ft of the unweathered unit. Suspicions about the integrity of MW-3024 arose with data collected after remediation activities in the late 1990s, and MW-3040 was installed to assess and supplement MW-3024.
Well MW-3040 is screened across the bottom 10 ft of the 20 ft zone that well MW-3024 is screened across and has exhibited similar concentrations as MW-3024. Uranium results (0.2–0.3 pCi/L since 2011) from well MW-4042, on the same well pad as well MW-4040 but screened deeper in the unweathered unit, indicate that uranium has not migrated into the deeper part of the unweathered unit.

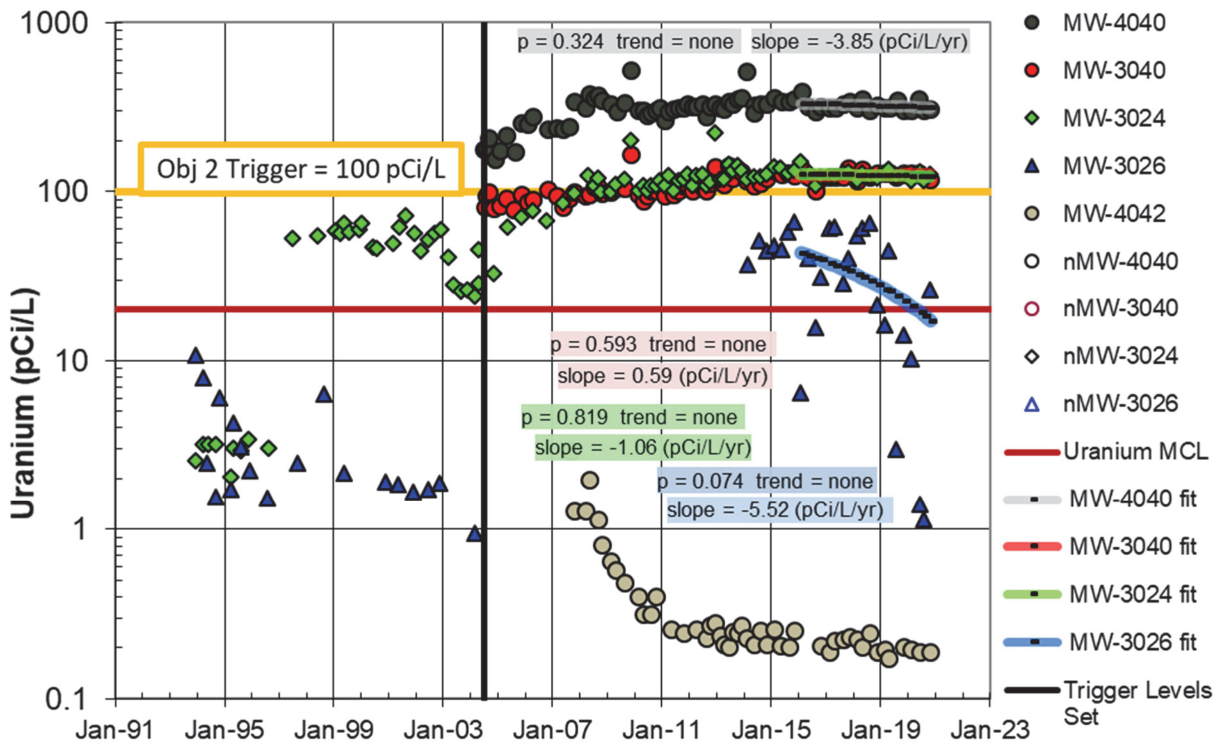
2.3.4 Uranium Detection Monitoring Results

Well MW-4043 is the only downgradient unweathered unit well with elevated uranium (Figure 8). Uranium levels are steadily decreasing at MW-4043.



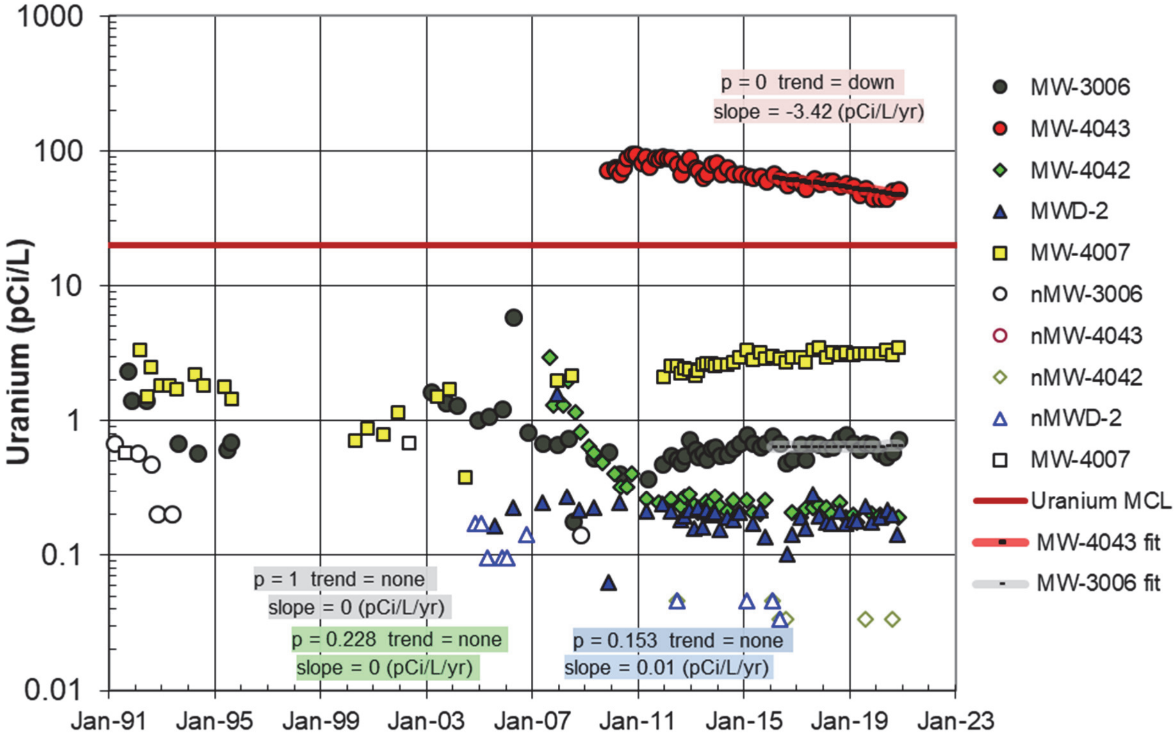
Abbreviation: pCi/L/yr = picocuries per liter per year

Figure 6. Uranium in Performance Monitoring Wells—Weathered Unit



Abbreviation: pCi/L/yr = picocuries per liter per year

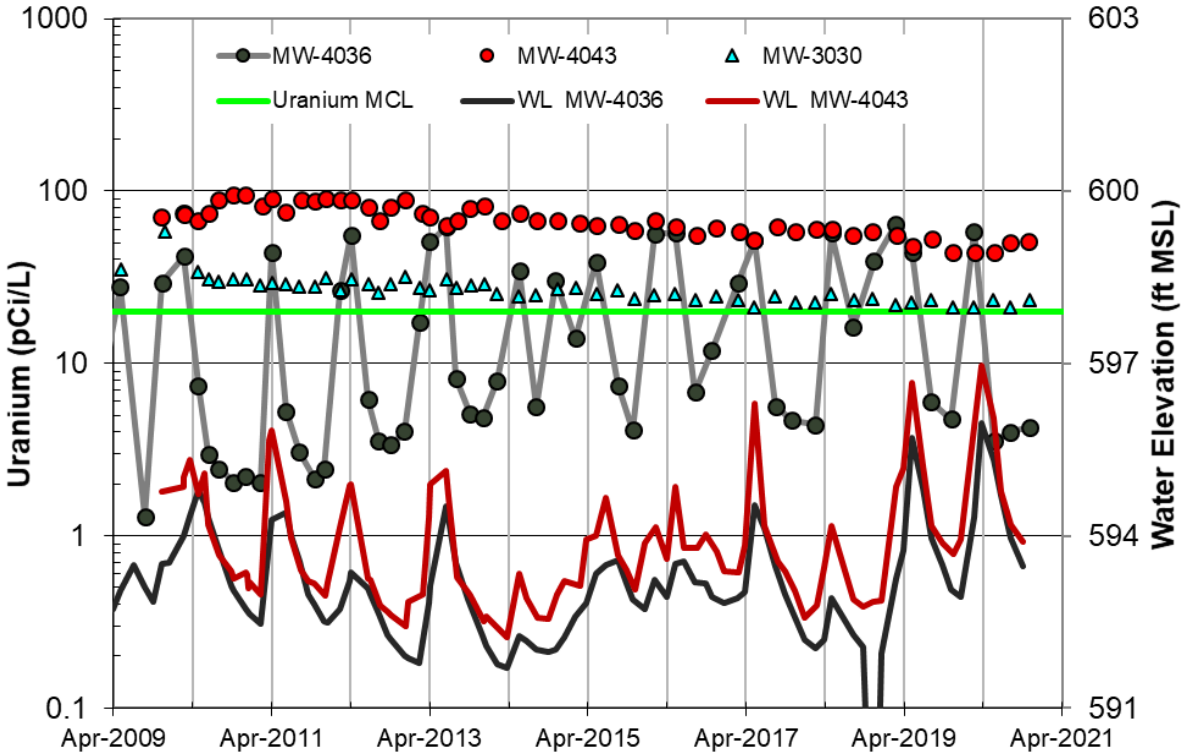
Figure 7. Uranium in Performance Monitoring Wells—Unweathered Unit



Abbreviation: pCi/L/yr = picocuries per liter per year

Figure 8. Uranium in Detection Monitoring Wells—Unweathered Unit

In the weathered unit, uranium levels have been at or below typical background levels for all monitoring wells except MW-4036 (Figure 9). None of the weathered unit detection monitoring wells have a discernible trend. Uranium levels in MW-4036 vary seasonally, ranging from 3.5 to 65 pCi/L from 2015 through 2020. Uranium concentrations in MW-4036 vary nearly 2 orders of magnitude, ranging from higher than those in upgradient impacted area well MW-3030 to near weathered unit background levels (about 2 pCi/L) during the year. The variation in this well is a response to seasonal effects that cause water levels in the unweathered unit to rise more than those in the overlying weathered unit, creating a seasonal upward vertical gradient, typically most pronounced in the winter and spring. Uranium concentrations in weathered unit well MW-4036 are similar to those in unweathered unit well MW-4043 when the upward gradient is at its highest. When there is little to no upward gradient, concentrations in MW-4036 decline to near-background levels for uranium. These data suggest that uranium has migrated horizontally from the impacted area in the unweathered unit within the paleochannel. The higher uranium concentrations in MW-4036 are not decreasing, suggesting there may be contribution from a shallow secondary source that is oxidized when water levels are low and mobilized when water levels are relatively high.

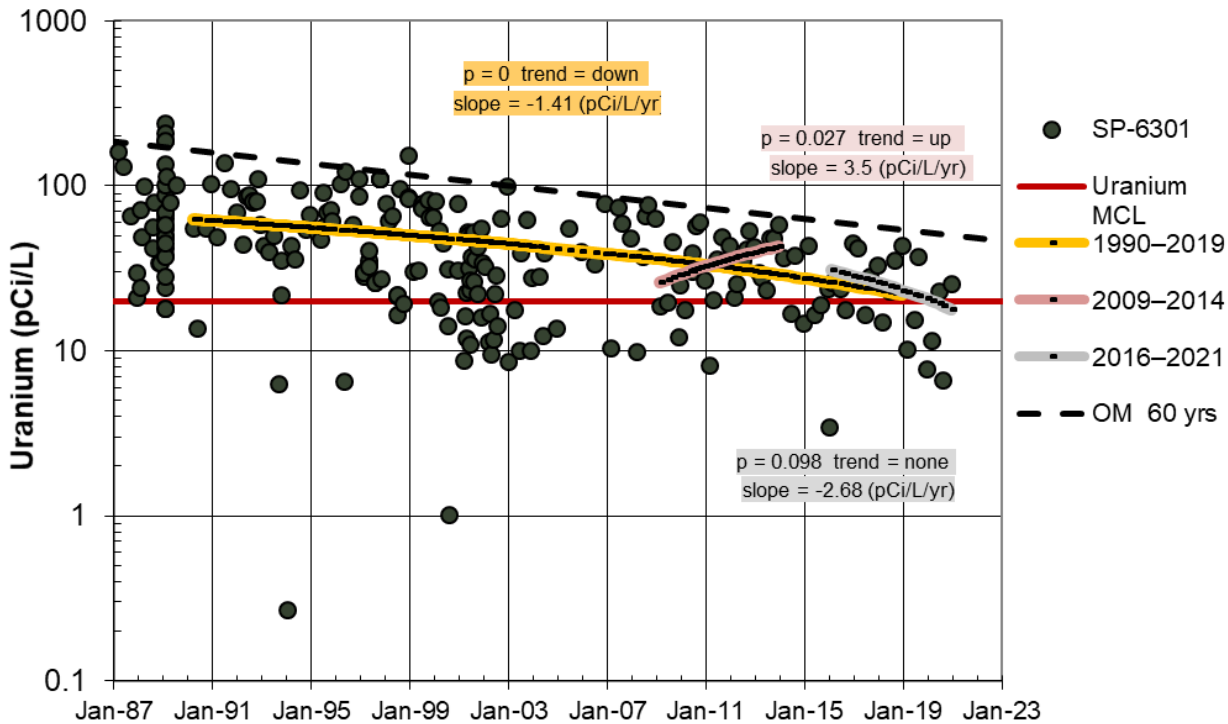


Abbreviation: WL = water level, MSL = mean sea level

Figure 9. Seasonally Variable Uranium in MW-4036

In general, the distribution of uranium has expanded along the western side of the Raffinate Pits area, as indicated by the variable uranium values reported in MW-4036 and the elevated uranium levels measured in MW-4043. The presence of uranium in downgradient springs SP-6201, with a 5-year average value of 6.6 pCi/L, and at Burgermeister Spring also supports the conclusion of downgradient migration of uranium.

Uranium concentrations at Burgermeister Spring (SP-6301) continue to vary by approximately one order of magnitude but remain within historical ranges. Identifying trends in the Burgermeister Spring uranium results over 5-year intervals has been problematic because the results have varied so greatly. The period from 2009 through 2014 suggested an uptrend. The period from 2015 through 2020 indicates no trend with little slope. The trending of data constrained to a 5-year period can be influenced by just a few data points. A longer time frame provides a more reliable trend that can be projected forward. The chart in Figure 10 provides linear regression fits, Mann-Kendall trends, and slopes for three time periods. If the current (and past) trend of decreasing uranium concentrations at Burgermeister Spring continues, baseflow uranium levels (yearly maximums) will be below the 20 pCi/L drinking water standard in 20 years.



Abbreviation: pCi/L/yr = picocuries per liter per year

Figure 10. Trends in Uranium Levels at Burgermeister Spring SP-6301

3.0 Weldon Spring Site LM/NLN Collaboration

The Weldon Spring Site LM/NLN collaboration effort began on September 15, 2021, and ended on November 17, 2021. It consisted of five team meetings. Attachment B contains information pertaining to the process, including:

- A copy of the collaboration schedule.
- Working meeting agendas, which include participants.
- Working meeting notes.

3.1 Scope of the LM/NLN Collaboration

The Weldon Spring Site LM/NLN collaboration team was challenged with developing recommendations to help resolve the issues identified in the Sixth Five-Year review. Specific focus areas included evaluating (1) the need and location(s) for additional monitoring wells to further delineate the uranium plume in the unweathered unit and (2) alternative solutions for removing residual uranium sources and restoring groundwater at the site.

The overall objective of the team was to answer the following three questions:

1. What are we doing that we should keep doing?
2. What are we doing that we should stop doing?
3. What are we *not* doing that we should be doing?

In addressing these questions, recommendations focused on planned activities and the current status at the site as a starting point. LM gave recommendation criteria, which required that the recommendations be consensus-driven, be actionable in 1–5 years, and directly address risk.

3.2 Process Used to Develop Recommendations and Actions

In general, recommendations and actions were developed to assist with resolution of the issues identified in the Sixth Five-Year review. Specific focus areas included evaluating the need and location(s) for additional monitoring wells to further delineate the uranium plume in the unweathered unit and to evaluate alternative solutions for removing residual uranium sources and restoring groundwater at the site.

Recommendations researched by the team were documented in written narratives. The narratives are summarized in Section 3.3, and presented in full in Attachment A. Within each narrative, several supporting technologies are described and prioritized based on difficulty of implementation at the Weldon Spring Site and order of magnitude costs. Technologies that were judged as having the most potential to address the focus areas became the basis for the site implementation strategy discussed in Section 3.4.

The LM/NLN collaboration recommendations that are related to the ORD comments are in Table 3. This table was developed in Narrative 7, which is included in Attachment A. The reference to tiers is from recent EPA MNA guidance (EPA 2015).

- **Tier 1:** Demonstrate active contaminant removal from groundwater and evaluate dissolved plume stability (based on site-specific data).
- **Tier 2:** Determine rate and mechanism of contaminant attenuation.
- **Tier 3:** Determine long-term capacity for attenuation and stability; i.e., is the attenuation mechanism irreversible under current and anticipated site conditions?
- **Tier 4:** Design a performance monitoring program, define triggers for MNA failure, and develop contingency planning.

Table 3. Alignment of 2020 ORD Memorandum Comments with LM/NLN Collaboration Recommendations

EPA ORD Comment/ Objective	***LM/NLN Collaboration Consensus Recommendations (Synopsis)***
For inorganic contaminants, evaluation of contaminant specific attenuation considering the most recent (2015) guidance documents related to metals, radionuclides, and inorganic anions – directly focusing on organized data collection and evaluation using the tiered lines of evidence.	The recommended technologies and strategies were developed based on the EPA (2015) guidance, supplemented by ITRC guidance and recent literature. The various technology narratives are generally aligned with the EPA-recommended tiered lines of evidence. (Narratives 1, 2, 5, and 6)
Explicitly account for the full range of uranium sources, the potential for uranium mobilization, and the various mechanisms of uranium attenuation (mass balance). (Tiers 1, 2, 3, and 4 and site management)	Recommend developing a mass balance site conceptual model for the Weldon Spring Site that accounts for source mass flux/discharge, attenuation mechanisms, and contaminant inventories throughout the subsurface. Consider use of a reduced order model (e.g., REMChlor-MD) to formalize the mass balance. Considering that most areas have little uranium impact, emphasis should be placed on zones where remnant uranium has been identified and is not currently attenuating, primarily the zone in the upper part of the unweathered bedrock where the weathered bedrock transitions to unweathered bedrock. Evaluate wells (e.g., MW-4040) currently assigned to the upper portion of the unweathered zone to determine “connectedness” to the active flowing plume using borehole dilutions tests (or similar field tests) in existing wells. Use FLUTe transmissivity testing in new boreholes. (Narrative 1)
Documentation of site-specific attenuation mechanisms that reduce the quantity, toxicity, and/or mobility of contaminants. For the identified attenuation process, provide data related to attenuation rates and capacity/sustainability. (Tiers 2 and 3)	Recommend supplementary geochemical modeling combined with opportunistic testing of existing core material focusing in and around fractures. Recommend visual examination of stored core materials to start this process. A subset of activities, selected from a range of laboratory tests (chemical analysis, batch leaching, sequential leaching, and imaging), are recommended, and the final mix of specific activities should be based on evolving data (generally applying less costly methods first and moving toward more costly methods as appropriate). Consider emerging attenuation mechanisms such as matrix diffusion (i.e., scoping models and supplemental contaminant profiling in core material). (Narrative 5 and 6)
Review and examine whether the current monitoring well network is adequate to meet MNA objectives and if the MNA remedy is functioning as expected – provide more information on the lateral and vertical extent of the plume. (Tier 1 and site management)	Recommend targeted geophysical survey lines and/or an RPM study to better define (1) the lateral and vertical fracture network and (2) the boundaries and structure of the more highly fractured “paleochannel” (as a surrogate/supplement for enhanced lateral plume delineation). Additional evaluation of technology alternatives is recommended due to potential weaknesses and strength of the alternative methods. An implementation plan to down-select the methods to be used is recommended, including consultation with potential vendors and follow-up on technical challenges for application in karst. Plan future well locations to increase confidence in the extent of uranium in the unweathered zone, both horizontally and vertically, and to collect samples that can be used to assess attenuation mechanisms other than dilution and dispersion. Depending on connectivity and geophysical testing results, consider a potential new well near the former Raffinate Pits area (e.g., near/downgradient of MW-4040) screened over the middle portion of the unweathered zone to help refine the vertical extent of uranium. (Narratives 3 and 4)

Table 3. Alignment of 2020 ORD Memorandum Comments with LM/NLN Collaboration Recommendations (continued)

EPA ORD Comment/ Objective	***LM/NLN Collaboration Consensus Recommendations (Synopsis)***
Provide an assessment of the robustness of the MNA remedy and examine contingencies as needed. (Tier 1 and site management)	Apply traditional tools for evaluating existing monitoring data but deemphasize bulk plume metrics such as center of mass and other method of moments calculations due to the high heterogeneity and "patchiness" associated with karst aquifers. Focus on trends of analytes in individual wells (e.g., Mann-Kendall method) and apply over sufficient time horizons to minimize short-term trends (e.g., El Niño and La Niña) and pay attention to the seasonality and variability typical of karst aquifer systems. Evaluate options to continue or adjust the MNA remedy, including options for technical impracticability or enhanced attenuation to address disconnected contaminants present in the transition interval near the raffinate pits. (Narratives 4 and 7)

Abbreviations:
ITRC = Interstate Technology and Regulatory Council
RPM = residual potential method

3.3 Summary of Narratives

Narrative No. 1: Mass Balance and Mass Flux Conceptual Model

The objective of this narrative is to propose a refined site-specific conceptualization framed in terms of mass balance. This model provides the potential for better understanding the performance and progression of the CERCLA MNA remedy, to help identify areas of interest or potential concerns, and to highlight areas of technical opportunity. The narrative focuses on the need to assess the connectivity of contaminated water to the flowing aquifer and determine if the contaminants are effectively "trapped" in terms of the MNA mass balance. The narrative also recommends the performance of reduced order mass balance-focused modeling using tools that account for key mechanisms impacting plume concentrations and plume projections over time and field tests to improve understanding of the connectivity of contaminants present in the interval where the weathered bedrock transitions to the unweathered bedrock.

The benefits are that incorporating mass balance concepts is straightforward and consistent with current EPA guidance. Refining the site conceptual model has the potential to support risk management and support a technically based continuation of an MNA-based strategy. The Weldon Spring Site would benefit from data confirming the degree of connectivity (or the lack of connectivity) between the high concentrations measured in transition wells and the active-flowing groundwater system. The data also could better delineate the spatial extent (near field or downgradient) of the pockets of higher contamination in the transition interval. The recommended actions are straightforward, and all can be performed by the LMS contractor or subcontractors.

The technologies considered include REMChlor-MD modeling, high flow, tracer and borehole dilution testing, and FLUTe transmissivity profiling.

Narrative No. 2: Emergent Plum Behavior/Statistical Techniques

The objective of this narrative is to recommend the use of different statistical techniques that quantify trends in the plume to project risk reduction over time. Statistical techniques can be applied to existing historical and current site analytical data, and hydrogeologic factors and the location of potential receptors can be considered to help optimize a well monitoring system.

The benefits are that well-based statistical techniques can be easily employed to determine if concentration at a well is increasing, steady, decreasing, or inconclusive. The statistical tools provide quantitative metrics that can be used to evaluate MNA at the site. The potential recommended actions are straightforward, and all can be performed by the LMS contractor.

The techniques considered include trend analysis, data sufficiency for wells, Mann-Kendall Test, and stretched exponentials.

Narrative No. 3: Evaluation of Proposed Wells and Alternative Geophysical Techniques for Plume Delineation

The objective of this narrative is to evaluate alternative geophysical techniques to delineate subsurface structures to identify potential transmissive pathways (e.g., fracture features and bedding planes) and propose locations for additional monitoring wells to improve the delineation of vertical and lateral contaminant distribution to support the MNA remedy at the site.

The benefits are that the geophysical methods presented are considered technologically mature. Geophysics at the site would benefit in the detection and location of major fractures, fracture zones, and/or bedding plane features, and in locating future wells to improve the groundwater monitoring network.

The technologies considered include a large variety of geophysical methods, including aerial, ground-based, borehole, and cross-hole methods.

Narrative No. 4: Technologies to Identify Flow Paths in Karst Terrain

The objective of this narrative is to recommend various methods (new techniques or a combination of techniques) that can be used to identify areas of more or less groundwater flow in both the horizontal and vertical directions near and downgradient of residual sources. The narrative focuses on how the different approaches apply to understanding the subsurface in karst terrains.

The benefits are that the narrative focuses on methods and techniques to assist with the characterization of karst geology.

The technologies considered include geotechnical, surface geophysics, and borehole geophysics.

Narrative No. 5: Natural Attenuation Mechanisms

The objectives of this narrative are (1) to discuss additional laboratory characterization and geotechnical modeling that have the potential to identify the presence of natural attenuation mechanisms for uranium and (2) to assess the long-term stability and mobility of aqueous (e.g., matrix diffusion from uranium within partially-connected fractures), absorbed (e.g., on iron oxides or pyrite minerals in fractures), and solid phases of uranium (e.g., U-carbonates, silicates, or phosphates). If natural attenuation processes can be demonstrated as viable and as responsible for decreases or attenuated uranium mass flux, this could provide the technical basis for continuation of the selected MNA remedy.

The benefits are that geochemical modeling is relatively inexpensive to perform and has been performed previously to evaluate natural attenuation viability. Performing laboratory experiments is an established approach for directly evaluating the viability of geochemical mechanisms for attenuating uranium flux, and the existing inventory of core materials from previously drill wells that are currently stored onsite can be utilized.

The technologies considered include geochemical modeling, batch extraction experiments, sequential liquid extraction, leach experiments on secondary minerals in fractures from core samples, and solid phase characterization on secondary minerals in fractures from core samples.

Narrative No. 6: Matrix Diffusion as a Natural Attenuation Mechanism

The objective of this narrative is to incorporate matrix diffusion as a recognized MNA mechanism at the Weldon Spring Site, based on the karst aquifer conditions. Inclusion of matrix diffusion as a mechanism contributing to MNA requires additional documentation in the form of models or calculations and measurements in core material. Three potential approaches are identified and described: (1) scoping models, (2) contaminant profiling in core material, and (3) site models that incorporated matrix diffusion or dual domain models.

The benefits are that completion of this advancement would provide a more complete conceptual model of attenuation processes impacting the plume, an improved understanding of historical and projected plume concentration profiles, and an improved basis for managing the MNA remedy and any contingency actions.

The technologies include the use of scoping models and contaminant profiling in the core material.

Narrative No. 7: Status and Performance of the MNA Remedy

The objective of this narrative is to focus on the status and performance of the MNA remedy to date and discuss options for continuing and/or implementing adjunct and supplementary strategies as needed in the future.

The benefit of this narrative is to summarize recommended paths forward.

The technologies include methods discussed in previous narratives.

3.4 Actionable Recommendations

The following recommendations and associated technologies resulted from the LM/NLN collaboration and are actionable within the next 1 to 5 years:

1. Evaluate trends in wells using statistical methods such as Mann-Kendall using data from longer time periods (Narrative 2).
   - The Weldon team has used the Mann-Kendall test to predict trends since the MNA remedy began but have been constrained formally to a 5-year analysis window by regulatory agreement. The Weldon team has been showing longer time-frames in the Annual Report to show more complete trends.
   - Work with regulators to formally allow flexibility in extending the current 5-year trending period when appropriate (i.e., for locations with highly variable concentrations).
2. Assess connectivity between the upper unweathered unit and the surrounding formation to determine whether the persistent elevated uranium concentrations are restricted to isolated areas (Narrative 1).
   - Perform high-flow sampling of certain unweathered unit wells.
   - Perform tracer testing on certain unweathered unit wells.
   - Based on the above results, conduct borehole dilution testing of certain unweathered unit wells.
3. Develop a uranium mass balance and mass flux estimate at the site (i.e., determine where the uranium is and where it is going) (Narrative 1).
   - Use remediation evaluation modeling (REMChlor -MD) to assess source removal and subsequent plume attenuation from a remnant source.
4. Assess the potential for uranium attenuation mechanisms in the weathered karst aquifer not related to dilution and dispersion (Narratives 4, 5, and 6).
   - Look at fractures of existing core materials from previously drilled wells (and those from future wells or boreholes) for sorption and precipitation.
   - Consider matrix diffusion as a nonconventional attenuating mechanism.
   - Use geochemical modeling to evaluate the probability that alternative natural attenuation mechanisms, such as precipitation of uranium-rich minerals on fracture faces, could be occurring at the site.
5. Refine estimates of the vertical and lateral extent of uranium at the site, focusing on the upper part of the unweathered unit near the raffinate pits and downgradient in the western paleochannel (Narratives 3 and 4).
   - Use geophysical survey results to optimally position future wells.
   - Use the geophysical survey results as a surrogate/supplement for lateral plume delineation, where warranted.
   - Target geophysical surveys to image lateral and vertical fracture networks and the boundaries/structure of the more highly fractured "paleochannel."

6. In addition to geophysical logging, conduct FLUTe transmissivity profiling on future wells to identify preferential flow zones. Use targeted flow meter testing on high transmissivity zones to quantify flow (Narrative 1).

Figure 11 provides a recommended sequencing for implementation of the technologies noted in the narratives. Additional details and levels of effort are provided in individual narratives provided in Attachment A. The timeline presented in Figure 11 is subject to the availability of resources, stakeholder coordination (as appropriate), and regulatory approval (as appropriate). The data collected from each implemented recommendations will guide the priority and determine the need for execution of subsequent recommendations. The collaborative approach between LM, EPA, MDNR, and the LMS contractor will continue throughout the implementation of the recommendations.

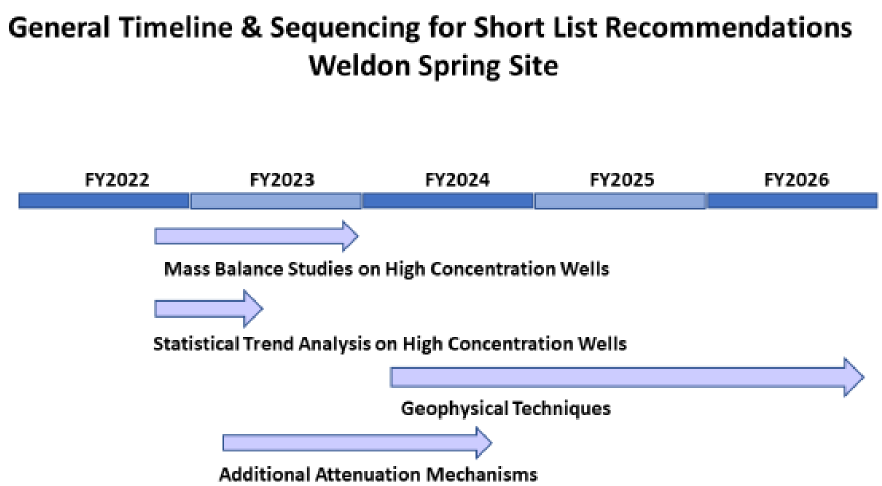


Figure 11. Implementation Sequence for LM/NLN Collaboration Recommendations

It should be noted that implementation has begun on some of the recommendations. The existing core material from previously drilled wells has been inventoried and visually inspected to confirm availability of samples for testing. Statistical analysis in the next annual report (for calendar year 2022) will evaluate longer time frames for trending as warranted for more realistic assessments of MNA progress and improved long-term predictions.

4.0 Conclusions

Regulatory risk was identified as the only "high" risk driver for the Weldon Spring Site. The Weldon Spring Site has been addressing an issue regarding the groundwater remedy since the GWOU ROD (DOE 2004a) was issued in January 2004. The issue of the extent of uranium impact at the site arose when monitoring wells MW-3040 and MW-4040 were installed to delineate the vertical extent of uranium in the Raffinate Pits area. Elevated concentrations of uranium were unexpectedly discovered in the upper portion of the unweathered unit. Before this, the unweathered unit was not believed to be impacted. Wells MW-3040 and MW-4040 were drilled in May 2004 as the MNA fixed trigger values were being established in the RD/RA Work Plan in July 2004 (DOE 2004b). Sample results for these wells were not available until

August 2004. The result from the first sample collected June 30, 2004, at well MW-4040 was 178 pCi/L, exceeding the 100 pCi/L trigger value agreed to in the RD/RA Work Plan. The trigger level became a concern for EPA and MDNR because this indicated that the nature and extent of contamination in the unweathered Burlington Keokuk Limestone bedrock below the Chemical Plant area had not been fully characterized. Uranium concentrations in wells MW-3040 and MW-4040 trended upward for the next 5 to 10 years. DOE believes the impacted area fixed uranium trigger value was set prematurely, before an adequate dataset had been collected. Concentrations are expected to be decreasing or stable for an MNA remedy. The trigger levels are indicators of MNA progress and are established to alert of increasing concentrations.

The data collected from the implemented recommendations will ultimately be used to address the issues noted in the Sixth Five-Year Review (DOE 2021) and to enhance the groundwater monitoring network to support the MNA remedy. The technologies will also determine whether certain wells are isolated and may support the need for a TI waiver for the upper unweathered unit near the former raffinate pits.

4.1 What Is the Weldon Spring Site Doing That They Should Keep Doing (Affirm)?

- Affirmed that natural attenuation as a core strategy in the current and future management and remediation of Weldon Spring Site.
- Affirmed the DOE decision to de-emphasize bulk plume statistics (such as center of mass and related method of moments calculations) due to the highly heterogeneous karst setting and the associated “patchy” and dynamic plume behaviors.
- Affirmed that existing wells provide a reasonable baseline conceptualization of the plume and concentration trends, which affirms (with adjustments) the plans for additional well installations to address regulatory questions about the lateral and vertical extent of the plume.

4.2 What Is the Weldon Spring Site Doing That They Should Stop Doing (Replace)?

- Recommend flexible time periods for monitoring well trend statistics, not based on preset-fixed (“short”) time intervals. The fixed time period approach is not sufficiently flexible for the observed dynamic concentration behaviors in this karst system and how these vary with cyclical weather patterns.

4.3 What Is the Weldon Spring Site Not Doing That They Should Be Doing in the Near Future (Next 1–5 years) (Supplement)?

- Recommend that future plans and responses to regulators be developed and structured using the MNA lines of evidence from guidance documents for inorganic contaminants in 2010.
- Recommend high-flow sampling and tracer testing of certain unweathered unit wells.
- Recommend borehole dilution testing of transition interval wells (and representative control wells in other intervals) to assess the connectivity with the active plume.
- Recommend FLUTe transmissivity profiling in boreholes when drilling new wells.

- Recommend additional characterization of traditional and nontraditional uranium attenuation mechanisms in the weathered karst aquifer.
- Recommend supplementary geochemical modeling combined with opportunistic testing of existing core material focusing in and around fractures starting with existing core materials held in the Weldon Spring Site inventory. This will help with the documentation of site-specific attenuation mechanisms that reduce the quantity, toxicity, or mobility of contaminants.
- Recommend performing a targeted geophysical survey and/or residual potential method (also called RPM) study to better define the lateral and vertical fracture network and the boundaries and structure of the more highly fractured "paleochannel" (as a surrogate or supplement for lateral plume delineation). These surveys will examine whether the current monitoring well network is adequate to meet MNA objectives and whether the MNA remedy is functioning properly.

5.0 Level of Effort Costs

Level of effort costs for each actionable recommendation are provided in the individual narratives in Attachment A. Table 4 provides a summary of the rough order of magnitude costs (Class 4 estimates according to the DOE Guide 413.3-21A, *Cost Estimating Guide)* and labor hours for these actions. Detailed cost estimates using a formal DOE cost-estimating technique will be generated to support implementation decisions.

Table 4. Class 4 Rough Order of Magnitude Estimates for Actions

Action	Labor Hours	Other Direct Costs
High Flow Sampling (Mass Balance Studies)	60	
Tracer Testing (Mass Balance Studies)	360	
Borehole Dilution Testing (Mass Balance Studies)	60	
REMChlor-MD Modeling (Mass Balance Studies)	30	
Core Analysis (Additional Attenuation Mechanisms)	40	
Geochemical Modeling (Additional Attenuation Mechanisms)	160	
Geophysical Surveys (Geophysical Techniques)	200	

Note:
Actual project completion costs can be -30% to +50% of total estimated project costs.

6.0 Lessons Learned

The following input was received:

- Attendees for the nonmoderated meetings should have been limited to only NLN members and the Weldon Spring Site team, as these meetings were intended to be used as working meetings.
- The use of the Microsoft Teams platform for team meeting and the GlobalSCAPE Enhanced File Transfer (also called eFT) website to share documents worked well.

- Given COVID-19 travel restrictions, site visits could not be made. However, virtual site tours were effective.
- The Weldon Spring Site is a mature CERCLA site with decades of available data and a long regulatory history. The LM/NLN collaboration might have benefitted from having more time for data review and assimilation after the kickoff meeting.
- Open and frequent communication between the NLN and an LMS lead led to a successful partnership.
- Determining and communicating the project schedule for the report at the beginning of the project allowed team members to plan for their individual review periods and ensured the team remained on schedule for finalization of the report.
- By creating clear goals with narrow focus areas, the LM/NLN collaboration team was able to eliminate distractions from other items that may be of interest on a large site and ensure direct focus on those issues. This allowed for the team to produce a wide range of robust and detailed recommendations.

7.0 References

40 CFR 141. U.S. Environmental Protection Agency, "National Primary Drinking Water Regulations," *Code of Federal Regulations*.

10 CSR 20-7.031. "Water Quality Standards," Missouri Department of Natural Resources Clean Water Commission, *Missouri Code of State Regulations.*

DOE (U.S. Department of Energy), 1990. *Record of Decision for the Management of the Bulk Wastes at the Weldon Spring Quarry*, DOE/OR/21548-317, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, September.

DOE (U.S. Department of Energy), 1992. *Remedial Investigation for the Chemical Plant Area of the Weldon Spring Sites,* DOE/OR/21548-074, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, November.

DOE (U.S. Department of Energy), 1993. *Record of Decision for Remedial Action at the Chemical Plant Area of the Weldon Spring Site*, DOE/OR/21548-376, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, September.

DOE (U.S. Department of Energy), 1996a. *Decision Document for the Southeast Drainage*, DOE/OR/21548-584, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, November.

DOE (U.S. Department of Energy), 1996b. *Engineering Evaluation/Cost Analysis for the Proposed Removal Action at the Southeast Drainage near the Weldon Spring Site, Weldon Spring, Missouri*, DOE/OR/21548-584, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, August.

DOE (U.S. Department of Energy), 1997. *Remedial Investigation for the Groundwater Operable Units at the Chemical Plant Area and the Ordnance Works Area, Weldon Spring, Missouri*, DOE/OR/21548-571, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, July.

DOE (U.S. Department of Energy), 1998. *Record of Decision for the Remedial Action for the Quarry Residuals Operable Unit at the Weldon Spring Site, Weldon Spring, Missouri*, DOE/OR/21548-725, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, September.

DOE (U.S. Department of Energy), 1999. *Southeast Drainage Closeout Report Vicinity Properties DA4 and MDC7*, Rev. 0, DOE/OR/21548-772, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, September.

DOE (U.S. Department of Energy), 2000. *Interim Record of Decision for Remedial Action for the Groundwater Operable Unit at the Chemical Plant Area of the Weldon Spring Site*, DOE/OR/21548-798, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, September.

DOE (U.S. Department of Energy), 2003. *Quarry Residuals Operable Unit Remedial Action Report*, DOE/OR/21548-927, Oak Ridge Operations Office, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, November.

DOE (U.S. Department of Energy), 2004a. *Record of Decision for the Final Remedial Action for the Groundwater Operable Unit at the Chemical Plant Area of the Weldon Spring Site*, DOE/GJ/79491-936a, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, January.

DOE (U.S. Department of Energy), 2004b. *Remedial Design/Remedial Action Work Plan for the Final Remedial Action for the Groundwater Operable Unit at the Weldon Spring Site*, DOE/GJ/79491-943, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, July.

DOE (U.S. Department of Energy), 2004c. *Chemical Plant Operable Unit Remedial Action Report*, DOE/GJ/79491-909, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, January.

DOE (U.S. Department of Energy), 2005a. *Interim Remedial Action Report for the Groundwater Operable Unit of the Weldon Spring Site*, DOE/GJ/79491-952, Office of Legacy Management, March.

DOE (U.S. Department of Energy), 2005b. *Explanation of Significant Differences, Weldon Spring Site*, Office of Legacy Management, February.

DOE (U.S. Department of Energy), 2008a. *Long-Term Surveillance and Maintenance Plan for the U.S. Department of Energy Weldon Spring, Missouri, Site*, LMS/WEL/S00790, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, December.

DOE (U.S. Department of Energy), 2008b. *Baseline Concentrations of the Chemical Plant Operable Unit Monitored Natural Attenuation Network at the Weldon Spring Site,* LMS/WEL/S02589, Weldon Spring Site Remedial Action Project, Weldon Spring, Missouri, December.

DOE (U.S. Department of Energy), 2021. *Weldon Spring Site Sixth Five-Year Review*, LMS/WEL/S31922, Office of Legacy Management, September.

DOE Guide 413.3-21A, *Cost Estimating Guide*, U.S. Department of Energy, June 6, 2018.

EPA (U.S. Environmental Protection Agency), 2015. *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites*, Directive 9283.1-36.

EPA (U.S. Environmental Protection Agency), 2020. *Monitored Natural Attenuation of Uranium, Weldon Spring Site, Missouri* (20-R07-005), July.

Helsel, D.R., and R.M. Hirsch, 2002. *Statistical Methods in Water Resources*, Techniques of Water-Resources Investigations of the United States Geological Survey, Book 4, *Hydrologic Analysis and Interpretation*.

Attachment A

Narratives for Actions

Narrative 1: Technology/Strategy: Mass Balance and Mass Flux Conceptual Model

Summary Information

The current decision for the Weldon Spring Site Groundwater Operable Unit (GWOU) remedy is monitored natural attenuation (MNA). In general, the MNA remedy has progressed appropriately since implementation, as demonstrated in the groundwater monitoring wells in the weathered portion of the karst aquifer and in the distal discharge springs/seeps; contaminant concentrations have decreased (with a high degree of statistical significance) since the closure of the raffinate pits and removal of the associated contaminated sludges, soils, and overburden sediments. MNA is an environmental management strategy that relies on a variety of attenuation processes to transform or immobilize contaminants. MNA is appropriate at sites where contamination poses relatively low risks, the plume or plumes are stable or shrinking, and the natural attenuation processes are projected to achieve remedial objectives in a reasonable time frame. The conceptual model of natural attenuation as a mass balance between the loading (mass flux from residual contamination in the subsurface) and attenuation of contaminants in the plume is a powerful framework for understanding, documenting, and managing MNA.

At the Weldon Spring Site, the U.S. Department of Energy Office of Legacy Management (LM) collaborative scientists and engineers proposed a refined site-specific conceptualization framed in terms of mass balance and mass flux, with a focus on the intervals and areas where remnant uranium mass (including physical/chemical state) remains at the site and where it can migrate. This model helps personnel (1) better understand the performance and progression of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) MNA remedy; (2) identify areas of interest or potential concerns; and (3) highlight areas of technical opportunity for the Weldon Spring Site team and regulators to discuss and explore. The geology at the Weldon Spring Site has been well documented by multiple organizations and agencies.

The Burlington-Keokuk Limestone underlying the site has been divided into two separate units based on indications of weathering and the resulting hydraulic properties. The higher hydraulic conductivity of the shallower weathered unit is the result of abundant well-connected fractures, vertical and horizontal, and weathering features such as vugs and solution channels. At depth, where there are fewer, more isolated fractures, the hydraulic conductivity is lower, and the formation is classified as the unweathered unit. Abundant flow in the weathered unit results in significant flushing that readily attenuates contamination in this unit. In the unweathered unit, with its isolated fractures and limited flow, it is difficult to flush contamination in a reasonable time frame. When the raffinate pits were full, the pronounced downward gradient forced contamination into the upper part of the unweathered unit. The highest persistent concentrations of remnant uranium at the site occur in this transition interval at the upper part of the unweathered unit. The transition from weathered to unweathered is irregular, with fracturing more abundant in the paleochannels that appear to laterally constrain contaminant migration.

The two locations where uranium concentrations are above trigger levels and are not decreasing are in the upper part of the unweathered unit. It is recommended that additional focus be placed on the transition between the weathered and unweathered units in areas where uranium mass was introduced (raffinate pits) and downgradient in the paleochannel. The recommendation for the Weldon Spring Site team and regulators is to further refine and confirm the uranium mass balance/mass flux conceptualization for the site by implementing select technology recommendations. This narrative serves as an overarching conceptualization and links to the other narratives developed during the collaboration. A few specific technologies that address crucial technical topics related to this transition interval are recommended within this narrative.

Focus Area(s): All.

Description

The U.S. Environmental Protection Agency (EPA) recently provided a detailed technical assessment related to the status, progress, and structure of the Weldon Spring Site GWOU MNA remedy. This effort was summarized in detail in an EPA Office of Research and Development (ORD) memorandum and in the associated administrative transmittal. In general, the regulatory assessment centered on a few key topics and objectives that represent regulatory policies and standard protocols for natural attenuation remedies implemented under CERCLA. Specific topics and objectives included:

- CERCLA MNA remedies recognize dilution and dispersion as attenuation processes and allow for these to contribute to an MNA remedy; however, recent EPA guidance developed for CERCLA (EPA 2010; EPA 2015) does not generally support MNA remedies based solely on dilution and dispersion. To fully meet CERCLA guidelines and protocols, EPA has identified the following topics:
    - In accordance with the most recent (EPA 2010; EPA 2015) guidance documents, for inorganic contaminants, an evaluation of contaminant-specific attenuation related to metals, radionuclides, and inorganic anions should:
        - Have clear and organized data and evaluation using the tiered lines of evidence.
        - Document the site-specific attenuation mechanisms that reduce the quantity, toxicity, and/or mobility of contaminants.
        - Explicitly account for the full range of uranium sources, the potential for uranium mobilization, and the various mechanisms of uranium attenuation (mass balance).
        - Provide data related to attenuation rates and capacity/sustainability for the identified attenuation process.
    - The current monitoring well network should be reviewed and examined to determine whether it is adequate to meet MNA objectives and whether the MNA remedy is functioning properly, including providing more information on the lateral and vertical extent of the plume.
    - An assessment of the robustness of the MNA remedy should be provided, and contingencies should be examined as needed.

These core objectives will be addressed throughout the work of the collaborative efforts.

To support efficiently obtaining information to support future MNA remedy decisions, Weldon Spring Site LM/NLN collaboration team refined the conceptual model to focus on the area of the upper unweathered bedrock where the weathered (significant flow) bedrock transitions to the unweathered (limited flow) bedrock. It is in this transition interval near the former raffinate pits (two locations) where elevated uranium concentrations are not decreasing (Figure 1). This figure depicts the conditions during two distinct time frames. In Figure 1, the “Leading Edge” panel shows historical conditions, representing the period when the raffinate pits were in use, and the “Trailing Edge” panel shows current conditions, following cessation of operations, bulk contaminant removal, and backfilling of the former raffinate ponds. Scaled blue arrows depict the water flux boundary conditions, and scaled red arrows depict the general mass flux throughout the subsurface. While the raffinate pits were in use, relatively large amounts of contaminated water and contamination locally entered the subsurface, moving through and contaminating overburden sediments and entering the fractured karst aquifer.

The karst is characterized by horizontal and vertical fractures that were formed by weathering; the fracture density decreases gradationally as a function of depth and is influenced spatially by relic paleochannels. While the gradational nature of the weathered-unweathered transition has been documented and recognized, the vertical distribution of fractures has traditionally been simplified into two zones, a weathered and an unweathered zone, for purposes of planning and conceptualization. Figure 1 shows the transition interval with several potentially important contaminant-related properties. The current condition ("Trailing Edge") panel of Figure 1 graphically depicts the raffinate pit remedial actions and the qualitative impacts on contamination. In Figure 2, two types of key subzone processes are highlighted: (A) matrix diffusion as water flows through horizontal (and vertical) fractures and (B) trapped residuals in dead end vertical fractures (i.e., in the transition interval at the terminus of the vertical fracture). The focused zoom-in sketches further describe the two highlighted processes and show how they impact the leading edge and trailing edge of the Weldon Spring Site groundwater plumes.

The work of the Weldon Spring Site LM/NLN collaboration team will focus on the transition interval, on a mass balance-based understanding of MNA, and on methods to efficiently characterize and advance a protective and technically based strategy for managing groundwater at the Weldon Spring Site.

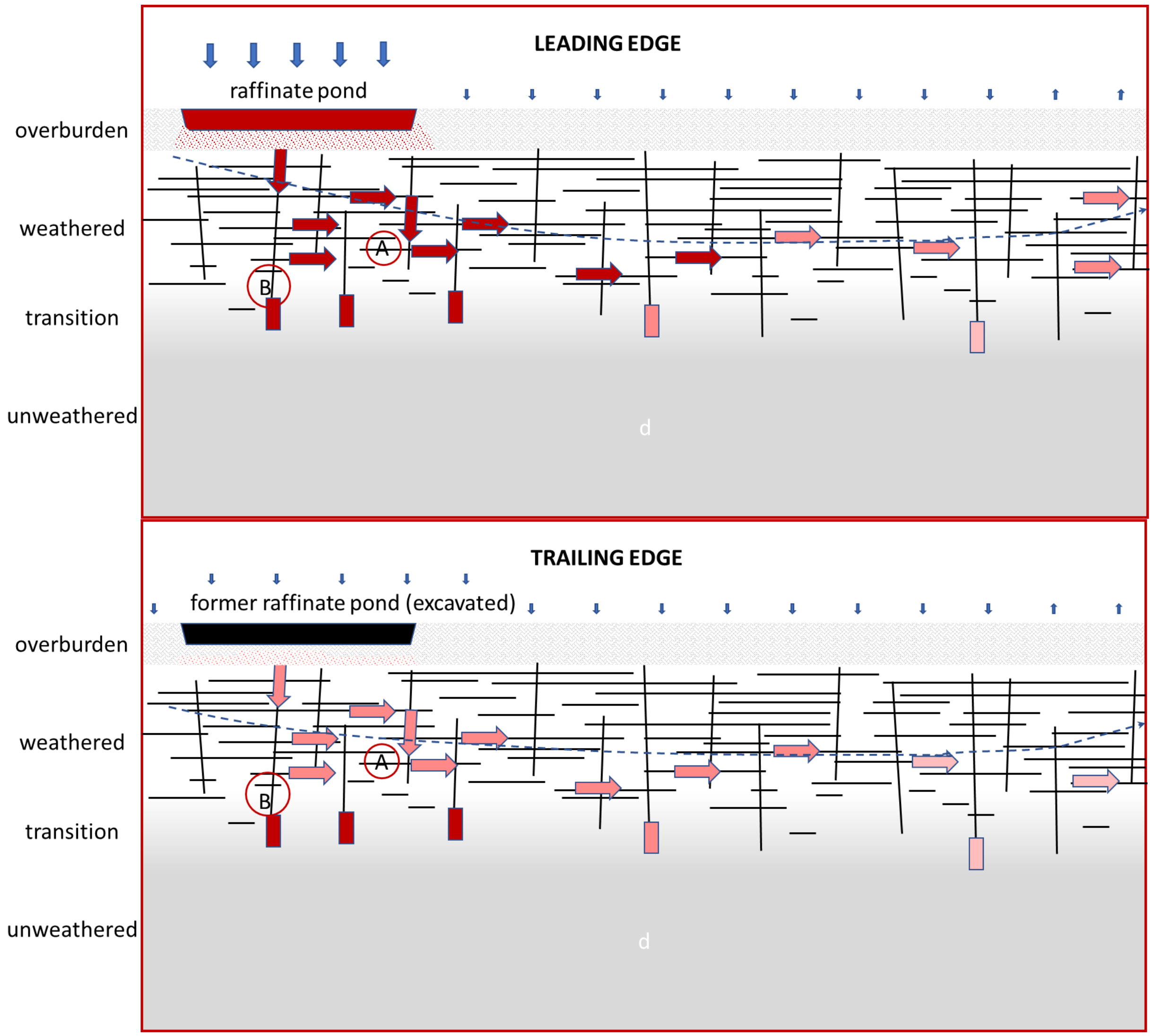


Figure 1. Simplified depiction of the groundwater plume associated at the Weldon Spring site – depicting conditions during operation (upper) and postoperation (lower).

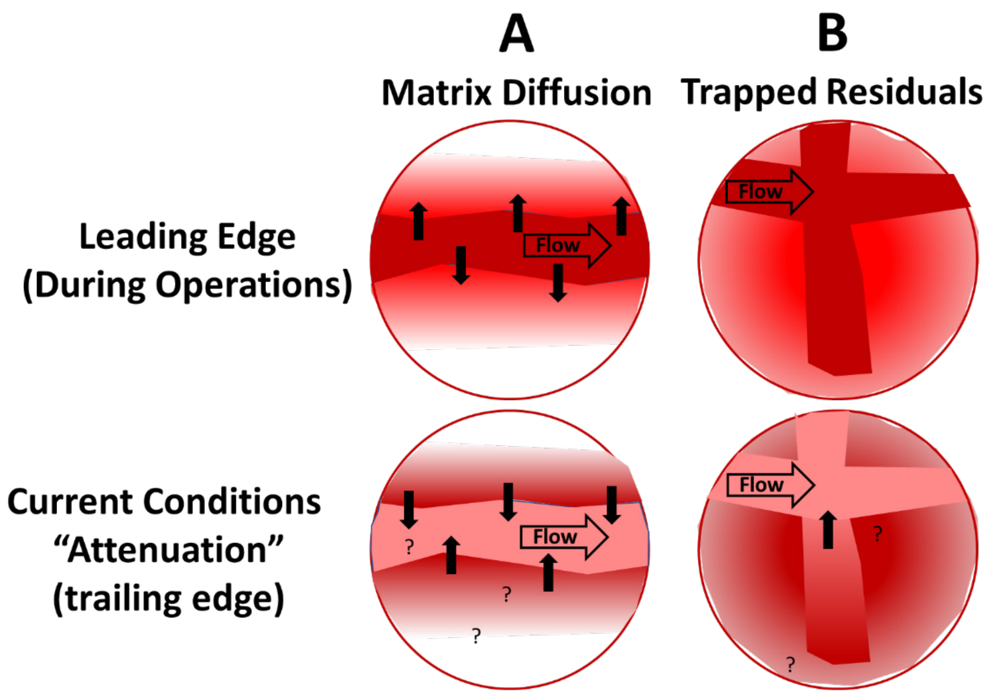


Figure 2. Simplified depiction of target conceptual model topics to support understanding and refining the MNA remedy for locations A & B during the "leading edge" and "trailing edge" conditions.

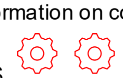
Development Status

The mass balance basis of MNA had been implicit in the guidance for MNA since its initial development by EPA in the 1990s. Championed by researchers like Frank Chapelle of the U.S. Geological Survey and John Wilson of EPA, mass balance became an explicit tool and basis for MNA in the early 2000s (see Looney et al. 2006; Chapelle et al. 2007; Wilson 2011) and was highlighted in the 2015 EPA guidance volumes for MNA of inorganics (EPA 2015). In its recent site-specific review of the Weldon Spring Site remedy, EPA ORD noted that additional information and documentation is needed to adequately meet the CERCLA basis for MNA and highlighted the need to (1) update the documentation based on the EPA (2015) guidance for MNA of inorganic contaminants and (2) organize the information to ensure that all of the required tiers (multiple lines of evidence) are adequately addressed. The various products of the Weldon Spring Site LM/NLN collaboration team focused on these specific topics in all the technology narratives.

The importance of the transition interval between weathered and unweathered limestonekarst is notable for specific locations near former contaminant sources (e.g., well MW-4040). Contamination may become trapped in the lower portion of isolated vertical fractures that are cutoff from the predominant flow system with little to no potential for advection. These areas of remnant contamination can have persistently high concentrations and act as a slow releasing secondary source through diffusion with a similar release rate to dissolution of a mineral phase or a sorbed/bound contaminant. If flow in and out of these isolated areas is sufficiently limited, the potential contribution of contaminant mass flux to the active-flowing groundwater system may be so slow that the overall system can be considered a standard MNA remedy. To evaluate this conceptual strategy, additional data are needed to assess the connectivity of contaminated water to the flowing aquifer and to determine if the contaminants are effectively "trapped" in terms of the MNA mass balance. For this specific narrative, a number of targeted technologies are described in Table 1 with a triage description and prioritized recommendation.

Table 1. Targeted Technologies with a Triage Description and Prioritized Recommendation

Technology	Description	Advantages / Disadvantages	Example References	Consensus
Scoping Modeling	Perform mass balance modeling using reduced order tools like REMChlor-MD.	Tool implements simple strategy for assessing the key components of the mass balance, including source mass flux (accounting for raffinate pond removal and residual source releases) and attenuation processes (including matrix diffusion). $	Falta et al. 2018; Farhat et al. 2018	Recommended
High-Flow Sampling of More Recently Installed Wells MW-4040 and MW-4043	Conduct sampling on more recently installed wells after purging multiple well volumes. Micro-purge sampling was instituted across LM prior to their installation.	This would collect samples from the formation out from the wellbore. If there is poor connectivity and limited flow, micro-purge sampling may be repeatedly sampling from the same limited volume near the well. Also, this would provide information on flow (e.g., does the well draw down and recover quickly). Purge water will have to be captured.		Recommended – High Priority
Tracer Test	Multi-well test to directly examine the potential connections between locations in the subsurface. This test employs tracers monitored by periodic sampling or active pumping.	Tracer tests are fast, are economical, and have had a very high success rate at the Weldon Spring Site in the past. The tests would determine the connectivity as well as the groundwater flow rate from wells MW-4036, MW-4040, and MW-4043 to Burgermeister Spring, possibly to each other, and possibly to the MW-2 well pair. A tracer test would not impact groundwater samples. $	Many	Recommended – High Priority
Borehole Dilution Test	Single well test deployed in the screen zone of wells using a passive tracers and array of sensors to determine the amount and depth of local water flow.	Relatively simple, mature, and low cost. After protocols are developed, a modular system could be quickly deployed and easily monitored. Minimal disturbance to local flow conditions deployed in existing well screen. Impactful data. $	Fahrmeier et al. 2021	Recommended – High Priority
Integrated Borehole Flowmeter Test	Single well test deployed in the screen zone of wells using a small pump at the top of the screen and to depth profiling of flow and concentration inside the well to determine depth profile of relative permeability and concentration in formation.	Relatively simple, mature, and moderate cost. After protocols developed, modular system quickly deployed and easily monitored. Minimal disturbance to local flow conditions deployed in existing well screen. More complex than borehole dilution and minimal benefit from increased capabilities Impactful data. $$	Many	Backup – alternative to borehole dilution test.

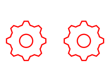
Push Pull Test	Single well test deployed in the screen zone of wells using active injection of tracers, a shut-in period and recovery of tracers to determine local water flow, physical processes, chemical reactions, and reaction rates.	Moderately mature, and moderate cost. After protocols are developed, a modular system can be quickly deployed and monitored with moderate effort. Some disturbance may occur to local flow conditions. Is deployed in existing well screen. The test is more complex than borehole dilution, and there would be minimal benefit from increased capabilities. Impactful data.  $$	Wang et al. 2021	Backup – alternative to borehole dilution test.
Transmissivity Profiling (FLUTe)	Single well test deployed in open borehole to provide transmissivity profile. It identifies the locations of active horizontal-connected fractures over the entire saturated thickness.	Mature commercially available technology that has been widely applied to fractured rock. After protocols are developed, a modular system can be quickly deployed and easily monitored. Causes minimal disturbance to local flow conditions. Is deployed in open borehole prior to well completion. Impactful data.  $$	Keller et al. 2006: Keller et al. 2013; FLUTe 2021	Supplemental information – recommended if feasible during installation of new wells. Would provide data for all zones: weathered, transition, and unweathered.
WaterFLUTe Concentration Profiling (FLUTe)	Single well test deployed in open borehole to provide concentration profile with multilevel samplers at different depths.	Mature commercially available technology that has been widely applied to fractured rock. After protocols are developed, modular system can be quickly deployed and easily monitored. Causes minimal disturbance to local flow conditions. Is deployed in open borehole prior to well completion. Impactful data.  $$	Cherry et al. 2007; FLUTe 2021	Supplemental information – recommended if feasible during installation of new wells. Would provide data for all zones: weathered, transition, and unweathered.
Thermal Transmissivity Profiling (FLUTe)	Single well test deployed in open borehole to provide transmissivity profile. Uses heat and cooling profiles to identify locations of active horizontal-connected fractures over the entire saturated thickness.	Research tool. Similar to transmissivity profiling but not commercially available. Early data suggest potential for higher accuracy, but significant site-specific development would be needed for application.  $$	Coleman et al. 2015	Backup – alternative to transmissivity profiling.
Pump Test	Multi-well test to directly examine the potential connections between locations in the subsurface. Pressures are monitored in all surrounding wells.	A mature, site-specific testing strategy that requires significant planning and cost. Requires closely spaced and properly positioned wells. Significant technical risk of indeterminant data in fractured systems if large numbers of closely spaced wells are not available. If successful, provides definitive information on connectivity.  $$$	many	Backup – not recommended at this time due to costs and implementation challenges. Could be a potential future technology based on information from recommended technologies.

Notes:
Order of magnitude costs (approximate ranges): $ = $0–$50,000, $$ = $50,000–$150,000, $$$ >$150,000
Implementability:

 = not complex

 = somewhat complex

 = more complex

 = most complex

The recommendations from this narrative include performance of reduced order mass balance focused modeling using (1) tools that account for key mechanisms impacting plume concentrations and plume projections over time (such as REMChlor-MD) and (2) field tests to improve understanding of the connectivity of flow in transition wells near the former raffinate pits to the dominant flow system. The two primary recommended field technologies to improve understanding of the transition interval are borehole dilution tests in existing wells and FLUTe transmissivity profiling in open boreholes (if feasible during new drilling). WaterFLUTe multilevel concentration sampling could be co-deployed as an adjunct technology in open boreholes to collect additional concentration profile data if the Weldon Spring Site collaboration technical team deems that useful. The most promising specific approach for borehole dilution testing is to uniformly deploy salt (e.g., sodium bromide) in the solution in a well screen below a packer assembly, followed by monitoring conductivity over time at multiple depths below the packer. Figures 3 and 4 show example results for borehole dilution tests in existing wells and FLUTe transmissivity profiling.

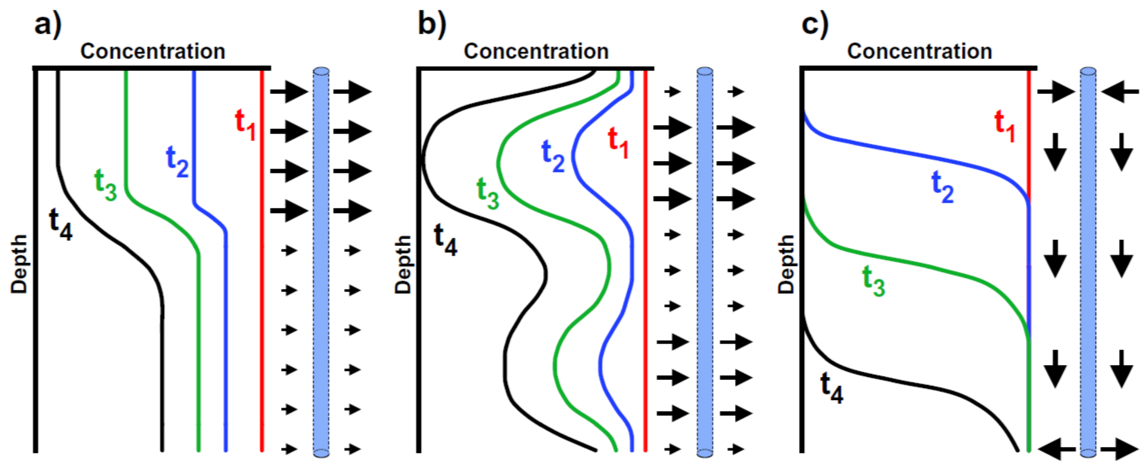


Figure 3. Example information from borehole dilution testing for three scenarios (in all cases demonstrating that the well is on contact with active fractured flow system). The data are collected in existing well screen and the information applies only to the screened interval. (Adapted from Fahrmeier et al. 2021.)

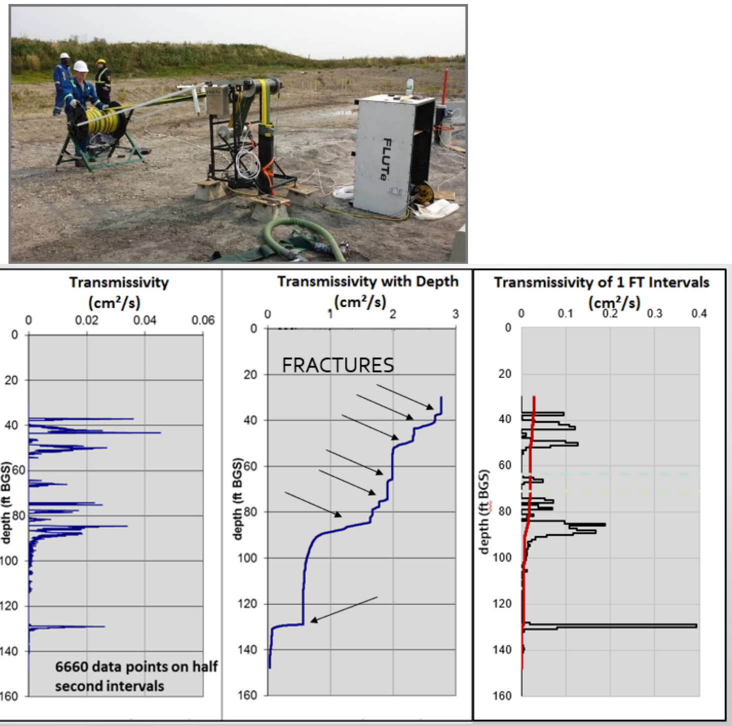


Figure 4. Example information from FLUTe transmissivity profiling system. The data are collected over the entire saturated thickness. This example data shows 150-foot depth collected in approximately 1 hour after setup.

Weldon Spring Site-Specific Advantages/Disadvantages

Incorporating mass balance concepts is straightforward and consistent with current EPA guidance and recent regulatory reviews. Refining the site conceptual model described in this narrative and the related narratives has the potential to support risk management and support a technically based continuation of an MNA-based strategy.

Technology Inter-Relationships

As shown in Figure 5, this narrative provides a framework that integrates all the other narratives developed by the Weldon Spring Site LM/NLN collaboration team.

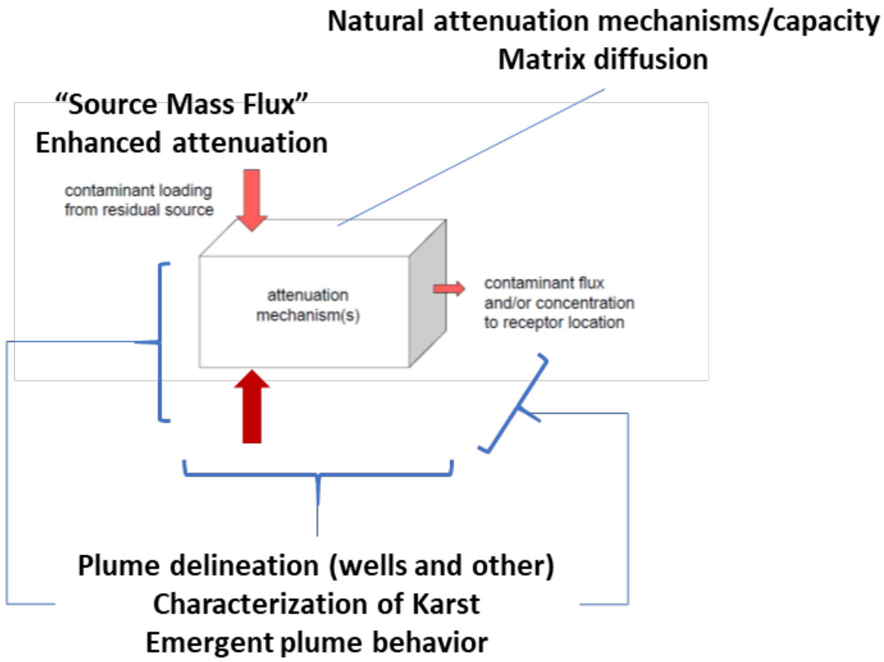


Figure 5. Integrated concept for the Weldon Spring High Risk Site narrative and inputs and outputs of the mass balance conceptual model

Data Gaps: The Weldon Spring Site LM/NLN collaboration team would benefit from data that would (1) help confirm the degree of connectivity (or lack of connection) of the high concentrations measured in transition wells near the former raffinate pits to the active-flowing groundwater system and (2) help delineate the spatial extent (near field or downgradient) of the pockets of higher contamination in the transition interval.

Implementation Details

The potential recommended actions are straightforward, and all can be performed by the Legacy Management Support (LMS) contractor, or its consultants, and as an extension to the planned baseline activities. Continued dialog with National Laboratory Network scientists and engineers is available if needed. The following are scheduling recommendations:

- **Fiscal year (FY) 2022 (late) to FY 2023 (mid) – REMChlor-MD scoping mass balance model:** This work could be performed by the LMS contractor or (if staff time limited) by a recognized expert contractor consultant (e.g., Shahla Farhat or Chick Newell of GSI Environmental Inc.)
- **FY 2023 (early) – borehole dilution tests**
- **FY 2023 (mid, coincident with installation of new wells) –FLUTe transmissivity profiling.** Use WaterFLUTe for concentration profiling if the Weldon Spring Site LM/NLN collaboration team determines that would be useful.

References

Chapelle, F.H., J. Novak, J. Parker, B.G. Campbell, M.A. Widdowson, 2007. *Framework for Assessing the Sustainability of Monitored Natural Attenuation*, USGS Circular 1303, U.S. Geological Survey, Reston, Virginia.

Cherry, J.A., B.L. Parker, and C. Keller, 2007. "A New Depth-Discrete Multilevel Monitoring Approach for Fractured Rock," *Ground Water Monitoring & Remediation*, 27: 57–70.

Coleman, T.I., B.L. Parker, C.H. Maldaner, and M.J. Mondanos, 2015. "Groundwater flow characterization in a fractured bedrock aquifer using active DTS tests in sealed boreholes," *Journal of Hydrology*, 528: 449-462, available at https://doi.org/10.1016/j.jhydrol.2015.06.061.

EPA (U.S. Environmental Protection Agency), 2010. *Monitored Natural Attenuation of Inorganic Contaminants in Ground Water, Volume III—Assessment for Radionuclides Including Americium, Cesium, Iodine, Plutonium, Radium, Radon, Strontium, Technetium, Thorium, Tritium, and Uranium,* EPA600-R-10-093, Office of Research and Development, Washington, D.C.

EPA (U.S. Environmental Protection Agency), 2015. *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites*, Directive 9283.1-36, Office of Solid Waste and Emergency Response, Washington, D.C.

Fahrmeier, N., N. Goeppert, and N. Goldscheider, 2021. "Comparative application and optimization of different single-borehole dilution test techniques," *Hydrogeology Journal,* (2021) 29:199–211, available at https://doi.org/10.1007/s10040-020-02271-2.

Falta, R.W., S.K. Farhat, C.J. Newell, and K. Lynch, 2018. REMChlor-MD, developed for the Environmental Security Technology Certification Program (ESTCP) by Clemson University, Clemson, South Carolina, and GSI Environmental Inc., Houston, Texas. Available at https://www.gsienv.com/product/serdp-estcp/.

Farhat, S.K., C.J. Newell, R.W. Falta, and K. Lynch, 2018. *REMChlor-MD User's Manual Version 1.0*, ESTCP ER-201426, U.S. Department of Defense Environmental Security Technology Certification Program, available at https://www.gsienv.com/product/serdp-estcp/.

FLUTe, 2021. Information pages on transmissivity profiling and multilevel sampling available at https://www.flut.com/transmissivity-profiling, https://www.flut.com/water-flute.

Keller, C.E., J.A. Cherry, and B.L. Parker, 2006. Comparison of the FLUTe Hydraulic Conductivity Profiling results with Straddle Packer measurements, Presentation at Geologic Society of America conference in Philadelphia, PA, October 25, 2006. Available at: https://8119d2e4-0087-4f86-8b93-0777b716a4b2.filesusr.com/ugd/4a7663_55a0019ff3c746328b17ed6f61ee2c8c.pdf.

Keller, C.E., J.A. Cherry, and B.L. Parker, 2013. "New Method for Continuous Transmissivity Profiling in Fractured Rock," *Groundwater,* https://doi.org/10.1111/gwat.12064.

Looney, B.B., K.M. Vangelas, K. Adams, K. F. Chappelle, T.O. Early, and C.H. Sink, 2006. *Mass Balance: A Key to Advancing Monitored and Enhanced Attenuation for Chlorinated Solvents*, WSRC-STI-2006-00082, U.S. Department of Energy Office of Scientific and Technical Information, Oak Ridge, Tennessee, available at: https://www.osti.gov/biblio/891672.

Wang, Q., A. Jin, H. Zhan, Y. Chen, W. Shi, H. Liu, and Y. Wang, 2021. "Revisiting simplified model of a single-well push–pull test for estimating regional flow velocity," *Journal of Hydrology* 601: 126711, https://doi.org/10.1016/j.jhydrol.2021.126711.

Wilson, J.T., 2011. *An Approach for Evaluating the Progress of Natural Attenuation in Groundwater*, U.S. Environmental Protection Agency Office of Research and Development National Risk Management Research Laboratory, Ada, Oklahoma.

Narrative 2: Technology/Strategy: Emergent Plume Behavior/Statistical Techniques

Summary Information

Objective and Potential for Risk Reduction: Emergent plume behavior can be characterized using statistical techniques that quantify trends in the plume to reduce risk. Statistical techniques can be applied to historical and current site analytical data, and hydrogeologic factors and the location of potential receptors can be considered to help optimize a well monitoring system. Statistical techniques such as trend analysis, moment analysis, data sufficiency, groundwater models, and differences in measurements from different well locations can be used to recommend future sampling frequency, location, and density in order to assess plume stability (Aziz et al. 2003). These mature statistical techniques directly address Tier 1 for the lines of evidence.

These techniques can be used to demonstrate active contaminant removal from groundwater and to evaluate dissolved plume stability. Recent advances in machine learning have been shown in many cases to outperform these traditional approaches in terms of accuracy and speed. The U.S. Department of Energy (DOE) has a new Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications (SMART) program to take advantage of these recent breakthroughs in machine learning that could be leveraged to analyze the Weldon Spring, Site. However, traditional statistical methods are likely sufficient to provide strong lines of evidence on plume stability at the site.

Focus Area: All

Description

Since the Weldon Spring Site is a karst system where preferential pathways and complex plume shapes exist, extra care must be taken when utilizing statistical techniques. The Weldon Spring Site team has refrained from contouring the concentration data as a smooth-continuous plume for this reason. In general, statistical techniques to analyze specific wells at the Weldon Spring Site can be highly valuable. For example, a Mann-Kendall test can be used to calculate the probability that concentrations at a well are increasing, stable, or decreasing. Karst aquifers and other fractured and highly heterogeneous groundwater systems typically exhibit high variability in response to seasonal and climate factors such as El Niño and La Niña cycles. The Weldon Spring Site team has used the Mann-Kendall test to predict trends since the monitored natural attenuation remedy began but have been constrained to a 5-year analysis window by regulatory agreement. Care must be taken on determining the time window used for these techniques, and longer time frames (e.g., full dataset or similar extended time frames based on site knowledge) may provide more reliable results. Recent Weldon Spring Site annual reports have highlighted the fallacy of using Mann-Kendall analysis with a strict 5-year time window for variable datasets, in particular for uranium concentrations at Burgermeister Spring that vary by an order of magnitude. They have included longer time frames in the annual reports to show the actual trends. The 5-year window almost always results in no predicted trend. Using a time window of 10 or more years for the Burgermeister Spring data overcomes the natural variability, consistently predicting a long-term downward trend. We recommend that longer time windows be evaluated for highly variable datasets in addition to the fixed 5-year window.

Traditional bulk plume techniques and metrics that analyze the entire plume are problematic for karst systems due to the high heterogeneity. For example, the various method of moments parameters that estimate center of mass and spread of the plume might not be meaningful in a karst system where fast flow paths lead to complex plume shapes. Table 1 and Figure 1 below describes different techniques and assesses their applicability to the Weldon Spring Site.

Table 1. Statistical techniques for characterizing emergent plume behavior.

Technique	Description	Applicability to Weldon Springs	Apply to Well or Plume	Recommendation
Trend Analysis	Identifies temporal trends, plume characteristics (shrinking/expanding), time until target concentrations are met, influence of groundwater. Supports evaluation of geochemical indicators and graphical presentation of historical groundwater data.	Mature technique to shed light on plume stability. Individual well trend analysis represents important Tier 1 data types.	Well or Plume	Yes
Data Sufficiency for Wells	Sequential T-Test and Student's T-Test are used to determine (1) if concentrations are statistically below the cleanup goal and (2) how many more samples may be required to demonstrate location is statistically below the cleanup level.	Mature technique to help determine if existing wells are sufficient and if new wells are needed.	Well	Yes
Mann-Kendall Test	Determine if concentrations are statistically increasing, decreasing, or stable.	Mature technique to determine if concentrations are increasing, stable, or decreasing.	Well	Yes
Stretched Exponentials	May provide improved projections of future attenuation-controlled concentrations for controlling mechanisms such as matrix diffusion, sorption, or mineralization.	New technique with sound mathematical foundation to evaluate attenuation mechanisms (e.g., matrix diffusion, sorption) that accounts for long tails present at many sites.	Well	Yes
Numerical Modeling	Allows testing different hypotheses on new well locations.	Mature technique but more difficult to set up than the statistical techniques.	Well or Plume	Possible
Machine Learning	Alternative method for evaluating plume that may identify new trends.	Less mature technique, but large ongoing DOE programs can be leveraged.	Well or Plume	Possible
Moment Analysis	Plume data are used to estimate the moments (center of mass and spread).	Mature technique to quantitively assess the plume. Might not be useful at Weldon Spring Site because the site is a karst system with preferential flow paths.	Plume	No
Spatial Temporal Optimization	Qualitative and quantitative metrics for identifying redundant monitoring locations and for identifying areas of high uncertainty that may require more monitoring locations.	Mature technique to assist with evaluating new well locations. Might not be useful at the Weldon Spring Site because the site is a karst system with preferential flow paths.	Plume	No

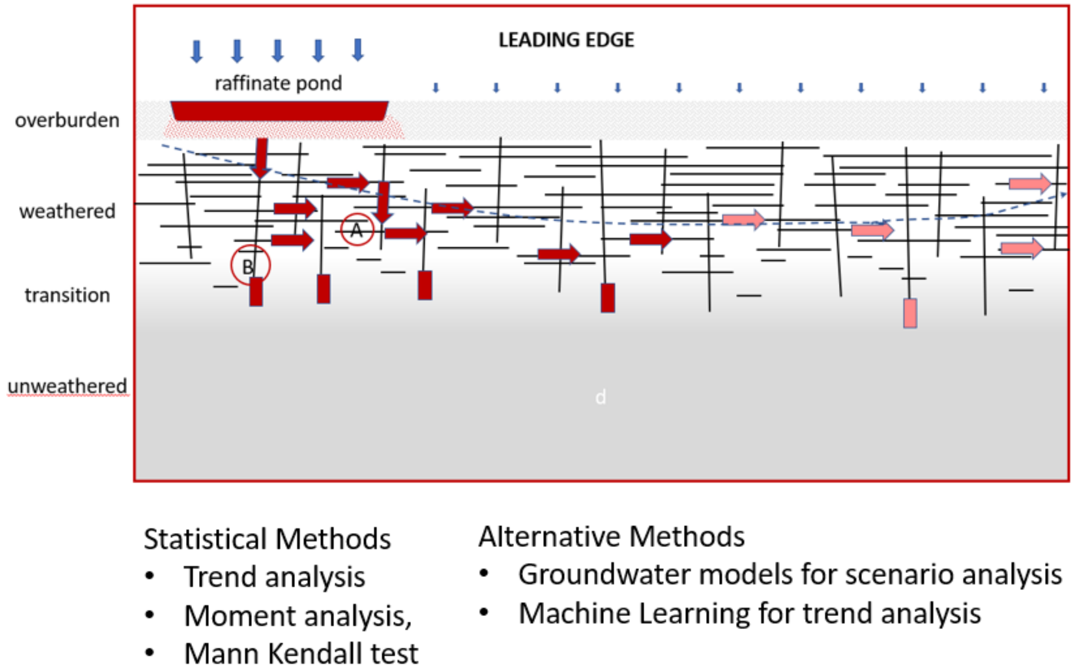


Figure 1. Statisical techniques for analyzing trends in the plume behavior

Development Status

The recommended statistical techniques are mature, and software such as MAROS or modules within the Earth Volumetric Studio (EVS) can be used to evaluate these wells. No EVS model has been developed for the Weldon Spring Site, so using the statistical techniques could be conducted outside of EVS for the site.

Weldon Spring Site-Specific Advantages/Disadvantages

Advantages:

- Well-based statistical techniques can be easily employed to determine if concentration at a well is increasing, steady, decreasing, or inconclusive.
- These statistical tools provide quantitative metrics that can be used to evaluate monitored natural attenuation at the site.

Disadvantages:

- Many statistical techniques are often used to quantify areal extent of a plume, but these tools cannot be employed for Karst systems due to the complex shape of the plume.

Implementation Details

The potential recommended actions are straightforward, and all can be performed by the Legacy Management Support contractor (or its consultants) through an extension to the planned baseline activities. Continued dialog with DOE National Laboratory Network scientists and engineers is available, if needed.

The recommended actions in this narrative could occur from fiscal year (FY) 2022 (mid) to FY 2023 (early). The actions involved well-based statistical techniques that are inexpensive and simple to implement to quantitatively evaluate the high concentration well trends at Weldon Springs. Software such as Maros can be used. As part of this narrative:

1. A Mann-Kendall test using full-time series data, with care taken due to noisy data, can be used to determine if high concentration wells are decreasing, stable, increasing, or inconclusive.
2. Stretched exponentials can be used to provide insight on attenuation mechanisms such as matrix diffusion and sorption.

References

Aziz, J. J., M. Ling, H. S. Rifai, C. J. Newell, and J. R. Gonzales, 2003. “MAROS: A decision support system for optimizing monitoring plans,” *Groundwater*, 41(3), 355-367.

Narrative 3: Technology/Strategy: Evaluation of Proposed Wells and Alternative Geophysical Techniques for Plume Delineation

Summary Information

Objective and Potential for Risk Reduction: Geophysical methods are sensitive to porosity and lithological contrasts, pore fluid conductivity, and temperature. Performing repeat surveys or leaving sensors in place for time-lapse imaging can potentially allow monitoring of water table fluctuations and tracer additions by focusing on subsurface changes rather than static features. Although time-lapse monitoring can reveal changes in pore fluid conductivity, mature geophysical methods do not have the ability to differentiate between chemical phases or to provide direct geochemical concentrations of contaminants at the Weldon Spring Site. Therefore, the specific contribution of geophysics at this site would be the detection of the location and continuity of major fractures, fracture zones, and bedding plane features, through either static or time-lapse imaging.

The assessment of monitored natural attenuation (MNA) is based on ground-water geochemistry (aqueous and solid speciation), stable chemical phases, and stability of the sorbed uranium (Ford and Wilkin 2010). Therefore, geophysical methods cannot replace direct sampling for meeting MNA requirements. Rather, geophysical methods could be used as part of a holistic site characterization approach whereby these methods add spatial information about areas between boreholes (and possibly temporal information between instances of direct sampling) to supplement existing datasets. Geophysical methods could also be used to help select the locations of new monitoring wells. Combining borehole and geophysical information can be a powerful way to update the Weldon Spring Site conceptual site model to assess mass balance and plume stability.

Narrative No. 4: *Technologies to Identify Flow Paths in Karst Terrain* will address geophysical methods from a site characterization perspective, and this narrative will focus more directly on siting and characterization related to new well locations. Implementation details will be applicable to both narratives.

Focus Area(s): All.

Description

In response to persistent uranium concentrations in the unweathered unit near the former raffinate pits and elevated uranium at two downgradient wells and Burgermeister Spring, an evaluation of proposed wells and alternative geophysical techniques for plume delineation was undertaken. This was guided by an independent technical review (U.S. Environmental Protection Agency [EPA] Office of Research and Development [ORD] correspondence dated July 21, 2020, 20-R07-005) of the MNA remedy at the Weldon Spring Site. In this correspondence, EPA cites the 2015 guidance and states "demonstration of plume stability must involve delineating contaminant distribution in all three dimensions and designing a monitoring network to assess the plume over time." While boreholes provide high-resolution information over space and time, this point scale information can misrepresent subsurface structure, particularly in karst terrains where hydraulic conductivity can vary by orders of magnitude over short distances. Geophysical technologies can image at multiple scales and can provide information on a larger subsurface volume. To this end, geophysical technologies are being evaluated to delineate subsurface structure to (1) identify potential transmissive pathways (e.g., fracture features and bedding planes) and (2) assist in choosing locations for new monitoring wells to improve the delineation of vertical and lateral contaminant distribution to support the MNA remedy at the site.

Geophysical measurements can be collected using borehole logging tools, using sensors in single or multiple boreholes, or from sensors positioned on the ground surface or flown as an aerial array. Borehole logging methods provide the highest resolution of information with the lowest scale of investigation (i.e., spatial coverage); furthermore, they provide information colocated with boring log descriptions. Well tests can estimate hydrogeologic parameters, such as porosity and hydraulic conductivity, that can be correlated to geophysical properties. Surface geophysical methods provide the lowest resolution of information with the highest scale of investigation, and they are noninvasive or minimally invasive. The method or methods chosen often depend on site characterization goals (e.g., identification of lithologic variations, fracture network properties, depth to basement rock) and are often driven by site logistics, including the positioning of infrastructure or obstructions. For assistance, refer to the best practice guide for geophysical method selection by Day-Lewis (Day-Lewis et al. 2017) and to an associated Microsoft Excel-based tool that supports user entry to define project goals and general site conditions (Day-Lewis, Johnson et al. 2016).

It is common for site investigations to combine geophysical methods to provide multiple lines of evidence in identifying subsurface structures. In karst environments, multiple geophysical methods have been used, including electrical resistivity tomography (ERT) and self-potential (SP) (Robert, Dassargues et al. 2011) and ERT and multichannel analysis of surface waves (MASW) (Bashir 2018). Compared to monitoring wells, the combined use of multiple geophysical methods is cost-effective and can reduce uncertainty where geophysical results seem ambiguous.

The geophysical methods to be considered for the Weldon Spring Site are presented in Table 1. The methods include aerial, ground-based, borehole, and cross-hole. Some of the methods listed in the table can also be used for karst characterization, which is discussed in more detail in Narrative No.4. The table indicates the comparative method cost, implementability, and impact of metallic infrastructure for each method. Cross-well methods (i.e., with a scale of investigation of ~1 to 10^2 meters [m]) were also considered, and these are reviewed in Narrative No. 4.

Table 1. Comparison of Applicability Factors for Geophysical Methods at Weldon Spring Site

Geophysical Method	Parameter/Target	Considerations at Weldon Spring Site	Factors
Aerial surveys (Scale of Investigation >10^5 m)			
Airborne EM (SkyTEM) https://skytem.com/geophysical-surveys/	Electrical conductivity	✓ Short flight lines (<2 km). ✓ Smaller surveys are less cost-effective. ✓ Impacted by power lines. ✓ Minimum 500 ft from buildings.	$$$
Ground-based surface surveys (Scale of investigation ~10^2 to 10^5 m)			
Ground-based EM; tTEM (Auken, Foged et al. 2019)	Electrical conductivity	✓ A trailing distance of 14 m is required between the ATV and the receiving coil. ✓ This method not practical on some types of terrain.	$$

Geophysical Method	Parameter/Target	Considerations at Weldon Spring Site	Factors
Ground-based EM; DualEM-842	Electrical conductivity	✓ The investigation depth might not be sufficient to image the transition zone and/or the unweathered zone.	$$
ERT (Ward 1988)	Electrical conductivity; Changes in electrical conductivity	✓ Might not be able to resolve smaller fracture features. ✓ Time-lapse ERT imaging may be able to resolve subsurface structure better than static imaging.	$$
GPR (Annan 2009)	Radargram of velocity/depth reflectors	✓ A highly conductive overburden will attenuate the signal, thus limiting the investigation depth. ✓ Imaging depths ~15 m might not be deep enough to meet all site objectives.	$
Seismic reflection (Steeples 2005)	Elastic wave velocities and attenuation	✓ A near-surface fast layer could limit resolution of deeper structures.	$$
Seismic refraction (Rabbel 2010)	Elastic wave velocities and attenuation	✓ Site logistics could prohibit placement of lines long enough to image deep targets.	$$
MASW (Park, Miller et al. 1999)	Shear wave velocities	✓ Active seismic sources might not generate surface waves with long enough wavelengths to sufficiently sample the target. ✓ Measures shallower imaging depths than other seismic methods.	$$
SP (Vichabian and Morgan 2002)	Streaming or redox potential	✓ Provides guidance about where to do other geophysical surveys. ✓ Provides qualitative assessment. Redox potentials are unlikely to be detected at this site. ✓ Has been used with other geophysical methods (e.g., ERT) to help interpret results and site wells.	$
Borehole surveys (Scale of investigation ~10-1 to 1 m)			
Borehole EM EM39, 1.5 m	Vertical profile of electrical conductivity	✓ Cannot be used in metal-cased wells. ✓ Measurements can be collected along the length of PVC-cased wells.	$$
NMR JP175, 9–10 inches JP350, 13–15 inches	Vertical profile estimation of dual porosities	✓ Cannot be used in metal-cased wells. ✓ Drilling method can impact the nominal boring diameter and/or how much drilling mud is pushed into the formation.	$$
GPR	Single-hole reflection GPR	✓ Cannot be used in metal-cased wells. ✓ Can provide information on fractures at depth.	$
Cross-hole surveys (scale of investigation (Scale of investigation 0.5m – 2m) Factors do not include the well installation costs			
GPR	Cross-hole tomography	✓ Cannot be used in metal-cased wells. ✓ Provides improved imaging capability in the borehole.	$
ERT	Cross-hole ERT tomography	✓ Provides improved resolution because it is in the borehole. ✓ Can be fused with seismic and GPR.	$$
Seismic Tomography	Cross-hole seismic tomography	✓ Provides improved resolution because it is in the borehole. ✓ Can be fused with the ERT and GPR.	$$

Notes:

Cost $ – $$$ Implementability Impacted by Metallic Infrastructure

Weathered/Unweathered topography Voids Lithology Groundwater flow direction

Abbreviations:
ATV = all-terrain vehicle; EM =Electromagnetics; ft = feet; GPR = ground-penetrating radar; km = kilometer; NMR=nuclear magnetic resonance; SP=self potential

Based on the information in Table 1, specific geophysical recommendations are provided in Figure 1. Site infrastructure will have a major impact on the implementability of geophysics at the Weldon Spring Site. There is less infrastructure outside of the site boundaries, so geophysical investigations are likely to have more success delineating the western paleochannel region than areas within the site boundary. Generally, geophysics will provide better shallow lateral delineation (e.g., contrasts) than deeper vertical delineation. Several options are proposed to provide delineation within the western paleochannel, including:

1. **towedEM (tTEM) (bold yellow lines in Figure 1):** This option relies on all-terrain vehicle (ATV) accessible locations within roadways and open areas to investigate paleochannel extent, depth, and pinch-outs. Pacific Northwest National Laboratory testing of tTEM has shown interference within about 30 m of well casings and about 100 m for lateral metallic objects (e.g., fences, pipes). Any unknown buried infrastructure, including the water or nitroaromatic production lines, could impact the ability of electromagnetics (EM) to resolve subsurface features.
2. **Combined two-dimensional ERT, seismic, and SP along the roadway containing MWS-2 and MWD-2 (dashed bold yellow lines):** This would be a more localized survey aimed at delineating the width of the western paleochannel. This survey would provide a higher resolution of subsurface karst than Option 1. It could also provide proof-of-concept if this method was used at other locations to delineate the width of the western paleochannel.

A final evaluation of options 1 and 2 above should be conducted after a site-feasibility study that would evaluate historical documents (to look for the presence of piping, foundations) and expected resolution depths. A major water line and a nitroaromatic production line of unknown material have been identified. Exact locations and construction material of these lines would need to be determined prior to conducting geophysical surveys.

3. **Time-lapse three-dimensional (3D) ERT downgradient of MW-4036:** This option is a lower priority. Using time-lapse imaging from electrodes left in place, this survey could potentially capture natural changes in water levels, revealing dominant flow pathways. An ionic tracer injection would enhance the electrical contrast, increasing the ability of ERT to image transmissive pathways.

Inside the site boundaries, the ability of geophysics to image subsurface structure (fracture zones, large fractures, bedding planes for lateral plume delineation, etc.) will be more challenging due to the presence of current and past infrastructure, particularly in and around the former raffinate pits. Away from this area, colocated geophysical surveys using ERT, self potential (SP), and seismics could reduce ambiguity in the individual survey results. The location of colocated geophysical surveys should be determined after other site investigations take place (e.g., borehole dilution and statistical analyses).

Other general recommendations include:

- **Borehole logging within existing PVC-cased wells:** Each well construction diagram would need to be assessed individually. Exploration radiuses are shown in Table 1. Table 2 is a review of implementability for four identified PVC-cased wells.

Table 2. Geophysical Borehole Logging Implementability for Weldon Spring Site Wells

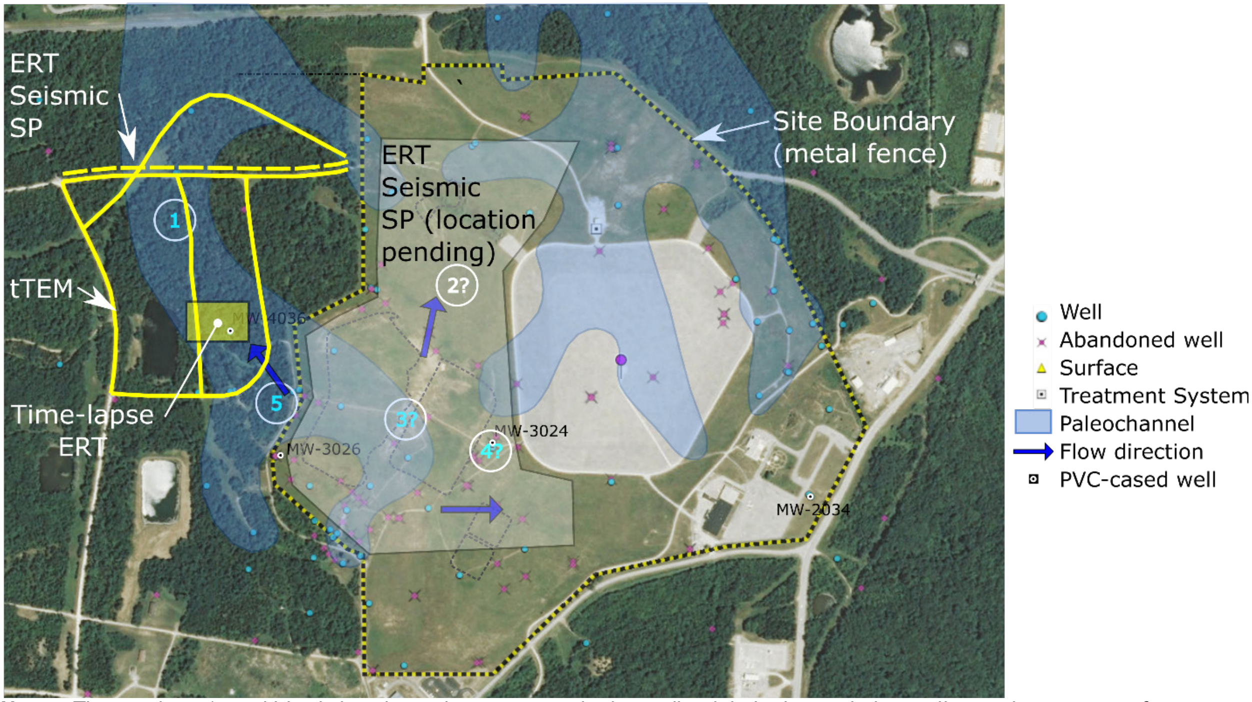
Well Construction Log (PVC)	EM-39	NMR (JP175)[a]
MW-2034	✓	Marginal, depending on quality of drilling and centralization
MW-3024	✓	X
MW-3026	✓	✓
MW-4036	✓	✓ Bottom 10 feet only

Note:
[a] Well logs reviewed by Vista Clara.

- **Use PVC casing for new wells:** PVC well casing allows for repeat borehole logging. An alternative is to emplace ERT electrodes on the exterior of the well casing which would allow for (1) temporal borehole geoelectrical monitoring, (2) surface to borehole ERT monitoring, and (3) cross-well imaging to another well (refer Narrative No. 4).
- **Use borehole geophysical logging to fully characterize new monitoring wells**: Many logs would need to be collected in open wells at the time of drilling. Recommendations include acoustic televiewer, optical televiewer caliper, single flowmeter, induced polarization, SP, normal resistivity, and magnetic susceptibility. Cost and effectiveness should be reviewed upon implementation with an experienced borehole logging operator.

Narrative No. 4 contains additional information and recommendations.

Figure 1 shows potential new monitoring well locations inferred from past EPA correspondence along with other site features that can influence areas of investigation (e.g., paleochannel locations, flow directions, well locations). Recommended geophysical investigations are outlined on the figure.



Notes: The numbers 1–5 within circles show where new monitoring wells might be located, depending on the outcome of geophysical investigations and borehole dilution tests. White numerals designate lateral delineation well locations, and aqua numerals designate vertical delineation well locations.

Figure 1. Potential New Monitoring Well Locations

The five potential new monitoring well locations shown in Figure 1 are described below:

- **Area 1:** The July 2020 EPA ORD memo suggested a need for vertical delineation around wells MWS-2 and MWD-2 to ensure uranium concentrations are not bypassing these shallow and deep screened intervals. Several geophysical methods have been recommended to laterally delineate the extent of the western paleochannel; this information can be used to recommend installing a new well in this area. Preference could be given to locations where geophysical methods reveal deeper voids (between screened wells MWS-2 and MWD-2 intervals) to provide vertical delineation.

  Also, as part of Area 1, vertical delineation has been requested for the area around wells MW-4043 and MW-4036, which have closely screen intervals that are relatively shallow. Without further information, it is not clear whether another monitoring well at this location would provide vertical and lateral delineation or information on the fluctuating uranium concentrations in well MW-4036. Geophysical investigations could be used to inform decisions in this area.

- **Area 2:** It is not clear that a new monitoring well in Area 2 is necessary, because the existing well network might be sufficient. For example, on the northern portion of the site, weathered wells (MW-2021, MW-2022, MW-2023) and unweathered wells (MW-2002, MW-2005, MW-2032) are below the uranium maximum contaminant level (MCL). In addition, in the MW-3023 (weathered), MW-3003 (transition), and MW-3006 (unweathered) well cluster immediately north of Raffinate Pit 4, all the wells have low uranium concentrations.

- **Area 3:** To evaluate the need for a new monitoring well in Area 3, the first new evidence to be sought should be borehole dilution tests at surrounding high concentration wells to evaluate connectedness in the unweathered unit. Moving this potential new well location downgradient and installing it as a nested well could provide useful lateral and vertical delineation.

- **Area 4:** To determine the location and need for a new monitoring well in Area 4, the first new evidence to be sought should be the recommended borehole dilution tests to evaluate connectedness in the unweathered unit (wells MW-3040 and MW-3024). There is a shallower well near this location (MW-3025) that has uranium concentrations below the MCL. A well at this location screened deeper (about 30 feet) than well MW-3040 would improve the vertical delineation of uranium west of the raffinate pits.
- **Area 5:** There are higher and lower uranium concentrations in wells MW-4040 and MW-4042, respectively, and there is a large gap in between these screened intervals. To provide better vertical delineation, a new well between the screened interval depths of these adjacent wells is recommended at this location.

Development Status

While instrumentation and analyses are continually updated, the geophysical methods presented here are considered technologically mature and have been used over decades at hundreds of sites for characterization and, increasingly, for time-lapse monitoring.

Weldon Spring Site-Specific Advantages/Disadvantages

Surface geophysical measurements are a bulk measurement; therefore, resolution degrades as depth increases. In addition, the overburden and/or weathered formation may prohibit resolutions of features at depth. Cross-well geophysical measurements could overcome this limitation. This is detailed further in Narrative No. 4.

Technology Inter-Relationships

The evaluation here will be directly impacted by information gained from other site activities, and especially by new information about mass-flux determination laterally and vertically in areas of high uranium concentrations. Uranium would not, at the current concentrations, provide a contrast in subsurface properties that would be distinguishable through geophysical imaging. Therefore, the primary focus of geophysical investigations should be to determine the propensity for uranium to migrate in the subsurface through major fractures, fracture zones, and/or major bedding planes. Any additional methods focused specifically on the characterization of karst would be of use in siting new wells, including static and time-lapse cross-well imaging and surface-to-borehole imaging. Narrative No. 4 is intertwined with this narrative.

Data Gaps: Feasibility evaluations conducted prior to field investigations are another check of the applicability of geophysical methods. Feasibility evaluations should use the most up-to-date conceptual site model. A reevaluation or fine-tuning of geophysical methods should be undertaken using all current information prior to actual field work taking place.

Implementation Details

All geophysical recommendations are for readily available equipment. Implementation hinges on information gained from (1) mass-balance flux borehole tests, (2) results of feasibility evaluations, and (3) other site information (e.g. the presence of infrastructure) not considered in this document.

Table 3. Recommendations for Weldon Spring Site Wells

Location	Recommendation	Information	
Go/No-Go Decision and Realistic Expectations of Resolution			
P	Limited feasibility study (historical record review of site infrastructure, numerical modeling) of geophysical methods using existing geologic and contaminant maps	Ability of geophysics to resolve synthetic features that are representative of the western paleochannel	Higher priority
S	Limited feasibility study (historical record review of site infrastructure, numerical modeling) of geophysical methods using existing geologic and contaminant maps	Ability of geophysics to resolve synthetic features that are representative of the site inner boundaries	Medium priority
Site and/or Minimize the Number of New Wells			
P	tTEM imaging in existing roadways and open areas[1]	Lateral and vertical extent of the plume	Higher priority
P	Colocated ERT and SP surveys Seismic (MASW / refraction)[a]	Lateral and vertical extent of the plume	Higher priority
P	3D ERT time-lapse imaging downstream of well MW-4036	Transient lateral and vertical extent of the plume	Medium priority
S	Colocated ERT and SP surveys Seismic (MASW / refraction)	Lateral and vertical extent of the plume	Medium priority
Characterization of Karst and Supplementary Information			
S	Joint Inversion of Multiple Geophysical Surveys from existing surveys collected	Lateral and vertical extent of the plume	Medium priority
P, S	Borehole logging of existing PVC-cased wells [less priority to well MW-2034]	Detailed vertical profile of transmissive zones	Medium priority
P, S	Geophysical logging of new wells	Detailed vertical profile of transmissive zones	Medium priority
P, S	PVC-cased new wells	Detailed vertical profile of well properties	Low priority
P, S	PVC-cased new wells with ERT electrodes	Transient vertical profile of changes over time	Low priority
P, S	Cross-well geophysical imaging	Vertical extent of the plume	Low priority
P, S	Geotechnical investigations (e.g., coring)	Horizontal and vertical fracture patterns	Low priority

Notes:
[a] To be further evaluated based on site feasibility investigations.

Abbreviations:
P = Western Paleochannel
S = Interior site boundary

References

Annan, A. P. (2009). Electromagnetic principles of ground penetrating radar, chapter. **1**.

Auken, E., N. Foged, J. J. Larsen, K. V. T. Lassen, P. K. Maurya, S. M. Dath, and T. T. Eiskjaer (2019). "tTEM - A towed transient electromagnetic system for detailed 3D imaging of the top 70 m of the subsurface." Geophysics **84**(1): E13-E22.

Bashir, N. (2018). The utility of geophysical techniques to image the shallow subsurface karst areas in Missouri. Doctoral Dissertation, Missouri S&T.

Day-Lewis, F. D., C. D. Johnson, L. D. Slater, J. L. Robinson, J. H. Williams, C. L. Boyden, D. Werkema, and J. W. Lane (2016). A Fractured Rock Geophysical Toolbox Method Selection Tool. Groundwater. **54:** 315-316.

Day-Lewis, F. D., L. D. Slater, J. Robinson, C. D. Johnson, N. Terry, and D. Werkema (2017). An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites. Journal of Environmental Management, Elsevier**:** 709-720.

Ford, R. and R. Wilkin (2010). Monitored Natural Attenuation of Inorganic Contaminants in Ground Water Volume 3 Assessment for Radionuclides Including Tritium, Radon, Strontium, Technetium, Uranium, Iodine, Radium, Thorium, Cesium, and Plutonium-Americium. U. S. E. P. Agency. Washington, DC.

Park, C. B., R. D. Miller, and J. Xia (1999). "Multichannel analysis of surface waves." Geophysics **/64**(3): 8.

Rabbel, W. (2010). Seismic methods. Groundwater Geophysics: A Tool for Hydrogeology. R. Kirsch. Berlin, Springer**:** 23-84.

Robert, T., A. Dassargues, S. Brouyère, O. Kaufmann, V. Hallet, and F. Nguyen (2011). Assessing the contribution of electrical resistivity tomography (ERT) and self-potential (SP) methods for a water well drilling program in fractured/karstified limestones. Journal of Applied Geophysics, Elsevier B.V. **75:** 42-53.

Steeples, D. W. (2005). Shallow Seismic Methods. Hydrogeophysics. Y. Rubin and S. S. Hubbard. Dordrecht, Springer Netherlands**:** 215-251.

Vichabian, Y., and F. D. Morgan (2002). "Self potentials in cave detection." Geophysics **21**: 866-871.

Ward, S. (1988). The resistivity and induced polarization methods. Symposium on the Application of Geophysics to Engineering and Environmental Problems**:** 147-189.

Narrative No. 4: Technology/Strategy: Technologies to Identify Flow Paths in Karst Terrain

Summary Information:

Understanding karst terrain and its effects on subsurface hydrology and contaminant transport can be challenging. Specifically, for the Weldon Spring Site, the challenge is to better resolve the location of karst features, such as preferential flow paths that can influence contaminant migration from residual sources. Geophysical and geotechnical techniques can be used to image areas of increased fracturing that influences flow as well as zones where fractures are less abundant or poorly connected and groundwater flow is limited.

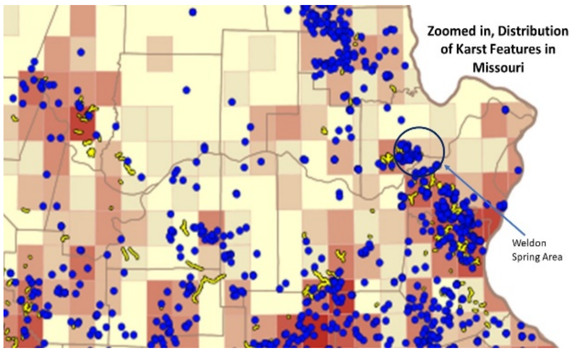
In general, geophysical techniques lose resolution with distance as they provide an integrated measurement (spatially averaged) of the subsurface. Surface geophysical techniques lose resolution with depth and borehole methods. This allows for sensors and sources to be closer to the area being evaluated so they do not lose resolution away from the borehole. Geotechnical techniques can provide good resolution with depth but lack horizontal continuity. The objective of this narrative is to recommend various methods, new techniques, or combinations of techniques that can be used to identify areas of more or less groundwater flow in both the horizontal and vertical directions near and downgradient of residual sources.

Focus Area(s): All

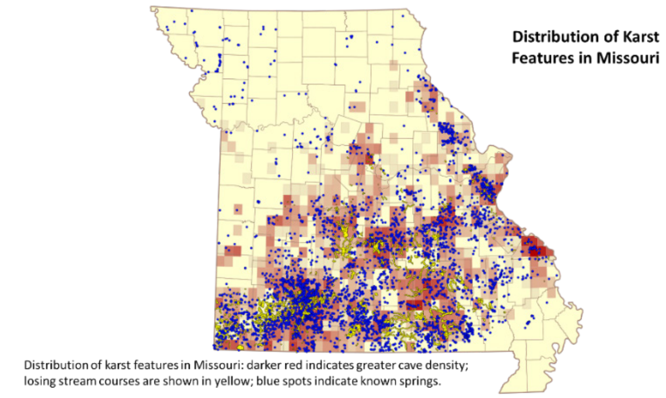
Description

Background:

Karst terrains are characterized by closed depressions, subterranean drainage, and void spaces that range from small-scale features (dissolution enlarged fractures) to those as large as caves for well-developed karst. The subterranean channels and caves form by the dissolution of limestone that is below the water table. Dissolution channels or preferred flow paths are also formed above the water table by the dissolution of fractures that carry seepage water to the water table. The Weldon Spring Site is on the border of an area with a high number of karst features (Figure 1). This is evident by the losing stream near the site and the nearby Burgermeister Spring. At the Weldon Spring Site, an extensive geotechnical study of the disposal cell site was performed prior to the disposal cell's construction to ensure no dissolution features were present at a scale that could impact the stability of the structure.



a)



b)

Figure 1. (a) Map showing distribution of karst springs (blue) and losing streams in yellow. The darker the background color, the higher the frequency of karst features. (b) Zoomed-in portion of the map focusing on the Weldon Spring area.

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Characterization Approaches:

There are several characterization approaches that have been used to understand the impact that tectonic stress and dissolution have had on the subsurface limestone at the Weldon Spring Site and to evaluate whether this impact has provided dissolution channels for preferential subsurface flow. Refining the dimensions of the preferential flow features and reconfirming areas where data do not suggest the presence of preferential flow features may be fruitful. While many of these approaches are also useful for evaluating proposed new well locations and plume delineation, they are also discussed in this section with an emphasis as to how they specifically apply to understanding the subsurface in karst terrains.

In karst characterization, as in plume delineation and most other geophysical challenges, a single geophysical method can provide ambiguous results. To overcome this problem, multiple geophysical techniques are often used. Quite often this is done qualitatively by visually comparing the results of the multiple methods. Recently there have been advances in fusing the data using algorithms, and there have also been advances in joint inversion of the data based on fundamental principles/parameters. How this applies to the Weldon Spring Site are addressed in the “Implementation Details” section.

Development Status

This section describes the approach taken to implement the individual recommended characterization approaches. The purpose of this subsection is to provide characterization options based on different budgets that may be available.

Geotechnical

Geotechnical well logging and water level measurements are valuable tools for the characterization of karst terrains and should be utilized. Groundwater elevations should be correlated with future streaming potential measurement. High-fidelity well logging and coring of key sections should be included with the installation of any new wells. The cost of the high-fidelity well logging should be minimal. The cost to core a well will have to be examined and then evaluated from a cost/benefits point of view. Ideally, all data will be used to develop a three-dimensional subsurface visualization/interpretation of the lithology at the site using software such as Earth Volumetric Studio.

Surface Methods – Geophysical

Streaming Potentials: The first geophysical method should be an area wide two-dimensional (2D) streaming potential study. This measurement will provide flow vectors for the area. While the method may seem simple to implement, an inexperienced operator/collector might obtain results that are difficult to interpret. There are many subtleties in collecting streaming potential data that an experienced practitioner will be able to implement. A streaming potential survey should be collected in both the wet season and dry season to help extract more information out of the data. The interpreted streaming potential data should help in deciding where to conduct the other geophysical studies. The streaming potential results should be correlated to the potentiometric surfaces to provide continuity between sparsely located wells. A side benefit of the streaming potential survey may be that, if the streaming potential signal is removed from the data, there may be a background self-potential signal associated with chemical reactions. While these signals may be present at the site, they might not be large enough to be measured using the self-potential method. However, if there appears to be a correlation between known chemical reactions and the self-potential signal, then further investigation may be warranted. For more information on this approach, see the "Self Potentials in Cave Detection" paper (Vichabian and Morgan 2002).

Mise-a-la-Masse or Residual Potential Method (also called RPM): At the Weldon Spring Site, this method ideally would involve placing a current electrode at Burgermeister Spring and the associated ground electrode at a well on the south east side of the site. The associated surface potentials will be mapped with the ground electrode used as the reference. A detailed potential map should be constructed of the site and outside the site to the boundary at Highway D. If there is continuous preferential fluid flow (channelized flow) between the site and Burgermeister Spring (as suggested by past tracer tests), the electrical current will follow the preferential flow paths and the associated potentials will be mapped on the surface. If the data suggests results that differ from the present paleochannel maps, additional data may be collected between Highway D and Burgermeister Spring to more fully understand the flow pattern. Roads between the site and Burgermeister Spring present some logistical issues. However, previous field experience suggests that these logistical challenges are solvable for reasonable costs.

Fusion of Electrical Resistivity Tomography (ERT) and Seismic: Unless the streaming potential signal from the self-potential survey suggests otherwise, it is proposed that a 2D ERT survey be done across the paleochannel to better understand the weathered zone and the unweathered zone interface in that region. The purpose of this survey would be to look for conductive regions that will indicate areas of higher fluid conductivity and possibly channelized flow. However, there may be some ambiguity in the measurement interpretation, such as clay layers providing similar signals. To overcome this ambiguity, it is proposed that a seismic tomographic surface refraction survey be conducted along the same line and that the data be jointly inverted with the ERT data. The power of this approach is that the joint inversion should help distinguish those regions that are clay-filled zones versus water-filled fractures. See Figure 2 for the type of results this can provide (Glaser et al. 2021).

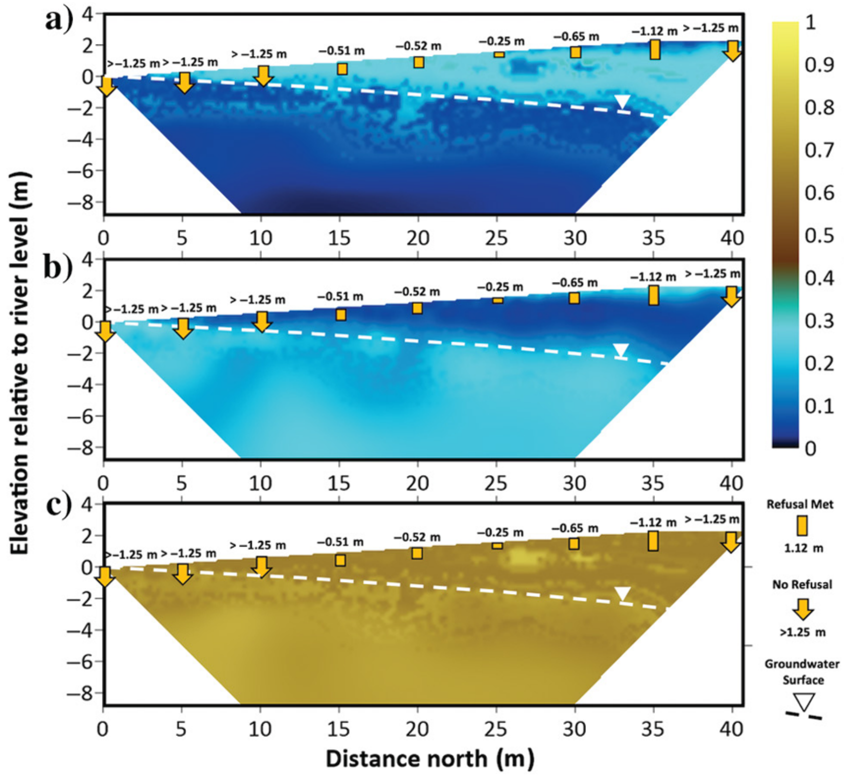

Figure 2. Stacked section showing results of the three primary constituents—(a) air fraction, (b) water fraction, and (c) matrix fraction—as calculated from the Joint Profile Method (JPM) model using electrical resistivity and seismic refraction.

Subsurface Methods (Borehole Geophysics)

While surface geophysical methods are relatively cost-effective to implement and can provide significant value, they can lack the resolution needed to image individual flow channels, if the flow channels are smaller than 1 or 2 meters at the targeted depths. At these depths, a volume of 2 meters to 3 meters is integrated to provide a single answer for the volume, which can allow small but important features to be missed. These challenges can be overcome by sensors and sources closer to the region of interest by using boreholes.

If drilling equipment is already onsite for other work, it can be cost-effective to drill relatively small exploration wells that can be used for geophysical monitoring. These temporary wells do not require the added completion expense that can be associated with permanent monitoring wells.

Borehole ERT and Seismic: Like the surface measurements described earlier, borehole ERT and borehole seismic can be of great value, but there can be ambiguity when using them individually. By using them jointly in a borehole as described above, the ambiguity can be minimized while improving the resolution. By appropriately designing the survey and the spacing of the boreholes, resolution down to the submeter level can be achieved. Two possible locations are proposed: (1) at the paleochannel to understand whether a fracture network extends down into the unweathered zone where uranium may have migrated and (2) at the existing region where uranium contamination was detected in deep wells in the upper portion of the unweathered zone. This will help facilitate understanding the extent of the connectivity of this region. This will be done only if the push-pull test or other hydraulic tests indicate there is connectivity in this region. The data collection in the weathered and unweathered zones (and the transition zone) is an excellent region where ground-penetrating radar (GPR) works well, and it would be a good addition to the joint inversion to further constrain the results.

Crosshole Borehole GPR: Crosshole borehole GPR is a low-cost approach to gain more information on the region of interest. Like ERT and seismic, it has ambiguity associated with its results when used alone. But when it is used with seismic and ERT in a joint inversion for percent solid matrix, percent fluid, and percent air, it can further constrain the solution. These three geophysical techniques respond to air, water, and the solid matrix differently, and when they are fused together using mixing laws, they provide a powerful interpretation of the subsurface.

Borehole Reflection GPR: This approach has the potential to show the vertical factures near a single borehole. Currently, there is no directionality associated with the GPR signal, so the orientation of the vertical fractures will be unclear. However, there is preliminary work being done by the National Energy Technology Laboratory and the Cold Regions Research and Engineering Laboratory of the U.S. Army Corps of Engineers that could demonstrate the feasibility of a directional antenna. As of February 2022, it was expected that a directional antenna would be demonstrated in the next month or two. If the directional antenna works, it will allow for the location and orientation of the fractures to be determined. An example of how GPR images fracture is shown in Figure 3. This is also a low-cost method to implement and it can be used on existing PVC cased wells.

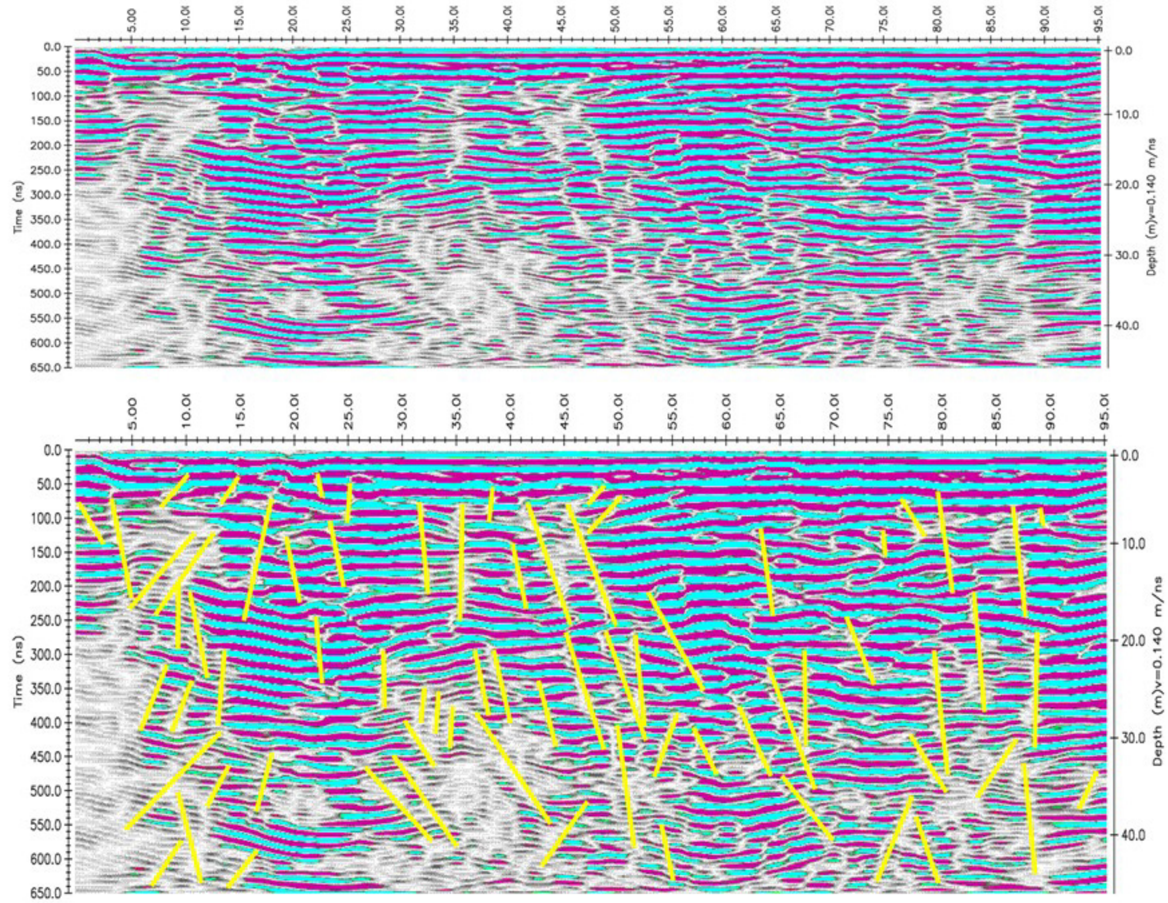

Figure 3. A GPR image of Harrison's Cave in Barbados. The yellow lines indicate fractures in the limestone (Morgan and Reppert 2010).

Implementation Details

1. If testing indicates connectivity between the deep high-concentration wells and the rest of the site:

   a. To determine the extent of the connectivity in the vicinity of the borehole, design and conduct borehole geophysical surveys to examine the connectivity/fracture network in the vicinity of the borehole, and then use crosshole seismic, ERT, and GPR to provide higher resolution images of the unweathered zone. If the directional GRP antenna is available, also conduct GPR reflection surveys to image fractures.

   b. To better understand the interconnectivity of the site to Burgermeister Spring (and to possibly assist in the placement of more detailed geophysics), a mise-a-la-masse survey should be conducted. This will provide an overall sitewide image of the major flow paths.

   c. If a more detailed analysis of the flow paths (paleochannel) is desired, then surface geophysics using ERT and seismic refraction should be done at selected locations determined from the mise-a-la-masse method. The seismic and ERT methods should be jointly inverted for the percent air, water, and solid matrix in the subsurface region of the survey.

d. While the streaming potential survey will be useful for determining flow vectors, the flow paths between the site and Burgermeister Spring can be achieved using the mise-a-la-masse method, which most likely has a better signal to noise ratio. At this point it is not recommended that the streaming potential measurements be used unless a confirmation of the mise-a-la-masse method is desired.

2. If testing indicates poor connectivity between the deep high-concentration wells and the rest of the site:

a. No investigation of the unweathered zone should be done.

b. Items b and c from Item 1 above should be done if more information on the flow channels is desired for selecting the sites of future wells.

References

Vischabian, Y., and F.D. Morgan, 2002. “Self Potentials in Cave Detection,” *The Leading Edge*, September.

Glaser, D.R., K. Burch, D.L. Brinkley, and P.M. Reppert, 2021. “Multi-method Geophysical Localization of Deep Voids through Secondary Signatures,” *Geophysics*, 86, WA139-WA152.

Morgan, F.D., and P.M. Reppert, 2010. *Geophysical Investigation of Harrisons Cave.*

Narrative No. 5: Technology/Strategy: Natural Attenuation Mechanisms

Summary Information

Objective and Potential for Risk Reduction: Uranium concentrations at the Weldon Spring Site are decreasing in weathered-zone wells and Burgermeister Spring. However, it is unknown if this is solely attributed to hydrodynamic dispersion and dilution or if geochemical natural attenuation (NA) mechanisms are partially responsible. Traditional nondispersive geochemical mechanisms (e.g., reduction, adsorption, or precipitation) in karst systems are expected to be weak and have not been adequately documented at the Weldon Spring Site beyond the overburden sediments below the former raffinate pits. Additional characterization of rates and capacities of NA mechanisms in the weathered karst aquifer is needed to assess if mass flux is being decreased through NA processes in accordance with updated U.S. Environmental Protection Agency (EPA) guidance for monitored natural attenuation (MNA) remedies (EPA 2010). If NA mechanisms can be demonstrated as being viable and/or responsible for decreased or attenuated uranium mass flux, this could provide the technical basis needed for continuation of the selected MNA remedy.

Focus Area: Focus Area 2.

Description

Additional laboratory characterization and geochemical modeling has the potential to (1) identify the presence of NA mechanisms for uranium and (2) assess the long-term stability and mobility of aqueous (e.g., matrix diffusion from uranium within partially connected fractures), adsorbed (e.g., on iron oxides or pyrite minerals in fractures [Zachara et al. 2007]), and solid phases of uranium (e.g., U-carbonates, silicates, or phosphates). For example, aqueous Ca-uranyl-carbonate species sorb to iron oxides and calcite, and over time some uranium is incorporated into calcite (Smith and Szecsody 2011). Uranium can also precipitate in specific mineral phases, depending on interactions of uranium and co-contaminants with natural sediments, which may not occur with just uranium in the natural porous media (Arai et al. 2007). Figure 1 provides a conceptualization of possible geochemical mechanisms responsible for attenuated flux of uranium mass currently within different zones and portions of the uranium-groundwater migration pathway for the site.

Geochemical equilibrium modeling and laboratory sorption experiments at the Weldon Spring Site in the 1990s indicated the likelihood of adsorption of uranium to iron and manganese oxides and clay minerals in the overburden sediments (Schumacher 1993). It is possible that precipitation of uranium as carbonate, phosphate, and vanadate precipitates within the overburden sediments below the raffinate-pit source area occurred as well. The long-term stability-mobility and geochemical controls for desorption or dissolution of uranium in the overburden still need to be evaluated. An EPA Office of Research and Development letter identified these as "important" data gaps and recommended the following factors be considered further for the overburden sediments: solid-phase concentrations of uranium and solubility-controlling reactions, aqueous and solid-phase uranium speciation, sorption-desorption reactions, and characterization of aquifer solids using modern techniques.

Schumacher (1993) concluded that reduction of uranium to the less-mobile U(IV) species, precipitation of U(VI) minerals, or adsorption within the weathered and unweathered groundwater flow system is not likely, given the geochemical conditions. However, Schumacher's discussion of possible uranium sorption reactions only considered calcite and was based on the thermodynamic equilibrium constants available at the time compared to those presently available. For example, the earlier conclusions that carnotite (i.e., U-vanadate) as the only likely precipitate may need to be updated to include U-carbonate and U-silicates. Other complexants in the raffinate pits (PO_4, F, Cu, Li, MoO_4), even if only small concentrations leach into sediments and the weathered carbonate, can complex with U(VI) and may precipitate. In a separate study of uranium attenuation in oxic carbonate aquifers, it was concluded that U(VI) incorporation into calcite and precipitation of liebigite (a Ca-uranyl-carbonate mineral) occurred and decreased the aqueous U(VI) concentration (Nolan et al. 2021). In addition, recent data from aqueous uranium species interactions with Hanford (Washington) sediments show adsorption of uranium to iron oxyhydroxides (Zachara et al. 2007). That suggests that the reactions of aqueous uranium species with iron oxides, iron sulfides, or carbonate secondary minerals in fractures in the weathered and unweathered units at the Weldon Spring Site is a potential NA mechanism. Iron oxide staining in fractures and clay-filled voids in the weathered unit and fresh pyrite within fractures in the unweathered unit have been observed (Schumacher 1993). If uranium adsorption or precipitation is occurring within the unweathered unit, and if those NA mechanisms can be characterized and quantified (relative rates of attenuation and mobility), then it would greatly strengthen the technical basis for the current MNA remedy. When present, iron sulfides (i.e., pyrite, mackinawite) could reduce U(VI) aqueous phases to U(IV) and can coprecipitate as mixed Fe and U oxides (Zachara et al. 2007).

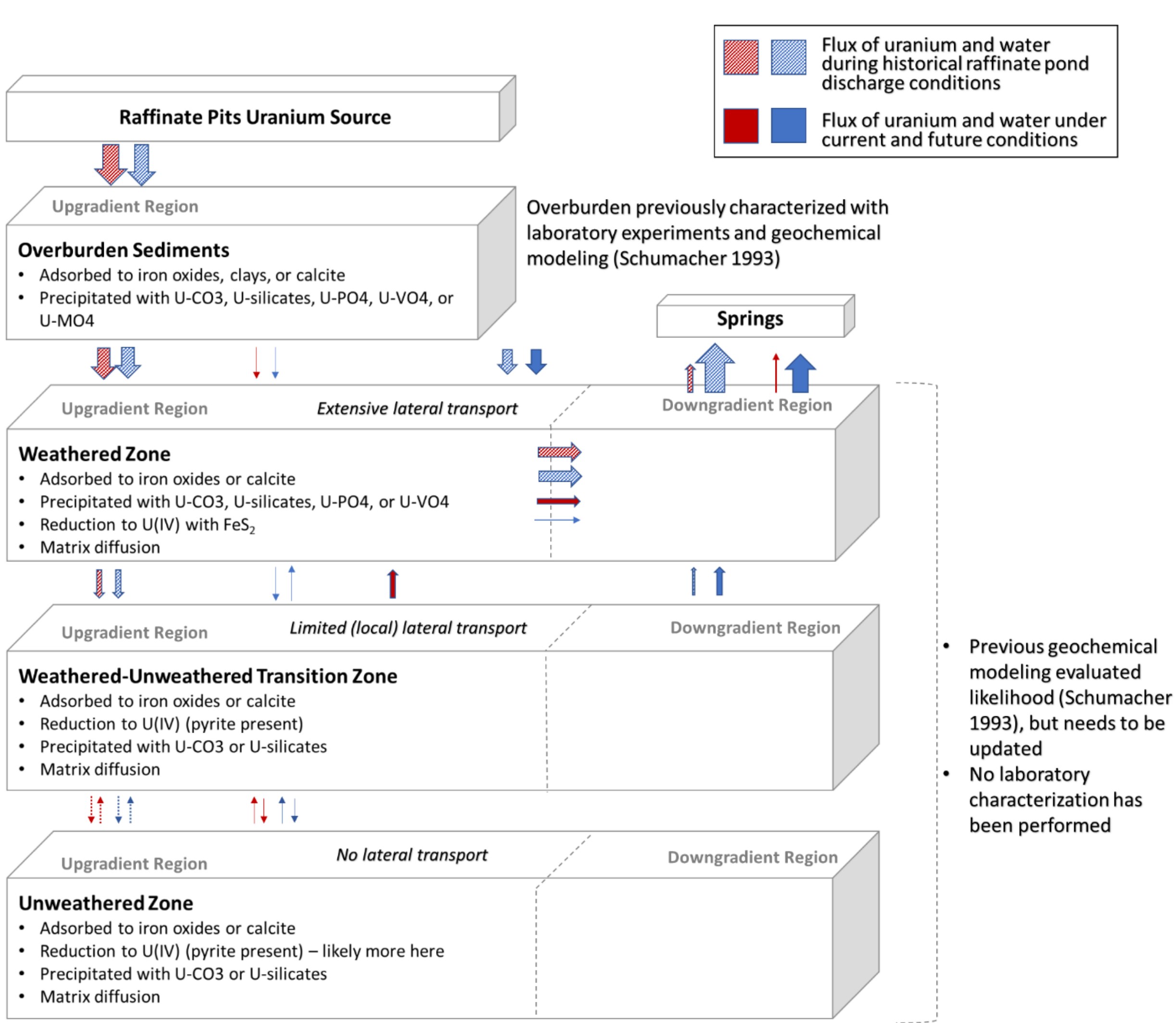

Figure 1. Conceptual diagram showing potential geochemical mechanisms for attenuating the flux of uranium within different zones of the groundwater contaminant migration pathway at the Weldon Spring Site.

Methods and Technologies for Evaluation of Natural Attenuation Mechanisms: There are multiple characterization methods or technologies that can further evaluate[1] the likelihood or confirm the presence of the nondispersive NA mechanisms (conceptualized in Figure 1) for uranium within the overburden, weathered, transition, and unweathered zones. Table 1 summarizes these methods and their associated relation to EPA MNA assessment tiers, objectives, site-specific considerations, and a relative indication of the implementability, cost, and impact toward demonstrating NA of uranium. Methods are listed in order of recommended phases of implementation, and results from each phase of characterization would inform the

[1] Previous evaluations of natural attenuation mechanisms are summarized in Schumacher 1993 and the Supplemental Feasibility Study (DOE 1999). The geochemical characterization methods listed here in Table 1 extend previous work.

decision to proceed to the next phase and determine the number and selection of samples to be analyzed (similar to the approach demonstrated in Szecsody et al. 2020). Each phase of the characterization has the potential to provide increasingly impactful information needed for EPA Tier II (rate and mechanism of uranium attenuation) and Tier III (long-term capacity for attenuation and stability) assessments. For example, if batch leach tests indicate there are measurable quantities of uranium mass adsorbed to or precipitated with secondary minerals in fractures, characterization might proceed to the next phase involving sequential extraction and/or solid-phase characterization on the samples having the highest uranium concentrations. Alternatively, if no solid-phase or adsorbed uranium can be extracted from secondary mineral materials, then characterization would end, or alternative methods would be identified.

Development Status

Geochemical modeling, batch leach, and sequential extractions are mature geochemical characterization methods with established use for evaluating the potential and presence of natural attenuation of uranium through adsorption and precipitation (Szecsody et al. 2020). However, for geochemical modeling of uranium, there was a significant update of equilibrium constants in 2020 (NEA 2020) compared to the previous set of equilibrium constants (Guillaumont et al. 2003). Solid-phase characterization methods are less mature, and capabilities and detection limits are continuing to improve. It is expected that fewer institutions or facilities have the capabilities and instrument run-time availability, and it can take time to acquire access to beamlines at the Advanced Photon Source at Argonne National Laboratories or the Stanford Linear Accelerator for performing state-of-science methods such as micro X-ray diffraction analysis (also called µ-XRD), micro X-ray fluorescence (µ-XRF), X-ray absorption near edge structure (XANES), or extended x-ray absorption structure (EXAFS).

Weldon Spring Site-Specific Advantages/Disadvantages

Advantages include:

- Geochemical modeling is relatively inexpensive to perform and has been performed previously[2] to evaluate natural attenuation viability (Schumacher 1993).
- Performing laboratory experiments is an established approach for directly evaluating the viability of geochemical mechanisms for attenuating uranium flux.
- Could utilize existing archived cores.
- Phased characterization approach involves less-expensive and more-implementable methods in the beginning and progresses to more increasingly expensive and challenging methods based on results from each phase. Risk of investment is minimized with this approach.
- Results provide information that could be used as inputs to future reactive transport modeling.
- Analyses can utilize existing core sample material.

[2] Equilibrium constants used in geochemical modeling have been updated and revised since previous modeling evaluations were performed in the 1990's (Schumacher 1993) and additional groundwater chemistry information is now available.

Disadvantages include:

- Obtaining sufficient[3] secondary mineral material from fractures may be difficult, time-consuming, and require multiple core samples.
- Additional borehole sampling may be needed to obtain sufficient material from fractures for experiments.
- Solid-phase characterization is relatively expensive.
- Results may be inconclusive if adsorbed or solid-phase uranium concentrations are below detection limits.

Technology Inter-Relationships

The methods identified in this narrative dovetail with those in the mass-flux/mass-balance narrative. Hydraulic testing implemented in the mass-flux narrative (e.g., borehole dilution and push-pull tracer tests) will help indicate the hydraulic connectiveness and provide estimates of groundwater velocity at tested well locations. For locations with a combination of relatively high aqueous uranium concentrations and high groundwater velocities, the attenuation mechanisms and mobility at these locations and in the downgradient direction become important. On the other hand, for locations that are not hydraulically connected or that have low groundwater velocities, the natural attenuation mechanism might be less important, even if concentrations of uranium in groundwater are high. Investing in the geochemical characterization at these low-uranium flux locations might not be warranted.

Data Gaps: Geochemical modeling requires groundwater chemistry from each of the major zones and portions of the contaminant migration pathway (Figure 1). The current groundwater monitoring plan might need to be expanded temporarily to include additional analytes needed for modeling (e.g., pH, oxidation-reduction potential [Eh], major ion chemistry, trace metals).

Next Steps: Table 1 lists the phased geochemical characterization approach and the associated implementation considerations. The laboratory characterization requires using existing and additional core samples. Collection of new cores will need to be integrated into the overall project schedule. Core intervals should include the overburden, weathered, and unweathered units since each of these units need to be evaluated.

Implementation Details

Fiscal year (FY) 2023 (early) to FY 2023 (mid)

1. Inventory available core samples stored in conex containers on the site.
    - (a) Identify core sample depth intervals and interpreted hydrogeologic unit (from borehole logs).
    - (b) Visually inspect the cores to identify the amount of secondary minerals, precipitates, or coatings apparent in fractures.

[3] Laboratory experiments will likely require up to about 10 grams of material per sample.

2. If the archived cores have insufficient fracture material for laboratory experiments, or if the new wells being drilled are near or immediately downgradient from the raffinate pit source area, then develop a plan for collecting additional borehole core samples during drilling of applicable boreholes.
    (a) Cores near the Raffinate Pit 4 area would be relatively more valuable since aqueous, adsorbed, and solid-phase uranium concentrations are expected to be higher near the source area.
3. Perform limited scoping evaluations on solid-phase material in fractures material (if present in the existing cores) using scanning electron microscopy (SEM), spot elemental analysis, or x-ray fluorescence (XRF). These can be performed at a relatively low cost, and the results will help inform the decision to proceed with more detailed (and expensive) solid-phase characterization methods in subsequent phases of the characterization effort (described below).
4. Assemble available groundwater chemistry data for weathered and unweathered zone wells on the site.
    (a) This should include pH, Eh, major ion chemistry, trace metals.
    (b) If insufficient data exist, plan for additional sampling and analyses in upcoming sample events.
5. Perform geochemical (thermodynamic) modeling for aqueous uranium species, solubility, and equilibrium for the overburden, weathered, and unweathered zones.
    (a) Identify the potential or viability of uranium precipitates to form (e.g., U-CO3, U-silicates, U-PO4, U-VO4, or U-MO4).
    (b) Compare results to previous modeling summarized in Schumacher (1993).

FY 2023 (mid) to FY 2023 (late)

1. During drilling of additional boreholes, collect additional core samples for potential laboratory characterization.
    (a) Log and inventory fractures and associated secondary minerals that might be present in the cores.
    (b) Subsample solid-phase material or coatings from fractures and voids in cores.

FY 2024 (early) to FY 2024 (late)

1. If the combination of archived and newly collected cores contain sufficient secondary mineral mass within fractures, then proceed to the batch extraction experiments.
    (a) Extract and quantify the total mass of adsorbed and solid-phase uranium contained within fractures.

2. Perform sequential extraction experiments on samples from the same depth intervals that contain detectible and sufficient mass of extractable uranium from the batch experiments. If no uranium is detected in batch experiments, laboratory experiments stop there.

   (a) Quantify the mass of uranium (and other associated metals) that can be extracted through a sequence of liquid solutions with increasingly strong extraction.

   (b) Identify uranium mass associated with adsorbed and solid phases of varying composition (e.g., adsorbed to iron oxides, calcite or pyrite, precipitated with carbonates, silicates, phosphates).

3. Perform solid-phase characterization on samples with the highest uranium concentrations from the sequential extractions among the various uranium-associated phases.

   (a) Identify uranium precipitate composition, morphology, and oxidation state using solid-phase characterization methods that include

      - μ-XRF and scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) for two-dimensional (2D) elemental mapping
      - XANES for oxidation state of uranium minerals
      - EXAFS to identify uranium mineral species.

References

Arai, Y., M.A. Marcus, N. Tamura, J.A. Davis, and J.M. Zachara, 2007. Spectroscopic evidence for uranium bearing precipitates in vadose zone sediments at the Hanford 300-area site. *Environmental science & technology*, *41*(13), 4633-4639.

DOE (U.S. Department of Energy), 1999. *Supplemental Feasibility Study for Remedial Action for the Groundwater Operable Unit at the Chemical Plant Area of the Weldon Spring Site, Weldon Spring, Missouri*, DOE/OR/21548-783.

EPA (U.S. Environmental Protection Agency), 2010. *Monitored Natural Attenuation of Inorganic Contaminants in Ground Water, Volume III—Assessment for Radionuclides Including Americium, Cesium, Iodine, Plutonium, Radium, Radon, Strontium, Technetium, Thorium, Tritium, and Uranium*, EPA600-R-10-093, Office of Research and Development, Washington, D.C.

Guillaumont, R., and F.J. Mompean, 2003. *Update on the chemical thermodynamics of uranium, neptunium, plutonium, americium and technetium* (Vol. 5, pp. 64-70). Amsterdam: Elsevier.

NEA (Nuclear Energy Agency), 2020. Vol. 9. *Chemical Thermodynamics Second update on the chemical thermodynamics of U, Np, Pu, Am, and Tc*, OECD Nuclear Energy Agency Data Bank, Eds., North Holland Elsevier Science Publishers B. V., Amsterdam, The Netherlands,

Nolan, P., S. Bone, K. Campbell, D. Pan, O. Healy, M. Strange, J. Bargar, and K. Weber, 2021. "Uranium(VI) attenuation in a carbonate-bearing oxic alluvial aquifer," *J. Hazardous Materials,* 412, https://doi.org/10.1016/j.jhazmat.2021.125089.

Schumacher, J.G., 1993. *Geochemistry and Migration of Contaminants at the Weldon Spring Chemical Plant Site, St. Charles County, Missouri – 1989-91*. USGS Open File Report 93-433.

Smith, S.C., and J. Szecsody, 2011, "Influence of contact time on the extraction of 233-uranyl spike and contaminant uranium from Hanford Site sediment," *Radiochimica Acta*, 99, 693-704.

Szecsody, J.E., H.E. Emerson, R.D. Mackley, C.T. Resch, B.N. Gartman, C.I. Pearce, S.A. Saslow, O. Qafoku, K.A. Rod, M.K. Nims, S.R. Baum, and I.I. Leavy, 2020. *Evaluation of the Change in Uranium Mobility in Sediments from the Hanford 300-FF-5 Stage B Polyphosphate Field Injection*, PNNL-29650, Pacific Northwest National Laboratory, Richland, Washington.

Zachara, J., C. Liu, C. Brown, S. Kelly, J. Christensen, J. McKinley, J. Davis, J. Serne, E. Dresel, and W. Um, 2007. *A Site-Wide Perspective on Uranium Geochemistry at the Hanford Site*. PNNL-17031, Pacific Northwest National Laboratory, Richland, Washington.

Table 1. Methods for Evaluating Natural Attenuation Mechanisms for Uranium at Weldon Spring Site.

EPA MNA Tier[a]	Method	Objectives	Considerations for Implementation	Factors[b]
Tier II	Geochemical modeling (aqueous speciation, solubility, and equilibrium) using updated equilibrium constants for the overburden, weathered, and unweathered zones	Identify the potential or viability of uranium precipitates based on site-specific geochemical conditions	May require additional groundwater chemistry analyses (e.g., pH, Eh, major ion chemistry, trace metals). Does not provide an indication for attenuation by adsorption. This early work could also include developing an inventory of available core material and scoping evaluations (e.g., test samples using SEM and XRF) to inform the selection of subsequent solid-phase characterization (listed below).	$!!
Tier II and III	Batch extraction experiments on secondary minerals in fractures from weathered and unweathered zone core samples	Quantify total mass of uranium associated with adsorbed and solid-phases within fractures	Requires subsampling of secondary minerals within fractures. Additional samples from the weathered and unweathered units may be needed. Could be difficult to obtain sufficient mass needed for experiments. No differentiation between adsorbed and solid-phase uranium leached.	$$!!
Tier II and III	Sequential liquid extraction and leach experiments on secondary minerals in fractures from weathered and unweathered zone core samples	Quantify relative mass and mobility of uranium associated with various adsorbed and solid-phases within fractures	Requires subsampling of secondary minerals within fractures. Additional samples from the weathered and unweathered units may be needed. Could be difficult to obtain sufficient mass needed for experiments.	$$$!!!
Tier II and III	Solid phase characterization[c] on secondary minerals in fractures from weathered and unweathered zone samples	Identify uranium precipitate composition, morphology, and oxidation state	Requires subsampling of secondary minerals within fractures. Additional samples from the weathered and unweathered units may be needed. Could be difficult to obtain sufficient mass needed for experiments. Requires access to specialized instruments and facilities capable of performing these advanced methods.	$$$$!!!!

[a] Tier II – Determine rate and mechanism of uranium attenuation; Tier III – Determine long-term capacity for attenuation and stability

[b] Implementability: Easy Moderate Challenging Cost: Low $ Medium $$ High $$$ Very High $$$$ Impact: Low ! Medium !! High !!! Very High !!!!

[c] Solid phase characterization methods include: micro X-ray fluorescence (μ-XRF) and scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) for 2D elemental mapping, X-ray absorption near edge structure (XANES) for oxidation state of uranium minerals, and extended x-ray absorption structure (EXAFS) to identify uranium mineral species.

Narrative No. 6: Technology/Strategy: Matrix Diffusion as a Natural Attenuation Mechanism

Summary Information

Past and emerging scientific literature demonstrates that matrix diffusion plays a role in attenuating the expansion of groundwater plumes at many sites. For example, parametric modeling applied to a heterogeneous geologic site with a constant source and no degradation in the plume has documented that matrix diffusion alone can significantly reduce plume lengths (based on a target regulatory standard) at appropriate sites, down to 20% of the baseline length compared to no matrix diffusion (Farhat et al. preprint). In general, this modeling indicated that, over time, matrix diffusion results in lower concentrations throughout the plume and smaller plume footprints. Importantly, the impacts of matrix diffusion are functionally and mathematically equivalent to recognized natural attenuation mechanisms such as sorption. Like sorption, matrix diffusion reduces the peak dissolved concentration in groundwater in the plume but has the collateral impact of increasing total remediation time frame by extending "plume tailing." Matrix diffusion is particularly important in karst systems (such as at the Weldon Spring Site because the carbonate matrix comprises the bulk of the aquifer volume, and the fracture network where water actively flows comprises a small portion of the aquifer volume. The consensus recommendation for the Weldon Spring Site collaboration team (consisting of the U.S. Department of Energy [DOE] Office of Legacy Management [LM] and the DOE National Laboratory Network [NLN]) and regulators is to assess the potential role of matrix diffusion in attenuating key contaminants, incorporate this as a recognized mechanism in the monitored natural attenuation (MNA) remedy at this site, and account for the collateral (negative) impacts of matrix diffusion by incorporation into projections of remediation time frame if necessary.

Focus Area: Remedy Evaluation.

Description

Although destructive (or transformative) processes that decrease the quantity, toxicity, or mobility of contaminants are the most beneficial and preferred mechanisms to support MNA in controlling groundwater plumes, nondestructive processes, such as immobilization via sorption, are also recognized as viable MNA processes (EPA 2010). The potential role of matrix diffusion in MNA was recently recognized by the National Academies of Sciences, Engineering, and Medicine (2020):

> "Matrix diffusion can be considered a natural attenuation process, because it attenuates the rate at which contaminants migrate in the forward direction, and it attenuates the contaminant discharge into the mobile fluid in the reverse direction…."

The potential impact of matrix diffusion has been quantitatively documented in the scientific literature. For example, early studies by Sudicky (Sudicky et al. 1985) demonstrated the impact of matrix diffusion in a simple lab study of a high permeability sand layer sandwiched between two silt units (Figure 1). Comparison of the theoretical breakthrough curve to the attenuated breakthrough curve showed that the time to reach 35% of the source concentration increased from 9 days to 38 days (i.e., the plume was slowed by 75%). While this experiment used sand and silt, similar matrix diffusion impacts would be expected for a heterogeneous fractured karst system. Sudicky's early studies, later research, and emerging attenuation focused modeling support incorporation of matrix diffusion as an attenuation mechanism that is analogous to sorption.

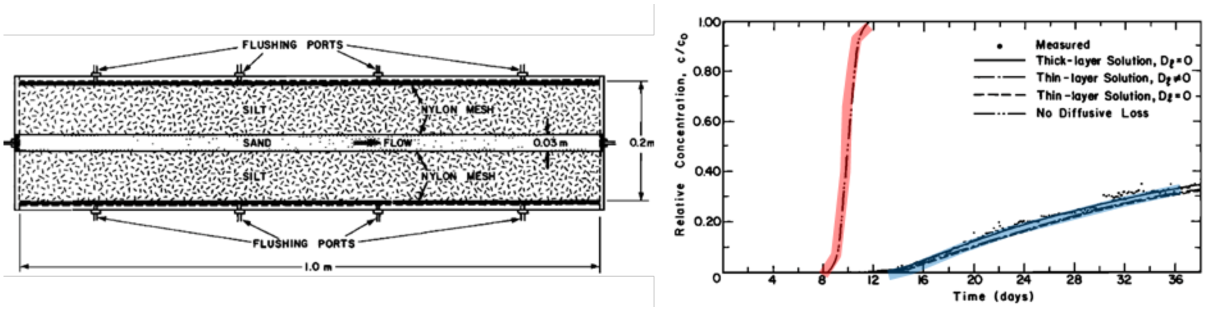

Figure 1. Attenuation impacts of matrix diffusion demonstrated in simple layered laboratory study (graphic adapted from Sudicky [Sudicky et al. 1985])

Development Status

Considering matrix diffusion as an attenuation mechanism is a straightforward concept that has significant documentation in the literature. Contaminant diffusion in and out of low permeability (low-k) zones in the subsurface is recognized as an important groundwater fate and transport process (Fetter 1999; National Research Council 2005; National Research Council 2013; Sale et al. 2013; Hadley and Newell 2014). Geologic heterogeneity and attendant matrix diffusion are two of the most prevalent hydrogeologic conditions found at hazardous waste sites (National Research Council 2005). Therefore, the presence of this heterogeneity should be considered a default assumption when working at groundwater cleanup sites (Payne et al. 2006). The literature demonstrates that matrix diffusion can provide significant attenuation of peak concentrations and plume growth, particularly for karst systems and similar settings in which most of the flow occurs in preferential flow zones or fractures. However, to date, matrix diffusion has not been recognized as an attenuation mechanism in U.S. Environmental Protection Agency (EPA) guidance documents. Additional modeling and documentation (see below) may be needed to incorporate matrix diffusion into the MNA paradigm at the Weldon Spring Site.

Weldon Spring Site-Specific Advantages/Disadvantages

Incorporating matrix diffusion as a recognized MNA mechanism at the Weldon Spring Site is justified, in general, based on the karst aquifer conditions. Advantages of this advancement would be a more complete conceptual model of attenuation processes impacting the plume, an improved understanding of historical and projected plume concentration profiles, and an improved basis for managing the MNA remedy and any contingency actions.

Technology Inter-Relationships

Matrix diffusion fits (as a subitem) within attenuation mechanisms discussion in Narrative No 7. This topic was broken out into this separate narrative because it is the only mechanism proposed during the Weldon Spring Site LM/NLN collaboration team technical brainstorming that is not currently recognized in EPA MNA guidance. That necessitated some additional documentation and recommended activities to confirm and quantify impacts. If confirmed, this concept also relates to the line of evidence (Tier 1) because it would have potential impacts on the projected plume attenuation progression over time and the remediation time frame.

Data Gaps: Inclusion of matrix diffusion as a mechanism contributing to MNA requires additional documentation in the form of models or calculations and measurements in core material. Three potential approaches are identified and described in the" Implementation Details" section below: (1) scoping models, (2) contaminant profiling in core material, and (3) sitewide models that incorporate matrix diffusion (or dual domain models).

Implementation Details

The three technologies/approaches for consideration in advancing this concept are:

1. **Scoping models:** Perform simple (e.g., one-dimensional single fracture) modeling to document the potential magnitude and contribution of matrix diffusion to attenuating contaminants in the weathered fractured karst paleochannels at the Weldon Spring Site. A base case simulation with input parameters scaled to the Weldon Spring Site along with the upper and lower bound cases to quantify the uncertainty would (1) provide information to the Weldon Spring Site collaboration team and regulators and (2) support improved technically based management of the MNA remedy in assessing performance and potential contingency actions. Note that this work should be coordinated with the recommended mass balance scoping modeling (e.g., REMChlor-MD) in Narrative No. 1: *Mass Balance and Mass Flux Conceptual Model*. Cost: **$** (minor change to baseline). Time frame: Fiscal year (FY) 2023.
2. **Contaminant profiling in core material:** Perform in conjunction with planned laboratory testing described in Narrative No. 6 These tests would be performed on existing (archived) core material or on new core material collected during upcoming drilling activities if required, and it would include depth profiling of contaminants near any fractures identified in the core. The penetration of contaminants into, and the resulting concentration profile in, the carbonate matrix, combined with site history, would provide actionable information on the extent and significance of matrix diffusion at the site. This semiquantitative information could be used in refining the site conceptual model and in improving the understanding of past and projected dynamic concentration trends throughout the plume. Cost: **$$** (perform in combination with some of the recommended lab work from MNA mechanisms narrative). Time frame: FY 2022 or FY 2023.
3. **Sitewide models that incorporate matrix diffusion (or dual domain models):** Perform more complete sitewide modeling using codes that are designed for fractured systems and that incorporate matrix diffusion explicitly or by mathematical methods such as dual domain. Note that this technology approach represents a significant effort and would be challenging to accomplish. Thus, the Weldon Spring Site collaboration team recommends that this approach be tabled. The approach could be implemented in the future if the previous activities are not sufficient to either eliminate or incorporate matrix diffusion in the listing of recognized attenuation mechanisms at the Weldon Spring Site. Cost: **$$$.** Time frame: future if needed.

The potential recommended actions are straightforward, and all can be performed by the Legacy Management Support contractor, or their consultants, within an extension to the planned baseline activities. Continued dialog with NLN scientists and engineers is available if needed. Proposed scheduling is as follows:

FY 2023 (early): Scoping models

FY 2023 (early to mid): Contaminant profiling in core material

References

EPA (U.S. Environmental Protection Agency), 2010. *Monitored Natural Attenuation of Inorganic Contaminants in Ground Water, Volume III—Assessment for Radionuclides Including Americium, Cesium, Iodine, Plutonium, Radium, Radon, Strontium, Technetium, Thorium, Tritium, and Uranium,* EPA600-R-10-093, Office of Research and Development, Washington, D.C.

Farhat, S.K., C.J. Newell, S.A. Lee, B.B. Looney and R.W. Falta, preprint. Impact of Matrix Diffusion on the Migration of Groundwater Plumes for Non-Degradable Compounds such as Perfluoroalkyl Acids (PFAAs), submitted to *Journal of Contaminant Hydrogeology*, 2021.

Fetter, C.W., T.B. Boving, and D.K. Kreamer, 1999. *Contaminant hydrogeology*. Vol. 406. Upper Saddle River, NJ: Prentice Hall.

Hadley, P.W., and C. Newell. 2014. "The New Potential for Understanding Groundwater Contaminant Transport," *Groundwater* 52(2): 174-86.

National Academies of Sciences, Engineering, and Medicine, 2020. *Characterization, Modeling, Monitoring, and Remediation of Fractured Rock,* National Academies Press, Washington, D.C. https://doi.org/1-.1722621742.

National Research Council, 2005. *Contaminants in the Subsurface: Source Zone Assessment and Remediation*, Washington, D.C.

National Research Council, 2013. *Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites,* Washington, D.C.

Payne, F. C., Suthersan, S. S., Nelson, D. K., Suarez, G., Tasker, I., & Akladiss, N. (2006). Enhanced reductive dechlorination of PCE in unconsolidated soils. *Remediation Journal: The Journal of Environmental Cleanup Costs, Technologies & Techniques*, *17*(1), 5-21.

Sale, T., B. Parker, C.J. Newell, J.F. Devlin, D.T. Adamson, S. Chapman, and K. Saller, 2013. *Management of Contaminants Stored in Low Permeability Zones, A State-of-the-Science Review,* developed for the Strategic Environmental Research and Development Program, SERDP project ER-1740, Alexandria, Virginia.

Sudicky, E.A., R.W. Gillham, and E.O. Frind, 1985. "Experimental Investigation of Solute Transport in Stratified Porous Media 1, The Nonreactive Case," *Water Resources Research* 21(7): 1035-1041.

Narrative No. 7: Technology/Strategy: Status and Performance of the MNA Remedy

Summary Information

The current remedy decision for the Weldon Spring Site Groundwater Operable Unit (GWOU) is monitored natural attenuation (MNA). This narrative focuses on the status and performance of the MNA remedy to date and on the options of continuing and/or implementing adjunct and supplementary strategies as needed in the future.

Description

Based on the diverse experiences of the technical experts on the Weldon Spring, Missouri, Site collaboration team (consisting of the U.S. Department of Energy [DOE] Office of Legacy Management [LM] and the DOE National Laboratory Network [NLN]), the consensus is that the current MNA remedy is generally performing well for the wells in the weathered portion of the karst aquifer and the most transmissive paleochannel pathway(s). For the monitoring wells in the weathered zone plume, the downgradient unweathered zone concentrations (well MW-4043) and the distal concentrations (e.g., Burgemeister Spring) are decreasing at rates that are reasonable and credible and that reach remediation goals in a reasonable time frame. In implementing the MNA remedy, key regulatory steps were taken, including removing the major sources of contamination "to the extent practicable." Specifically, the raffinate pits were remediated, contaminated sediments were removed, and contaminated soils were excavated until agreed-upon concentration levels were measured. These actions removed contaminant mass and reduced infiltration with the combined impact of significantly reducing and controlling the current and future source mass flux. While the overall assessment of the MNA remedy was generally positive and affirmed by the technical collaboration, key data and evolving regulatory policies from the past 20 years pinpointed a few key technical challenges for DOE to address. These challenges were summarized by the U.S. Environmental Protection Agency (EPA) in a recent communication (EPA 2021). Key observations from that EPA communication are in Table 1, along with the related recommendations from the Weldon Spring Site LM/NLN collaboration team:

Table 1. Key Observations from EPA Communications and Related Recommendations

EPA ORD Comment/Objective	***LM/NLN Collaboration Consensus Recommendations (Synopsis)***
For inorganic contaminants, evaluation of contaminant specific attenuation considering the most recent (2015) guidance documents related to metals, radionuclides, and inorganic anions – directly focusing on organized data collection and evaluation using the tiered lines of evidence	The recommended technologies and strategies were developed based on the EPA (2015) guidance, supplemented by ITRC guidance and recent literature. The various technology narratives are generally aligned with the EPA recommended tiered lines of evidence. (Narratives 1, 2, 5, and 6)
Explicitly account for the full range of uranium sources, the potential for uranium mobilization, and the various mechanisms of uranium attenuation (mass balance) (Tiers 1, 2, 3, and 4 and site management)	Recommend developing a mass balance site conceptual model for the Weldon Spring Site that accounts for source mass flux/discharge, attenuation mechanisms, and contaminant inventories throughout the subsurface. Consider use of a reduced order model (e.g., REMChlor-MD) to formalize the mass balance. Considering that most areas have little uranium impact, emphasis should be placed on zones where remnant uranium has been identified and is not currently attenuating, primarily the zone in the upper part of the unweathered bedrock where the weathered bedrock transitions to unweathered bedrock. Evaluate wells (e.g., MW-4040) currently assigned to the upper portion of the unweathered zone to determine “connectedness” to the active flowing plume using borehole dilutions tests (or similar field tests) in existing wells. Use FLUTE transmissivity testing in new boreholes. (Narrative 1)
Documentation of site-specific attenuation mechanisms that reduce the quantity, toxicity, and/or mobility of contaminants. For the identified attenuation process, provide data related to attenuation rates and capacity/sustainability. (Tiers 2 and 3)	Recommend supplementary geochemical modeling combined with opportunistic testing of existing core material focusing in and around fractures. Recommend visual examination of stored core materials to start this process. A subset of activities, selected from a range of range of laboratory tests (chemical analysis, batch leaching, sequential leaching, and imaging), are recommended, and the final mix of specific activities should be based on evolving data (generally applying less costly methods first and moving toward more costly methods as appropriate). Consider emerging attenuation mechanisms such as matrix diffusion (i.e., scoping models and supplemental contaminant profiling in core material). (Narrative 5 and 6)
Review and examine whether the current monitoring well network is adequate to meet MNA objectives and if the MNA remedy is functioning as expected – provide more information on the lateral and vertical extent of the plume (Tier 1 and site management)	Recommend targeted geophysical survey lines and/or an RPM study to better define (1) the lateral and vertical fracture network and (2) the boundaries and structure of the more highly fractured “paleochannel” (as a surrogate/supplement for enhanced lateral plume delineation). Additional evaluation of technology alternatives is recommended due to potential weaknesses and strength of the alternative methods. An implementation plan to down-select the methods to be used is recommended, including consultation with potential vendors and follow-up on technical challenges for application in karst. Plan future well locations to increase confidence in the extent of uranium in the unweathered zone, both horizontally and vertically, and to collect samples that can be used to assess attenuation mechanisms other than dilution and dispersion. Depending on connectivity and geophysical testing results, consider a potential new well near the former Raffinate Pits area (e.g., near/downgradient of MW-4040) screened over the middle portion of the unweathered zone to help refine the vertical extent of uranium. (Narratives 3 and 4)

Provide an assessment of the robustness of the MNA remedy and examine contingencies as needed (Tier 1 and site management)	Apply traditional tools for evaluating existing monitoring data but deemphasize bulk plume metrics such as center of mass and other method of moments calculations due to the high heterogeneity and "patchiness" associated with karst aquifers. Focus on trends of analytes in individual wells (e.g., Mann-Kendall method) and apply over sufficient time horizons to minimize short-term trends (e.g., El Niño and La Niña) and pay attention to the seasonality and variability typical of karst aquifer systems. Evaluate options to continue or adjust the MNA remedy, including options for technical impracticability or enhanced attenuation to address disconnected contaminants present in the transition interval near the raffinate pits. (Narratives 4 and 7)

Abbreviations: ITRC = Interstate Technology and Regulatory Council; ORD = Office of Research and Development; RPM = residual potential method

Development Status

The Weldon Spring Site LM/NLN collaboration team affirms and generally supports the MNA remedy decision. The performance of the remedy in the weathered zone is within the performance envelope of accepted MNA remedies throughout the nation. In general, the projections of concentration throughout weathered zone and in or near the distal discharge are on track to achieve regulatory objectives in reasonable (i.e., decades-long) time frames. Thus, the collaboration team believes that the Weldon Spring Site GWOU selected remedy of MNA is an appropriate, durable, and reasonable central component for current and future site environmental and legacy management. Notably, as is customary for MNA remedies, the original source mass flux was mitigated to the extent practicable (by removing the raffinate pits and underlying contaminated soil and reducing infiltration to natural levels); however, wells installed in the transition interval at two locations adjacent to the former raffinate pits currently have elevated uranium concentrations with no statistical trend. These wells might be isolated in an area of limited flow that limits dilution and dispersion. Based on this scenario, the collaboration team has outlined three potential strategies portfolios for consideration to improve the Weldon Spring Site GWOU remedy:

1. **Continued MNA:** This strategy is based on the observation that some residual source material exists at every site with an MNA remedy. In this case, the supporting data would include measurements and estimates of "acceptable" source mass flux from above (contamination in the remaining unexcavated soils under the former raffinate ponds) and from below (trapped and isolated high-concentration zones in the transition interval). In this case, the high aqueous concentrations in the transition zone would be treated like a typical solid phase mineral or sorbed phase material. The impact of this contamination on the weathered zone plume would be mathematically equivalent to these traditionally recognized attenuation mechanisms. This is a nontraditional strategy for addressing residual source mass flux, so clear and compelling documentation would be needed. This approach would also include additional documentation for the remedy to include key lines of evidence (tiers) from the 2010 and 2015 EPA guidance for inorganic contaminants (EPA 2010; EPA 2015). If justified based on the data, matrix diffusion could also be incorporated as a key attenuation process that might be particularly important in karst systems.

2. **MNA with addition of technical impracticability or alternate concentration limits for the isolated transition interval contamination:** This strategy is similar to MNA alone but it recognizes that the transition zone water and contamination are functionally isolated (if that is what the data show during the recommended field tests). This strategy portfolio has the additional step of recognizing this isolated contamination is an identifiable compartment that can be carved out and addressed in an integrated manner under a sibling regulatory paradigm.

3. **MNA with addition of enhanced attenuation for the isolated transition interval contamination:** This strategy is similar to MNA alone but it is focused on providing more robust isolation of the transition zone contamination. The recommended technologies for the enhanced attenuation would include in situ conversion of contaminants in the higher concentration, poorly attenuating zones into solids by one or more of the following options:

   a. Liquid amendment injection to promote in situ precipitation of minerals such as fluorapatite (i.e., targeted injection of phosphate and stannous fluoride) or apatite (i.e., targeted injection of phosphate). These strategies would generally provide for enhanced sorption and coprecipitation/precipitation of uranium mineral phases.

   b. Injecting solid sorbents (e.g., powdered bone char, solid apatite minerals) injected into the fractures.

   c. Enhanced isolation of the transition zone source material using amendments (silica gel "water glass," hydraulic cements, silicone, wax, etc.) to more definitively seal the connecting fractures. Amendment deployment could be done using angle drilling for access to vertical fractures and by use of dense amendments to encourage treatment of the base of the fracture network (see Figure 1 for example schematic configuration).

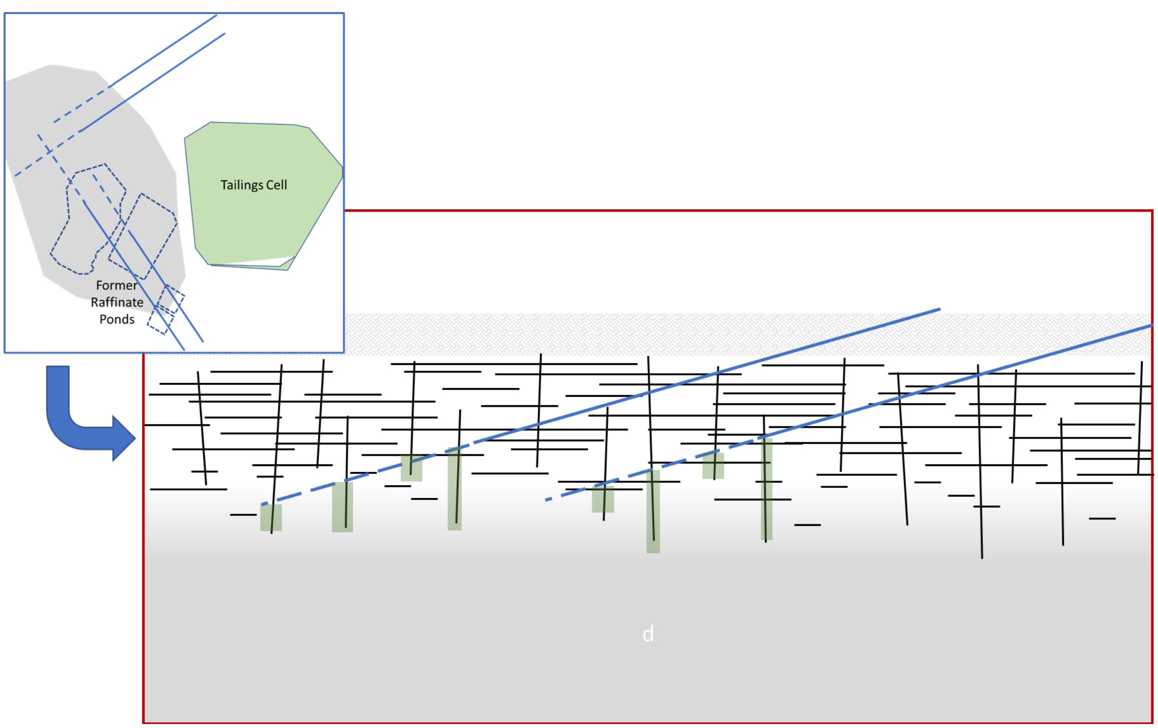

Figure 1. Conceptual diagram of potential configuration of a targeted amendment application for enhanced attenuation of groundwater that is isolated in the transition interval between the unweathered and weathered karst aquifer zones at Weldon Spring.

Implementation Details

Fiscal year (FY) 2022: Statistical techniques, inventory of core samples, begin mass balance focused modeling.

FY 2023: Continued mass balance-focused modeling, scoping for geochemical models, and scoping models for MNA and potential contingency actions.

FY 2023 to FY 2024: If justified based on data, perform laboratory testing of potential enhanced attenuation amendments and perform geophysical surveys for delineation of plume. Structural controls can be done coincident with geochemical studies (leaching tests and spectroscopic methods on archived or new core material).

FY 2024 to FY 2025: Develop responsive-technical-data-driven path forward that addresses regulatory comments on the status, performance, durability and sustainability of the MNA remedy, timed to support the next Comprehensive Environmental Response, Compensation, and Liability Act Five-Year Review.

References

EPA (U.S. Environmental Protection Agency), 2010. *Monitored Natural Attenuation of Inorganic Contaminants in Ground Water, Volume III—Assessment for Radionuclides Including Americium, Cesium, Iodine, Plutonium, Radium, Radon, Strontium, Technetium, Thorium, Tritium, and Uranium,* EPA600-R-10-093, Office of Research and Development, Washington, D.C.

EPA (U.S. Environmental Protection Agency), 2015. *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites*, Directive 9283.1-36, Office of Solid Waste and Emergency Response, Washington, D.C.

EPA (U.S. Environmental Protection Agency), 2021. *Technical Review of the Status of the Weldon Spring MNA Remedy,* Office of Research and Development.

Attachment B

LM/NLN Collaboration Team Documentation

Schedules
Working Group Meeting Agendas and Notes

Meeting Schedule

National Laboratory Network Collaboration
Weldon Spring Site

Meetings to be held in Microsoft Teams

The Weldon Spring Site will have a kick-off meeting and then 6 follow-up meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The meetings will be scheduled to last 1 ½ hours:

- Wednesday 15 September, 9am-4pm CDT – Kickoff Meeting (moderated)
- Wednesday 22 September, 1100am CDT – Full Team Meeting (moderated)
- Wednesday 6 October, 1100am CDT – Focus Area Technical Meeting (NOT moderated)
- Wednesday 13 October, 1100am CDT – Focus Area Technical Meeting (NOT moderated)
- Wednesday 3 November, 1100am CDT – Full Team Meeting (moderated)
- Wednesday 10 November, 1100am CST – Focus Area Technical Meeting (NOT moderated)
- Wednesday 17 November, 1100am CST – Wrap Up Meeting (moderated)

Meeting Agenda

National Laboratory Network Collaboration Kick-Off
Weldon Spring Site
September 15, 2021

11:00 AM – 5:15 PM Central Time
All Meeting Times shown in Central Time

Planned Attendees

DOE-LM: Deborah Barr, Gwen Hooten, David Shafer, Nicole Keller, Rebecca Roberts

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, Clay Carpenter, Nick Kiusalaas, Al Laase, Jeff Linn, Brackett Mays

National Laboratory Network: Carol Eddy-Dilek, Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan

MDNR: Taylor Grabner, Brandon Doster, Terry Hawkins

U.S. EPA: Danny O'Connor, Randy Brown

ORD: Dr. Rick Wilkin, Dr. Randall Ross

Meeting Moderator: Jennifer Nyman (Geosyntec)

Agenda

(All meeting times are approximate)

Introductions

11:00 - 11:10	**General Introductions (Jennifer Nyman)**
11:10 – 11:15	**DOE Site Manager Welcome (Rebecca Roberts)**

11:15 – 11:30 **Integrated LM/LMS/NLN Working Group and Review of Goals (Debbie Barr)**

11:30 – 11:40 **Overview of Regulatory Considerations (Rebecca Roberts)**

11:40 – 12:00 **Risk Ranking Overview (Clay Carpenter)**

12:00 – 12:30 **Synopsis of LM NLN Strategic Approach (Hari Viswanathan)**

12:30 – 1:30 **Break (Lunch)**

Weldon Spring Site, Presentations and Q&A

1:30 – 2:15 **Site History, Focus Areas and Virtual Site Tour (Terri Uhlmeyer, Rex Hodges)**

2:15 – 3:00 **Site Hydrogeology (Rex Hodges)**

3:00 – 3:15 **Break**

3:15 – 4:00 **ORD Review of Weldon Spring Site MNA Remedy (Dr. Rick Wilkin, Dr. Randall Ross)**

4:00 – 4:45 **"First Impressions" Discussion (Hari Viswanathan)**

Wrap-up

4:45 – 5:15 **Recap, Schedule Review, and Action Items (Jennifer Nyman)**

Meeting to be held Microsoft Teams

The Weldon Spring Site will have 6 follow-up meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The meetings will be schedule to last 1 ½ hours:

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Memorandum

Date: September 15, 2021

To: Navarro Research and Engineering, Inc.

From: Jennifer Nyman, Principal

Subject: Meeting Notes, September 15, 2021
National Laboratory Network Collaboration
Kick-Off Meeting
Weldon Spring Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the September 15, 2021, kick-off meeting with the United States Department of Energy, Office of Legacy Management (LM), RSI EnTech, LLC (RSI), the United States Environmental Protection Agency (U.S. EPA), and the Missouri Department of Natural Resources (MDNR) on the Weldon Spring Site as part of the integrated working group with the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS). The working group's charge is to develop recommendations to reduce the risk at the site within the context of the two defined focus areas.

The notes are summarized below by topic, followed by action items. The meeting agenda is attached. Technical details and background information about the site were presented on slides, final copies of which were posted to an electronic file transfer (EFT) site, and are not summarized herein.

The working group will continue assessment and development of recommendations over a series of follow-up meetings, culminating in a report of recommendations for risk reduction at the site.

INVITED ATTENDEES

Names shown in **bold** were identified as attending the meeting.

DOE-LM: Deborah Barr, Gwen Hooten, David Shafer, **Nicole Keller, Rebecca Roberts**

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, Clay Carpenter, Nick Kiusalaas, Al Laase, Jeff Linn, **Brackett Mays, Becky Cato**

NNLEMS: Carol Eddy-Dilek, Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan

MDNR: Taylor Grabner, Brandon Doster, Terry Hawkins

U.S. EPA: Danny O'Connor, Randy Brown

ORD: Dr. Rick Wilkin, Dr. Randall Ross

Meeting Moderator: Jennifer Nyman (Geosyntec)

INTRODUCTIONS AND DOE SITE MANAGER WELCOME

- Jennifer Nyman (Geosyntec) reviewed the meeting agenda and led a roll call of attendees. She indicated the intention for an internal working meeting involving brainstorming and culminating in recommendations. Decisions regarding proposed actions would be made after the working group process, followed by regulatory submittals and approvals as needed.
- Rebecca Roberts (LM), the Weldon Spring Site Manager, welcomed the group and reviewed the site-specific focus areas. She described the overall objective as defining an efficient and successful course of action.

INTEGRATED LM/LMS/NNLEMS WORKING GROUP AND REVIEW OF GOALS

- Debbie Barr (LM) provided background for and goals of the working group.
- Debbie stressed reaching a consensus among working group members and focusing on actionable recommendations to reduce LM's risk, with near-term results (in the next five years).
- Debbie emphasized three questions on which to focus:
    1. What are we doing that we should keep doing?
    2. What are we doing that we should stop doing?
    3. What are we not doing that we should be doing?
- Validation or critique of ongoing and currently planned activities is an important point of emphasis for this collaboration effort. The effort can also recommend supplemental activities that would reduce risk.

- Debbie indicated that recommendations are not commitments on LM's part; commitments will be made after assessing the recommendations against the program's needs. Recommendations adopted by LM would be subject to regulatory review and approval as required.

OVERVIEW OF REGULATORY CONSIDERATIONS

- Rebecca presented the overall regulatory setting for the site. It is regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); regulatory agencies are U.S. EPA Region 7 and MDNR.
- The operable unit (OU) of focus for this working group is the groundwater OU, for which monitored natural attenuation (MNA) was selected as a remedy in the Record of Decision (ROD) in 2004.
- Two issues were highlighted in the site's recent Five-Year Review, which are the focus areas for this working group: 1) benefit of additional characterization; and 2) alternative strategies to MNA.
- Danny O'Connor (U.S. EPA) summarized two issues from U.S. EPA's perspective. First, U.S. EPA does not view the current monitoring well network to be sufficient to meet the ROD objectives for MNA. The ROD assumed no contamination in the unweathered bedrock, but contamination was subsequently detected, yielding a data gap to be filled with respect to improved delineation of the vertical extent. Second, the groundwater remedy is not projected to meet the remedial action objective (RAO) of returning groundwater to beneficial use. Uranium concentrations in the source areas have remained unchanged.

RISK RANKING OVERVIEW

- Clay Carpenter (Navarro) described LM's risk screening evaluation process, for which priority setting considers four main risk categories: human health, stakeholder, regulatory, and institutional control (IC). Weldon Spring had the eighth-highest composite risk index in 2021.

SYNOPSIS OF NNLEMS STRATEGIC APPROACH

- Hari Viswanathan (NNLEMS) described the approach of the NNLEMS: using a focused process of refining/validating site conceptual models and matching technologies to site-specific needs. Conceptual models include frameworks of spatial, geochemical, temporal, and hydrological topics. Hari recognized Weldon Spring as a premier example of beneficial reuse.

- Brian Looney (NNLEMS) described promoting a common understanding by conceptualizing the MNA remedy and by following guidance, including the 1999 U.S. EPA Office of Solid Waste and Emergency Response (OSWER) Directive *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites* and the 2015 OSWER Directive *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites*. Brian reviewed the three lines of evidence in the former Directive and acknowledged that the U.S. EPA Office of Research and Development (ORD) followed the tiers of the latter Directive in their review memorandum.
- Hari summarized ideas from initial NNLEMS brainstorming on the two focus areas for this site. He also described the overall approach for the process, which will culminate in technology narratives on selected topics. An initial list of topics and preliminary assignments was presented:
    1. Focus Area 1
        - Evaluation of proposed 5 wells and alternative geophysical techniques for plume delineation (Judy/Rob)
        - Characterization of karst (Phil)
        - Well optimization (Hari)
        - Spatial survey of outcrop zone (Brian)
    2. Focus Area 2
        - Emergent plume behavior (Brian/Rob)
        - Natural attenuation mechanisms (Rob/Hari)
        - Mixed iron phase reduction for attenuation (Phil)
        - Matrix diffusion (Brian)
        - Enhanced attenuation to transition site to MNA (Brian/All)
- Brian added that the NNLEMS will prioritize recommendations based on impact and importance. LM will produce a final report. Brian anticipated significant alignment with the regulators.

SITE HISTORY AND VIRTUAL SITE TOUR

- Terri Uhlmeyer (RSI) provided an overview of the site, and Rex Hodges (RSI) provided a virtual site tour and review of historical aerial photos.
- The site was a facility for manufacturing of explosives and then a uranium feed materials plant. It was added to the National Priorities List in two parts in 1987 and 1989. Contaminants of concern (COCs) include uranium, trichloroethene (TCE), nitrate, and nitroaromatics. The focus of this effort is the migration of uranium, though Danny noted that the TCE plume is co-located with uranium detections.
- Rex noted that the raffinate pits (sources to groundwater) added 40 feet of hydraulic head that induced migration of uranium through or into fractures. Some uranium may be captured/immobilized in fractures.
- Terri reviewed ICs and site stewardship. Stewardship includes a visitor center and 23,000 visitors annually.
- In previous meetings, U.S. EPA mentioned remedial options other than MNA, such as technical impracticability (TI) and enhanced attenuation (EA). Brian shared his perspective that TI can be treated as a last resort and considered if all else fails. Danny indicated agreement. Rex added that other remedial options were considered and dismissed; pump and treat was not considered viable because of extended recovery times. Brian added consideration and quantification of additional attenuation mechanisms.
- Rex added the possibility that a historical change in sampling volume may have influenced concentrations. With the current micropurge approach, approximately one gallon of groundwater is removed. Rex suggested attempting removal of a larger volume, like 20 gallons, to help assess if the contamination is localized.
- Subsurface redox conditions are oxidizing at the former plant. Some other locations, at a greater distance from the former plant, are reducing, for example at the slough to the south.

SITE HYDROGEOLOGY

- Rex presented the site hydrogeology, including a groundwater divide that separates most groundwater flow to either the north or south. The shallow bedrock aquifer has weathered and unweathered sections, with fewer fractures at depth. Most monitoring well locations include paired wells screened in both sections. Increased fracturing is observed near streams. A preferential flow path exists at depth to the west along a stream. The vertical gradient is downward in the vicinity of the former raffinate pits (recharge area) transitioning upward (discharge area) to the north.

- Brian noted that water in disposal pits was often briny and dense, resulting in density-driven flow that tended to remain near the source.
- The wells where the highest uranium concentrations have been detected are located west of the cell.
- Hari and Rob Mackley (NNLEMS) asked about the possibility of estimating source mass. Rex replied it may not be realistic because of isolated flow.
- Judy Robinson (NNLEMS) asked about depths of the geologic units. The clay/till overburden has a maximum depth of around 10 to 15 feet, and the unweathered unit is encountered at approximately 55 feet below ground surface.
- Rex described results of dye tracer tests conducted in the weathered unit, which showed most flow arriving at Burgermeister Spring in as few as two to three days. Uranium concentrations in the weathered unit are decreasing. The unweathered unit does not have much flow and concentrations persist near the former raffinate pits.
- Hari asked about uranium transport off-site. Most flow transports to or past Burgermeister Spring. Rex suggested a water balance around the spring.
- Rex reviewed the six MNA objectives of the ROD and the trigger levels. Brian related these to the 1999 OSWER Directive lines of evidence. The objectives center on the first line of evidence. More information may be needed about the second and third lines of evidence.
- Rex reviewed concentration trends, which have been consistent for years. Hari confirmed that concentrations could be stable if mass is trapped in fractures, and Rex reminded the group that only a small volume is removed for sampling. At Burgermeister Spring the long-term uranium concentration trend is decreasing, though the decreasing trend is not always observed for shorter timeframes. If the long-term trend continues, the MCL may be reached in 25 years.
- Brian asked about how wells were drilled and completed. The holes were stable with drilling; the bedrock is very competent. Well screens were selected based on packer test results and are five to ten feet long.
- Phil Reppert (NNLEMS) asked whether spontaneous potential measurements were taken in the past. Measurements were taken near Burgermeister Spring but did not lead to useful conclusions.

ORD REVIEW OF WELDON SPRING SITE MNA REMEDY

- Rick Wilkin and Randall Ross (U.S. EPA ORD) introduced themselves and summarized ORD's recommendations for the site, which include:
    1. Apply technical frameworks for MNA of inorganics to the site. Options include EPA's and the Interstate Technology and Regulatory Council's (ITRC's) directives and guidance. EPA's guidance is not prescriptive but does outline topics to be considered.
    2. Consider a more complete range of uranium sources and the potential for mobilization from the sources, as well as attenuation mechanisms other than dilution and dispersion, such as sorption or precipitation/coprecipitation. Dilution and dispersion are polishing steps that are more appropriate to distal parts of the plume. Note that recent studies show complexity in uranium uptake and coprecipitation in carbonate systems. Once other attenuation mechanisms are identified, conditions that could reverse or limit the mechanism should be defined (i.e., stability must be demonstrated).
    3. Improve vertical and horizontal characterization. If dilution and dispersion are considered the site attenuation mechanisms, then monitoring should not be minimized. The monitoring well network should be increased. Vertical gaps exist at depth downgradient of the former raffinate pits, for example between MW-4036 and MW-4043, and between MWS-2 and MWD-2. The lateral distribution of wells is also sparse in some areas.
    4. Consider geophysical techniques for identifying preferential flow. Randall has used electrical resistivity imaging (ERI) to understand flow paths and visualize fractures and preferential pathways in a similar formation at another site. Transient ERI monitoring techniques, for example with precipitation events, yielded insights around sinkholes.
- Hari asked for metrics for sufficiency of well distribution and density. Rick said a discussion can be held; ORD's recommendation is based on expert judgment, review of other sites, and consideration of the complexity of the geology at this site.
- Hari asked if there was a concern that even five additional monitoring wells might miss pathways, given the karst setting. Randall agreed and noted that new wells can be sited with ERI, to target where flow is occurring. ERI should be applied both parallel and perpendicular to groundwater gradients.

- Rex asked about applying ERI aerially. Randall replied that resolution would be lost. Rex noted that higher water level and temperature variations have been observed in wells screened in the channel near the stream. Transducers are in place to monitor the wells, and data are presented in site reports.
- The question of historical borehole geophysics was raised. Becky Cato (RSI) said no large-scale event was conducted during well installation.
- Hari asked if ORD had any ideas of potential attenuation mechanisms. Rick suggested precipitation or coprecipitation of a mixed uranyl-carbonate phase. Rick outlined two potential approaches: 1) careful speciation with an up-to-date thermodynamic database and calculation of saturation indices, and 2) collection of core materials in targeted zones followed by characterization analysis, like with extraction tests, synchrotron-based techniques, x-ray diffraction (XRD), scanning electron microscopy (SEM), etc. Rick can send relevant literature.
- Brian summarized the 2015 OSWER Directive as expanding upon the 1999 OSWER Directive but using tiers. Tier 1 aligns with line of evidence 1, which current work is starting to address. In general, the NNLEMS team is well-aligned with the ideas ORD has discussed. Data indicate some stable concentration trends in near-field wells and some evidence for declining concentration trends in far-field wells; additional work is needed.
- Rick noted the potential benefit to remedial timeframe from further stabilizing the raffinate area (e.g., removing or controlling sources). Hari asked if all source control must be active. All ideas are on the table.

FIRST IMPRESSIONS DISCUSSION

- Hari led a discussion of the first impressions of the NNLEMS. Hari noted that most of the initial ideas for narratives (outlined above) still apply.
- Brian recognized the good work completed at the site. He raised the idea of considering the presence of iron minerals and considering matrix diffusion as an attenuation mechanism. He presented a thought experiment of matrix diffusion followed by application of an armoring agent, for example phosphate with stannous fluoride.
- Brian suggested revisiting the 2015 OSWER Directive and the 2007 and 2010 EPA technical documents and compiling a site conceptual site model (CSM). The difference between uranium and nitrate data at Burgermeister Spring might provide some insight. Increasing understanding of the site through geophysics and identification of attenuation mechanisms may relieve the need to install so many wells.

- Hari asked if phosphate amendment has been applied successfully for uranium; Brian noted application at Pacific Northwest National Laboratory (PNNL) and Uranium Mill Tailings Radiation Control Act (UMTRCA) sites, though this site's conditions are different. Rick said the main challenge is chemical delivery. Rex cautioned against disrupting decreasing trends. Brian said any amendment would target the source area.
- Judy noted the site is a good candidate for ERI and noted the potential value of transient geophysics, given differences in water levels in wet and dry seasons. She suggested considering the difference in weathered and unweathered units. Judy indicated that electromagnetic techniques can provide less-resolved measurements prior to ground-based semipermanent installations. Hari asked if low ion concentrations could present a challenge; Judy replied that the comparison of wet and dry seasons should help. Randall used a tracer test combined with ERI; the tracer was water with a slightly different temperature.
- Rob agreed with identifying attenuation mechanisms and suggested samples could be collected as new wells are drilled and sample analyses could be combined with thermodynamic analysis. Attenuation mechanisms are difficult to prove without solid-phase analysis. Rob noted the potential for different geochemistry near the source.
- Brian noted the importance in this case of uranium penetration into the karst and suggested laser ablation to work downward from the surface of a fracture. A challenge may be locating enough uranium in the solid phase. Phil noted that one of his scientists developed downhole Laser Induced Breakdown Spectroscopy (LIBS). Brian clarified that he was suggesting a bench study. Rex said some core samples are available.
- Rob agreed the change in sampling method may have influenced concentration trends and asked about the well development approach. Becky said it involved three well volumes and well parameter stabilization. She agreed that the change to micropurge sampling did seem to change concentrations.
- Rob asked whether the proposed ideas are within the bounds of the ROD. Danny said EPA will support active work and will be flexible on decision documents. Much of the proposed work could be conducted under the purview of pilot testing. If an approach is viable, then EPA would need to consider a decision document.
- Rob agreed with the need for an additional downgradient well at an intermediate depth.
- Phil said resistivity imaging, with or without seismic, can be very useful for fractures and flow paths and suggested ground penetrating radar (GPR) surveys, if they are possible

through the clay/silt layer. Spontaneous potential is good for redox reactions and flow paths. He noted geophysical methods are not foolproof.

- Of the initial list of ideas, Brian noted that a spatial survey of outcrops may not be a high priority here. Brian can prepare material on it, but it may not be prioritized highly. Otherwise, Brian thinks the list of ideas for narratives is good.

RECAP, SCHEDULE REVIEW, AND ACTION ITEMS

- Rebecca reminded the group to keep track of how to achieve the end goals of the working group. One goal is to avoid being in the same place in the next Five-Year Review, and another is to avoid subjectivity. Debbie thought the group is going in a great direction, based on this kick-off meeting.
- The schedule for the follow-up working group meetings was reviewed. Three additional group meetings are planned, interspersed with focus group meetings. The first working group meeting, on September 22, 2021, will focus on updated ideas from the NNLEMS, and then the working group will break into focus area groups.
- Action items included:
    1. Rick will send literature on potential uranium attenuation mechanisms.
    2. Terri will upload the presentations to the EFT site.

Attachments: Meeting Agenda

* * * * *

Meeting Agenda

National Laboratory Network Collaboration Meeting 1
Weldon Spring Site
September 22, 2021

11:00 AM – 12:30 PM Central Time
All Meeting Times shown in Central Time

Planned Attendees

DOE-LM: Deborah Barr, Gwen Hooten, David Shafer, Rebecca Roberts

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, Clay Carpenter, Nick Kiusalaas, Al Laase, Jeff Linn, Becky Cato

National Laboratory Network: Carol Eddy-Dilek, Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan

MDNR: Taylor Grabner, Brandon Doster, Terry Hawkins

U.S. EPA: Danny O'Connor, Randy Brown

Meeting Moderator: Jennifer Nyman (Geosyntec)

Agenda

(All meeting times are approximate)

11:00 – 11:05 **Meeting Overview (Jennifer Nyman)**

11:05 – 11:15 **Communications (Jennifer Nyman, Terri Uhlmeyer)**

- EFT Site
- Meeting notes
- Site documents
- Teams calls

11:15 – 11:20 **Review of Goals (Terri Uhlmeyer)**

11:20 – 11:40 **3D Visualization of Site, Additional Site Questions (Rex Hodges)**

11:40 – 12:20 **LM NLN (Hari Viswanathan)**

- NLN approach and recommendations
- Discussion
- Note anything to be added

12:20 – 12:30 **Wrap-Up and Action Items (Jennifer Nyman)**

Meeting to be held Microsoft Teams

The Weldon Spring Site will have 6 follow-up meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The meetings will be schedule to last 1 ½ hours:

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Memorandum

Date: September 22, 2021

To: Navarro Research and Engineering, Inc.

From: Jennifer Nyman, Principal

Subject: Meeting Notes, September 15, 2021
National Laboratory Network Collaboration
Meeting 1
Weldon Spring Site

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The notes are summarized below by topic, followed by action items. The meeting agenda is attached. Technical details and background information about the site were presented on slides, final copies of which were posted to an electronic file transfer (EFT) site and are not summarized herein.

The working group will continue assessment and development of recommendations during additional meetings, culminating in a report of recommendations for risk reduction at the site.

INVITED ATTENDEES

Names shown in **bold** were identified as attending the meeting.

DOE-LM: Deborah Barr, Gwen Hooten, David Shafer, Rebecca Roberts

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, **Nick Kiusalaas, Al Laase, Jeff Linn, Becky Cato**

NNLEMS: Carol Eddy-Dilek, **Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan, Emily Fabricatore**

MDNR: Taylor Grabner, Brandon Doster, Terry Hawkins, Ryan Seabaugh

U.S. EPA: Danny O'Connor, **Randy Brown**

Meeting Moderator: Jennifer Nyman (Geosyntec)

COMMUNICATIONS

- Jennifer Nyman (Geosyntec) reviewed communication avenues, including the electronic file transfer (EFT) site. Brian Looney (NNLEMS) indicated file sharing has been occurring by email as well; Brian will upload those documents to the EFT site.

REVIEW OF GOALS

- Jennifer reviewed the goals of the working group. Terri Uhlmeyer (RSI) reviewed the two focus areas and indicated interest to focus on the first focus area before the second. Rebecca Roberts (LM) said focusing on the first focus area will naturally lead to the second. For the first focus area, the group should assess alternative characterization methods, examine if additional groundwater wells are needed, and, if needed, determine specific methods for placement of wells. Hari Viswanathan (NNLEMS) indicated that NNLEMS can do so.

3D VISUALIZATION OF SITE, ADDITIONAL SITE QUESTIONS

- Rex Hodges (RSI) presented an ArcScene three-dimensional (3D) visualization of site features, wells, and water quality data. He indicated a focus on the high-concentration wells near the former raffinate pits, including wells MW-4040, MW-3040, and MW-3024. When considering results from decommissioned and existing wells, the high-concentration detections are relatively isolated. Rex noted nitrate concentrations are decreasing except at 4040. Uranium concentrations are lower in the shallow weathered unit.
- Brian asked about water production from the high-concentration wells. Becky Cato (RSI) said they did not produce water well; water could not be pumped from them for an extended period of time. Brian raised the idea of a push-pull or drift test, in which water with a tracer would be injected, and, after a period of time, be extracted and tracer mass analyzed.

- Rex pointed out the well pairs for which additional well depths are under consideration: MW-4043 and MW-4036, and MWS-2 and MWD-2.
- Brian asked about hydrodynamics around Burgermeister Spring. Becky replied that losing and gaining areas of surface water features were mapped; mostly the streams are losing. The area upstream of Burgermeister Spring is mostly dry. Becky noted that historical results may no longer apply, though, since Army contributions have ceased.
- Judy Robinson (NNLEMS) asked about the degree of confidence in the paleochannels. Becky indicated a high degree of confidence; they were inferred through a wealth of data and multiple lines of evidence. Rex noted a discussion with a vendor for aerial electromagnetic surveys; they indicated potential interference from remaining building materials and footprints. Brian questioned whether the precise location of the paleochannels is relevant, since the high-concentration wells are located in transition zones. Rex agreed. Becky pointed to vertical fracturing components associated with some wells; the challenge is assessing how deep and how connected the fracture zones are.
- Becky pointed the group to a key report on the hydrogeology of the site by Doug Mugel (USGS, 1997).
- Judy asked about the well casing material; it is important to know for a ground-based survey. Rex will provide that.
- Hari asked if the 3D visualization was provided to the regulators. It was in 2016. Hari asked whether the proposed five wells could be indicated; Rex shared a slide showing two wells for vertical delineation near high-concentration wells and three wells further from the source area for horizontal delineation.
- Rob Mackley (NNLEMS) asked about the source of the detections in MW-4040 and the upgradient hydraulic connection. Rob raised the possibility that it is not in an active groundwater flow path. Brian agreed that the connection should be better understood and reiterated the potential benefit of a push-pull or drift test.
- Phil Reppert (NNLEMS) asked about scale. The distance between MW-4040 and the next well is approximately 1,100 feet.

NNLEMS RECOMMENDATIONS

- Hari reiterated that moving forward, the NNLEMS will first evaluate the Focus Area 1. He presented the tiered approach from EPA, which will be one basis from which to evaluate the focus areas. Potential narrative topics were reviewed. They were the same as presented during the kick-off meeting, except for the deletion of the spatial survey of outcrop zone.

- Elevator pitches for Focus Area 1 were presented. Judy and Phil summarized multiple alternative geophysical techniques for consideration. Phil emphasized that each site responds differently to different methods.
- Hari noted a focus on low-cost and mature technologies.
- Hari said multiple approaches exist, including statistical approaches, for describing the source and delineation.
- Brian noted a challenge of defining objectives for the characterization tools and describing how they fit into strategic decision-making. This might fit within Judy and Phil's narrative on alternative geophysical techniques or may be a separate narrative about the flow system and integration.
- The topics for Focus Area 2 were reviewed. Phil raised the question of whether immobile mass would be acceptable to regulators; regulatory needs define the boundaries of characterization needs, for example for characterizing interconnectivity.
- Rex gave his opinion that approaches to immobilize uranium may not be worthwhile at this time, given the observed decreasing concentrations. Brian responded that the objective would be to control and reduce mass discharge, but characterization is recommended to be conducted first.
- Brian said that because technical impracticability (TI) is viewed as a last resort, a narrative is not planned on TI. Randy Brown (U.S. EPA) is the U.S. EPA Region 7 TI coordinator and said TI is a last resort, when a site is out of rope with respect to remedial alternatives. He added the TI zone must be well-defined horizontally and vertically. Rebecca said that U.S. EPA had previously indicated the need for additional characterization to support TI. Debbie Barr (LM) asked if the first focus area should be divided into remedial effort and TI. Brian said the current approach (tiers) will help make that determination; the focus is first on clean-up, and then if needed the results would be used to support TI. Randy agreed; it is a terminal conclusion. Brian concluded that a short narrative on TI may be included, but TI will not be emphasized at this time.

RECAP, SCHEDULE REVIEW, AND ACTION ITEMS

- The schedule for the follow-up meetings was reviewed. The next meeting is on Focus Area 1 and will be held on October 6, 2021.

- Debbie noted that the report for this working group must adhere to its schedule; its deadline is an LM-1 milestone.
- Action items included:
    1. Brian will upload working group files to the EFT site.
    2. Rex will provide a table of well materials.

Attachments: Meeting Agenda

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Meeting Agenda

National Laboratory Network Collaboration Meeting 2
Weldon Spring Site
November 3, 2021

11:00 AM – 12:30 PM Central Time
All Meeting Times shown in Central Time

Planned Attendees

DOE-LM: Deborah Barr, Gwen Hooten, David Shafer, Rebecca Roberts

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, Nick Kiusalaas, Al Laase, Jeff Linn, Becky Cato

Network of National Laboratories for Environmental Management and Stewardship (NNLEMS): Carol Eddy-Dilek, Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan

MDNR: Taylor Grabner, Brandon Doster, Terry Hawkins, Ryan Seabaugh

U.S. EPA: Danny O'Connor, Randy Brown

Meeting Moderator: Jennifer Nyman (Geosyntec)

Agenda

(All meeting times are approximate)

11:00 – 11:05 **Meeting Overview (Jennifer Nyman)**

11:05 – 11:10 **Communications (Jennifer Nyman, Terri Uhlmeyer)**

- EFT Site
- Meeting notes

11:10 – 12:20 LM NNLEMS (Hari Viswanathan)

- Overview of narratives recommendations; check for consensus
- Check if recommendations are actionable and if they directly address risk
- Prioritization approach (within each narrative)
- Discussion
- Note anything to be added

12:20 – 12:30 Wrap-Up and Action Items (Jennifer Nyman)

Meeting to be held Microsoft Teams

The Weldon Spring Site will have 6 follow-up meetings to develop risk-reduction recommendations, which will be finalized into one report. The meetings will be scheduled to last 1 ½ hours:

- Wednesday 10 November, 1100am CST – Focus Area Technical Meeting (NOT moderated)
- Wednesday 17 November, 1100am CST – Wrap Up Meeting (moderated)

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Memorandum

Date: November 3, 2021

To: RSI Entech, LLC

From: Jennifer Nyman, Principal

Subject: Meeting Notes, November 3, 2021
National Laboratory Network Collaboration
Meeting 2
Weldon Spring Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the November 3, 2021, meeting with the United States Department of Energy, Office of Legacy Management (LM), RSI EnTech, LLC (RSI), the United States Environmental Protection Agency (U.S. EPA), and the Missouri Department of Natural Resources (MDNR) on the Weldon Spring Site as part of the integrated working group with the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS). The working group's charge is to develop recommendations to reduce the risk at the site within the context of the two defined focus areas.

The notes are summarized below by topic, followed by action items. The meeting agenda is attached. Technical details and background information about the site were presented on slides.

The working group will continue assessment and development of recommendations during additional meetings, culminating in a report of recommendations for risk reduction at the site.

INVITED ATTENDEES

Names shown in **bold** were identified as attending the meeting.

DOE-LM: Deborah Barr, Gwen Hooten, **David Shafer, Rebecca Roberts**

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, **Nick Kiusalaas, Al Laase,** Jeff Linn, **Becky Cato**

NNLEMS: Carol Eddy-Dilek, **Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan,** Emily Fabricatore

MDNR: Taylor Grabner, Brandon Doster, **Terry Hawkins, Ryan Seabaugh**

U.S. EPA: Danny O'Connor, Randy Brown, Angela Sena

Meeting Moderator: Jennifer Nyman (Geosyntec)

COMMUNICATIONS

- Danny O'Connor (U.S. EPA) announced the transition to a new U.S. EPA remedial project manager (RPM) after Thanksgiving – Angela Sena – who was on the call.
- Jennifer Nyman (Geosyntec) asked for communication concerns or issues; none were raised.

OVERVIEW OF LM NNLEMS NARRATIVES

- Hari Viswanathan (NNLEMS) provided an overview of the current status of the narratives, which have been drafted. In the final two weeks of the working group, the narratives will be finalized and prioritized based on impact to monitored natural attenuation (MNA) lines of evidence. A suggested timeline will be prepared for implementing the recommendations (over the next three to five years) with go/no-go decision points. The first narrative is critical to the follow-on tasks.
- Hari reviewed the list of narratives for each focus area. For Focus Area 1, source mass balance/flux considers why concentrations are remaining high in some wells; the mass may not be interconnected within the aquifer system. If the mass is connected, then the next two narratives – evaluation of proposed wells and geophysical techniques, and characterization of karst – are important. Emergent plume behavior considers statistical approaches. More effort has been on Focus Area 1 than on 2.
- Focus Area 2 includes natural attenuation mechanisms and capacity and matrix diffusion. Brian Looney (NNLEMS) will also be providing information on enhanced attenuation as a stretch goal.
- Hari explained how the recommended technologies link in a mass balance approach.

SOURCE MASS BALANCE/FLUX

- Brian described how natural attenuation is, at its core, a mass balance. A mass balance paradigm will be established accounting for water and mass flux boundaries, transport, and attenuation processes. It will then be related to the MNA decision and the path forward.
- Technologies have been identified to test wells screened in the transition/upper weathered zone with stable concentration trends to assess the connectivity of the mass to the broader aquifer system. They include borehole dilution tests, push-pull tests, passive fluxmeters, and mass balance modeling. Each narrative will include a table of options for LM to consider; this narrative's table will include these four technologies.
- Brian presented a simplified conceptual site model and described mass flux movement and attenuation over time.
- Danny asked about the intention with respect to connectivity assessment. What if the mass is not connected? Brian offered his perspective that it may then be considered a secondary source, and enhanced attenuation could be considered.

EVALUATION OF PROPOSED WELLS AND GEOPHYSICAL TECHNIQUES

- Judy Robinson (NNLEMS) described what geophysics can offer and that the application of geophysics at Weldon Spring would depend on the source mass flux investigations (described above). Geophysics may be most useful at this site for detection of the location and continuity of major fractures, fracture zones, and/or bedding plane features either through static or time-lapse imaging.
- Judy presented a table evaluating geophysical method applicability at Weldon Spring. In the table each method is rated, including for the potential impacts by metallic infrastructure, which is important at Weldon Spring. Judy next presented specific recommendations for the western paleochannel (which has less infrastructure), specific recommendations for within the site boundaries, and other suggestions.

CHARACTERIZATION OF KARST

- Phil Reppert (NNLEMS) presented on approaches to characterize karst, which overlaps with the geophysics narrative. Goals for karst characterization include determining the inter-connectivity of channelized flow associated with deep high-concentration wells and providing better understanding of how the karst terrain impacts groundwater flow.

- If connectivity is indicated through geotechnical or hydraulic testing, cross-hole techniques can be used to improve resolution of channelized flow, and joint inversions of geophysical techniques can be used to remove ambiguity. Phil described how to maximize the information from new wells, including PVC casing, detailed drilling logs, and potentially coring.
- Next, Phil presented approaches for understanding contaminant transport in the karst, including self-potential and streaming potential surveys, focused surface surveys, and reflection ground penetrating radar (GPR).

EMERGENT PHENOMENA

- Hari described statistical tests for consideration. Some have already been applied at the site; NNLEMS agrees with the site team that the time window affects the results.
- These assessments provide a technically defensible analysis of well concentration trends, beyond visual inspection, and they are quick and easy to implement. Stretched exponentials are new and can often better describe attenuation trends, accounting for long tailing. Brian ran some trend analyses and found high-concentration wells tended to have increasing trends in their early years and then stable or decreasing trends after. Brian noted the importance of documenting a variety of trend analyses.
- Rex Hodges (RSI) noted that Mann-Kendall trend analysis using the most recent five years of data was required by a 2004 agreement with regulators. He added that the early increasing trends may have been due to impacts from excavation and equilibration. Brian indicated that trends using five years of data (as are currently conducted for the site) may need to be augmented by trend analysis with larger data sets, considering timing of site activities.

NATURAL ATTENUATION MECHANISMS

- Rob Mackley (NNLEMS) described how recent U.S. EPA directives indicate that dilution and dispersion can be part of MNA but generally not the primary mechanisms. Rob then discussed other potential attenuation mechanisms, including sorption and precipitation.
- Rob presented a conceptual diagram of potential fluxes between zones due to possible natural attenuation mechanisms and a table of how to evaluate these possible mechanisms with a phased and conditional approach.

- Rob noted historical geochemical modeling efforts and recommended updating them with current constants, particularly to understand potential uranium precipitates. Lab experiments, including sequential extractions, could follow. Solid-phase characterization can provide definitive evidence, but it is expensive, and facilities are limited. Al Laase (RSI) noted these activities and this general sequence were followed at the Monticello Mill Tailings Site (MMTS).

MATRIX DIFFUSION

- Brian described the narrative on matrix diffusion. Matrix diffusion usually receives attention because it contributes to extended remedial timeframes and concentration tailing, but, on the front end, it may be considered a non-traditional attenuation mechanism. Technologies for consideration in this narrative include scoping models that incorporate matrix diffusion, penetration profiling around observed fractures in cores, push-pull tests, leach tests, and mass transfer tests.
- Danny said that matrix diffusion sounds like back diffusion, which would not normally be considered for MNA. Danny would need a more technical perspective to review this proposed idea.

ENHANCED ATTENUATION

- Brian described that enhanced attenuation ideas could be held for the future as a contingency if mass flux from secondary sources is found to be unacceptable. Enhancement of solid phase formation or clogging could further reduce mass flux.
- Danny indicated that secondary sources near the raffinate pits make sense and provided the reminder that the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) has specific requirements for groundwater restoration, which include cleaning up the entire plume. The entire plume needs to be considered in calculating the remedial timeframe; this idea might support technical impracticability (TI). Brian agreed.

SCHEDULE REVIEW, AND ACTION ITEMS

- The schedule for the follow-up meetings was reviewed. The next meeting is on the Focus Areas and will be held on November 10, 2021.
- Action items included:

1. Developing prioritization of the narrative recommendations.
2. Preparation of a sequencing or decision flow chart and timeline.

Attachments: Meeting Agenda

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Meeting Agenda

National Laboratory Network Collaboration Meeting 3
Weldon Spring Site
November 17, 2021

11:00 AM – 12:30 PM Central Time
All Meeting Times shown in Central Time

Planned Attendees

DOE-LM: Deborah Barr, Gwen Hooten, David Shafer, Rebecca Roberts

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, Nick Kiusalaas, Al Laase, Jeff Linn, Becky Cato

Network of National Laboratories for Environmental Management and Stewardship (NNLEMS): Carol Eddy-Dilek, Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan

MDNR: Taylor Grabner, Brandon Doster, Terry Hawkins, Ryan Seabaugh

U.S. EPA: Danny O'Connor, Randy Brown, Angela Sena

Meeting Moderator: Jennifer Nyman (Geosyntec)

Agenda

(All meeting times are approximate)

11:00 – 11:05 **Meeting Overview (Jennifer Nyman)**

11:05 – 11:10 **Path Forward (Terri Uhlmeyer)**

- Report to LM

11:10 – 11:45 **Narrative Overview and Take-Home Messages (Brian Looney)**

11:45 – 12:20 **Implementation Plans (Hari Viswanathan)**

- Prioritization approach
- Sequencing/timelines
- Discussion

12:20 – 12:30 **Wrap-Up and Action Items (Jennifer Nyman)**

Meeting to be held Microsoft Teams.

Geosyntec consultants

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Memorandum

Date: November 17, 2021

To: RSI Entech, LLC

From: Jennifer Nyman, Principal

Subject: Meeting Notes, November 17, 2021
National Laboratory Network Collaboration
Meeting 3
Weldon Spring Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the November 17, 2021, meeting with the United States Department of Energy, Office of Legacy Management (LM), RSI EnTech, LLC (RSI), the United States Environmental Protection Agency (U.S. EPA), and the Missouri Department of Natural Resources (MDNR) on the Weldon Spring Site as part of the integrated working group with the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS). The working group's charge is to develop recommendations to reduce the risk at the site within the context of the two defined focus areas.

The notes are summarized below by topic, followed by action items. The meeting agenda is attached. Technical details and background information about the site were shared online during the meeting.

The working group has completed its development of recommendations, which it has presented in draft narratives that will be used in a report of recommendations for risk reduction at the site.

INVITED ATTENDEES

Names shown in **bold** were identified as attending the meeting.

DOE-LM: Deborah Barr, **Gwen Hooten, David Shafer, Rebecca Roberts**

RSI: Terri Uhlmeyer, Rex Hodges, Randy Thompson, John Homer, **Nick Kiusalaas, Al Laase, Jeff Linn, Becky Cato**

NNLEMS: Carol Eddy-Dilek, **Brian Looney, Rob Mackley, Phil Reppert, Judy Robinson, Hari Viswanathan,** Emily Fabricatore

MDNR: Taylor Grabner, Brandon Doster, **Terry Hawkins,** Ryan Seabaugh

U.S. EPA: Danny O'Connor, Randy Brown, Angela Sena

Meeting Moderator: Jennifer Nyman (Geosyntec)

PATH FORWARD

- NNLEMS has provided the site team with draft narratives for review and comment. Terri Uhlmeyer (RSI) described the path forward. The site team will return comments by December 3; Terri will then lead the preparation of the report, with input from NNLEMS; and the report will be finalized by June 30, 2022. Options will be evaluated and selected, in cooperation with regulators, with a milestone of September 2022 for agreement on a path forward.
- Rebecca (Becca) Roberts (LM) reiterated the intention to work over the next year with regulators to discuss recommendations and the plan for implementation. LM would like to get started with a path forward on which everyone is in agreement, including addressing issues raised during the Five-Year Review. The goal is to get a plan of action in place by the end of the fiscal year (September 2022). Becca will talk further with U.S. EPA and MDNR at the upcoming site inspection.

NARRATIVE OVERVIEW AND TAKE-HOME MESSAGES

- Hari Viswanathan (NNLEMS) described that the previous meeting provided details on the individual narratives. Brian Looney (NNLEMS) indicated that Rex Hodges (RSI) was very involved in the preparation of the narratives; the narratives reflect the independent NNLEMS perspective as informed by the site team's knowledge and by historical documents. NNLEMS has now prepared an overarching narrative that rolls up all the others. Brian said it focuses on the status and performance of the monitored natural attenuation (MNA) remedy to date and options of continuing and/or implementing adjunct and supplementary strategies as needed in the future.
- Brian provided a recap of the starting point. Comments from U.S. EPA Office of Research and Development (ORD) precipitated the site review. The consensus of NNLEMS is that the MNA remedy is performing reasonably well in the weathered aquifer; trends are declining at a reasonable rate. U.S. EPA identified some items to be addressed for robustness of the remedy.

- NNLEMS presumed a decision point a few years from now, corresponding to the next Five-Year Review, preceded by a period of data collection.
- The overarching narrative presents original comments from U.S. EPA alongside synopses of NNLEMS recommendations. Brian reviewed the comments and recommendations, including important decision points. The recommendations are described in detail in the individual narratives.
- Brian described three portfolios for LM to consider: 1) continued MNA, if source mass flux is found to be acceptable; 2) MNA with technical impracticability (TI) for remaining source mass contamination, if found to be isolated; and 3) MNA with enhanced attenuation for reducing mass flux from remaining sources to an acceptable level.
- Each NNLEMS team member reviewed their respective narratives, including Brian, Rob Mackley, Judy Robinson, Phil Reppert, and Hari.
- David Shafer (LM) asked about the potential need for identifying the formation of new mineral phases. He asked if core is available for that or if it needs to be performed in situ. Brian replied that the team is recommending identification of new mineral phases, using existing or new core material. The attenuation mechanisms in the karst may be weak, but they are non-zero, so the mechanisms need to be identified. Rex raised the idea of thin sections along factures to evaluate the matrix for matrix diffusion and to assess mineralization on fracture faces. Brian noted that he used the Matrix Diffusion Tool Kit with standard parameters for karst, predicted matrix diffusion to be significant.
- Becca appreciated the presentation of options and the level of detail and thanked the group.

IMPLEMENTATION PLANS

- Hari presented a high-level review of implementation plans with approximate timelines and sequencing.
- Hari noted the importance of the first narrative—that the transition zone be tested for connectivity with borehole dilution tests on existing wells and FLUTe for new wells. This assessment will inform go/no-go decisions for some subsequent narratives, such as geophysics. Brian said that vendor information could also be useful in deciding which geophysical techniques to use.
- Hari reiterated the valuable information from statistical analyses that can be obtained at a low cost.
- NNLEMS prioritized the recommendations, understanding budget limitations.

- Brian asked Rex how frequently results are reported to regulators. Rex replied they are reported annually, in a report that is pretty involved.
- Brian asked for input from the regulators. Danny O'Connor (U.S. EPA) said the approach is on a good path, from his perspective, though he noted that Angela Sena will be taking over his role soon. The Five-Year Review had milestone dates, but Angela can communicate shifts in the dates to Headquarters, as long as DOE-LM is working through the process. Randy Brown (U.S. EPA) thought the team did a great job and is making great progress. Brian acknowledged that the ORD scientists may be busy but requested that the conclusions be relayed back to them.

WRAP UP AND ACTION ITEMS

- Terri thanked the team for their hard work and quick turnaround. Becca reiterated it was a pleasure working with the group, and the recommendations are implementable and achievable.
- Action items included:
  1. The RSI site team will provide comments on the draft narratives.
  2. Terri will lead preparation of the report.

Attachments: Meeting Agenda

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