West Lake Operable Unit 3

Bridgeton Landfill, LLC, Cotter Corporation (N.S.L.), and the United States Department of Energy (“OU-3 Respondents”)

2022 Annual Hydrogeologic and Site Characterization Report

1 March 2023

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1 March 2023

West Lake Operable Unit 3

2022 Annual Hydrogeologic and Site Characterization Report

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Acronyms and Abbreviations

Name	Definition
µg/L	Micrograms per liter
$\mu g/m^3$	Micrograms per cubic meter
AA	Ambient air
AF	Attenuation factor
APS	Advanced Profiling System
Annual Report	Annual Hydrogeologic and Site Characterization Report
Bridgeton Landfill	Bridgeton Landfill, LLC
CAP	Corrective Action Plan
Cascade	Cascade Remediation Services, LLC
CHS	Cased Hole Sampler
COLOG	COLOG, Inc.
COPC	Constituent of potential concern
CSM	Conceptual site model
EB	Equipment blank
ECLD	Earth City Levee District
ERM	ERM Consulting & Engineering, Inc.
FB	Field blank
Feezor	Feezor Engineering, Inc.
FLUTe™	Flexible Underground Technologies™
FNU	Formazin Nephelometric Units
FS	Feasibility Study
FSP	Field Sampling Plan
gpd	Gallons per day
HBLD	Howard Bend Levee District
HVAC	Heating, ventilation, and air conditioning
IA	Indoor air
LCS	Leachate collection sump
LT	Long-term
MCL	Maximum contaminant level
MDC	Minimum detectable concentration
MDL	Method detection limit
MDNR	Missouri Department of Natural Resources
NMR	Nuclear magnetic resonance
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric Turbidity Units
ORP	Oxidation-reduction potential
OU	Operable Unit
OU-3 Respondents	Bridgeton Landfill, LLC, Cotter Corporation (N.S.L.), and the United States Department of Energy
Pace	Pace Analytical Services, LLC
PAH	Polycyclic aromatic hydrocarbon
pCi/g	Picocuries per gram
pCi/L	Picocuries per liter
ppmv	Parts per million by volume
PSQ	Principal study question

Q1	First quarter
Q2	Second quarter
Q3	Third quarter
Q4	Fourth quarter
QAPP	Quality Assurance Project Plan
QA/QC	Quality assurance / quality control
QC	Quality control
RI	Remedial Investigation
RIM	Radiologically impacted material
RL	Reporting limit
RSL	Regional screening level
SGR	Spectral gamma ray
Site	West Lake Landfill Superfund Site
SOP	Standard Operating Procedure
SSV	Sub-slab vapor
ST	Short-term
Tech Memo	Technical Memorandum
THF	Tetrahydrofuran
TMP	Temperature monitoring probe
TSM	Time stratigraphic marker
TSU	Time stratigraphic unit
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VI	Vapor intrusion
VISL	Vapor intrusion screening level
VOC	Volatile organic compound
Weaver	Weaver Consultants Group
WF	Water FLUTe™
WLM	Water level meter

EXECUTIVE SUMMARY

ERM Consulting & Engineering, Inc. (ERM) prepared this *2022 Annual Hydrogeologic and Site Characterization Report* on behalf of Bridgeton Landfill, LLC (Bridgeton Landfill), Cotter Corporation (N.S.L.), and the United States Department of Energy (collectively, "OU-3 Respondents") to describe the tasks completed at the West Lake Landfill Superfund Site (Site) for the ongoing Operable Unit 3 (OU-3) Remedial Investigation (RI) during the fourth quarter of 2021 through the third quarter of 2022 (the "reporting period"). These activities were executed in accordance with the OU-3 RI / Feasibility Study (FS) Work Plan (ERM 2020), as amended.

The following activities were completed during the reporting period:

- High-resolution characterization activities, including WATERLOO Advanced Profiling System™ (APS) profiling, continuous coring of alluvium and bedrock, geophysical logging, aquifer matrix sampling, and installation and development of monitoring wells.
- Monthly water level gauging of monitoring wells, stilling wells, and piezometers, and collection of high-resolution temporal groundwater level data from transducers installed in monitoring wells and stilling wells.
- Quarterly sampling of monitoring wells for laboratory analysis of over 300 constituents.
- Compilation of third-party data including precipitation, Missouri River stage, and relevant data collected and reported by the OU-1 and OU-2 consultant teams and the Bridgeton Landfill.
- Two quarterly vapor intrusion (VI) sampling events at five on-Site buildings.
- Data management, validation, visualization, and analysis to refine the conceptual site model.

A numeric cataloging of data collection activities during the reporting period and RI to date is provided in the table below.

	Reporting Period	RI to Date
WATERLOO APS™ Borings	5	20
WATERLOO APS™ (linear feet profiled, approximate)	720	1,800
Groundwater Screening Samples (approximate)	90	250
Geophysical Logging (linear feet, approximate)	2,300	5,200
Monitoring Well Screens Installed	44	93
Monthly Gauging Events	12	30
Groundwater Samples Collected (approximate)	600	1,000
VI Sampling Events	2	4

Note: The quantities presented in the "RI to Date" column include both activities completed prior to and during the reporting period. Four quarterly VI sampling events were completed over the course of five quarters because the Asphalt Plant building was sampled on a different schedule than the rest of the buildings.

WATERLOO APS™ and geophysical logging activities generated high-resolution geologic, hydrogeologic, and groundwater quality datasets, which were used to develop the geologic model and select the vertical well screen intervals for the RI well network. All monitoring wells in the United States Environmental Protection Agency-approved RI/FS Work Plan (ERM 2020) have been installed.

Eleven select constituents of potential concern (COPCs) were evaluated to understand the horizontal and vertical distribution of these constituents in groundwater at and near the Site: radium, uranium, thorium, arsenic, benzene, 1,4-dioxane, vinyl chloride, *cis*-1,2-dichloroethene, 2-methylnaphthalene, tetrahydrofuran, and 1,2,4-trimethylbenzene. These constituents are categorized as inorganic radionuclides (i.e., they have excess energy and undergo decay), inorganic non-radionuclides (i.e., trace metals and inorganic constituents that do not have excess energy and do not undergo decay), and organic molecules (i.e., compounds containing carbon-carbon and carbon-hydrogen bonds). The organic select COPCs are typically manmade chemicals. All of the inorganic select COPCs (including radionuclides) can occur naturally and are commonly found in Midwest groundwater.

Four quarterly VI sampling events were completed for each on-Site building during the 2021 and 2022 reporting periods collectively. The resultant data indicate that VI is not currently an issue for the on-Site buildings, except methane beneath the Engineering Building. No additional VI assessment is recommended for on-Site buildings. Methane management associated with the Engineering Building will continue to be performed by Bridgeton Landfill. Data from the ongoing OU-1 and OU-2 remedial design investigations and the ongoing OU-3 RI will be used to evaluate the potential for VI into off-Site buildings.

The RI was designed to answer five principal study questions (PSQs), which are presented in the table below. Significant progress has been made toward answering these questions; however, some additional data or data interpretations are necessary to answer some of the remaining PSQs, as documented in the following table.

PSQ	Progress Made Toward Answering the PSQ	Additional Data or Activities Needed to Answer the PSQ
PSQ-1: Are COPCs present in groundwater at concentrations/ activities above screening levels?	Groundwater analytical results through third quarter 2022 are validated and compared to screening levels; some COPCs are present in groundwater at concentrations/activities above screening levels.	None; sufficient data are available to address this PSQ.
PSQ-2: What is the vertical and horizontal spatial distribution of COPCs at concentrations/activities above screening levels in groundwater?	All monitoring wells required by the RI/FS Work Plan were installed, surveyed, gauged monthly, and sampled quarterly. Analytical results for 10 select COPCs are plotted on plan-view maps by geologic interval and in cross-section to evaluate the vertical and horizontal spatial distribution of these constituents at concentrations/activities above screening levels. The vertical and horizontal spatial distribution of many COPCs has been defined; additional off-Site wells are needed to complete the delineation of COPCs above screening levels.	Sufficient data are available to address this PSQ for most COPCs. Additional data are needed to evaluate the horizontal extent of certain COPCs (e.g., 1,4-dioxane) in alluvial groundwater to the west of the Site. ■ Install, develop, and sample off-Site step-in and step-out wells and continue to compare the analytical results to screening levels. ■ If 1,4-dioxane is detected in bedrock at off-Site locations where it was detected in lower alluvium, additional data may be required to determine the lateral extent of 1,4-dioxane in bedrock.
PSQ-3: Are the COPCs Site-related?	Historical OU-1 radiologically impacted material data were reviewed and leachate analytical data and matrix (alluvium and bedrock) analytical data were generated and reviewed; some of the organic COPCs (i.e., volatile organic compounds and 1,4-dioxane) could be Site-related. Inorganic COPCs (i.e., radionuclides and arsenic) appear to be largely naturally occurring[1]. Evaluation of whether landfill	■ Conduct additional evaluation of existing groundwater analytical data to evaluate potential impacts of landfill conditions on groundwater and naturally occurring COPCs. ■ Continue sampling background wells, define background conditions, and compare on- and off-Site COPC results to background conditions.

[1] The organic COPCs are not detected in upgradient groundwater samples collected along the eastern and southern Site boundaries but are found in downgradient groundwater samples collected along the western Site boundary. A detailed discussion of radionuclide geochemistry and its effects on radionuclide mobility in groundwater is presented in Section 4.6.

PSQ	Progress Made Toward Answering the PSQ	Additional Data or Activities Needed to Answer the PSQ
	conditions could have mobilized naturally occurring COPCs is in progress.	
PSQ-4: What are the sources of Site-related COPCs in groundwater?	Radiologically impacted material, matrix, leachate, and groundwater analytical data were reviewed. Potential landfill sources of Site-related COPCs in groundwater have been evaluated. Evaluation of additional potential sources is in progress.	■ Conduct additional evaluation of existing groundwater analytical data and data that will be generated during the 2023 reporting period to evaluate potential mobilization of naturally occurring metals (e.g., radium and arsenic) due to changes in oxidation-reduction conditions. ■ Install, develop, and sample off-Site step-in and step-out wells to evaluate the potential for other contributing sources. ■ Evaluate mixtures of COPCs to identify unique signatures that can be correlated to potential sources.
PSQ-5: Where could Site-related COPCs migrate in the future?	Environmental sequence stratigraphy has been defined and significant progress has been made toward understanding the groundwater flow system, which forms the basis for understanding where COPCs may migrate in the future. High-resolution geologic and aquifer characteristic data, precipitation, and river stage data were reviewed, and a preliminary understanding of hydraulic boundary conditions was developed. The groundwater flow system is dynamic and affected by Missouri River water levels. Net groundwater flow is to the northwest, consistent with where COPCs have been detected: COPCs in alluvial groundwater are detected along the western Site boundary and to the west of the Site, and COPCs in bedrock groundwater are detected to the north of the Site.	■ Apply and confirm the geologic model in areas where step-in and step-out wells are drilled. ■ Move transducers, as documented in Technical Memorandum 26, to further evaluate the orientation and magnitude of transient hydraulic gradients. ■ Continue to evaluate transducer[2], river stage, and precipitation data to better understand the dynamic groundwater flow regime and surface water/groundwater interactions in the vicinity of the Site. ■ Continue to evaluate temporal COPC concentration/activities. ■ Continue to evaluate the hydraulic boundary conditions. ■ Continue to refine and update the conceptual site model.

[2] Per Technical Memorandum 26 (dated 19 December 2022), the distribution of pressure transducers will be expanded as some existing pressure transducers are moved to new locations and new pressure transducers are installed. A full reporting period of transducer data will also be collected for off-Site monitoring well locations that were installed during the 2022 reporting period.

1. INTRODUCTION

ERM Consulting & Engineering, Inc. (ERM) has prepared this *2022 Annual Hydrogeologic and Site Characterization Report* (Annual Report) on behalf of Bridgeton Landfill, LLC (Bridgeton Landfill), Cotter Corporation (N.S.L.), and the United States Department of Energy (collectively, “OU-3 Respondents”) to describe the tasks completed at the West Lake Landfill Superfund Site (Site) under the Remedial Investigation (RI) / Feasibility Study (FS) Work Plan for Site-wide groundwater (Operable Unit [OU-] 3; ERM 2020) for the period from fourth quarter (Q4) 2021 through third quarter (Q3) 2022 (the “reporting period”).

This report has been prepared in accordance with the OU-3 RI/FS Statement of Work attachment to the Administrative Settlement Agreement and Order on Consent and incorporates pertinent comments on the 2021 Annual Report (ERM 2022b) received from the United States Environmental Protection Agency (USEPA) via email dated 17 November 2022. This report describes the activities completed by ERM and other OU-3 contractors under the RI/FS Work Plan (ERM 2020) for the reporting period, including deviations from the Field Sampling Plan (FSP; Volume 2a of the 2020 RI/FS Work Plan) and Quality Assurance Project Plan (QAPP; Volume 2b of the 2020 RI/FS Work Plan), and preliminary updates to the conceptual site model (CSM).

Since initiation of the OU-3 investigation in Q4 2020, annual reports have been submitted on a calendar year basis; however, due to the time required for laboratory sample analysis and data validation, it was not feasible to include validated data from Q4 into annual reports by the submittal deadline of 1 March of the following year. As discussed with USEPA during a call on 23 March 2022 and documented in a letter dated 30 March 2022, USEPA requested changing the reporting period from a calendar year basis to Q4 of the previous year through Q3 of the current reporting year.

This report is organized as follows:

- Section 2: Status of Tasks Completed or In Progress—Describes field work completed and third-party data generated during the reporting period.
- Section 3: Results—Provides the reporting period data generated from the activities described in Section 2.
- Section 4: Conceptual Site Model Update—Provides an update on the CSM using data generated and evaluations completed from the start of the RI through the end of the reporting period.
- Section 5: Next Steps—Lists additional data collection and evaluation required to complete the RI.

1.1 Description of the Problem and Progress Update

As stated in the QAPP (ERM 2020), the following problem statement was developed for the OU-3 RI/FS:

> *Petroleum hydrocarbons, volatile organic compounds (VOCs), trace metals, trace anions, and various radionuclides have been detected in groundwater at the Site. The nature and extent of Site-related impacts to groundwater, indoor air, and groundwater-related impacts to surface water and sediment are unknown. An improved understanding of the nature, extent, and source(s) of groundwater contamination at the Site, and the mechanisms of contaminant migration, will be used to:*
>
> 1. *Assess the potential for Site-related contamination to migrate beyond Site boundaries into critical exposure pathways;*

2. *Determine the current and predicted future risks posed to human health and the environment; and*
3. *Develop potential groundwater remedies as necessary.*

To address the problem statement, eight principal study questions (PSQs) were developed and documented in the RI/FS Work Plan (ERM 2020). PSQ-1 through PSQ-5 relate to addressing the primary data gaps while PSQ-6 through PSQ-8 relate to risk assessment and the need for a remedy. Data inputs for PSQ-1 through PSQ-5 are defined in the QAPP (ERM 2020) and progress made through the end of the 2022 reporting period towards answering these PSQs is summarized in the table below, along with the relevant report section(s) where this information is presented. A similar table is included in Section 5 that summarizes next steps needed to answer the PSQs.

Table 1-1: PSQ Progress Summary

PSQ	Progress Made Towards Answering the PSQ	Relevant Report Section
PSQ-1: Are constituents of potential concern (COPCs) present in groundwater at concentrations/activities above screening levels?	Groundwater analytical results through Q3 2022 are validated and compared to screening levels; some COPCs are present in groundwater at concentrations/activities above screening levels.	Section 3.7 and Tables 14a through 14h
PSQ-2: What is the vertical and horizontal spatial distribution of COPCs at concentrations/activities above screening levels in groundwater?	All monitoring wells required by the RI/FS Work Plan were installed, surveyed, gauged monthly and sampled quarterly. Analytical results for 10 select COPCs are plotted on plan-view maps by geologic interval and in cross-section to evaluate the vertical and horizontal spatial distribution of these constituents at concentrations/activities above screening levels. The vertical and horizontal spatial distribution of many COPCs has been defined; additional off-Site wells are needed to complete the delineation of COPCs above screening levels.	Section 4.6, Tables 4 and 14a through 14h, Figures 9a through 16b, and Appendix K
PSQ-3: Are the COPCs Site-related?	Historical OU-1 radiologically impacted material (RIM) data were reviewed and leachate analytical data and matrix (alluvium and bedrock) analytical data were generated and reviewed; some of the organic COPCs (i.e., VOCs and 1,4-dioxane) could be Site-related. Inorganic COPCs (i.e., radionuclides and arsenic) appear to be largely naturally occurring[3]. Evaluation of whether landfill conditions could have mobilized naturally occurring COPCs is in progress.	Section 4.6, Table 12, and Figures 17 and 18
PSQ-4: What are the sources of Site-related COPCs in groundwater?	RIM, matrix, leachate, and groundwater analytical data were reviewed. Potential landfill sources of Site-related COPCs in groundwater have been evaluated and evaluation of additional potential sources is in progress.	Section 4.6.1 Table 12, and Figures 17 and 18
PSQ-5: Where could Site-related COPCs migrate in the future?	Environmental sequence stratigraphy has been defined and significant progress has been made towards understanding the groundwater flow system, which forms the basis for understanding where COPCs may migrate in the future. High-resolution geologic and aquifer characteristic data, precipitation, and river stage data were reviewed, and a preliminary understanding of hydraulic boundary conditions was developed. The groundwater flow system is dynamic	Sections 4.5 and 4.6

[3] The organic COPCs are not detected in upgradient groundwater samples collected along the eastern and southern Site boundaries but are found in downgradient groundwater samples collected along the western Site boundary. A detailed discussion of radionuclide geochemistry and its effects on radionuclide mobility in groundwater is presented in Appendix S.

PSQ	Progress Made Towards Answering the PSQ	Relevant Report Section
	and affected by Missouri River water levels. Net groundwater flow is to the west-northwest, consistent with where COPCs have been detected: COPCs in alluvial groundwater are detected along the western Site boundary and to the west of the Site and COPCs in bedrock groundwater are detected to the north of the Site.	

1.2 Disclaimer

The OU-3 RI high-resolution well installation program as proposed in the RI/FS Work Plan is now complete. However, the OU-3 groundwater sampling program is ongoing, and additional data collection is expected to address data gaps identified during the RI investigation. This Annual Report provides a summary of activities completed and data collected during the reporting period but is not intended to provide the comprehensive Site dataset or interpretation of all data collected to date. It is not appropriate to develop final interpretations regarding Site conditions in this Annual Report, since those interpretations may change as additional data are collected and interpreted. Any interpretations presented herein are subject to revision as additional data are collected and interpreted. As noted in the RI/FS Work Plan, the RI Report will be prepared following completion of Site characterization activities and will summarize the findings of the RI process and provide final interpretation of data collected, including the final CSM.

2. STATUS OF TASKS COMPLETED OR IN PROGRESS

2.1 Summary of Approved Technical Memos

During the reporting period, USEPA approved changes to the RI/FS Work Plan, FSP, and QAPP that were documented in Technical Memoranda (Tech Memos), summarized in the table below[4]. Additional details about the approved changes can be found in the referenced Tech Memo documents.

Table 2-1: Summary of Tech Memos and USEPA Approvals

Tech Memo	Submittal Date	USEPA Approval Date[5]	Summary of Change
Tech Memo 10	2 April 2021; Revised 19 May and 17 September 2021	3 November 2021	■ Changes to high-resolution data collection for bedrock borings
Tech Memo 12	21 April 2021; Revised 15 June 2021, 17 September 2021, 13 May 2022, and 28 May 2022	8 June 2022	■ Well construction and completion changes ■ Well development and equipment decontamination procedure changes
Tech Memo 15	13 May 2021; Revised 24 August 2021	7 April 2022	■ Piezometer installation scope and location changes
Tech Memo 17	29 July 2021; Revised 31 August 2021	8 October 2021	■ Schedule changes
Tech Memo 18	24 August 2021; Addendum 11 October 2021; Revised 28 January and 15 August 2022	Pending	■ Reduction in laboratory methods for groundwater sampling at some well locations
Tech Memo 19	17 September 2021	7 April 2022	■ Off-Site well location changes
Tech Memo 20	20 October 2021	1 November 2021	■ Stilling well location changes
Tech Memo 21	9 November 2021; Revised 18 November and 10 December 2021	14 April 2022	■ Drilling method changes ■ Well construction changes
Tech Memo 22	30 December 2021	30 December 2021	■ Stilling well location changes
Tech Memo 23	4 February 2022; Revised 28 May 2022	8 June 2022	■ Addition of the Water FLUTe™ (WF) by Flexible Liner Underground Technologies (FLUTe™) of Alcalde, New Mexico as an approved system for multi-level wells
Tech Memo 24	11 February 2022	18 February 2022	■ Weekend work procedure modification at APS-017
Tech Memo 25	1 July 2022 (draft)	Pending	■ Addition of new Standard Operating Procedure (SOP) for leachate sampling and modification to laboratory methods for leachate sampling

[4] Tech Memos 1 through 9, 11, 13, 14, and 16 were submitted and approved by USEPA during prior reporting periods and are summarized in the 2020 and 2021 Annual Reports (ERM 2022a, 2022b).

[5] Approval date is as of the end of the reporting period (Q3 2022); all pending approvals at the end of the reporting period have since been approved.

2.2 OU-3 Monitoring Well Network, Repairs, and Maintenance

2.2.1 OU-3 Monitoring Well Network

As part of initial OU-3 activities, ERM conducted a well inventory of all existing (i.e., pre-RI wells) at the Site (Figure 1a). The results of well inventory activities conducted during prior reporting periods were summarized in the *Well Inventory Summary Report* (dated 16 November 2020; revised 5 April 2021) and the *Addendum to the Revised Well Inventory Summary Report* (dated 29 July 2021). On 15 October 2021, ERM submitted an *Updated Addendum to the Revised Well Inventory Summary Report* to document additional assessment activities completed at one monitoring well (MO-2-SD) between July and September 2021.

On 31 August 2022, ERM submitted a second revision to the *Well Inventory Summary Report* to incorporate previously submitted addenda, respond to USEPA comments received on 16 June 2022, and provide a comprehensive update on the status of all existing (i.e., pre-RI) monitoring wells within the OU-3 network. The report included the results of the off-Site water supply well inventory performed by Feezor Engineering, Inc. (Feezor) of Chatham, Illinois. The *Revised Well Inventory Summary Report* proposed changes to the OU-3 monitoring well network, as summarized below. Monitoring wells referenced in Table 2-2 are shown on Figure 1a.

Table 2-2: OU-3 Monitoring Well Network Recommendations and Schedule

Well	OU-3 Status	Recommendation	Status (as of end of Q3 2022)
I-4	Inactive	Abandon due to an obstruction that cannot be repaired. I-4 was replaced by new well MW-112, which has three alluvial screens.	Pending approval from Missouri Department of Natural Resources (MDNR) and Missouri Geologic Survey
LR-100	Active (gauging only)	Discontinue sampling; this leachate riser is screened in waste and samples collected from this location are not representative of groundwater conditions. Retain for gauging purposes only.	Sampling discontinued as of Q4 2022
MO-1-SS	Active (gauging only)	Remove from the OU-3 quarterly sampling program due to the presence of bentonite in the well screen and retain for gauging purposes only.	Monthly gauging initiated in July 2022
PZ-112-AS	Inactive	Abandon due to an obstruction that cannot be repaired. PZ-112-AS was replaced by new well MW-112, which has three alluvial screens.	Pending approval from MDNR and Missouri Geologic Survey
PZ-204-SS	Inactive	Remove from OU-3 program and replace with PZ-204A-SS. Well will be retained for landfill gas monitoring purposes.	Sampling discontinued as of Q3 2022

Note: The I-4, PZ-112-AS, and PZ-204-AS recommendations were approved by USEPA in a letter dated 16 June 2022. MDNR had not approved abandonment of I-4 and PZ-112-AS as of the end of the reporting period but has since provided approval. USEPA approval of the LR-100 and MO-1-SS recommendations was pending as of the end of the reporting period.

2.2.2 Leachate Collection Sumps

Leachate collection sumps (LCSs) in Bridgeton Landfill are a component of a larger leachate collection system. The LCSs and other locations that were pumping at the end of Q3 2022 are shown on Figure 2. The operational status and sampling frequency of LCSs are presented below in Table 2-3. Operational

LCSs require periodic downtime for maintenance. Pumping locations shown on Figure 2 intercept leachate.

Two additional LCSs were added to the quarterly sampling program in first quarter (Q1) 2022: LCS-5B, after installation of a sampling port by Bridgeton Landfill, and LCS-6B, by deactivating the pump at least four hours in advance of sampling to allow for accumulation of a sufficient volume of liquid for sample collection.

Table 2-3: Leachate Collection Sump Status

LCS ID	Location	Constructed Screened Interval (feet below ground surface)	Operational and Pumping Status	Sampling Frequency
LCS-1D	South Quarry	187–247	Not operational	Unable to be sampled
LCS-2D	South Quarry	197.25–257.25	Not operational	Unable to be sampled
LCS-3D	South Quarry	40–138	Operational, pumps continuously	Quarterly
LCS-4B	South Quarry	235–295	Not operational	Unable to be sampled
LCS-5A	North Quarry	140–290	Operational, pumps continuously	Quarterly
LCS-5B	North Quarry	145–295	Operational, pumps intermittently due to low leachate levels and yield	Quarterly starting in Q1 2022
LCS-6B	North Quarry	45–85	Operational, pumps intermittently due to low leachate levels and yield	Quarterly starting in Q1 2022

Notes: Six LCSs are permitted by MDNR under Permit Number 0118912 (LCS-1D, LCS-2D, LCS-3D, LCS-4B, LCS-5B, and LCS-6B). Screened intervals listed above were taken from LCS construction logs and do not take into account potential landfill settlement after installation.

Except for LCS-3D, the LCSs in the South Quarry of Bridgeton Landfill are not operational due to a heat-producing subsurface reaction within the Bridgeton Landfill South Quarry, as described in the *Work Plan – South Quarry Subsurface Assessment Actions & Leachate Collection Sump (LCS) Installations* (Feezor 2018). Certain settlement and temperature conditions must be met before the South Quarry LCSs can safely be replaced (Feezor 2018). As documented in the November 2022 *Annual Report: South Quarry Subsurface Conditions Monitoring for LCS Installations* (Feezor 2022), as of the end of Q3 2022, those conditions have not yet been met. Three LCSs are not shown on Figure 2 or listed in Table 2-3 above because they are not operational, not permitted, and not able to be sampled because the collection sump is compromised (LCS-3C) or the sump has been abandoned (LCS-4C and LCS-6).

2.2.3 Monitoring Well Repairs, Maintenance, and Survey Activities

The following monitoring well repair, maintenance, and/or survey activities were conducted during the reporting period:

- Seven multi-level FLUTe™ Cased Hole Sampler (CHS) well systems were repaired or replaced during Q4 2021 due to a small leak in the end seal of the liner. Six wells were repaired by FLUTe™

personnel between 18 and 26 October 2021 (MW-111, MW-112, MW-213, MW-303, MW-304, and MW-605). The MW-401 liner was replaced with a new liner on 3 November 2021 because the previous liner was damaged during the October 2021 repair activities. The repaired CHS well systems were resurveyed by Weaver Consultants Group (Weaver) of Collinsville, Illinois[6] on 7 January 2022 and were later resurveyed for transducer calibration purposes on 5 July 2022.

- Newly installed piezometers were surveyed on 5 July 2022.
- Tubing extensions were added to MW-111 in February 2022 because the tubing bundle settled following October 2021 repair activities. MW-111 was resurveyed by Weaver on 5 July 2022.
- Dry bags were installed at MW-605 on 17 March 2022 to prevent surface water infiltration.
- On 10 June 2022, Bulldog Drilling of Dupo, Illinois repaired PZ-207-AS, with Feezor providing oversight. Approximately 6 inches of polyvinyl chloride casing were removed from the top of the monitoring well because the steel protective casing would not close. The elevation of the modified top of casing was resurveyed by Weaver on 10 June 2022.
- Newly installed monitoring wells were surveyed on 1 and 18 August 2022.

All survey data collected from monitoring wells during the reporting period are included in Table 1a.

Following the October 2021 CHS repairs, a monthly review of multi-level well integrity was implemented beginning in January 2022 to verify the systems were dilated and functioning properly in accordance with methods described in SOP #10. All multi-level systems functioned properly for the remainder of the reporting period, and no further repairs were needed. Documentation of the monthly multi-level well integrity review, starting in January 2022, is provided in Appendix A.

Monitoring well locations are shown on Figures 1a, 1b, and 1c. No other repair or maintenance activities were conducted at monitoring wells during the reporting period.

2.3 High-Resolution Site Characterization and Monitoring Well Installation

2.3.1 Schedule

High-resolution site characterization and monitoring well installation activities were completed during the reporting period in accordance with the field schedule (FSP Figure 8-1; ERM 2020) and USEPA-approved changes to that schedule, as summarized below.

- 31 August 2021: ERM submitted Revised Tech Memo 17[7] to request a six-month schedule extension for the off-Site high-resolution well installation program, which was paused at the end of June 2021 as the OU-3 Respondents worked to secure access to the remaining off-Site monitoring well locations. The updated field schedule specified that off-Site well installation would resume by 15 November 2021 and would be completed by 5 August 2022.
- 8 October 2021: USEPA conditionally approved the field schedule modification.
- 15 November 2021: Off-Site drilling activities resumed in accordance with the approved schedule.
- 3 January 2022: The OU-3 Respondents secured legal access to all remaining off-Site monitoring well locations except for MW-403, which was relocated on Site (Tech Memo 19).

[6] Survey data are collected by Weaver and checked and signed by a Missouri-licensed professional land surveyor from Metron Surveying & Layout Co. of O’Fallon, Missouri.

[7] Tech Memo 17 was originally submitted on 29 July 2021 and was revised in response to USEPA comments received 17 August 2021.

- 2 August 2022: ERM, on behalf of the OU-3 Respondents, requested a one-week extension to the monitoring well installation program. At the time, all monitoring wells were installed, but four bedrock wells (MW-603-P1, MW-603-P2, MW-604-P1, and MW-604-P2) took longer to develop than anticipated due to low yield.
- 10 August 2022: USEPA approved the schedule extension request.
- 12 August 2022: All monitoring wells were installed and developed in accordance with the field schedule.

2.3.2 WATERLOO APS™

Between 1 and 23 February 2022, ERM and Cascade Remediation Services, LLC (Cascade) completed vertical groundwater profiling activities at five off-Site locations using the WATERLOO Advanced Profiling System (APS)™. The field parameter data shown on the WATERLOO APS™ field logs (Appendix B) were used by Cascade to determine when a representative groundwater sample could be collected by comparing the results to stabilization criteria noted in the FSP. Consistent with the FSP, in certain instances of low groundwater yield, groundwater samples were collected without collecting a full set of stabilized field parameter data, as shown in Appendix B. See Table 2-4 below and attached Figure 3 for a summary of WATERLOO APS™ borings completed during the reporting period.

Table 2-4: Completed WATERLOO APS™ Borings

WATERLOO APS™ Location	Associated Monitoring Well Cluster	Termination Depth (feet below ground surface)	Bedrock Depth (feet below ground surface)	Number of Discrete-Interval Groundwater Samples Collected	Date Profile Completed
APS-009	MW-406	115.1	113.5	20	6 February 2022
APS-014	MW-500	110.0	113.5	20	14 February 2022
APS-015	MW-501	109.0	109.0	20	18 February 2022
APS-016	MW-502	99.0	111.0	18	23 February 2022
APS-017	MW-503	110.2	115.0	10	20 February 2022

Notes: Bedrock depths listed above are based on field observations during borehole advancement via rotosonic drilling methods because it is not possible for the WATERLOO APS™ tooling to penetrate bedrock. Boreholes for monitoring wells were advanced as close to the associated WATERLOO APS™ as feasible, generally within a 10-foot radius. For the co-located APS-009 and MW-406 borings, the bedrock surface elevation varied by 1.6 feet between the two closely spaced boring locations, as evidenced by the greater depth to bedrock measured in the WATERLOO APS™ boring.

WATERLOO APS™ borings were advanced to refusal. As shown in Table 2-4 and documented in previous annual reports (ERM 2022a, 2022b), total boring depths were greater than the target depth of 70 feet indicated in the FSP, and at all but one location, the WATERLOO APS™ tooling effectively reached the top of bedrock (i.e., the tooling either encountered refusal at the top of bedrock or within 5 feet of bedrock, as later confirmed during advancement of co-located borings using rotosonic drilling methods).

A Stage 1 validation was performed on all screening data to verify accuracy and completeness of the dataset prior to use. An internal review checklist was completed for each data set and any identified data quality issues were communicated to the project team. Appendix B includes the WATERLOO APS™ logs, including field (e.g., index of hydraulic conductivity, specific conductivity, dissolved oxygen, pH, and oxidation-reduction potential [ORP]) and analytical data obtained using this tool.

The following USEPA-approved modifications to portions of the FSP pertaining to the WATERLOO APS™ vertical groundwater profiling program were made during the reporting period:

- The sampling interval was changed from a 5-foot to a 10-foot interval at APS-017, to meet a time-sensitive request from the property owner to limit the work to weekends only (Tech Memo 24).
- APS-010 was not completed because access was not granted by the property owner. The co-located monitoring well, MW-403, was re-located on-Site (adjacent to existing well I-65). The WATERLOO APS™ boring could not be completed at the on-Site location because the WATERLOO APS™ truck could not safely access this area due to a steep slope; instead, well screen intervals at MW-403 were selected based on geophysical logging results (Tech Memo 19).
- The locations of APS-014, APS-016, and APS-017 were adjusted due to access restrictions or limitations (Tech Memo 19).

The following deviations from the FSP and/or QAPP were noted:

- Groundwater samples were not collected for analysis of filtered (dissolved) metals or general chemistry parameters at one depth interval from three locations due to low permeability of the sampling intervals, resulting in insufficient sample volume to fill all sample bottles: APS-015 at an approximate depth of 65 feet; APS-016 at an approximate depth of 85 feet; and APS-017 at an approximate depth of 100 feet. Only VOCs were analyzed at these sample depths.
- The equipment blank (EB) samples were named to correspond to the location of each sample (e.g., EB-APS-009) instead of incrementally (e.g., EB-001).

WATERLOO APS™ boring locations completed during the reporting period were surveyed by Weaver on 16 March 2022; survey data are provided in the attached Table 1b. The results from WATERLOO APS™ borings completed during the reporting period are discussed in Section 3.1.

2.3.3 Borehole Advancement and Borehole Geophysical Logging

ERM and Cascade completed rotosonic drilling activities at 13 locations between 15 November 2021 and 30 June 2022 using a combined rotosonic and air rotary drilling rig. During this time, monitoring wells were installed at all remaining monitoring well locations included under the FSP, as summarized in Table 2-5 in Section 2.3.6. Appendix C provides the boring logs depicting lithology, percentage of core recovery, VOC screening data, and well completion data for the 13 locations completed during the reporting period.

Throughout the rotosonic drilling program, COLOG, Inc. (COLOG) of Lakewood, Colorado periodically mobilized to the Site to complete borehole geophysical logging activities in accordance with the FSP. Geophysical logging was completed at each monitoring well location installed during the reporting period to provide high-resolution vertical profiling of various geologic, hydrogeologic, and water-quality parameters. Table 2 summarizes borehole geophysical logging tools and activities conducted at each location during the reporting period. Geophysical logs are included in Appendix D. Borehole geophysical logging tools that do not require field calibration were calibrated by COLOG at their facility in Colorado prior to arrival at the Site. Tools that require periodic field calibration (e.g., caliper tool) were calibrated by COLOG in the field using appropriate calibration standards prior to use with oversight by ERM for verification purposes. Calibration logs for the 2021 and 2022 reporting periods are included in Appendix D.

No deviations from the FSP or QAPP were noted with respect to rotosonic drilling and borehole geophysical logging activities conducted during the reporting period; however, the following USEPA-approved modifications to portions of the FSP pertaining to the drilling and geophysical logging program were made during the reporting period:

- MW-403 was re-located from an off-Site to an on-Site location, adjacent to I-65, because access was not granted by the property owner (Tech Memo 19).

- MW-603 and MW-604 were advanced using air rotary drilling methods instead of rotosonic drilling methods (Tech Memo 21).
- The amount of time that a background borehole (i.e., MW-600 series) is allowed to remain open between completion of geophysical logging and the start of well construction activities was extended from 48 to 72 hours (Tech Memo 21).
- Borehole geophysical logging was only conducted in the deepest borehole of each cluster of single-screen wells (i.e., MW-403-P2, MW-600-P3, MW-601-P3, and MW-603-P2) (Tech Memo 21).
- Although the requirement to collect multiple bedrock borehole groundwater samples to inform well screen selection was eliminated, one groundwater grab sample was collected from each of the bedrock boreholes advanced during the reporting period (MW-406, MW-500, MW-502, MW-602, MW-603, and MW-604) as documented in Tech Memo 10. Analytical results from borehole groundwater grab samples are included in Appendix D.

Locations of boreholes advanced during the reporting period are shown on Figures 1a, 1b, and 1c. Results of geophysical logging are discussed further in Section 3.2, and in relation to the geological boring logs in Section 3.3.

2.3.4 Aquifer Matrix Sampling

During the reporting period, aquifer matrix samples were collected from the MW-406, MW-500, MW-502, and MW-604 soil and/or bedrock cores (Figures 1a, 1b, and 1c). Consistent with Section 3.7 of the FSP, at least one aquifer matrix sample was collected from each representative type of soil and bedrock encountered within these boreholes based on results of borehole geophysical testing.[8] Alluvium and bedrock cores were stored in a secured container on ice pending selection of samples for analysis. For boreholes where both alluvium and bedrock samples were collected (MW-406, MW-500, and MW-502), up to 20 aquifer matrix samples were analyzed per boring. For the bedrock-only boring (MW-604), 10 aquifer matrix samples were analyzed. Each aquifer matrix sample was analyzed for the parameters listed in Tables 2-1b and/or 2-1c of the QAPP, except as noted below. EBs were collected from decontaminated rock hammers used during collection of bedrock samples, except at MW-604, which was advanced via air rotary drilling methods, since a rock hammer was not needed to collect samples at this location. No other non-disposable equipment was used during aquifer matrix sampling.

The following USEPA-approved modifications to portions of the FSP pertaining to aquifer matrix sampling were made during the reporting period:

- Analysis of aquifer matrix samples for moisture content and density were eliminated (Tech Memo 14).
- Alluvial aquifer matrix sample selection at MW-502 was based on borehole geophysical logs of the closest nearby bedrock location (MW-400) because COLOG was not available to conduct borehole geophysical logging at MW-502 within the shortest applicable laboratory holding time (14 days) for matrix sample analyses (approved by USEPA via email on 19 April 2022).

The following deviation from the FSP and QAPP was noted:

- EB samples were named according to sample location (e.g., EB-001-MW-406) instead of incrementally (e.g., EB-001). The EB submitted for MW-500 was inadvertently named EB-002-MW-500, but only one EB was submitted for this location.

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[8] Alluvial aquifer matrix samples were generally collected over a 1-foot interval; at MW-502, the sample above bedrock within the 100 to 110 feet below ground surface interval due to the limited core recovery at this interval.

Aquifer matrix sampling results are discussed in Section 3.4.

2.3.5 Monitoring Well Screen Selection

In accordance with the criteria described in Section 3.9 of the FSP, monitoring well screen intervals were selected using multiple lines of evidence from the high-resolution data generated from the WATERLOO APS™ and/or borehole geophysical logging tools. Monitoring well locations are shown on Figures 1a, 1b, and 1c and WATERLOO APS™ locations are shown on Figure 2. Table 3 provides the selected screen intervals and the rationale for each screen interval for all wells installed during the reporting period. In accordance with the FSP, screen interval selections were communicated to the USEPA prior to well installation.

The following USEPA-approved modifications to portions of the FSP pertaining to well screen selection were made during the reporting period:

- MW-403 was re-located to an on-Site location, adjacent to I-65, because access to the proposed off-Site location was not granted by the property owner. The number of screen intervals at MW-403 was reduced from three alluvial screens to two alluvial screens, since I-65 is not currently planned for abandonment and can therefore be retained in the OU-3 monitoring program as an alluvial well. Due to the reduction in the number of well screens, the well construction of MW-403 was changed from a multi-level well to a cluster of two conventional, single-screen wells (Tech Memo 19).
- MW-500-P5, MW-502-P5, and MW-602-P5 were screened within the Warsaw Formation because the St. Louis Formation was not present, and the Salem Formation was not thick enough to accommodate more than one bedrock screen at these locations. The FSP indicated that wells would not be installed in the Warsaw Formation, but USEPA did not approve a reduction in the number of bedrock screens at these locations. Installation of wells within the Warsaw Formation is documented in Tech Memo 15.

2.3.6 Monitoring Well Installation

Following borehole advancement, testing, and well screen selection, monitoring wells were installed as either conventional single-screen wells or multi-level WF wells. Figures 1a and 1b show the OU-3 monitoring well network, including on-Site and off-Site monitoring wells installed during 2021 and 2022, as well as existing pre-RI wells. Figure 1c shows the off-Site network of background monitoring wells, piezometers, and stilling wells. Information pertaining to monitoring wells installed during the reporting period is summarized in Table 2-5 below. Well construction information for wells installed during this reporting period is provided in Table 4; corresponding survey data for these wells are provided in Table 1a. Well construction logs for monitoring wells installed during the reporting period are provided in Appendix C.

Table 2-5: Monitoring Well Completions

Location ID	Number of Alluvium/ Bedrock Well Screens	Well Construction Completion Date	FLUTe™ System Installation Date	Well Type
MW-402	3/0	21 June 2022	21 July 2022	WF
MW-403	2/0	30 June 2022	NA	Single-screen well cluster
MW-406	3/2	21 April 2022	22 April 2022	WF
MW-500	3/2	6 April 2022	7 April 2022	WF

Location ID	Number of Alluvium/ Bedrock Well Screens	Well Construction Completion Date	FLUTe™ System Installation Date	Well Type
MW-501	3/0	8 April 2022	9 April 2022	WF
MW-502	3/2	20 June 2022	20 July 2022	WF
MW-503	3/0	20 May 2022	22 May 2022	WF
MW-504	3/0	9 May 2022	10 May 2022	WF
MW-600	3/0	21 November 2021	NA	Single-screen well cluster
MW-601	3/0	23 November 2021	NA	Single-screen well cluster
MW-602	3/2	17 May 2022	18 May 2022	WF
MW-603	0/2	21 December 2021	NA	Single-screen well cluster
MW-604	0/2	30 January 2022	NA	Single-screen well cluster

Note: "NA" = not applicable because FLUTe™ systems are not installed in conventional single-screen wells.

The following USEPA-approved modifications to portions of the FSP pertaining to well construction activities were made during the reporting period:

- The WF was added as an approved multi-level well system (Tech Memo 23).
- The monitoring well type at five locations (MW-403, MW-600, MW-601, MW-603, and MW-604) was changed from multi-level CHS well systems to 2-inch, single-screen well clusters (Tech Memos 19 and 21).

The following deviations from the FSP were noted:

- In October 2021, seven multi-level CHS well systems were thought to be insufficiently dilated relative to the manufacturer's specifications (MW-111, MW-112, MW-213, MW-303, MW-304, MW-401, and MW-605). After reviewing the data and visiting the Site to inspect the liners, FLUTe™ determined that these well systems were leaking due to a manufacturing defect. FLUTe™ was on Site from 18 to 26 October 2021 to assess and repair the CHS liners. Details regarding the leaks and repair process were provided to USEPA in a memo dated 19 November 2021. As described in Section 2.2.3, a monthly review of multi-level well integrity has been implemented to monitor for potential future leaks; documentation of the monthly multi-level well integrity review is provided in Appendix A.
- Drilling rods were not fully decontaminated in accordance with FSP SOP #18 during the drilling at background wells MW-600-P1, MW-600-P2, and MW-600-P3 because decontamination procedures were not previously specified for multiple boreholes drilled at the same location. USEPA clarified in the field that full decontamination must be performed between each individual borehole at the designated on-Site decontamination pad. See Section 3.7.1 for further information on analytical data collected from the MW-600 well cluster.
- MW-601-P2 was installed with one extra foot of sand filter pack at the top of the screen (3 feet instead of 2 feet) due to miscommunication between ERM and the driller. The extra foot of sand is documented on the well construction log and does not substantively impact the well.

2.4 Monitoring Well Development

Newly installed monitoring wells were developed by ERM or by Cascade with ERM oversight. All new wells were developed prior to incorporation into gauging or sampling events, as specified in the FSP and SOP #09. New, dedicated bladder pumps were installed in single-screen wells following well development. Tables 2-6 and 2-7 below summarize well development dates during this reporting period. A summary of well development information for new single-screen and new multi-level wells installed during the reporting period is provided in Tables 5a and 5b, respectively.

Table 2-6: Monitoring Well Development Summary—Single-Screen Wells

Well(s) Developed	Well Development Date(s)
MW-600-P1, MW-600-P2, MW-600-P3, MW-601-P1, MW-601-P2, and MW-601-P3	6-7 December 2021
MW-403-P1 and MW-403-P2	7 July 2022
MW-603-P1	11 July, 9-12 August 2022
MW-603-P2	19-20 July, 9-10 August 2022
MW-604-P1 and MW-604-P2	8-12 August 2022

Table 2-7: Monitoring Well Development Summary—Multi-Level Wells

Well Systems Developed	Phase 1 Well Development Date(s)	FLUTe^{TM} System Installation	Phase 2 Well Development Date(s)
MW-406, MW-500, MW-501	3-8 June 2022	5-9 June 2022	24 June 2022
MW-504	1-3 June 2022	13 July 2022	25 July 2022
MW-402, MW-503, MW-602	12-19 July 2022	15-21 July 2022	25-29 July 2022
MW-502	16-17 July 2022	4 August 2022	4-5 August 2022

The following USEPA-approved modifications to portions of the FSP pertaining to well development activities were made during the reporting period:

- Deep bedrock single-screen well couplets at MW-603 and MW-604 were developed using an air-lift pump because these wells were too deep to be developed using a submersible pump (Tech Memo 12).
- Multi-level well systems at MW-402, MW-502, and MW-503 were developed during Phase 1 of well development using an air-lift pump inside the packed-off borehole intervals, instead of a submersible pump (which was used during Phase 1 of well development at all other multi-level wells developed during the reporting period). The use of an air-lift pump was requested by USEPA via email on 14 July 2022 to maximize purge rate.
- None of the MW-603- and MW-604-series wells achieved the turbidity goal of 10 Nephelometric Turbidity Units (NTU) because all four wells are installed in low-yield bedrock. The maximum purge criterion of five times the well volume was achieved at three of four wells (all except MW-604-P1). Fewer than three times the well volume were purged from MW-604-P1 due to its extremely low yield. ERM gave progress updates on these locations to USEPA verbally and via email on 11 August 2022. USEPA concurred with ERM’s approach and sent an email on 12 August 2022 requesting a write-up of the field actions completed, recharge rates observed, total volume purged, purge rates, and planned sample schedule, which ERM sent via email on 15 August 2022.

The following deviations from the FSP and/or QAPP were noted:

- During Phase 2 of well development at multi-level wells MW-406, MW-500, and MW-501, turbidity was inadvertently measured in Formazin Nephelometric Units (FNU) instead of NTU. FNU and NTU are measured using different methods but are generally considered interchangeable and acceptable to achieve project objectives.

- During Phase 2 of well development, the final turbidity readings at two bedrock well screens (MW-500-P5 and MW-502-P5) were greater than the goal of 10 NTU. These well screens are installed in the Warsaw Formation and exhibit low yield.

Monitoring well locations are shown on Figures 1a, 1b, and 1c. Tables 5a and 5b include a summary of well development information for the reporting period, including volumes purged, field parameters, and results.

2.5 Monitoring Well Gauging

Monthly gauging of the OU-3 well network during the reporting period was completed by Feezor. Newly installed monitoring wells were incorporated into the gauging events following well development. Water level meters (WLMs) used during monthly gauging were calibrated by Feezor in December 2021 and January 2022.

During each gauging event, certain wells could not be gauged for various reasons, such as a lack of legal access. During the reporting period, three existing pre-RI wells were added to the gauging list: MW-103 (starting in September 2022), MW-104 (starting in June 2022), and MO-1-SS (starting in July 2022). PZ-204-SS was removed from the gauging list starting in July 2022. These changes to the gauging list were documented in the *Revised Well Inventory Summary Report* (ERM 2022c). Monitoring well locations are shown on Figures 1a, 1b, and 1c.

The following deviations from the FSP were noted:

- MW-401-P1, -P2, and -P3 were not gauged in November 2021 because the well was being repaired, as discussed in Section 2.2.3.
- PZ-302-AS was not gauged in February 2022 because depth to water was below the top of the bladder pump and the WLM could not be advanced past the top of the pump. In March 2022, the water level was also below the top of the pump, but the pump was temporarily removed to gauge the well. The well was allowed to equilibrate, was gauged, and the pump was re-deployed down the well on the same day. If this situation occurs again, the pump will be temporarily removed again to collect an accurate groundwater level measurement.
- I-66 was not gauged in February 2022 because the location was not safely accessible due to snow and ice in the area.
- MW-605-P1 and -P2 could not be gauged in March 2022 because the depth to water was very low and the WLM could not be lowered to the water table.
- Seven CHS ports could not be gauged in May 2022 because the WLM could not be advanced to the water table[9]:
    - MW-304-P2
    - MW-404-P1, -P3, -P4, and -P5
    - MW-605-P1 and -P2

Monthly gauging data are discussed in Section 3.5.1.

[9] The WLM used to gauge these wells was replaced after the May 2022 gauging event.

2.6 Transducer Deployment and Monitoring

The WF monitoring wells were manufactured with built-in pressure transducers. Pressure transducers were also installed in stilling wells SG-500, SG-501, SG-502, and SG-503 during the reporting period (Figure 1c). Transducers equipped with telemetry were installed in MW-600-P2 and MW-601-P2 in January 2022 to monitor these wells in real-time for potential flowing artesian conditions. As described in Section 2.8, one transducer was deployed in an existing (i.e., pre-RI) off-Site piezometer, Howard Bend Levee District (HBLD) PZ-5, on 9 March 2022. Transducer data were downloaded from all locations during monthly gauging events and transducers were periodically calibrated at multi-level CHS and WF locations using survey data, transducer readings, and synchronous WLM gauging measurements.

Due to multiple hardware issues with the Solinst® transducers installed in stilling wells, stilling well transducers were replaced with new, In-Situ® Rugged TROLL transducers in Q3 2022, or will be replaced in Q4 2022, once surface water levels have receded sufficiently to allow for safe access to the remaining locations. In addition, the stilling well construction was modified to allow the transducers to be removed more easily; the updated stilling well schematic is provided in Appendix E. In-Situ® Rugged TROLL transducers have equivalent range, resolution, and accuracy as the Solinst® transducers, and are consistent with the transducer specifications listed in Table 3-1d of the QAPP.

A summary of transducer deployment and monitoring at each location during the reporting period, including deviations from the FSP, is provided below:

- **SG-200**: Feezor discovered a broken data cable in August 2022; all data were recovered from the old transducer and a new In-Situ® transducer was installed in the modified stilling well on 13 September 2022.
- **SG-400**: Feezor will proactively install a new In-Situ® transducer in the modified stilling well in Q4 2022.
- **SG-500**: Feezor was unable to download data from this transducer in July 2022; a new In-Situ® transducer will be installed and transducer data recovery will be attempted by Solinst® in Q4 2022. The outcome will be documented in the 2023 Annual Report.
- **SG-501**: Feezor was unable to download data from this transducer in July 2022; a new In-Situ® transducer will be installed and transducer data recovery will be attempted by Solinst® in Q4 2022. The outcome will be documented in the 2023 Annual Report.
- **SG-502**: Feezor was unable to download data from this transducer in July 2022; a new In-Situ® transducer was installed in the modified stilling well on 15 September 2022 and transducer data recovery will be attempted by Solinst® in Q4 2022. The outcome will be documented in the 2023 Annual Report.
- **SG-503**: Feezor was unable to download data from this transducer in September 2022 and water levels made this location unsafe to access during the reporting period; a new In-Situ® transducer will be installed and the stilling well construction will be modified once surface water levels have receded sufficiently to allow for safe access to the stilling well. Transducer data recovery will be attempted by Solinst® upon retrieval of the old transducer. The outcome of future work at this location will be documented in the 2023 Annual Report.
- **SG-504**: Feezor discovered a damaged data cable in July 2021; the data cable could not be inspected, repaired, or replaced because elevated surface water levels prevented safe access to the stilling well at that time and for several months thereafter. Feezor was planning to fix the cable in October 2021 once water levels receded, but the property was sold, and a new access agreement was not executed until 10 February 2022. The transducer was not responsive when accessed on 9

March 2022 and data could not be recovered by Solinst® for the period from 3 June 2021 through 9 March 2022. Feezor installed a new Solinst® transducer in March 2022. Feezor was unable to download data from the new transducer in July 2022; a new In-Situ® transducer was installed in the modified stilling well on 14 September 2022 and transducer data recovery will be attempted by Solinst® in Q4 2022. The outcome will be documented in the 2023 Annual Report.

- **SG-505**: Feezor was unable to download data from this transducer in November 2021. The transducer was replaced with a new Solinst® transducer on 13 January 2022 and the faulty transducer was sent to Solinst® for repair and data recovery, but Solinst® was unable to recover the data due to a faulty electronic component that caused the battery to prematurely drain. Feezor was unable to download data from this transducer in July 2022; a new In-Situ® transducer was installed in the modified stilling well on 2 September 2022. Solinst® recovered data from 13 January 2022 through 1 June 2022.
- **SG-600**: Feezor was unable to download data from this transducer in March 2022 and a new Solinst® transducer was installed on 25 March 2022. Solinst® recovered data through 7 February 2022. Feezor was unable to download data from this transducer in July 2022; a new In-Situ® transducer installed and transducer data recovery will be attempted by Solinst® in Q4 2022. The outcome will be documented in the 2023 Annual Report.
- **MW-500-P5:** During July 2022, Feezor determined that the transducer had not been logging data after the CHS well system was installed on 9 June 2022. FLUTe™ personnel corrected this issue, and the transducer began logging data on 14 July 2022.

Transducer data are discussed in Section 3.5.2.

2.7 Monitoring Well and Leachate Collection Sump Sampling

ERM and Feezor completed four quarters of groundwater sampling during the reporting period, as summarized in Table 2-8 below. Figures 4 through 7c show the monitoring wells and LCSs that were sampled during each quarterly sampling event. Table 6 lists monitoring wells and LCSs sampled during each quarterly event.

Table 2-8: Summary of Groundwater Monitoring Events

Quarterly Sampling Event	Dates	Monitoring Wells Sampled	LCSs Sampled
Q4 2021	2-19 November 2021	107	2
Q1 2022	8 February-3 March 2022	127	4
Q2 2022	2-26 May 2022	132	4
Q3 2022	2-25 August 2022	171	4

A summary of field parameters recorded at each monitoring well at the time of sampling is provided in Appendix F. Due to the aeration that occurs during the collection of field parameters at multi-level wells, dissolved oxygen measurements from multi-level wells are not considered representative, as indicated by an “X” qualifier. As noted in the FSP, dissolved oxygen measurements from multi-level wells are recorded for reference only. Field parameter data quality is further discussed in Section 3.8. Field parameters are not collected at LCSs, consistent with the FSP.

Sampling events were conducted in 20 business days or less in accordance with Figure 8-1 of the FSP. Wells were sampled in a generally consistent order from least to most impacted based on prior sampling results. New monitoring wells were generally added to the end of the sampling order. ERM reviewed and revised the sampling order quarterly to reflect the results of groundwater analytical data from newly sampled wells. Quality assurance / quality control (QA/QC) samples were collected during each quarterly sampling event at the frequency prescribed in the QAPP.

As noted in Section 2.2.2, two LCSs were added to the OU-3 monitoring program in Q1 2022: LCS-5B and LCS-6B. As summarized in Tech Memo 25, LCS sampling procedures were updated to minimize headspace in volatile organic analysis (VOA) vials. Starting in second quarter (Q2) 2022, leachate samples were pre-chilled prior to filling VOA vials, and starting in Q3 2022, an additional set of leachate samples was collected in unpreserved VOA vials to give the laboratory the option to analyze unpreserved samples if all preserved samples are received with headspace. These modifications to the LCS sampling procedure were documented in SOP #21 which was submitted to USEPA with Tech Memo 25.

ERM conducted a field audit of groundwater sampling activities during Q4 2021, Q1 2022, and Q3 2022 using the Field Audit form (Appendix F of the QAPP). The completed Field Audit forms are provided in Appendix G.

Many Site monitoring wells have low yield (i.e., drawdown does not stabilize within the criteria defined in the FSP), which can impact the way the well is sampled. Some very low yield wells go dry during purging and the field parameters do not stabilize before the well goes dry. Other very low yield wells go dry during sampling, and the well must be sampled over a multi-day period. For some very low yield wells, a modified sample collection order is used to ensure that the highest priority samples are collected. Many other wells have low yield (i.e., drawdown does not stabilize within the criteria defined in the FSP) but are still able to be sampled without modifications. Specific details about sampling of these very low yield wells are described below. Nearly all wells with drawdown issues are screened within bedrock; however, not all bedrock wells at the Site exhibit low yields. Bedrock wells that exhibit adequate yields to enable low-flow sampling with minimal drawdown intersect transmissive bedrock fractures that represent preferential groundwater flow paths within bedrock. Bedrock wells that exhibit low yields intersect either low-transmissivity fractures or the bedrock matrix, neither of which represent preferential groundwater flow paths within bedrock.

- During this reporting period, monitoring well PZ-302-AS could not be sampled within one day due to its very low yield, which is consistent with previous sampling events. Feezor returned to the well multiple times over a two- to three-day period to collect all required samples from this well. During Q3 2022, three newly installed sampling ports also had to be sampled over a multiple-day period due to very low yield (MW-500-P5, MW-502-P5, and MW-602-P5). All three of these sampling ports are installed in the Warsaw Formation. All required samples were collected from these very low-yield wells, with one exception noted below.
- In Q3 2022, a modified sampling method and sample collection order was used at S-53 because the well screen is occluded with sand, resulting in very low yield. Following USEPA approval provided via an email dated 5 August 2022, groundwater samples were collected from S-53 using a peristaltic pump and bailer (instead of bladder pump) and using a modified sample collection order to prioritize collection of samples for VOC and radiochemistry analyses. The same modified sample collection order was also used at MW-604-P1 due to its very low yield. Both S-53 and MW-604-P1 took three or more days to sample; all required samples were collected from these very low-yield wells, with one exception noted below. The standard and modified sample collection orders are provided in Table 7.

The following deviations from the FSP and/or QAPP were noted:

- During each quarterly event, drawdown did not stabilize to within 0.3 foot of the initial depth to water at numerous monitoring wells, shaded gray in Table 6, despite maintaining flow rates within the acceptable range for low-flow sampling methods (i.e., less than 500 milliliters per minute). Attempts were made to control drawdown, including lowering pumping rates, without success. There are 49 wells that consistently drew down during each reporting period quarterly event, which indicates that these wells have low yields.

- Certain field parameters were not within the stabilization criterion defined by the FSP at the time of sample collection at the monitoring wells listed below:
  - Field parameters were not stable at PZ-302-AS during any of the four quarterly sampling events in the reporting period because the well repeatedly went dry before stabilization could be achieved.
  - Field parameters were not stable at S-53 during Q3 2022 because the well went dry before stabilization could be achieved.
  - ORP was not stable at PZ-111-KS during the Q2 2022 sampling event due to field error. The final three readings were within 25 millivolts of each other, instead of 10 millivolts.
- Field QC samples were collected at the frequency set forth in the FSP and QAPP during each sampling event except for EB-002-WQ-20211101 in Q4 2021, which was taken at a frequency of one per 22 samples, instead of one per 20. Field QC frequencies were discussed with the entire field team prior to the Q1 2022 sampling event to prevent this issue from happening again.
- During Q3 2022, all required samples were collected from low-yield wells except for filtered (dissolved) metals and dissolved organic carbon at MW-602-P5 and filtered (dissolved) thorium/uranium and dissolved organic carbon at S-53.

Groundwater and leachate analytical data are discussed in Section 3.7. During the reporting period, some wells had to be resampled for certain parameters due to laboratory error or bottle breakage, resulting in sample collection on multiple days and outside of the normal sampling order. In all cases, resampling was completed before the end of the scheduled sampling event. Details and data quality impacts, if any, are discussed in Section 3.7.1.

2.8 Piezometer Installation

Five piezometers were proposed in the FSP to provide supplemental groundwater level measurements at off-Site locations to support calibration of the forthcoming groundwater model (PZ-700 series). During the reporting period, two of the five piezometers (PZ-702 and PZ-703) were replaced with pre-existing (i.e., pre-RI) piezometers that were installed by others, and the remaining three piezometers (PZ-700, PZ-701, and PZ-704) were installed (Figure 1c).

The OU-3 Respondents were unable to secure access to a suitable location for PZ-703 but were able to obtain monthly gauging data from 10 existing piezometers (PZ-1 through PZ-10) in HBLD. Proposed locations PZ-702 and PZ-703 were replaced by data from the 10 existing HBLD piezometers (Tech Memo 15). The OU-3 Respondents installed a transducer in HBLD piezometer PZ-5 on 9 March 2022 and began monthly gauging and transducer download of PZ-5 beginning in April 2022. Other piezometer locations were adjusted due to safety and access issues (Tech Memos 2, 15, and 20). Piezometer locations are shown on Figure 1c.

Between 14 and 20 June 2022, Feezor oversaw the installation of PZ-700, PZ-701, and PZ-704 by Environmental Works of East Carondelet, Illinois. All three piezometers were installed with flush-mount surface completions, developed by Feezor between 17 and 20 June 2022, and surveyed by Weaver on 5 July 2022. All three piezometers were added to the monthly gauging program in July 2022. Piezometer construction information and survey data are provided in Table 8. Piezometer gauging data are provided in Appendix K. Piezometer construction logs are included in Appendix C.

2.9 Stilling Well Installation and Monitoring

Four stilling wells were installed in January 2022 (SG-501 through SG-503) and March 2022 (SG-500). Weaver surveyed new stilling wells on 16 March 2022 and 12 April 2022. Stilling well locations are shown on Figure 1c and survey data are provided in Table 9. Three stilling wells installed during a prior reporting period (SG-504, SG-505, and SG-600) were resurveyed in March 2022 due to changes in equipment described in Section 2.6. Stilling wells are equipped with pressure transducers and the surface water elevation data are downloaded monthly, concurrent with monthly gauging events.

As described in Section 2.6, multiple hardware issues were encountered with transducers installed in stilling wells during the reporting period. All Solinst® transducers installed in stilling wells were replaced with new, In-Situ® Rugged TROLL transducers in Q3 2022 or will be replaced in Q4 2022 once water levels have receded and the locations can be safely accessed. The outcome of these equipment replacements at stilling wells will be summarized in the 2023 Annual Report. Additionally, the stilling well design was modified at all locations (except SG-503, until the location can be safely accessed) for improved access to the transducer in case repairs or other maintenance are needed. The modified stilling well design is attached as Appendix E. Stilling well water level data are discussed in Section 3.5.2.

2.10 Third-Party Data

As described in Section 3.19 of the FSP, ERM obtains third-party data for evaluation. Third-party data sources include:

- Bridgeton Sanitary Landfill weekly, monthly, quarterly, and annual data submittals to MDNR
- Monthly gauging data from HBLD piezometers PZ-1 through PZ-10 (Figure 1c)
- Daily precipitation data from National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center's St. Louis Airport International Station
- Meteorological data from the on-Site meteorological station
- Missouri River stage data from United States Geological Survey (USGS) stream gauge 06935965 at St. Charles, Missouri

2.10.1 Bridgeton Landfill Submittals to MDNR

Bridgeton Landfill operates an MDNR-approved leachate collection system that includes LCSs and numerous other landfill liquid collection sumps, landfill gas extraction wells, and condensate collection locations. The leachate collection system is shown on Figure 2. Within Bridgeton Landfill, there are also temperature monitoring probes (TMPs), which measure subsurface temperature, and gas monitoring probes, which measure landfill gas.

Landfill operational data are summarized in the weekly, monthly, quarterly, and annual reports submitted by Bridgeton Landfill to MDNR.

- Weekly submittals include TMP data and leachate liquid levels in LCS-3D, LCS-4B, LCS-5B, and LCS-6B, which are operational and outfitted with data logging transducers. In some cases, the liquid level in the LCS is below the depth of the transducer and leachate liquid level data cannot be recorded. Weekly reports also summarize work completed in the past week and planned for the upcoming week.
- Monthly submittals include landfill gas collection volumes, landfill gas quality data, landfill settlement, bird monitoring data, natural gas usage, and leachate pretreatment volume data.

- Quarterly Landfill Gas Corrective Action Updates provide gas monitoring data and review the status of gas migration control measures.
- Annual reports prepared by Feezor on behalf of Bridgeton Landfill document the South Quarry Subsurface Conditions Monitoring for LCS Installation. Annual reports describe the results of monitoring the subsurface conditions in the South Quarry portion of Bridgeton Landfill, as described in Section 2.2.2. Annual reports include the TMP, landfill gas temperature, and settlement data for the relevant reporting period and describe planned upcoming activities.

Much of the data and information provided in the Bridgeton Landfill submittals are relevant to operation of Bridgeton Landfill but are not needed to answer the OU-3 PSQs and are therefore not used by OU-3. Landfill gas monitoring data from the Quarterly Landfill Gas Corrective Action Updates were reviewed to inform the OU-3 VI evaluation as discussed in Section 3.9. Leachate collection volumes from the monthly submittals are summarized in Section 3.6 and were used to inform the Bridgeton Landfill water balance, as discussed in Section 4.

2.10.2 Monthly Gauging Data from HBLD

ERM began receiving monthly groundwater elevation data from HBLD for existing (i.e., pre-RI) piezometers PZ-1 through PZ-10 starting in February 2022 (Figure 1c). HBLD shared data dating back to July 2005. HBLD stopped gauging PZ-5 starting in March 2022, once this location was added to the OU-3 monthly gauging program. HBLD groundwater elevation data are stored in ERM's EQUIS™ project database and are used to inform the understanding of the regional water table, as discussed in Section 3.5.

2.10.3 Precipitation and River Stage Data

The on-Site meteorological station and the NOAA weather station at St. Louis Lambert Airport both measure precipitation; however, the NOAA weather station data is governed by more robust quality control processes and is therefore used as the primary source of OU-3 precipitation data. Precipitation data from the NOAA weather station and Missouri River stage data from the USGS stream gauge are stored in ERM's EQUIS™ project database and are used to inform the understanding of the hydrogeology, as discussed in Section 4.

2.11 Vapor Intrusion Investigation Activities

During the reporting period, ERM completed two quarterly VI sampling events in October 2021 and January 2022 at five on-Site buildings shown on Figure 8a (the Engineering Building, the Pump House, the Scale House, the Pretreatment Building Office, and the Asphalt Plant Building). The VI sampling events involved collection of paired indoor air (IA) and sub-slab vapor (SSV) samples and outdoor ambient air (AA) samples. The fourth and final proposed VI sampling event at the Engineering Building, the Pump House, the Scale House, and the Pretreatment Building Office was completed in Q4 2021. Due to property access issues delaying the start of sampling at the Asphalt Plant Building, the fourth and final proposed VI sampling event at that building was completed in Q1 2022. Additionally, "short-term" (ST) soil vapor radon readings were collected from all SSV points in the five buildings during Q1 2022.

2.11.1 Sampling Locations

VI sampling locations were selected based on factors associated with building construction and use, including the following: envelope openings; interior partitions (e.g., walls or dividers); subsurface footers; known sub-slab conduits; vapor mitigation systems; heating, ventilation, and air conditioning (HVAC) systems; and known areas of chemical usage or storage. The sampling location(s) for each building are shown on Figures 8a through 8f.

2.11.1.1 Engineering Building (approximately 5,700 square feet)

This building has two distinct sections, each constructed at a different time. Based on visual observations, the building is slab-on-grade construction partitioned into offices, a conference room, a breakroom, restrooms, storage areas, and a garage. Doorways into individual rooms generally remain open. A ceiling vent fan in the front restroom operates continuously to assist with the turnover of air within the building. The building has a centralized forced-air electric HVAC system located in the utility room next to the conference room (i.e., in the central portion of the building). Known subsurface utilities in the building are the water and sanitary sewer lines servicing the restrooms and the floor drain in the HVAC room. Electric service to the Engineering Building is provided through overhead electric supply lines. Sewer lines drain to a sanitary collection tank off the south side of the building. No subsurface natural gas or propane services are provided to the building. Based on size, building use, and location of the subsurface utilities, three co-located SSV and IA sampling locations were defined within this building (one in each of the three main rooms of the building): in the foyer, the conference room adjacent to the HVAC room floor drain sewer line, and the garage area.

2.11.1.2 Scale House (approximately 275 square feet)

This building is elevated approximately 5 feet above ground surface and consists of a raised-concrete perimeter wall, which is filled with granular backfill. The building has a modular-type construction and the air space below the building floor has an air intake pipe and a blower, which draws air through the space below the building and then vents it to the atmosphere. The building has two rooms: the control room and a restroom. The restroom door is open except when it is in use. The building has a centralized forced-air electric HVAC system located in the utility room on the western end of the building. Electric service to the Scale House is provided through overhead electric supply lines. Known subsurface utilities within this building are the water and sanitary sewer lines servicing the restroom, which drains to a holding tank on the outside of the building to the south. No subsurface natural gas or propane services are provided to the building. Based on building use, the IA sample location was placed in the center of the control room out of the way so as not interfere with daily activities. Because this building is elevated, the SSV sample was collected through the air intake of the venting system.

2.11.1.3 Pump House (approximately 675 square feet)

This building is partitioned into two approximately equal sections: a vacant area and a pump maintenance area. Based on visual observations, the building is a wood frame, slab-on-grade construction. HVAC is provided by an electric ceiling-mounted heater and a window air conditioning unit. Electric service to the Pump House is provided by subsurface electrical supply lines. Based on size and use, one co-located SSV and IA sampling location was identified in a central portion of the pump maintenance area of the building.

2.11.1.4 Pretreatment Building Office (approximately 700 square feet)

This office area is attached to the south side of the 21,000 square foot Pretreatment Building and is partitioned into three areas: an open office area, a locker room, and a restroom. The doors to the locker room and restroom are open except when in use. Based on visual observations, the building is concrete slab-on-grade construction with poured or tilt-up concrete walls. The office area has a separate HVAC system from the pretreatment plant area of the building. Known subsurface utilities are sanitary sewer and water lines servicing the restroom and kitchenette area in the office. Based on size and use, one co-located SSV and IA sampling location was identified in a central portion of the office area where it would not interfere with daily activities.

2.11.1.5 Asphalt Plant Building (approximately 675 square feet)

This building is generally open and contains a control room on an elevated wooden platform, electrical switchgear, and a small kitchen area. Based on visual observations, the building is slab-on-grade construction with brick or wood frame walls covered with exterior siding. There are no known subsurface utilities underlying the building. There is no restroom or potable water service to the building. Although potable water is not provided to the building, any liquids that would be dumped into the sink in the kitchen area would drain to a sewer line on the exterior of the building. The building is serviced by one central HVAC system. Electric service to the Asphalt Plant is provided through overhead electric supply lines. No subsurface natural gas or propane services are provided to the building. Based on building size and use, one co-located SSV and IA sampling location was identified in the central portion of the building, away from the elevated wooden platform in an area where it would not interfere with daily activities.

2.11.1.6 Outdoor Ambient Air Locations

For each building, the associated AA sample was placed in the predominant upwind direction at the time of sampling relative to the building location. For consistency, if the predominant wind direction was the same as a previous sampling event, the AA sample was placed in the same general location as the previous event.

2.11.2 Building Surveys, Sample Collection, and Sample Analysis

Initial building surveys were completed in 2021 prior to the first sampling event. Building survey results were checked for substantial changes prior to each subsequent sampling event. When possible, products that contain VOCs were temporarily removed from the buildings at least 24 hours prior to each sampling event. Appendix H includes a summary of building survey information. There were no significant modifications to buildings, their contents, or their use noted during follow-up building surveys performed prior to subsequent sampling events. VOC-containing products temporarily removed prior to subsequent sampling events were consistent with those removed prior to the initial event.

Following the pre-sampling surveys, ERM collected co-located SSV (5-minute sample) and IA (8-hour sample) samples and associated upwind AA (8-hour samples) samples for analysis of the parameters specified in the QAPP. During the Q1 2022 sampling event, ERM also collected a ST radon sample from the SSV points in each building over a 30-minute or 3.5-hour period, depending on how long it took for the readings to stabilize (i.e., less than 10 percent change in radon activity).

Table 2-9 below summarizes the VI sampling activities conducted during the reporting period. Samples were collected under what was considered normal operating conditions for each building. VI sampling results are discussed in Section 3.9.

Table 2-9: Summary of Vapor Intrusion Sampling Activities

Building	Q4 2021 (Oct 2021)	Q1 2022 (January 2022)
Engineering Building	IA + AA + SSV	ST SSV Radon
Scale House	IA + AA + SSV	ST SSV Radon
Pump House	IA + AA + SSV	ST SSV Radon
Pretreatment Building Office	IA + AA + SSV	ST SSV Radon
Asphalt Plant Building	IA + AA + SSV	IA + AA + SSV + ST SSV Radon

The following deviation from the FSP and QAPP was noted:

- A field duplicate was not collected for sub-slab soil gas from the Asphalt Plant Building during the Q1 2022 sampling event due to a faulty canister provided by the laboratory.

3. RESULTS

3.1 Vertical Profiling in Groundwater

Groundwater analytical results from WATERLOO APS™ borings completed during the reporting period are presented in Table 10a; the analytical results for associated WATERLOO APS™ QC samples are presented in Table 10b. Table 10c summarizes WATERLOO APS™ sample depths and associated monitoring well screen intervals. Groundwater analytical results from WATERLOO APS™ samples are compared to groundwater analytical results from associated screen intervals in nearby monitoring wells in Table 11.

WATERLOO APS™ groundwater analytical results are generally consistent with groundwater analytical results from nearby monitoring wells where comparable data are available, as shown in Table 11. The WATERLOO APS™ data were compared to data from the Q3 2022 groundwater monitoring event because this was the first quarterly monitoring event completed after all corresponding monitoring wells were installed.

Groundwater samples collected from monitoring wells represent flow-weighted averages across the saturated well screen interval, whereas groundwater samples collected from WATERLOO APS™ borings are collected from a discrete 4-inch interval. Due to this difference in sampling interval length, individual analyte concentrations may not be comparable between the two sampling devices (i.e., monitoring wells can sample approximately 30 4-inch intervals whereas the WATERLOO APS™ samples only one of them at a time); however, the list of analytes detected from both monitoring devices are comparable. In most WATERLOO APS™ samples, all analytes detected at concentrations above laboratory reporting limits (RLs) were also detected in the corresponding monitoring well samples. Several samples are J-qualified, meaning the reported result is an estimate that is less than the reporting detection limit but greater than the method detection limit (MDL). The WATERLOO APS™ analytical results are considered screening data and were not validated; therefore, the qualifiers in this data set were assigned by the laboratory. In several cases the reporting detection limits used for the WATERLOO APS™ analytical results differed from those used for the data in the corresponding monitoring well samples. With one exception, all analyte concentrations were comparable between the two sampling devices despite any differences in RLs. A discrepancy was observed between the two sampling devices for vinyl chloride with a concentration of 0.94 J micrograms per liter (µg/L) in APS-015 compared to 16.1 µg/L in MW-501-P3. The difference in concentration between the WATERLOO APS™ and the monitoring well sample is due to the difference in sampling interval.

3.2 Geophysical Logging

Geophysical logging results were used to assess various geologic and hydrogeologic properties, as summarized below in Table 3-1. ERM used the collective dataset to interpret geologic conditions, to inform monitoring well screen interval selection (as discussed in Section 2.3.5), and to update the CSM (as discussed in Section 4). Spatial correlation of geophysical logs was completed using characteristic curve-matching methods to assess lateral continuity in lithology and develop two-dimensional and three-dimensional visualizations of geologic stratigraphy. Appendix I includes a more detailed discussion regarding how various indicators and geophysical logs were used to correlate changes in geology/stratigraphy between well locations. Table 3-1 includes a summary of the various geophysical tools used during this reporting period. A more detailed version of this table was included as Table 3-3 in the FSP.

Table 3-1: Implemented Geophysical Methods and Their Data Use

Geophysical Method	Derived Hydrogeologic Properties
Nuclear Magnetic Resonance (NMR)	Total porosity, pore size distribution (mobile/capillary bound/clay bound porosity), hydraulic conductivity, transmissivity, lithology, residual water saturation (vadose zone)
Dual Induction	Lithology, pore fluid chemistry (Total Dissolved Solids)
Natural Gamma	Lithology, presence of anthropogenic gamma emitting radionuclides
Spectral Gamma	Identify and quantify the amount of uranium, thorium, and potassium-40 isotopes in boreholes from natural or anthropogenic sources
Caliper	Stability of borehole, presence of washouts, location of fractures
Fluid Temperature/Resistivity	Intervals of groundwater fluid moving into or out of borehole (e.g., open fractures)
Acoustic Televiewer	Identify lithologic bedding and contacts, fractures, fracture aperture and orientation; Identify well construction and integrity (run in well casing)
Corehole Dynamic Flowmeter	Identify intervals of groundwater flow into or out of the borehole; quantify flow volumes from yielding intervals; estimate hydraulic conductivity of yielding intervals or fractures; identify and quantify ambient flow under vertical gradients; aquifer hydraulic conductivity from short-term aquifer pumping test

For each well where geophysical logging was conducted, a combined summary log is presented for the alluvium and bedrock logging runs in Appendix D. Results of spectral gamma radiation station testing, corehole dynamic flowmeter testing, depth-specific groundwater sampling, and an analysis of the acoustic televiewer fracture data are also included in Appendix D.

Multiple tools were used that can independently detect changes in lithologic properties or groundwater quality characteristics, and in combination provide multiple lines of evidence for such changes. For example, both gamma and electrical conductivity logs will respond to higher clay content and serve as lithologic indicators, but the electrical conductivity will also respond to the presence of elevated inorganic solute concentrations in groundwater (i.e., constituents that affect the electrical conductivity of groundwater). If there is an observed increase in the electrical conductivity without a similar increase in gamma radiation, it can be assumed that the electrical conductivity response is due to water quality rather than lithology. This can be especially useful at landfill sites, where elevated inorganic solute concentrations in groundwater are often observed.

Nothing anomalous was identified while examining the spectral gamma ray (SGR) data relative to the natural gamma data, the long and short conductivity data, or NMR data. Many well locations intersect a shallow zone with clay-bound and capillary-bound fluid, which is associated with an increase in both natural gamma and SGR activities; this shift is most significant in the uranium and thorium series data. These increased gamma activities are associated with the loess material in the shallow zone. Other wells have thin clay and capillary bound fluid zones deeper within the alluvial sequence, but without such significant shifts in SGR as seen in the shallower sections. Some wells have deeper zones with significant shifts in long and short conductivity, but without corresponding shifts in natural gamma or SGR suggesting changes in pore water chemistry (i.e., increased in total dissolved solids rather than soil matrix materials. Natural and SGR counts in bedrock are generally quite low, except in intervals characterized as argillaceous limestone and claystone.

3.3 Geological Boring Logs

Borings completed during rotosonic drilling activities within the reporting period are shown on attached Figures 1a through 1c. Boring logs of recovered rotosonic core associated with these locations are provided in Appendix C.

A comparison of the geologic interpretations derived from the various geophysical logs with the lithological descriptions observed and recorded on the boring logs generally shows a good correlation. Intervals where NMR data indicated relatively high mobile porosity and hydraulic conductivity within the alluvium are typically described in the boring logs as sands and gravels. Thin beds (typically less than 1-foot thick) of finer-grained silty and clayey material observed in the borings correspond to zones of increased capillary bound material in the NMR geophysical logs[10]. These thin beds of lower permeability material also correspond to higher values in the electrical conductivity and natural gamma logs, which have higher vertical resolution than the NMR tool (generally less than 0.1 feet). Although there is generally good correlation between the geophysical and geologic logs, incomplete core recovery is a common problem that affects the accuracy of depth interpretations on boring logs. As such, it is common to see small discrepancies between measured depths of certain geologic features on the geophysical logs versus the boring logs.

In bedrock, variations in limestone type and rock quality are often subtle and are more readily detected by geophysical tools than visual observation (e.g., the degree of clay mineral content can be determined using the natural gamma log but cannot be easily discerned visually). Because of this, ERM's field geologists used the geophysical logs to support field identification of formation contacts and other rock quality variations that could otherwise be difficult to determine visually. Bedrock boring logs correlate well with the acoustic televiewer and mechanical caliper results for fracture identification.

The geological boring logs include total VOC headspace concentrations that were measured in soil using a photoionization detector. Additionally, one groundwater screening sample was collected from each open bedrock borehole and analyzed for VOCs; these results are included in Appendix D, Table D-1. Since the groundwater screening samples in bedrock were not depth-specific, they were not included on the boring logs and were not used to inform the selection of well screen intervals. Instead, groundwater analytical screening results from the WATERLOO APS™ borings were used as a more reliable source for quantifying the presence of VOCs below the water table in alluvium, and the collective interpretation of the geophysical logs, as described in Section 3.2, was used to select well screen intervals in bedrock. ERM used both the geophysical logs and boring logs as a collaborative dataset to develop the CSM and make geological interpretations.

3.4 Aquifer Matrix Sampling

Validated aquifer matrix analytical data are provided in Table 12[11]; the analytical results for associated QC samples are presented in Table 13. Data validation reports from the reporting period are provided as Appendix J.

Several general chemistry results for samples collected for MW-404 and MW-502 were rejected due to temperature and holding time exceedances; however, the metals and radiochemistry parameters were analyzed within holding time and did not have temperature preservation requirements. A total of 142

[10] The vertical resolution of the NMR logs is about 1.5 feet, so the hydraulic characteristics of geologic horizons that are thinner than this will be averaged with surrounding material. In some cases, if a layer is very thin (i.e., inches), the averaged NMR data may not allow for identification of the layer; however, in most cases, the NMR data allow for identification of relatively thin features, but the mobile porosity and hydraulic conductivity data may be biased due to averaging with surrounding materials.

[11] Tables 12 and 13 contain validated data from both the 2021 and 2022 reporting periods for completeness.

aquifer matrix results were qualified as rejected out of 4,590 total results for an overall completeness rate of 96.9 percent. The rejected parameters do not hinder matrix characterization activities at the Site.

Radionuclide data collected from aquifer matrix samples are discussed in Section 4.6.

3.5 Groundwater Elevation Monitoring

3.5.1 Monthly Monitoring Well Gauging

Monthly gauging of the OU-3 well network was completed throughout the reporting period, as described in Section 2.5. Monthly gauging data are presented in Appendix K and monthly potentiometric surface maps for the reporting period are provided in Appendix L. Monitoring well installation activities were ongoing throughout much of the 2022 reporting period, increasing the density of monitoring locations as well as the spatial and vertical coverage of the well network. As such, available water level data and resulting potentiometric maps evolved throughout the 2022 reporting period and allowed for the generation of more comprehensive potentiometric maps as the well network became more complete. Many of the on-Site well installation activities were completed during the first half of the reporting period (i.e., Q4 2021 through Q1 2022), while off-Site well installations were completed in Q3 2022.

Until the off-Site well network was complete and gauged for the first time in Q3 2022, the approach for potentiometric mapping remained consistent with the approach used during the 2021 reporting period. This approach treated the alluvium as a single flow system and combined the previously (i.e., pre-RI) categorized “shallow”, “intermediate”, and “deep” alluvium wells into a single map, which honored the lowest head value at each well cluster (presumed to be representative of the most transmissive interval within the alluvium) for contouring. These single unit alluvium potentiometric maps were also generated for Q4 2021 through Q2 2022. Hydraulic gradient direction and therefore presumed groundwater flow directions are generally to the northwest, though seasonal variability affects the overall direction.

Beginning in Q3 (July) 2022, separate potentiometric surface maps were prepared for the recharacterized “Upper”, “Middle”, and “Lower” alluvium time stratigraphic units (TSUs). Additional discussion of how these alluvium units were discretized and how wells were assigned to each alluvium unit is included in Appendix I and in Section 4.4. At locations where multiple wells within a cluster are screened within the same alluvial unit, the lowest head value within the well cluster was used for contouring, unless otherwise noted on the maps. Additional discussion of the hydraulic influences on seasonal variability in groundwater elevations and resulting groundwater flow directions is provided in Sections 4.3. and 4.5.

Bedrock at the Site consists of four primary formations (St. Louis, Salem, Warsaw, and Keokuk). However, monthly potentiometric maps generated for the bedrock well network are simplified into two mapping units. Hydraulic head data for wells screened within the St. Louis and Salem Formations are grouped into a single map unit, as these formations are sequential to one another, share similar hydrogeologic characteristics (such as their respective range in hydraulic conductivity values), transition gradually, and are observed to have very similar hydraulic heads. Bedrock wells screened within the St. Louis and Salem Formations have primarily been arrayed around the perimeter of the former quarries (i.e., the Bridgeton Landfill), with most wells located on the south side of Bridgeton Landfill. For this reason, potentiometric maps produced during the 2021 reporting period and Q4 2021 through Q2 2022 of this reporting period only present potentiometric contours in the immediate vicinity of the Bridgeton Landfill. Well installation activities completed during the 2022 reporting period have increased the spatial coverage of the Salem Formation bedrock well network in other areas of the Site, as well as off-Site (Figure 1c). Expansion of the well network now allows for contouring of head data for these formations in areas further to the north and northwest of the Bridgeton Landfill beneath the entire Site and off-Site to the north and west. The St. Louis Formation has been scoured and removed within the alluvial valley a short distance north of the Bridgeton Landfill (Figure 4-18) and as a result, the newly installed bedrock wells are primarily Salem Formation wells. For consistency, in the few instances where there are paired St. Louis Formation and Salem Formation wells north and west of the Bridgeton Landfill, the Q3 potentiometric maps relied on the water level value from the well installed in the Salem Formation. Potentiometric surface maps for the St. Louis and Salem Formations contour head data to the south and east of Bridgeton Landfill utilizing a 10-foot contour interval due to the steep hydraulic gradients in these areas. Beginning in Q3 (July) 2022, a second set of contours using a 0.25-foot interval have been added to the St. Louis and Salem potentiometric maps to evaluate head data north and west of Bridgeton Landfill where the hydraulic gradient in the bedrock units is much lower. In this portion of the Site, the St. Louis Formation has been eroded and is absent, and the Salem Formation is in physical contact and hydraulic communication with the overlying alluvium. As a result, the gradient flattens and converges with that of the alluvial aquifer. While the magnitude of the groundwater gradient is considerably different between areas southeast and northwest of the Bridgeton Landfill, a general hydraulic gradient and groundwater flow direction to the northwest is observed throughout the bedrock formations.

The Warsaw Formation has lower bulk hydraulic conductivity values (generally one to two orders of magnitude; Figure 4-14) than the St. Louis and Salem Formations, and potentiometric surface maps are not generated using the Warsaw Formation wells. Four monitoring wells screened in the Keokuk Formation are presented in a separate monthly potentiometric surface map to evaluate groundwater elevations and flow direction. Monthly head data from the Keokuk Formation wells have generally been consistent throughout the 2022 reporting period. Data indicate a general hydraulic gradient and presumed groundwater flow direction to the northwest, consistent with gradient direction in the St. Louis Formation and Salem Formation bedrock units (see Section 4.5.7).

Vertical hydraulic gradients were evaluated for individual on-Site well clusters by plotting groundwater elevation time-series plots (i.e., both multi-level wells and well clusters) where well screens were set in different alluvium TSUs and in bedrock. Section 4.5.6.3 provides a detailed discussion regarding the vertical gradient analysis. In the northern and central portions of the Site, vertical hydraulic gradients are quite small, and the Salem Formation appears to be in communication within the alluvial valley. The plots for well groups located closer to the bedrock uplands area indicate an upward vertical hydraulic gradient between bedrock and alluvium. Upward vertical gradients are observed between the Keokuk Formation and the Salem and St. Louis Formations (10- to 20-foot head differences in nested Keokuk and Salem/St. Louis Formation wells) demonstrating the confining nature of the Warsaw Formation.

At the end of 2021, ERM began obtaining information about the LCSs, landfill liquids extraction system, and landfill characteristics from Bridgeton Landfill staff. Figure 2 is a map showing landfill liquid condensate collection locations, LCSs and other landfill liquids recovery locations that were pumping at the end of the reporting period. Between 1 October 2021 and 30 September 2022, the leachate pretreatment plant treated 37,339,876 gallons[12], which included leachate and condensate from LCSs, gas extraction wells, and condensate collection locations within the Bridgeton Landfill, and K-128, which is located adjacent to the western boundary of the Bridgeton Landfill.

The operational status of the LCSs within the Bridgeton Landfill South Quarry was discussed in Section 2.2.2. Liquid levels are not collected from the LCSs, for the reasons discussed in Section 2.2.2. During 2023, pressure transducers will be moved to alluvial wells located adjacent to the Bridgeton Landfill South Quarry to improve spatial coverage of continuously monitored water levels across the Site, which will also help investigate the potential effects, as applicable, of landfill liquids pumping within the alluvial aquifer.

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[12] Leachate pretreatment plant volumes are operational field data that have not been verified or validated. These data represent volumes of water that came to the pretreatment plant through the West Lake Lift Station and the leachate collection system force main to TK-200. These values exclude potentially impacted stormwater volumes and water used in leachate pretreatment plant processes. As with any field data, there is the possibility of errors, omissions, or irregularities as a result of technical malfunctions, operational changes, or a variety of other reasons which could impact the accuracy and/or completeness of the data.

3.5.2 Pressure Transducer Data

Pressure transducer data are downloaded from monitoring wells, stilling wells, and one piezometer during monthly gauging events. Pressure readings recorded on the transducers are used to calculate surface water (stilling wells) and groundwater (monitoring wells/piezometers) water level data once per hour. High-resolution surface water and groundwater elevation data have been plotted as hydrographs (Appendix M) to allow analysis of temporal changes in groundwater and surface water elevations, evaluate vertical and horizontal hydraulic gradients, and evaluate effects of liquid removal from within the Bridgeton Landfill on water levels in bedrock wells adjacent to this landfill. Discussion of the interpretations developed using pressure transducer data are included in Section 4.5.

The pressure transducers installed in the existing (pre-RI) monitoring wells (Table 3-1c of the FSP), stilling wells, and one piezometer (PZ-5) have recorded data throughout the reporting period, aside from exceptions due to operational issues related to the stilling wells, which are noted in Sections 2.6 and 2.9. The pressure transducers installed in the CHS and WF multi-level wells began recording data as the multi-level wells were installed and have generally operated continuously since that time. MW-502 was the final multi-level well installed; the transducers at this location began recording in early August 2022.

Hydrographs from transducers installed in bedrock well locations (Appendix K) show a response to purging during sampling. These occurrences appear as instantaneous drawdown followed by relatively quick recharge. The drawdown and duration of the recharge is the result of low transmissivity, creating a recharge cycle that lasts longer than the transducer logging interval (one hour).

3.5.3 Groundwater Elevation Data Quality Review

A robust, three-step QA/QC process was developed during Q2 2022 and implemented monthly to identify gauging data discrepancies (disagreement between manual measurements and digitally collected water level gauging data collected from transducers) and potential data anomalies (disagreement between manual gauging data and corresponding transducer data). The first step is QC of the manual water level gauging data received from the field. The second step is assessment of water level data for potential anomalies between manual gauging data and corresponding transducer data. The third step is the individual review of potential anomalous data flagged by the Python program (explained in further detail below). This QA/QC process is described in detail in Appendix K and summarized below.

1. Water level data collected from the Site are reviewed to ensure that manual measurements that are documented both on hardcopy field sheets and recorded digitally are in complete agreement for quality assurance. Any discrepancies between the two data forms are corrected manually and noted in the database.
2. Transducer data are downloaded and compared to corresponding monthly manual water level measurements. A Python programming language script is employed to quantitatively compare the two water level data sets to identify potentially anomalous water level data. Potentially anomalous data are flagged for further review and consideration for their use in generating potentiometric surface maps.
3. Data flagged by the Python program are reviewed against historical manual water level (time series) and transducer data to assess water level trends at each monitoring location and better characterize potentially anomalous data in the context of historical data trends. Data deemed to be anomalous are indicated on their respective potentiometric maps and are not used to develop groundwater contours.

A summary of anomalous data is included in Appendix K. Additionally, any transducer data used on potentiometric surface maps in place of anomalous manual gauging data are also indicated in Appendix K. All gauging data are included in the respective hydrographs for completeness.

3.6 Third-Party Data

Relevant third-party data collected during the reporting period were evaluated as part of the OU-3 RI, as described in Section 3.19 of the FSP and as amended by Tech Memo 15. The third-party data types and sources of data collected during the reporting period included certain data generated by Bridgeton Landfill, precipitation data from the NOAA weather station, river stage data from the USGS, and off-Site piezometer (owned and operated by HBLD) data, as listed in Section 2.10 of this report.

Precipitation, river stage, and piezometer data are plotted to enable temporal comparison of precipitation, river stage, groundwater, and surface water elevation. Hydrographs showing the HBLD piezometer gauging, Missouri River stage, and precipitation data are included as Appendix M. The relationship between groundwater and surface water elevations and precipitation data is discussed further in Sections 4.3 and 4.5.

ERM reviewed the monthly leachate treatment volumes from the Bridgeton Landfill reports discussed in Section 2.10. Data from the reporting period were tabulated and are shown on the plot below (Figure 3-1). Available OU-1, OU-2, and Bridgeton Landfill gas monitoring probe data were also reviewed, and these results are discussed in Section 3.9.

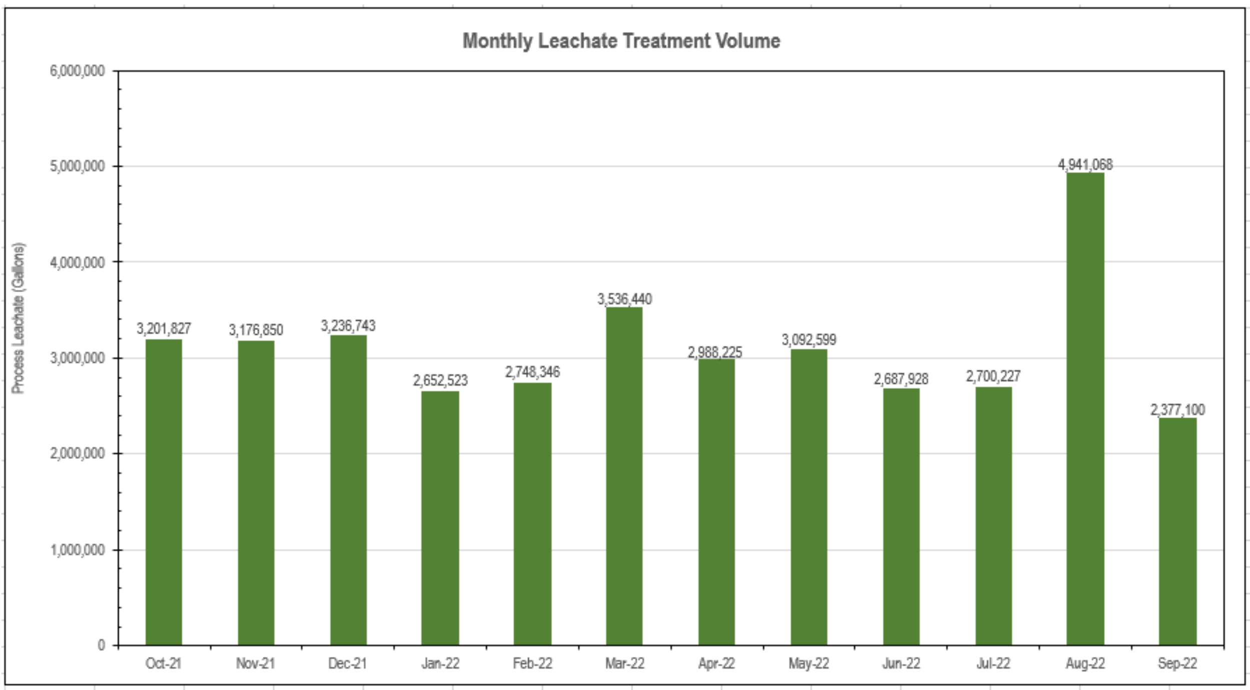

Figure 3-1: Monthly Leachate Treatment Volume

3.7 Groundwater and Leachate Analytical Results

Validated analytical data for groundwater and leachate from the reporting period are provided in Tables 14a through 14h and Tables 15a through 15h, respectively. Validated field QC sample data from the reporting period are provided in Tables 16a through 16c. Data validation reports are provided in Appendix J.

The attached tables include highlighting to identify detect and non-detect results that are greater than the USEPA maximum contaminant levels (MCLs) and/or the regional screening levels (RSLs)—both of which are used here for comparison purposes. As specified in the QAPP, the RSLs are used to answer the

PSQs related to the presence and distribution of COPCs. MCLs are also provided for informational purposes as specified in the Statement of Work. For some of the highlighted non-detect analytes, the laboratory RL in the USEPA-approved QAPP is higher than the MCL or RSL. The attached tables also include any relevant validation qualifiers. Section 3.7.1 and Appendix O include additional discussion related to analytical data quality for the reporting period.

Statistical summaries and box and whisker plots for the validated groundwater data are provided in Appendix N. The statistical summaries (Appendix N) include all analytes that were detected at concentrations above the laboratory RL in at least one sample and are separated by the unfiltered (total) and the filtered (dissolved) data. Field duplicate samples were excluded from the statistical summaries. Box and whisker plots are provided for analytes that were detected at concentrations above the laboratory RL in at least five samples to show the Site-wide range of detected values for these analytes. For analytes with established MCLs and/or RSLs, the MCLs and/or RSLs are shown on the box and whisker plots for comparison purposes. These statistical summaries and plots are included to provide quick visualizations of descriptive statistics for individual analytes and comparisons of analytes against MCLs and/or RSLs, when available. Additional statistical analysis of the data, as specified in Section 4.3.2 of the QAPP, will be completed when all RI data have been collected.

Over 300 analytes are evaluated. Eleven COPCs, listed alphabetically, were selected[13] (referred to as "select COPCs") to discuss in the text. Plan view maps and cross-section figures for alluvium and bedrock groundwater are included for eight of the 11 COPCs, as noted below:

- Arsenic (Figures 9a and 9b)
- Benzene (Figures 10a and 10b)
- cis-1-2-Dichloroethene (Figures 11a and 11b)
- 1,4-Dioxane (Figures 12a and 12b)
- 2-Methylnaphthalene (see discussion below)
- Combined radium 226/228 (Figures 13a and 13b)
- Tetrahydrofuran (THF; Figures 14a and 14b)
- 1,2,4-trimethylbenzene (see discussion below)
- Uranium (Figures 15a and 15b)
- Vinyl chloride (Figures 16a and 16b)
- Thorium Isotopes (see discussion below)

For eight of the 11 analytes listed above, the reporting period average and range of detected concentrations, along with the frequencies of detections and MCL and/or RSL exceedances in alluvium and bedrock groundwater are summarized in the table below. The reporting period average and range of detections in leachate for each select COPC are also provided. For all averages and ranges presented, unfiltered (total) data are used, field duplicates are included, and samples identified as non-detect are excluded. 2-Methylnaphthalene, 1,2,4-trimethylbenzene, thorium-230, and thorium-232 were all detected in fewer than 8 percent of bedrock and alluvium groundwater samples. 2-Methylnaphthalene was only detected above the RSL of 3.6 µg/L in 1.3 percent of alluvial samples, and in no bedrock samples. 1,2,4-trimethylbenzene was only detected above the RSL of 5.6 µg/L in 2.6 percent of alluvial samples, and in

[13] These COPCs were selected following a quantitative process based on USEPA Superfund risk assessment guidance (USEPA 1989). The purpose of the COPC selection was to develop a list of analytes to represent visually on figures while the RI is in progress, since it would be impractical to try to show all 350 analytes are assessed as part of the RI on figures. USEPA requested that thorium isotopes be included in the list.

no bedrock samples. Thorium isotopes are not directly regulated but they were present in minimal concentrations with a combined maximum concentration below 1.0 picocuries per liter (pCi/L). Plan view and cross-section figures for 2-methylnaphthene, 1,2,4-trimethylbenzene, and thorium isotopes were presented in the 2021 Annual Report but since they are only detected in a small percentage of samples in localized areas, these figures do not provide additional value for visualization and therefore were not included with this report.

Table 3-2: Groundwater and Leachate Analytical Summary Table

		Arsenic	Benzene	cis-1,2-DCE	1,4-dioxane	Radium-226/228[14]	THF	Uranium	Vinyl Chloride
	Unit	µg/L	µg/L	µg/L	µg/L	pCi/L	µg/L	µg/L	µg/L
Alluvium	Average Detected Result	32.3	96.2	1.46	281	4.08	621	0.937	2.64
	Range of Detected Results	0.11J to 551	0.26J to 877	0.19 to 16.2	0.597J to 15,900[15]	0.837 to 12.3	1.3J to 20,200	0.009J to 12.3	0.46J to 16.1
	Average Background Concentration16	1.41	0.71J	ND	6.70	2.58	ND	1.29	ND
	Range of Background Concentrations4	0.13J to 3.3J	0.71J to 0.71J	ND	3.81 to 9.47	1.28 to 3.68	ND	0.059J to 7.7	ND
	RSL	0.052	0.46	2.5	0.46	NA	340	0.40	0.019
	MCL	10	5	70	NA	5	NA	30	2
	Percent Detections Above RSL	100%	92.9%[17]	12.2%	100%	NA	10.8%	31.1%[5]	100%
	Percent Detections Above MCL	30.9%	48.2%	0%	NA	31.7%	NA	0%	44.4%

[14] Radium-226/228 refers to the combined sum of activities from isotopes radium-226 and radium-228.

[15] On 18 November 2022 Bridgeton Landfill resampled I-73 and PZ-205-AS for 1,4-dioxane. The 1,4-dioxane concentrations in I-73 and PZ-205-AS were 2,130 and 1,410 µg/L, respectively, which confirmed that the Q3 2022 results were anomalous.

[16] Only includes data from Q3, 2022 where data were available for all background monitoring well locations.

[17] Although the method reporting limit of 1.0 µg/L is above the RSL, the MDL is lower, so J-qualified values (estimated below the reporting limit) were included.

		Arsenic	Benzene	cis-1,2-DCE	1,4-dioxane	Radium-226/228[14]	THF	Uranium	Vinyl Chloride
	Unit	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**pCi/L**	**µg/L**	**µg/L**	**µg/L**
Bedrock	Average Detected Result	3.46	21.7	0.62	152	5.62	87.2	1.36	1.6
	Range of Detected Results	0.11J to 42.8	0.39J to 180	0.26J to 1.00	0.731 to 5,600	1.22 to 44	1.6J to 741	0.023J to 15.7	0.59J to 2.7
	Average Background Concentration[3]	2.54	0.42J	ND	4.32	2.40	ND	3.14	ND
	Range of Background Concentrations[3]	0.35 to 5.0	0.42J to 0.42J	ND	1.58 to 7.06	0.98 to 5.12	ND	0.13 to 15.7	ND
	RSL	0.052	0.46	2.5	0.46	NA	340	0.40	0.019
	MCL	10	5	70	NA	5	NA	30	2
	Percent Detections Above RSL	100%	91.3%[5]	0%	100%	NA	7.35%	65.1%[5]	100%
	Percent Detections Above MCL	8.6%	30.4%	0%	NA	26.2%	NA	0%	33.3%
Leachate	Range of Detected Results	10.8 to 592	2.9J to 247	1.2J to 1.8J	221 to 10,300 µg/L	6.02J to 22.5J	74.0 to 8,430	0.02J to 0.40J	NA
	Percent Detects	100%	87.5%	12.5%	100%	93.8%	100%	38.9%	0%

Note: All values reported are for unfiltered (total) groundwater samples collected during the reporting period.
cis-1,2-DCE = cis-1,2-dichloroethene, THF = tetrahydrofuran, ND = not detected, NA = not applicable.

3.7.1 Groundwater and Leachate Data Quality Summary

The laboratory met the approved RLs in the project QAPP with some exceptions. In most cases the instances of elevated RLs were due to high concentrations of other target analytes and/or matrix interferences. Other variances in RLs for extractable methods were due to variances in initial sample volume used for extraction or the presence of sediment in the sample after extraction. In rare cases, lower sample volumes resulted in RLs slightly higher than the QAPP RLs. Field teams were reminded prior to all sampling events to fill all sample bottles completely to maximize sample volume and minimize the variability in method RLs; however, this may not have been possible in all instances due to low yields for some of the wells. Laboratory decisions that impact the method RL of a constituent are made on a quarterly basis to achieve the best sensitivity during every sampling event. Results with values between the MDL and the method RL are reported as detected but with estimated concentration (J-flagged) to provide some additional sensitivity. Non-detect radiochemistry results that did not meet the required project detection limit are identified in the validation reports and were qualified as “UJ” per Multi-Agency Radiological Laboratory Analytical Protocol guidance (USEPA 2004). ERM will continue to monitor laboratory RLs closely. The following changes to analyte sensitivity occurred during the reporting period:

- Iron RL increased from 50 µg/L to 100 µg/L prior to the Q3 2022 sampling. The increased RL is still below the lowest screening level in the QAPP of 300 µg/L.
- Total alkalinity, bicarbonate alkalinity, and carbonate alkalinity RLs increased from 2,000 µg/L to 10,000 µg/L prior to the Q3 2022 sampling. The project QAPP does not have screening levels for these analytes.
- Iodide MDL increased from 91 to 147 µg/L (note: the RL did not change) prior to the Q3 2022 sampling. Both the MDL (old and new) and RL for iodide are above the lowest screening level of 20 µg/L in the QAPP. These changes were a result of the ongoing annual verification of MDLs performed by Pace Analytical Services, LLC (Pace).

No major impacts to the overall data quality are expected due to changes in the RLs listed above. The higher MDL for iodide may result in fewer trace-level detections, but the sensitivity at the RL has not changed. Data presented in Tables 14a through 15h include the RL for each non-detect analyte relative to the RL at the time of analysis.

As shown in Tables 16a through 16c, detections in field QC blanks for non-radiochemistry analytes were typically trace-level detections below the RL, with some exceptions. Table 3-3 shows the relative frequency of analytes detected in each type of blank collected in the field above the RL or minimum detectable concentration (MDC) during the reporting period to provide an overview of trends and possible contamination sources. Trip blanks are not included in Tables 16a through 16c. Only three instances of analytes detected above the RL in trip blanks occurred during the reporting period. These included total petroleum hydrocarbon ranges C6-C12 in one trip blank from Q2 2022, likely due to laboratory contamination, and one detection of methylene chloride just above the RL Q3 2022. No analytes were detected above the RL in filter blanks, as shown in Table 16c. Due to a lack of detections, trip blanks and filter blanks were not included in Table 3-3.

Table 3-3: Frequency of Detections in Field-Collected Blanks Above the RL or MDC

Quarter	Q4 2021		Q1 2022		Q2 2022		Q3 2022	
Blank Type	EB	FB	EB	FB	EB	FB	EB	FB
Fraction	Total	Total	Total	Total	Total	Total	Total	Total
Sample Count	8	6	9	8	10	8	19	10
Analyte								
Bicarbonate Alkalinity as CaCO3	7	NA	9	NA	7	NA	0	NA
Alkalinity, Total as CaCO3	7	NA	9	NA	7	NA	0	NA
Ammoniacal Nitrogen NH3N	0	NA	0	NA	1	NA	0	NA
Chemical Oxygen Demand	0	NA	0	NA	3	NA	0	NA
Cyanide CN-	0	NA	1	NA	0	NA	0	NA
Nitrite + Nitrate as N	0	NA	3	NA	0	NA	0	NA
Carbon dioxide	0	0	0	1	0	0	1	0
Methane	0	2	2	1	1	1	0	0
Aluminum	0	0	0	0	0	1	0	0
Chromium	0	0	0	0	0	0	1	0
Chromium (VI)	0	0	0	0	0	0	1	0
Copper	0	0	0	0	1	0	2	0
Manganese	0	0	0	0	1	0	0	0
Nickel	0	0	0	0	0	0	1	0
Caprolactam	0	0	0	0	1	0	0	0
Toluene	0	0	0	1	0	0	0	0
Carbon disulfide	0	0	0	0	0	0	1	0
Methylene chloride	0	0	0	0	0	0	0	0
Radium-226	0	0	0	0	1	1	1	1
Radium-228	1	0	0	0	0	1	2	0
Uranium-234	2	2	1	1	1	2	4	2
Uranium-235	0	3	0	2	0	2	1	2
Uranium-238	0	5	1	1	2	1	1	2
Tritium	2	0	0	0	0	1	0	2

EB = equipment blank, FB = field blank, NA = not applicable.

None of the non-radiochemistry select COPCs identified and discussed in Section 3.7 were detected in any of the equipment, field, filter, or trip blank samples above the RL. For radiochemistry COPCs, radium-228 was detected in three EB samples and one FB sample during the reporting period. Radium-226 was detected in one EB and one FB in both Q2 and Q3 2022 events. All detections were above the MDC, but below the project required RL. A total of 33 radium-228 and 23 radium-226 results were conservatively qualified as estimated with a potential high bias ("J+") due to potential equipment and/or field blank contamination. Monitoring well locations that required qualification more than once in the reporting period due to radium-228 or radium-226 equipment blank and/or field blank contamination were wells MW-400-P1, MW-400-P2, MW-400-P3, and MW-400-P4 for radium-228 only. Associated combined radium-226/228 results were also qualified as estimated with a potential high bias.

As described in Section 2.3.6, drilling rods were not decontaminated in complete accordance with the SOP between drilling at co-located background wells MW-600-P1, MW-600-P2, and MW-600-P3. Based on a review of analytical data collected from these locations during three quarterly sampling events (Q1 through Q3 2022), there is no evidence of cross contamination between boreholes due to the lack of decontamination. The lowest COPC concentrations were detected in the deepest well (MW-600-P3), which was drilled first, and detections at each well have been generally consistent over three quarters of sampling.

In accordance with the QAPP, sample results were rejected during validation if there were serious deficiencies in meeting QC criteria and if the presence or absence of the analyte in the sample could not be verified. Rejected values have been flagged with an "R" qualifier and included in the summary tables. Rejected data have not been (and will not be) used to meet the objectives of the RI/FS or for other data interpretation purposes. A total of 169 results were rejected out of over 194,000 reportable results from monitoring well and LCS samples collected during the reporting period, for a completeness rate of 99.9 percent. The number of rejections generally declined over the reporting period, with 59 results rejected in Q4 2021, 46 in Q1 2022, 50 in Q2 2022, and 14 in Q3 2022. The decrease in rejections in Q3 2022 is related to changes in laboratory procedure; while laboratory control spike recoveries for hexachloroethane and hexachlorocyclopentadiene below 10 percent are allowed by the method, prior to Q3 2022 ERM requested that the laboratory reanalyze any batch with a laboratory control spike recovery below 10 percent to meet the project's data quality objectives. Rejections of hexachloroethane and hexachlorocyclopentadiene accounted for 45 of the total 169 rejected results, all from Q4 2021 to Q2 2022, with no rejections in Q3 2022 after the change was implemented. The completeness rate complies with the 95 percent completeness objective detailed in the QAPP. The OU-3 Respondents expect to generate enough usable data for these analytes during the RI to adequately assess the project's principal study questions. ERM will continue to closely review rejected data and consider alternative analytical methods, as needed, if the project data quality objectives are routinely not being met.

During the reporting period, several wells were resampled for a subset of methods due to laboratory and field shipping and handling errors. Because most wells were resampled, data losses were limited to one tritium field duplicate result and one carbon dioxide result, as discussed below. A detailed account of other resampling situations can be found in Appendix O.

- In Q4 2021, the tritium bottle for the I-9 sample broke in transit from Pace Indianapolis to Pace Pittsburgh. In Q2 2022, the tritium bottles for PZ-113-SS, D-89, and EB-009 samples broke in transit from Pace Indianapolis to Pace Pittsburgh. For all lost tritium samples, Pace Indianapolis filled a new 500-milliliter unpreserved amber bottle with extra sample volume from one of the two 1,000-milliliter unpreserved amber bottles collected for herbicide analysis and sent the sample to Pace Pittsburgh for tritium analysis. No impact to data quality is expected. After repeated instances of broken tritium bottles during inter-lab transport, ERM requested that Pace perform a root cause investigation. Pace provided a corrective action letter detailing findings and follow-up actions, which included improved packaging of samples.
- In Q3 2022, the tritium bottle for field duplicate DUP-007 (parent PZ-111-SS) broke in transit from Pace Indianapolis to Pace Pittsburgh. DUP-007 did not have additional unpreserved sample volume available. The field duplicate for tritium was not resampled since there were no issues with the parent sample; however, the broken bottle resulted in loss of a duplicate data point for tritium at PZ-111-SS.

ERM will continue to assess the frequency of broken bottles during transport and request additional mitigation measures, if needed.

- In Q2 2022, ERM was notified that Pace Gulf Coast had misplaced the vials for Method RSK-175 analysis for wells MW-113, MW-400-P4, and equipment blank EB-001. Pace Indianapolis was able to provide additional unpreserved vials to Pace Gulf Coast to perform the analysis outside of holding time. Only carbon dioxide for sample MW-113 could not be reported due to lack of sample volume, since only one additional vial was available. Data was qualified accordingly related to holding time deficiencies. ERM was notified of the loss after the end Q2 sampling event was completed and resampling was not feasible.

Additional notes related to analytical data quality for the reporting period sampling events are detailed below:

- In Q1 2022, analysis of herbicides by Method 8321 was added to all leachate samples in an attempt to achieve lower laboratory RLs. Due to various laboratory quality control issues found in Method 8321 analysis in Q1 2022, useful lower RLs were not achieved. Method 8321 was included on all leachate samples again in Q2 and Q3 2022. Method 8321 RLs were compared to those obtained by Method 8151 for Q2 and Q3 2022. In Q2 2022, Method 8321 herbicide RLs were generally lower than Method 8151 (2 µg/L versus 9 µg/L), however, lower RLs were not consistently achieved across all herbicide compounds or leachate sample locations. In Q3 2022, Method 8321 herbicide RLs were generally higher than Method 8151 (20 µg/L versus 9 µg/L). ERM will reassess the value of continued use of Method 8321 for future sampling events.
- Headspace greater than six millimeters was often noted in most or all of the preserved vials collected for each LCS location for volatile analysis (Methods 8260C, 8260C-SIM, 8011, and RSK-175) upon receipt at the laboratory. Whenever possible, vials without headspace are used for analysis. Generally, the assessment of headspace during login is overly conservative, and the bench chemist re-measures for headspace prior to analysis, noting any headspace issues on the run logs. In most cases during the reporting period, despite headspace being routinely observed in vials during login, only volatile results for two leachate samples required qualification due to vials with headspace being used for analysis. Regardless, ERM has taken steps to try to limit headspace in leachate sample upon receipt as feasible. Beginning in Q2 2022, ERM and Feezor implemented a Leachate Sampling SOP #21 that included cooling the leachate samples prior to transfer to sample vials in an effort to reduce headspace and possible data qualification. During the Q2 2022 sampling event, the laboratory noted that the majority of the preserved leachate sample vials continued to contain headspace greater than six millimeters. Beginning in Q3 2022, ERM and Feezor began collecting both preserved and unpreserved sample vials at the LCSs. Upon laboratory receipt of preserved and unpreserved Q3 2022 sample vials, it was noted that 36 out of 50 preserved vials contained headspace, and 33 out of 50 unpreserved vials contained headspace upon receipt at the laboratory. While the unpreserved vials have a shorter holding time and still contain headspace, ERM plans to continue to collect both sets of vials to provide additional opportunities for the laboratory to analyze vials without headspace.
- In Q1 2022, all target polycyclic aromatic hydrocarbon (PAH) compounds were detected at similar concentrations at well location MO-3-SS. PAHs have not been detected above the MDL in the three previous sampling events or any of the subsequent sampling events at this location. ERM suspects that the sample could have been inadvertently spiked with a PAH standard solution; however, the laboratory and the validators performed a thorough review of the data and could not find any evidence of human error or quality control deficiencies. By the time the anomalous results were identified, the field sample and extracts had already been disposed of, and reanalysis was not possible. Without any additional evidence to support a field or laboratory deficiency, the validators

kept the results as reportable. In accordance with the QAPP, once the OU-3 quarterly groundwater sampling is complete, ERM will review the entire data set for these locations, including use of outlier tests using appropriate statistical techniques, to determine final usability of these PAH results.

- In Q1 2022, the laboratory used hydrochloric acid-preserved vials for Method 8321B analysis due to erroneously logged samples during time of receipt. The laboratory stated that due to the hydrolysis step initially requiring the pH of the sample to be adjusted to greater than 12 standard pH units and then reduced back to less than 2 standard pH units, acid preservation of the original sample is not expected to have any impacts to the final results.
- In Q3 2022, several PAHs were detected at wells I-65, MW-501-P1, MW-501-P2, MW-501-P3, MW-401-P1, MW-401-P2, and MW-401-P3. Unlike the anomalous PAH detections at MO-3-SS described above, there was a mixture of detect and non-detect target PAH analytes. When compared to all PAH data collected for these wells during quarterly sampling prior to Q3 2022, I-65 had no PAH detections in the seven previous quarters of sampling and the MW-401 well series had no PAH detections in the two previous quarters of sampling. Q3 2022 was the first sampling event for the MW-501 series; thus, there were no prior data available for comparison. All these samples were analyzed in the same laboratory analytical batch and had similarly patterned chromatographs, which suggests the PAH detections may be anomalous; however, the laboratory and validators performed a thorough review of the data and could not find any additional supporting evidence of laboratory error or field contamination. There were other samples in the analytical batch, both West Lake OU-3 samples and non-client samples, analyzed before and after the noted samples, that were non-detect for all PAHs, indicating that sample carry-over is unlikely. Aside from the analytical batch, there were no other common variables between the samples: I-65 and the MW-501 series wells were sampled on the same day, but by two different sampling teams using different equipment, and the MW-401 series wells were sampled the next day by a team using a different WLM than was used at I-65 and MW-501. Field blanks were not planned or collected at these locations. Without any additional evidence to support a field or laboratory deficiency, the validators kept the results as reportable. In accordance with the QAPP, once the OU-3 quarterly groundwater sampling is complete, ERM will review the entire data set for these locations, including use of outlier tests using appropriate statistical techniques, to determine final usability of these PAH results.
- In Q3 2022, abnormally high concentrations for carbon dioxide were initially reported in field blank FB-002 and equipment blank EB-009. ERM requested the laboratory reevaluate the abnormally high blank concentrations. The laboratory determined that the two samples had been incorrectly analyzed at a 20 times dilution, and the solvent peak had been quantitated by their software in error. The analyst caught the error and reanalyzed both samples undiluted within holding time, however, the incorrect result was reported as final. The laboratory reissued the data package with the appropriate results. A formal corrective action letter will be prepared by the laboratory.

3.8 Groundwater Field Parameter Data Quality Summary

A summary of field parameters recorded at each monitoring well at the time of sampling is provided in Appendix F. Due to the aeration that occurs during the collection of field parameters at multi-level wells, dissolved oxygen measurements from multi-level wells are not considered representative, as indicated by an “X” qualifier. As noted in the FSP, dissolved oxygen measurements from multi-level wells are recorded for reference only.

During this reporting period, the following potentially anomalous field parameters were identified:

- During the Q1 2022 event, elevated pH readings were recorded at the four locations listed below.
    - PZ-100-SS (8.48 standard pH units; pH range for this location is 6.83-7.53).

  - PZ-100-SD (8.65 standard pH units; pH range for this location is 6.94-7.67).
  - PZ-100-KS (9.13 standard pH units; pH range for this location is 7.43-7.68).
  - MW-304-P3 (9.09 standard pH units; pH range for this location is 7.31-8.04).

- During the Q1 2022 event, low temperatures were recorded at MW-304-P3 (8.3 degrees Celsius), which is unlikely for natural groundwater. Temperatures measured on the same day from MW-304-P1 and MW-304-P2 were between 14.0 and 14.4 degrees Celsius.
- During the Q3 2022 event, dissolved oxygen was measured at 50.7 and 42.2 milligrams per liter at MW-213-P1 and MW-213-P2, respectively. These values are well above the maximum possible level of dissolved oxygen. Previous dissolved oxygen readings at these locations ranged from 1.34 to 7.53 milligrams per liter. Based on these multiple lines of evidence, the two dissolved oxygen readings were changed from 50.7 to 5.07 and 42.2 to 4.22 milligrams per liter, respectively.

Field staff have access to historical field parameter data and have been instructed to compare field parameters to historical ranges to identify potential inconsistencies in the field.

3.9 Vapor Intrusion Sampling Results

As described in Section 5.3.9 of the OU-3 RI/FS Work Plan, the vapor intrusion evaluation includes an evaluation of the potential for VI into Site buildings and an evaluation of vadose zone soil gas quality, using landfill gas data generated by Bridgeton Landfill, OU-1, and OU-2. Results of reporting period sampling activities are presented below.

3.9.1 OU-3 Investigation Activities

Vapor intrusion sampling was completed at Site buildings as described in Section 2.11. Validated IA/AA VOC and methane analytical results for samples collected during the reporting period are presented in Table 17. Validated ST SSV radon results for samples collected during the reporting period are presented in Table 18. Validated SSV VOC, methane, and fixed gases (oxygen gas and carbon dioxide) results for samples collected during the reporting period are shown in Table 19. All laboratory analytical data underwent a Stage 2B validation and the validation reports are included in Appendix J. No VI data from the reporting period were qualified as rejected during validation.

For some samples, the laboratory MDL for acrolein and/or 1,2-dibromo-3-chloropropane exceeded the USEPA SSV vapor intrusion screening level (VISL) or IA VISL. In the cases where MDLs exceeded VISLs, the MDL values were highlighted, although the compounds were not detected. Variations in RLs and MDLs were the result of two reasons:

- Variability in canister pressures upon receipt at the laboratory for both IA/AA and SSV samples.
- Laboratory corrections were made for the helium dilution for SSV VOCs. The analytical method was modified by the laboratory to include helium as a dilutant gas in place of zero-grade air, which is included on the laboratory's National Environmental Laboratory Accreditation Program scope of accreditation. When necessary, analytical sample volumes were adjusted by a correction factor for containers pressurized with helium; this occurred with the Scale House, Pump House, Pretreatment Office Building, and Asphalt Plant Building samples.

3.9.1.1 VOC Results

Analytes that were detected in IA and SSV at concentrations above their respective VISLs are discussed below. Outdoor AA concentrations do not have a screening level but are presented in Table 17 for comparison to IA results. VOCs detected at concentrations above IA or SSV VISLs are listed by building below. The VOCs detected above IA VISLs were also detected above the laboratory MDL in their respective outdoor AA samples. In the case of acrolein, detected concentrations in the outdoor AA samples were also above the IA VISL. At all sample locations in OU-3 during Q4 2021, acrolein concentrations in IA were greater than acrolein concentrations in outdoor AA. For the sample collected in Q1 2022 at the Asphalt Plant Building, acrolein concentrations in the IA were less than acrolein concentrations in the outdoor AA.

Engineering Building

- IA: Acrolein was detected at concentrations exceeding the USEPA IA commercial VISL in the Q4 2021 sampling event.
- SSV: Acrolein was detected at a concentration exceeding the USEPA SSV commercial VISL (or the reporting limited exceeded the VISL) at all sampling locations during the Q4 2021 sampling event.

Scale House

- IA: Acrolein and isopropyl alcohol were detected at concentrations exceeding their respective USEPA IA commercial VISLs during the Q4 2021 sampling event.

Pump House and Pretreatment Office Building

- IA: Acrolein was detected at a concentration exceeding the USEPA IA commercial VISL during the Q4 2021 sampling event.

Asphalt Plant Building

- IA: Acrolein was detected at concentrations exceeding the USEPA IA commercial VISL during the Q4 2021 and Q1 2022 sampling events.

3.9.1.2 Methane Results

During the Q4 2021 sampling event at the Engineering Building, methane was detected in two SSV samples at concentrations exceeding the Site-specific screening level of 10,000 parts per million by volume (ppmv). Methane was not detected in any other SSV or IA samples collected during Q4 2021 or any of the samples collected during Q1, Q2, or Q3, 2022 at concentrations above the Site-specific screening level during the reporting period.

As a safety measure, Bridgeton Landfill continuously monitors methane inside the Engineering Building as part of their landfill methane management program. The landfill methane management program utilizes SAFE-T-ALERT® alarms in the Engineering Building[18], which trigger at 25 percent of the lower explosive limit, which is equivalent to a total methane concentration of 1.25 percent. The highest total methane concentration detected in SSV beneath the building was 0.24 percent, which is less than the methane alarm trigger value (i.e., 1.1 percent for methane). Methane management associated with the Engineering Building will continue to be performed by Bridgeton Landfill.

3.9.1.3 Radon Results

In January 2022, SSV radon readings were collected from all five buildings (Engineering Building, Scale House, Pump House, Pretreatment Office Building, and Asphalt Plant Building). All radon concentrations were below the USEPA action level of 4.0 pCi/L and the QAPP screening level of 2.0 pCi/L for each of the five buildings.

[18] SAFE-T-ALERT® systems are also operating in the Scale House, Pretreatment Building Office, and Asphalt Plant and issue alarms for methane and propane

3.10 OU-1/OU-2 Investigation and Bridgeton Landfill Gas Monitoring Activities

OU-1 and OU-2 consultant teams will conduct landfill gas monitoring as part of their respective remedial design investigations and Bridgeton Landfill monitors landfill gas as part of MDNR solid waste regulation requirements. OU-1, OU-2, and Bridgeton Landfill gas monitoring data will be evaluated against the OU-3 RI/FS Work Plan criteria and results of that evaluation will be reported in the RI Report. Updates regarding these investigation and monitoring activities in the reporting period are described below.

3.10.1.1 OU-1 Investigation Activities

The OU-1 consultant team will evaluate subsurface occurrences and potential migration of landfill gas at OU-1 in accordance with the *Methane Gas Monitoring Plan, West Lake Landfill Superfund Site, Operable Unit 1* (Weaver 2020). USEPA provided comments on the *Methane Gas Monitoring Plan* on 16 September 2022. A revised *Methane Gas Monitoring Plan* had not been submitted as of the end of the reporting period.

3.10.1.2 OU-2 Investigation Activities

During the reporting period, the OU-2 consultant team conducted perimeter landfill gas sampling along the western boundary of the Inactive Sanitary Landfill, in accordance with the *Explosive Gas Monitoring Plan* (Geosyntec Consultants 2021). OU-2 developed an *Explosive Gas Monitoring Corrective Action Plan* (CAP; Geosyntec Consultants 2022) in response to detections of methane above threshold values established in the *Explosive Gas Monitoring Plan* at four perimeter landfill gas monitoring wells.

The initial CAP to address landfill gas readings at perimeter landfill gas monitoring well BRISL004 was submitted on 15 November 2021, and was subsequently revised on 10 February 2022, following receipt of comments from USEPA and MDNR on 11 January 2022. An addendum to the CAP was submitted on 19 August 2022 after methane was detected above threshold values at three other landfill gas monitoring wells BRISL001, BRISL002, and BRISL003. The initial CAP and CAP addendum were combined into one document and revised to address USEPA comments and submitted on 23 November 2022.

OU-2 reports the landfill gas monitoring results to USEPA monthly and as of the end of the reporting period, methane is only detected above threshold values in one perimeter landfill gas monitoring well (BRISL004). Landfill gas monitoring results are summarized in the CAP. As described in the CAP, OU-2 has proposed additional landfill gas monitoring and investigation activities. Following the additional monitoring investigation, OU-2 will submit a Summary of Findings to USEPA which will outline the proposed next steps for the corrective action. USEPA had not approved the OU-2 CAP as of the end of the reporting period.

3.10.1.3 Bridgeton Landfill Gas Monitoring Activities

During the reporting period, Bridgeton Landfill conducted weekly landfill gas monitoring in accordance with MDNR solid waste regulations. Landfill gas probe monitoring data was emailed to MDNR by Bridgeton Landfill personnel weekly during the monitoring period. Bridgeton Landfill has also been submitting quarterly Landfill Gas Corrective Action Plan reports to MDNR in accordance with the July 2013 *Landfill Gas Correction Action Plan Updated* (Civil & Environmental Consultants, Inc. and Weaver Boos Consultants 2013). During this reporting period there were no methane detections above one percent in any Bridgeton Landfill gas monitoring locations[19].

[19] Landfill Gas Corrective Action Plan Reports are no longer being submitted quarterly as of Q4 2022. This change in reporting will be documented in the 2023 Annual Report.

3.11 Vapor Intrusion Assessment Summary

The purpose of the VI evaluation work described in the USEPA-approved RI/FS Work Plan was to evaluate the following three areas:

- VI occurrence beneath the off-Site areas
- Migration of landfill gas or other vapors from the landfills into the off-Site areas[20]
- Migration of landfill gas or other vapors into the on-Site occupied buildings

3.11.1 Evaluation of Landfill Gas and VI Impacts into Off-Site Areas

As the OU-3 RI and the OU-1 and OU-2 remedial design are ongoing, determinations regarding landfill gas and VI impacts into off-site areas are still in development.

3.11.2 Evaluation of VI Impacts from Chemical Occurrence in Groundwater

Groundwater data will be compared to groundwater VISLs after all proposed monitoring wells have been installed and sampled and sufficient data have been generated. This evaluation will be discussed in the RI Report.

3.11.3 Evaluation of Landfill Gas and VI Impacts into On-Site Buildings

The VI assessment of on-Site buildings indicates that VI is not currently an issue for the Engineering Building, Scale House, Pump House, Pretreatment Office Building, and the Asphalt Plant Building, and the SSV concentrations do not indicate the potential for future VI under on-Site buildings, with the possible exception of methane beneath the Engineering Building, which is discussed further in Section 3.11.3.3.

Based on the findings of the VI sampling and assessment conducted in 2021 and 2022 at the Engineering Building, Scale House, Pump House, Pretreatment Office Building, and the Asphalt Plant Building, additional VOC, radon, or methane VI assessment in on-Site buildings is not recommended.

3.11.3.1 VOCs

VOCs detected in IA at concentrations above their respective VISLs were infrequent, except for acrolein, which is discussed in more detail below. ERM reviewed the IA sample exceedance data to further evaluate those compounds relative to their respective VISLs. Nonane, naphthalene, isopropyl alcohol, ethyl acetate, ethylbenzene, tetrachloroethene, and 1,2-dibromo-3-chloropropane were detected in IA samples at concentrations above VISLs but were not detected in the companion SSV samples at concentrations above their respective USEPA VISLs and in each case were detected at higher concentrations in the IA sample than in the companion SSV sample (Table 3-4). Except for 1,2-dibromo-3-chloropropane, these compounds were also detected at concentrations above laboratory MDLs in outdoor AA samples. Therefore, these compounds are attributable to the use and/or storage of products containing VOCs within the affected building(s)[21] and/or the presence of these compounds in outdoor AA.

[20] The Bridgeton Landfill has historically operated and continues to operate a landfill gas extraction system to prevent off-Site migration of landfill gas, minimizing the potential for and conducts regular monitoring of off-Site migration of landfill gas in the vadose zone.

[21] Although ERM removed identified VOC-containing products from the buildings prior to the sampling events, previous product storage and use, employee occupancy, visitors to the buildings, personal activities, and unlabeled or non-VOC-labeled products may have been present, resulting in ongoing sources of VOCs to IA within the buildings.

Table 3-4: Summary of VOCs Detected Above VISLs in IA (Excluding Acrolein)

Companion IA-SSV Sample Location	Date	Analyte	IA Result µg/m3	IA VISL µg/m3	SSV Result µg/m3	SSV VISL µg/m3	AA Result µg/m3
AI-001 / GB-001 / AO-001 Engineering Building (Foyer)	14-17 January 2021	Naphthalene	1.7	1.31	< 0.54 U	43.8	0.033 J
	14-17 January 2021	Tetrachloroethene	26	17.5	0.49 J	584	0.030 J
AI-002 / GB-002 / AO-001 Engineering Building (Conference Room)	21-23 July 2021	1,2-Dibromo-3-chloropropane	0.032 J	0.0204	<0.49 J	0.681	< 0.015 U
	21-23 July 2021	Ethyl Acetate	88 J	30.7	< 1.4 UJ	1020	6.5 J
AI-003 / GB-003 / AO-001 Engineering Building Garage/Storage Room	21-23 July 2021	Ethylbenzene	60	49.1	15	1640	0.22
	21-23 July 2021	Naphthalene	1.6 J	1.31	1.4 J	43.8	0.081 J
	11-14 January 2021	Nonane	12	8.76	0.46 J	292	< 0.13 U
	14-17 January 2021	Nonane	9.2	8.76	0.46 J	292	< 0.12 U
AI-006 / GB-006 / AO-002 Scale House	11-17 January 2021	Isopropyl alcohol	98	87.6	2.7 J	2920	< 0.35 U
	27-28 October 2021	Isopropyl alcohol	340	87.6	< 1.0 U	2920	3.7

Note: Where there was a duplicate sample collected at a sample location, the higher concentration of the two analyses is displayed

µg/m^3 = micrograms per cubic meter

Qualifier Definition:

J = Estimated concentration

U = The analyte was analyzed for but was not detected at or above the referenced RL.

As noted in the 2021 Annual Report (ERM 2022b), acrolein was consistently detected in IA, AA, and SSV samples at concentrations above applicable and very low VISLs[22]. The acrolein concentration ranges detected in all three media are similar, as shown in Figure 3-2 below. Acrolein is a common background compound (Weisel et al. 2005; ATSDR 2007; USEPA 2011b; MDEQ 2012; USEPA 2012) that was detected in each of the ambient air samples in 2021 and 2022 at concentrations generally consistent with background concentrations presented in the literature.

[22] The applicable VISLs are 0.00876 micrograms per cubic meter (µg/m^3) for indoor air and 0.292 µg/m^3 for soil vapor.

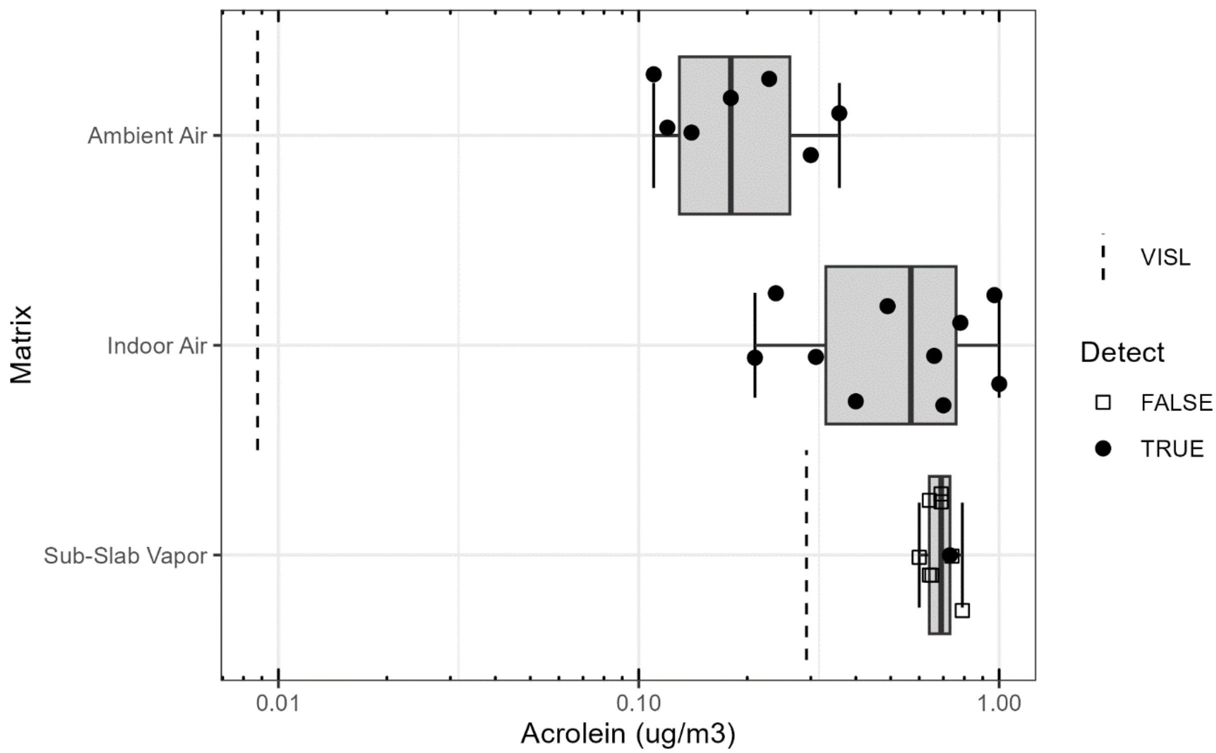

Figure 3-2: Acrolein Box and Whisker Plots

Box and whisker plots for acrolein results from IA, outdoor AA, and SSV samples. Detected results are solid circles, non-detect results are open squares. Concentration of acrolein is presented on a log scale. The box and whisker plots illustrate that the concentration ranges detected in all three media are similar.

To further evaluate acrolein, attenuation factors (AFs) were calculated for acrolein by dividing the acrolein IA concentration by the acrolein SSV concentration for each IA/SSV co-located sampling pair for each sampling event (Table 3-5). The calculated AFs ranged between 0.17 and 4.09. USEPA empirically derived AFs for buildings not influenced by background indoor air sources with a default AF of 0.03, but values as low as 0.0003 were noted (USEPA 2012).[23] The acrolein AFs that approach or exceed 1 indicate that IA concentrations are similar to, or exceed, SSV concentrations. Under these conditions, the SSV is unlikely to be—and, when the AF exceeds 1, cannot be—the source of the IA detections. In conclusion, the presence of acrolein in IA is not attributable to VI.

[23] Empirical studies for AFs in commercial/industrial buildings in California completed by Ettinger et al. (2018) and Lahvis and Ettinger (2021) identified 95th percentile AFs of 0.0025 and 0.0008, respectively. In addition, other empirical studies for industrial buildings outside of California (one on large industrial buildings and one evaluating radon AFs as a surrogate for VOC AFs) found 95th percentile AFs of 0.0002 and 0.007, respectively (Eklund et al. 2021 and Nawikas 2021).

Table 3-5: Calculated Acrolein Attenuation Factors

Companion IA/SSV Sample Location	Date Collected				
	11-14 January 2021	14-16 April 2021	21-23 July 2021	27-28 October 2021	24 January 2022
AI-001 / GB-001	0.17	0.25	1.27	ND	NA
AI-002 / GB-002	ND	ND	0.50	1.37	NA
AI-003 / GB-003	0.29	0.51	4.09	ND	NA
AI-004 / GB-004	0.20	ND	0.17	ND	NA
AI-005 / GB-005	ND	0.86	0.51	ND	NA
AI-006 / GB-006	ND	ND	1.00	ND	NA
AI-007 / GB-007	NA	0.66	1.76	ND	ND

Note: Where there was a duplicate sample collected at a sample location, the higher concentration of the two results was used to calculate the AF.

ND = No detection of acrolein in the IA or SSV sample above laboratory MDL

NA = Not available. VI sampling program included four sampling events at each location; due to a delay in access, VI sampling at AI-007 / GB-007 was not initiated until Q2 2021.

3.11.3.2 Radon

Review of the ST radon data collected in Q1 2022 indicated that significantly higher radon concentrations were measured in SSV samples than in the co-located IA samples, indicating that the building slabs effectively prevent radon from migrating into Site buildings. Therefore, radon VI is not occurring, and ST IA and LT IA radon concentrations were below the USEPA action level and below the Site-specific screening level in each building.

3.11.3.3 Methane

Methane was detected in SSV samples collected beneath the Engineering Building at concentrations ranging from 1,800 to 240,000 ppmv. Methane concentrations detected in IA samples collected from within the Engineering Building ranged from 4.8 to 52 ppmv; these concentrations are below the Site screening level. In addition, there is a continuous methane monitoring system in this building that will sound an alarm if elevated methane concentrations are detected in IA within this building. The highest methane concentrations in both SSV (240,000 ppmv) and IA (52 ppmv) were detected beneath and within the conference room within the Engineering Building, respectively. The calculated AF for this room is 0.0002. Given the extremely low AF and continuous methane monitoring system present within the Engineering Building, the potential for methane VI is being adequately monitored.

4. CONCEPTUAL SITE MODEL UPDATE

A CSM is a tool used to describe a contaminated site based on existing information (USACE 2012; USEPA 2011a), and addresses each of the environmental media. **Development of a CSM is an iterative process, such that the CSM should be reviewed and revised as necessary as additional data are collected.** In accordance with the Statement of Work, the focus of this project is the groundwater medium. The groundwater CSM provides an understanding and summary of the known and potential sources of groundwater contamination; potential release mechanisms; potential routes of migration, including known or suspected preferential pathways; groundwater flow (vertical and horizontal); Missouri River and groundwater interaction; factors that control contaminant distribution; and potential human and environmental receptors. A preliminary CSM was presented in the RI/FS Work Plan (ERM 2020) and subsequently updated in the 2021 Annual Report (ERM 2022b). This section of the report provides an update to the CSM based on data generated and analyses completed through the 2022 reporting period. The CSM will be further revised in future annual reports and in the RI Report.

The focus of the CSM presentation in this report is to provide a basis for evaluating the sufficiency of the data collected for completion of the RI (i.e., addressing the PSQs) and to identify remaining data gaps, if any, that need to be addressed to complete the RI. The CSM is organized as follows:

- Section 4.1: CSM Summary—Provides a comprehensive overview of the CSM.
- Section 4.2: Overview, CSM Data Inputs, and Scale—Describes data inputs used to develop the CSM and the scale at which data were collected and assessed.
- Section 4.3: Hydrologic Setting—Describes the location of the Site within the regional, basin, and local scale hydrologic setting.
- Section 4.4: Geology—Describes the geologic model, which provides the foundation for the understanding of the Site hydrogeology.
- Section 4.5: Hydrogeology—Describes the features that influence the Site hydrogeology and the groundwater flow system, including flow direction and flux.
- Section 4.6: Groundwater Constituents of Potential Concern—Describes the nature and extent of select COPCs. This section includes an assessment of potential sources of radium in groundwater.

Significant updates to the CSM developed during this reporting period include the following:

- The alluvium stratigraphic interpretation was refined, and stratigraphic markers were shown to be consistent at a regional scale. The alluvium is divided into three TSUs: Upper, Middle, and Lower Alluvium.
- The bedrock geologic model was expanded with the installation of bedrock wells north/northwest of the Site and upgradient of the Site. The bedrock stratigraphic interpretation did not change significantly, but there is improved understanding of the bedrock structure.
- All monitoring wells were assigned to an Alluvium TSU or to a bedrock unit and the updated geologic model was used as a framework for plotting and interpreting groundwater elevation and COPC concentration/activity data.
- High-resolution temporal groundwater, surface water, and precipitation data were evaluated; the alluvium groundwater flow system beneath and proximal to the Site is highly dynamic and primarily influenced by Missouri River levels.

- Groundwater gradients were evaluated; the horizontal gradient in alluvium is primarily to the west/northwest. The orientation of the horizontal hydraulic gradients in the alluvium is highly variable and not effectively represented by monthly groundwater elevation contour maps.
- Daily flow vectors (magnitude and direction) were created from the transducer data from the alluvial aquifer beneath the northern portion of the Site to effectively represent the dynamic horizontal hydraulic gradients in alluvium. Groundwater flow velocities in alluvium are very slow due to extremely low hydraulic gradients. The net annual groundwater flow velocity and direction at the Site for alluvium for the reporting period is 19 to 25 feet per year to the west-northwest.
- Groundwater flux through the bedrock and alluvial aquifers was evaluated; most groundwater flux occurs through the alluvial aquifer.
- Temporal variability in COPC concentration/activity level and composition in Site groundwater were evaluated and found to be generally consistent over time, possibly owing to the very slow groundwater flow velocity at the Site. Only a small number of alluvium and bedrock wells exhibit changes in COPC composition or concentration/activity level.
- A detailed evaluation of potential radionuclide sources, including RIM placed at the Site and natural alluvial and bedrock aquifer materials, was conducted. This review included analysis of radium isotope ratios in groundwater and aquifer matrix samples. While RIM associated with the Manhattan Engineer District project processing has historically shown a radium isotope ratio that is predominantly radium-226 (see Figure 4-46), the aquifer matrix samples have lower proportions of radium-226 than RIM (see Figure 4-50) and the radium isotope ratios in the aquifer matrix samples are consistent with literature values for groundwater from sand and gravel and carbonate bedrock aquifer (see Figure 4-53). These data indicate that RIM is not the source of radium in Site groundwater, and that radium detected in Site groundwater originates from the natural aquifer materials.
- Off-site wells were installed, sampled, and evaluated and 1,4-dioxane was identified as the primary COPC in off-Site groundwater.

The focus of the CSM presentation in this report is to provide a basis for evaluating the sufficiency of the data collected for completion of the RI (i.e., addressing the PSQs) and to identify remaining data gaps, if any, that need to be addressed to complete the RI.

4.1 CSM Summary

The Site is located within the Missouri River valley where the Missouri River valley approaches the confluence of three major river systems: the Missouri, Mississippi, and Illinois Rivers. The Missouri River valley is incised into carbonate bedrock and filled with unconsolidated alluvium to a depth of approximately 110 feet in the northern portion of the Site. Groundwater in the alluvium is in direct communication with the river systems. In the southern portion of the Site, the alluvial valley pinches out against bedrock uplands and the Site is underlain by carbonate bedrock where the former quarry was developed. ERM estimated groundwater flux through the bedrock and alluvial aquifers and showed that most of the groundwater flux beneath the Site occurs within the alluvial aquifer (Section 4.5.8). As part of this analysis, ERM evaluated high-resolution precipitation, river stage, and groundwater elevation data (Section 4.5.1 through Section 4.5.5) to evaluate the relative influences of various hydrologic influences on Site groundwater flow (e.g., recharge and discharge areas). Seasonal Missouri River stage elevations were observed to have the greatest effect on the groundwater flow system beneath the Site, although major precipitation events in the area can influence river stages and therefore groundwater flow to some extent.

ERM completed a detailed interpretation of Site geology using environmental sequence stratigraphy (Shultz et al. 2017) as a framework for interpreting a large volume of high-resolution geophysical data from logging completed in alluvium and bedrock. The resultant geologic model[24] includes two time stratigraphic markers (TSMs) that separate the alluvium into three TSUs. This model is consistent with the geologic literature for sediment deposition within the Missouri River valley from the Pleistocene to the present (Anderson et al. 2021) and was used as a framework from which to evaluate hydrogeologic and solute distribution data.

Interpretation of daily, high-resolution groundwater elevation data demonstrated that the groundwater flow system is dynamic, with groundwater elevations changing up to 5 feet annually, resulting in short-term variability in the orientation of hydraulic gradients (Section 4.5.6.2). Though the flow system is dynamic, the horizontal and vertical hydraulic gradients are very low (i.e., generally less than 0.0003 feet/foot in alluvium), reflecting the high hydraulic conductivity of alluvial sediments. The impact of low hydraulic gradients is that the net annual groundwater flow rate within the alluvial aquifer is also very low (i.e., less than 25 feet per year). During the reporting period, the direction of the hydraulic gradient over a calendar year varied by as much as 225 degrees (from southwest to northeast) in the northern portion of the alluvial aquifer; however, the net groundwater flow direction in alluvium was to the west-northwest. Based on data generated to date, while the TSUs identified in alluvium do not represent separate hydrogeologic units, NMR geophysical logging shows they are separated by thin layers (1- to 5-feet thick) of lower hydraulic conductivity sediments with increased amounts of capillary bound water; these thin layers are referred to as TSMs. These TSMs represent a change in the depositional flow regime during which vertical accretion of finer fluvial sediments occurred. As such, the TSMs likely inhibit vertical groundwater flow in some areas, although they do not prevent vertical flow when the aquifer is stressed and therefore, the alluvial aquifer can be considered to act as a single hydrogeologic unit[25].

Sources of chemical contributions to groundwater include the six historical waste disposal areas at the Site, natural sources, and possibly nearby industrial facilities. By their nature, landfills are heterogeneous source areas (i.e., they contain a variety of waste materials deposited randomly throughout the overall volume of waste material) and in addition to heterogeneity, significant anisotropy exists that affects fluid flow within landfills (e.g., Bendz and Singh 1999). Landfill operations at the Site commenced in approximately 1952 and continued until 2004, with each landfill operating over different time periods, as documented in the RI/FS Work Plan (ERM 2020). All the landfills at the Site have been covered with low-permeability soil or an ethylene vinyl alcohol cover. During the reporting period, only relatively low solute concentrations have generally been detected in shallow groundwater around these landfills, suggesting that any leachate currently migrating out of these landfills contains low solute concentrations.

ERM evaluated solutes in groundwater using a combination of high-resolution WATERLOO APS™ discrete-interval groundwater sample analytical results, geophysical data, and temporal groundwater analytical results from the Site monitoring wells. ERM's interpretation of solutes in groundwater has focused on eleven COPCs ("select COPCs") identified in Section 4.6. Interpretation of these data demonstrate that elevated solute concentrations exist in some wells located adjacent to the South Quarry of the Bridgeton Landfill and along the western Site boundary. Relatively low solute concentrations are generally observed along the northern, eastern, and southern Site boundaries, and in off-Site areas, with two exceptions: elevated 1,4-dioxane and vinyl chloride concentrations in alluvial groundwater in MW-501, located west of the Site, and elevated 1,4-dioxane concentrations in bedrock groundwater in MW-406, located north-northeast of the Site.

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[24] A preliminary interpretation of geologic stratigraphy was presented in the 2021 Annual Report (ERM 2022b) and has been revised in this report.

[25] This is an important interpretation and one that will continue to be evaluated as more data are generated.

ERM evaluated radionuclides (i.e., uranium, thorium, and radium) in solid matrices (i.e., alluvium and bedrock, and radionuclide levels in RIM based on data generated by the OU-1 consultant team) and radionuclide occurrences in groundwater to evaluate the source(s) and distribution of radionuclides detected in groundwater. In general, low to non-detectable uranium and thorium concentrations were identified in on-Site, off-Site, and background groundwater, with all uranium concentrations below the MCL (note: thorium is generally insoluble and does not have an MCL). Radium was the only radionuclide detected in groundwater at activity levels (note: radium levels are reported as activity levels rather than concentrations) above the MCL. Evaluation of radionuclide isotopic signature data for all tested solid media (i.e., RIM and aquifer matrix samples) and groundwater demonstrated that the source of radium in groundwater is naturally occurring soil and bedrock, not RIM (see Section 4.6.1 below). Additional evaluation is required to determine if landfill conditions may have impacted aquifer geochemistry in ways that could have mobilized radium from native aquifer matrix materials into groundwater (e.g., due to changed oxidation-reduction conditions).

4.2 Overview, CSM Data Inputs, and Scale

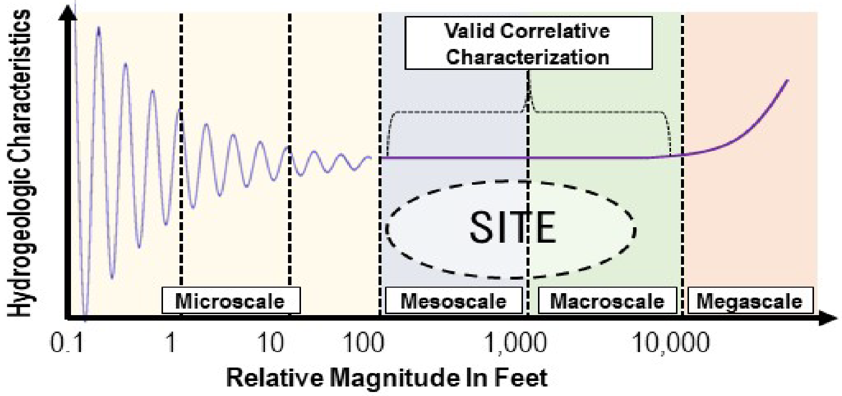
Remedial investigations require the collection of several data types that must be synthesized into a CSM. Some data are collected at high vertical or temporal resolutions, but it is impractical to collect data at high spatial resolution. Because data are collected at various scales, CSMs are typically developed at the scale of the lowest-resolution dataset[26], while honoring data from higher-resolution datasets. This concept is regularly applied in the geosciences at the following scales: microscale (less than 100 feet), mesoscale (100 to 1,000 feet), macroscale (1,000 to 10,000 feet), and megascale (greater than 10,000 feet) (see Figure 4-1 below).

From a geologic perspective, microscale looks at details of soil and rock properties such as soil composition, particle size, and texture, including rounding, sorting/grading and vertical changes in texture (coarsening or fining upward) (Payne et al. 2008; Figure 4-1 below). These microscale details can be evaluated using one or more of the sources of data described in Sections 3.2 and 3.3. From these observations, larger-scale patterns at the mesoscale and macroscale can be identified that relate to facies and facies sequences of depositional environments (Appendix I). These elements of the CSM are critical to understanding mass flux through preferential pathways of advective groundwater flow and mass storage in intervals where contaminant transport is limited by sorption and diffusion. Megascale considerations that have regional influence must also be considered, and generally involve understanding the nature of the depositional environment (Anderson et al. 2021) and the potential for large-scale geologic features to affect the groundwater flow system.

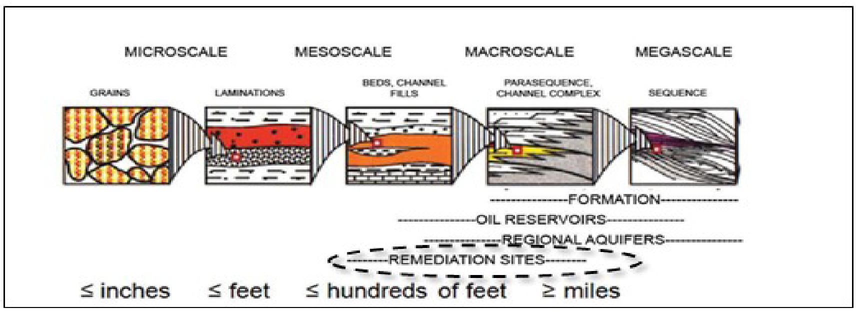
Due to the nature of depositional environments, hydrogeologic characteristics are heterogeneous at the microscale, relatively consistent at the mesoscale and macroscale, and become heterogeneous again at the megascale (e.g., Woessner and Poeter 2020; see Figure 4-1 below).

The scale of the Site, defined by the outermost extent of landfilled materials, is about 4,500 feet (in the general north-south direction) by 3,200 feet (in the general east-west direction). The Site perimeter monitoring wells are spaced approximately 500 feet apart, which enables interpretation of Site data at the mesoscale. Background wells are spaced approximately 3,000 to 5,000 feet apart, which enables interpretation of background data at the mesoscale to macroscale. Therefore, the horizontal scale of the CSM presented below is mesoscale to macroscale, with vertical geological, hydrogeological, and sometimes groundwater chemistry data generally presented at the microscale.

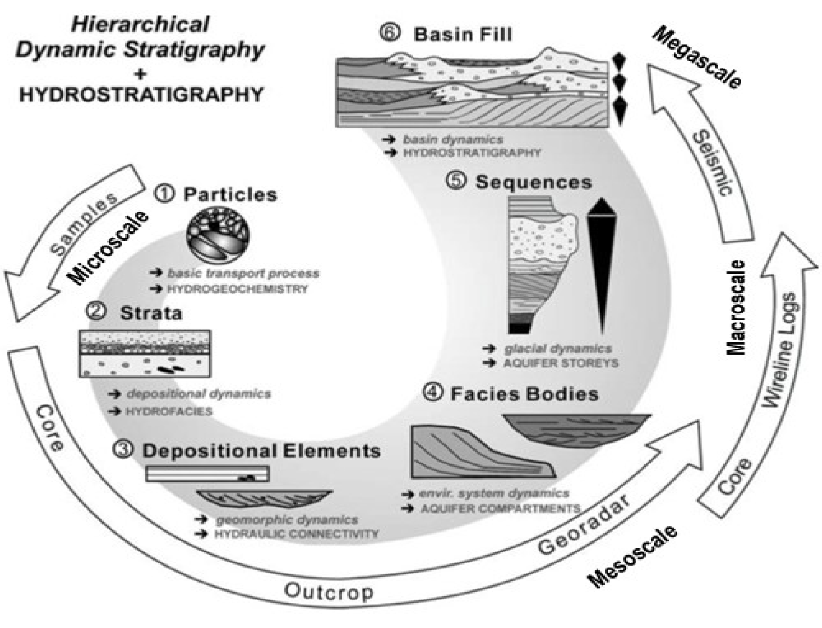
[26] This scale often varies based on the size of the Site.



Modified from Woessner and Poeter 2020



Adapted from AAPG 1987 (modified from Krause et al. 1987)



Adapted from Remediation Hydraulics, Payne et al. 2008

Figure 4-1: Illustrations of Scale

The three images in Figure 4-1 illustrate the micro-, meso-, macro-, and megascales. Vertically, high-resolution site investigation data are collected at the microscale. Microscale data (e.g., soil and rock properties) and megascale data (e.g., the depositional environment) inform the CSM, which exists at the meso- and macroscales.

4.3 Hydrologic Setting

In developing the CSM, the hydrologic setting was evaluated at the regional (megascale), basin (macroscale to megascale), and local scale (mesoscale to macroscale). Illustrations of each setting are presented below.

4.3.1 Regional Hydrologic Setting (Megascale)

The regional-scale hydrologic setting is the river valley and upland setting that exists at the megascale. The Site is located in a region that includes the confluence of three major North American river systems: the Missouri River, the Illinois River, and the Mississippi River (Figure 4-2). The Illinois and Mississippi Rivers drain the mid-western portion of North America whereas the Missouri River has its headwaters in the northern Rocky Mountains. As such, the Missouri River is expected to respond to seasonal variations in flow patterns independently from the Mississippi and Illinois rivers; yet, as the Missouri River approaches the confluence river stages in all three rivers generally follow similar patterns (Figures 4-3 and 4-4).

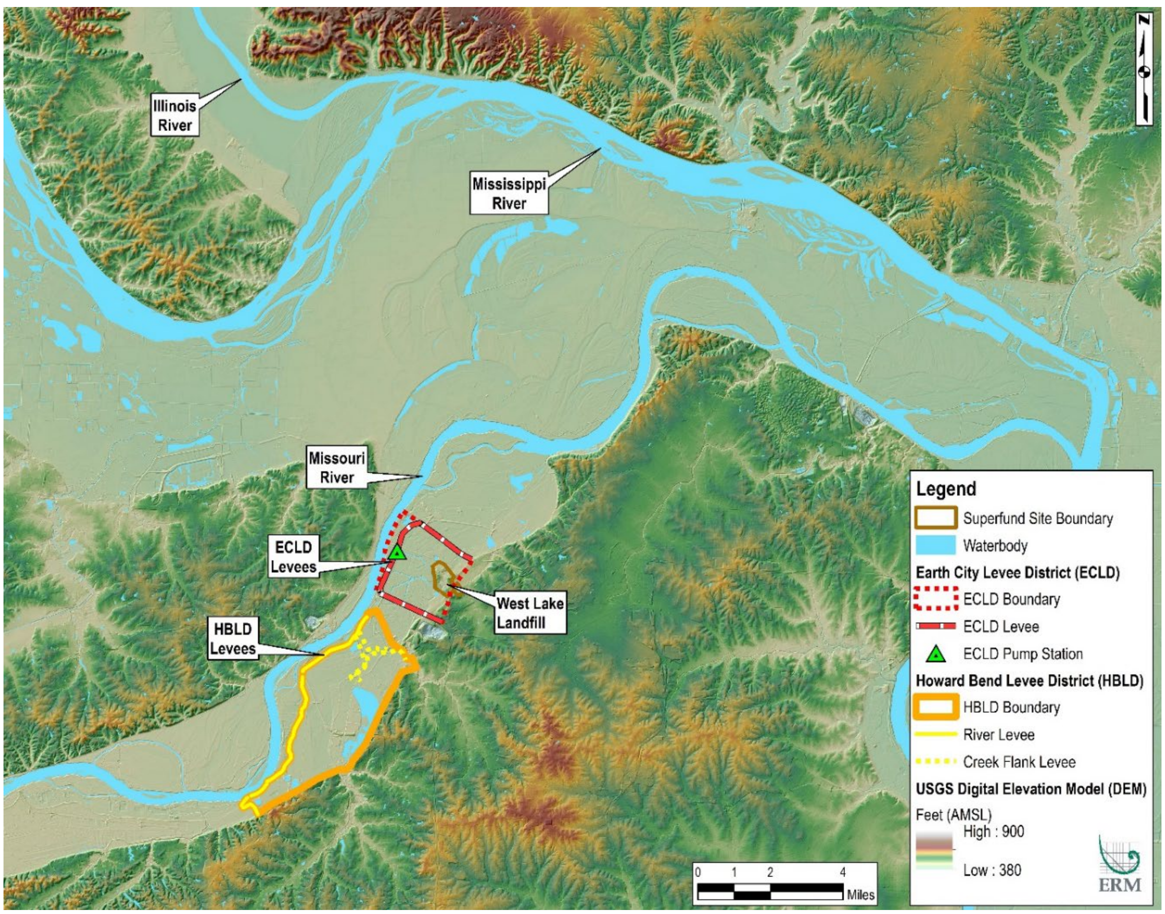


Figure 4-2: Regional Hydrologic Setting

The Site is in a region at the confluence of three major river systems: the Missouri River, the Mississippi River, and the Illinois River. The Site is located on the Missouri River floodplain in an area where the floodplain is incised and constricted laterally by bedrock outcrops to the north and south. Also shown in this figure are the boundaries of the HBLD and the Earth City Levee District (ECLD), with the location of the associated pump station noted.

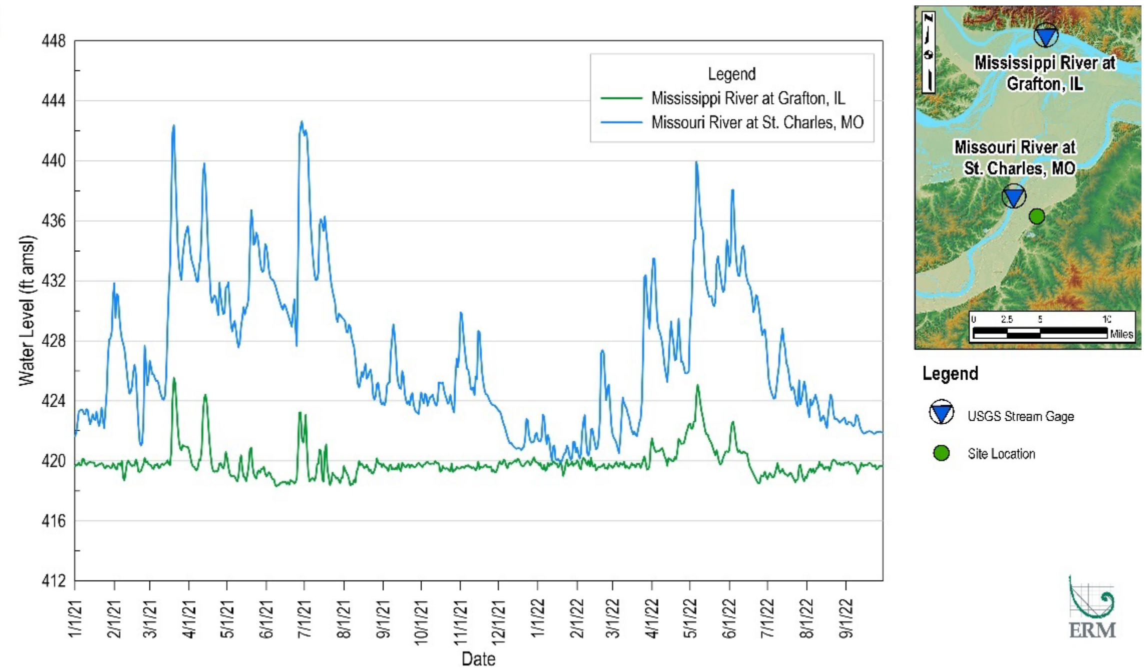


Figure 4-3: Comparison of Missouri and Mississippi River Stages

River stage changes in the Mississippi and Missouri Rivers generally follow similar patterns during the spring and summer, though Mississippi River level fluctuations are less significant than those observed for the Missouri River.

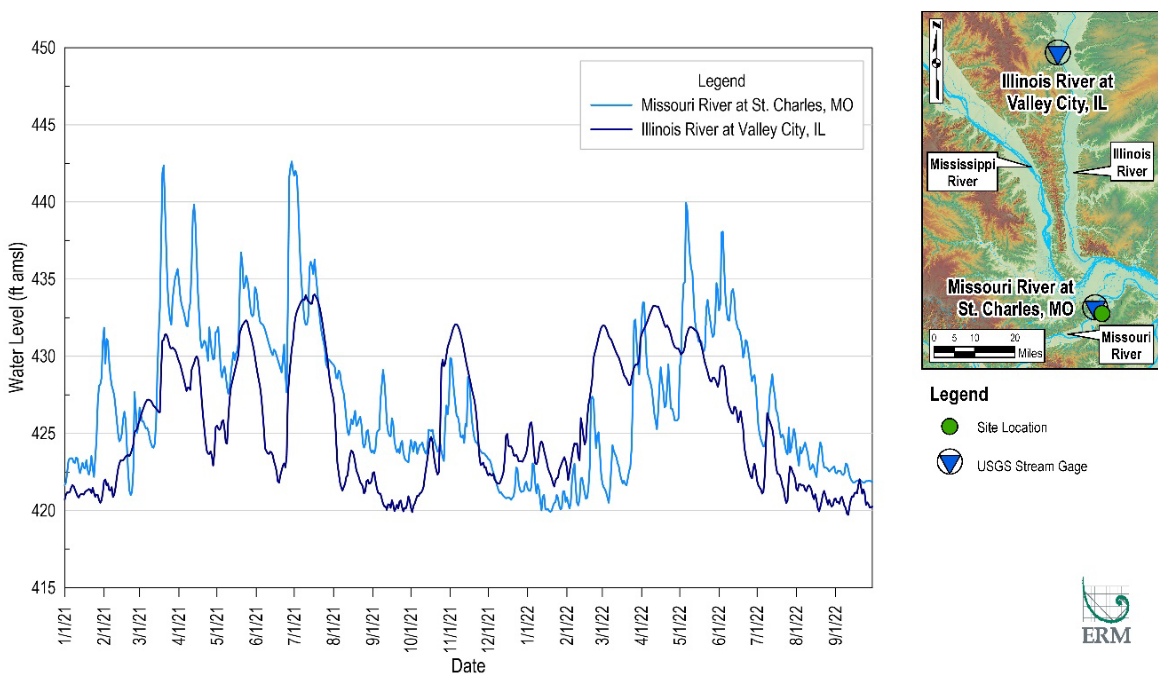


Figure 4-4: Comparison of Missouri and Illinois River Stages

River stage changes in the Missouri and Illinois Rivers generally follow similar patterns. There are larger fluctuations in the Missouri and Illinois River stages than in the Mississippi River stage (see Figure 4-3 above).

The Site is located on the Missouri River floodplain in an area where the floodplain is incised and constricted laterally by bedrock outcrops to the north and south. East of the Site, the Missouri River floodplain eventually widens and joins the floodplain of the Mississippi River. The Illinois River joins the Mississippi River floodplain north of the Site. Flow volume in the Mississippi River is greater than in the Missouri River and the river stage in the Missouri River may be influenced by the Mississippi and Illinois Rivers when those rivers are at flood stage. The constrained nature of the Missouri River and Illinois River floodplains appear to result in larger fluctuations in river stages compared to the Mississippi River (Figures 4-3 and 4-4).

4.3.2 Basin Hydrologic Setting (Macroscale to Megascale)

The basin-scale hydrologic setting is macroscale to megascale and includes the Cowmire Creek-Missouri River Watershed and a portion of the Creve Coeur Creek Watershed, as shown in Figure 4-5.

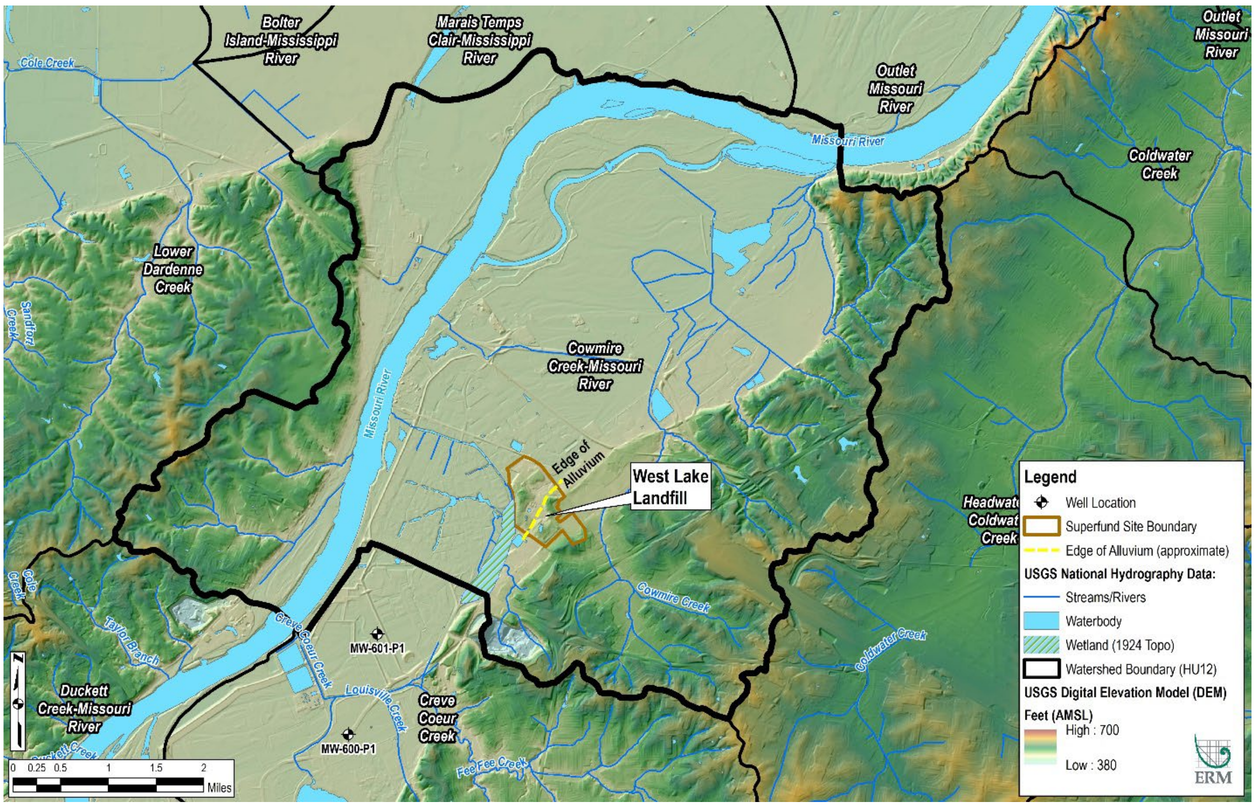


Figure 4-5: Basin-Scale Hydrologic Setting

The Site is in the Cowmire Creek-Missouri River Watershed, which is outlined in a bold black line.

4.3.3 Local-Scale Hydrologic Setting (Macroscale)

There are two local-scale levee districts located within the Missouri River floodplain: the HBLD, which is located approximately 2 miles southwest of the Site, and the ECLD, which is located immediately west of the Site. The levee district locations are shown on Figure 4-2, and the two levee districts are described below.

4.3.3.1 Howard Bend Levee District

HBLD encompasses approximately 8,300 acres along the southern side of the Missouri River (Figure 4-2). It was established in 1987 to protect and reclaim land primarily for agricultural purposes and provides protection from flood waters for the western portion of Maryland Heights. Figure 4-6 illustrates the layout of the HBLD, which consists of a 7.6-mile levee designed to provide protection from a 500-year flood event, along with additional levees that provide flood control management of the Creve Coeur and Fee Fee Creeks and Creve Coeur Lake. Management of the district is limited to maintenance of the levee system (additional information at https://howardbend.com).

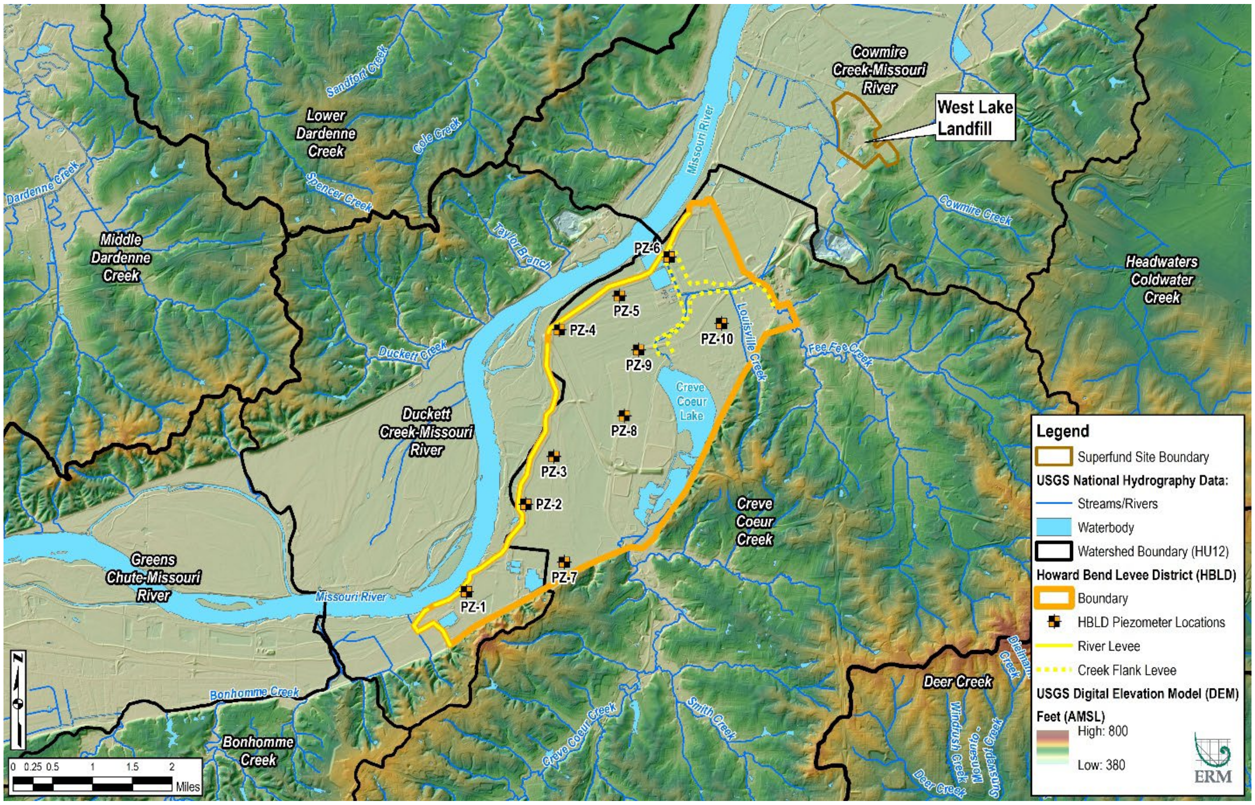


Figure 4-6: Howard Bend Levee District

The 500-year flood rated levee is shown as a yellow line and runs approximately parallel to the Missouri River.

In 2005, HBLD installed 10 piezometers within HBLD (hereafter referred to as "HBLD piezometers"). These piezometers are gauged monthly by HBLD's consultant (see Section 2.10.2) to monitor water table elevations on the landside of the levee (Figure 4-6). As part of the OU-3 RI, Feezor installed a pressure transducer in one of the HBLD piezometers (PZ-5) to provide more detailed water level data. The HBLD groundwater elevation data are discussed in Section 4.5.5.

4.3.3.2 Earth City Levee District

ECLD is a 1,891-acre political subdivision of the State of Missouri located adjacent to the Site (Figure 4-2). More than half of the ECLD (1,107 acres) is in unincorporated St. Louis County (Earth City) and the remainder (i.e., 784 acres) is in the City of Bridgeton. The ECLD is comprised of businesses in industrial and business parks that are protected from Missouri River flooding by a flood control system. ERM obtained information about the ECLD flood control system from the ECLD website and through conversations with D. Jerry Leigh, the Vice President of A.M.C.I. Flood Plain Management, Inc., a real estate management and consulting company that manages the business, real estate, and day-to-day flood control system of ECLD. On 28 April 2022, members of ERM's technical team completed a tour of the ECLD with D. Jerry Leigh to learn about the flood control system with a focus on its potential influence on regional groundwater flow.

The flood control system consists of four primary components, which are shown on Figures 4-7 and 4-8a and 4-8b below:

- A three-reach levee system rated to provide protection from a 500-year flood event
- 83 relief wells that protect the levee system during flood events from under-seepage by conveying groundwater to the engineered water body by gravity flow or pumps, where necessary
- An engineered water body, which consists of a series of interconnected ditches, channels, and surface water canals that contain storm water from precipitation and groundwater from the relief wells
- A pump station that moves water from the engineered water body back to the Missouri River when the surface water elevation within the water body rises to 432.86 feet above mean sea level

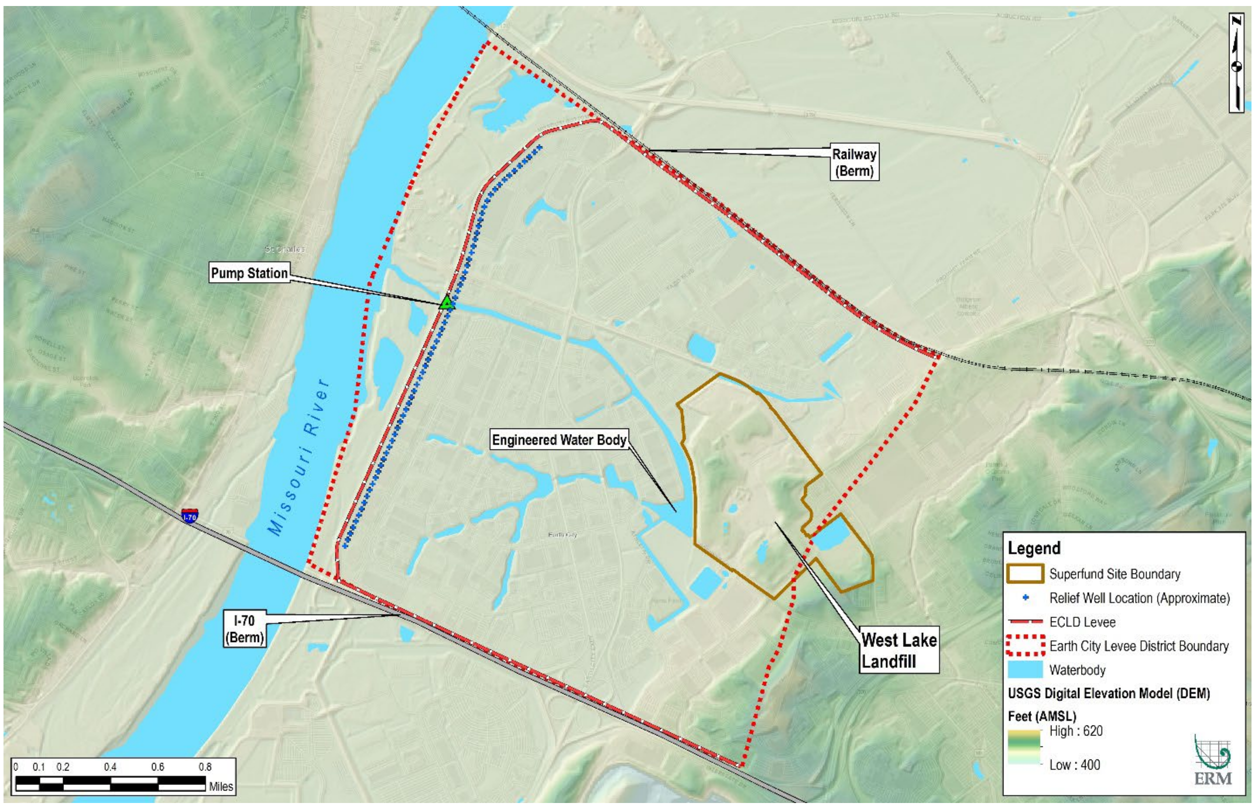


Figure 4-7: Earth City Levee District

The 500-year flood rated levee consists of three reaches: one reach of the levee is parallel to the Missouri River; the other two reaches of the levee are perpendicular to the Missouri River and are located on highway and railroad berms. The relief wells are located to the east of the levee that is parallel to the Missouri River.

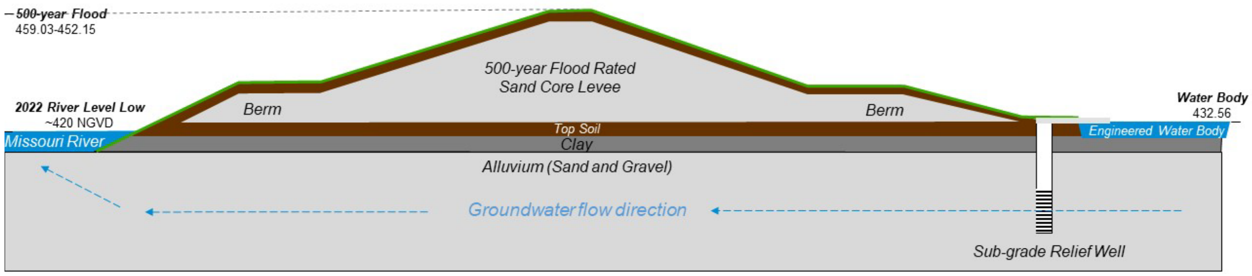
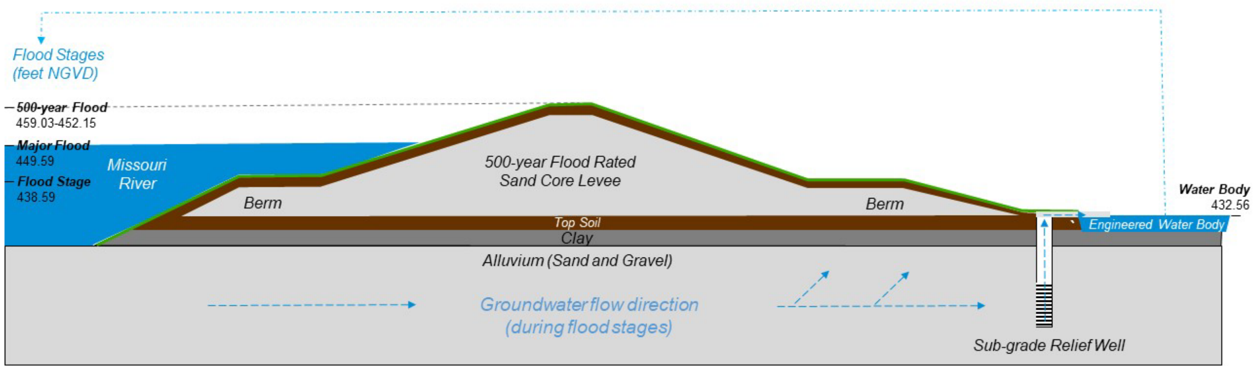


Figure 4-8a: Earth City Levee District During Normal Non-Flood Operations

Cartoon schematic of ECLD flood control components (not to scale) showing groundwater flow direction during normal non-flood stage of the Missouri River. Graphic modified from earthcityld.com and from graphics included in a 2008 USEPA letter to U.S. Senator Christopher Bond.



Cartoon schematic of ECLD flood control components (not to scale) showing groundwater flow direction during flood stage of the Missouri River. Graphic modified from earthcityld.com and from graphics included in a 2008 USEPA letter to U.S. Senator Christopher Bond.

Figure 4-8b: Earth City Levee District During Flood Operations

Water levels in the engineered water body are maintained to a maximum elevation of around 432.56 feet above mean sea level and are approximately equivalent to the water table elevation (Figure 4-8a). The engineered water body can go dry during periods of drought, per correspondence with D. Jerry Leigh. Water is not added to the engineered water body to maintain water levels so the engineered water body is not a source of recharge to groundwater, although in some circumstances, the water body may be proactively pumped down in anticipation of a large rain event creating a temporary depression in the water table adjacent to the engineered water body. The bottom elevation of the engineered water body is unknown, but from conversations with D. Jerry Leigh, ERM understands that the engineered water body is shallow, and the depth is on the order of 3 to 5 feet (i.e., the bottom elevation is likely between 429 and 427 feet above mean sea level). Under non-flooding conditions, when groundwater gradients are toward the Missouri River, groundwater in the underlying alluvial aquifer can flow beneath the engineered water body and levee system toward the Missouri River and the relief wells do not affect groundwater flow.

The relief wells capture groundwater only during flood events when water levels outside the levee are greater than inside the levee, creating a pressure gradient that results in groundwater underflow beneath the levee. Under those conditions, water levels rise in the relief wells (which are manifolded together) and drain via gravity to the engineered water body (Figure 4-8b). There are also a smaller number of relief wells equipped with pumps that can also move water to the engineered water body. The automated pump station activates when the water level in the water body reaches 432.86 feet above mean sea level. If water levels in the engineered water body rise above the maintenance level, water is pumped from the engineered water body to the Missouri River. This results in an upper boundary condition for the water table elevation that prevents flooding within the ECLD. The Missouri River is incised into and constrained on both sides by bedrock and is the ultimate discharge boundary for the alluvial aquifer.

Figure 4-9 shows the relationship between precipitation events, Missouri River stage levels, and the engineered water body elevation measured at stilling well SG-504 (location shown in the inset). The impact of ECLD operations on Site groundwater elevations is further discussed in Section 4.5.4.

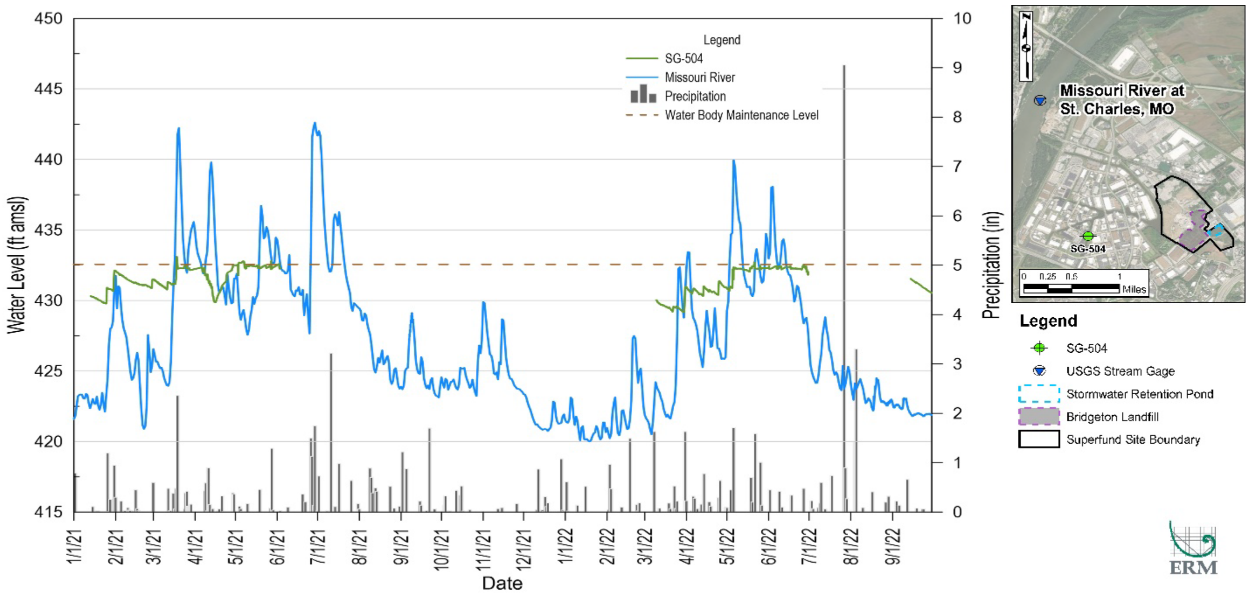


Figure 4-9: Relationship Between Precipitation Events, Missouri River Stage Levels, and the Engineered Water Body Elevation

The graph shows that water levels in the Missouri River (blue line) rise after large precipitation events (gray bars) (e.g., early April 2021). Generally, water levels in the Engineered Water Body (green line) are relatively stable near the engineered water body maintenance level (brown dashed line). The engineered water body elevation is maintained or lowered in response to large precipitation events (e.g., the engineered water body was proactively pumped down in anticipation of a large precipitation event in late April 2021).

Summary

The Site is located within a bedrock valley where the Missouri River valley approaches the convergence of three major river systems. Groundwater is present in the alluvium and in the carbonate bedrock formations. Most groundwater beneath the Site flows through the alluvial aquifer, which is hydraulically connected to the Missouri River. Missouri River stage elevations vary throughout the year and impact groundwater flow within the alluvial aquifer.

4.4 Geology

A generalized geologic cross-section showing the major geologic units present at and near the Site is shown on Figure 4-10. The geology at and near the Site provides the framework needed to evaluate hydrogeology and supports answering PSQ-5 (*Where could site related COPCs migrate in the future?*) The geologic units shown are discussed in more detail below.

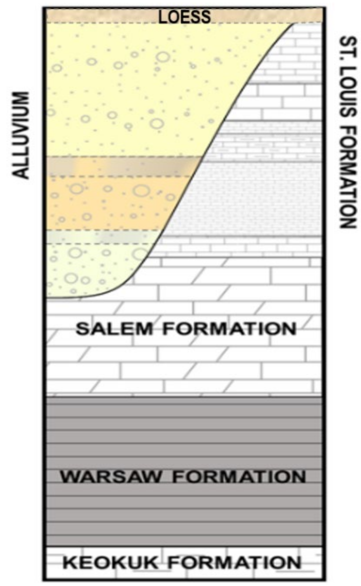


Figure 4-10: Generalized Geologic Cross-Section

The generalized cross-section shows the alluvium and major bedrock geologic units present at and near the Site.

4.4.1 Bedrock

Details regarding the various bedrock formations present at the Site were initially provided in a report named *Hydrogeologic Characterization Report for the Bridgeton Active Sanitary Landfill, Bridgeton Missouri, Volume I* (Golder & Associates 1995). During the reporting period, the number of on- and off-Site bedrock wells increased and ERM developed a greater understanding of the bedrock stratigraphy, geographic occurrence, and hydrogeologic properties of the primary bedrock formations of interest to the RI, including (from oldest to youngest) the Warsaw Formation, the Salem Formation, and the St. Louis Formation (Figure 4-11). All three formations are primarily composed of carbonate limestone, dolomite, and mudstone/shale rock types that were deposited in a shallow inland sea environment during the early to mid-Mississippian geologic time period. Four existing (i.e., pre-RI) boreholes at the Site penetrate the Keokuk Formation, which is underlying the Warsaw Formation. As described in the RI/FS Work Plan, water levels in the Keokuk Formation are consistently higher than those in the St. Louis and Salem Formations, resulting in consistent upward vertical hydraulic gradients, and further characterization of the Keokuk Formation is not warranted because it is unlikely that there is a mechanism that exists to create widespread migration of COPCs from the Site downward into this formation (ERM 2020).

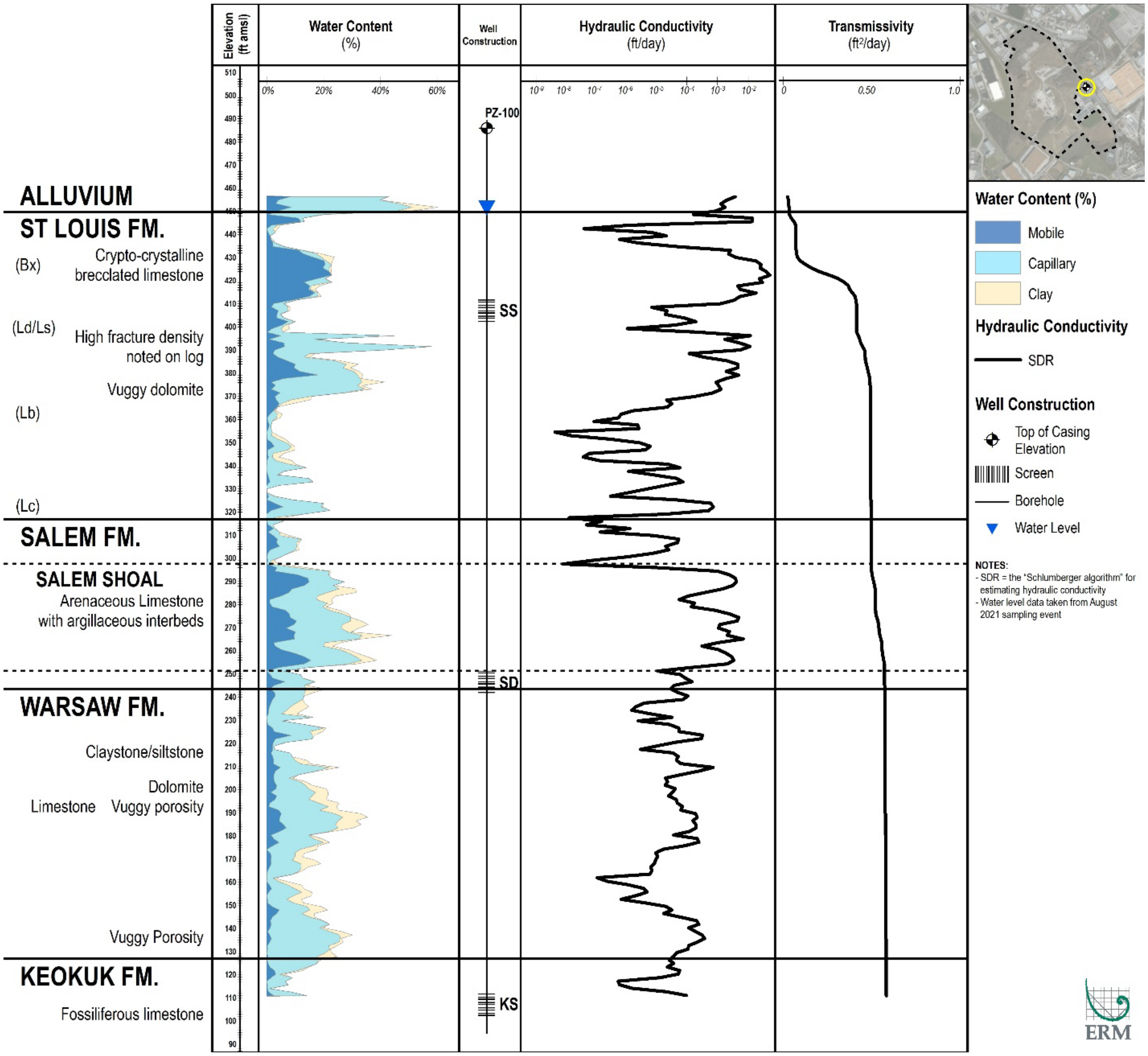


Figure 4-11: Bedrock Type Section for PZ-100-KS

The bedrock type section shows the NMR geophysical logging data and bedrock core descriptions at PZ-100-KS (Keokuk Formation). Monitoring well screen depths for adjacent wells PZ-100-SD (Salem Formation) and PZ-100-SS (St. Louis Formation) are also shown. As shown on the NMR geophysical log, the mobile water content is higher in the St. Louis and Salem Formations than it is in the Warsaw Formation.

As described in the 2021 Annual Report (ERM 2022b), prior to the OU-3 RI, the contact depths between the St. Louis and Salem Formations and the Salem and Warsaw Formations were unknown in the northern and western areas of the Site. There were few bedrock wells in areas underlain by alluvial valley sediments, and those that existed were relatively close to the alluvial valley margin. Because alluvial processes incised into and removed bedrock material, it was unclear where within the stratigraphic column bedrock would first be encountered. Following installation of MW-400, MW-404, and MW-304 and correlation of the respective geophysical logs with logs that were available for existing (i.e. pre-RI) wells in upland areas of the Site, it was determined that the St. Louis Formation and, in some areas, the upper portion of the Salem Formation were absent in the northern and western areas of the Site and that alluvium is in direct contact with the Salem Formation in these areas (Figure 4-12). Due to the uncertain depth of the various bedrock units, and because the St. Louis Formation was completely absent beneath the northern portion of the Site, these three initial wells were drilled into the Warsaw Formation and the deepest screen interval was installed in the Warsaw Formation.

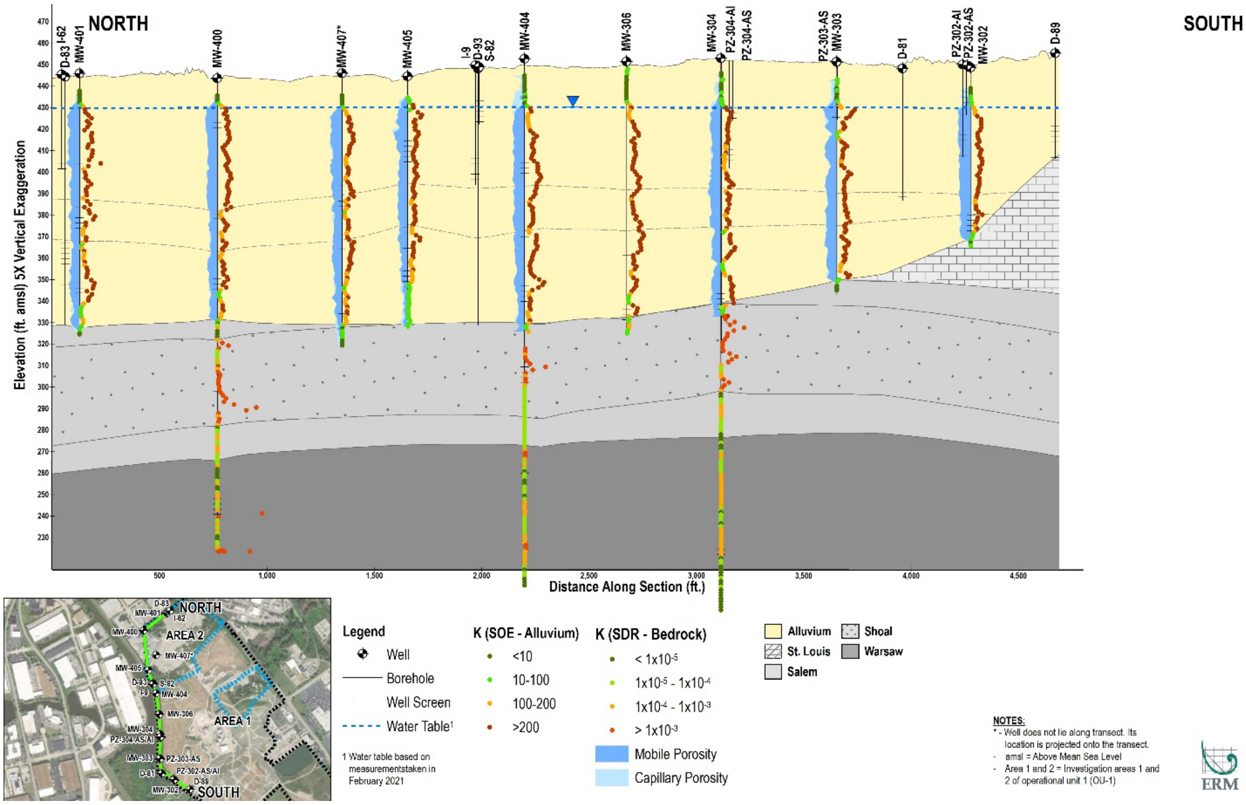


Figure 4-12: Cross-Section Showing the Relationship Between Alluvium and Bedrock Formations from Upland Areas to the Alluvial Valley

The north-south cross-sections shows alluvium and bedrock stratigraphy at the Site. In the upland area (south end of cross-section), the St. Louis and Salem Formations are present. Beneath the alluvial valley (north end of cross-section), the St. Louis Formation is eroded and the Salem Formation is in direct communication with alluvium. A more conductive interval of the Salem Formation (the Salem Shoal Sequence, discussed in Section 4.4.1.2) is also in direct communication with alluvium in the middle of the cross-section.

4.4.1.1 Warsaw Formation

The Warsaw Formation is present beneath the entire investigation area (i.e., the Site and off-Site locations, where background wells have been installed). The Warsaw Formation can be divided into two distinct lithologic zones: an upper shale-dominated zone and a lower limestone-dominated zone (Spreng 1961; Harrison 1997). Using data from wells installed prior to and during the reporting period, the top of the Warsaw Formation dips to the east-southeast at a rate of approximately 0.015 feet per foot (80 feet per mile) (Figure 4-13).

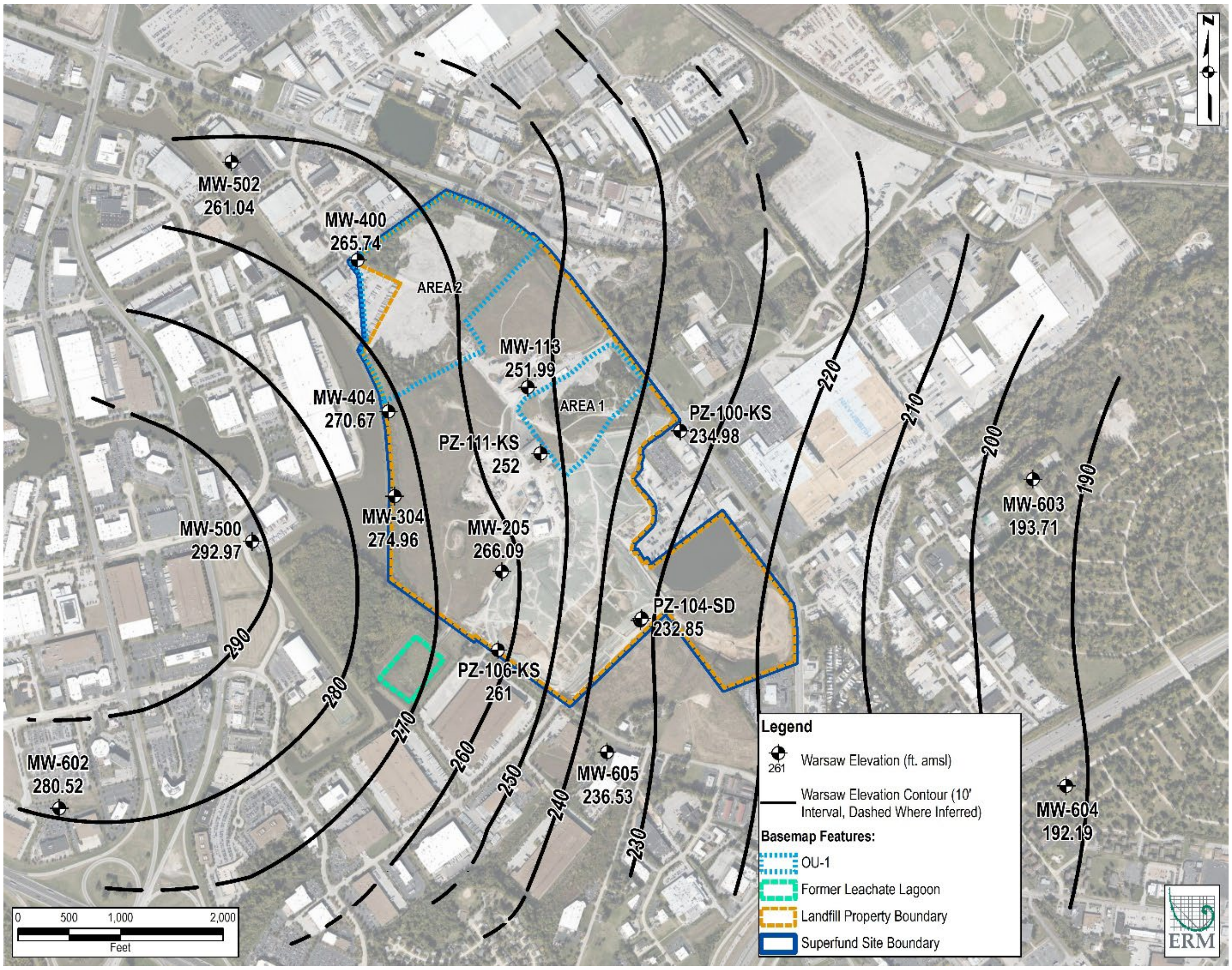


Figure 4-13: Top of the Warsaw Formation Structure Map

The Warsaw Formation structure map shows that the contact between the Salem and Warsaw Formations dips to the east.

The contact between the Salem and Warsaw Formations is marked by a layer of shale or mudstone that is generally 5- to 10-feet thick. This layer is easily identified on borehole geophysical logs due to the increased clay mineral content resulting in increased gamma activity and electrical conductivity as observed on natural gamma and induction logs, but this layer is not visually apparent in the bedrock cores. The example geophysical log from MW-205, shown below on Figure 4-14, illustrates these characteristics in the first and second columns from the left. Similar characteristics were observed at boreholes installed in 2022.

NMR geophysical logs show a decrease in total porosity within the Warsaw Formation that is characterized by predominately capillary and clay-bound water within the bedrock matrix and lesser amounts of mobile water (see total fluid volume column, which depicts NMR data, on Figure 4-14 below). Acoustic televiewer data show a reduction in the frequency of open fractures in the Warsaw Formation relative to the overlying formations (i.e., colored “tadpole” symbols in the far-right Column 9 depict the orientation and openness of each bedrock bedding-plane or fracture identified from the acoustic televiewer log; red tadpoles represent interpreted open fractures). Based on NMR results, the estimated bulk hydraulic conductivity[27] of the Warsaw Formation is approximately $1x10^{-4}$ to $1x10^{-6}$ feet per day with a maximum hydraulic conductivity of $8x10^{-2}$ in fractured intervals, where present. The bulk hydraulic conductivity is approximately one to two orders of magnitude lower than the hydraulic conductivity of the more highly conductive intervals of the Salem and St. Louis Formations.

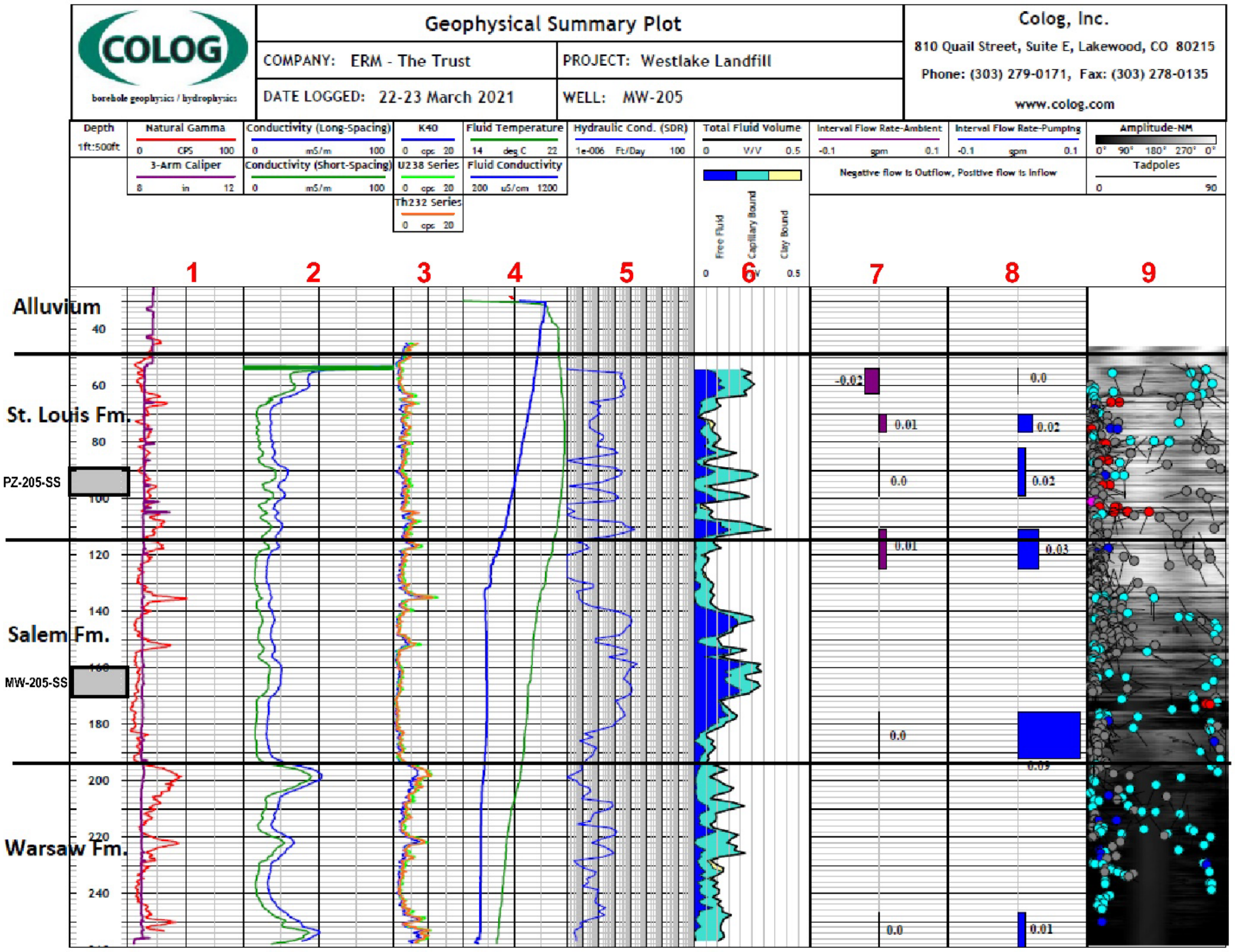


Figure 4-14: Geophysical Logging Results at MW-205

Figure 4-14 illustrates the high density of open, low-angle fractures in the St. Louis Formation (acoustic televiewer log, Column 9); the elevated mobile matrix porosity and hydraulic conductivity within the Salem Shoal Sequence (Columns 5 and 6); and the increased gamma counts, and bulk conductivity associated with the Warsaw Formation (Columns 1 and 2).

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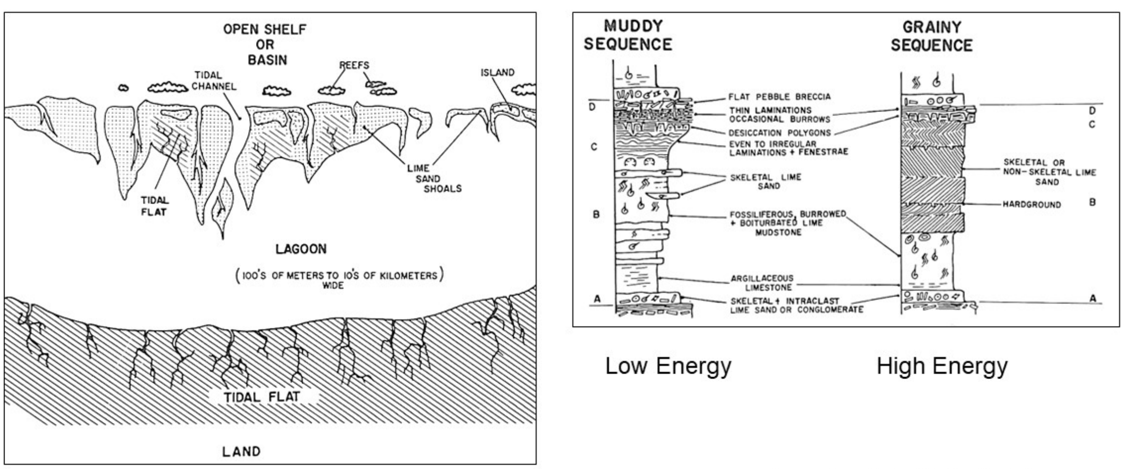
27 The NMR tool typically underestimates hydraulic conductivity of individual fractures in fractured bedrock because it averages data over approximately 1.5-foot intervals and cannot measure the hydraulic conductivity of individual fractures (see discussion in Section 3.2). Therefore, the data generated by this tool represent an average of hydraulic parameter values over the vertical measurement interval. As such, the hydraulic properties of individual fractures are not accurately defined by the NMR data. Instead, the NMR data represent bulk hydraulic property data for the entire measurement interval.

4.4.1.2 Salem Formation

The Salem Formation is present beneath the entire investigation area, although the upper portion of it has been incised by alluvial processes within the Missouri River alluvial valley[28]. The Salem Formation is fully intact in the upland portion of the investigation area where it is overlain by the St. Louis Formation. The Salem Formation is composed primarily of arenaceous[29] limestone with argillaceous[30] interbeds at the top and bottom sandwiching an approximately 40- to 50-foot-thick interval that has elevated hydraulic conductivity and mobile porosity (see NMR logging data labeled “Hydraulic Cond.” and “Total Fluid Volume” on Figure 4-14) called the “Salem Shoal Sequence.” The elevated matrix porosity within the Salem Shoal Sequence suggests that this is an arenaceous lime sand, typical of shoal sediments in carbonate depositional environments, as illustrated on Figure 4-15. NMR data show that the average hydraulic conductivity in the Salem Shoal Sequence is approximately two orders of magnitude greater than the hydraulic conductivity in the Salem Formation bedrock above and below the Salem Shoal Sequence (Figure 4-16). Similar characteristics were observed at wells installed in the 2022 reporting period.

Acoustic televiewer data show few open fractures in the Salem Formation (Figure 4-14); most open fractures within the Salem Formation occur near the alluvium/bedrock contact in areas where the upper portion of the Salem Formation (i.e., the portion above the Shoal Sequence) subcrops beneath alluvium. The Salem Shoal Sequence is in direct contact and hydraulic communication with alluvium along the western margin of the Site, as shown by the brown cross-hatched line on Figure 4-17. Like the Warsaw Formation, the Salem Formation dips to the east-southeast at a rate of approximately 0.015 feet per foot (80 feet per mile), although a mound in the upper surface of the Salem Formation is observed beneath the central and western portion of the Site where the Salem Shoal Sequence is thickest (Figure 4-17).



Carbonate Environments

Adapted from Facies Models, Geologic Association of Canada, Department of Earth Sciences, University of Waterloo, 1983

Figure 4-15: Carbonate Depositional Environments of Lime Sand Shoals

A plan view map of a carbonate depositional environment that forms a lime sand shoal is shown at left. The sequence stratigraphy at this depositional environment is shown at right.

[28] The alluvial valley margin is approximated by the 410-foot contour line shown on the bedrock surface contour map presented in Figure 4-18.

[29] Arenaceous: defined as consisting of sand or particles of a substance similar to sand.

[30] Argillaceous: defined as consisting of, or containing, clay.

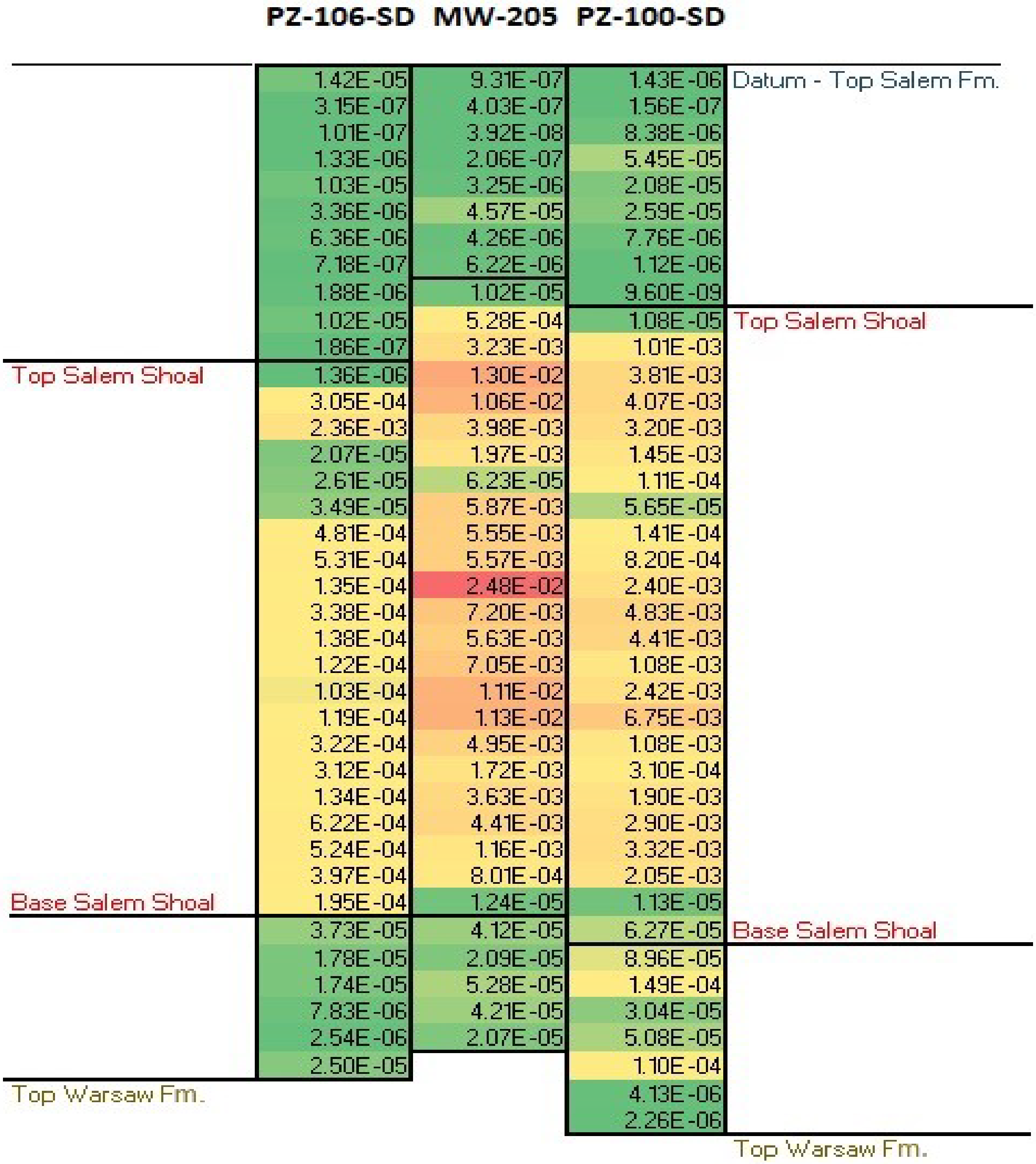


Figure 4-16: Hydraulic Conductivity Data in the Salem Formation at PZ-106-SD, MW-205, and PZ-100-SD

High-resolution, NMR-derived hydraulic conductivity data in feet per day are color-coded from low (green) to high (red) to illustrate that the hydraulic conductivity values are higher (yellows, oranges, and red highlighting) within the Salem Shoal Sequence and are lower (green highlighting) above and below the Salem Shoal Sequence.

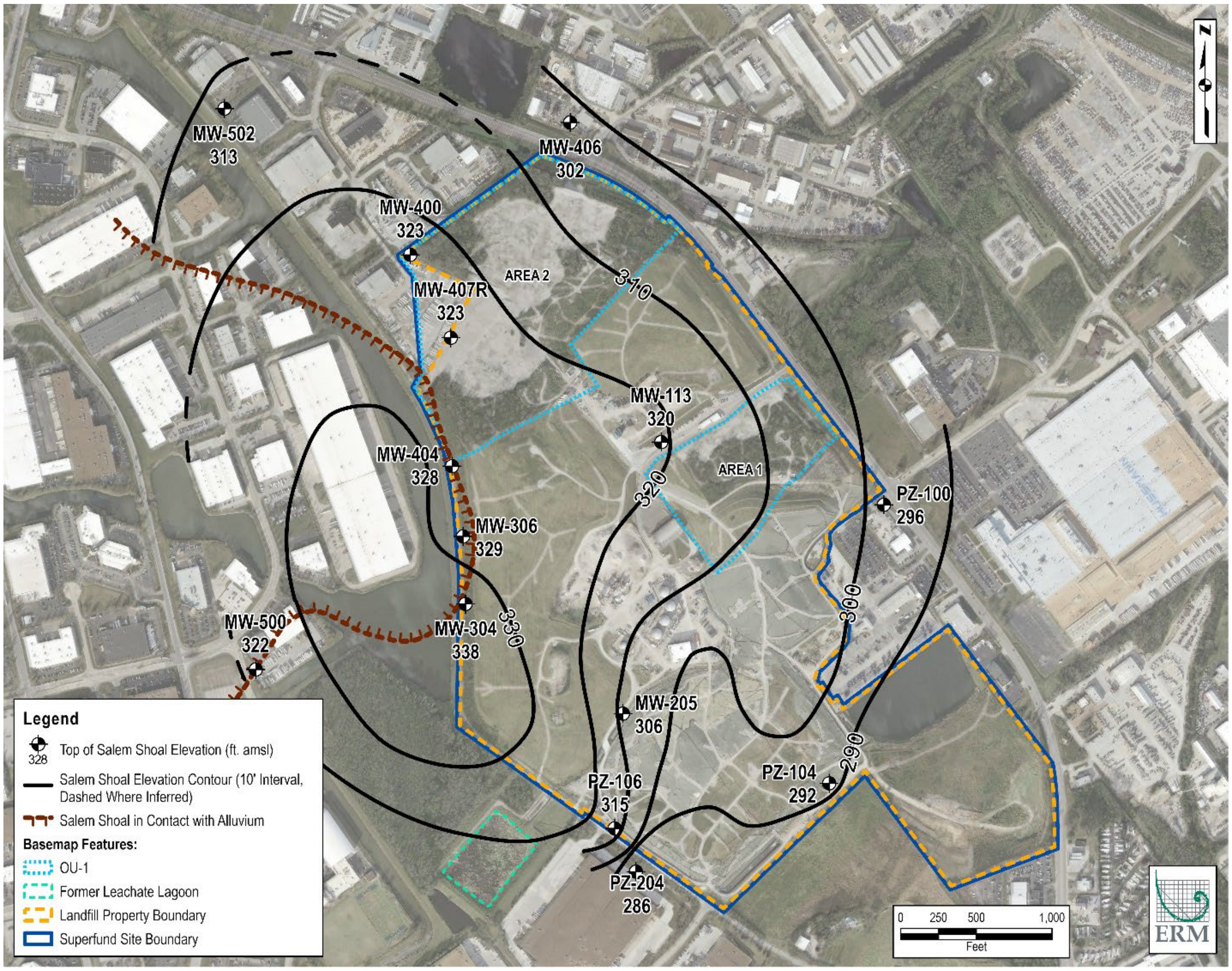


Figure 4-17: Top of the Salem Shoal Sequence Structure Map

This figure shows the geometry of the top of the Salem Shoal Sequence and where this sequence is in direct communication with alluvium (brown hatching).

4.4.1.3 St. Louis Formation

The St. Louis Formation is present in the southern upland area of the Site but is absent beneath the Missouri River alluvial valley (see Figure 4-12). The St. Louis Formation is composed of a mixture of fossiliferous and argillaceous limestone and dolomite. The contact between the St. Louis Formation and underlying Salem Formation is somewhat gradational. For this investigation, the contact was defined by historical boring logs and rock descriptions that were compared to newly acquired geophysical logs and then correlated across the Site in areas where the St. Louis Formation is present. Acoustic televiewer and NMR data indicate that porosity and hydraulic conductivity within the St. Louis Formation are primarily controlled by open fractures that are typically low angle, although some high-angle fractures are also observed (Figure 4-14). Similar characteristics were observed at wells installed during the 2022 reporting period. Intervals of elevated mobile porosity observed on the NMR logs appear to be associated with fractures rather than matrix porosity. NMR data indicate that hydraulic conductivities in the St. Louis Formation range from 1×10^{-2} to 1×10^{-7} feet per day, but as noted in Sections 3.2 and 4.4.1.1, the NMR tool measures bulk rock hydraulic properties and is not able to measure hydraulic properties of individual fractures. As such, the NMR data likely underestimate hydraulic conductivity within intervals where the fracture density is low, but the fractures are highly transmissive compared to the formation matrix.

The lateral extent of the St. Louis Formation, beyond which it has been fully eroded by the alluvial valley, is at an elevation of approximately 340 feet to 350 feet (Figure 4-18).

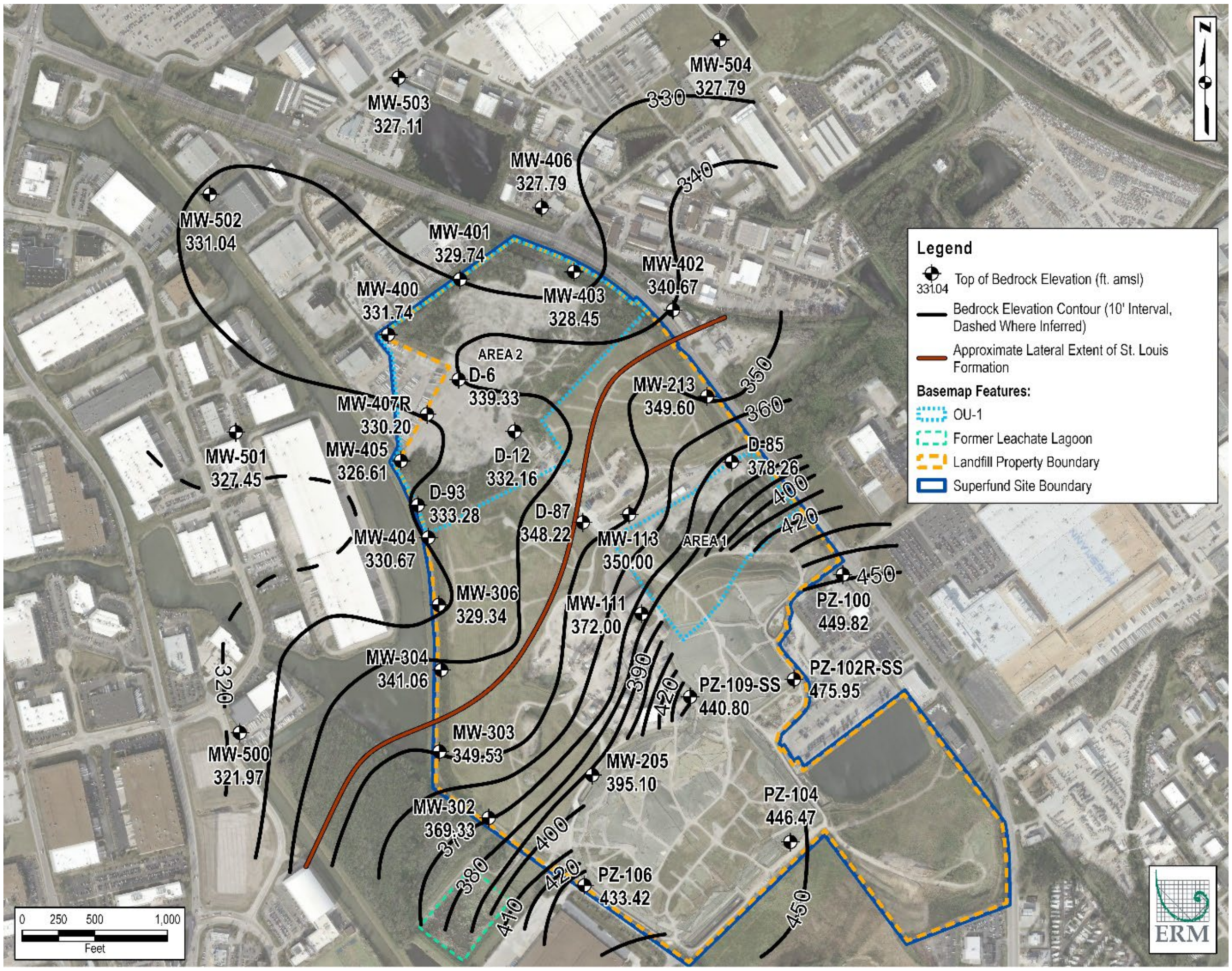


Figure 4-18: Top of Bedrock (Undifferentiated) Structural Map

The top of bedrock structure map shows a bedrock high (i.e., ridge) in the northern portion of the Site and the approximate lateral extent of the St. Louis Formation beyond which the Salem Formation underlies alluvium.

Summary

The bedrock beneath the Site and surrounding area is part of four geologic formations, some of which have been partially or completely eroded within the alluvial valley. These units, from youngest/shallowest to oldest/deepest, are defined in the geologic literature as the St. Louis, Salem, Warsaw, and Keokuk Formations. All four formations are comprised of carbonate rocks, which are a type of sedimentary rock consisting of carbonate minerals. Within the Salem Formation, ERM identified a subunit called the Salem Shoal Sequence. Due to the physical properties of the Salem Shoal Sequence, more groundwater flows through this portion of the bedrock aquifer than through the other bedrock units. The geologic model was used as a framework for evaluating hydrogeologic and solute (i.e., substance dissolved in water) distribution data.

4.4.2 Alluvium

4.4.2.1 Alluvium Saturated Thickness

Saturated alluvium is thickest (approximately 100 feet) along the northwestern and northern boundary of the Site and thins rapidly along the alluvial valley contact with bedrock to the south, where the alluvium pinches out. Figure 4-19 shows the saturated thickness of alluvium based on the morphology of the alluvial valley.

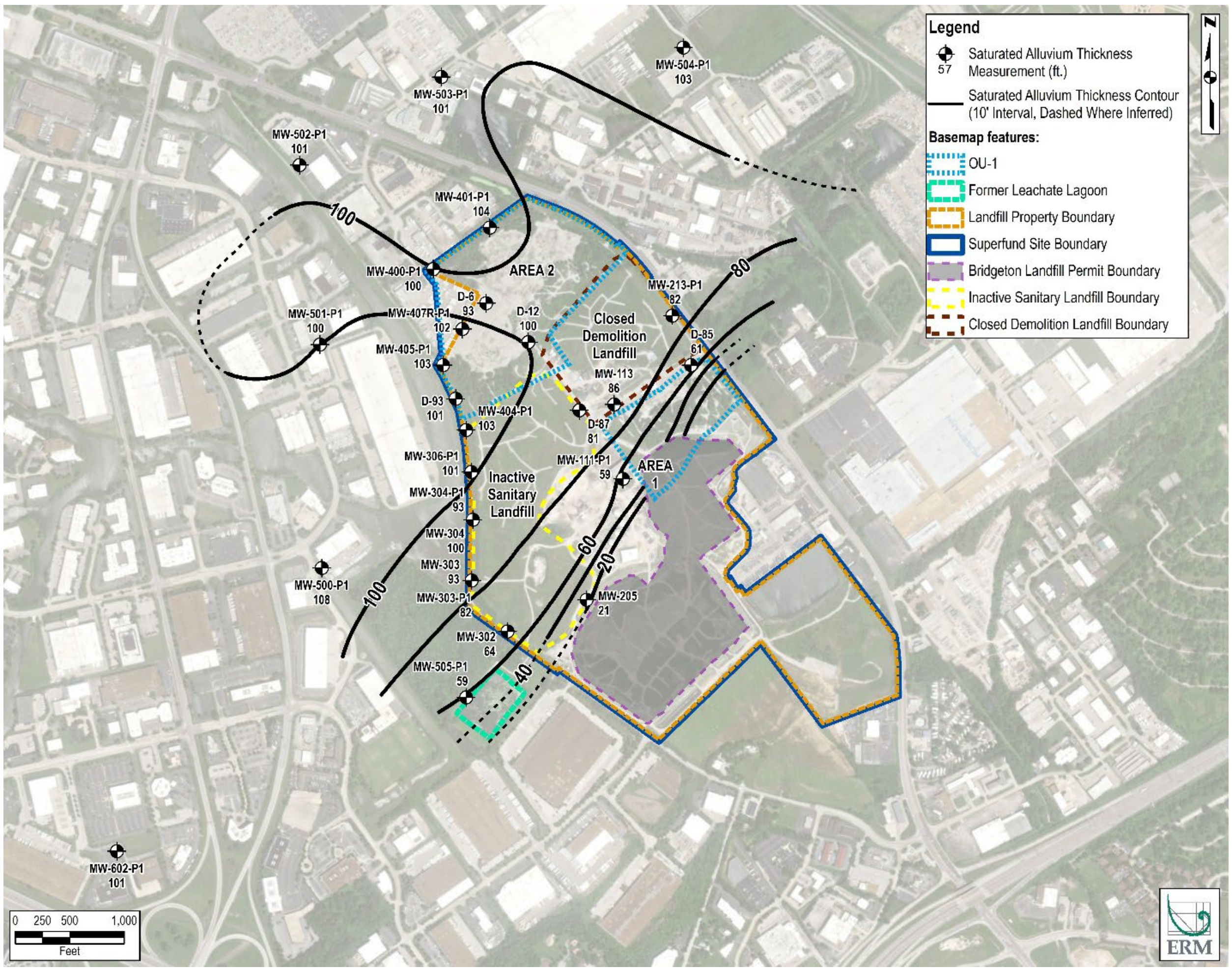


Figure 4-19: Saturated Thickness of Alluvium

The map shows that the saturated thickness of alluvium is greater in the northern portion of the Site. Alluvium pinches out along the edge of Bridgeton Landfill.

As described in Anderson et al. (2021), highly variable water and sediment input related to climate extremes during the last glacial cycle (Pleistocene) resulted in both incision and sediment aggradation at rates much different than today (Holocene). The Missouri River rapidly incised and aggraded up to 90 feet of sediment in two climate-driven cycles over a period of about 15,000 years from the Last Glacial Maximum to about 8,000 years ago. Stabilization after each incision and aggradation event promoted lateral migration of the river and construction of a fluvial surface above a corresponding alluvial deposit with the same name, as shown on Figure 4-20. These fluvial surfaces typically consist of finer-grained sand deposits as compared to the coarser-grained sand and gravel alluvial deposits.

The updated CSM identifies a series of stacked, coarsening-upward sequences of sediments associated with high-energy systems deposited during retreat of the Pleistocene ice sheet.

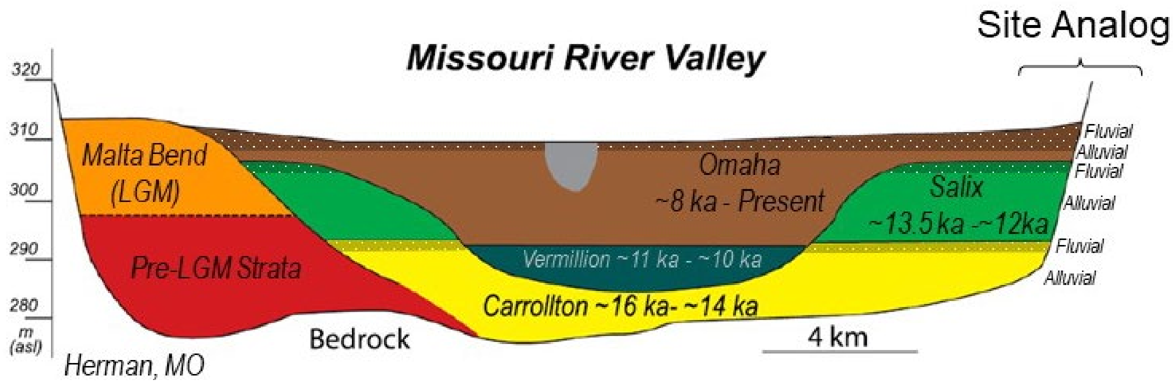


Figure 4-20: Conceptual Model of Cyclic Incision and Sediment Aggradation Associated with Pleistocene Glaciation in the Missouri River Valley

Figure modified from Anderson et al. 2021. LGM = Last Glacial Maximum, m (asl) = meters above sea level, km = kilometers, ka = thousands of years ago

4.4.2.2 Time Stratigraphic Markers

Review of NMR geophysical data indicated the presence of stacked sequences of coarsening-upward alluvial deposits that have increasing total and mobile porosity. These sequences are separated by thin fluvial interbeds of reduced porosity that define TSMs. This stratigraphy is consistent with that described by Anderson et al. (2021). The high-energy, coarsening-upward sequences (TSUs) and less permeable fluvial interbeds (TSMs) are laterally extensive and can be correlated across the investigation area.

In the 2021 Annual Report (ERM 2022b), ERM initially identified five potential TSUs within the alluvial stratigraphic sequence, which included three coarsening-upward sand and gravel sequences (previously defined as TSU-1, TSU-3, and TSU-5) separated by finer-grained, lower-hydraulic conductivity fluvial interbed TSMs (previously defined as TSU-2 and TSU-4), as shown on the right side of Figure 4-21. A sixth TSU (TSU-0) consists of finer-grained sediments, interpreted as loess, which was deposited after the Pleistocene glacial deposits. TSU-0 is mostly unsaturated except at the base of the unit in some areas of the Site.

During this reporting period, additional wells were installed off-Site at distances up to 8 miles from the Site. Using the more spatially extensive dataset, ERM evaluated the TSMs for megascale lateral continuity and found the former TSMs to be consistent within the Site boundary, but less consistent at greater distances from the Site. As a result, ERM redefined the alluvial sequence stratigraphy into three alluvium sequences separated by two TSMs, which are laterally consistent at the megascale.

The former sequence stratigraphy defined in the 2021 Annual Report (ERM 2022b) is shown on the left side of Figure 4-21 (i.e., Site-scale TSUs) and the updated sequence stratigraphy defined in this report is shown on the right side of Figure 4-21 (i.e., Re-defined Regional TSUs).

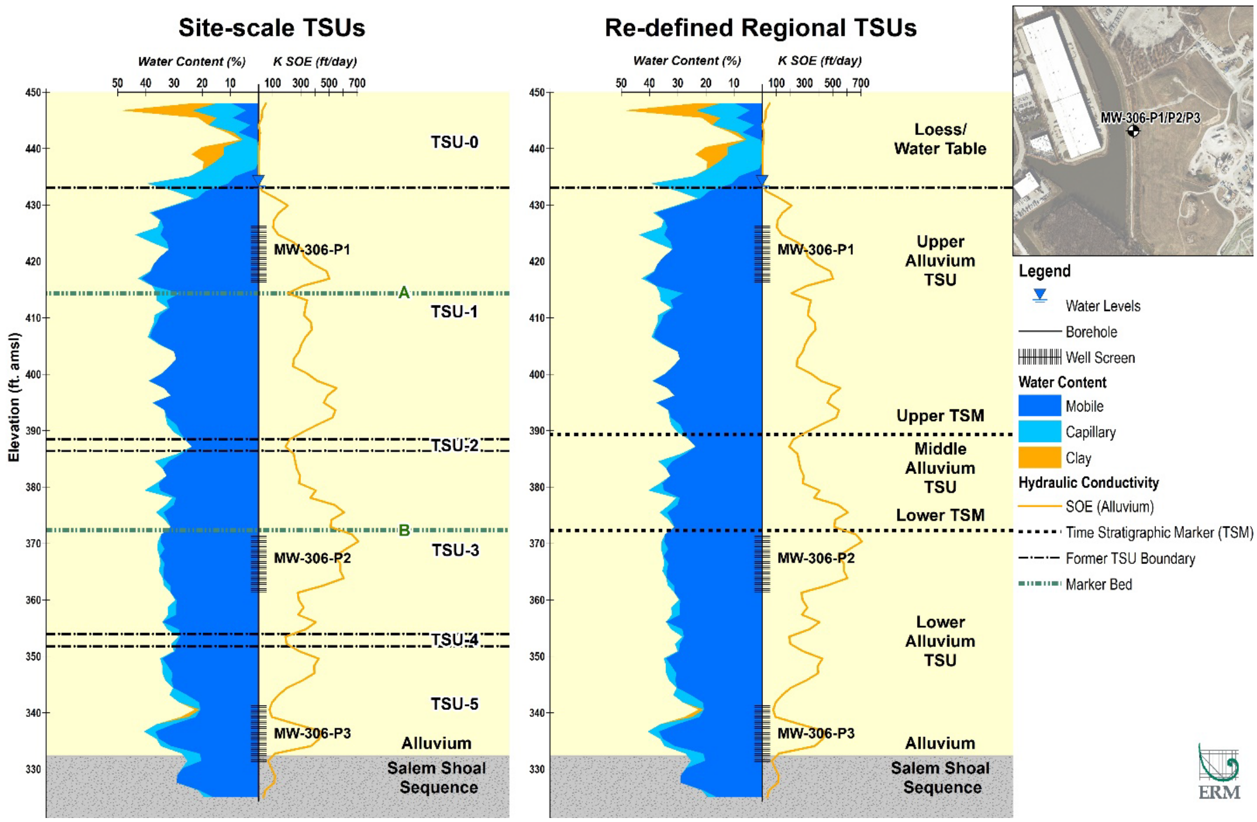


Figure 4-21: TSU Model Update Based on Local and Regional Scale Correlations

The side-by-side logs show how the TSU model was modified from five TSUs at the Site-scale to three TSUs with two TSMs, which can be correlated at the megascale.

Figures 4-22 and 4-23 demonstrate the laterally continuous nature of the TSUs and TSMs across the investigation area. The re-defined model is consistent with the Missouri River Valley analog described above (see Figure 4-20), with three primary periods of sediment aggradation separated by two TSMs. TSMs may introduce additional vertical anisotropy within the overall alluvial sequence, but they are not considered aquitards that would prevent vertical flow of groundwater in the presence of aquifer stresses (i.e., areas of recharge, discharge, or induced stresses).

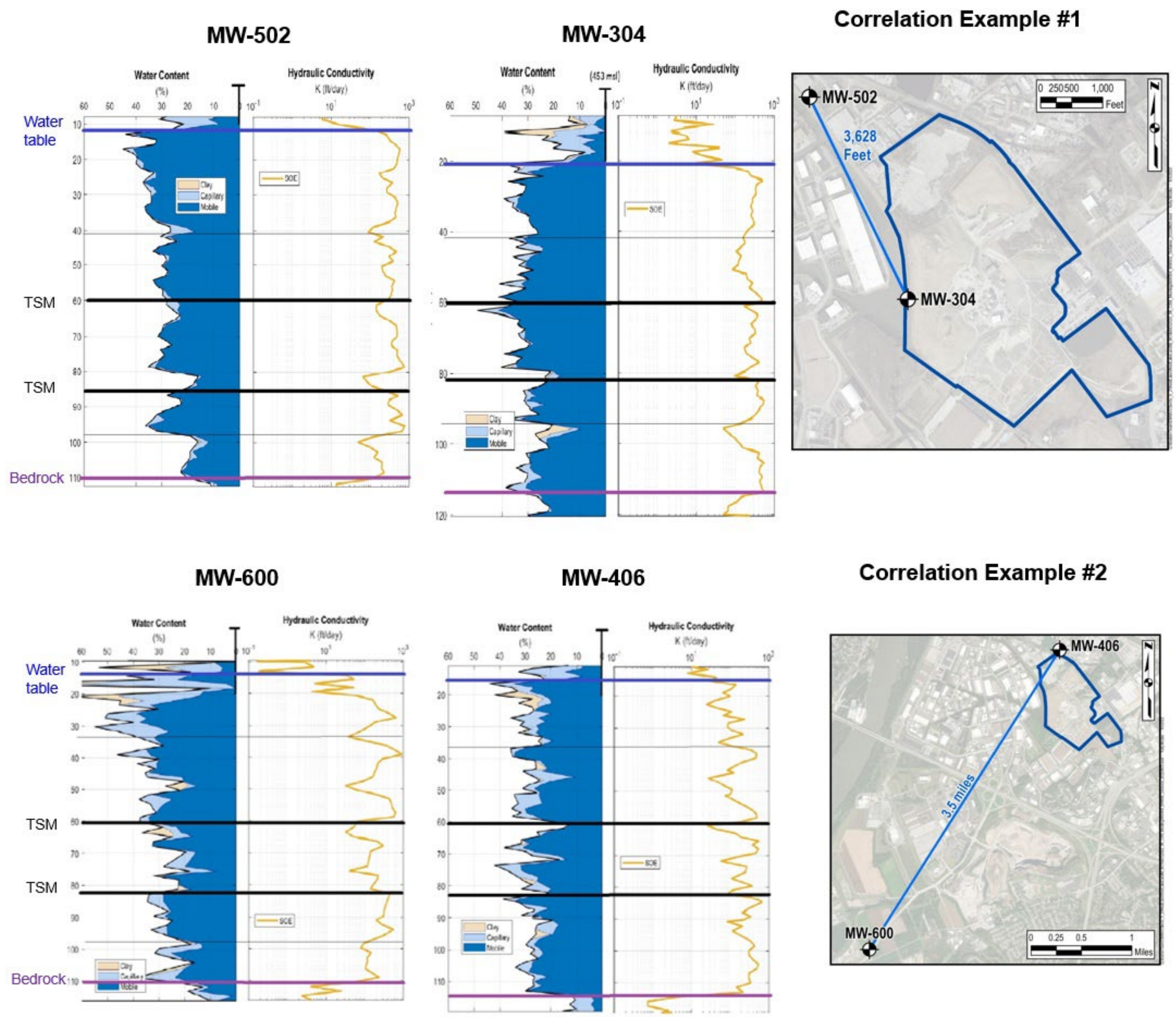


Figure 4-22: Examples of Regional Correlation of TSUs and TSMs

The example correlation pairs show how the TSMs are consistent close to the Site (i.e., MW-502 and MW-304) and at distances farther from the Site (i.e., MW-600 and MW-406).

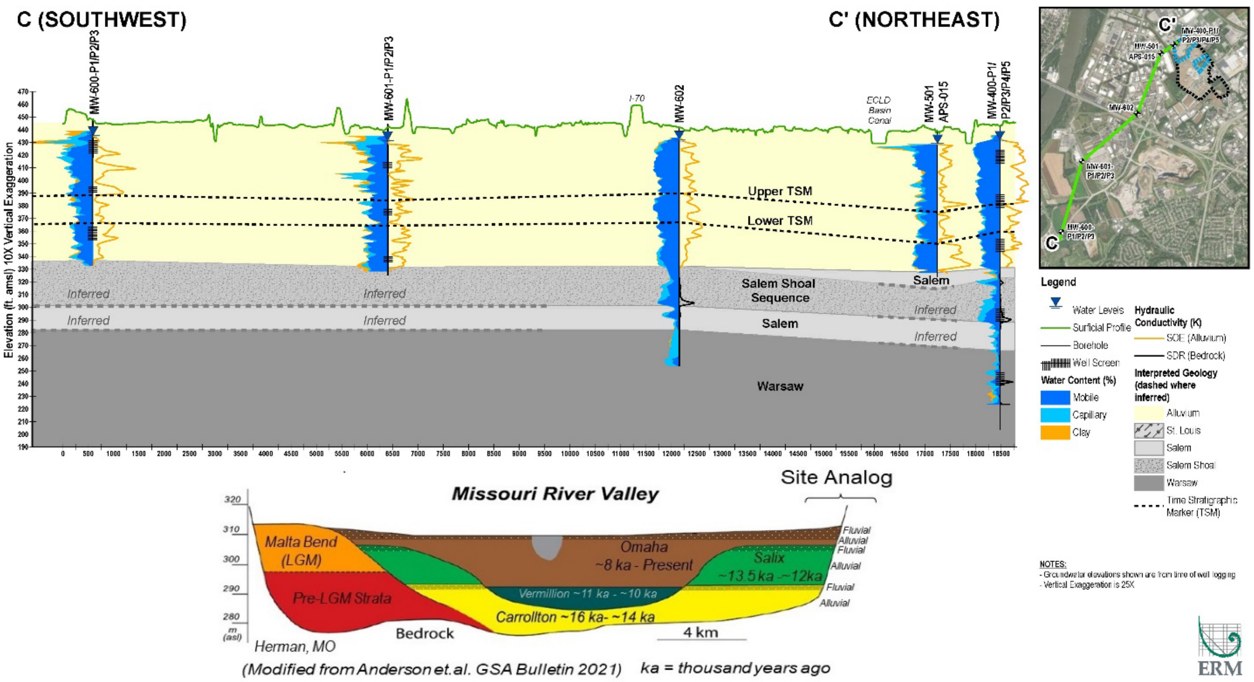


Figure 4-23: Regional Geologic Cross-Section

A regional cross-section shows the geologic model including the re-defined TSUs, TSMs, and the bedrock units.

The re-defined TSUs are identified as follows:

- Lower Alluvium: represents coarse sediment aggradation within a high-energy flow system
- Middle Alluvium: represents a change in depositional dynamics under a somewhat lower-energy flow system
- Upper Alluvium: formed under coarse sediment aggradation within a high-energy flow system

The Loess/Water Table[31] unit consists of finer-grained loess that was deposited on top of the glacially deposited alluvial sediments (primary aquifer). The loess is a separate unit that is either unsaturated or partially saturated in places where the water table occurs in the loess, but the loess deposits are not considered to be part of the regional alluvial aquifer.

ERM input the TSMs into a geologic model to define the TSUs in three-dimensions across the study area. All previously existing (i.e., pre-RI) and newly installed monitoring wells were assigned to one of the three TSUs or to the Loess/Water Table unit. If a well was screened primarily in one TSU (i.e., greater than 90 percent), then it was assigned to that primary TSU. If a well was screened more evenly across two TSUs, it was assigned to both units. The process for defining TSMs and TSUs is explained in more detail in Appendix I, monitoring well TSU assignments are listed in Appendix P, and the summary table below lists the number of wells assigned to each TSU (note: wells assigned to two TSUs are counted under the Middle/Lower Alluvium and Upper/Middle Alluvium categories).

[31] Some pre-existing (i.e., pre-RI) wells are screened within the Loess/Water Table. No new RI wells were installed in this unit.

Table 4-1: Summary of Groundwater Monitoring Well TSU Assignments

TSU	Number of Well Screens
Lower Alluvium	28
Middle/Lower Alluvium	7
Middle Alluvium	9
Upper/Middle Alluvium	10
Upper Alluvium	43
Loess/Water Table	7

The distribution of well screens is consistent with the thickness and extent of the alluvium TSUs. Including wells that are screened across units, there are:

- 35 well screens partially or completely in the Lower Alluvium, which has an intermediate thickness;
- 26 well screens partially or completely in the Middle Alluvium, which is the thinnest TSU; and,
- 53 well screens partially or completely in the Upper Alluvium, which is the thickest and most laterally extensive TSU.

There are alluvium wells in each TSU around the downgradient perimeter of the Site, which meets the monitoring needs of the RI.

Summary

The alluvium beneath the Site and surrounding area consists primarily of sand and gravel and for the purpose of this investigation has been divided into three units: the Upper, Middle, and Lower Alluvium. These units are referred to as Time Stratigraphic Units (TSUs) because the alluvium in each unit was deposited at the same time. The alluvium units were defined using environmental sequence stratigraphy methods and are consistent with alluvium units for the region that are described in the geologic literature.

4.5 Hydrogeology

Various types of hydrogeologic data, such as horizontal and vertical hydraulic gradients, are presented and interpreted to further describe the groundwater flow system within the alluvial and bedrock aquifers underlying the study area at the microscale, mesoscale, macroscale, and megascale. These data are presented in Sections 4.5.6 and 4.5.7. The evaluation of the groundwater flow system within the alluvial and bedrock aquifers informs PSQ-5 (*Where could Site-related COPCs migrate in the future?*).

4.5.1 Groundwater Response to Landfill Operations

The groundwater flow system at the Site is affected by the landfill caps, which are designed to limit meteoric recharge and the landfill liquid collection system in the Bridgeton Landfill. Monthly leachate collection volumes for the reporting period are shown on Figure 3-1, in Section 3. ERM evaluated available transducer data in monitoring wells surrounding the Bridgeton Landfill, all of which are located in bedrock, and did not identify measurable hydraulic responses to operation of the landfill liquid collection system (i.e., when pumps cycle on and off, periodic drawdown and recovery signatures propagate readily through fractured bedrock aquifers; no evidence of drawdown and recovery signatures was noted in the transducer data collected from bedrock monitoring wells located around the Bridgeton Landfill).

Following the 2022 reporting period, ERM submitted Tech Memo 26, which proposed adding and relocating transducers in alluvium monitoring wells closer to Bridgeton Landfill. Tech Memo 26 was subsequently approved by USEPA, and pressure transducers will be relocated in Q1 2023. Evaluation of potential hydraulic responses in alluvium to operation of the landfill liquid collection system will be discussed in the 2023 Annual Report.

4.5.2 Groundwater Response to Missouri River Stage

Figure 4-24 presents Missouri River stage data, precipitation data measured at the St. Louis Lambert Airport NOAA weather station, and Site groundwater elevation data from several representative Site monitoring wells for the reporting period. Site groundwater elevations fluctuated by up to 5 feet annually. Generally, Site groundwater levels began rising in early March, peaked in mid-July, declined from August to December, and reached their lowest levels in January and February. This rising and falling pattern in Site groundwater elevations closely mimics seasonal river stage fluctuations. Seasonal Missouri River stage elevations have the greatest effect on the groundwater flow system beneath the Site, although major precipitation events in the area can influence river stages and therefore groundwater elevations and flow to some extent.

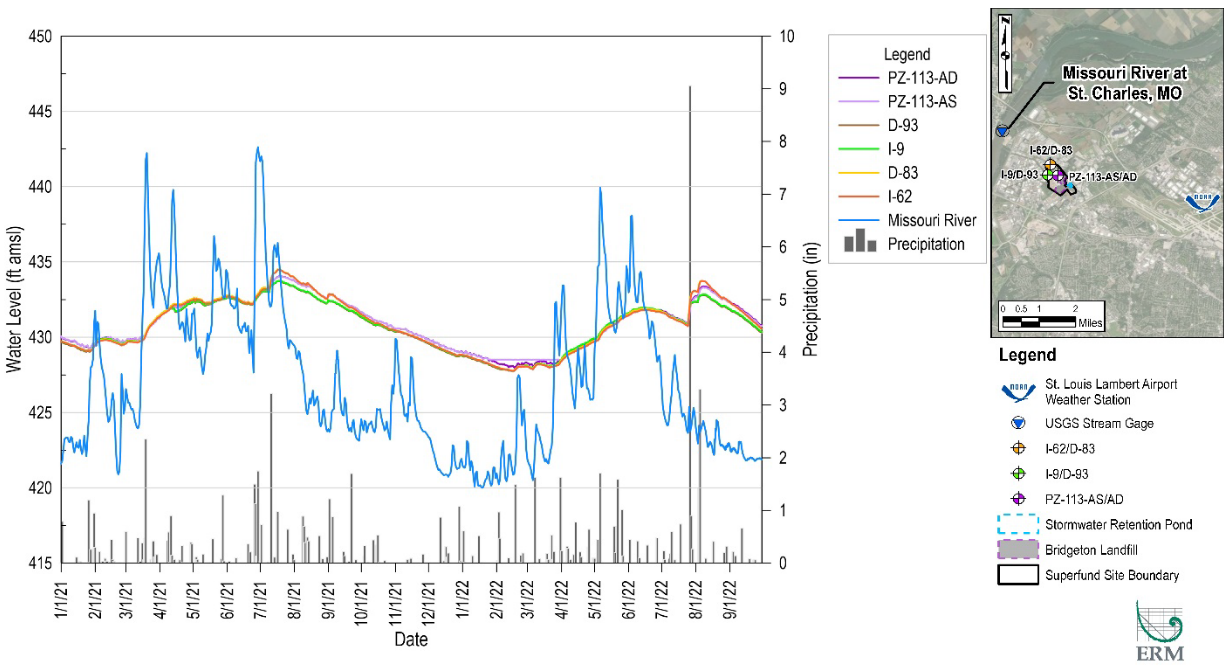


Figure 4-24: Alluvium Groundwater and Missouri River Stage Comparison

The graph shows that Site groundwater (colored lines) rise and fall seasonally, following the same pattern as the seasonal trends in the Missouri River Stage.

As shown on Figure 4-26, river stage has a greater effect on Site groundwater elevations than meteoric recharge following precipitation events; the seasonal rise and fall of the Missouri River causes a seasonal rise and fall in Site groundwater elevation, which in turn affects the magnitude and direction of hydraulic gradients, as discussed for the alluvial aquifer in Section 4.5.6.

4.5.3 Groundwater Response to Meteoric Recharge

Figure 4-25 compares precipitation data measured at the St. Louis Lambert Airport NOAA weather station to groundwater elevations measured at six representative Site monitoring wells. PZ-202-SS is a shallow bedrock well located directly adjacent to the on-Site stormwater retention basin, which collects runoff from a wide area; groundwater levels in PZ-202-SS respond to meteoric recharge from precipitation events. However, at the remaining Site wells, there is very little correlation between changes in groundwater levels and precipitation other than during the most extreme rainfall events (e.g., the rainfall event that occurred on 27 July 2021). Groundwater recharge from infiltration of precipitation events does not appear to have a significant effect on water table elevations considering the combined effects of runoff, evapotranspiration, landfill caps, shallow unconsolidated and unsaturated loess deposits that limit percolation rates, and the elevated porosity and storage capacity of the underlying, unconfined-alluvial aquifer.

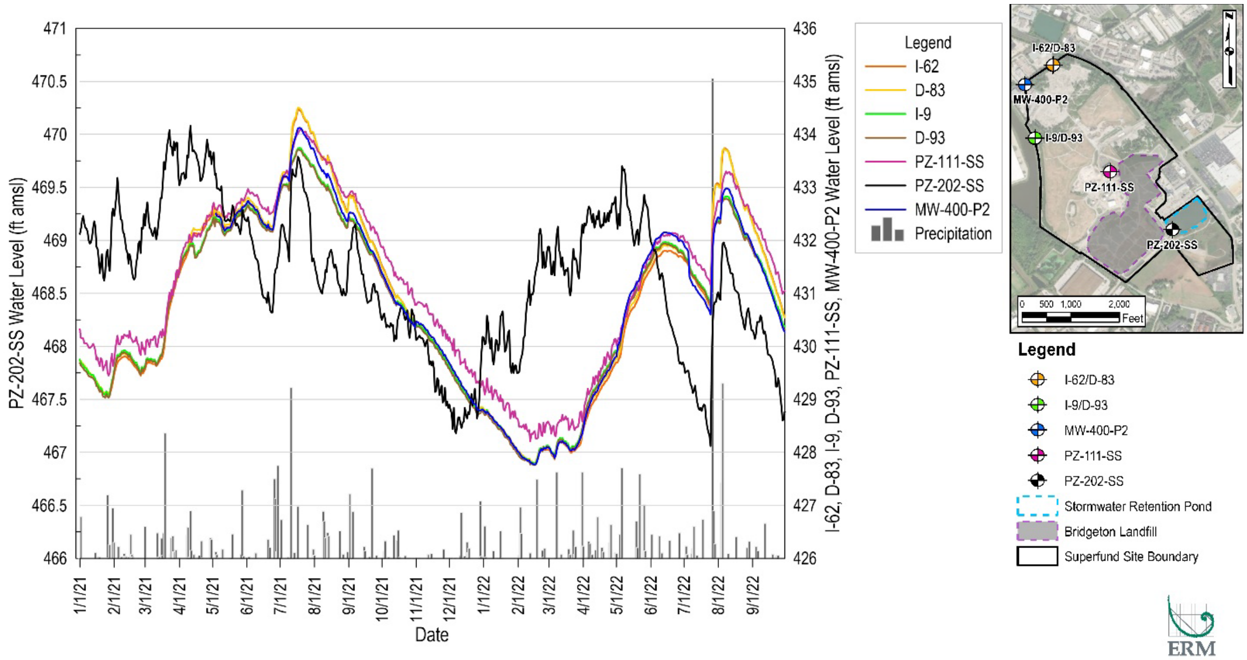


Figure 4-25: Groundwater and Precipitation Comparison

In representative Site wells, groundwater levels (colored lines) rise and fall seasonally. In PZ-202-SS, which is located adjacent to the Site stormwater retention pond, groundwater levels respond to precipitation events, potentially due to the proximity of the stormwater pond.

4.5.4 Groundwater Response to Earth City Levee District Engineered Water Body Levels

As discussed in Section 4.3.3.2, the ECLD actively manages the water table and surface water elevations within its levee district, which contrasts with the HBLD (Section 4.3.3.1), where groundwater and surface water elevations are not actively managed. Given this difference in how the two levee districts are operated, it is possible that Site groundwater elevations and hydraulic gradients within the ECLD may vary differently than those within the HBLD. However, because of transducer failures (see Section 2.9), which limited collection of surface water elevation data from the ECLD engineered water body, and the limited availability of high-resolution off-Site groundwater elevation data during the reporting period (because off-Site wells were not installed until Q2 2022), evaluation of the effects of ECLD's active management of the groundwater and surface water elevations was limited during the reporting period. Further evaluation of the effects of ECLD's active management of groundwater and surface water elevations will be completed in 2023 using available transducer data from off-Site wells and stilling wells and will be included in the 2023 Annual Report.

4.5.5 Howard Bend Levee District Groundwater Level Response to Missouri River Stage

Figure 4-26 presents groundwater elevation data from a representative set of HBLD piezometers and Missouri River stage data for the last two years. These data demonstrate that several miles upriver of the Site, in an area outside the influence of the ECLD, seasonal fluctuations in groundwater elevations mimic those observed within the Site monitoring well network—not only during 2021, but also during 2020.

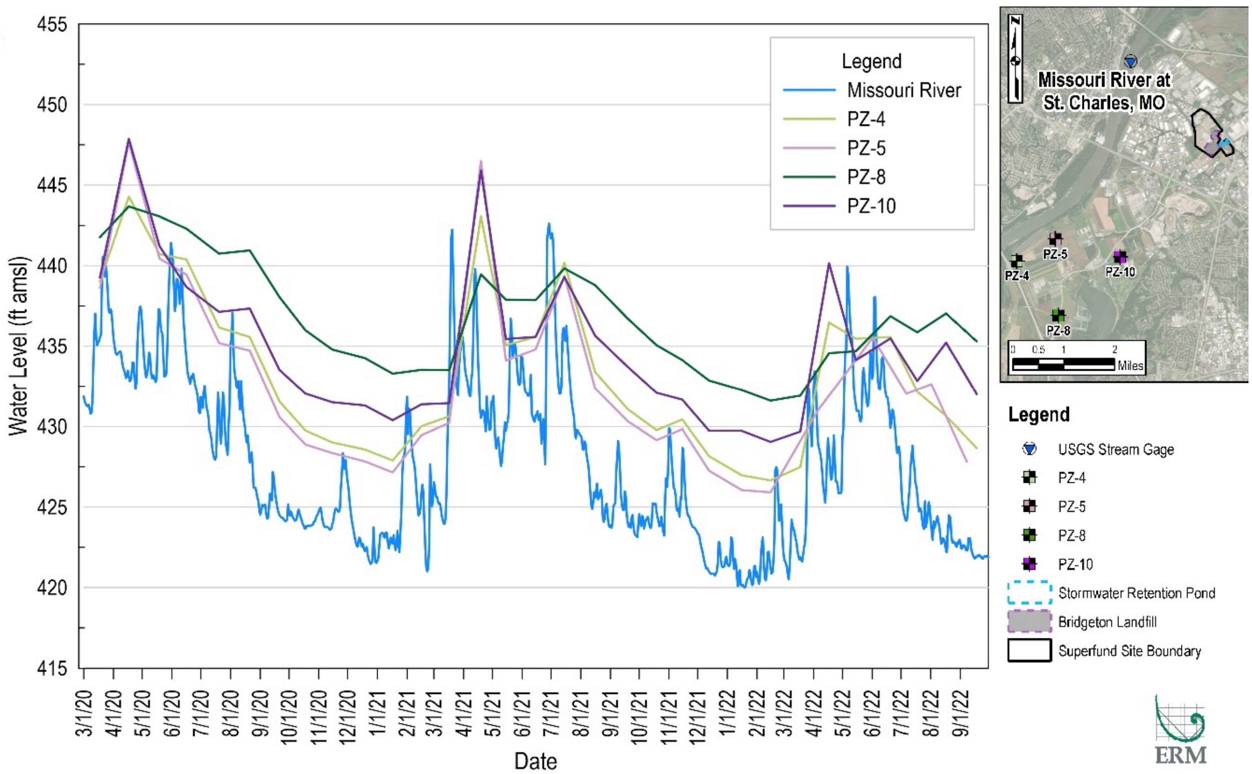


Figure 4-26: HBLD Piezometer and Missouri River Elevations

The graph shows a temporary groundwater flow direction reversal during periods of high Missouri River stage elevation; during flood events, groundwater elevation in piezometers located farther away from the Missouri River (i.e., PZ-10 and PZ-8) is temporarily higher than in piezometers located closer to the Missouri River (i.e., PZ-5 and PZ-4).

4.5.6 Alluvial Aquifer

As described in Section 4.4.2.2, the alluvial aquifer is divided into three primary TSUs (Upper, Middle and Lower Alluvium) based on interpretation of environmental sequence stratigraphy. The three alluvial TSUs consist of relatively high permeability sand and gravel deposits separated by thin TSMs composed of finer-grained sands and silts.

Hydraulic conductivity values (i.e., permeability values, not groundwater flow rates) for the alluvium were calculated from NMR data and vary by an order of magnitude within alluvium (approximately 50 to 500 feet per day)[32] (Figure 4-27) and represent both the TSUs (higher permeability intervals) and the TSMs (lower permeability intervals).

32 Hydraulic conductivity values within the alluvium are generally two to four orders of magnitude greater (sometimes more) than those measured in bedrock.

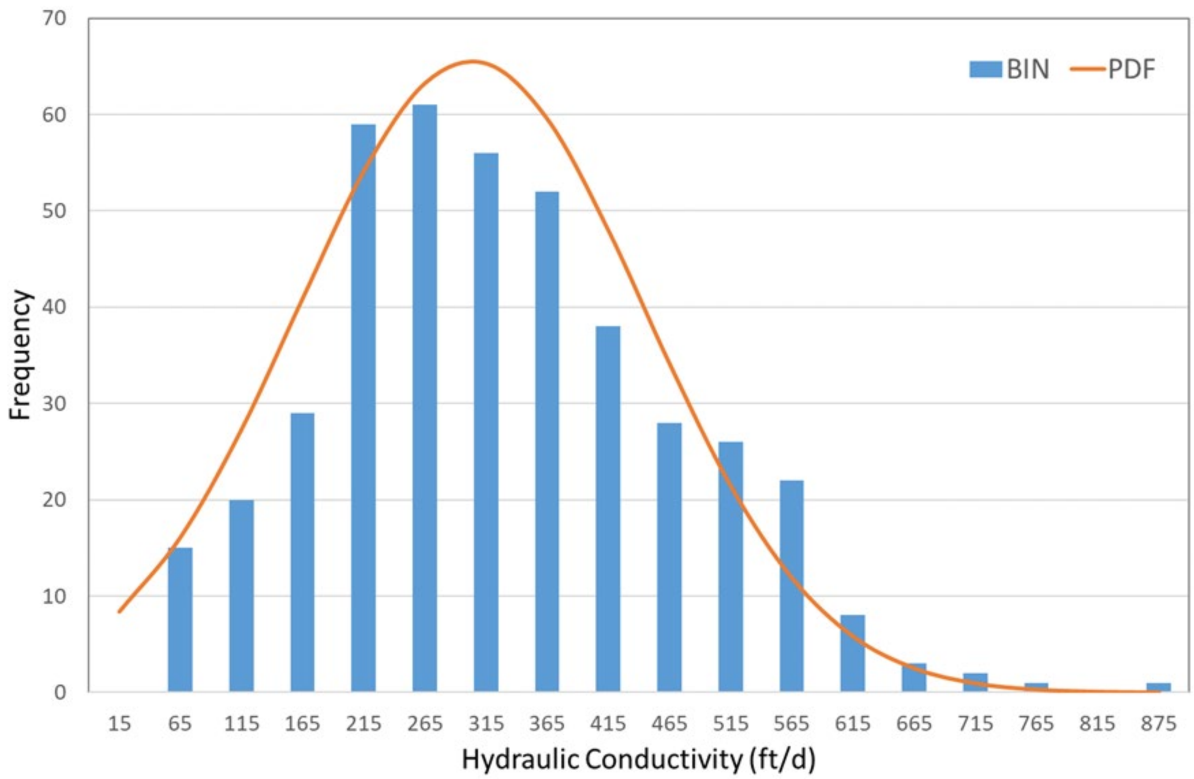


Figure 4-27: Site-wide Alluvium Hydraulic Conductivity Distribution from NMR Data

The hydraulic conductivity data were placed in bins discretized across the range of hydraulic conductivity values to derive a frequency number (i.e., number of NMR data points that fall into the specific hydraulic conductivity range) for each bin. A probability density function curve was then fit to the frequency data.

Note: ft/d = feet per day; PDF = probability density function.

Figure 4-28 presents a hypothetical illustration of variability in hydraulic conductivity values across the TSM separating the Upper and Middle Alluvium TSUs (note: the same concept applies between the Middle and Lower TSUs), which would result in vertical anisotropy that would favor horizontal over vertical groundwater flow in the alluvial aquifer, in the absence of aquifer stresses. In general, a horizontal to vertical anisotropy ratio of up to 10:1 may be assumed for most alluvial depositional environments (Freeze and Cherry 1979).

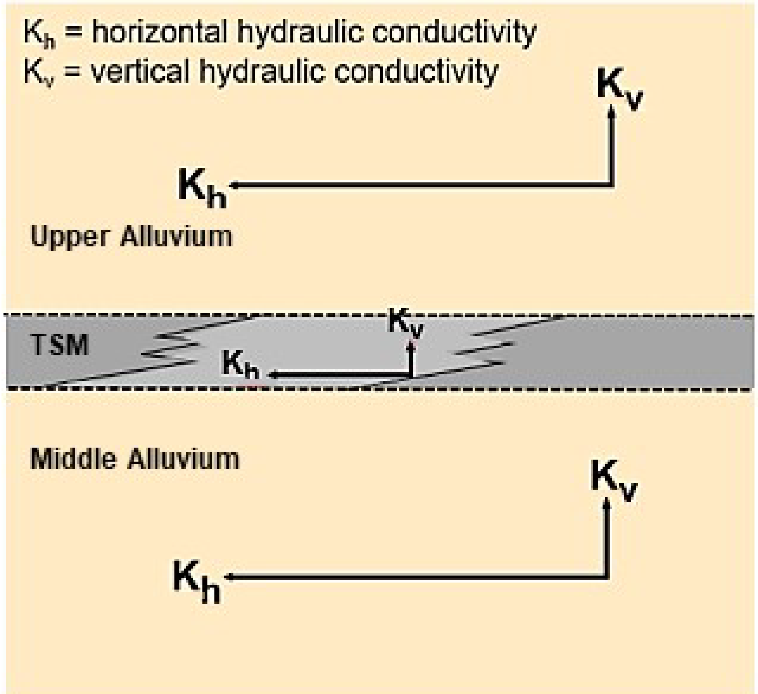


Figure 4-28: Illustration of Horizontal and Vertical Hydraulic Conductivity

The cartoon schematic illustrates anisotropy: horizontal hydraulic conductivity is greater than vertical hydraulic conductivity. Note: this figure is not to scale.

Though the Upper, Middle, and Lower Alluvium have been defined and correlated regionally, evaluation of how these units affect groundwater flow is still in progress. As noted in Section 4.5.2, groundwater elevations vary seasonally and result in some variability in the orientation and magnitude of the horizontal and vertical hydraulic gradients. Evaluation of hydraulic gradients and the groundwater flow system was conducted during the reporting period, with the following limitations:

- Off-Site wells were not installed until Q2 2022 so there is limited reporting period transducer data for off-Site locations.
- Transducer data were not available for the ECLD's engineered water body during most of the reporting period.

Further evaluation of hydraulic gradients and the groundwater flow system is ongoing.

4.5.6.1 Alluvium Potentiometric Surface Maps

As described in Section 3.5.1, potentiometric surface maps for the alluvial aquifer previously included all alluvium wells on a single map that represented the alluvium as a single hydrostratigraphic unit, honoring the lowest head value at each well cluster for contouring (presuming the lowest head to be representative of the most transmissive interval). During the reporting period, ERM refined the CSM and our approach to preparing alluvium potentiometric surface maps has evolved: alluvium is now discretized into three TSUs (i.e., Upper, Middle, and Lower Alluvium) separated by two TSMs and a 0.25-foot groundwater contour interval is used (previously maps were prepared using a 1-foot or 0.5-foot contour interval).

Beginning in July 2022, ERM prepared separate potentiometric surface maps for the Upper, Middle, and Lower Alluvium to enable observation of variations in the orientation and magnitude of the horizontal hydraulic gradient within each of these TSUs[33] (Appendix L, Figures L-10 through L-12). In some cases, wells are screened across two TSUs and groundwater elevations for those wells were evaluated to determine if they should be assigned to one or both TSUs for mapping purposes.

The ECLD engineered water body located adjacent to the western Site boundary is shallow (5 feet or less), and although specific details of the water body's construction have not been made available to the OU-3 Respondents, it is assumed, based on the geology of the Site area, that the water body is likely constructed in fine-grained loess sediments. The underlying alluvial aquifer extends to depths of 100 feet or more and is in direct communication with the Missouri River. While the engineered water body is deep enough to intersect the water table, it does not represent a boundary condition to the underlying alluvial aquifer.

Groundwater within the underlying alluvial aquifer does not appear to be affected by the ECLD engineered water body and therefore groundwater elevation contours were prepared exclusive of surface water elevation data from this water body. Evaluation of the interaction between surface water in the engineered water body and groundwater water levels is ongoing. This evaluation may be refined as more data become available.

4.5.6.2 Horizontal Hydraulic Gradient, Vector and Flow Distance Analyses

As noted in Sections 4.5.2 and 4.5.6.1.1, groundwater elevations within Site monitoring wells vary daily and seasonally. Given that an extensive network of on-Site monitoring wells is fitted with pressure transducers, ERM evaluated the impacts of this temporal variability on the orientation and magnitude of the horizontal hydraulic gradient by calculating these parameters daily from 1 July 2021 through 1 July 2022. The on-Site alluvial aquifer was broken into two geographic areas, based on review of potentiometric surface maps prepared for the Site (Appendix L). These areas were referred to as the northern and southern portions of the on-Site alluvial aquifer; however, because there were no on-Site monitoring wells in the southernmost portion of the alluvial aquifer that were fitted with pressure transducers during the reporting period, results from only the northern portion of the alluvial aquifer are included in this report. The methodology and data used to conduct this analysis are discussed in Appendix Q.

Figure 4-29 presents the orientations and magnitude of the horizontal hydraulic gradients for Upper Alluvium, Middle Alluvium, and Lower Alluvium daily over a one-year period for wells located within the northern portion of the alluvial aquifer. Horizontal hydraulic gradients ranged from 0.002 feet per foot to 0.039 feet per foot and were generally similar among the Upper Alluvium, Middle Alluvium, and Lower Alluvium. The magnitude of the horizontal hydraulic gradient was lowest during the fall and winter, increased during the spring, peaked during early summer, and decreased later in the summer. The orientation of the horizontal hydraulic gradient was consistently toward the northwest during the fall and winter and varied throughout the remainder of the year. On a smaller scale, in addition to the general seasonal trends both gradient magnitude and flow direction demonstrate daily variability across the Site.

[33] For contouring purposes, at locations where multiple wells within a cluster are screened within the same alluvial unit, the lowest head value was used to develop groundwater contours, except where anomalous data were identified. On the maps, head values excluded from contouring are in light gray text and anomalous head values are identified with an asterisk.

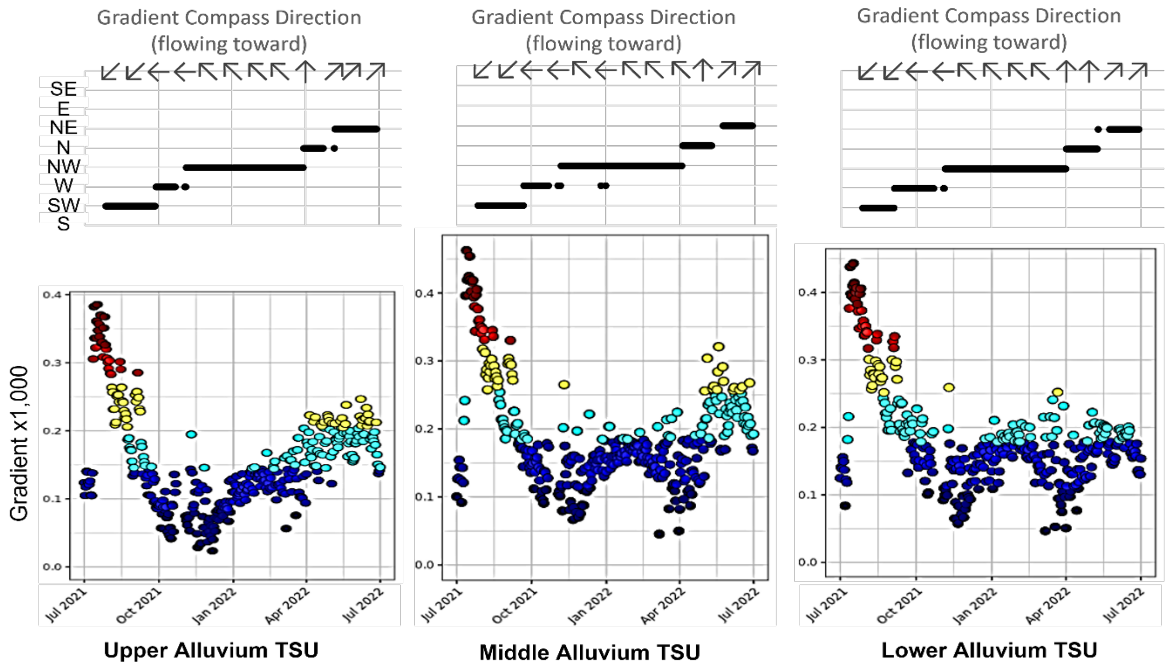


Figure 4-29: Flow Direction and Horizontal Gradient (1 July 2021 through 1 July 2022, Northern Portion of On-Site Alluvial Aquifer)

The plots show similar trends within each TSU: during July through December when the gradient trend is decreasing, the gradient direction is turning from southwest to northwest. During the generally increasing gradient trend from April through June, which is more pronounced in the Upper and Middle Alluvium, the gradient direction continues to shift toward the northeast.

Given the variability in the orientation and magnitude of the horizontal hydraulic gradient throughout the year, a vector analysis was completed to estimate the net direction and distance of groundwater flow during the one-year evaluation period within the northern portion of the on-Site alluvial aquifer. As shown on Figure 4-30, the net groundwater flow in the Upper Alluvium, Middle Alluvium, and Lower Alluvium was to the west-northwest, with net groundwater flow distances ranging from approximately 19 to 25 feet per year.

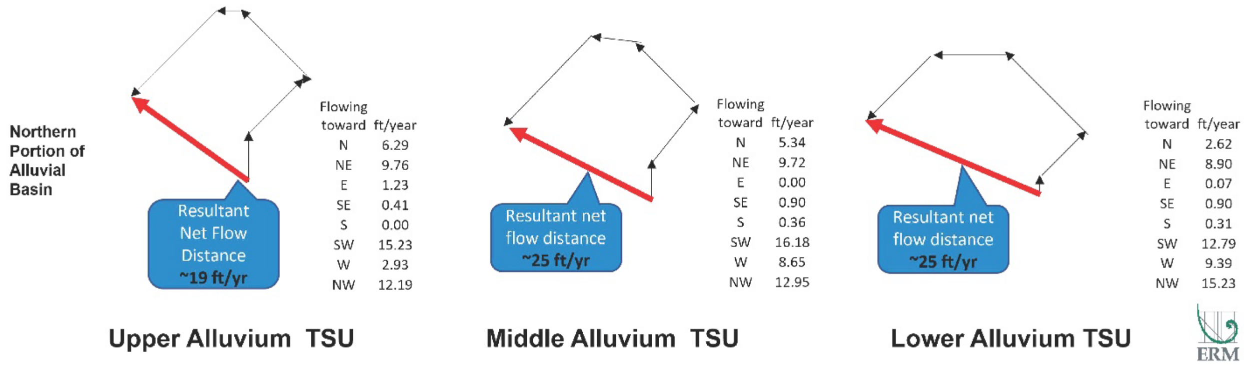


Figure 4-30: Vector Analyses for the Northern Portion of the On-Site Alluvial Aquifer

The vector analysis shows a consistent net flow distance and direction in the Upper Alluvium, Middle Alluvium, and Lower Alluvium in the northern portion of the on-Site Alluvial Aquifer.

Figure 4-31 compares the orientation of horizontal hydraulic gradient data for the Upper Alluvium, Middle Alluvium, and Lower Alluvium within the northern portion of the on-Site alluvial aquifer to a Missouri River hydrograph for the same time presented in the two previous figures. These plots demonstrate that, while the Missouri River stage is relatively steady during the fall and winter, groundwater flow is to the northwest. Once the Missouri River begins to rise in the spring, the groundwater flow shifts toward the northeast. The period of decreased hydraulic gradient in the summer and fall correlates with decreased Missouri River stage during the same period, and the period of increased horizontal hydraulic gradient in the spring and early summer correlates with increased Missouri River stage during that same time period. These observations suggest that the Missouri River strongly influences the hydraulic gradient within the on-Site alluvial aquifer. Seasonal changes in groundwater flow direction result in tortuous flow paths and relatively low net annual groundwater flow distances (i.e., 19 to 25 feet per year).

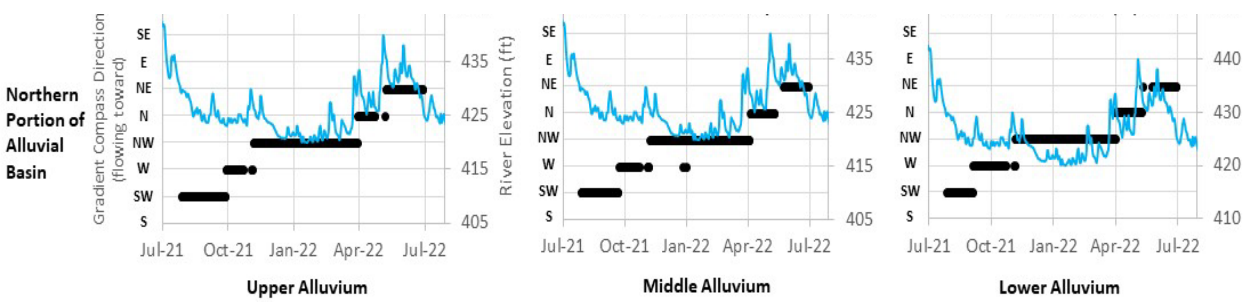


Figure 4-31: Orientation of Horizontal Hydraulic Gradient Data for the Northern Portion of the On-Site Alluvial Aquifer Relative to the Missouri River

The plots show similar trends in the Upper Alluvium, Middle Alluvium and Lower Alluvium; during decreasing river stage from July through December, the gradient direction shifts from southwest to northwest. As the river stage increases from April through June the gradient direction continues to shift from northwest to northeast.

Collectively, this analysis demonstrates that monthly potentiometric surface maps may be of limited utility at this Site, as they represent data collected within a dynamic flow system that may experience seasonal changes over the course of a month as well as fluctuations during the day of the monthly gauging event. ERM believes that the data analysis and presentation approach included in this section of the report is a more appropriate way to represent the dynamic nature of alluvial groundwater flow system at the Site. Recognizing that potentiometric surface maps are a standard tool for depicting the orientation and magnitude of horizontal hydraulic gradients, ERM has included one set of maps for August 2022, which are representative of the annual net groundwater flow direction (see Figures 4-32, 4-33 and 4-34).

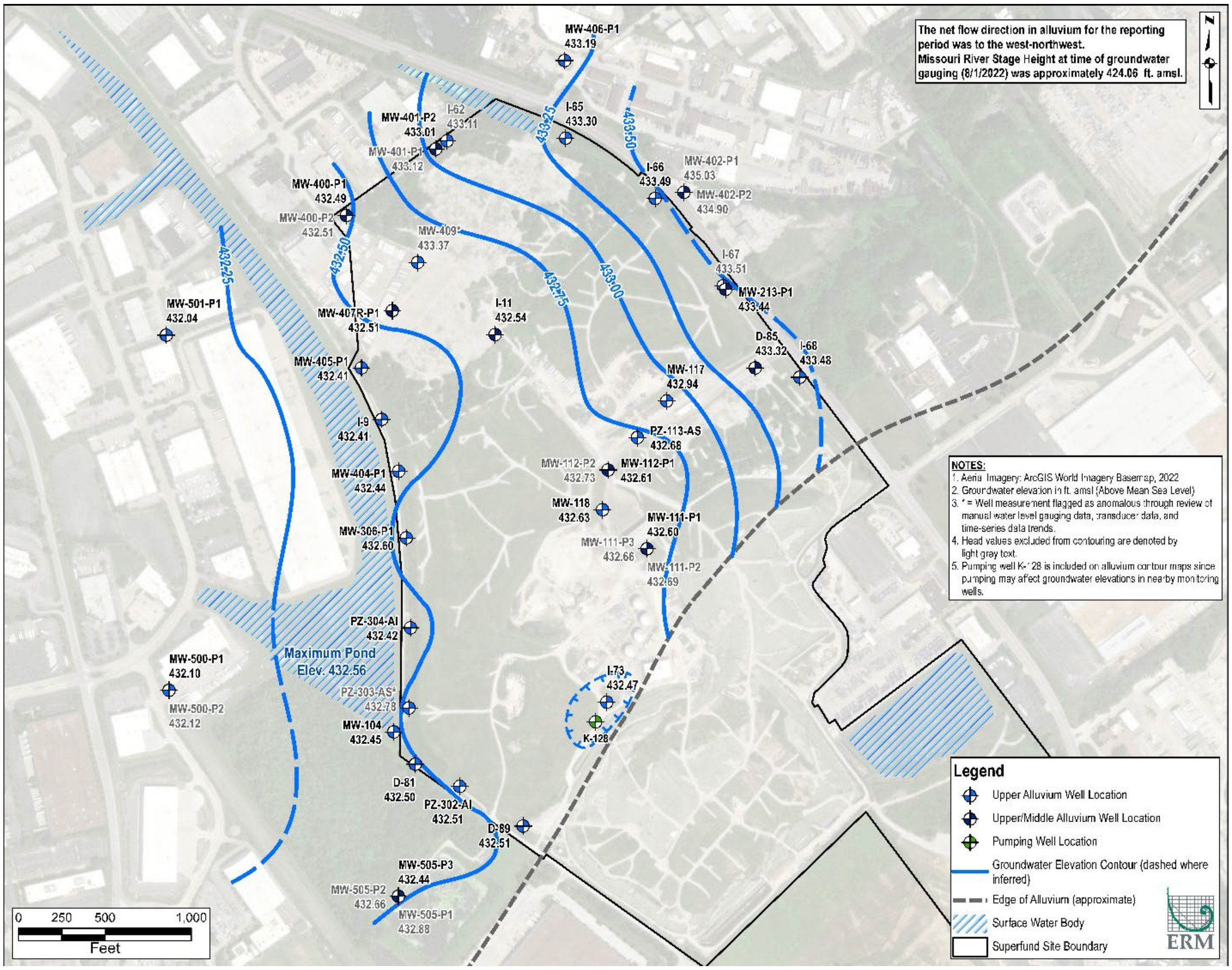


Figure 4-32: Upper Alluvium Potentiometric Surface Map – August 2022

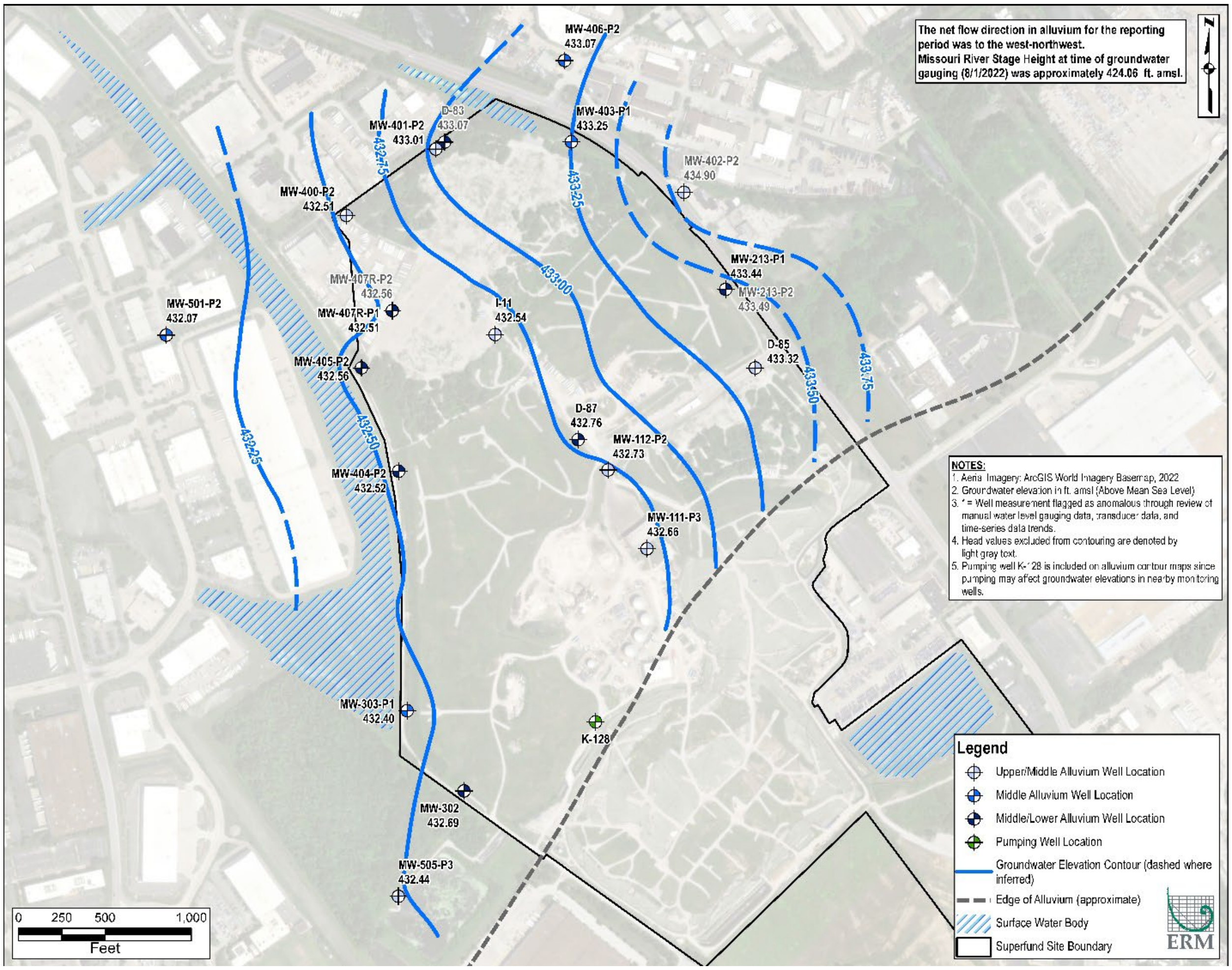


Figure 4-33: Middle Alluvium Potentiometric Surface Map – August 2022

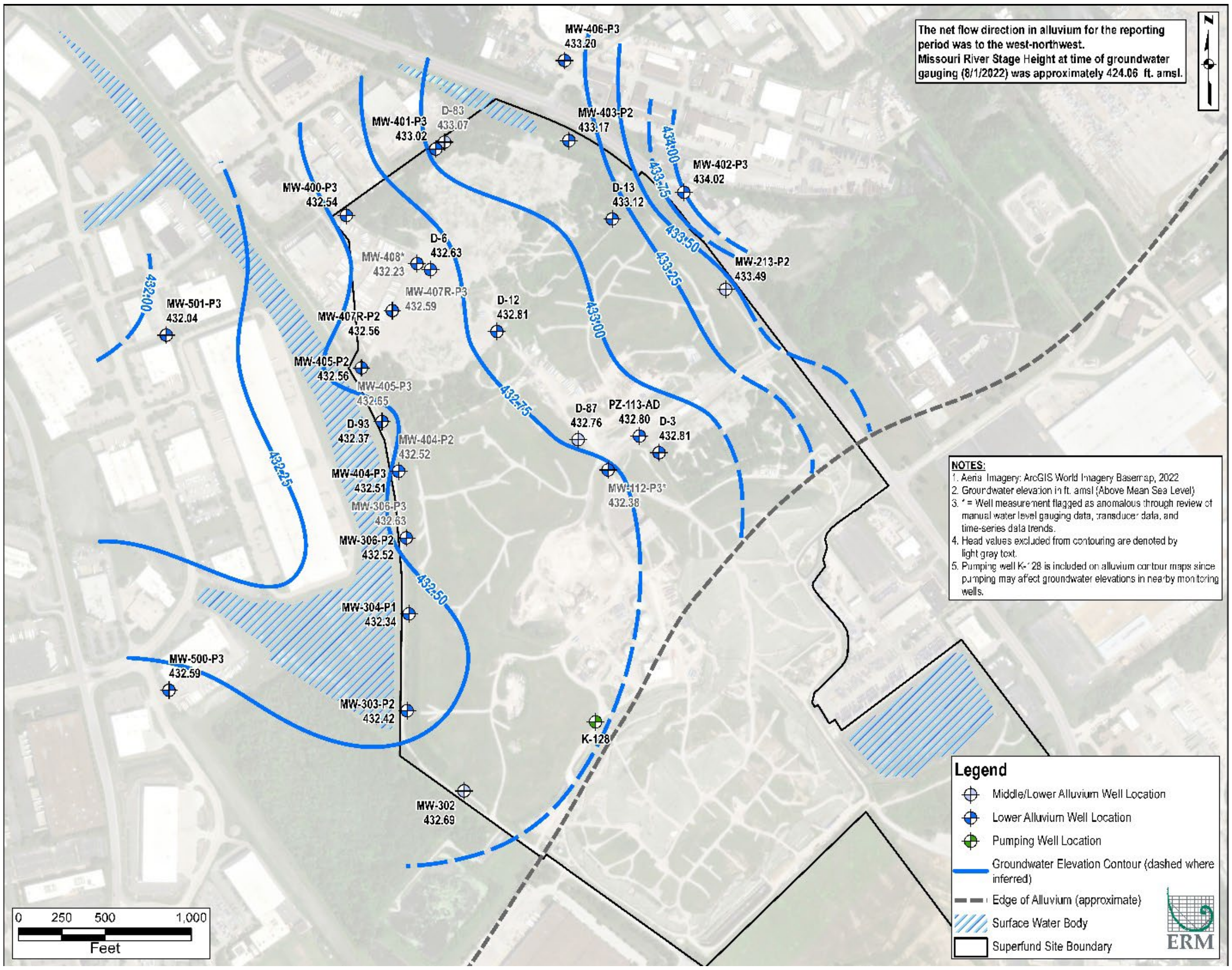


Figure 4-34: Lower Alluvium Potentiometric Surface Map – August 2022

4.5.6.3 Vertical Hydraulic Gradient Analyses—Flow Net Analyses

Vertical hydraulic gradients were evaluated primarily for individual on-Site well clusters by plotting groundwater elevation time-series plots (i.e., both multi-level wells and well clusters) where well screens were set in different alluvium TSUs and in bedrock, including:

- MW-400-P1/P2/P3/P4/P5;
- MW-404-P1/P2/P3/P4/P5;
- PZ-304-AS/AI and MW-304-P1/P2/P3;
- PZ-113-AS/AD/SS and MW-113; and,
- PZ-205-AS/SS and MW-205.

The water level time-series plots, along with composite geophysical logs depicting well screen intervals for each well group, are presented in Figures 4-35, 4-36, 4-37, 4-38, and 4-39. The plots for well groups in the northern and central portions of the Site indicate that vertical hydraulic gradients are quite small, indicating that the bedrock aquifer in these areas is in communication within the overlying alluvial aquifer (Figures 4-35, 4-36, and 4-37). The plots for well groups located closer to the bedrock uplands area indicate an upward vertical hydraulic gradient between bedrock and alluvium (Figures 4-38 and 4-39). For the MW-113/PZ-113 cluster (Figure 4-38) the vertical gradient is subtle but consistently upward between wells screened in the Salem Formation and those screened in alluvium. At the MW-205/PZ-205 cluster (Figure 4-39), the upward gradient between the well screened in the Salem Formation and wells screened in the overlying St. Louis Formation and alluvium is much more pronounced, due to a layer at the top of the Salem Formation that exhibits very low hydraulic conductivity, no mobile porosity, and no open fractures, as shown on the geophysical logs (the yellow star on Figure 4-39).

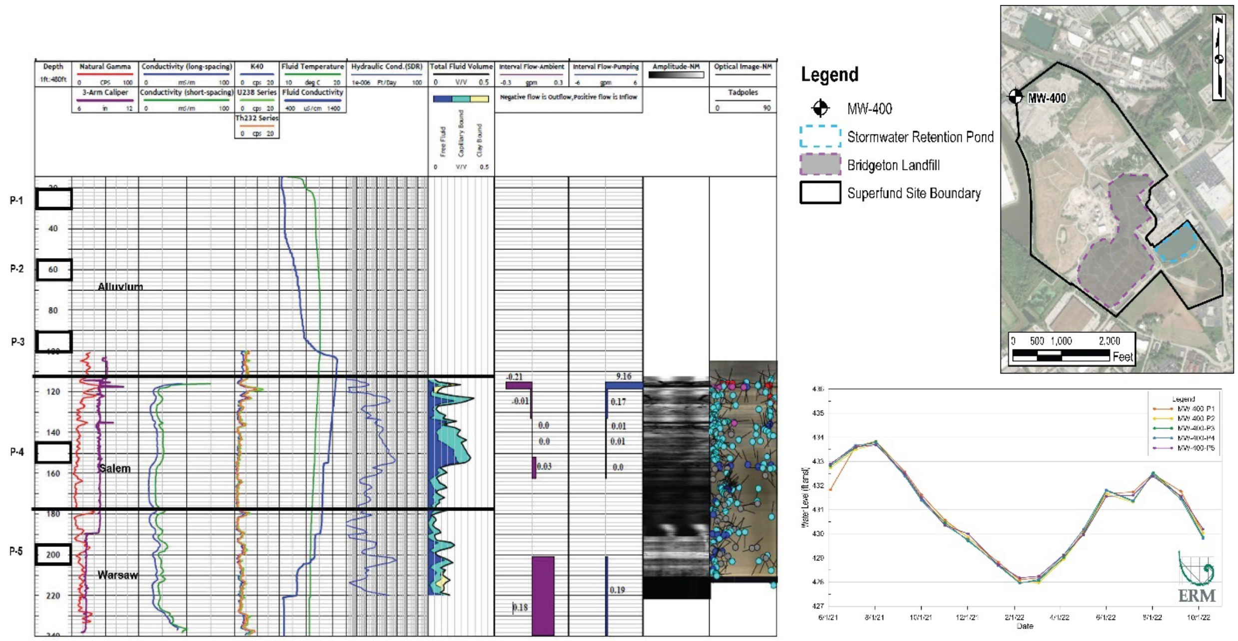


Figure 4-35: Vertical Gradient Review – MW-400 P1/P2/P3/P4/P5

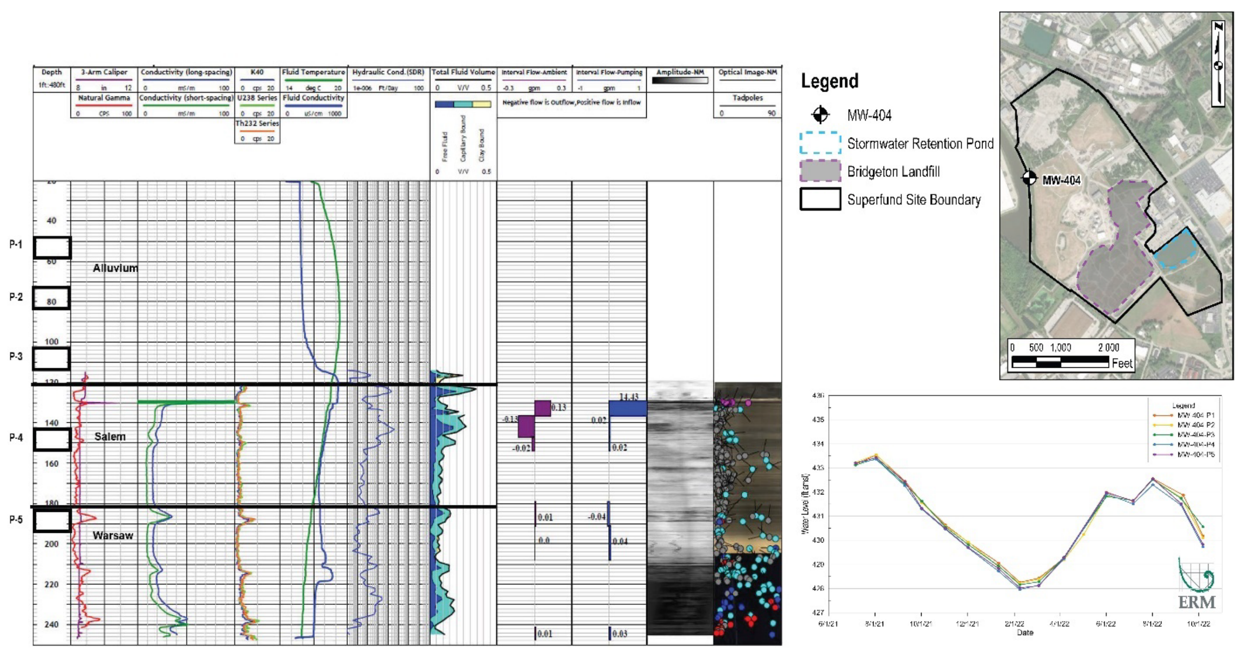


Figure 4-36: Vertical Gradient Review – MW-404 P1/P2/P3/P4/P5

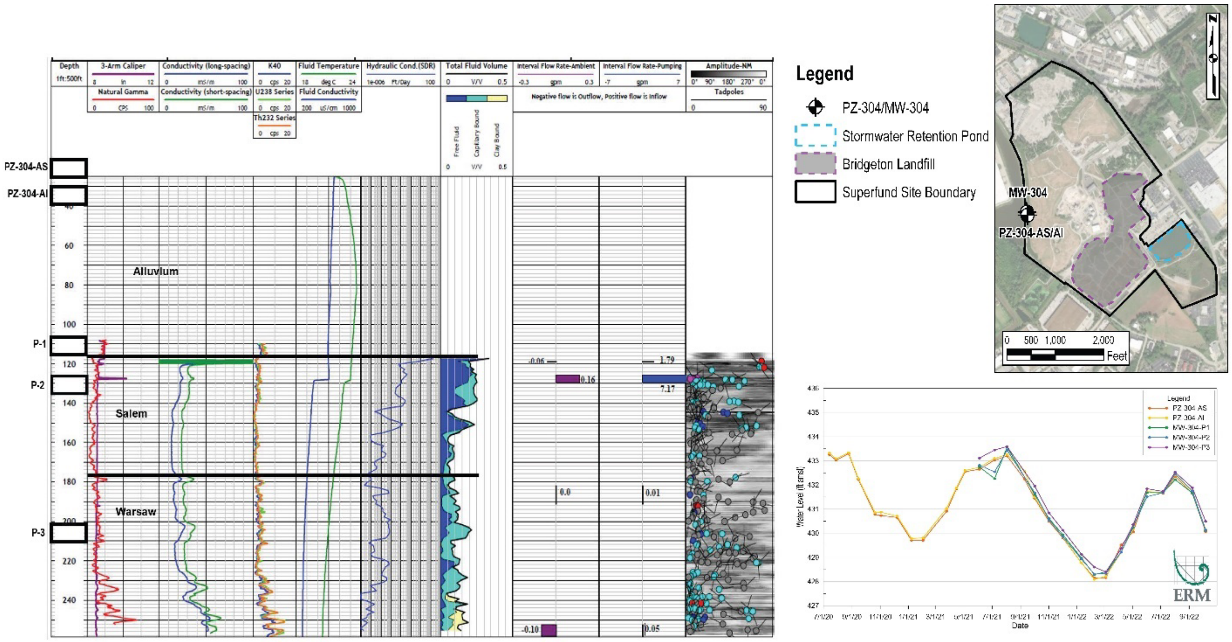


Figure 4-37: Vertical Gradient Review – PZ-304-AS/AI and MW-304-P1/P2/P3

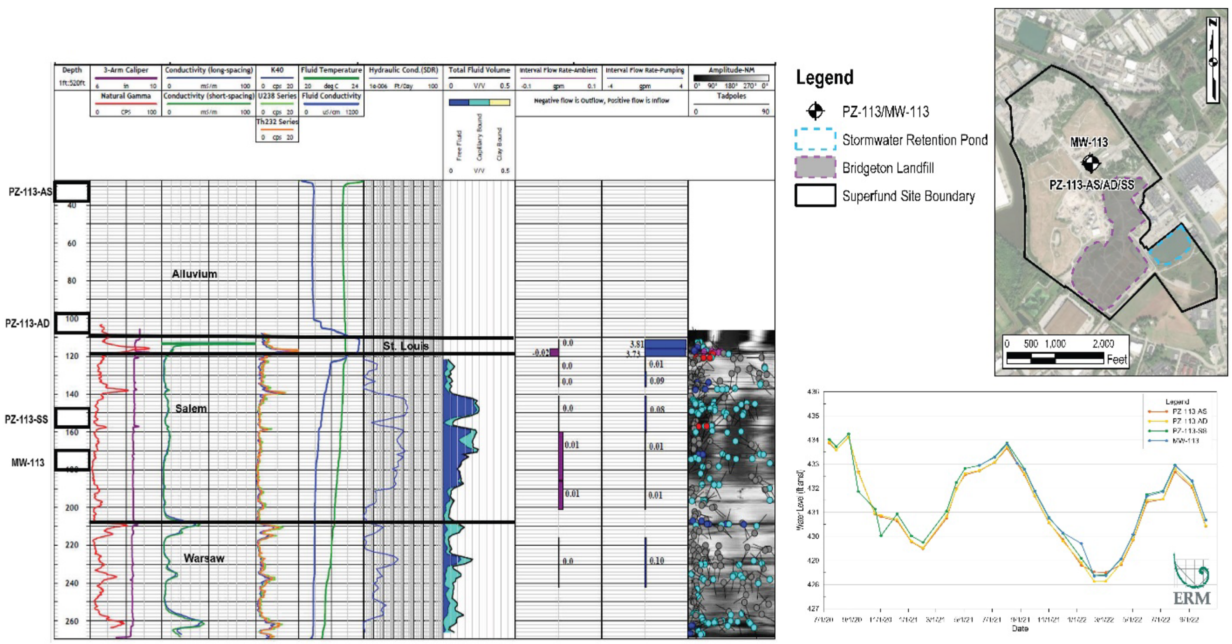


Figure 4-38: Vertical Gradient Review – PZ-113-AS, PZ-113-AD, PZ-113-SS and MW-113

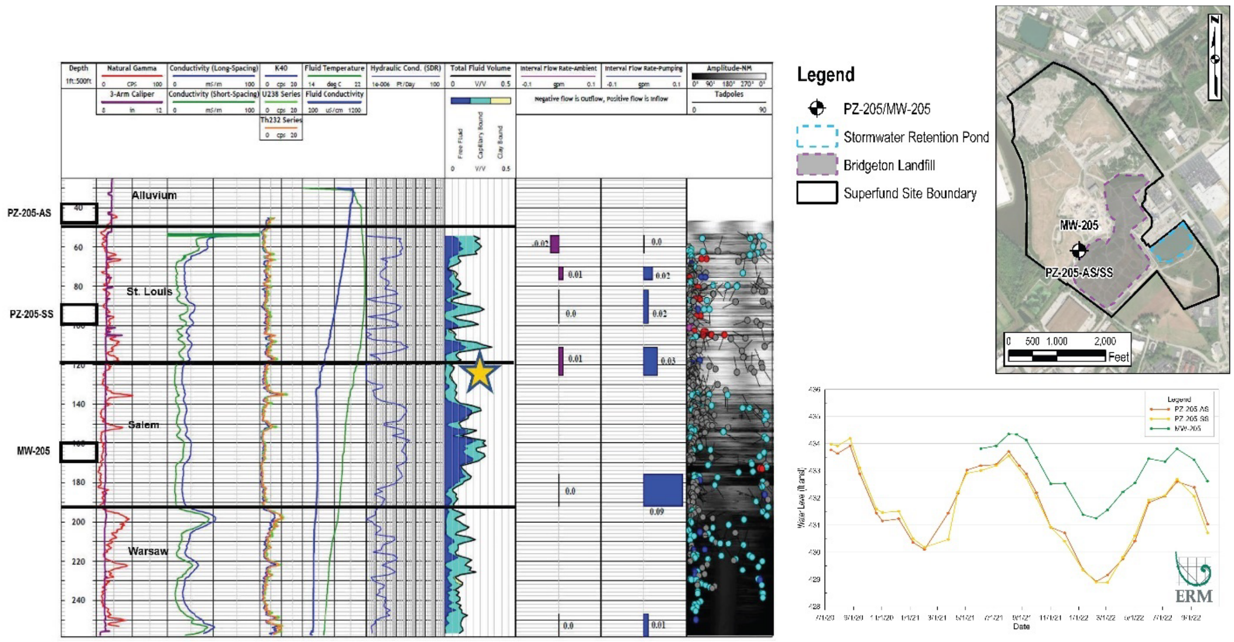


Figure 4-39: Vertical Gradient Review – PZ-205-AS, PZ-205-SS, and MW-205

Vertical gradient cross-sections with modified flow nets[34] were developed for two transects, one along the norther border of the Site and one across the mid-section of the Site that generally follow the predominant flow direction. Flow nets are a graphical representation of two-dimensional steady-state groundwater flow through the aquifer and are presented in Figure 4-40. The August 2022 gauging event is the first event that included the entire well network installed during the reporting period and was selected to illustrate vertical gradient effects on groundwater flow. The August 2022 gauging event also represents flow under falling water conditions that are more reflective of net annual gradient conditions. Given that the modified flow nets incorporate off-Site wells, only one set is included in this report; additional flow nets will be prepared and included in the 2023 Annual Report to represent Site-wide vertical hydraulic gradients during additional seasons.

For this evaluation, the flow nets are described as “modified flow nets” as they do not follow traditional requirements of flow net development. Flow nets are traditionally constructed based on static flow conditions along flow lines parallel to the flow direction and using equivalent vertical and horizontal scales to show conservation of mass within flow tubes. The scale of the Site and the transient nature of flow direction makes meeting those requirements impractical. Nevertheless, ERM plotted the data on a transect and produced a modified flow net that demonstrates the vertical components of flow within the alluvial aquifer.

[34] The flow nets presented in Figure 4-40 are “modified” because a flow net is typically prepared along a groundwater flow line. Because hydraulic gradients at this Site vary over time, the orientation of the flow nets is sometimes tangential to the groundwater flow lines. However, the modified flow nets provide a representative depiction of the groundwater flow system in the vertical dimension.

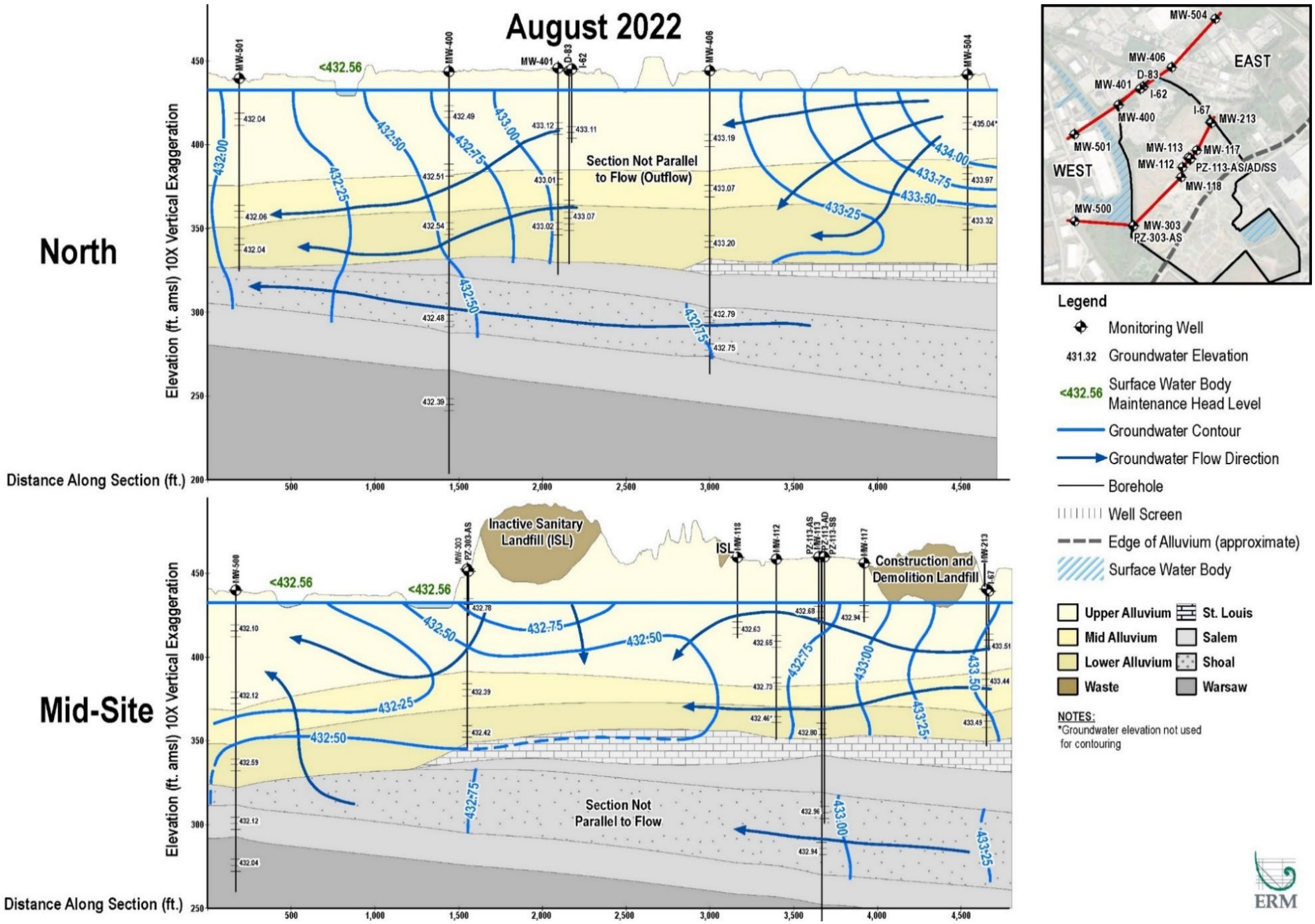


Figure 4-40: Vertical Gradient Cross-section/Flow Nets – North and Mid-Site, August 2022

The North flow net shows an apparent off-Site recharge area located northeast of the Site and very slight downward vertical hydraulic gradients from Upper Alluvium into the Middle Alluvium along most of the flow net. Horizontal groundwater flow is occurring within the Middle Alluvium, Lower Alluvium, and Salem Shoal Sequence. The Mid-Site flow net shows horizontal groundwater flow in the eastern portion of the Site and within the Middle Alluvium and Lower Alluvium across the entire Site. Sources of recharge create a downward vertical hydraulic gradient from the Upper Alluvium into the Middle Alluvium in the western portion of the Site[35]. To the west of the Site, an upward vertical hydraulic gradient exists starting with the Salem Shoal Sequence and extending upward into the Upper Alluvium, indicating that bedrock groundwater may be discharging into the alluvial aquifer in this area during August 2022, although the flux would be very low considering the low hydraulic conductivity and groundwater gradient within bedrock.

Additional temporal and quantitative evaluation of vertical hydraulic gradients in both on- and off-Site areas will be conducted during 2023.

4.5.7 Bedrock Aquifers

The discussion of groundwater flow within the bedrock aquifer is separated into two geographically distinct areas: the bedrock uplands area south of Bridgeton Landfill North and South Quarries, and bedrock directly underlying the alluvial valley north of Bridgeton Landfill North and South Quarries. The Bridgeton Landfill North and South Quarries are located within the bedrock uplands to the south but at the boundary between those two areas.

In the uplands area, the full sequence of St. Louis, Salem (including the Salem Shoal Sequence), Warsaw, and Keokuk Formations is present, with the St. Louis Formation either exposed at the ground surface or buried beneath shallow loess deposits. Groundwater flow in bedrock outside of the Bridgeton Landfill in this area occurs primarily through bedrock fractures, except within the Salem Shoal Sequence, where matrix flow is dominant.

North of the Bridgeton Landfill, the alluvial valley incised into bedrock, creating a disconformity where the St. Louis Formation is partially to completely eroded and the underlying Salem Formation is partially eroded in some areas. Groundwater flow in this area occurs primarily via matrix flow through the Salem Shoal Sequence.

The bedrock surface topography is shown on Figure 4-18. The former bedrock quarry now represented by the Bridgeton Landfill was excavated vertically into bedrock and terminated at or near the top of the Warsaw Formation. To the north of the north wall of the former quarry, the bedrock surface slopes steeply from near the ground surface to a depth of just over 100 feet below ground surface within the Site boundary as shown in Figure 4-12. Within the alluvial valley, the bedrock surface is relatively flat at a depth of about 100 to 120 feet below ground surface.

Horizontal hydraulic gradients in each of the bedrock formations in the uplands area are to the north and are more than an order of magnitude greater than horizontal hydraulic gradients in bedrock beneath the alluvial valley. Horizontal hydraulic gradient maps for the combined St. Louis and Salem Formations for August 2022 (Figure 4-41) show some convergence of flow toward the former quarry, indicating that the Bridgeton Landfill represents a sink for bedrock groundwater flow. Recharge to the former quarry is primarily offset by leachate extraction from the Bridgeton Landfill. Horizontal hydraulic gradients in the underlying Keokuk Formation show underflow beneath the former quarry with no apparent influence of the quarry on groundwater flow within this formation (Figure 4-42).

[35] The August 2022 gauging event was conducted about one week after an historic rainfall event (about 9 inches of rainfall was recorded at the St. Louis airport on 25 and 26 July 2022).

To the north of the Bridgeton Landfill North and South Quarries, horizontal hydraulic gradients are very flat, like those noted for the overlying alluvial aquifer, and indicate that bedrock is in general communication with the overlying alluvial aquifer.

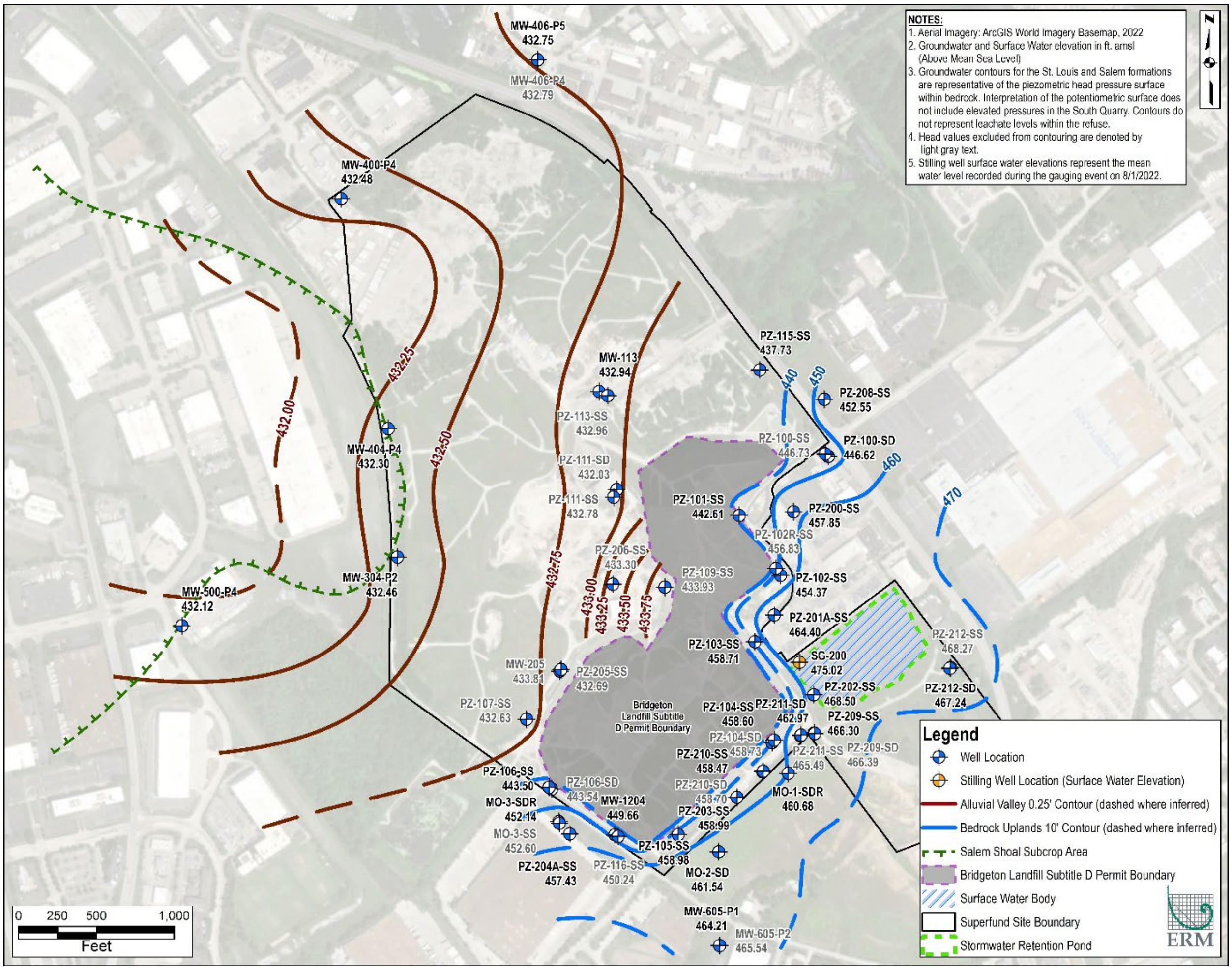


Figure 4-41: Combined St. Louis and Salem Formations Potentiometric Surface Map – August 2022

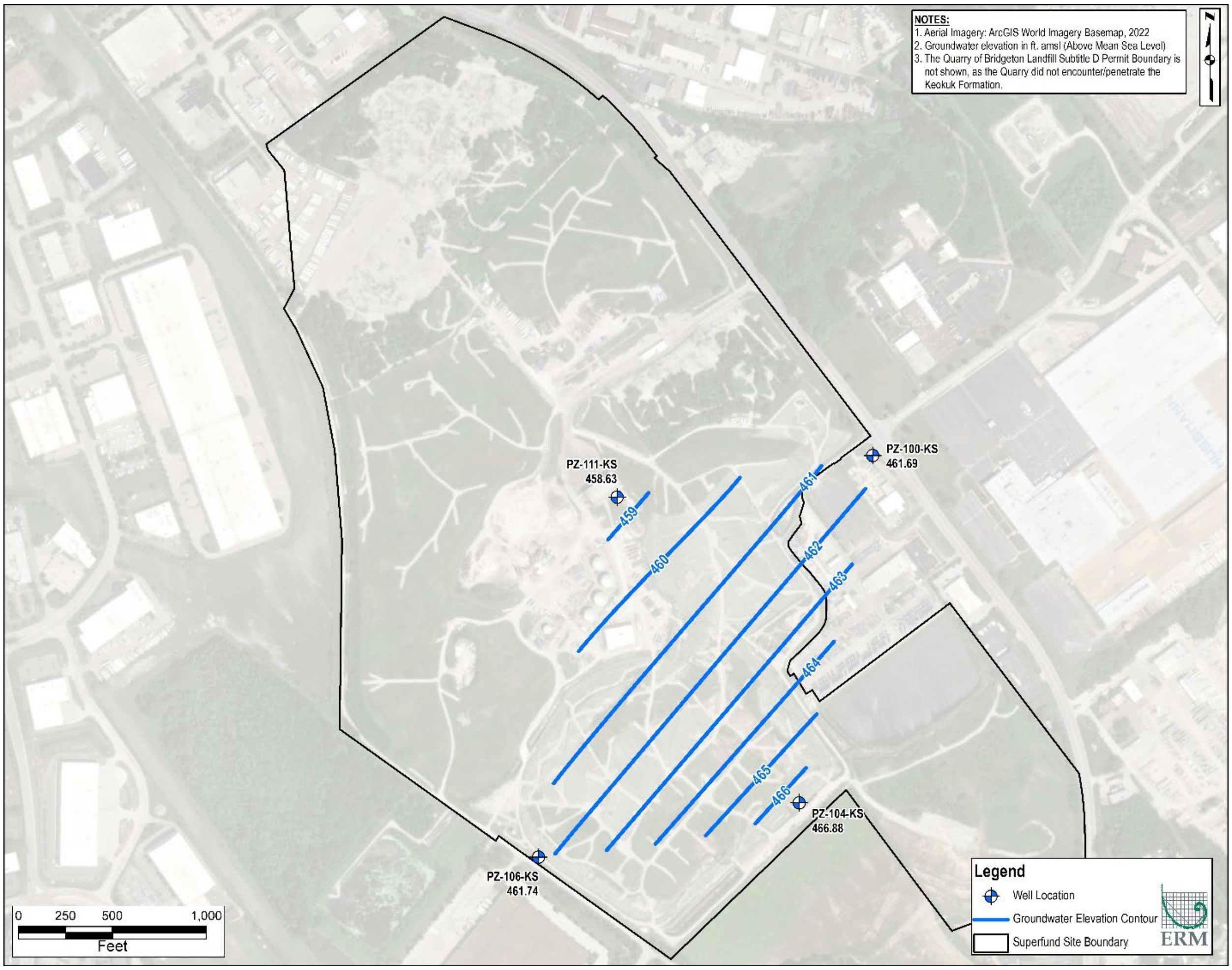


Figure 4-42: Keokuk Formation Potentiometric Surface Map – August 2022

4.5.8 Groundwater Flux

Groundwater flux estimates were developed to compare groundwater flux within bedrock and alluvium. Groundwater flux calculations are presented in Appendix R.

Due to variability in the magnitude and direction of groundwater gradients at the Site, groundwater flux was calculated for the alluvial aquifer for two predominant flow conditions (fall and winter) to provide a range of values. Alluvium groundwater flux for the fall and winter were approximately 250,000 gallons per day (gpd) and 175,000 gpd, respectively. Bedrock groundwater flux is less than 1,000 gpd, which is two orders of magnitude lower than the alluvium flux. Flux transects and flux values are shown on Figure 4-43 and are based on static groundwater flow conditions (assuming a single gradient direction). In reality, the groundwater flow direction is transient so the calculations of flux represent order of magnitude approximations. When considering only the static condition, the results confirm that alluvium groundwater flux could potentially be two orders of magnitude greater than bedrock groundwater flux.

A preliminary water balance was prepared for the Bridgeton Landfill that included potential sources of water to the quarry and liquids removed from the quarry. To be inclusive, potential sources of water to the quarry included in the water balance were groundwater recharge from upland bedrock, potential meteoric recharge, and liquids produced from waste degradation and fill compaction. Liquids removed as leachate and condensate from gas extraction wells were based on data provided by the landfill operators and reported to regulatory agencies, including liquid leachate and condensate extraction volumes minus the estimated extraction of water from extraction well K-128 located directly adjacent to or within the Inactive Sanitary Landfill, near the north side of the quarry. The results of the water balance suggests that the landfill liquids removal is greater than landfill liquids influx. The water balance summary is included in Appendix R.

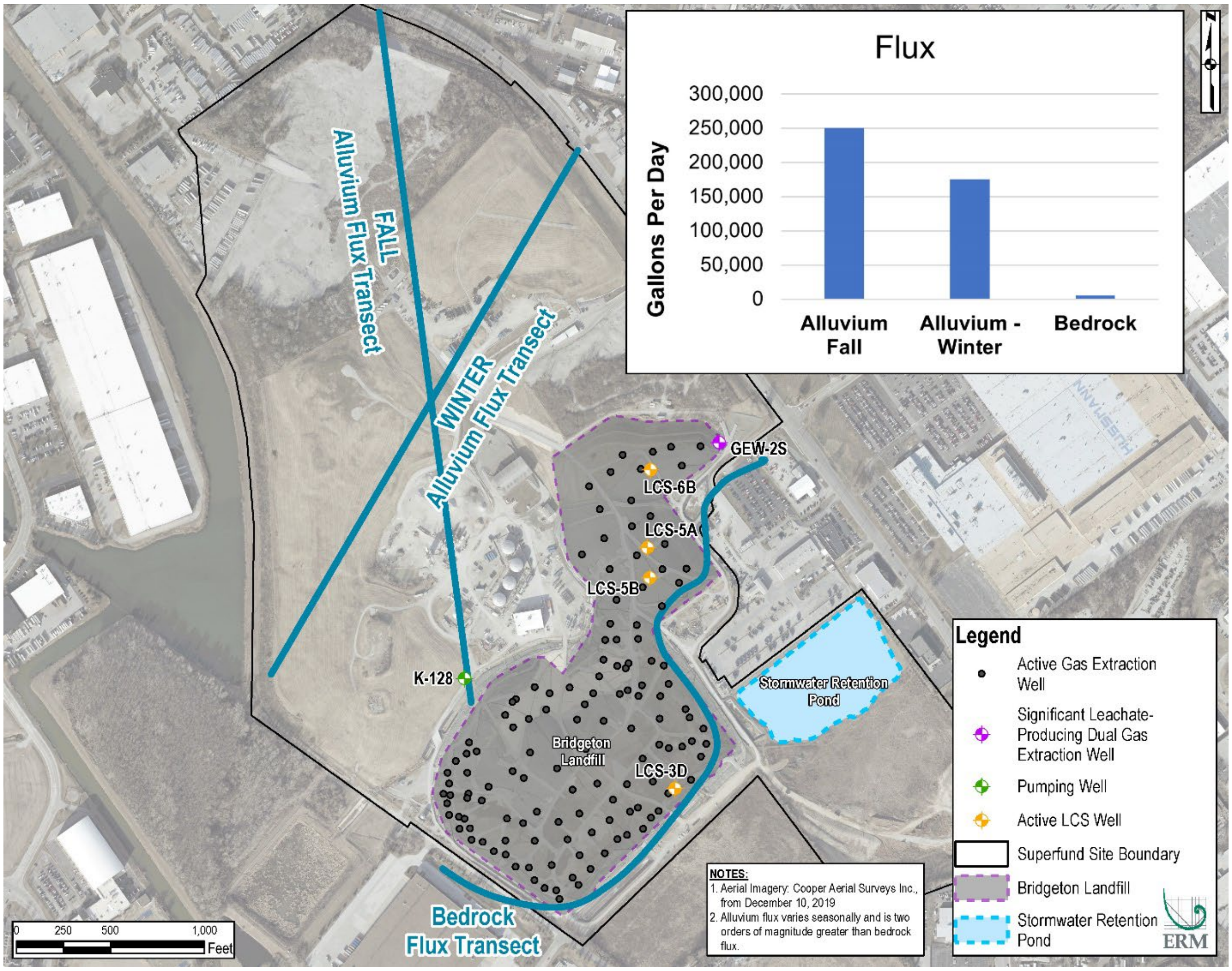


Figure 4-43: Site-Wide Water Balance

Summary

Interpretation of daily, high-resolution groundwater elevation data within the alluvial aquifer over a one-year period demonstrated that the groundwater flow system is dynamic and the groundwater flow direction changes throughout the year, with a net flow direction in alluvium to the west-northwest. The horizontal and vertical hydraulic gradients are very low, reflecting the high hydraulic conductivity of alluvial sediment. The impact of the low hydraulic gradient is that the net annual groundwater flow rate within the alluvial aquifer is also very low (i.e., less than 25 feet per year). The estimated groundwater flux through the alluvial aquifer is potentially orders of magnitude higher than flux through the bedrock aquifer.

4.6 Groundwater Constituents of Potential Concern

ERM evaluated the distribution of 11 select COPCs, including three radionuclides (radium, uranium, and thorium), seven organic compounds (benzene, 1,4-dioxane, vinyl chloride, *cis*-1,2-dichloroethene, 2-methylnaphthalene, THF, and 1,2,4-trimethylbenzene), and one metal (arsenic). Selection of these COPCs was described in the 2021 Annual Report (ERM 2022b); thorium did not meet the selection criteria, but was evaluated at the request of USEPA. A risk assessment to evaluate all analytes to determine COPCs and potential risks to receptors will be performed as part of the baseline risk assessment and will be documented in the RI Report. The select COPC list was developed in 2021 to provide a list of analytes to discuss in the 2021 Annual Report text, to show on report figures, and to help answer PSQ-1 (*Are COPCs present in groundwater at concentrations/activities above screening levels?*) and PSQ-2 (*What is the vertical and horizontal spatial distribution of COPCs at concentrations/activities above screening levels in groundwater?*). Four of the select COPCs discussed in the 2021 Annual Report and this 2022 Annual Report are detected infrequently and/or at low concentrations and will not be discussed in future annual reports:

- Uranium because all concentrations are below the MCL.
- Thorium isotopes because the detection frequency is low (less than 10 percent) and there is no directly applicable MCL for these isotopes.
- 2-Methylnaphthalene because the detection frequency is low (less than 10 percent) and there is no MCL.
- 1,2,4-Trimethylbenzene because the detection frequency is low (less than 10 percent) and there is no MCL.

Evaluation of potential natural and anthropogenic sources of COPCs is ongoing to answer PSQ-3 (*Are the COPCs Site related?)* and PSQ-4 (*What are the sources of Site-related COPCs in groundwater?*). Evaluation of background conditions for naturally occurring elements and compounds has not yet begun; it will be completed once sufficient background data are available. Most off-Site wells were sampled for the first time in Q3 2022; thus, only a limited discussion of off-Site groundwater quality is included in this report. The following subsections focus on presenting basic information about the horizontal and vertical distribution of the select COPCs. More detailed discussions of groundwater geochemistry will be included in later documents, including the 2023 Annual Report and the RI Report. The groundwater chemistry and geochemistry data will be integrated with the geology and hydrogeology data to address PSQ-5 (*Where could Site-related COPCs migrate in the future?*) in the RI Report.

4.6.1 Radionuclides and RIM

RIM has been identified in portions of the Site, as described below in Section 4.6.1.4.1. Because of this, radionuclides (e.g., radium, thorium, and uranium isotopes) are of particular interest in Site groundwater. However, these radionuclides are also naturally occurring elements in soils and bedrock. Radium has been reported to be present in groundwater across the midwestern United States (Szabo et al. 2012; Sturchio et al. 2001). Therefore, the OU-3 RI was designed to evaluate the source(s) and mechanisms affecting the origin, distribution, and transport of radionuclides in Site groundwater, as documented in the following OU-3 RI/FS PSQs:

- **PSQ-3:** Are the COPCs Site-related?
- **PSQ-4:** What are the sources of Site-related COPCs in groundwater?
- **PSQ-5:** Where could Site-related COPCs migrate in the future?

This section provides an overview of radionuclide geochemistry, including radioactive decay chains and groundwater transport. It also includes a description of the nature and extent of radium, uranium, and thorium in Site groundwater and discusses the four potential sources of radionuclides in groundwater that were identified by the USGS (2015):

- Potential for leaching from RIM;
- Potential for radium concentrations in groundwater to be within natural variability;
- Potential leaching of radium from technically enhanced naturally occurring radioactive materials within traditional municipal and demolition waste; and
- Mobilization of radium from naturally occurring aquifer materials.

To evaluate these potential sources of radium in groundwater, soil and bedrock matrix samples were collected as part of the OU-3 RI; the data are discussed in Section 4.6.1.4.4.

4.6.1.1 Applicable Regulatory Standards

Radium is the primary radionuclide identified in Site groundwater. USEPA has established an MCL of 5 pCi/L for the sum of radium-226 and radium-228 activities. Radium isotopes can be created from the radioactive decay of uranium and thorium isotopes (see Appendix S), so these precursor radionuclides are also discussed in this section. Uranium in groundwater is not regulated as a radionuclide (i.e., it is not reported in units of activity); instead, it is regulated as a metal and is reported in units of concentration, with an MCL of 30 μg/L. Thorium isotopes are not directly regulated in groundwater.

4.6.1.2 Overview of Radionuclide Geochemistry

The geochemical behavior of radionuclides varies by element and isotope. All radionuclides spontaneously decay to produce other isotopes. The rate of decay of each isotope is quantified using a half-life (i.e., the length of time required for half of the precursor isotope to transform into a product isotope). There are three radioactive decay series that produce radium isotopes, which are identified by the initial precursor isotope: uranium-238, uranium-235, and thorium-232. These decay series are shown on Figure 4-44 below. These radioactive decays are measured as activity, which is used to quantify radionuclides in groundwater. These decay series are essential to the CSM to identify potential natural and anthropogenic sources of radium in groundwater.

Like other metals, radionuclides can be transported in groundwater if they are able to be dissolved or otherwise liberated from aquifer matrix material into groundwater. Several processes can affect the mobility of radionuclides in groundwater, including oxidation-reduction reactions, dissolution and precipitation, adsorption and desorption, and complexation. Details of the geochemical processes that govern the fate and transport of select radionuclides in groundwater are provided in Appendix S.

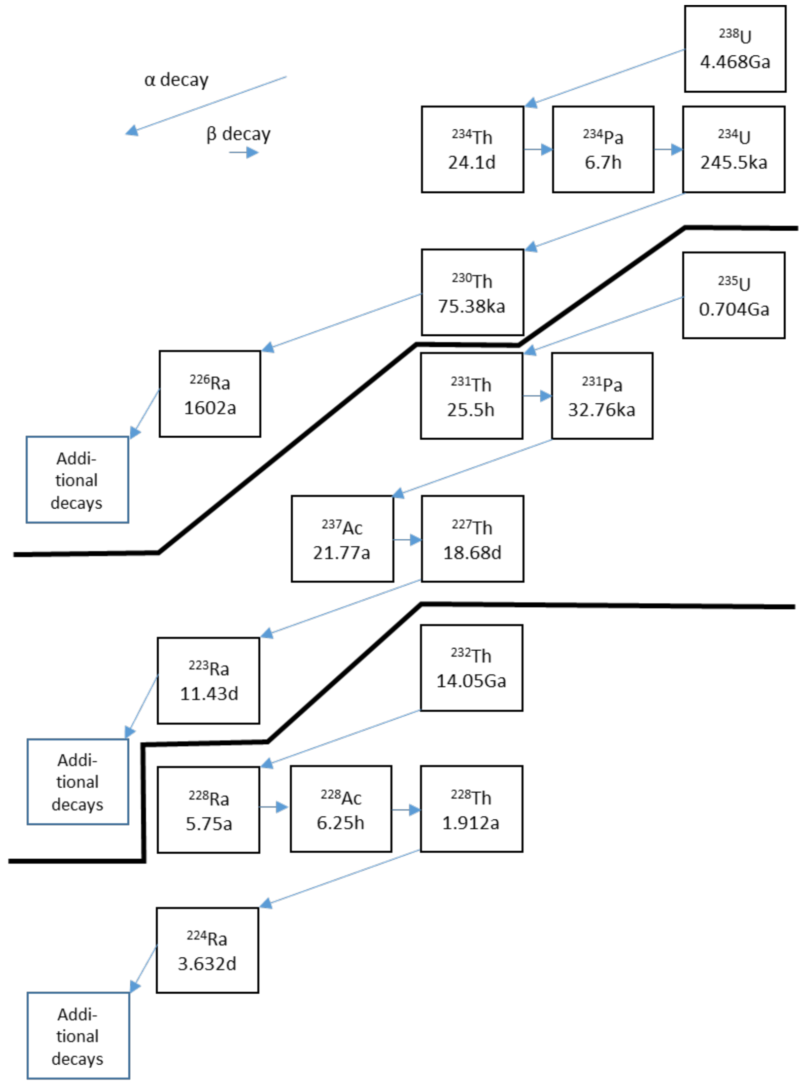


Figure 4-44: Select Portions of Uranium-238, Uranium-235, and Thorium-232 Decay Series

The half-life for each isotope is shown with units of Ga=billion years, ka=thousand years, a=year, d=day, and h=hour. A decay = alpha decay, β = beta decay

The transport of radionuclides in groundwater is like that of other metals and is highly dependent on geochemical conditions. The behavior of each radionuclide depends on the element (e.g., thorium, uranium, or radium), but does not vary for each isotope (e.g., the partitioning and transport of radium-226 and radium-228 are identical). Conditions that cause certain radionuclides to be more mobile in groundwater can explain elevated groundwater concentrations/activities, while conditions that reduce mobility will cause groundwater concentrations/activities to decrease over time. In general, radium is more mobile under reducing conditions, uranium is more mobile under oxidizing conditions, and thorium is considered immobile (IAEA 2014).

4.6.1.3 Nature and Extent of Radionuclide COPCs

Radium

The spatial distribution of combined radium-226 and radium-228 activities in groundwater samples collected during Q3 2022 (i.e., the most extensive groundwater sampling round conducted during the reporting period) are presented for background wells on Figure 4-45, and for on-Site and off-Site wells on Figure 4-46. The vertical distribution of combined radium-226 and radium-228 activities in groundwater samples collected along the western Site boundary during Q3 2022 is shown on Figure 13b. A summary of radium activity levels is provided in Table 4-2 below. The pie charts on Figures 13a and 13b reflect the ratio of radium-226 and radium-228 activities in the samples. Generally, in groundwater samples from bedrock wells, radium-226 activity is higher than radium-228 activity and in groundwater samples from alluvium wells, radium-228 activity is equal to or greater than radium-226 activity.

Table 4-2: Summary of Radium Activity Data in Groundwater for Q3 2022

Category	Alluvium	Bedrock
Percent of wells containing detectable radium-226 and/or radium-228 (total or dissolved)	67% (unfiltered [total]) 68% (filtered [dissolved])	65% (unfiltered [total]) 75% (filtered [dissolved])
Maximum unfiltered (total) combined radium-226/radium-228 activity	12.1 pCi/L	37.9 pCi/L
Maximum filtered (dissolved) combined radium-226/radium-228 activity	11.8 pCi/L	30.2 pCi/L
Average detected unfiltered (total) combined radium-226/radium-228 activity	3.82 pCi/L	5.08 pCi/L
Average detected filtered (dissolved) combined radium-226/radium-228 activity	3.84 pCi/L	4.38 pCi/L
Combined radium-226/radium-228 activity reported for Midwest groundwater: 50th percentile	0.30 pCi/L[1]	5.90 pCi/L[2]
Combined radium-226/radium-228 activity reported for Midwest groundwater: maximum reported	8.40 pCi/L[1]	11.3 pCi/L[2]

[1]*Glacial sand and gravel aquifer (Szabo et al., 2012).* [2]*Mid-continent and Ozark Plateau aquifer (Szabo et al., 2012).*

Data presented on Figure 4-45 demonstrate that combined radium-226/radium-228 activity levels were above the laboratory minimum detectible limit in nine of 17 background groundwater samples collected during Q3 2022; activity levels in one background groundwater sample exceeded the MCL. In all but one background alluvium groundwater sample, radium-228 activities were higher than radium-226 activities for samples where both isotopes were detected, consistent with the isotope ratios in the alluvium aquifer matrix samples (see Section 4.6.1.4.4 below). The only exception was in the groundwater sample from background monitoring well MW-602-P3; in this sample, the radium-226 activity was slightly higher than the radium-228 activity. Both activity levels were close to the laboratory minimum detectable limit and the ratio of radium-226 activity to radium-228 activity may be reversed within the uncertainty values reported by the laboratory. In background bedrock groundwater samples, radium-226 activities were higher than radium-228 activities in all samples where both isotopes were detected, consistent with isotope ratios in the bedrock aquifer matrix samples. Published data for background wells in the vicinity of the Site reported combined radium-226/228 ratios greater than 1 in filtered (dissolved) samples from bedrock and less than 1 in filtered (dissolved) samples from alluvium (USGS 2015). These isotope ratios are consistent with the samples collected from off-Site wells during the reporting period. Given that only one round of background well samples have been collected, detailed comparison of Site and background data has not yet been conducted. This comparison will be completed during the 2023 reporting period.

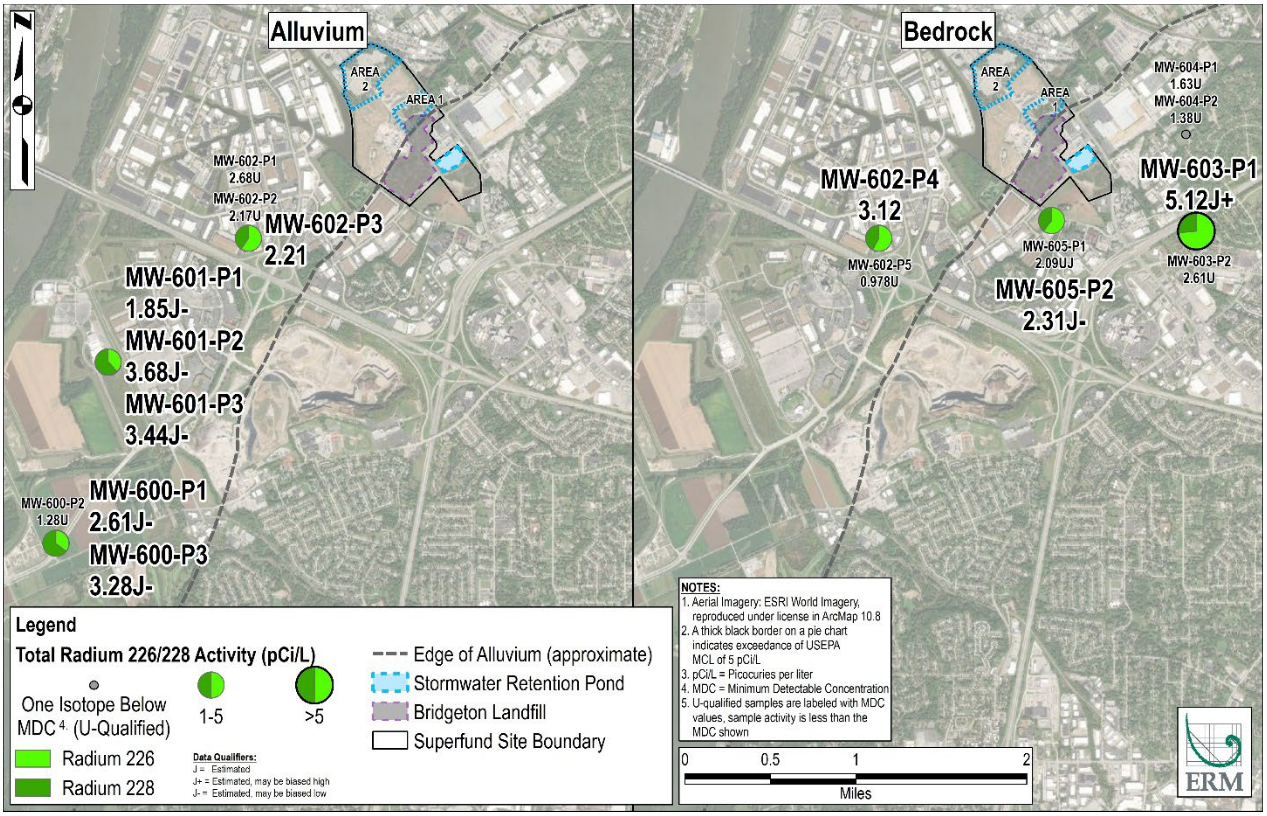


Figure 4-45: Radium Isotopic Signatures and Activity Levels from Background Wells - Q3 2022

Figure shows the combined unfiltered (total) radium-226/radium-228 ratios and activity levels in background alluvium and bedrock well samples.

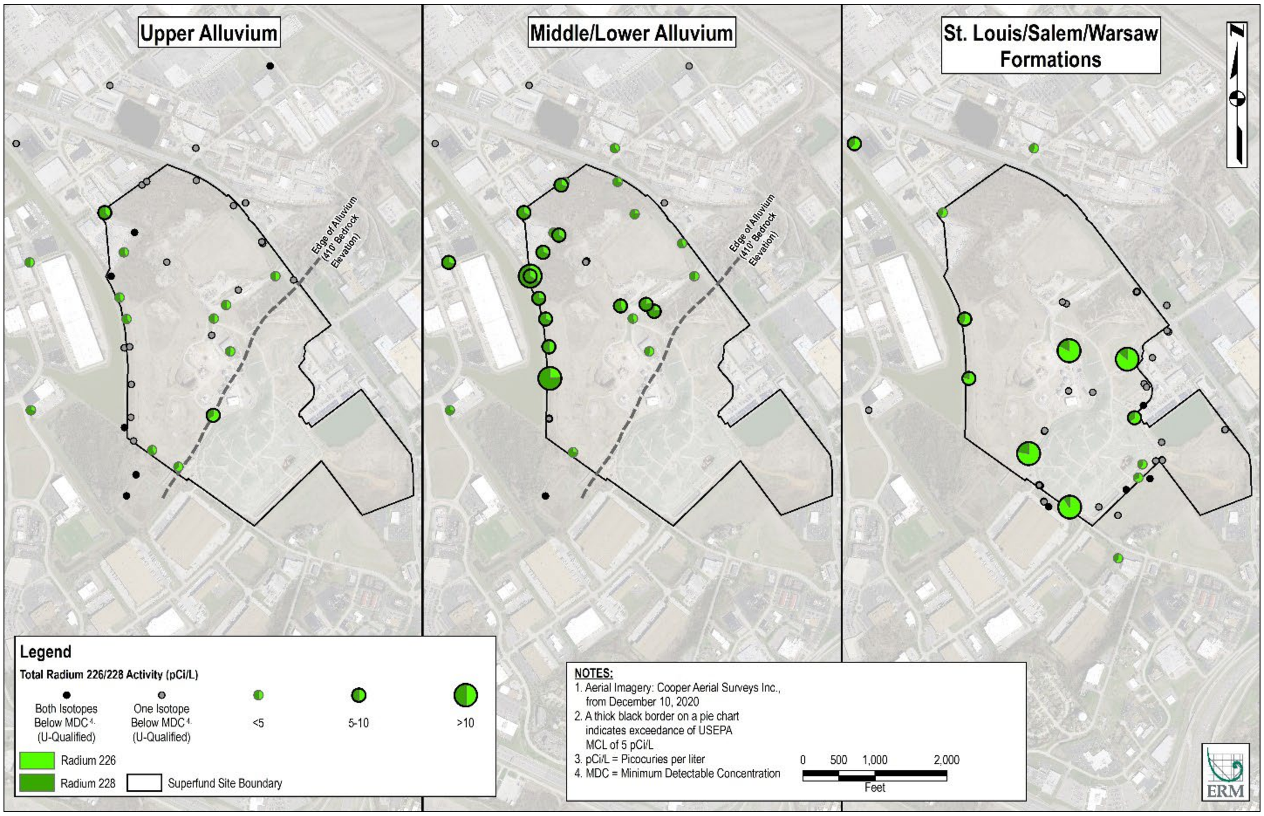


Figure 4-46: Radium Isotopic Signatures and Activity Levels from On-Site and Off-Site Wells - Q3 2022

Figure shows the combined unfiltered (total) radium-226/radium-228 ratios and activity levels; note, this map excludes background well locations, which are shown on Figure 4-45.

Data presented on Figures 4-46 and 13b demonstrate that combined unfiltered (total) radium-226/ radium-228 activity levels are lowest in Upper Alluvium samples and generally increase in Middle Alluvium and Lower Alluvium samples collected from the central, western, and northwestern portions of the on-Site and off-Site well network. Combined unfiltered (total) radium-226/radium-228 activity levels in wells located along the eastern and southern Site boundaries are consistent with the background well data presented on Figure 4-45. The highest combined unfiltered (total) radium-226/radium-228 activity levels were detected in bedrock.

Uranium

As shown on Figure 4-47, unfiltered (total) uranium was detected in all background groundwater samples collected during Q3 2022. The highest concentration of unfiltered (total) uranium in all well samples was detected in the Q3 2022 groundwater sample from background bedrock well MW-604-P1. The unfiltered (total) uranium concentration detected in the groundwater sample from background bedrock well MW-600-P1 was among the highest concentrations detected in alluvium groundwater samples from all wells.

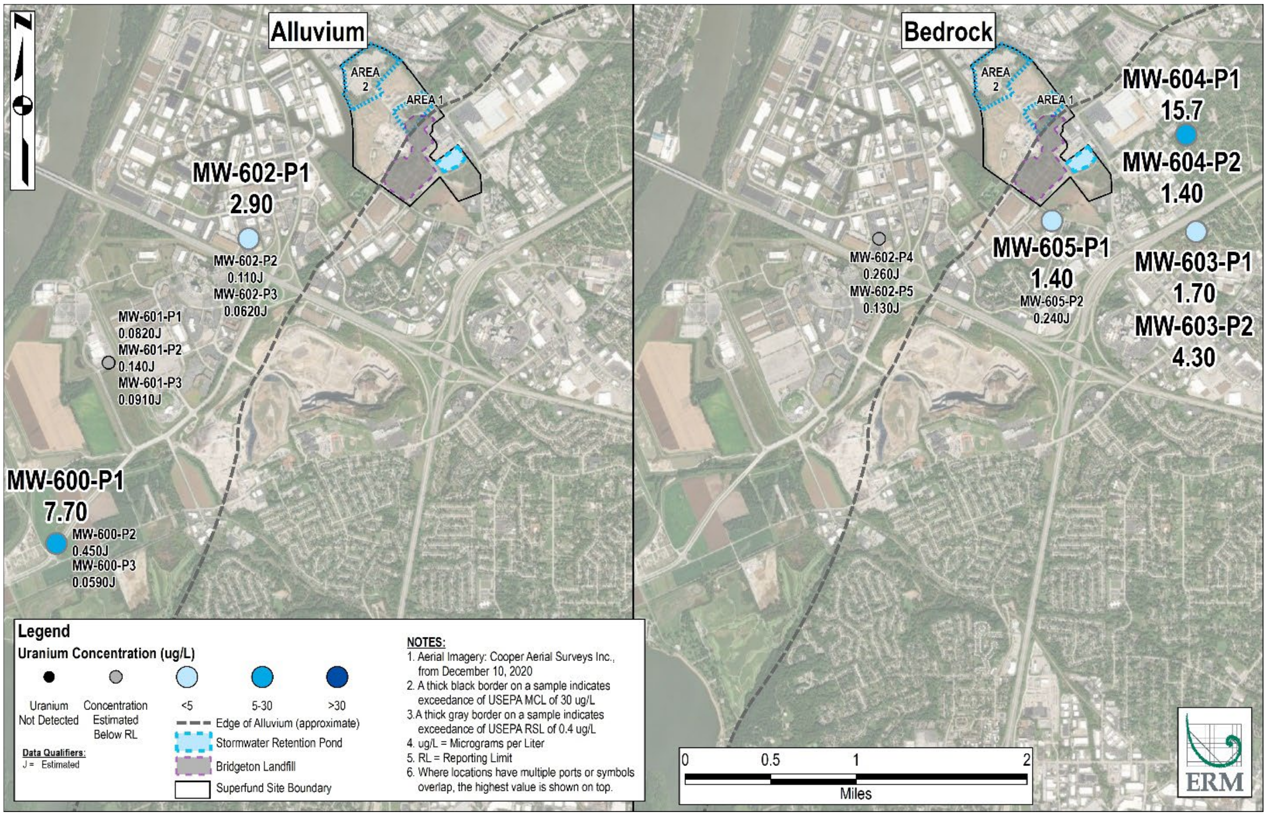


Figure 4-47: Unfiltered (Total) Uranium Concentrations from Background Wells - Q3 2022

During Q3 2022, unfiltered (total) uranium was detected in nearly all alluvium and bedrock groundwater samples, often at J-flagged (estimated) concentrations, with the highest concentrations generally detected in Upper Alluvium and in bedrock groundwater samples; higher concentrations in bedrock groundwater samples were primarily from wells on the upgradient (southern) side of the Bridgeton Landfill North and South Quarries (Figure 4-48 and 15b). All unfiltered (total) uranium concentrations were below the MCL of 30 µg/L and were generally consistent with background concentrations presented in Figure 4-47, suggesting that uranium in groundwater is naturally occurring.

The distribution of uranium in groundwater is generally inverse to that of radium in groundwater because these two radionuclides have different geochemical characteristics. As discussed in Appendix S, uranium is more mobile under oxidizing groundwater conditions while radium is more mobile under reducing groundwater conditions. For this reason, the lowest unfiltered (total) uranium concentrations are generally detected in Middle and Lower Alluvium and on the downgradient side of the Bridgeton Landfill North and South Quarries, which is where the highest radium activity levels were found. Based on this difference in transport behavior, uranium and radium are not expected to be present at high concentrations/activities in the same groundwater samples.

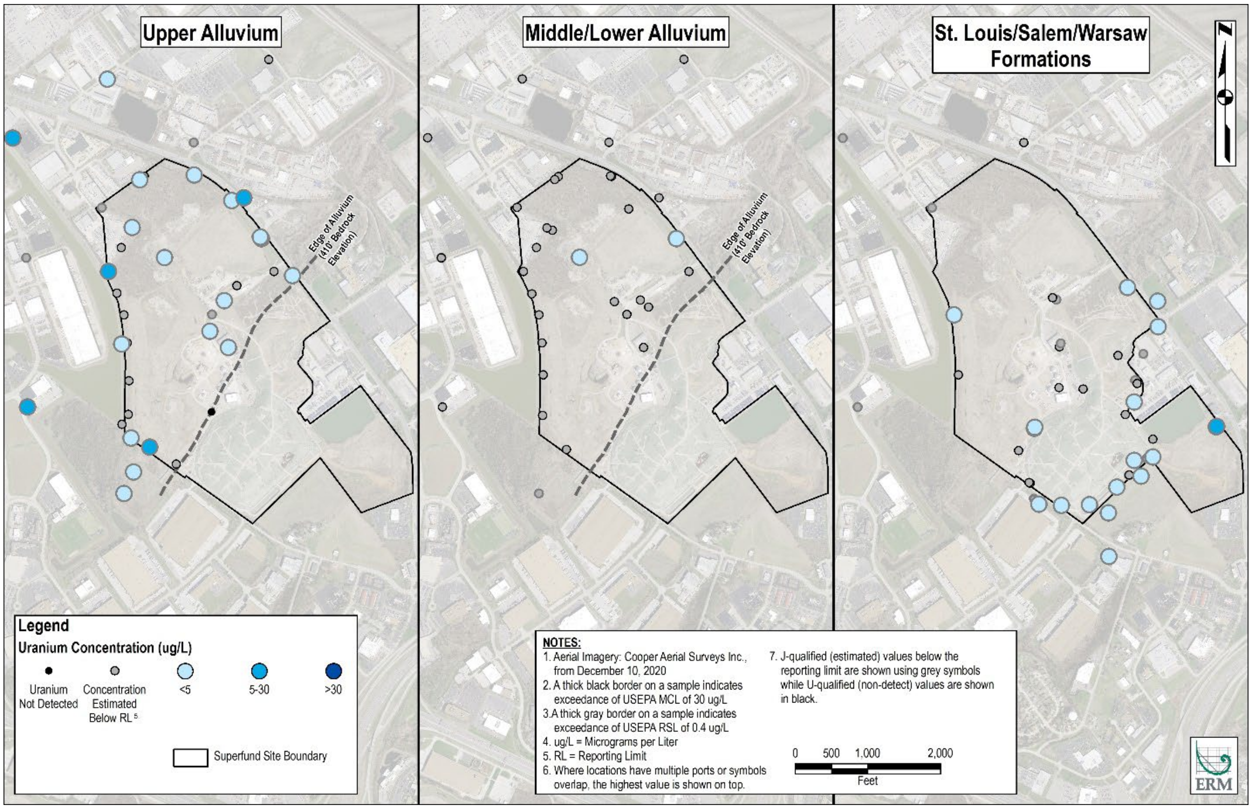


Figure 4-48: Unfiltered (Total) Uranium Concentrations from On-Site and Off-Site Monitoring Wells - Q3 2022

Thorium

During Q3 2022, thorium-230 and thorium-232 were detected in less than five percent of all groundwater samples, with the highest activities being 0.135 and 0.036 pCi/L, respectively. These data are consistent with thorium's very low aqueous solubility and mobility within groundwater. Because of the low activities and infrequent detections, figures showing the horizontal and vertical distributions of thorium isotopes were not created, consistent with the 2021 Annual Report.

4.6.1.4 Potential Sources of Radionuclides in Groundwater

The USGS identified four general hypotheses for the origin of filtered (dissolved) combined radium in Site groundwater at activity levels above the USEPA MCL (USGS 2015), which are discussed in the subsections below:

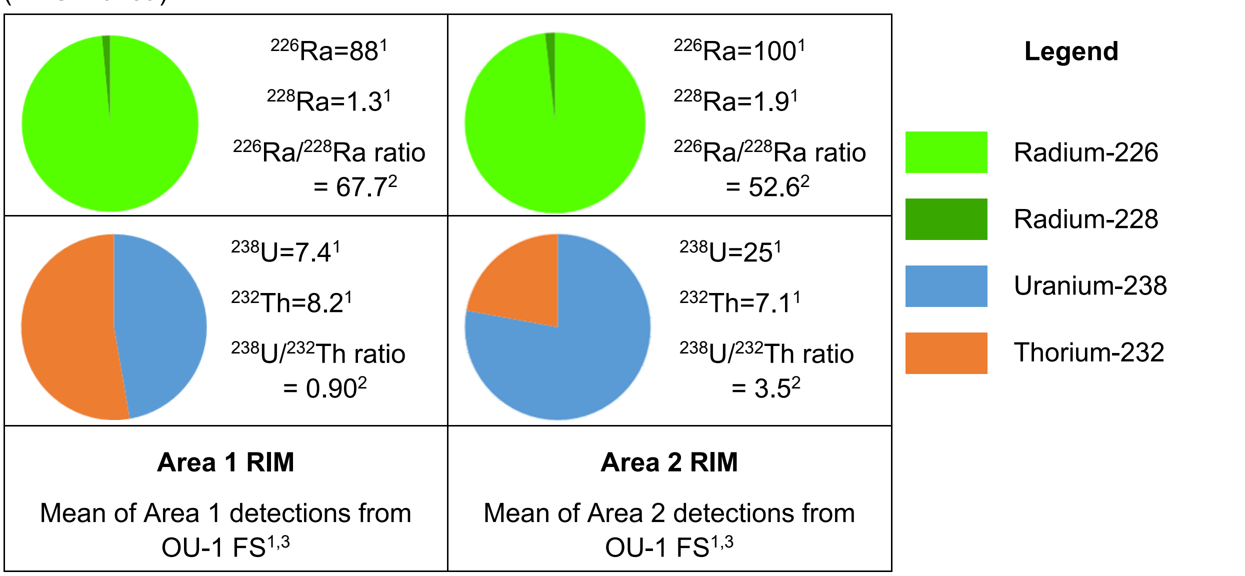
- Potential for leaching from RIM (Section 4.6.1.4.1)
- Potential for radium concentrations in groundwater to be within natural variability (Section 4.6.1.4.2)
- Potential leaching of radium from technically enhanced naturally occurring radioactive materials within traditional municipal and demolition waste (Section 4.6.1.4.3)
- Mobilization of radium from naturally occurring aquifer materials (Section 4.6.1.4.4)

The USGS further stated that, except for the radium in groundwater samples from the Site being within natural variation in groundwater, no single hypothesis can be invoked to explain all the occurrences of radium above the USEPA MCL. The following subsections discuss these potential sources of radionuclides, particularly radium, in Site groundwater.

RIM

Leached barium sulfate residue generated by Mallinckrodt Chemical Works during uranium processing for the Manhattan Engineer District was initially stored at the St. Louis Airport Site and subsequently moved to nearby 9200 Latty Avenue in Hazelwood, Missouri in 1966 (EMSI 2018b). A Nuclear Regulatory Commission investigation conducted in 1976 reported that approximately 8,700 tons of leached barium sulfate residues, together with approximately 39,000 tons of soil removed from the top 12 to 18 inches of the Latty Avenue site, were transported to the West Lake Landfill over a 3-month period from 16 July through 9 October 1973 (USEPA 2008; NRC 1976; NRC 1988; RMC 1982).

The source material of the leached barium sulfate residues was uranium ores; therefore, isotopes related to the uranium-238 decay series are more abundant than isotopes related to the thorium-232 decay series. Due to processing, however, Manhattan Engineer District project residues are not in secular equilibrium and contain higher thorium (particularly thorium-230, a product of uranium-238) activities than uranium and radium activities. Figure 4-49 presents the average radium-226 and radium-228 and uranium-238 and thorium-232 activities for material containing RIM in Areas 1 and 2 of the Site. In both locations, radium-226 is the predominant radium isotope and activities are substantially higher than those observed in aquifer matrix samples (see Figure 4-50). Uranium-238 (the precursor of radium-226) activities are substantially lower because the uranium was extracted, and the resulting materials are not in secular equilibrium. Thorium-230 isotopes in RIM are the primary source of radium in these materials (EMSI 2018a).



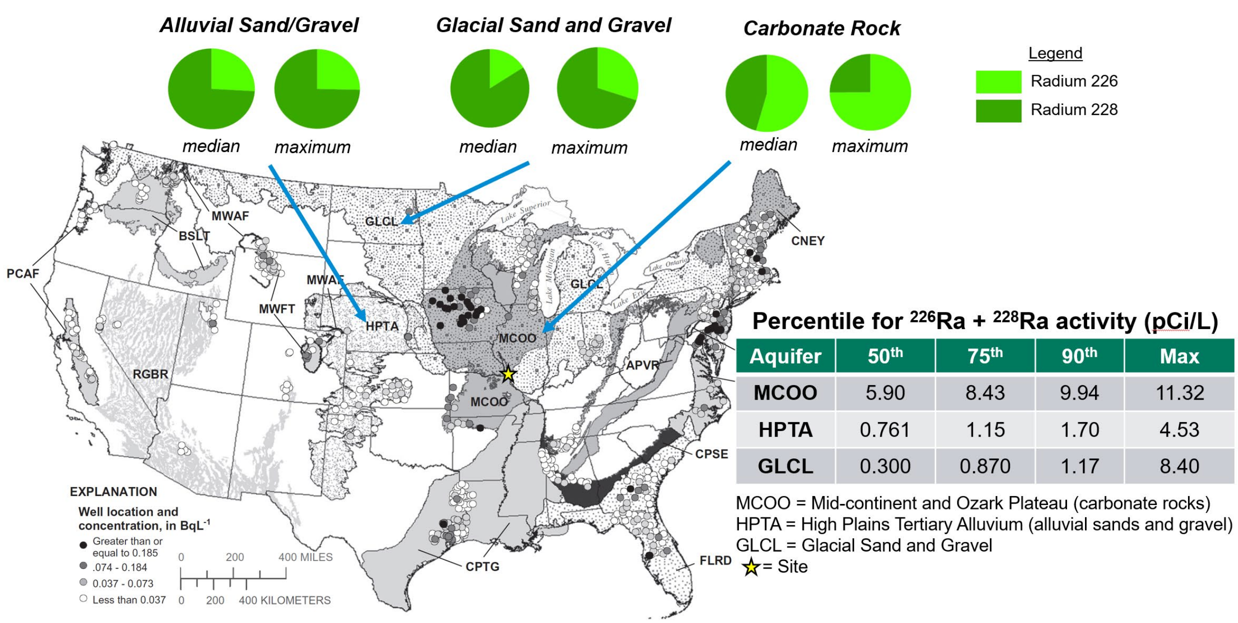
[1]Mean activity in units of picocuries per gram (pCi/g). [2]Dimensionless ratio of mean activities. [3]Final Feasibility Study, West Lake Landfill Operable Unit-1 (EMSI 2018a).

Figure 4-49: Mean Radium-226, Radium-228, Uranium-238, and Thorium-230 Activities in RIM Samples from Area 1 and Area 2

The radium-226 to radium-228 ratios in alluvium groundwater samples are lower than those for bedrock groundwater samples (see Section 4.6.1.3.1), which is consistent with the aquifer matrix data presented in Section 4.6.1.4.4 and the literature data presented in Figure 4-52. These data indicate that the radium present in the alluvium and bedrock groundwater samples was derived from alluvial sands and carbonate bedrock, respectively—not from RIM. Solids containing RIM have a different isotopic ratio than the alluvial sands (i.e., RIM has higher radium-226 activity relative to radium-228 activity due to uranium-238 within the source material [EMSI 2018a; Tables 2, 3, and 4]). The radium isotopic signatures in alluvial groundwater exhibit low radium-226 to radium-228 ratios. If the radium in alluvial groundwater had been leached directly from RIM, an increased proportion of radium-226 would be observed. This condition was not observed in any alluvium groundwater samples.

Natural Groundwater

Groundwater naturally contains radionuclides, including radium-226 and radium-228 and the activities can exceed MCLs without anthropogenic influence (Szabo et al. 2012). The radium-226 to radium-228 isotope ratios in natural groundwater systems vary between aquifers and depend on the aquifer geology. As shown in Figure 4-50, sand and gravel aquifers have, on average, higher radium-228 activities than radium-226 activities while carbonate rock aquifers have higher radium-226 activities relative to radium-228 activities. In the data collected to date, the radium isotopic ratios in Site and background groundwater samples (see Section 4.6.1.3) are consistent with those presented in the literature for Midwest aquifers (e.g., Szabo et al. 2012), as shown below in Figure 4-50. Only one round of groundwater analytical results has been collected from newly installed background monitoring wells, so there is insufficient data to determine if the combined radium-226/228 activities measured on Site are within the range of naturally occurring radium activities in the region. A comprehensive background evaluation will be performed, and the results will be presented in future submittals.



Aquifer	50th	75th	90th	Max
MCOO	5.90	8.43	9.94	11.32
HPTA	0.761	1.15	1.70	4.53
GLCL	0.300	0.870	1.17	8.40

Figure 4-50: Radium Isotopic Signatures and Combined Radium-226/Radium-228 Activity Levels for Natural Groundwaters in the Midwest

Figure modified from Szabo et al. 2012.

Non-RIM Waste Material

Waste materials, including combustion byproducts, sewage sludge, consumer goods, and building materials, may contain naturally occurring radiological materials, including radium isotopes and their precursor atoms (uranium-238 and thorium-232) (Brennan 1997; USGS 2015; Nandutu and Kim 2021). If radionuclides in groundwater are coming from non-RIM waste material, they would be co-located in groundwater with other organic and inorganic analytes that are also present in landfills. An evaluation of potential on-Site sources of COPCs to groundwater is ongoing. When this assessment is complete, the relationship between radium activities and potential leachate impacts will be evaluated to determine if non-RIM waste material is a substantial contributor of radium in groundwater.

Mobilization of Radium in Limestone Bedrock and Alluvium

The geologic materials that comprise aquifers consist of minerals that contain naturally-occurring radionuclides. Aquifer matrix samples were collected to assess the composition and activity of radionuclides in alluvium and bedrock matrix materials. Aquifer matrix sample data collected in 2021 and 2022 are included in Table 12. The aquifer matrix sampling program is summarized in Table 4-3 and Figure 4-51 below.

Table 4-3: Summary of Aquifer Matrix Sample Numbers by Well

Well ID	Number of Alluvial Aquifer Matrix Samples	Number of Bedrock Aquifer Matrix Samples
MW-404	NA	14
MW-407R	11	NA
MW-406	10	8
MW-500	10	7
MW-502	10	NA
MW-604	NA	10

NA = not available, an alluvial or bedrock aquifer matrix sample was not collected from this location

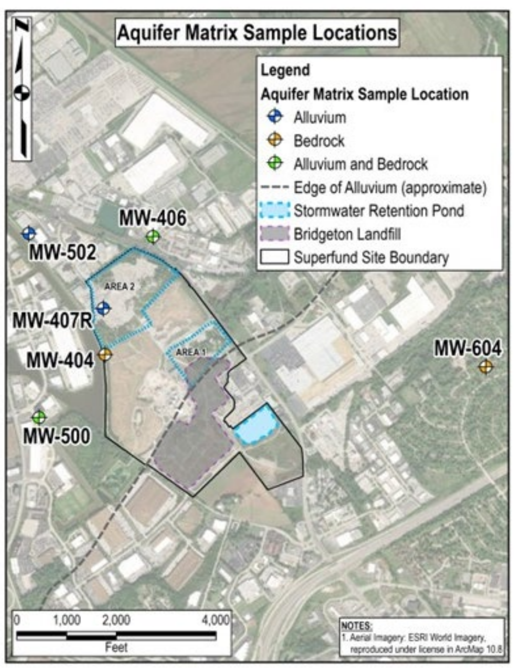
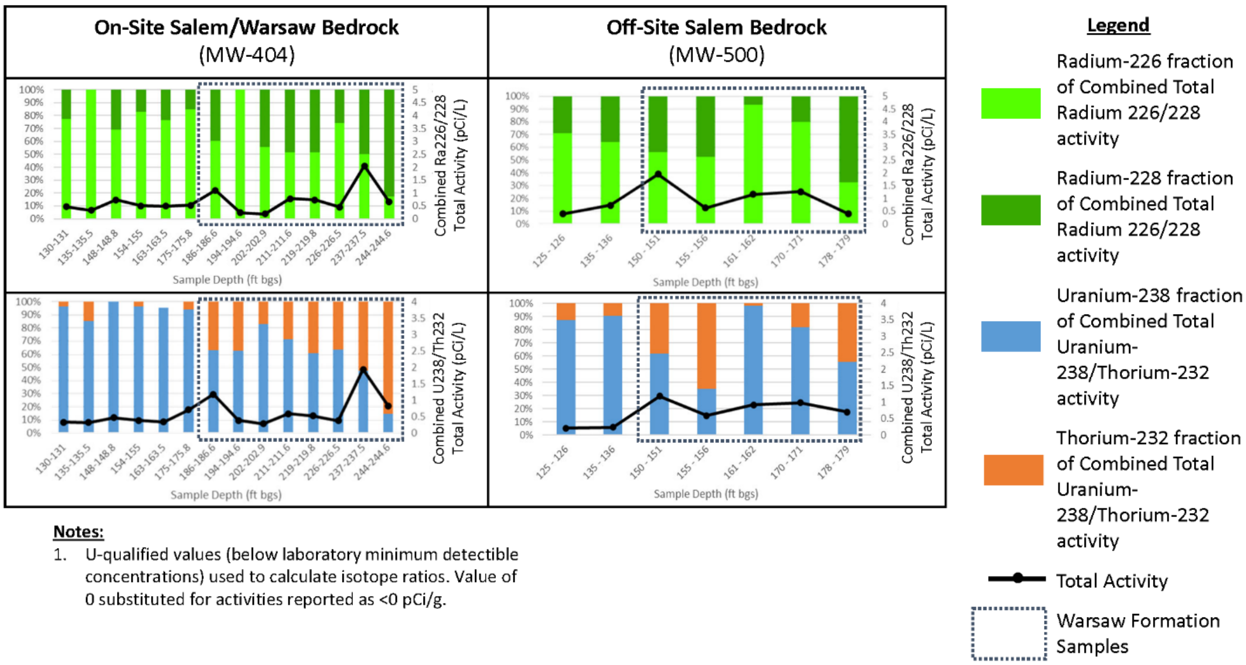


Figure 4-51: Location of Aquifer Matrix Samples

Alluvial (n=41) and bedrock (n=39) aquifer matrix samples were collected from representative geologic materials at six well locations shown on the figure with a focus on intervals where the spectral gamma data suggested the potential presence of radionuclides.

Combined radium-226/radium-228 activities, radium-226/radium-228 isotope ratios, combined uranium-238/thorium-232 activities, and uranium-238/thorium-232 isotope ratios for bedrock and alluvial aquifer matrix samples are shown on Figures 17 and 18, respectively. Select examples of bedrock and alluvial aquifer matrix isotope ratios are reproduced as Figures 4-52 and 4-53, below. Overall:

- Isotope ratios in both bedrock and alluvial aquifer matrix have limited variability in a given location; and
- Radium-226 to radium-228 activity ratios are similar to those of their precursor isotopes uranium-238/thorium-232.



Notes:

1. U-qualified values (below laboratory minimum detectible concentrations) used to calculate isotope ratios. Value of 0 substituted for activities reported as <0 pCi/g.

Figure 4-52: Radium-226, Radium-228, Uranium-238, and Thorium-232 Activities by Depth for Select Bedrock Aquifer Matrix Samples

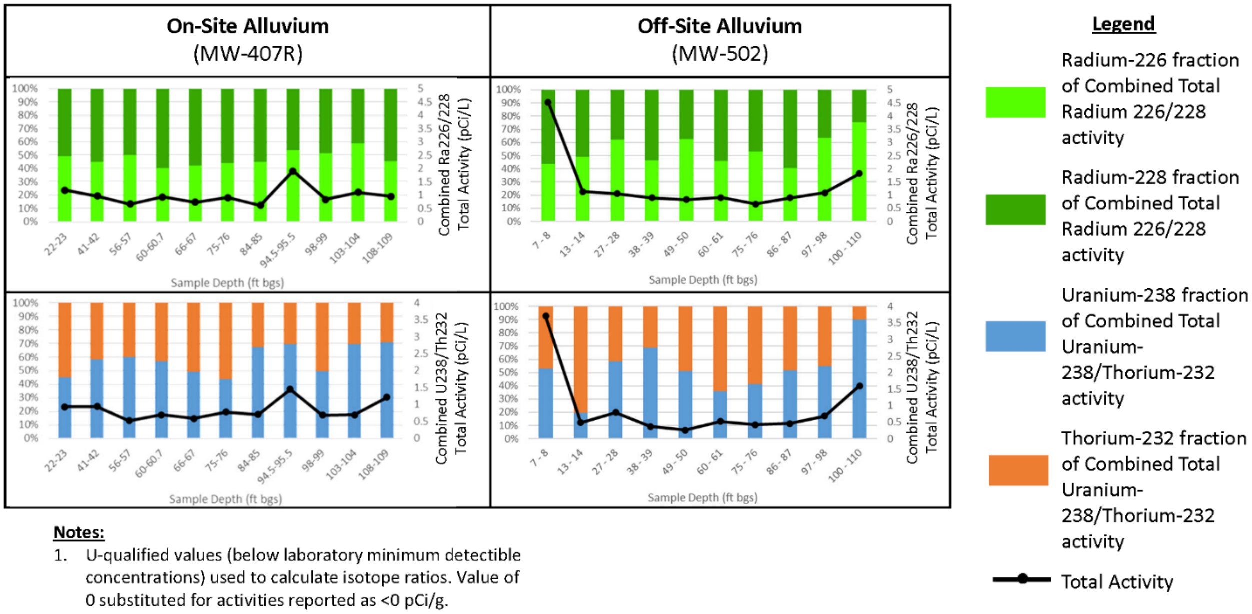


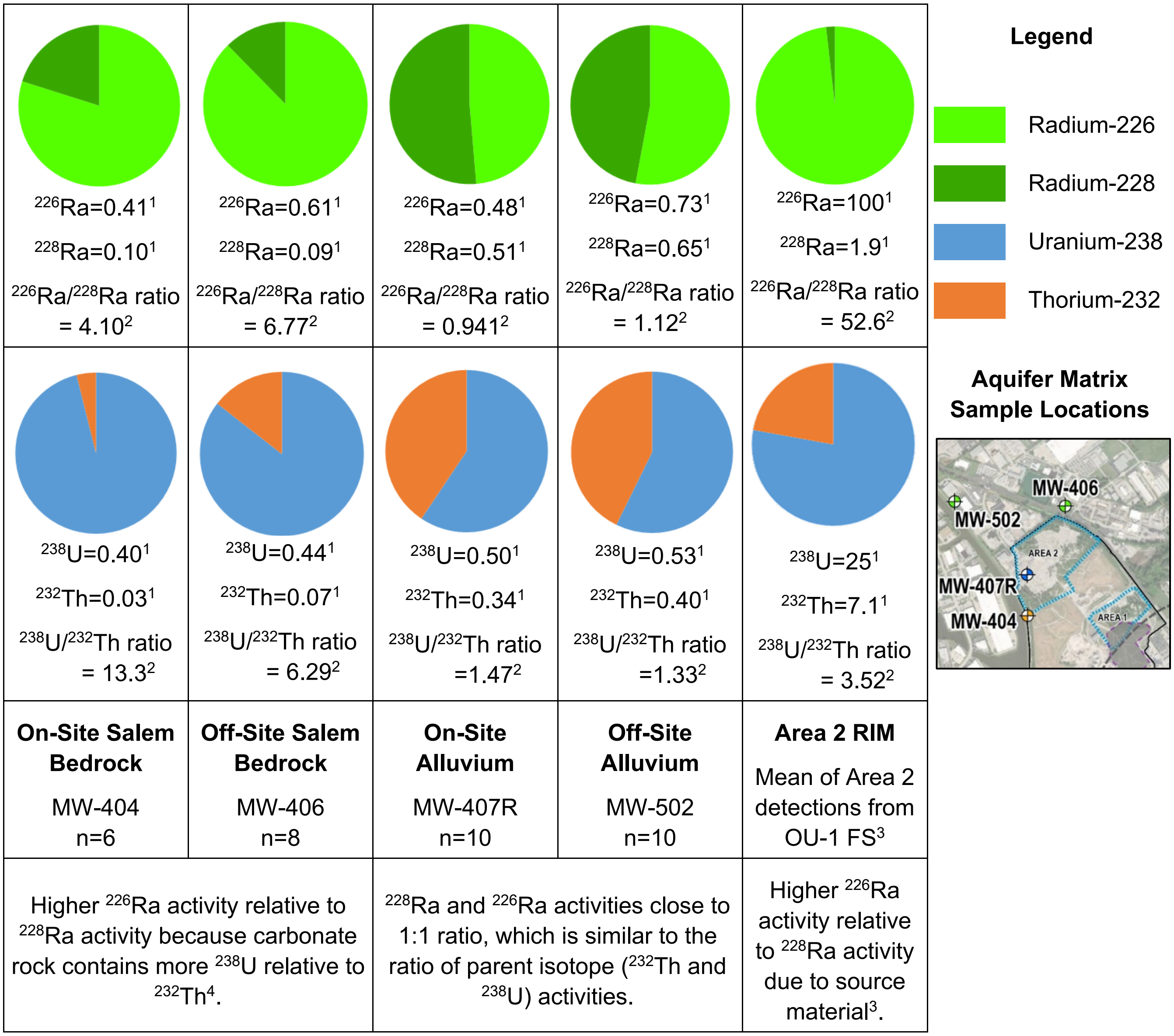
Figure 4-53: Radium-226, Radium-228, Uranium-238, and Thorium-232 Activities by Depth for Select Alluvial Aquifer Matrix Samples

In alluvial aquifer matrix samples, the combined radium activity was approximately 1 pCi/g for most of the samples and there was little variability in combined radium-226/-228 activities across samples and between the on-Site and off-Site locations, with two exceptions, both of which exhibited different geologic characteristics than the other samples collected:

- Sample collected at MW-502 from 7 to 8 feet below ground surface consisted of clay and exhibited a combined radium-226/-228 activity of 4.53 pCi/g
- Sample collected at MW-407R from 94.5 to 95.5 feet below ground surface contained organic matter and exhibited a combined radium-226/-228 activity of 1.91 pCi/g

In bedrock aquifer matrix samples, the combined radium activity was approximately 0.5 to 2 pCi/g, and there was little variability in combined uranium-238/thorium-232 activities across samples and between the on-Site and off-Site locations. Slight increases in both combined radium-226/-228 and combined uranium-238/thorium-232 activities were noted in the argillaceous rock at the top of the Warsaw Formation (see Figure 17).

Due to the low variability between samples of similar material, average activities were used to calculate isotope ratios for each material at each location where aquifer matrix samples were collected. These average isotope ratios for select locations and for soil containing RIM are shown on Figure 4-54.



[1]Mean activity in units of pCi/g. [2]Dimensionless ratio of mean activities. [3]Final Feasibility Study, West Lake Landfill Operable Unit-1 (EMSI 2018a). [4]Szabo et al., 2012.

Figure 4-54: Mean Radium-226, Radium-228, Uranium-238, and Thorium-230 Activities in Aquifer Matrix Samples

The average ratios of radium-226/-228 in alluvium and RIM aquifer matrix samples were approximately 1 and 50, respectively. The radium-226/-228 ratios in bedrock aquifer matrix samples ranged from approximately 4 to 7. The radium-226/-228 ratios for the naturally occurring matrices at the Site (i.e., alluvium and bedrock) are distinctly different than the ratio for RIM. Because the rate and amount of leaching and transport of radium is the same for both isotopes, when evaluating the potential source(s) of radium in groundwater, the isotopic signatures can be used to determine from which aquifer matrix source the radium was derived.

The on-Site and off-Site uranium-238/thorium-232 and radium-226/-228 isotope ratios in bedrock aquifer matrix samples are greater than one, indicating that the activities of isotopes in the uranium-238 decay series exceed those of the thorium-232 decay series. These ratios are consistent with those reported in the literature for carbonate rocks, which are found beneath the Site (i.e., they contain more uranium-238 than thorium-232 due to the geological conditions in which they formed; Sturchio et al. 2001; Tagma et. al 2011; Vinson 2011).

The Warsaw Formation is geologically different from the Salem Formation, which is reflected in the isotopic signatures for the two formations (see Figure 4-50 above). Aquifer matrix samples collected from the Warsaw Formation generally exhibit lower uranium-238/thorium-232 and radium-226/-228 ratios than samples obtained from the Salem Formation.

The radium isotope ratios in Site, off-Site, and background groundwater samples were described in Section 4.6.1.3 and are shown on attached Figures 13a and 13b and in-text Figures 4-52 and 4-53. In nearly all locations, the radium isotope ratios in groundwater are similar to the isotope ratios in the associated aquifer matrix samples, indicating that the radium in groundwater is derived from the aquifer matrix. Both alluvium and bedrock groundwater in the downgradient portion of the Site (i.e., along the western Site boundary) generally exhibit higher combined unfiltered (total) radium-226/-228 activity levels than groundwater in samples from the upgradient portion of the Site. Evaluation of the potential effects of landfill operations on aquifer geochemical conditions and potential mobilization of naturally occurring radium is ongoing.

As described in Appendix S, the geochemical processes responsible for mobilizing radium from aquifer matrices into groundwater are reversible when geochemical conditions change (e.g., become more oxidizing). If Site-related changes to aquifer geochemistry have mobilized or are mobilizing naturally-occurring radium, these effects are expected to be local to the Site boundaries; downgradient of the Site, radium activities will return to background levels through natural processes (i.e., precipitation and/or adsorption). To date, a limited number of samples have been collected from off-Site and background wells. Additional evaluation of background activities/concentrations, groundwater geochemistry, and source signatures is ongoing and multiple lines of evidence will be used to evaluate potential sources of radium in groundwater.

Summary

Radium, which is a naturally occurring radionuclide, is the primary radionuclide of potential concern in groundwater at the Site. A detailed evaluation of potential radionuclide sources was conducted that evaluated RIM placed at the Site and natural alluvial and bedrock aquifer materials as potential sources of radium in groundwater. Additional analysis of the potential effects of landfill conditions on the natural aquifer source materials is ongoing. The source evaluation (including assessment of isotope ratios and other factors) indicated that radium detected in Site groundwater originates from the natural aquifer materials rather than from RIM placed at the Site.

Radium was detected in about half of the groundwater samples collected from alluvium and bedrock wells upgradient of the Site (i.e., to the east and south of the Site) that are designated as background locations. Activity levels of radium exceeded the USEPA MCL in one background sample. Radium activity levels in samples from off-Site wells closer to the Site (i.e., to the west and north of the Site) were less than the USEPA MCL in nearly all samples and were consistent with the range of activities in background samples. Radium was detected in about two-thirds of the groundwater samples collected from alluvium and bedrock wells located at and near the Site. The highest radium activity levels in groundwater were generally detected along the western downgradient Site boundary in Middle and Lower Alluvium and bedrock groundwater.

4.6.2 Nature and Extent of Select Non-radionuclide Compounds of Potential Concern

This section describes the nature and extent of select COPCs (in alphabetical order): arsenic, benzene, *cis*-1,2-dichloroethene, 1,4-dioxane, 2-methylnaphthalene, THF, 1,2,4-trimethylbenzene, and vinyl chloride. Analysis of potential sources of these select COPCs is ongoing. Arsenic is a naturally occurring metal that can be present from natural sources or from arsenic-containing wastes (e.g., treated wood) (Jambeck et al., 2007, Zhang et al., 2016). The remainder of the select COPCs are organic compounds. VOCs and other organic compounds are known to be present in landfill leachate and gases, typically from disposal of household and commercial products (Kjeldsen et al. 2002; Klett et al. 2005). VOCs may also come from other industrial sources (e.g., the adjacent PM Resources site and the Missouri Asphalt Plant located on the landfill property). The physical properties, potential sources, biodegradation pathways, and effect of groundwater geochemistry on the transport of these select COPCs are discussed in Appendix S.

4.6.2.1 Arsenic

The spatial distribution of arsenic in groundwater during Q3 2022 is shown on Figure 9a and the vertical distribution of arsenic in groundwater along the western Site boundary is shown on Figure 9b. During Q3 2022, arsenic (unfiltered [total]) was detected in groundwater within 98 percent of alluvium and 97 percent of bedrock well samples. The highest concentrations of arsenic were present in the Upper Alluvium and in the central and southern portions of the Site, with lower concentrations in the Middle Alluvium and Lower Alluvium. In background, on-Site, and off-Site monitoring wells, arsenic was detected above the MCL of 10 µg/L in only one off-Site alluvium monitoring well sample (MW-501-P1) and in one off-Site bedrock monitoring well sample (MW-502-P5). Delineation of the extent of arsenic in off-Site groundwater is ongoing.

4.6.2.2 Benzene

The spatial distribution of benzene in groundwater during Q3 2022 is shown on Figure 10a and the vertical distribution of benzene in groundwater along the western Site boundary is shown on Figure 10b. During Q3 2022, benzene was detected in groundwater within 23 percent of alluvium and 18 percent of bedrock well samples. All benzene detections occurred within the southern half of the Site; benzene was not detected in groundwater in the northern half of the Site and in the northern portion of the Inactive Sanitary Landfill, the Closed Demolition Landfill, or Area 2. Benzene occurrences at concentrations above the MCL were only identified in groundwater in bedrock adjacent to the Bridgeton Landfill South Quarry and in alluvium in the south/southeast and west margins of the Inactive Sanitary Landfill. Benzene was not detected at concentrations above the laboratory RL of 1.00 µg/L in any of the recently installed background, on-Site, or off-Site monitoring wells that were first sampled in Q3 2022. Based on the data available to date, the extent of benzene impacts to groundwater is limited to monitoring wells present on the Site.

4.6.2.3 cis-1,2-Dicholorethene

The spatial distribution of *cis*-1,2-dichloroethene in groundwater during Q3 2022 is shown on Figure 11a and the vertical distribution of *cis*-1,2-dichloroethene in groundwater along the western Site boundary is shown on Figure 11b. During Q3 2022, *cis*-1,2-dichloroethene was detected in groundwater within 18 percent of alluvium and 2.7 percent of bedrock well samples. *cis*-1,2-Dichloroethene was detected in groundwater almost solely in alluvium wells along the western Site boundary and was not detected in the northern, central, or eastern portions of the Site. There was one detection in bedrock groundwater on the western Site boundary. All detections were below the MCL. *cis*-1,2-Dichloroethene was detected in one recently installed off-Site well: MW-501-P3. *cis*-1,2-Dichloroethene concentrations were below the laboratory RL of 1.00 µg/L in all other recently installed off-Site and background wells. Delineation of the extent of *cis*-1,2-dichloroethene in off-Site groundwater is ongoing.

4.6.2.4 1,4-Dioxane

The spatial distribution of 1,4-dioxane in groundwater during Q3 2022 is shown on Figure 12a and the vertical distribution of 1,4-dioxane in groundwater along the western Site boundary is shown on Figure 12b. During Q3 2022, 1,4-dioxane was detected in groundwater within 66 percent of alluvium and 64 percent of bedrock well samples. 1,4-Dioxane was widespread in groundwater in both alluvium and bedrock wells across the Site, except for the northeastern Site boundary in alluvium and the southeastern Site boundary in bedrock where this compound was minimally detected. 1,4-Dioxane was detected in seven background well samples with the highest concentration being 9.47 µg/L in MW-602-P2. 1,4-Dioxane was detected in several recently installed off-Site wells, with the highest detections in MW-406-P4, MW-501-P3, and MW-501-P2 at 235 µg/L, 222 µg/L, and 163 µg/L, respectively. Delineation of the extent of 1,4-dioxane in off-Site groundwater is ongoing.

4.6.2.5 2-Methylnaphthalene

During Q3 2022, 2-methylnaphthalene was detected in groundwater within 9.7 percent of alluvium well samples and was not detected in any bedrock well samples. The highest concentration (31.5 µg/L) was recorded in one alluvium groundwater well sample along the western Site boundary while all other concentrations were 1.5 µg/L or lower. Due to the limited distribution of 2-methylnaphthalene at the Site, maps and cross-sections were not prepared, consistent with the 2021 Annual Report. 2-Methylnaphthalene was not detected above the laboratory RL of 1.00 µg/L in any recently installed background, on-Site, or off-Site monitoring wells and the extent of 2-methylnaphthalene impacts to groundwater are limited to the Site.

4.6.2.6 Tetrahydrofuran

The spatial distribution of THF in groundwater during Q3 2022 is shown on Figure 14a and the vertical distribution of THF in groundwater along the western Site boundary is shown on Figure 14b. During Q3 2022, THF was detected in groundwater within 26 percent of alluvium and 21 percent of bedrock well samples. THF was widely detected in groundwater in both alluvium and bedrock in the western and southern portions of the Site but was detected in only one well in the northeastern portion of the Site. THF was detected at 21.0 J µg/L in the recently installed off-Site monitoring well MW-501-P3. THF was not detected above the laboratory RL of 20.0 µg/L in any other recently installed background, on-Site, or off-Site monitoring wells.

4.6.2.7 1,2,4-Trimethylbenzene

During Q3 2022, 1,2,4-trimethylbenzene was detected in groundwater within 4.4 percent of alluvium well samples but was not detected in any bedrock well samples. All detections were in wells in the southwestern portion of the Site. Due to the limited distribution of 1,2,4-trimethylbenzene at the Site, maps and cross-sections were not prepared, consistent with the 2021 Annual Report. 1,2,4-Trimethylbenzene was not detected above the laboratory RL of 5.00 µg/L in any of the recently installed background, on-Site, or off-Site monitoring wells and the extent of 1,2,4,-trimethylbenzene impacts to groundwater is limited to the Site.

4.6.2.8 Vinyl chloride

The spatial distribution of vinyl chloride in groundwater during Q3 2022 is shown on Figure 16a and the vertical distribution of vinyl chloride in groundwater along the western Site boundary is shown on Figure 16b. During Q3 2022, vinyl chloride was detected in groundwater within 11 percent of alluvium and 1.4 percent of bedrock well samples. Vinyl chloride was detected in groundwater almost solely in Middle and Lower Alluvium wells along the western Site boundary. It was not detected in the northern, central, or eastern portions of the Site. Of all recently installed background, on-Site, and off-Site monitoring wells, vinyl chloride was detected in only three off-Site monitoring wells: MW-501-P1 (J-qualified), MW-501-P2, and MW-501-P3. Delineation of the extent of vinyl chloride in off-Site groundwater is ongoing.

Summary

The horizontal and vertical distribution of the non-radionuclide select COPCs has been largely defined, except for certain COPCs (e.g., 1,4-dioxane), which have been detected in samples from off-Site wells at concentrations greater than the applicable screening levels or MCLs. Additional investigation activities will be conducted to define the horizontal and vertical distribution, and to evaluate the potential source(s) of these constituents.

4.6.3 Time-Series Plots for Select Groundwater COPCs

Appendix T includes time-series plots for 10 select COPCs for each monitoring well sampled during the reporting period. Time-series plots of thorium isotopes were excluded due to the low detection frequency of these analytes. Each time-series plot includes all data collected from Q4 2020 through Q3 2022 (eight quarters of sampling for wells that were installed prior to Q4 2020). There is no apparent seasonality in any of these data. Concentrations/activities of select COPCs are generally stable in most locations. There are a small number of well-analyte pairs that display apparent increases or decreases over time. These potential trends will be evaluated statistically, in accordance with requirements presented in the QAPP when an appropriate amount of data have been generated.

4.6.4 Summary of Nature and Extent of Select Groundwater COPCs

ERM evaluated the distribution of eleven select COPCs to address PSQ-1 (Are COPCs present in groundwater at concentrations/activities above screening levels?) and PSQ-2 (What is the vertical and horizontal spatial distribution of COPCs at concentrations/activities above screening levels in groundwater?).

Of the three radionuclides evaluated, radium is more mobile in reducing groundwater conditions, uranium is more mobile under oxidizing groundwater conditions, and thorium is generally immobile in groundwater. As expected, radium activities and uranium concentrations were generally inversely distributed, and thorium was generally not detected in groundwater.

To evaluate potential sources of radium in groundwater, ERM compared the radium isotope ratios in various source matrices (i.e., RIM, alluvium, and bedrock) to those in groundwater. In RIM, nearly all of the radium activity is from radium-226; in alluvium, radium-226 and radium-228 activities are similar; and in bedrock, radium-228 activities exceed the radium-226 activities. In both bedrock and alluvial groundwater samples collected from background, on-Site, and off-Site wells, the radium isotope ratios are similar to the isotope ratios in the respective aquifer matrix samples and there is no evidence of increased radium-226 activity from RIM. These data demonstrate that leaching of RIM is not a significant source of radium in Site groundwater and that the radium detected in groundwater is derived from natural source materials. Evaluation of the various potential sources of radium in groundwater is ongoing and will be documented in future reports.

Of the select COPCs presented, four (uranium, thorium isotopes, 2-methylnaphthalene, and 1,2,4-trimethylbenzene) were detected infrequently or at concentrations below the MCL and will not be discussed further in future annual reports. Additional evaluation of the remaining select COPCs is ongoing to assess potential natural and anthropogenic sources to answer PSQ-3 *(Are the COPCs Site related?)* and PSQ-4 *(What are the sources of Site-related COPCs in groundwater?)*.

An assessment of time-series plots for 10 of the select COPCs (thorium isotopes were excluded due to the low frequency of detection) shows that there is no apparent seasonality in the concentrations/activities. For most well-analyte pairs the concentration/activities for each analyte are stable. There are a small number of well-analyte pairs that display apparent increases or decreases over time. These potential trends will be evaluated statistically, in accordance with requirements presented in the QAPP when an appropriate amount of data have been generated.

5. NEXT STEPS

As summarized in Sections 2 and 3, a significant amount of field work has been completed and data generated as part of the ongoing RI. Much of these data have been interpreted and presented in the updated CSM (Section 4). However, additional data or data interpretations are necessary to answer some of the remaining PSQs, as documented in the following table.

Principal Study Question	Additional Data or Activities Needed to Answer the PSQ
PSQ-1: Are COPCs present in groundwater at concentrations/activities above screening levels?	■ None; sufficient data are available to address this PSQ.
PSQ-2: What is the vertical and horizontal spatial distribution of COPCs at concentrations/activities above screening levels in groundwater?	■ Sufficient data are available to address this PSQ for most COPCs. Additional data are needed to evaluate the horizontal extent of certain COPCs (e.g., 1,4-dioxane) in alluvial groundwater to the west of the Site. ■ Install, develop, and sample off-Site step-in and step-out wells and continue to compare the analytical results to screening levels. ■ If 1,4-dioxane is detected in bedrock at off-Site locations where it was detected in lower alluvium, additional data may be required to determine the lateral extent of 1,4-dioxane in bedrock.
PSQ-3: Are the COPCs Site-related?	■ Conduct additional evaluation of existing groundwater analytical data to evaluate potential impacts of landfill conditions on groundwater and naturally occurring COPCs. ■ Continue sampling background wells, define background conditions, and compare on and off-Site COPC results to background conditions.
PSQ-4: What are the sources of Site-related COPCs in groundwater?	■ Conduct additional evaluation of existing groundwater analytical data and data that will be generated during the 2023 reporting period to evaluate potential mobilization of naturally occurring metals (e.g., radium and arsenic) due to changes in oxidation-reduction conditions. ■ Install, develop, and sample off-Site step-in and step-out wells to evaluate the potential for other contributing sources.
PSQ-5: Where could Site-related COPCs migrate in the future?	■ Apply and confirm the geologic model in areas where step-in and step-out wells are drilled. ■ Move transducers, as documented in Tech Memo 26, to further evaluate the orientation and magnitude of transient hydraulic gradients. ■ Continue to evaluate transducer[36], river stage, and precipitation data to better understand the dynamic groundwater flow regime and surface water/groundwater interactions in the vicinity of the Site. ■ Continue to evaluate temporal COPC concentration/activity. ■ Continue to evaluate the hydraulic boundary conditions. ■ Continue to refine and update the conceptual site model.

[36] Per Tech Memo 26, the distribution of pressure transducers will be expanded as some existing pressure transducers are moved to new locations and new pressure transducers are installed. A full reporting period of transducer data will also be collected for off-Site monitoring well locations that were installed during the 2022 reporting period.

The following activities are proposed for OU-3 during the 2023 reporting period:

- Adjust the deployment of pressure transducers, as documented in Tech Memo 26.
- Install step-in and step-out wells, as documented in a Work Plan Addendum (ERM 2023), including borehole advancement, core logging, borehole geophysical logging, and well construction and development.
- Complete monitoring well gauging and sampling.
- Complete monthly transducer data downloads.
- Complete additional data interpretation activities, as presented in the table above.
- Replace the monthly potentiometric surface maps with daily representations of the orientation and magnitude of the horizontal hydraulic gradient, consistent with those presented in Figures 4-32 to 4-34.

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