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NNLEMS

Environmental Management and Stewardship

Moab Uranium Mill Tailings Remedial Action Project Site: Collaboration to Support Development of the Groundwater Corrective Action

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REVIEWS AND APPROVALS

AUTHORS:

Keaton Belli Digitally signed by Keaton Belli
Date: 2023.09.12 09:07:23 -07'00'

Keaton Belli **Date**

Geosyntec Consultants, Inc.

BRIAN LOONEY (Affiliate) Digitally signed by BRIAN LOONEY (Affiliate)
Date: 2023.09.12 11:52:39 -04'00'

Brian Looney, Team 3 Co-Lead **Date**

Savannah River National Laboratory

Jennifer Nyman Digitally signed by Jennifer Nyman
Date: 2023.09.12 09:25:35 -07'00'

Jennifer Nyman **Date**

Geosyntec Consultants, Inc.

TECHNICAL REVIEWERS:

Amoret L. Bunn Digitally signed by Amoret L. Bunn
Date: 2023.09.12 11:45:16 -07'00'

Amoret Bunn, Team 1 Lead **Date**

Pacific Northwest National Laboratory

Andrew Tompson Digitally signed by Andrew Tompson
Date: 2023.09.19 13:54:55 -07'00'

Andrew Tompson, Team 2 Lead **Date**

Lawrence Livermore National Laboratory

Gilles Yves A Bussod Digitally signed by Gilles Yves A Bussod
Date: 2023.09.19 13:44:24 -06'00'

Gilles Bussod, Team 3 Co-Lead **Date**

Los Alamos National Laboratory

APPROVAL:

MARK KAUTSKY Digitally signed by MARK KAUTSKY
Date: 2023.09.21 15:34:41 -06'00'

____

Mark Kautsky, AS&T Program Manager **Date**

Department of Energy Office of Legacy Management

ELIZABETH MORAN Digitally signed by ELIZABETH MORAN
Date: 2023.10.02 16:22:21 -06'00'

____

Liz Moran, MOAB UMTRA Project Environmental Manager **Date**

Department of Energy Office of Environmental Management

CHRISTOPHER PULSKAMP Digitally signed by CHRISTOPHER PULSKAMP
Date: 2023.10.03 08:09:12 -06'00'

____

Chris Pulskamp, Project Engineer, MOAB UMTRA Project **Date**

Department of Energy Office of Environmental Management

Ming Zhu Digitally signed by Ming Zhu
Date: 2023.10.03 15:20:11 -04'00'

____

Ming Zhu, Senior Advisor for Laboratory Policy **Date**

Department of Energy Office of Environmental Management

Contributors

Thank you to the NNLEMS participants, industry contributors, Moab SMEs, and DOE HQ support who facilitated and enhanced this effort. *Team leads are marked with an asterisk.*

Lawrence Berkeley National Laboratory

Ken Williams

Lawrence Livermore National Laboratory

Andrew Thompson*

Los Alamos National Laboratory

Gilles Bussod*

James Lee

Pacific Northwest National Laboratory

Amoret Bunn*

Frederick Day-Lewis

Katie Muller

Sandia National Laboratories

Kris Kuhlman

Savannah River National Laboratory

Hansell Gonzalez-Raymat

Brian Looney*

Geosyntec

Keaton Belli

Jennifer Nyman

DOE-EM HQ

Ming Zhu

DOE-LM HQ

Mark Kautsky

EnTech

Ron Kent

Al Lasse

MOAB UMTRA Project

Elizabeth Moran

Chris Pulskamp

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Executive Summary

The U.S. Department of Energy (DOE) Office of Environmental Management (EM) is responsible for surface remediation of the Moab Uranium Mill Tailings Remedial Action (UMTRA) Project Site (the site). Surface remediation consists of relocating tailings to the disposal cell at Crescent Junction, Utah, and may be completed as early as 2027. After completion of surface remediation, the site may be transferred to the DOE Office of Legacy Management (LM), which will be responsible for managing contaminated groundwater, protecting the Colorado River and the surrounding environment, and operating remediation systems toward groundwater regulatory standards and closure. DOE is currently operating interim systems that reduce risks by pumping and managing contaminated groundwater and clean surface water.

DOE is currently developing a Groundwater Compliance Action Plan (GCAP) with a 2025 target date. The GCAP will define a technically defensible groundwater remediation strategy for Nuclear Regulatory Commission (NRC) concurrence and future implementation.

To advance the development of a GCAP for the site, a virtual collaboration was held between LM, EM, and the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) in the third and fourth quarters of 2022. The objectives of the collaboration were to

- identify information and data gaps and factors that may impact development of a defensible GCAP;
- develop recommendations for closing data gaps;
- prioritize recommendations and prepare a sequenced and spatially targeted strategy for structuring the GCAP to maximize efficiency and effectiveness; and
- identify technologies and approaches for consideration in the GCAP.

The overarching charge of the collaboration was to generate actionable recommendations that advance the development of a defensible GCAP. Three teams of working group members were created to address focused topics of importance to DOE, regulators, and stakeholders and to highlight approaches to provide efficient and effective management/mitigation of risks at the site following relocation of tailings and wastes. The three working group teams were:

- Team 1: GCAP development status, requirements, and path forward.
- Team 2: Groundwater contamination related topics.
- Team 3: Potential DOE response actions to include in the GCAP.

Each team developed a long list of preliminary recommendations. Preliminary recommendations were evaluated based on suitability to site conditions and implementability. Based on the evaluation, a short list of actionable recommendations was created. Each actionable recommendation was developed into a narrative that includes a long-form summary of the recommendation; how it may be implemented at the site; prerequisites and data gaps to address before implementation; and other considerations.

The primary recommendation from Team 1 was implementation of adaptive site management as a remedial management strategy. There was wide agreement amongst the collaboration participants that the site meets the Interstate Technology and Regulatory Council definition of a complex site, and therefore, adaptive site management is appropriate for navigating towards closure. Collaboration participants agreed that adaptive site management can and should be implemented immediately.

The primary recommendation from Team 2 was development of a numerical groundwater flow and transport model, to be initiated as soon as possible, to support selection of a compliance strategy. A large majority of collaboration participants, including the NRC, agreed that due to the complexity of the site, a numerical model would be needed to support GCAP development. A second high-priority recommendation from Team 2 was to perform additional site characterization in the near-term to support numerical model development. Narratives developed by Team 2 provide a number of recommended site characterization technologies that support development of a numerical model and selection of a compliance strategy in the GCAP, such as transient aquifer monitoring; geochemical evaluations; isotope, tracer, and molecular biology tools; sediment/water interface measurements; borehole and geophysical assessments; and soil gas surveys. The participants recommended a relatively large number of near-term characterization tools, many of which provide scoping information to assess alternative site conceptual model behaviors. Due to the size of the site characterization scope recommended by Team 2, it was recommended to establish a new position for a technology portfolio manager to oversee scope development, schedule, data collection, and reporting for GCAP-related site characterization activities. This “enhanced baseline” strategy would focus on synergy between the actions, reduce logistical challenges, minimize redundancies, and generally facilitate efficient and effective implementation of the various actions.

Team 3 provided a portfolio of response actions that may be implemented in sequence or in parallel across multiple spatial zones to achieve the site objectives. Due to the complexity of site conditions, a single response action is unlikely to effectively achieve the cleanup goals. The response actions developed by Team 3 serve as a menu of technologies for consideration by the site with application to meet medium-term and long-term cleanup objectives. These technologies were not prioritized or sequenced because additional site characterization activities (Team 2 recommendations) are needed before remedial alternatives can be evaluated.

Prioritization and sequencing of the actionable recommendations were developed with the goal of receiving NRC concurrence on the GCAP by the target date and assuming that surface remediation at the site would be completed by 2028. Recommended near-term actions include incorporation of adaptive site management into remedial management of the site, development of a numerical groundwater flow model, and several site characterization activities, including field pilot testing of recommended technologies to evaluate their effectiveness under site conditions.

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Acronyms and Abbreviations

2D	two-dimensional
3D	three-dimensional
ACL	alternate concentration limit
bgs	below ground surface
CFR	Code of Federal Regulations
COC	contaminant of concern
COPC	contaminant of potential concern
CSM	conceptual site model
DOE	United States Department of Energy
EIS	Environmental Impact Statement
EM	Office of Environmental Management
EMI	electromagnetic induction
EPA	United States Environmental Protection Agency
FO-DTS	fiber-optic distributed temperature sensing
FWS	Fish and Wildlife Service
GCAP	Groundwater Compliance Action Plan
Geosyntec	Geosyntec Consultants, Inc.
IA	interim action
ITRC	Interstate Technology and Regulatory Council
LM	Office of Legacy Management
LMS	Legacy Management Support
MCL	maximum contaminant level
NNLEMS	Network of National Laboratories for Environmental Management and Stewardship
NRC Standard Review Plan	*Standard Review Plan for the Review of DOE Plans for Achieving Regulatory Compliance at Sites with Contaminated Ground Water Under Title I of the Uranium Mill Tailings Radiation Control Act*
NRC	Nuclear Regulatory Commission
North Wind	North Wind Portage, Inc.
PEIS	Programmatic Environmental Impact Statement
ROD	Record of Decision
SME	subject matter expert
SOWP	site observational work plan
SRNL	Savannah River National Laboratory
the site	Moab Uranium Mill Tailings Remedial Action Project Site
TIR	thermal infrared
UMTRA	uranium mill tailings remedial action
UMTRCA	Uranium Mill Tailings Radiation Control Act
VTPs	vertical temperature profiles

1. Introduction

The U.S. Department of Energy (DOE) Office of Environmental Management (EM) is responsible for surface remediation of the Moab Uranium Mill Tailings Remedial Action (UMTRA) Project Site (the site). Surface remediation consists of relocating tailings to the disposal cell at Crescent Junction, Utah, and may be completed as early as 2028. Upon completion of surface remediation, the site is planned for transfer to the DOE Office of Legacy Management (LM), which will be responsible for remediation of groundwater to achieve regulatory standards and closure. The 2005 Record of Decision (ROD) for the site specifies that DOE select and document a treatment technology in a Groundwater Compliance Action Plan (GCAP). Concurrence of the GCAP by the Nuclear Regulatory Commission (NRC) is required before the remedy can be implemented. In anticipation of transition of the site from EM to LM, DOE would like to receive NRC concurrence on the GCAP by a target date of 2025.

To advance the development of a defensible GCAP for the site, a collaboration was held between LM, EM, and the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS). This collaboration leveraged the knowledge and expertise of NNLEMS subject matter experts to address the challenges of groundwater remediation at the site, one of the most complex Uranium Mill Tailings Radiation Control Act (UMTRCA) sites in the nation. Actionable recommendations that support the development of a GCAP were generated by the collaboration participants. This report documents the collaboration and presents the actionable recommendations.

1.1 Objectives and Scope

Participants in the NNLEMS collaboration included EM, LM, North Wind Portage, Inc. (North Wind) (EM contractor for the site),[1] NNLEMS subject matter experts, RSI EnTech (LM contractor), Geosyntec Consultants, Inc. (Geosyntec) (North Wind subcontractor for the site), and NRC. Additional stakeholders were also invited as observers. The objectives of the collaboration were to

- evaluate site information and consider information gaps and factors that directly contribute to the site's approach to development of a defensible GCAP; and
- identify needs and develop actionable recommendations for acquiring data and closing data gaps for approaches to effectively and efficiently prepare a GCAP.

The primary charge of the collaboration was to generate actionable recommendations that advance the development of a defensible GCAP. Recommendations are considered actionable if they are 1) detailed enough to be implemented quickly and efficiently if EM decides to proceed, and 2) designed to achieve the GCAP requirements of NUREG-1724 (NRC, 2000). Actionable recommendations include management and mitigation strategies that provide opportunities for (or that are compatible with) a beneficial end state, effectively control risks, and meet regulator and stakeholder requirements/needs/expectations.

1.2 Collaboration Process

The NNLEMS collaboration process for the site is summarized as follows:

[1] And S&K Logistics Services, the former EM contractor, at the beginning of the collaboration.

- A two-day virtual kickoff meeting was held on September 13 and 14, 2022, to orient participants to the site history, conceptual site model (CSM), regulatory framework, and collaboration objectives and to brainstorm preliminary recommendations.
- Three teams of working group members were created to address focused topics of importance to DOE, regulators, and stakeholders and to highlight some of the key challenges that limit efficient and effective management/mitigation of risks at the site following relocation of tailings and wastes. Working group members (NNLEMS subject matter experts [SMEs], Legacy Management Support [LMS], North Wind, and Geosyntec) were assigned to each team based on their interests and areas of expertise. A team leader was responsible for coordinating with members and leading the effort to generate recommendations. The three working group teams were:
  - Team 1: GCAP development status, requirements, and path forward.
  - Team 2: Groundwater contamination related topics.
  - Team 3: Potential DOE response actions to include in the GCAP.
- Five virtual team meetings were held during the weeks of October 3, October 17, October 24, November 7, and November 28, 2022. Each team convened individually to generate actionable recommendations. The process consisted of:
  - Generating a long list of preliminary recommendations.
  - Generating a "pitch sheet" for each preliminary recommendation that summarized the recommendation, including the objective, a description, how the recommendation matched to the site conditions, implementability, implementation time frame, and inter-relationships with other technologies.
  - Reviewing the pitch sheets and down-selecting recommendations for a short list of actionable recommendations.
  - Generating a long form "narrative" for each actionable recommendation on the short list that expanded upon the summary provided in the pitch sheet.
  - Identifying priority recommendations.
- Seven virtual full-team (moderated) meetings to report progress and facilitate discussion amongst the teams were held on September 20, September 27, October 11, November 1, November 15, December 6, and December 20, 2022.
- An implementation timeline was developed for the actionable recommendations.

The organizations invited to participate included the following:

- EM
- LM
- North Wind (EM contractor for the site)[2]
- RSI EnTech, an LM contractor (LMS)

[2] And S&K Logistics Services, the former EM contractor, at the beginning of the collaboration.

- NNLEMS:
  - Savannah River National Laboratory (SRNL)
  - Pacific Northwest National Laboratory
  - Sandia National Laboratories
  - Lawrence Livermore National Laboratory
  - Lawrence Berkeley National Laboratory
  - Los Alamos National Laboratory
- Geosyntec (as participant and moderator)
- NRC
- Utah Division of Forestry, Fire and State Lands (as an observer)
- Utah Division of Water Quality (as an observer)
- Grand County (as an observer)

Individual names and affiliations of those invited are noted on the meeting agendas included in Appendix A. This multiorganizational collaboration covered a broad range of topics and brought many voices together to formulate the recommendations that are detailed in this report. At the end of the team meetings, recommendations and associated narratives developed by each team were compiled by SRNL and Geosyntec. Recommendations are summarized in Section 3.

2. Site Background

2.1 Site History

The DOE Moab UMTRA project site is a former uranium ore-processing facility approximately 3 miles northwest of the city of Moab in Grand County, Utah, adjacent to the Colorado River (Figure 1). Throughout the lifetime of the facility, an estimated 16 million tons of uranium mill tailings accumulated in an unlined impoundment (pile) in the floodplain of the Colorado River, which resulted in contamination of groundwater (Figure 2) (DOE, 2020). Groundwater contamination also resulted from mill site operations to the northeast of the tailings pile (DOE, 2012a). An interim cover was placed on the tailings pile as part of decommissioning activities between 1988 and 1995. In 2001, the title of the property and responsibility for remediation of the tailings pile and contaminated groundwater beneath the site were transferred to DOE, and in April 2009, DOE began relocating the tailings to the disposal cell at Crescent Junction, Utah. Surface remediation is ongoing and may be complete as early as 2028.

The 2005 Record of Decision (ROD) identified ammonium as the primary contaminant of concern (COC) in groundwater and surface water and manganese, copper, sulfate, and uranium as contaminants of potential concern (COPCs) (DOE, 2005b). Additional COPCs include selenium and arsenic. Over time, contaminants migrated in groundwater downgradient of the former tailings pile and are discharging into the Colorado River. The Final Environmental Impact Statement (EIS) included a Biological Assessment and a Fish and Wildlife Service (FWS) Biological Opinion that identified the floodplain and Colorado River segment adjacent to the site as critical habitat for endangered fish species (DOE, 2005a). The Biological Opinion is based on DOE's commitment to conduct active remediation. To limit ecological risk from contaminated groundwater discharging to critical habitat areas along the Colorado River, the 2005 ROD prescribed interim actions (IAs), which currently include groundwater extraction, freshwater injection, and surface water diversion (DOE, 2005b). The Biological Opinion requires biota and surface water monitoring to ensure the effectiveness of the IAs (DOE, 2005a).

2.2 Conceptual Site Model Summary

The site is bordered on the north and southwest by steep sandstone cliffs. Surface water features include the Colorado River, which forms the southeastern boundary of the site, and Moab Wash, an ephemeral stream that runs northwest to southeast through the center of the site and joins with the Colorado River. A conceptualized cross section of the site is shown in Figure 3. The site is located along the Moab Fault, which roughly follows Moab Wash northwest towards Moab Canyon. Site lithology consists of a surface layer of overbank deposits (0 to 20 feet below ground surface [bgs]) composed of silty sand, sand, and clays that is underlain by valley fill composed of sandy gravel to approximately 400 feet bgs. Groundwater is encountered at approximately 15 feet bgs. Groundwater typically flows towards the southeast during river base flow conditions (river gaining conditions) and reverses direction near the riverbank during spring runoff (river losing conditions). Freshwater in the unconfined alluvial aquifer is underlain by a brine zone that varies seasonally in elevation but is often encountered at approximately 55 feet bgs (DOE, 2003).

The tailings pile, the former ore storage area and former mill site facilities serve(d) as sources of ammonia and/or uranium to soil and groundwater at the site. The tailings pile, located in the western portion of the site, is a primary source of ammonia to soil and groundwater. Seepage of liquids within the tailings led to ammonia- and uranium-contaminated groundwater and soil beneath the tailings, some of which is present in the deep brine zone (DOE, 2003). The former ore storage area in the northeast corner of the site serve(d) as a primary source of uranium to soil and groundwater. During operation of the mill site, a large volume of debris associated with milling operations was transferred to an area between the former mill and the Colorado River and disposed of in a number of unlined pits (DOE, 2012a). Elevated concentrations of uranium are present in groundwater and soil within this area and the former milling facility, referred to as the northeastern uranium plume. The northeastern uranium plume is comingled with the uranium plume associated with the tailings pile. Ammonia is not a component of the northeastern uranium plume.

Transport of ammonium and uranium in groundwater is retarded by sorption and cation exchange onto aquifer solids (DOE, 2003). As upgradient groundwater flushes through the site towards the Colorado River, solid-associated ammonium and uranium are mobilized as the aquifer solids equilibrate with groundwater. Thus, impacted soils in the vadose and saturated zones act as long-term sources of ammonium and uranium to groundwater. In the absence of active remediation, ammonium- and uranium-impacted groundwater eventually discharges to the Colorado River, leading to exceedances of surface water quality standards.

A detailed CSM is presented in the 2003 Site Observational Work Plan (SOWP) (DOE, 2003). Additional site characterization activities have been performed since 2003, including investigations of the brine zone (DOE, 2002) and northeastern uranium plume (DOE, 2012a). The CSM was used to develop a groundwater flow model for the site (DOE, 2012b). Future numerical modeling efforts will need to incorporate data collected since 2011 and additional site characterization data to address data gaps in the CSM. Outstanding data gaps include the mass and distribution of secondary contaminant sources (solid-associated ammonium and uranium); the mass and distribution of contaminants within the deeper brine zone; the mass flux of contaminants between the freshwater and brine zones, the effect of high ionic strength groundwater on contaminant mobility, especially in the freshwater-brine transition zone; groundwater flow paths within the brine zone; and the remedial time frames (Geosyntec, 2021).

2.3 Current Groundwater Compliance Strategy

DOE began operating an IA groundwater system in 2003 to limit ecological risk from contaminated groundwater discharging to potential endangered fish habitat areas along the Colorado River. The objectives of the IA system are to 1) remove contaminant mass through groundwater extraction, 2) reduce the discharge of ammonium-contaminated groundwater to side channels of the river that may be suitable habitat for endangered aquatic species, and 3) provide performance data to select and design a final groundwater remedy. The interim action groundwater system consists of three primary components:

- Groundwater extraction wells remove contaminant mass from the aquifer and limit the mass of contaminants discharging to the Colorado River. Currently, eight groundwater extraction wells are located between the tailings pile and the river. Extracted groundwater is used for dust suppression atop the tailings.
- Freshwater injection wells create a hydraulic barrier that reduces discharge of contaminated groundwater to habitat areas along the river. Additionally, contaminants are diluted prior to discharge into the river. Currently, 10 freshwater extraction wells are used to inject filtered river water between the groundwater extraction wells and the river.

- Surface water diversion is used when suitable habits develop along the river for endangered young-of-year fish. The surface water diversion system delivers freshwater to necessary areas along the river to reduce ammonium concentrations below surface water standards.

Annual Groundwater Program Reports (e.g., DOE, 2022) demonstrate that, when operational, the IA system functions as designed to remove contaminant mass from the aquifer and maintain surface water ammonium concentrations within critical habitat areas below regulatory standards. Because disposition of extracted groundwater relies on the presence and future removal of tailings (extracted groundwater is applied to the tailings for dust suppression), reconfiguration or discontinuation of the IA system will be necessary once tailings removal is complete.

2.4 GCAP Background and Current Status

The 2005 ROD states that "final selection of a treatment technology will be documented in the GCAP that will be developed after the Remedial Action Plan" (DOE, 2005b). The GCAP will present remedial action alternatives, remedial action selection, the implementation plan for the remedial design and remedial action, the compliance strategy for groundwater protection, and the groundwater monitoring plan. GCAP requirements are established in the following documents:

- Title 40 Code of Federal Regulations (CFR), Section 192 (40 CFR 192) (United States Environmental Protection Agency [EPA], 1995), which establishes groundwater concentration limits based on background water quality, maximum contaminant levels (MCLs), alternate concentration limits (ACLs), or supplemental standards.
- The *Final Programmatic Environmental Impact Statement for the Uranium Mill Tailings Remedial Action Ground Water Project* (PEIS) (DOE, 1996).
- The draft *Standard Review Plan for the Review of DOE Plans for Achieving Regulatory Compliance at Sites with Contaminated Ground Water Under Title I of the Uranium Mill Tailings Radiation Control Act* (NRC Standard Review Plan; NUREG-1724) (NRC, 2000), which provides requirements for NRC's review of the GCAP.

40 CFR 192 states that compliance is to be achieved in the "upper aquifer," which remains to be defined for the site. The PEIS prescribes a decision framework for selection of a groundwater compliance strategy. If groundwater contamination is present, the PEIS decision framework is followed to select one of the following compliance strategies: no remediation; no remediation with application of supplemental standards; no remediation with application of ACLs; natural flushing; natural flushing with active remediation; active remediation; or technical impracticability (DOE, 1996). If the compliance strategy used to achieve the groundwater standards includes natural flushing (in full or in part), groundwater cleanup must be accomplished within 100 years (40 CFR 192.12). The NRC Standard Review Plan specifies the use of groundwater flow and transport models for evaluating the effectiveness of natural flushing. The preferred alternative selected in the 2005 ROD is application of supplemental standards and implementation of active remediation until long-term goals are achieved (DOE, 2005b).

Surface remediation at the site is expected to be completed by 2028, at which time responsibility for the site is planned for transition from EM to LM. An approved GCAP is targeted before the transition of the site to LM. Several tasks need to be conducted prior to or during preparation of the GCAP, including potential additional site characterization, establishment of groundwater standards, identification of remedial alternatives and cost comparisons, prediction of remedial timeframe, and source soil mass analysis.

A secondary source evaluation is planned for early 2023 to evaluate the longevity of impacted soil as a long-term secondary source of uranium and ammonium to groundwater. The secondary source evaluation is currently scoped to include soil and groundwater collection and sampling; column flushing tests to identify the duration of flushing needed to achieve groundwater standards; chemical extractions of site soil to quantify and evaluate the mobility of solid-phase uranium; and batch incubations to evaluate whether biological ammonium oxidation (nitrification) is occurring in groundwater.

3. Actionable Recommendations and Considerations

The primary outcome of the NNLEMS collaboration was a set of actionable recommendations that advance the development of a defensible GCAP. This section presents the actionable recommendations developed by each working group team. The three working group teams were

- Team 1: GCAP development status, requirements, and path forward (Section 3.1);
- Team 2: Groundwater contamination related topics (Section 3.2); and
- Team 3: Potential DOE response actions to include in the GCAP (Section 3.3).

The focus area and objectives of each team are described in the respective sections below. Additionally, the collaboration as a whole considered the following topics:

- Summarizing the strategic framework for understanding spatial and temporal conditions, key zones, zone interfaces, and mass transfer
- Evaluation of options for natural attenuation, flushing, risk assessment and mitigation, supplemental standards, alternate concentrations limits, and related strategies
- Evaluation of end state alternatives, focusing on path toward sustainable, passive, long-term management strategies that limit risk

The primary and highest priority recommendations were 1) implementation of adaptive site management as a remedial strategy; 2) development of a numerical groundwater flow and transport model; and 3) performing additional site characterization to refine the CSM and support development of the GCAP. These recommendations were identified as crucial to development of a defensible GCAP that can address the unique challenges of the site. Implementation of these recommendations is strongly encouraged to commence in 2023. Prioritization and suggested sequencing of the recommendations developed during the collaboration are discussed in Section 4.

Additional details on each preliminary recommendation (the long list) are included in Appendix B. Narratives for each selected actionable recommendation (the short list) are included in Appendix C.

3.1 Team 1: GCAP Development, Requirements, and Path Forward

Team 1 focused on identifying and developing actionable recommendations and considerations related to advancing the development of the GCAP, ensuring the GCAP meets regulatory requirements, and the path forward towards implementing the GCAP. Team 1 focused specifically on the following topics:

- Development of a common understanding of GCAP requirements (i.e., what is sufficient and necessary to meet the requirements of NUREG-1724 [NRC, 2000] and other regulatory guidelines)
- Assessment of the CSM, focusing on recommendations to advance existing progress and take advantage of affirmation opportunities where appropriate

NNLEMS review is also available as a final check on completeness before documents are forwarded for NRC review.

The following sections summarize the development and evaluation of preliminary recommendations (long list) and the actionable recommendations (short list) developed by Team 1.

3.1.1 Development and Evaluation of Preliminary Recommendations

The long list of preliminary recommendations generated by Team 1 and the decision on whether to retain each recommendation for the short list is summarized in the table below.

Preliminary Recommendation	Retained for Short List?
Adaptive site management	Yes
Biotic ligand models for copper and selenium	No—Could be considered in the future by the Moab team as they finalize ecological toxicity (ecotox) targets

Appendix B provides additional details on each preliminary recommendation, including the objective; a description; whether the recommendation is well-suited to conditions at the site; the level of implementability; the implementation time frame; possible inter-relationships with other recommendations; and the decision on whether to include each item on the short list.

Actionable, short-listed recommendations identified by Team 1 are summarized in the following section.

3.1.2 Summary of Actionable Recommendation

The preliminary recommendation to incorporate adaptive site management into the remedial management strategy for the site was retained for the short list and developed into an actionable recommendation. A narrative was developed, which includes the objective; a description; graphics that illustrate key points of the recommendation; whether the recommendation is well-suited to conditions at the site; the level of implementability; exemplars that represent successful implementation of the recommendation; key references to support the recommendation; possible inter-relationships with other recommendations; suggested sequencing of the recommendations, including prerequisites and data gaps/needs; the time frame of implementation; and the consensus of the working group. The narrative for adaptive site management is included in Appendix C.

The following section summarizes the actionable recommendation generated by Team 1 to help advance the site toward approval of a GCAP and closure.

3.1.2.1 Adaptive Site Management

Adaptive site management was recommended to be incorporated into the remedial management strategy at the site. Adaptive site management is a comprehensive, flexible, and iterative process of remediation management that is well-suited for complex sites, where there is significant uncertainty in remedy performance predictions (Figure 4) (Interstate Technology and Regulatory Council [ITRC], 2017). Adaptive site management includes periodically evaluating and, if needed, adjusting the remedial approach, which may involve multiple technologies at any one time and changes in technologies over time, to achieve interim and site objectives. A typical interim objective is achieving a specified reduction in contaminant concentration or mass flux within a defined time period. A typical site objective (i.e., the end state of the site) is to restore groundwater to applicable regulatory standards (ITRC, 2017). Site remediation managers adapt or adjust the selected remedy over time in response to remedy performance to keep the remedy on track to meet interim objectives. The CSM is refined using information gained from remedy performance.

The complexity of the site conditions may be better addressed with adaptive site management than a single prescriptive remedy. While adaptive site management is not explicitly addressed by existing UMTRCA/NRC guidance and requirements, it is also not precluded. Adaptive site management could be implemented as an approach during GCAP development and incorporate options for remedy optimization as cleanup progresses.

Based on the conceptualization of the site, an eventual adaptive site management strategy will need to address several spatial zones—each having unique environmental risk management goals/objectives—and several target timeframes. A notional example of spatial zonation of the site that was developed by the working group to support an adaptive site management strategy is shown in Figure 5. This example zonation is used to spatially organize the other actionable recommendations and is referenced within the accompanying narratives.

Recommended path forward: Principles of adaptive site management could begin to be used by the site team immediately. The adaptive site management process should be considered for structuring the remedy in the GCAP.

3.2 Team 2: Groundwater Contamination-related Topics

Team 2 focused on identifying and developing actionable recommendations and considerations to address data gaps and needs related to characterization of the current state of groundwater contamination and forecasting its future evolution. Specifically, Team 2 focused on the following topics:

- Physical sampling and monitoring to better characterize subsurface geology, contaminant source area(s) above and below the water table, and the freshwater-brine interface;
- Flow and temperature-based sampling and monitoring to 1) quantify groundwater flow and potential transport interactions between the aquifer and the river, and 2) to document transient hydraulic signals in the system for use as a characterization tool;
- Geochemical sampling, monitoring, and tracers to 1) characterize uranium mobility and solid-phase partitioning in the freshwater and brine zones, and 2) better understand groundwater residence times and flow pathways throughout the system; and most importantly,
- Numerical modeling, including CSM refinement and data worth analyses, that is informed by historical data, new data and insights collected during future site characterization activities (above), and considerations for the effects of climate change.

The following sections summarize the development and evaluation of preliminary recommendations (long list) and the actionable recommendations (short list) developed by Team 2.

3.2.1 Development and Evaluation of Preliminary Recommendations

The long list of preliminary recommendations generated by Team 2 and the decision on whether to retain each recommendation for the short list is summarized in the table below.

Category	Preliminary Recommendation	Retained for Short List?
Numerical Model Development and Support	2D Cross-Sectional Scoping Assessment of Brine Interface Dynamics	Yes—Consider with other numerical modeling recommendations
	3D Numerical Model Considerations	Yes—Consider with other numerical modeling recommendations
	3D Visualization to Support Refinement of the CSM and Construction of Numerical Models	Yes—Consider with other numerical modeling recommendations
	Alternative Reduced Order Models to Project Flushing Time Frame	Yes—Consider with other numerical modeling recommendations
	Data Worth Analysis	Yes—Consider with other numerical modeling recommendations
	Conceptual Hydrologic Model	Yes—Consider with other numerical modeling recommendations
	Climate Change and Other Uncontrolled Factors	Yes
Physical Sampling, Monitoring, and Characterization	Borehole Logging	Yes—Consider with other borehole and geophysical survey methods
	Vertical or Angled Boreholes	Yes—Consider with other borehole and geophysical survey methods
	Geophysical Surveys for Mapping Brine	Yes—Consider with other borehole and geophysical survey methods
	Soil Gas Surveys to Refine Residual Source Area	Yes
Flow Sampling, Monitoring, Characterization	Distributed Temperature Sensing for Detection and Monitoring of Seepage, to Support Sampling and Real-Time Operations for In-Stream Dilution	Yes—Consider with other surface water-groundwater interface measurements
	Flux Chambers	Yes—Consider with other surface water-groundwater interface measurements
	Thermal Infrared Imaging for Detection and Monitoring of Seepage to Support Sampling and Real-Time Operations for In-Stream Dilution	Yes—Consider with other surface water-groundwater interface measurements
	Free Transient Signal Analysis	Yes
Geochemical Sampling, Monitoring, Characterization	Evaluation of Geochemical Processes at the Brine-Freshwater Transition Zone	Yes—Consider with other geochemical evaluation recommendations
	Evaluation of Solid-Phase Uranium Speciation	Yes—Consider with other geochemical evaluation recommendations
	Focused Evaluation of Brine Impacts to Uranium Geochemistry and Mineral Solubility	Yes—Consider with other geochemical evaluation recommendations
	Isotope and Tracer Opportunities	Yes—Consider with other isotope and tracer recommendations
	Molecular Biology and Isotope Techniques to Evaluate Biological Ammonium Degradation (Nitrification)	Yes—Consider with other isotope and tracer recommendations

Notes: 2D - two-dimensional; 3D - three-dimensional

All of the preliminary recommendations generated by Team 2 were either developed into actionable recommendations or combined with other preliminary recommendations to form an actionable recommendation related to a specific focus area (e.g., numerical modeling). Although all of the preliminary recommendations were developed into actionable recommendations in some form, not all of the preliminary recommendations are regarded as high-priority, near-term items. Priorities and sequencing of the actionable recommendations developed by Team 2 are discussed in Section 4.2.

Appendix B provides additional details on each preliminary recommendation, including the objective; a description; whether the recommendation is well-suited to conditions at the site; the level of implementability; the implementation time frame; possible inter-relationships with other recommendations; and the decision on whether to include each item on the short list.

3.2.2 Summary of Actionable Recommendations

From the list of preliminary recommendations generated by Team 2, nine actionable recommendations rooted in the above categories were developed:

- Numerical Model Development
- Alternative Reduced-Order Models
- Transient Aquifer Monitoring
- Geochemical Evaluation of Mineral Solids and Uranium Geochemistry
- Isotope, Tracer, and Molecular Biology Tools
- Sediment/Water Interface Measurements
- Borehole and Geophysical Assessments
- Soil Gas Surveys to Refine Residual Source Areas
- Climate Change and Other Uncontrolled Factors

The highest priority recommendation is development of a numerical groundwater flow and transport model. Prioritization of the remaining Team 2 recommendations should be viewed through the lens of numerical model development, remedial alternatives comparison, and remedy selection. Selection and implementation of the characterization portfolio should address key uncertainties associated with each of the framework spatial zones identified to support adaptive site management and the interfaces between the spatial zones. For example, for the residual contamination in the deep subsurface brine zone, the primary focus could be 1) on whether the contamination is migrating or staying in place and 2) quantifying future predictions on the source mass flux away from the brine zone to the more active overlying aquifer zone. Team 2 affirmed the secondary source evaluation that is planned for 2023. Expansion of the secondary source evaluation to include additional Team 2 recommendations (e.g., geochemical evaluation of mineral solids and uranium geochemistry; isotope, tracer, and molecular biology tools; borehole and geophysical assessments) is recommended. Sequencing of the Team 2 recommendations is discussed in Section 4.2.

Due to the size and diversity of the site characterization scope recommended by Team 2, the NNLEMS endorses consideration of a new position for a Moab technology portfolio manager – this person could efficiently oversee scope development, schedule, data collection, and reporting for GCAP-related site characterization activities. If implemented, this role could be established under DOE as part of the site team or subcontracted through the site team. The NNLEMS recommends a plus-up in funding for this position be included in the site budget until GCAP concurrence is attained.

A narrative was developed for each actionable recommendation, which includes the objective; a description; graphics that illustrate key points of the recommendation; whether the recommendation is well-suited to conditions at the site; the level of implementability; exemplars that represent successful implementation of the recommendation; key references to support the recommendation; possible inter-relationships with other recommendations; suggested sequencing of the recommendations, including prerequisites and data gaps/needs; the time frame of implementation; and the consensus of the working group. Narratives for each actionable recommendation are included in Appendix C.

Actionable recommendations generated by Team 2 to help advance the site toward approval of a GCAP and closure are summarized below.

3.2.2.1 Numerical Model Development

Team 2 recommended configuring and calibrating an updated 3D numerical groundwater flow and contaminant transport model for the site and using it to forecast contaminant plume evolution and evaluate the efficacy of potential compliance or remedial strategies. Example forecasts of interest include remediation timeframes and future contaminant concentrations at points of compliance and points of exposure. Forecasts such as these are typically developed for several site management scenarios, including passive (e.g., natural flushing or alternate concentration limits) and active (e.g., groundwater extraction or amendment injection) compliance strategies. Developing appropriate forecasts requires application of mathematical models, which can be simple or complex. The development of an appropriate model will support the development of a defensible GCAP that is acceptable to regulators and stakeholders. The site has a long history of using numerical models to support site management decisions, and development of a comprehensive 3D numerical flow model for GCAP development is recommended. Use of models and platforms that simplify and integrate data input; uncertainty and parameter estimation; model construction; and data/model visualization are recommended as these tools support efficient and effective workflow.

The CSM is the starting point for a numerical model. The CSM describes processes controlling groundwater movement and contaminant migration at a site, and it highlights key site features that need to be represented in a numerical model to achieve project objectives. Misunderstandings in the CSM become misspecifications in the numerical model, potentially causing inaccurate forecasts that could lead to poor site management decisions. The site has a mature CSM, though it is noted that CSM development is an iterative activity and the CSM should be updated to incorporate new information as it becomes available. For example, the CSM should be updated to incorporate results of the 2023 secondary source evaluation and additional site characterization activities recommended by Team 2. Before initiating numerical modeling, the CSM should be reviewed and refined, as necessary. CSM review includes a thorough reevaluation of historical data, identification of data gaps, and refinement of the conceptualization as data gaps are addressed. This process can be aided by 3D visualization tools, such as Seequent's Leapfrog, which was recently used to perform geologic and plume modeling for the site.

The current CSM for the site emphasizes several complex processes that might control the distribution of contaminants. These processes are covered in more detail in the appended narrative (Appendix C), but include residual and secondary source contamination, the brine interface, seasonal fluctuations and influence of the Colorado River, various biogeochemical cycles, and aquifer heterogeneity. Determining the appropriate level of model complexity to represent these processes and features is a challenge. A model that is too complex becomes unmanageable because of lengthy run times, numerical instability, and difficult parameterization. On the other hand, oversimplified models will fail to reasonably represent important processes, resulting in unacceptable bias in model predictions. Development of data quality objectives (DQOs) is recommended to ensure that data generated during site characterization and modeling activities are adequate to support decisions (EPA, 2000). Preliminary modeling with uncertainty analysis can also help determine an appropriate level of complexity for a 3D numerical model. This preliminary modeling may include development of simple, focused models to improve understanding of specific aspects of the system and/or testing alternative configurations of the full 3D numerical model to gauge the sensitivity of model predictions to various simulated processes.

Similarly, a 2D cross-sectional model (or models) may improve understanding of several of the core processes identified in the narrative. Cross-sectional models are relatively straightforward to set up and have been applied previously at Moab (e.g., in the SOWP) (DOE, 2003). These models could assist with adequately representing the freshwater-brine interface in a subsequent 3D numerical model. If this sort of preliminary modeling is preformed prior to additional data collection at the site, a preliminary version of the 3D numerical model could be used for data worth analysis. This analysis approximates the reduction in predictive uncertainty that can be achieved by incorporating additional new data into the model and can be performed before new data is collected and before the model is calibrated; it helps to focus efforts collecting data that will be most informative for making key site management decisions, improving efficiency of efforts to reduce risk.

The narrative provides a discussion of the available modeling codes/tools available to Moab and considerations regarding the need for specific functionality (e.g., density-dependent flow treatment, geochemical reaction simulation, and visualization), costs, and implementability.

Recommendation for path forward: Identify numerical modeling software that is suitable for the site, considering that LM will eventually inherit the model and continue developing it. Develop data quality objectives for numerical modeling. Develop an updated groundwater flow model that incorporates the results of additional site characterization (other Team 2 recommendations). Develop the numerical groundwater flow model while additional site characterization data to support a transport model is collected.

3.2.2.2 Alternative Reduced Order Models

Team 2 recommended the development of reduced order models as a useful adjunct to more complex numerical models. These models can assist in stakeholder communication because they are simpler and more straightforward to describe. For example, when projecting contaminant flushing, many reduced order models mimic first-order exponential decay. However, models that exhibit more pronounced "tailing" (e.g., due to mass transfer limitations and slow release from residual or secondary sources) will not be accurately represented by this function. More recent projections of these timeframes have been modeled using stretched exponential and power functions that more closely match the observed "tailing." The processes affecting groundwater flushing and remedy performance are numerous, complicated, and interacting. Comprehensively modeling these systems is challenging, but recent studies and implementation have indicated that these exponential and power functions provide improved modeling performance while remaining relatively accessible for stakeholders. The narrative for this topic includes a comparison of these reduced order modeling approaches for a groundwater pump and treat system at the DOE Savannah River Site. A similar approach could be implemented with relatively minimal effort for Moab.

Recommendation for path forward: Alternative reduced-order numerical models should be considered for evaluating the feasibility of natural flushing using the secondary source investigation column studies anticipated in 2023.

3.2.2.3 Transient Aquifer Monitoring

Continued and improved collection of high-frequency (e.g., hourly or more frequent) groundwater parameter data was recommended at the site as a means to better characterize and understand the overall groundwater behavior in the system. Specifically, significant transient reversals, largely driven by river stage, exist in the shallow groundwater regime at Moab. Infiltration of river water into the shallow aquifer can be measured by tracking changes in temperature, salinity, dissolved oxygen, pH, and other parameters. Performing high-frequency monitoring of such parameters at locations across the site may aid in constraining and calibrating site numerical models (both traditional time-domain disturbed models and reduced-order frequency domain models).

The recommended approach for monitoring does not require the implementation of new technologies, but rather the focused observation, comparison, and analysis of groundwater and river hydraulic data (e.g., from United States Geologic Survey sensors). Data that are not already being collected should start being collected as soon as possible to ensure sufficiently large datasets that capture variability on the scale of years. Details of the proposed data analysis approaches and linkage to groundwater models are described further in the narrative, along with references to studies on which Moab may draw upon.

Recommendation for path forward: Installation of transducers that collect groundwater elevation and conductivity data (at a minimum) should be deployed in existing groundwater monitoring wells as soon as possible to maximize the duration of the dataset for calibration of the numerical groundwater flow model and refinement of the CSM.

3.2.2.4 Geochemical Evaluation of Mineral Solids and Uranium Geochemistry

Team 2 recommended additional efforts to characterize uranium speciation and geochemistry as it pertains to solid-associated uranium, which may serve as a secondary source of uranium to groundwater after the surface tailings removal is complete. Solid-phase uranium in the former mill site area is also expected to serve as a long-term source of uranium to the northeast uranium plume. It is expected that only a fraction of the solid-associated uranium could be mobilized from the vadose zone, freshwater saturated zone, and freshwater-brine transition zone as some species are more recalcitrant. However, a quantitative understanding of the various geochemical processes involved is necessary to design an effective remedy and predict the remedial time frame under different scenarios. While all three of the aforementioned environments are important at the site, the team noted the freshwater-brine transition zone as a particular geochemical data gap. The freshwater-brine transition zone can comprise a significant volume in the subsurface since it shifts significantly with the river stage.

To better understand uranium mobility at the site, it was recommended that equilibrium geochemical modeling be performed to assess aqueous complexation and partitioning between dissolved and solid phases (e.g., sorption, precipitation) and how these processes are influenced by ionic strength. While these models incorporate assumptions (i.e., that the system is at equilibrium) and should not be used for making remedial decisions alone, they would provide an estimate of geochemical conditions and elucidate processes governing uranium stability at the site. It was also recommended that the site undertake characterization of the solid-phase uranium present at the site. The degree to which solid-phase uranium may be remobilized to groundwater is determined, in part, by its solid-phase speciation (e.g., adsorbed, precipitated, co-precipitated). Sampling of soil and aquifer material followed by advanced analytical techniques that can quantify the redox state of solid materials (e.g., x-ray adsorption spectroscopy and x-ray photoelectron spectroscopy) would be valuable. Further, the team recommends sequential extractions, batch and/or column testing be performed using site materials to assess the mobility of solid-associated uranium in a laboratory setting under various conditions (e.g., a high ionic strength brine alternating with freshwater). Sequential solid-phase extractions and column flushing tests using site soil and groundwater are planned for 2023 as part of the secondary source investigation. Extractions and column testing have been employed at DOE's Monticello Mill Tailings Site, among others, with success, and those efforts may serve as a guide for Moab. Additional details regarding proposed extraction sequences, analytical approaches, and equilibrium geochemical modeling are included in the narrative.

Recommendation for path forward: Geochemical equilibrium modeling should proceed in the near-term to evaluate the effects of high ionic strength groundwater on uranium mobility. If results of the geochemical modeling indicate that uranium mobility is impacted by changes in ionic strength (i.e., fluctuations in the depth of the freshwater-brine interface), then laboratory studies included in the upcoming secondary source evaluation should be expanded to evaluate these processes further.

3.2.2.5 Isotope, Tracer, and Molecular Biology Tools

The team recommended assessing the potential for using natural and anthropogenic tracers (stable isotopes and radionuclides), age dating tools, and molecular biological tools at the site. These tools could be used to refine and enhance the CSM, numerical flow models, and enhance understanding of microbial ecology as it pertains to ammonium attenuation.

Intrinsic (naturally occurring) tracers can be used to date and trace young waters, which may help elucidate the interactions between brine zones and overlying freshwater layers at Moab. The most promising young water tracers may be those that most closely track with the water molecule (i.e., radioactive tritium and stable isotopes of hydrogen and oxygen). Short synopses of how these tracers record the influence of processes (e.g., evaporation) are presented in the narrative. Anthropogenic tracers, such as chlorofluorocarbons, may also be useful at the site. Sampling for these tracers could be incorporated into routine groundwater monitoring at the site.

On the microbiological side, various tools are available to identify and quantify the subsurface microbial community and ecology. Analyses that quantify the presence of certain genes that encode enzymes involved in nitrogen cycling may be useful for Moab. These sorts of analyses would provide confirmatory lines of evidence that ammonium transformation (i.e., degradation) pathways are active at the site, with measurements of stable isotopes of nitrogen and oxygen in various nitrogen species (e.g. nitrate, nitrite) providing additional insight into the specific nitrogen transformation pathways present (e.g. nitrification, denitrification). Laboratory, bench-scale experiments could also be coupled to these analytical techniques to assess the kinetics of ammonium degradation and confirmation of which microbial pathways are most likely to occur in site groundwater, with rates then included in the groundwater model. Batch reactor tests with site groundwater to evaluate microbial ammonium oxidation (nitrification) are already planned for 2023 as part of the secondary source investigation. Further discussion of these tools is provided in the narrative, along with some suggestions for mitigating challenges that may arise from performing microbial analyses on radionuclide-bearing samples.

Recommendation for path forward: Laboratories that can perform isotope, tracer, and molecular biology analyses and can accept Moab groundwater samples should be identified in the near term. The upcoming secondary source evaluation could be expanded to include collection of additional groundwater samples for these analyses.

3.2.2.6 Sediment/Water Interface Measurements

Team 2 recommended characterization and monitoring at the sediment/water interface to support characterization of the temporal and spatial distribution of flux to the Colorado River. Surface water/aquifer interactions at the site are highly dynamic, with rapidly changing flux across the sediment/water interface. A number of technologies were recommended for consideration, including 1) flux chambers, 2) direct probes, 3) fiber optic distributed temperature sensing (FO-DTS), 4) thermal infrared imaging (TIR), and 5) vertical temperature profiles (VTPs). These technologies represent both direct (flux chambers and direct probes) and indirect (FO-DTS, TIR, VTPs) approaches to mapping and/or measuring flux.

Implementation of these technologies in combination would enable identification of the locations of focused discharge to the river in real time to operate the in-stream dilution system and mitigate contaminant impacts to aquatic biota. Additionally, measurements taken along the riverbed would indicate whether the brine zone is discharging directly into this river (the current CSM) or whether it is separated from the river by the freshwater zone. This has important implications for discharge of contaminants into the river and/or across the river to the Matheson Wetland Preserve.

Details regarding the implementability, advantages, and challenges of the specific technologies Team 2 recommended are included in the narrative included in Appendix C. References to example applications and detailed functionality are therein.

Recommendation for path forward: In 2023, a scoping field event should be performed to evaluate the feasibility of deploying sediment/water interface technologies in the Colorado River. If results of the field event indicate a likelihood of success, then a larger field event can be designed.

3.2.2.7 Borehole and Geophysical Assessments

New boreholes, borehole logging, and surface geophysical surveys have potential to improve the current understanding of groundwater contamination and subsurface conditions at the site. This information is critical to forecasting contaminant fate and transport and remedy performance. Implementation will reduce uncertainties associated with 1) contaminant distribution, 2) soil and aquifer properties and the hydrogeologic framework, and 3) brine distribution. Implementation will reduce risk drivers and support the GCAP.

Characterization approaches are divided into 1) installation of new boreholes, either vertical or angled, 2) borehole logging, and 3) geophysical surveys for subsurface salinity distribution. A range of technologies and methods are available for each of these approaches, and many are well established.

New boreholes would support geologic characterization of the subsurface, provide access for logging tools, and allow for cross-well hydraulic or geophysical testing. Vertical boreholes would be applicable widely across the site, and one or more angled borings could facilitate monitoring beneath the current tailings piles, while still present.

Borehole logging methods can be used to provide information on diverse physical and chemical parameters, which in turn provide insight into aquifer properties, water quality/chemistry, and geologic structure. Of particular relevance to characterization at Moab are electromagnetic induction, nuclear magnetic resonance, and borehole flowmeter. Respectively, these logging methods can be used to infer pore fluid salinity, estimate hydraulic conductivity, and, with some data analysis, estimate transmissivity and hydraulic heads of different aquifer layers.

Surface geophysical assessments are also relevant for characterizing groundwater salinity. Electromagnetic technologies include frequency- and time-domain tools suitable for both shallow (<30 feet) and deep (30-1,600 feet) target characterization depths, respectively. Electrical resistivity tomography is another method that may be useful for characterizing salinity and the brine interface. Pre-modeling is recommended prior to conducting these surveys to provide a basis for decision-making during active surveying and facilitate interpretation of results.

Recommendation for path forward: Borehole and geophysical assessments that utilize existing borings and monitoring wells and provide data to support numerical model development (e.g., electromagnetic induction to measure depth to the freshwater-brine interface) should be prioritized. Additional techniques could be deployed during the upcoming secondary source investigation when borings will be advanced to collect soil and groundwater.

3.2.2.8 Soil Gas Surveys to Refine Residual Source Areas

Team 2 recommended performing soil gas surveys (in the vadose zone above the water table), particularly for radon (a uranium decay daughter product) and ammonia (the deprotonated form of the ammonium ion), to help focus the deployment of source control technologies. Conducting a systematic survey for these gas-phase compounds could identify areas of residual contamination in the vadose zone or below the water table and geologic features, such as preferential flow pathways. For the compounds of interest at Moab, sampling could reasonably be conducted using simple field gas monitors without the need for laboratory analysis.

The use of radon (and radon daughter) signals as indicators of localized uranium source material has been documented. Testing for ammonia is somewhat more speculative, but given the large inventory of ammonium at the site and ease of field detection for ammonia gas, it is reasonable to consider this approach. This approach could have value in identifying the most significant source areas of residual ammonium contamination. Specific recommendations for the sampling grid, monitoring equipment, and other field considerations are included in the narrative for this topic.

Recommendation for path forward: A low-cost field pilot study to test the feasibility of this characterization approach is recommended in 2023. If results of the field study indicate that soil gas measurements can provide useful data to delineate secondary sources, then an expanded sampling event can be designed and performed in 2024.

3.2.2.9 Climate Change and Other Uncontrolled Factors

Broadly, it was recommended that climate change and other uncontrollable factors that may impact hydrologic processes at and near the site be considered in the quantitative design and prioritization of contaminant management or remediation strategies. Of particular importance are potential changes to flow rates and water quantities in the Colorado River, which have implications for the magnitude and directionality of annual groundwater flow reversals accompanying peak discharge and potential climate-driven decreases in peak discharge in the future. The rate of temperature increases in the Colorado River Basin has been larger than anywhere else in the lower contiguous United States. Generally, this has been associated with lower observed discharge since the year 2000, but climate change also has the potential to create a wider range of extreme events (e.g., heavy storms). Overall, the effects of climate change may lead to different ranges or magnitudes of processes than are observed today. Expected or predicted changes should be factored into remedial designs and strategies.

A list of some example processes and conditions that could be affected by climate change is included in the appended narrative. The team does not recommend the implementation of any specific technologies but does encourage 1) the development of an explicit list of quantitative characteristics pertinent to the site that could potentially be altered by climate change, 2) formulating processes for identifying where these factors enter into evolving contaminant evaluation and management strategies, 3) estimating potential changes in factors attributable to climate change and incorporating this information into design and prioritization of management or remediation strategies.

Recommendation for path forward: An explicit list of quantitative characteristics pertinent to the site that have the potential to be influenced by climate change and other uncontrollable factors should be developed. Climate change and other uncontrolled factors should be considered during development of the numerical model, particularly when estimating the remedial time frame under different scenarios.

3.3 Team 3: Potential DOE Response Actions to Include in the GCAP

Team 3 focused on identifying and developing a portfolio of potential response actions for inclusion in the GCAP. Team 3 focused specifically on the following topics:

- Feasibility of using low-cost, existing technologies that can be implemented in the short-term (e.g., biotreatment, evaporative ponds) to proactively address groundwater contamination at Moab and accelerate site closure while the GCAP is under development
- Field testing of active remedial technologies (commercially available and areas of active research), such as apatite-induced sequestration, biological or biogeochemical options, boundary condition modifications, and permeable reactive barriers
- Feasibility of passive and/or attenuation-based remedies
- End state opportunities/options including access, beneficial reuse, institutional controls, and mitigating risks

The following sections summarize the development and evaluation of preliminary recommendations (long list) and the actionable recommendations (short list) developed by Team 3.

3.3.1 Development and Evaluation of Preliminary Recommendations

The long list of preliminary recommendations generated by Team 3 and the decision on whether to retain each recommendation for the short list is summarized in the table below.

Preliminary Recommendation	Retained for Short List?
Natural and Enhanced Attenuation	Yes
Assess Response of System to Response Actions	No
Source Zone Clogging	Yes
Enhanced Flushing	No
Enhanced Pond Evaporation	No
Geophysical Monitoring to Assess Response of System to Response Actions	No
Groundwater Bypass	Yes
In Situ Hydroxyapatite Formation for Uranium Sequestration	Yes—Consider with other solid amendment recommendations
In Situ Struvite Precipitation for Sequestration of Ammonium	Yes—Consider with other solid amendment recommendations
Injection of Humate amendments for Uranium Sequestration	Yes—Consider with other solid amendment recommendations
Injection of Solid-Phase Amendments	Yes—Consider with other solid amendment recommendations
Limited Pump and Treat with Strategic Reinjection	Yes
Permeable Reactive Barrier Amendments	Yes—Consider with other solid amendment recommendations
Phytoevapotranspiration (Irrigation)	No
Reconfigure Channel of Moab Wash and/or Colorado River	Yes
Soil Blending and Deep Soil Mixing	Yes—Consider with other solid amendment recommendations
Green Surface Capping Over Areas of Residual Subsurface Sources	Yes

Enhanced pond evaporation and phytoevapotranspiration were not retained for the short list; however, the evaluation of these preliminary recommendations was documented and may be a useful resource in the future. Summaries of these preliminary recommendations are included in Appendix D.

Two additional actionable recommendations were added to the short list and developed into narratives:

- Amendments for in situ sequestration
- Deployment techniques for emplacing solid amendments

These narratives serve as a comprehensive review of technologies and as guidance for implementation of in situ sequestration.

Appendix B provides additional details on each preliminary recommendation, including the objective; a description; whether the recommendation is well-suited to conditions at the site; the level of implementability; the implementation time frame; possible inter-relationships with other recommendations; and the decision on whether to include each item on the short list.

Actionable recommendations identified by Team 3 are summarized in the following section.

3.3.2 Summary of Actionable Recommendations

Team 3 identified nine potential response actions that are recommended for consideration in the GCAP:

- Natural Attenuation
- Amendments for In Situ Sequestration
- Source Zone Clogging
- Solid Amendments for Treatment of Uranium and Ammonium
- Deployment Techniques for Emplacing Solid Amendments
- Groundwater Bypass and Hydrologic Controls
- Reconfigure Channel of Colorado River and/or Moab Wash
- Green Surface Capping Over Areas of Residual Subsurface Sources
- Interim Pump and Treat with Strategic Injection

Because additional site characterization is required for the GCAP and a numerical model to evaluate remedy scenarios has not yet been developed, recommendations for response actions cannot be made at this time. The actionable recommendations developed by Team 3 serve as a portfolio of response actions to achieve the short-term and medium-to-long-term remediation objectives of the site. The GCAP is required to present an evaluation of remedial alternatives; this portfolio provides options for those alternatives.

A narrative was developed for each actionable recommendation, which includes the objective; a description; graphics that illustrate key points of the recommendation; whether the recommendation is well-suited to conditions at the site; the level of implementability; exemplars that represent successful implementation of the recommendation; key references to support the recommendation; possible inter-relationships with other recommendations; suggested sequencing of the recommendations, including prerequisites and data gaps/needs; the time frame of implementation; and the consensus of the working group. Narratives for each actionable recommendation are included in Appendix C.

Actionable recommendations (response actions to consider) generated by Team 3 to help advance the site toward approval of a GCAP and closure are summarized below.

3.3.2.1 Natural and Enhanced Attenuation

Natural and enhanced attenuation should be considered as part of the groundwater remedy. These approaches would require an assessment to 1) supplement current efforts to provide technically defensible water and mass balances across the site, 2) refine the conceptualization of natural flushing and the time frame to achieve remedial objectives, and 3) structure the evaluation using multiple lines of evidence as described in EPA and ITRC guidance documents (EPA, 1999; 2007; 2010; and 2015; ITRC, 2010).

The conceptual model of natural attenuation as a mass balance between the loading (mass flux from residual contamination in the subsurface) and attenuation (e.g., sorption, biological transformation) of contaminants in the plume is a powerful framework for understanding, documenting, and managing monitored natural attenuation. EPA and ITRC guidelines encourage evaluation of attenuation based on multiple, tiered lines of evidence. These include

- documenting site-specific attenuation processes that reduce the quantity, toxicity, and/or mobility of contaminants;
- accounting for the full range of contaminant sources, the potential for mobilization, and the various mechanisms of attenuation; and
- providing data related to attenuation rates and capacity/sustainability for the identified attenuation process.

Assessment of attenuation processes would also provide insight about the degree to which natural processes retard the flushing of contaminants (due to sorption or matrix diffusion, or other non-destructive attenuation mechanisms). A better understanding of attenuation processes occurring at the site has the potential to improve the technical basis and defensibility of the projected natural flushing remedial time frame and development of potential enhanced attenuation strategies.

3.3.2.2 Amendments for In Situ Sequestration

The objective of in situ sequestration is to reduce ammonium and uranium solubility/mobility and limit the flux of these contaminants to the Colorado River. Injection of liquid amendments in the subsurface can be used to create a permeable reactive barrier that intercepts and removes these contaminants from groundwater through in situ precipitation and/or sequestration. Additionally, liquid amendments can be used to selectively isolate known or to-be-identified secondary sources zones, thereby limiting or greatly reducing their sustained and persistent contaminant loading to the aquifer system. This latter approach may be especially relevant to sources that could be identified during the planned 2023 secondary source zone characterization effort. Three approaches for in situ sequestration were developed as part of this narrative: 1) injection of calcium citrate and sodium phosphate to generate an in situ hydroxyapatite barrier to sequester uranium; 2) injection of reagents to induce the precipitation of struvite (an ammonium phosphate mineral); and 3) injection of a humate solution to form a coating on mineral surfaces which sequesters uranium and possibly ammonium. Approaches 1 and 2 may be combined due to the similar compositions of hydroxyapatite and struvite. Each approach is described in detail in the narrative included in Appendix C.

3.3.2.3 Source Zone Clogging

The objective of source zone clogging is to hydraulically isolate the residual contamination and reduce the source mass flux to the surrounding groundwater. This is a targeted technique that requires detailed knowledge of the source zone (depth, spatial extent, lithology, etc.). The technology would require characterization information that demonstrates reasonably small areas of high or significant residual contamination along with modeling that demonstrates that isolating or armoring the contamination would provide benefit to the adaptive site management and risk management for the site. Silica gel is the most common pore clogging material; however, innovative technologies such as heat and paraffin wax, polymers, and/or foams could also be considered. The target zone to support adaptive site management would be in the vadose zone and shallow groundwater in areas where residual and secondary sources are present.

3.3.2.4 Solid Amendments for Treatment of Uranium and Ammonium

Solid amendments can be added to the subsurface to decrease aqueous plume concentrations or source areas/hot spots in situ via geochemical sequestration mechanisms. Many solid-phase amendments target mobile uranium specifically through either sorption, reductive precipitation, or incorporation/co-precipitation into a solid phase (or a combination of various mechanisms). The narrative for this actionable recommendation includes a survey of solid-phase amendments for uranium and/or ammonium treatment (Appendix C). An understanding of mobile contaminant phases and aquifer biogeochemistry will be needed to identify which solid-phase amendment might be applicable to the site. Bench-scale and pilot testing would eventually be needed to evaluate the efficacy of the solid amendments under ex situ and in situ conditions.

3.3.2.5 Deployment Techniques for Emplacing Solid Amendments

A number of techniques and technologies for deployment of solid amendments for contaminant treatment were highlighted by Team 3. Given the conditions, the Team recommended two general techniques for Moab: 1) injection and 2) trenching/soil mixing. Injection techniques are generally recommended for deeper soils whereas trenching/soil mixing is generally recommended for shallower soils. Aggressive injection techniques that are generally utilized in low-permeability zones (e.g., fracturing or jetting) are not recommended for the site because deeper soils are characterized by high hydraulic conductivity. A number of factors, including particle size of the amendment, depth and volume of the treatment zone, and subsurface heterogeneity, will impact remedy design and implementation. Various considerations for implementation are discussed in further detail in the narrative (Appendix C). To address different areas at the site, a combination of different techniques may be most effective. The most suitable amendment composition and emplacement scheme should be evaluated in conjunction with each other and involve bench-scale testing followed by pilot-scale testing.

3.3.2.6 Groundwater Bypass and Hydrologic Controls

Team 3 recommended that the site consider supplementing, expanding, or modifying its implementation of hydrologic boundary controls to isolate contaminated groundwater. The ultimate goal of such a technology would be to limit contaminant flux to critical habitats (and receptors) in the Colorado River. The technology physically utilizes upgradient groundwater, treated groundwater, or upstream river water to alter hydrologic driving forces in the subsurface. Applications can either be active or passive in nature and can also be operated strategically depending on seasonal changes or periods of higher sensitivity/risk. Currently, an active strategy is being implemented using injection of upstream river water and groundwater extraction.

While a passive-only groundwater bypass system (i.e., “geosiphon”) may not be viable at Moab given the available head at the site, this could be further evaluated using the site model. Possible strategies for application of active bypass or boundary condition modification systems are recommended for consideration and would include augmentation or modification of the existing approach. If the site were divided into zones as part of an adaptive site management strategy, different targeted strategies may be reasonably implemented in different areas of the site. Overall, this technology represents a useful and readily implementable technology, with potential for a passive/semi-passive approach, that could sequester contaminant sources and limit mass flux to the Colorado River and adjacent habitats.

3.3.2.7 Reconfigure Channel of Colorado River and/or Moab Wash

Reconfiguration of the channel of the Colorado River and/or the Moab Wash was recommended by Team 3 to protect critical habitat from the efflux of contaminants from Moab groundwater. Potential deployment scenarios include a) restructuring the current channel/influents to provide spawning habitat during critical times of the year in areas that are unimpacted by the plume, or b) rerouting the river channel further from the site (restoring a more natural river course and abandoning the current "artificial" channel location that was engineered to bring water closer to the mill site). The site is currently planning to restore a natural braided stream character to the Moab Wash as part of post-mill site transition activities. Potential reconfiguration options for the Colorado River channel should be coupled with this already planned activity. Rerouting the river channel would require significant planning, time, and close coordination with regulators and the public. In the near term, information on erosion and deposition processes in the river, the location and dynamics of critical habitats, and protective criteria for these habitats, as well as how the influent water from the wash can interact to beneficially (or adversely) impact risks to the river, should be collected. In the medium and long term, inclusion of modeling scenarios that envision other types of river/wash reconfiguration and relocation are recommended.

3.3.2.8 Green Surface Capping Over Areas of Residual Subsurface Sources

Team 3 recommended the use of "green" surface capping over areas of residual subsurface sources to limit infiltration of precipitation and reduce mobilization of contaminants from the vadose zone to the water table. In this context, "green" materials are simultaneously non-toxic, mechanically strong, durable, ultraviolet and freeze-thaw resistant, and cost effective. In addition to limiting contaminant migration from the vadose zone, impermeable surfaces can serve as access roads that can support heavy equipment and/or withstand a range of weather conditions and uses during restoration construction activities. The objective of this recommendation is to utilize a cost-effective, green, accelerated lithification technology that is adaptively engineered and shaped from locally sourced soils and rock aggregates to form rock-hard materials on location. The geology and soils in the Moab area are well suited for this soil and aggregate accelerated lithification process. Laboratory testing will be needed to design the appropriate formulation to meet the needs of the site.

3.3.2.9 Interim Pump and Treat with Strategic Injection

Interim pump and treat with strategic injection was recommended as a limited mid-term option for controlling pumped groundwater following tailings relocation prior to long term sustainable (passive) management strategies. The goal of this approach is to limit efflux of ammonium, uranium, and other contaminants to the Colorado River and provide contaminant removal and groundwater concentration reduction while long-term passive solutions are being developed and implemented. A potential groundwater treatment train that focuses on separating ammonium from uranium, providing high quality water for beneficial uses, and minimizing secondary wastes is included in the narrative for this recommendation (Appendix C). Developing a pathway for the pumped water, minimizing secondary wastes, and integrating the pumping objectives into an overall GCAP plan for the site are keys to supporting interim pump and treat. In the near term, scoping activities are recommended, such as geochemical equilibrium modeling and bench-scale tests to evaluate scaling under relevant geochemical conditions (pH adjustment, heat). Additional treatability testing would be needed to evaluate contaminant removal processes. If this concept is selected by the site team for inclusion in the GCAP, next steps include project design and generating a procurement package for implementation.

4. Priorities and Sequencing of Actionable Recommendations

The highest priority recommendation of the collaboration was development of a numerical groundwater flow and transport model. Additional site characterization is also recommended to address outstanding data gaps in the CSM. A primary goal of the Moab UMTRA Site is to receive NRC concurrence on the site before the site is transitioned to LM. Because of the relatively short time frame for completion of site characterization activities that support GCAP development, strategic prioritization and sequencing of the actionable recommendations developed by each working group team is necessary.

This section describes the suggested timeline for implementation of the actionable recommendations described in Section 3. A Gannt chart summarizing the sequencing and timeline for implementation is presented in Figure 6.

4.1 Team 1: GCAP development, requirements, and path forward

Incorporation of adaptive site management into the remedial management strategy of the site is the highest priority recommendation of Team 1. There was unanimous concurrence amongst Team 1 and the other collaboration participants that the site meets the ITRC definition of a “complex site” (ITRC, 2017). Therefore, incorporation of adaptive site management into the GCAP was strongly supported by Team 1 as a best practice for achieving site closure in a reasonable time frame.

Adaptive site management is recommended for immediate implementation. Adaptive site management can and should be implemented immediately because it 1) provides a framework for sequencing the other actionable recommendations, 2) does not have prerequisites to implement, and 3) requires eventual buy-in from NRC for inclusion in the GCAP, which may take time to cultivate. Discussions with NRC to educate regulators about adaptive site management and convey why it is appropriate for the site are recommended from an early stage in the GCAP development process to maximize the likelihood of receiving NRC concurrence on the GCAP.

An assessment of natural and enhanced attenuation is also recommended for immediate implementation. Evaluating natural and enhanced attenuation early in the GCAP preparation process will identify data gaps and inform the sequencing of additional site characterization activities.

4.2 Team 2: Groundwater contamination-related topics

The highest priority recommendation of the collaboration is numerical model development. A large majority of collaboration participants, including NRC, agreed that development of a numerical groundwater flow and contaminant transport model is needed to support selection of a groundwater compliance strategy in the GCAP. In fact, the NRC Standard Review Plan requires the use of groundwater flow and transport models for evaluating the effectiveness of natural flushing (NRC, 2000). During Day 2 of the collaboration kickoff meeting, NRC expressed the expectation for development of a numerical model to support the GCAP.

Development of a numerical model is an iterative process that relates closely with the site characterization process (Figure 7). For example, numerical model development begins with refinement, documentation, and vetting of the CSM, which is based on site characterization data. Simultaneously, development of an alternative reduced-order model is recommended to identify data gaps that must be addressed before a full numerical model can be developed. In turn, these data gaps/needs will be addressed by additional site investigations, including other Team 2 recommendations. The model can also be used to prioritize and optimize additional site characterization efforts (data worth analysis). Development and calibration of a numerical groundwater flow model will be followed by development and calibration of a numerical transport model. A numerical groundwater flow model was developed in 2011 (DOE, 2012b), which can serve as a basis for development of an updated flow model that reflects a revised CSM based on the newly collected hydrogeological data. Upon completion of the groundwater flow model, a numerical transport model can be developed and calibrated using historical and newly collected site characterization data.

Under adaptive site management, the CSM is iteratively tested and, if needed, refined using remedy performance data (ITRC, 2017). Changes to the CSM should be propagated to the numerical model to ensure that remedial time frame predictions are based on the most up to date CSM. Thus, numerical groundwater modeling is also an iterative process involving refinement of the models to match the CSM (Figure 7). This process can be conceptualized using two models: a "GCAP Basis Model" and a "GCAP Adaptation Model." The GCAP Basis Model is used to provide a technical basis for "early" response actions, such as interim remedies that may be proposed between NRC concurrence of the GCAP and completion of surface remediation. During this time period, refinement of the CSM will lead to development of the GCAP Adaptation Model, which will provide a technical basis for "mid-to-late" response actions, such as response actions that are implemented after completion of surface remediation. The GCAP Adaptation Model would continue to be refined throughout the lifetime of the site using remedy performance data.

Prioritization of the remaining Team 2 recommendations should be viewed through the lens of numerical model development, remedial alternatives comparisons, and remedy selection. Sequencing of the remaining Team 2 recommendations should support numerical model development, which is recommended in the near term. That is, recommendations that support development of a groundwater flow model should be generally prioritized before recommendations that support development of a transport model. Based on these considerations, the suggested sequencing of the remaining Team 2 actionable recommendations is as follows (Figure 6):

1. Alternative Reduced-Order Models. Alternative reduced-order models can be used to perform screening-level evaluations of natural flushing before a full numerical groundwater flow and transport model is developed. A batch flushing model was recently developed to evaluate the remedial time frame of natural flushing above the brine interface (Geosyntec, 2022a; 2022b). The batch flushing model identified key data gaps to refine the remedial time frame (ammonium sorption coefficients and biodegradation rates and uranium transport processes). This recommendation includes development of reduced-order models that may generate more accurate predictions of remedial time frame than models that predict first-order decay of contaminant concentrations.
2. Transient Aquifer Monitoring. High frequency (hourly or more frequent) groundwater elevation and conductivity data collected using transducers deployed in existing groundwater monitoring wells can be used to calibrate the groundwater flow model and support development of the CSM. A dataset that spans at least one year will be necessary to capture seasonal fluctuations in the groundwater table and depth of the freshwater-brine interface. Thus, deployment of transducers should be done as soon as possible.

3. Geochemical Evaluation of Mineral Solids and Uranium Geochemistry. Laboratory batch and column testing to quantity uranium and ammonium transport parameters was recommended based on the results of the batch pore flushing model (Geosyntec, 2022a; 2022b). These tests and additional solid-phase analysis of site soil to quantity solid-phase speciation of uranium are planned for 2023. This recommendation includes additional laboratory testing to evaluate the impact of brine on uranium mobility, especially in the freshwater-brine transition zone. Because implementation of this recommendation (soil and groundwater collection, laboratory testing, data analysis) takes a substantial amount of time, it should be initiated early in the GCAP development process.
4. Isotope, Tracer, and Molecular Biology Tools. Isotope and tracer tools provide critical insights into the hydrogeological properties of the freshwater and brine zones and should therefore be prioritized to support development of a groundwater flow model and assessment of remedial alternatives. Groundwater sampling to support implementation of this recommendation could be combined with the sampling effort to support the geochemical evaluation of mineral solids and uranium geochemistry.
5. Sediment/Water Interface Measurements. Sediment/water interface measurements along and across the Colorado River can be used to refine the hydrological CSM and support development of a groundwater flow model. This recommendation addresses key data gaps related to the flow path of groundwater within the freshwater and brine zones, such as whether the brine zone discharges into the Colorado River, identification of higher flow and/or discharge areas, and associated implications for contaminant transport. Additionally, sediment/water interface measurements can be used to optimize surface water diversion efforts to ensure protection of endangered species habitats along the river.
6. Borehole and Geophysical Assessments. Borehole and geophysical methods that address data gaps related to the freshwater-brine interface (e.g., electromagnetic induction [EMI]) should be prioritized over other geophysical methods. Data from these methods can be used to refine the hydrological CSM and support development of a groundwater flow model. Opportunities to use existing boreholes/monitoring wells should be identified before considering installation of new boreholes.
7. Soil Gas Surveys to Refine Residual Source Areas. Soil gas surveys are recommended to refine residual source areas and to support estimation of residual contaminant mass in the subsurface, particularly in the vadose zone. This data is critical for development of a transport model that can accurately predict the remedial time frame under different groundwater compliance strategies and to developing compliance strategies. Pilot testing of this approach is recommended before performing a full-scale investigation. Pilot testing could be performed earlier in the GCAP development process to evaluate whether this approach can be used for a full-scale investigation.
8. Climate Change and Other Uncontrolled Factors. This recommendation does not have an established implementation timeline. Rather, it should be considered throughout the GCAP process and beyond when relevant. For example, impacts of climate change and other uncontrolled factors could be incorporated into long-term numerical model simulations or used as a means to better interpret differences between historical and contemporary hydraulic data associated with the river or groundwater systems at the site

To achieve the goal of NRC concurrence of the GCAP before transition of the site to LM, implementation of Team 2 actionable recommendations should begin in fiscal year 2023. A suggested implementation time frame of each recommendation is shown on Figure 6.

4.3 Team 3: Potential DOE Response Actions to Include in the GCAP

The recommendations developed by Team 3 serve as a portfolio of options for groundwater response actions that should be considered for inclusion in the GCAP as part of the groundwater remedy (interim or final). These recommendations were not prioritized or sequenced because additional site characterization to address outstanding data gaps is required before remedy selection can proceed.

Under adaptive site management (Section 3.1.2.1), the remedial approach may involve multiple technologies at any one time and changes in technologies over time to achieve interim and site objectives (ITRC, 2017). Thus, the response actions developed by Team 3 should be simultaneously considered for implementation in sequence and in parallel to address specific interim and site objectives. Example combinations of response actions for achieving specific site objectives are below:

<u>Site Objective #1: Protect critical habitats along the Colorado River</u>

Potential response actions:

- Reconfiguration of Moab Wash to increase the distance between the source and the habitats
- In situ sequestration to decrease mass flux from source zone
- Interim pump and treat with strategic reinjection to achieve surface water standards within the Colorado River

<u>Site Objective #2: Decrease ammonium and uranium concentrations below groundwater standards within a defined time period</u>

Potential response actions:

- Targeted excavation and/or soil mixing
- In situ sequestration to decrease mass flux from source zone
- Interim pump and treat until tailings removal is complete to remove additional mass from the aquifer
- Natural or enhanced attenuation to achieve groundwater standards after active remediation is complete
- Green surface capping to decrease infiltration and mobilization of contaminants in the vadose zone

For each site objective, metric-based interim objectives would be established with clearly defined timelines (ITRC, 2017). The response actions listed above would then be sequenced to achieve the interim objectives and ultimately the site objective. These examples are meant to provide a framework for conceptualizing remedy selection and should not be seen as complete. Results of additional site characterization and numerical modeling may indicate that the above example response action combinations are not suited for the site or that additional response actions should be considered.

5. Consensus Statements

During the NNLEMS Collaboration, three working group teams developed actionable recommendations to advance the development of a defensible GCAP for the site. Each team started by brainstorming a long list of potential recommendations that were then evaluated based on suitability to conditions at the site and implementability. Based on this evaluation, a short list of actionable recommendations was generated. Various recommendations were consolidated to support development of a phased and spatially targeted GCAP using an adaptive site management framework. A narrative that includes additional details and implementation guidance was developed for each actionable recommendation.

The following consensus statements were developed by the collaboration participants to summarize the primary conclusions from the NNLEMS collaboration:

1. GCAP decisions and development will require support using numerical modeling.

    - Implementation of a numerical model that simulates the key site-specific processes and structures that control plume behaviors is essential to underpin the technical basis of the GCAP and support environmental and legacy management decisions.
    - Use of models and platforms that simplify and integrate data input; uncertainty and parameter estimation; model construction; and data/model visualization are recommended as these tools support efficient and effective workflow.

2. Moab is a “complex site” (ITRC, 2017), and the collaboration recommends developing a GCAP that is consistent with the challenges and emerging science and policy for such sites.

    - A one-step GCAP based on a single technology in unlikely to provide effective and efficient risk management. Development of a portfolio of remedial options is recommended.
    - The Moab collaboration process consensus recommendation is to develop a combined remedy with time-phased and site-specific objectives. For example, medium-term performance objectives would be used to manage and reduce risks to the Colorado River, and longer-term objectives would be used to achieve UMTRCA target groundwater concentrations throughout the entire useable aquifer.
    - Central to the recommended combined remedy is a strategy of matching technologies in time and space to maximize effectiveness and optimize performance. Spatial matching could consider the nature of contamination in different areas of the site and use technologies that address the specific conditions. Temporal matching could focus on active remedies to mitigate medium-term risks and transition to passive or semi-passive remedies based on conditions. Site-specific examples of spatial and temporal matching were developed by the collaboration team for use as a resource by the Moab team, regulators, and stakeholders (Figures 5a and 5b; Section 4.3); these should be refined with detailed site data.
    - The combined remedy should be structured to meet groundwater objectives over timeframes envisioned in UMTRCA and consider actions such as institutional controls (e.g., limiting use of groundwater) that are considered an integral component of the GCAP.
    - The combined remedy strategy should include contingencies and framework criteria for transitioning technologies.

3. Additional characterization is needed to inform GCAP development and to support selection and implementation of the most effective technologies to use for later temporal stages of the GCAP remedy.

    - Key data gaps remain that limit the effective selection, development, and implementation of groundwater remedies.
    - A portfolio of phased and targeted characterization activities will be needed to address the data gaps.
    - Selection and implementation of the characterization portfolio should address:

        - Key uncertainties associated with each of the framework spatial zones identified to support adaptive site management and the interfaces between the spatial zones. For example, for the residual contamination in the deep subsurface brine zone, the primary focus could be 1) on whether the contamination is migrating or staying in place and 2) quantifying future predictions on the source mass flux away from the brine zone to the more active overlying aquifer zone.
        - Timing the implementation of insertion points in the target schedule to support GCAP development, modeling data needs, and timeframes for decision making. In some cases, this might include an early deployment for proof of concept and scoping, followed by more comprehensive data collection if needed, and/or redirection if the scoping work results in promising and useful results that are actionable.

    - Early recommended characterization activities for the portfolio include:

        - Borehole related activities such as geophysical logs (electromagnetic induction and others), geochemical evaluations on core material and groundwater, and scoping evaluation of stable isotopes and tracers in groundwater
        - Scoping survey for the Colorado river using probes and temperature sensing techniques
        - Scoping soil gas surveys
        - Scoping analysis of temporal signals in the subsurface (e.g., with transducers)

    - Longer-term characterization recommendations for consideration by the Moab team include those listed above and other methods. Selection and implementation of the out-year portfolio composition should be guided by early scoping results. For example, some of the stable isotopes, tracers, soil gas or riverbed analytes may not provide clear or useful/actionable information. In this case, some of these items could be dropped or redirected to maximize the value of the longer-term characterization efforts.

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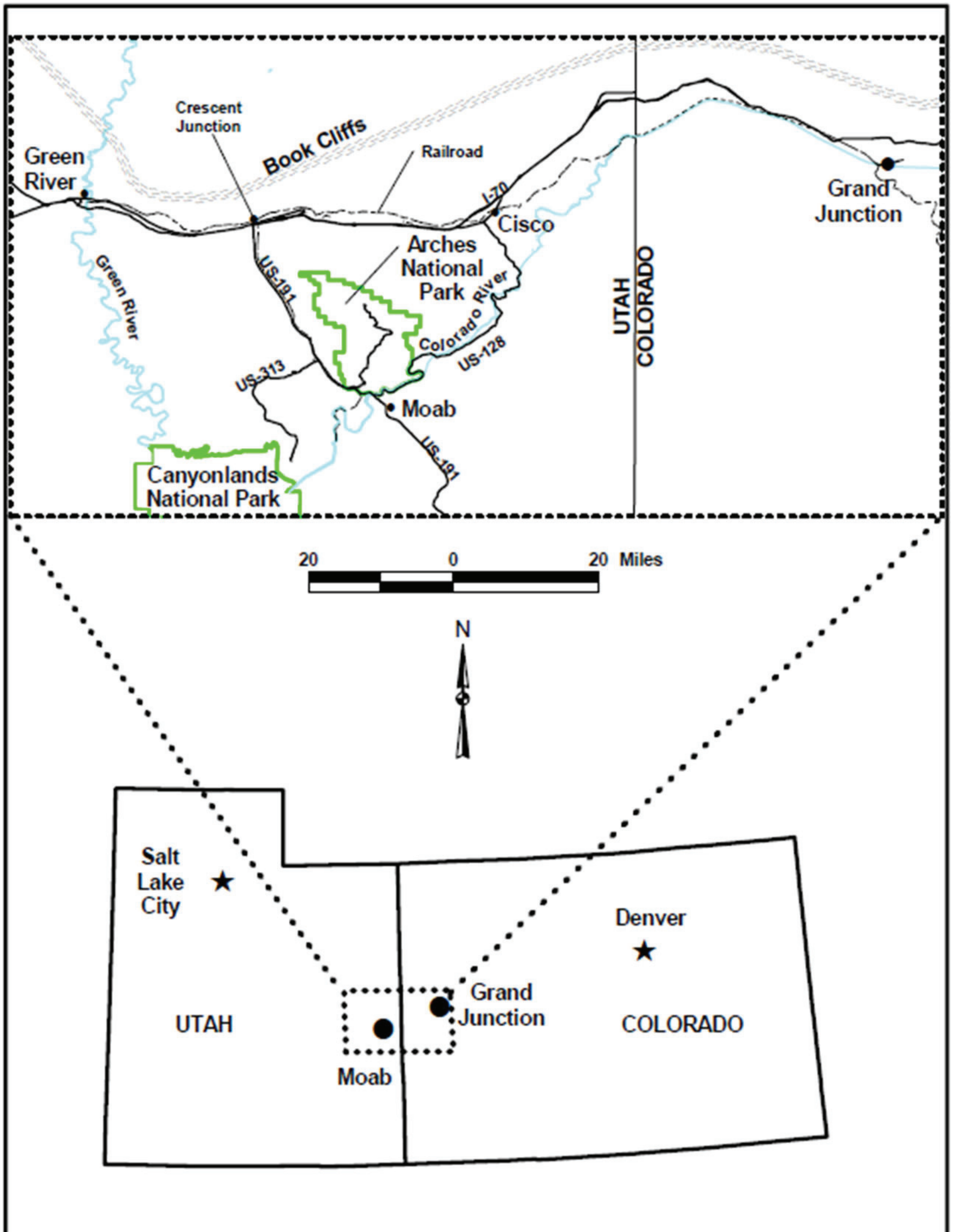
FIGURES



Source: United States Department of Energy. 2003. Site Observational Work Plan for the Moab, Utah, Site. GJO-2003-424-TAC. December.

Regional Location Map

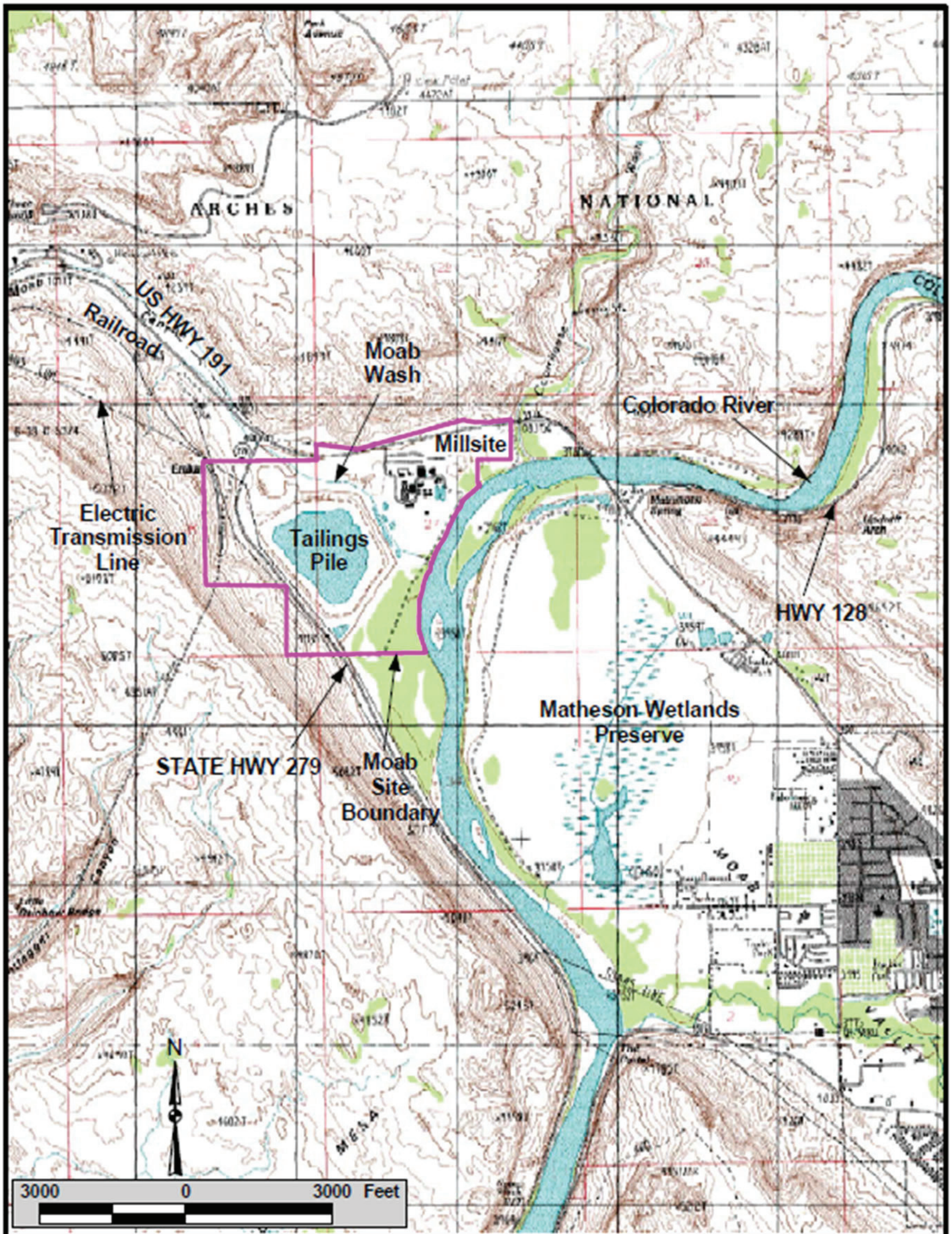
Moab UMTRA Project Site
Grand County, Utah

National Network of Laboratories
NNLEMS
Environmental Management and Stewardship

March 2023

Figure

1



Source: United States Department of Energy. 2003. Site Observational Work Plan for the Moab, Utah, Site. GJO-2003-424-TAC. December.

Site Location Map

Moab UMTRA Project Site
Grand County, Utah

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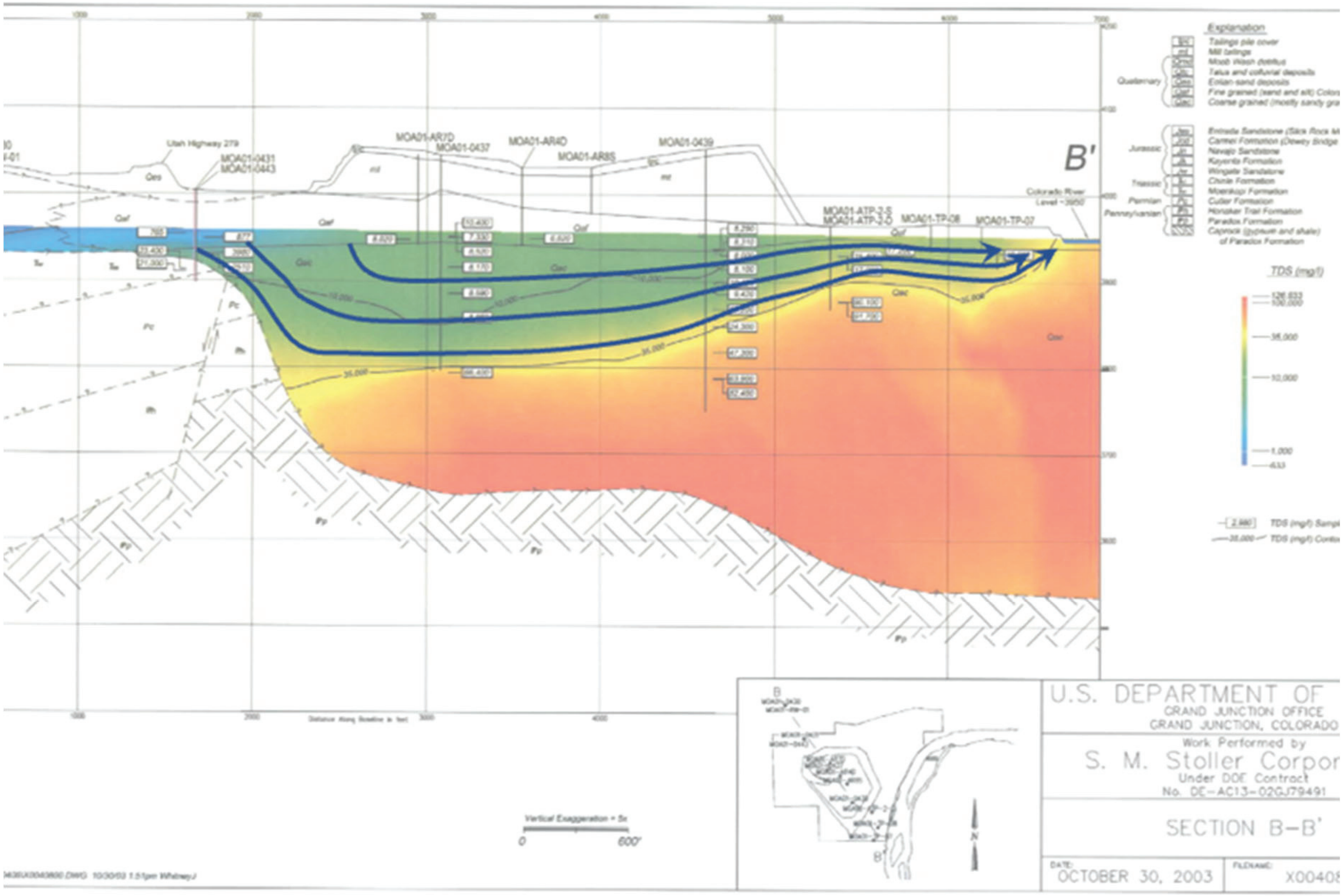
Environmental Management and Stewardship

March 2023

Figure

2



Note: Arrows represent hypothetical groundwater flow paths in the freshwater zone.

Conceptual Cross-Section of the Site

Moab UMTRA Project Site
Grand County, Utah

National Network of Laboratories NNLEMS Environmental Management and Stewardship

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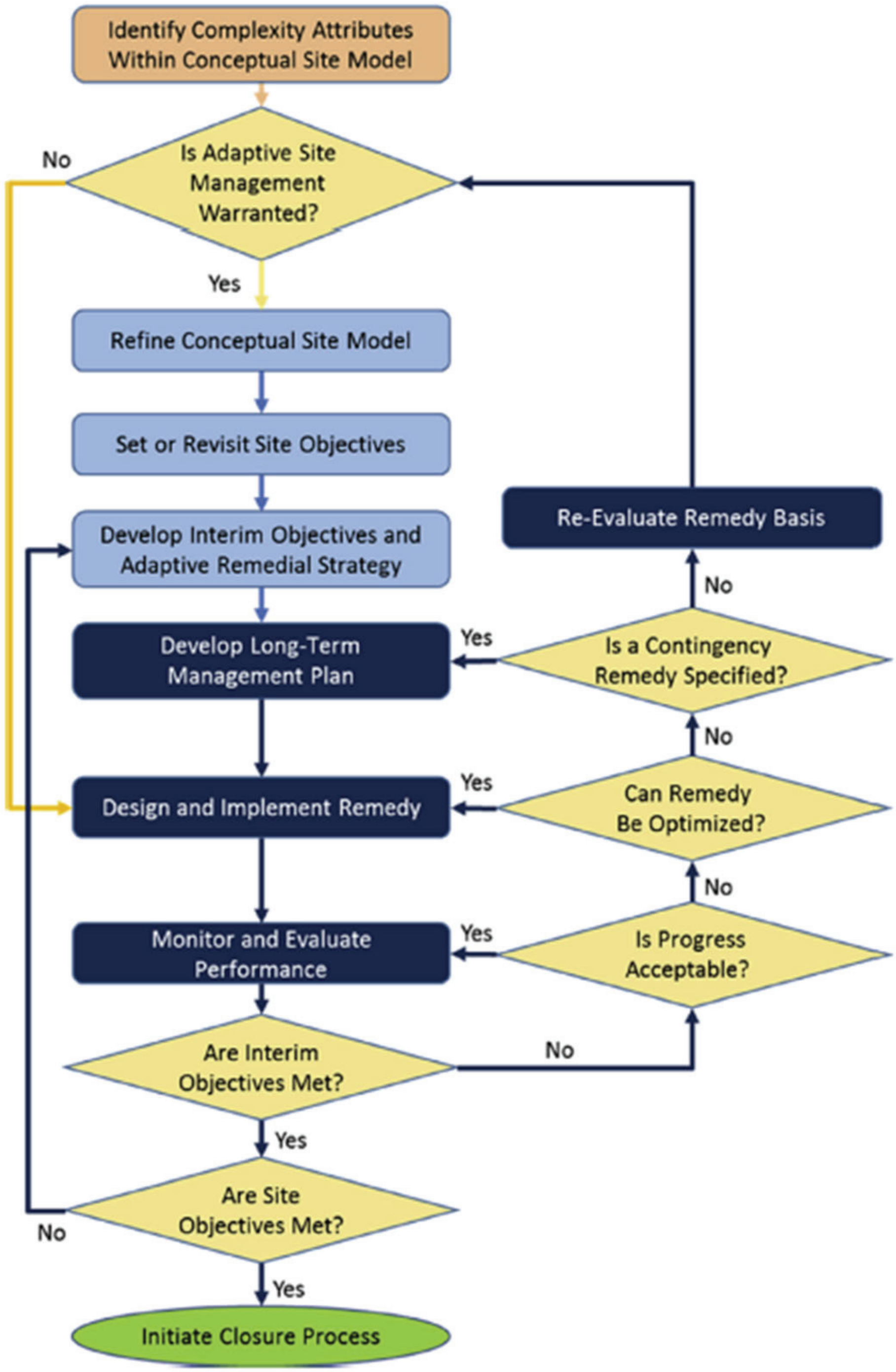
Figure 3



Source: Interstate Technology Regulatory Council. 2017. Remediation Management of Complex Sites, RMCS-1, Remediation Management of Complex Sites Team, Washington, D.C. http://rmcs-1.itrcweb.org/.

Adaptive Site Management Process

Moab UMTRA Project Site
Grand County, Utah

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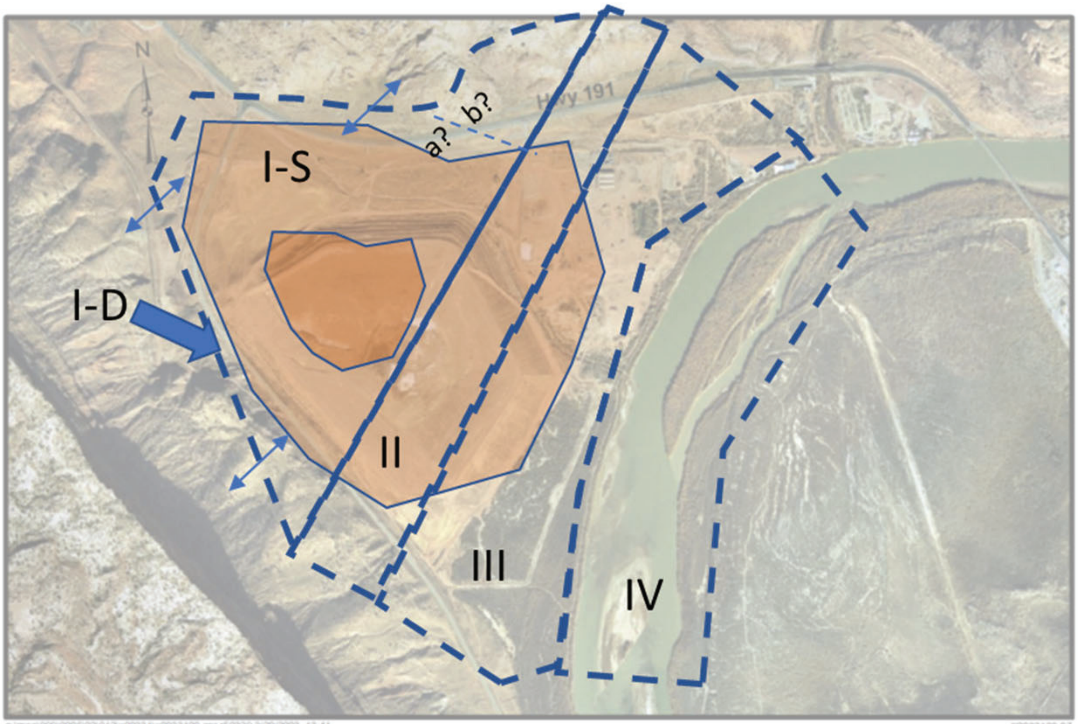
Figure 4



I-S Residual Source Zone (shallow)
I-D Residual Source Zone (deep/brine)
II Transition Zone
III River Protection Buffer Zone
IV River Management Zone

Notes – depicted shading is notional and not based on data – it is intended to demonstrate how information on potential residual sources could be leveraged to inform adaptive site management

Example Spatial Zonation of the Moab Site Plan View

Moab UMTRA Project Site
Grand County, Utah

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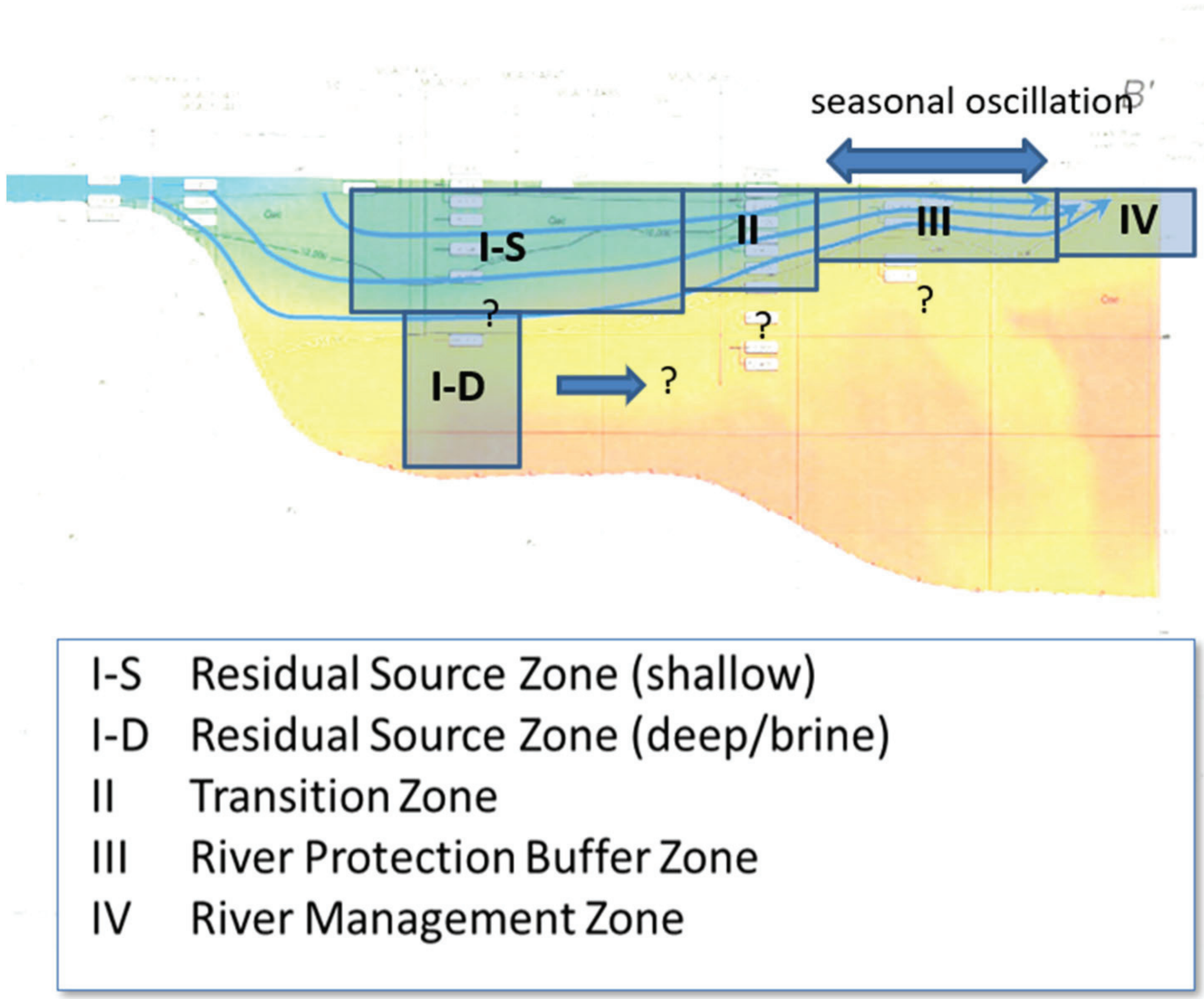
Figure 5a

March 2023



Example Spatial Zonation of the Moab Site Cross-Section

Moab UMTRA Project Site

Grand County, Utah

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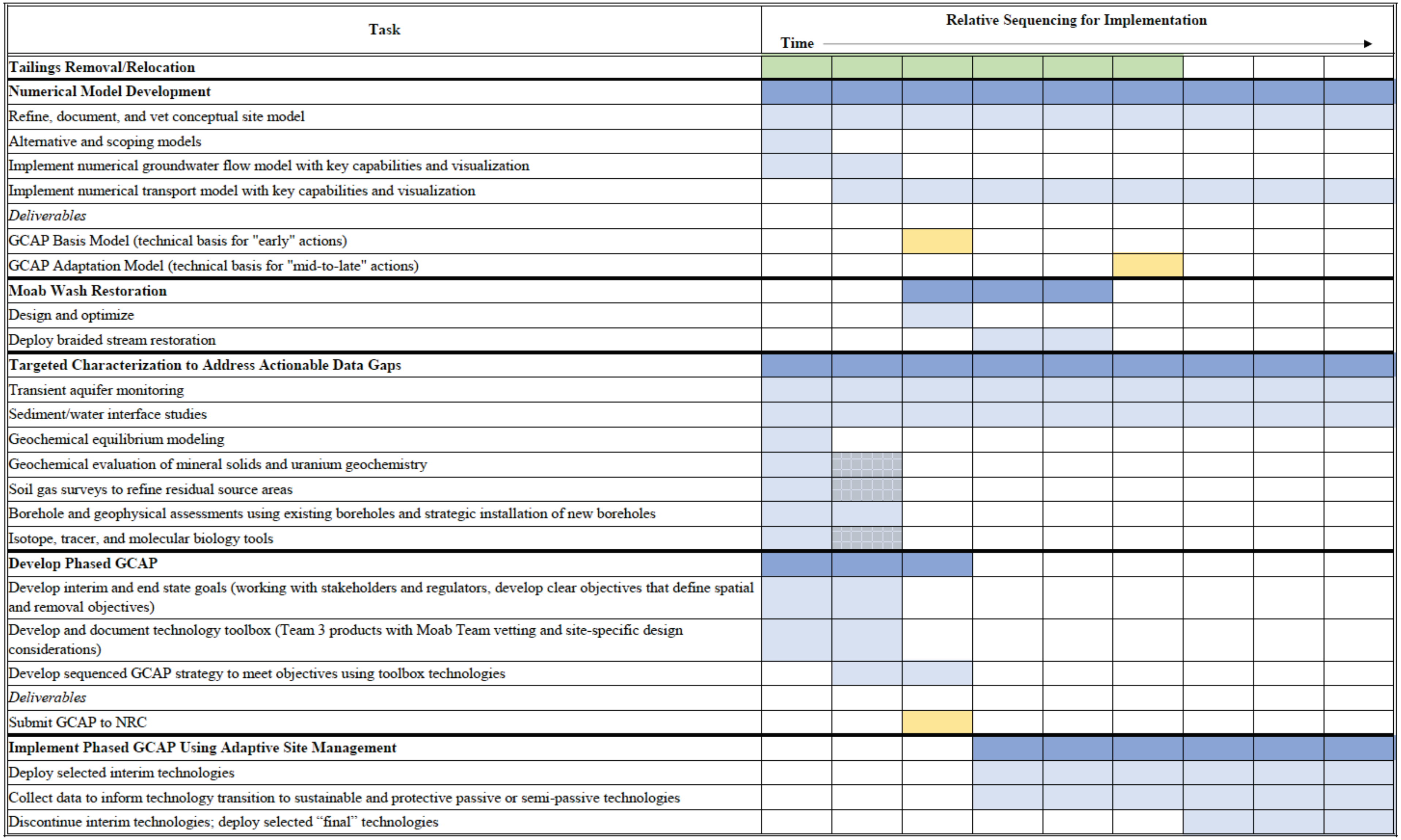
Figure 5b



Notes:

Hatched cells indicate that continuation of the task is dependent on successful scoping studies.

Surface remediation activities

Site characterization and GCAP activities

Deliverables

GCAP = groundwater compliance action plan

NRC = United States Nuclear Regulatory Commission

Sequencing and Timeline for Implementation of Recommendations

Moab UMTRA Project Site
Grand County, Utah

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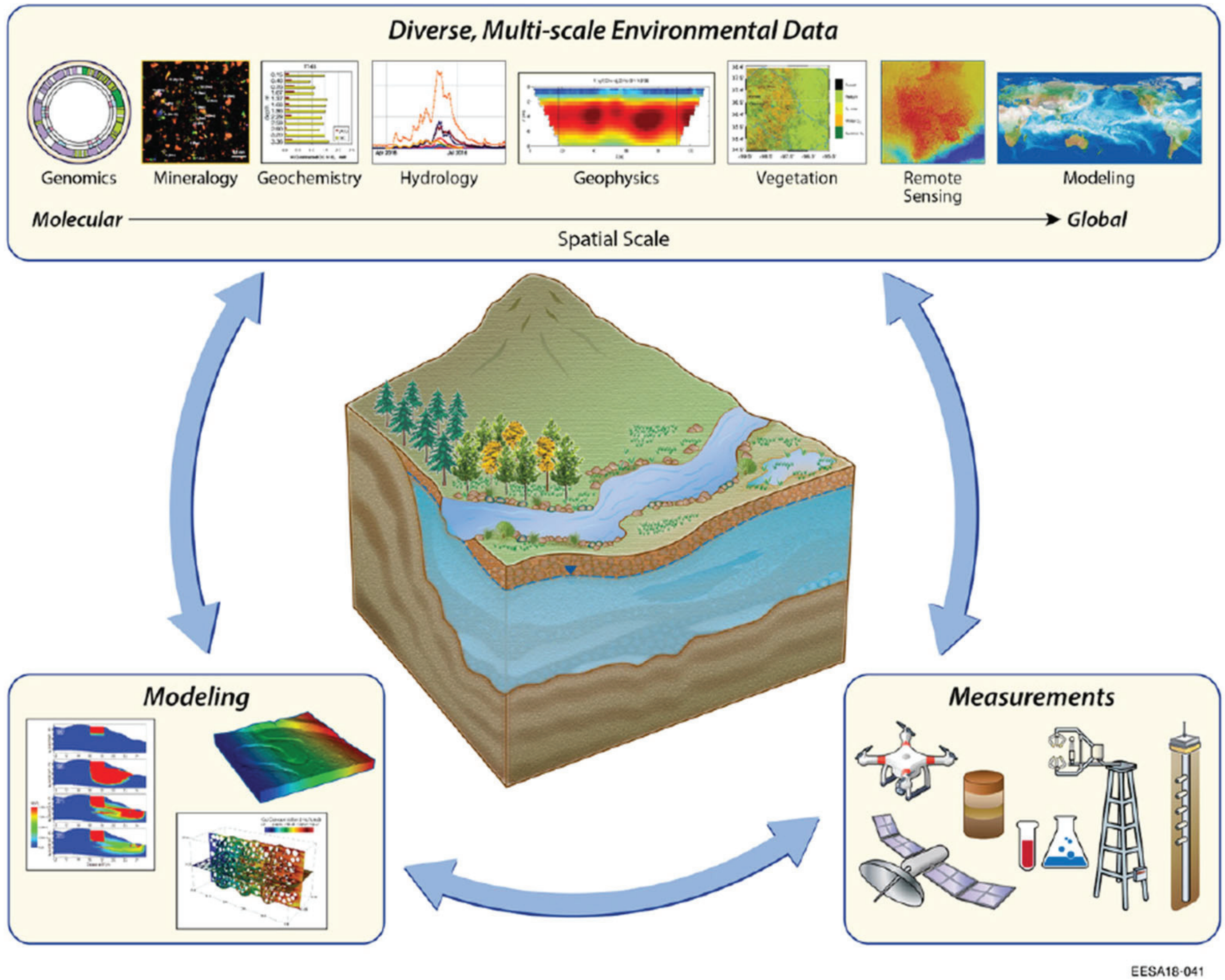
Figure 6



Source: C. Varadharajan, D. A. Agarwal, W. Brown, M. Burrus, R. W. H. Carroll, D. S. Christianson, B. Dafflon, D. Dwivedi, B. J. Enquist, B. Faybishenko, A. Henderson, M. Henderson, V. C. Hendrix, S. S. Hubbard, Z. Kakalia, A. Newman, B. Potter, H. Steltzer, R. Versteeg, K. H. Williams, C. Wilmer, and Y. Wu, 2019. Challenges in Building an End-to-End System for Acquisition, Management, and Integration of Diverse Data from Sensor Networks in Watersheds: Lessons from a Mountainous Community Observatory in East River, Colorado, IEEE Access, 7, 182796-182813, doi:10.1109/ACCESS.2019.2957793.

Illustration of Iterative Model Development and Implementation of Site Characterization Technologies

Moab UMTRA Project Site
Grand County, Utah

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March 2023

Figure 7

APPENDIX A:
Working Group Meeting Agendas and Notes

Geosyntec consultants

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 27, 2023

Subject: Meeting Notes, September 13, 2022
NNLEMS Collaboration, Kick-Off, Day 1
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the first of two days of the kick-off meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration was organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting. A list of invitees is attached.

DOE LM: Mark Kautsky, Bud Sokolovich, Diana Trettin, **Chuck Denton**, **David Shafer**, **Katie Mclain**

DOE EM: **Christopher Pulskamp**, Ming Zhu, Matt Udovitsch, **Zach Crouch**

RSI EnTech (RSI): Nick Kiusalaas, **Al Laase**, **Doc Richardson**, **Ron Kent**

Moab Contractors: **Liz Moran**, **James Ritchey**, **Barbara Michel**, Ken Kisiel

NNLEMS: Carol Eddy-Dilek (SRNL), **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, **Hansell Gonzalez Raymat (SRNL)**, **Amoret Bunn (PNNL)**, **Frederick Day-Lewis (PNNL)**, **Gilles Bussod (LANL)**, **Andrew Tompson (LLNL)**, **Kris Kuhlman (SNL)**, James Lee (LANL), **Ken Williams (LBNL)**

Nuclear Regulatory Commission (NRC): **Doug Mandeville**, **John Saxton**, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: **Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL])**, Lucy Parham (Utah Division of Water Quality), **Gregory Kinsman (North Wind Portage)**, Michael Pardue (NWP), **Swaine Skeen (SKLS)**, Thomas Prichard (SKLS), **Jessica Thatcher (Grand County)**, **Christian Johnson (PNNL)**, Tom Bachtell (SKLS), Thomas Metschies

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING SUMMARY

- Jennifer (Geosyntec) welcomed everyone to the meeting. Members of the Moab site team, EM, LM, and NRC were asked to give a brief introduction of themselves and their role as it relates to the Moab site.
- Jennifer briefly reviewed the objective of the site and the objective of the collaboration. The objective of the site it to achieve closure (i.e., cleanup standards are achieved). The objective of the collaboration is to provide recommendations to the Moab team to facilitate development of a GCAP.
- Jennifer reviewed the agenda for the meeting. The agenda is attached.
- Jennifer reminded participants to keep their video off and mics muted. Questions will be held until the end.
- Chris (EM) presented an overview of the regulatory considerations of the site. The four major documents that provide regulatory guidance are 40 CFR 192, the 1996 Final Programmatic Environmental Impact Statement (PEIS) for the UMTRA Ground Water Project, the 2005 Moab UMTRA Record of Decision, and the Nuclear Regulatory Commission regulation (NUREG) 1724.
- The tailings are being relocated to the Crescent Junction disposal cell. Completion of tailings relocation is expected by 2028. The goal is to receive NRC concurrence on the GCAP by 2025. GCAP review will follow a 30/60/90 process. The 60% document is expected to be submitted for comment early next fall (2023).
- Andy (LLNL) asked where the ammonia is coming from. It is coming from the milling process, which used ammonia.
- Gilles (LANL) asked how natural flushing with a time frame of 100 years is possible while endangered species are in the Colorado River. Jennifer responded that the requirements of the Endangered Species Act must still be met during the 100 years.

- Brian (SRNL) presented an overview of the approach for the collaboration. The presentation covered the approach and charge, criteria for collaboration products, objectives of the collaboration, a list of the participants, general expectations for participants, and first steps. The first steps include a brainstorming process. Participants should go in with an open mind. There is not one specific outcome that anyone is tied to. Participants will be asked to provide their initial thoughts during Day 2 of the kick-off.
- NNLEMS participants introduced themselves and their experience as it relates to the collaboration goals.
- James (Moab) presented on the site history and gave a virtual site tour, which included a video. EM initially had 107 sites in their portfolio; 16 sites remain. EM operates the disposal cell at the Moab UMTRA Project site. 1,400 tons of uranium were disposed of per day for 30 years. In 1998, the mill owner declared bankruptcy. In 2009, tailings removal commenced with 150 employees. The Moab community desires land reuse to benefit the area. Less than 30% of the tailings pile remained in 2021. Recently, waste shipments have been doubled. Critical habits of endangered species within the Colorado River must be protected. The focus is on moving to closure of the site. Once tailings removal is complete, the site is expected to be transferred to LM for continued monitoring and revitalization.
- Jennifer asked where the "contamination area (CA)" is located. It is the area where protection from exposure is enforced.
- David (LM) asked where the clay layer is from. It is believed to be natural material from ore processing that naturally separated as it was slurried.
- Amoret (PNNL) asked where the mill was located on the overview aerial image. Are the buildings further to the east along the river off-site? Yes, those buildings are commercial and include a hotel.
- Jennifer asked if the evaporation pond was lined? Yes. Were other ponds lined? During the mill process, the pond was unlined and was all over the pile. They would slurry the tailings into the pile, and eventually it saturated the tailings. Efforts were made to evaporate fluids.
- Andy asked if the ore is from off-site? Yes. This was a processing site for many mines in the area. The tailings pile is processed ore.
- Ken (LBNL) commented that uranium ore tends to be enriched in other metals/metalloids. Will we be focusing on traditional co-contaminants? Vanadium, arsenic, selenium, and molybdenum were mentioned previously. James responded that some of those are potential contaminants of concern. Liz will cover them in her presentation.

- Kris (SNL) asked if there was one milling process or if it changed over time? James replied that there were a few different processes, but he does not know the details. Over time, they increased efficiency of removing the actual uranium from the ore. Liz (Moab) added that they went back and forth on acid and alkaline extractions.
- Brian asked if there is a Moab-specific summary of processing. Liz said that it is included in the 2001 Shepard Miller report, which contains multiple volumes. Keaton (Geosyntec) will upload the report to the Sharepoint site.
- Liz presented on the site hydrogeology and conceptual site model. The presentation covered the site geology, groundwater flow, sources of inflow and outflow, background water quality, contaminants of concern, migration pathways, critical surface water habitat, and data gaps.
- Moab Wash is typically from precipitation. It ranges from dry to having significant flow.
- Brian noted that the width of the site is about a mile.
- Evapotranspiration is significant due to tamarisks, which are invasive and can grow in brackish water. Tamarisk roots grow deep. A beetle was introduced and killed tamarisks over the years. The site is now covered with more native vegetation.
- In 2003, discharge was 300 to 460 gallons per minute. Kris asked about the length of the reach. It is not in one square meter; it is over a long stretch of river. This information is included in the site observational work plan (SOWP).
- Brian noted that the SOWP together was an amazing effort. It is a pretty durable document and very insightful.
- Moving north across the site, the freshwater alluvial aquifer thickness increases. The freshwater zone pinches out towards river and comes up towards the south. It is complicated but also helps the team to know depths of extraction wells.
- Under high river flow conditions, the brine is suppressed. Total dissolved solids increase up to 100,000 milligrams per liter (mg/L), and the brine is elevated in ammonia.
- Endangered species within the Colorado River include the pikeminnow and razorback sucker.
- The site is bordered on either side by a canyon. Therefore, the background location is not consistent. The river opens up at the site. The Paradox Formation is local to Moab. There is complexity with respect to “background”. Within the Matheson wetland reserve across the Colorado River from the site, the Paradox Formation is shallow. Therefore, the groundwater there is briny.

- "Suitable habitats" are maintained thanks to Moab Wash. Sediment is discharged from the Wash, which forms sandbars. There used to be a backwater channel over the entire wellfield length. Suitable habitat is pretty much gone – it is currently about 1 foot wide. Deposition keeps creating new land between the tailings pile and river.
- The primary contaminants of focus are ammonia and uranium. Secondary contaminants of potential concern include copper, manganese, sulfate, selenium, and arsenic. Other metals and anions were sampled in 2003, but other contaminants of concern were not identified in EIS. Arsenic was added recently. Arsenic is above the standard within the pilot test area.
- Two toe drains exist at the pile for draining into the subsurface. These correlate with higher concentrations of ammonia.
- Kris and Andy asked about delineation of the plume boundary. Are these wells to the south providing this? The delineation is geologic and provided by the fault and cliffs to the south of the site.
- At approximately 50-150 feet below ground surface, 2 mg/L uranium might be due to brine.
- Kris asked why the deeper plume under the tailings pile is referred to as the "legacy" plume. It appears distinct and formed due to different transport processes (density flow with high total dissolved solids).
- Andy asked if there is a way to distinguish different sources of ammonia? These could be investigated more.
- Brian asked what the water level gradient is. The gradient is approximately 10 feet across the site.
- Brian commented that he is interested in information on seasonal impacts of river stage. This causes back and forth water movement. It suppresses and causes the freshwater-brine interface to move up and down.
- Kris suspects the old brine is not moving much.
- Kris asked where the water is coming from. It primarily comes from the Wash and upgradient groundwater. Kris asked if the team has stratigraphy and cross-sections. The team has borehole logs, not 3D models. They would love to develop these, and it is in the plan. Keaton later showed a 3D visualization used to support a simple pore flushing model.
- Kris noted that the contaminant contours intersect at the river. Does the brine discharge to river? Yes. Where depends on the river stage. Groundwater flows to the

river from both sides. Kris asked about variation in the river stage? It varies by about 12 feet.

- Andy asked about uranium radioactive daughter products. Is radium present? It has not been identified. Brian commented that he is surprised there is no radium in the brine.
- Keaton asked if there is uranium in the brine layer? Yes, at 50-150 feet below ground surface.
- Brian asked if isotopes vary between the freshwater and the brine zones. The team will have to check.
- Fred (PNNL) asked if real-time monitors are deployed to look at surface water/groundwater interactions. It would be simple to do. No. In the past they did have pressure transducers. Now, YSI meters are used to monitor multiple days in a row.
- Amoret asked if the team has background or reference values that might be used as background concentrations for contaminants. There are upgradient wells located across the highway. They are more within alluvial aquifer and not paradox bedrock. They are screened in the brine, too.
- Gilles commented that near the river the fresh water may be attenuating the contaminants and retarding their transport. Oscillations of river stage may be observed as signals in pressure/groundwater elevation across the site.
- Fred will upload relevant articles to the Sharepoint site.
- Kris asked if the river water chemistry is different from groundwater. Yes. Kris noted that temperature could be used a tracer.
- Liz presented on the standards, requirements, and interim actions of the site. The presentation covered an overview of groundwater and surface water contaminants of concern and potential concern, groundwater standards, cleanup action requirements, involvement of the Fish and Wildlife Service, a review of the initial/interim remedial action, successes and challenges of the interim action, and data gaps that can be addressed by the collaboration.
- Jennifer presented on the GCAP requirements and current approach. The presentation reviewed the GCAP requirements; remedial options and the proposed path forward; GCAP progress to-date and next steps; and GCAP goals of the NNLEMS collaboration.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer recapped the presentations that were given. Jennifer thanked everyone for their time and participation. Day 2 of the kick-off is scheduled for September 14, 2022. Jennifer reminded participants that they will be asked to share their first impressions and two to six ideas to advance the site towards a GCAP.
- The following action items were identified:
    - Liz will upload the slides that were presented to the Sharepoint site.
    - Keaton will upload the 3D model to the Sharepoint site.
    - Keaton will upload the 2001 Shepard Miller report to the Sharepoint site.
    - Fred will upload relevant articles to the Sharepoint site.
    - Liz will compile and consider nitrate data.
    - Participants are to gather their initial thoughts and be prepared to share two to six ideas during Day 2 of the kick-off.

Attachments: Meeting Agenda

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Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Kick-Off
Moab UMTRA Site
September 13-14, 2022

All meeting times shown in Mountain Time

Planned Attendees

DOE-LM: Mark Kautsky, David Shafer

DOE-EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

Meeting Moderator: Jennifer Nyman (Geosyntec)

RSI: Nick Kiusalaas, Al Laase, Doc Richardson, Ron Kent

SKLS: Liz Moran, James Ritchey

Network of National Laboratories for Environmental Management and Stewardship: Carol Eddy-Dilek (SRNL), Brian Looney (SRNL), Katie Muller (PNNL), Hansell Gonzalez Raymat (SRNL), Amoret Bunn (PNNL), Frederick Day-Lewis (PNNL), Gilles Bussod (LANL), Andrew Tompson (LLNL), Kris Kuhlman (SNL), Ken Williams (LBNL)

NRC: Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: Keaton Belli

Observers/Attendees: Tony Mancuso (UT FFSL), Lucy Parham (UT Div. of Water Quality), Ulf Barnekow (Wismut), Gregory Kinsman (NWP), Michael Pardue (NWP), Swaine Skeen (SKLS), Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS)

Agenda

(All meeting times are approximate)

September 13:

9:00 – 9:10	**General Introductions (Jennifer Nyman)**
9:10 – 9:15	**DOE Site Manager Welcome (Matt Udovitsch)**
9:15 – 9:30	**Integrated EM/LM/NNLEMS Working Group and Review of Goals (Mark Kautsky)**
9:30 – 9:50	**Overview of Regulatory Considerations (Chris Pulskamp)**
9:50 – 10:20	**Synopsis of LM NLN Strategic Approach (Brian Looney)**
10:20 – 10:35	**Break**
10:35 – 11:05	**Site History and Virtual Site Tour (James Ritchey)**
11:05 – 12:00	**Site Hydrogeology, CSM, Q&A (Liz Moran)**
12:00 – 1:00	**Break (Lunch)**
1:00 – 1:30	**Standards, Requirements, and Interim Actions (Liz Moran)**
1:30 – 3:00	**Groundwater Compliance Action Plan Requirements and Approach (Jennifer Nyman)**
3:00 – 3:15	**Break**
3:15 – 4:00	**Review of Days Presentations/Questions (Jennifer Nyman)**

September 14:

9:00 – 9:45	**"First Impressions" Discussion (Brian Looney)**
9:45– 10:15	**Focus Areas (Brian Looney)**
10:15 – 10:30	**Break**
10:30 – 11:30	**Recap, Schedule Review, and Action Items (Jennifer Nyman)**

Meeting to be held Microsoft Teams

The Moab UMTRA Site will have 7 follow-up full team meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The tentative dates for the focus area technical meetings are also listed below. There will be two focus groups that will meet at separate times. The meetings will be scheduled to last 1 ½ hours:

- **Tuesday 20 September, 1000am – Full Team Meeting (moderated)**
- Tuesday 27 September, 1000am/1200pm – Focus Area Technical Meeting (not moderated)
- **Tuesday 4 October, 1000am – Full Team Meeting (moderated)**
- Tuesday 11 October, 1000am/1200pm – Focus Area Technical Meeting (not moderated)
- **Tuesday 18 October, 1000am – Full Team Meeting (moderated)**
- Tuesday 25 October, 1000am/1200pm – Focus Area Technical Meeting (not moderated)
- **Tuesday 1 November, 1000am- Full Team Meeting (moderated)**
- Tuesday 8 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 15 November, 1000am- Full Team Meeting (moderated)**
- Tuesday 29 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 6 December, 1000am- Full Team Meeting (moderated)**
- Tuesday 13 December, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 20 December, 1000am- Full Team Meeting/Wrap-up (moderated)**

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 28, 2023

Subject: Meeting Notes, September 14, 2022
NNLEMS Collaboration, Kick-Off, Day 2
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the Day 2 of the kick-off meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration was organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting. A list of invitees is attached.

DOE LM: Mark Kautsky, Bud Sokolovich, Diana Trettin, **Chuck Denton**, **David Shafer**, **Katie Mclain**

DOE EM: **Christopher Pulskamp**, Ming Zhu, Matt Udovitsch, **Zach Crouch**

RSI EnTech (RSI): Nick Kiusalaas, **Al Laase**, **Doc Richardson**, **Ron Kent**

Moab Contractors: **Liz Moran**, **James Ritchey**, **Barbara Michel**, Ken Kisiel

NNLEMS: Carol Eddy-Dilek (SRNL), **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, **Hansell Gonzalez Raymat (SRNL)**, **Amoret Bunn (PNNL)**, **Frederick Day-Lewis (PNNL)**, **Gilles Bussod (LANL)**, **Andrew Tompson (LLNL)**, **Kris Kuhlman (SNL)**, James Lee (LANL), **Ken Williams (LBNL)**

Nuclear Regulatory Commission (NRC): **Doug Mandeville**, **John Saxton**, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: **Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL])**, Lucy Parham (Utah Division of Water Quality), **Gregory Kinsman (North Wind Portage)**, Michael Pardue (NWP), **Swaine Skeen (SKLS)**, Thomas Prichard (SKLS), **Jessica Thatcher (Grand County)**, **Christian Johnson (PNNL)**, Tom Bachtell (SKLS), Thomas Metschies

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING OVERVIEW

- Jennifer (Geosyntec) welcomed everyone to the meeting.
- Chris (EM) commented that Barbera (Moab) is recording the meeting. Let the team know if you are not okay with that. Barbara is taking notes.
- Brian (SRNL) led a discussion of everyone's first impressions. There was a lot of information presented yesterday. Two-way communication is desired. He noted that he may have suggested things that have already been considered. The collaboration is starting after a lot of work has already been done at the site.
- Brian reviewed the process for the collaboration. There will be three technical topic teams. Brian will send out a sheet for participants to volunteer to be a part of one or more of the teams.
- Brian shared that the purpose today is to develop a long list of ideas. Briefly, each participant will share 2-6 ideas in a list form. Brian will record. At the end, ideas will be aggregated into groupings. Participants do not need to provide reflections on everyone's ideas. Liz (Moab) and the Moab team can also share ideas.
- Brian shared his ideas:
  - Modeling will be important. Think about modern 3D numerical modeling, including visualizing the geology and hydrogeology.
  - There may be opportunities for the Moab team to include some interns or students to help with some things.
  - There are some alternatives to the reduced order model that Geosyntec did. The model looks like exponential decay. Stretched exponentials may be more representative of trends at a real environmental site.

- In terms of risk to the river, is there an opportunity to use biological risk models? There are models for selenium and copper.
- Molecular/biological tools can be used to evaluate nitrogen transformations.
- Uranium isotope analysis can be used for deeper wells in brine. Some literature shows brines enhance solubility of uranium, radon, and other metals. There could be enhanced solubilization from minerals down there. This could change the paradigm, including on the other side of the river.
- Regarding remediation, there are opportunities for combined remedies, such as hydraulic and chemical/biogeochemical methods. The site should consider adaptive management strategies and treatment trains. Regarding specific technologies, the team is currently testing apatite. Are other amendments possible? Brian was impressed with ideas of hydraulic controls and injecting river water that are currently in place. Groundwater bypass is another idea. Upgradient water could be connected with the river via a siphon. This would stagnate the plume. The upgradient water controls the boundary conditions and lowers the driving force through the site. Out of the box idea would be to reroute the Colorado River to a more natural, historical position. This would provide space to put in barriers between the site and the river.

- Mark (LM) joined the call and introduced himself. His involvement comes through the LM Applied Studies and Technology (AS&T) program. He will be doing less on the hydrological side of things, which is why Chuck (LM) is jumping in. He thanked Jennifer and Liz and their team and all the great work getting to the 30% design. The collaboration is getting a good jump start by having that in place. He thanked everyone who participated yesterday for their input. He was involved in this site during the environmental assessment. He was involved in the multi-phase modeling back then that considered the brine and density differences there (variable density modeling). The model was used to project clean up times based on removal of the tailings pile. He is sure those 20-year-old projections can be revised. He is curious what the collaboration participants can add.
- Hansell (SRNL) asked for clarification on ideas for amendments that could be used for the site. What will be an acceptable end state for an attenuated form? Or is the main goal to remove contaminants? Brian replied that it is all on the table today—enhanced removal and stabilization. Determining an acceptable end state is almost a separate track for the site team.
- Amoret (PNNL) shared her ideas:
  - She recommends anything to reduce the source term so to meet cleanup criteria as fast as we can. Her number one concern is considering remediation options in a manner that minimizes any drastic changes to the water quality of the Colorado

River. Amendments to the river would require further evaluation with respect to the health of fish. Amendments could be implemented in the wintertime to avoid the timeframe when young of the year are moving through the area. Phosphate amendments (apatite) were evaluated at Hanford for potential contribution to the river. The dilution factor for the Columbia River is very different than for Moab.

  - The dilution factor that was discussed (10) was a real wag. Anything that can be done to improve that number would help with remedy selection.
  - Regarding the endangered fish species, many COCs are affected by other water quality criteria. There are United States Environmental Protection Agency (EPA) tools to figure that out, but they require good data, like hardness. Otherwise, conservative information can used for the assessments. The team can look at other sources of information for hardness. Uptake of copper by fish depends on valence state of copper and movement across gills. The higher the hardness, the more competition from calcium and other ions and less opportunity for copper to transfer into the fish. This was an issue that had to be addressed in the environmental impact statement (EIS). Brian added that the biotic ligand model (BLM) has provisional application for selenium. Was this used at Monticello? It would be good to have examples in the region of how this would work. This would be quick.

- Fred (PNNL) presented his ideas:
  - He was very impressed with the presentation yesterday and the work done so far, including the Leapfrog 3D model and the current hydraulic control setup. Leapfrog has a lot of potential.
  - He has questions about how the Leapfrog data was interpolated; others did too. A system like Leapfrog is needed for visualization, data integration, and numerical modeling.
  - More monitoring data is needed in such a dynamic system. Opportunities include infrared imaging to look for where seeps are occurring to determine spatial distribution and timing and discharge. Handheld meters or drones could be used. Fiberoptic temperature sensing on the riverbed could be good. Labor costs decrease once it is deployed. Dynamic monitoring is valuable for hydraulic control systems.
  - Regarding characterization, there was some geophysical work done by the United States Geological Survey (USGS) across the river in the Matheson wetland preserve using electromagnetic induction for shallow characterization. It is good for finding depth to brine and mapping. It could even see down to bedrock. Before going to the field, simple evaluations should be performed to assess proof of concept. Geophysical measurements could be performed on cores or columns,

which would be an opportunity to get basic geophysical properties of the soil at very low costs. This data would help interpret field images. There are opportunities with using geophysics to monitoring amendments.

- Katie (PNNL) shared her ideas:
  - Geochemical conditions need to be understood more, including contaminant speciation. Understanding how some of these, like pH and redox, change along the flow path is also important. Understanding more about the groundwater/river interface and the transient nature of it is important.
  - A distribution coefficient (K_d) model could be appropriate, or a surface complexation model. These would help understand how some geochemical conditions might be incorporated into the model and how they affect fate and transport. These could be used to evaluate the proposed column tests. The column tests could be used to develop appropriate conceptual site models and parameters.
  - There is an opportunity for incorporating adaptive site management.
  - She would like to see a sensitivity analysis to evaluate uncertainty associated with site, such as concentration at discharge points.
- Andy (LLNL) shared his ideas:
  - Yesterday's presentation was great.
  - He is interested in fundamental hydrodynamics. There are three bodies of water, which are very transient and moving. What can we do to better understand that with respect to a model? Isotopic techniques could be used. He agrees with Fred regarding geophysical methods. He is curious how water gets into and under the river. The dynamics are very transient. All of these things will be relevant if the remedy involves hydraulic controls, injection barriers, or diversion upgradient. Viability will be affected. There are many uncertainties in the whole process.
  - Delineating the source term in terms of uranium and the legacy ammonia plume is important. How far down does it go? Will it bleed off? Will it be there a long time? When talking about a mass balance, we need to know what we are starting with and what is left in the unsaturated zone above the water table. Uncertainty there will propagate.
  - He agrees with Katie regarding contaminant mobility issues related to geochemistry.
  - There is still a question of how much mass will be discharged into the river. Modeling will play a role, and he is very interested in understanding the dynamic issues.

- Brian asked about isotopic techniques, including stable isotopes, radioisotopes, and tracers. He has not thought through them but will sit down and think about it. They could address questions such as the origin of the water, the source of contaminants, the residence time of the water in the system, and water sources. We should flush this out more. There are a lot of techniques that people have brought to problems like this.
- Brian noted that Mark mentioned early work on density issues. Is that work available? Yes, Mark believes it is. Mark will look at it and send information.
- Brian commented that isotopes and daughter products of uranium could be assessed. Daughter products may be due to uranium mining or natural uranium. The Nevada test site team is working on separating natural uranium. Brian had a case at Mound where road salt caused a brine and solubilized enough radium to exceed standards. Some of that may be of interest.
- Kris (SNL) shared his ideas:
  - The system as described seems incredibly transient and 3D, which makes it complicated. There are many transition zones: brine versus fresh water, reduced versus oxidized waters, warm versus cold waters. These are all free signals. He is interested in monitoring them in more detail. It is a great opportunity to understand the system better that does not involve pumping a ton of water out of the ground.
  - The system is very 3D. The river is curved and not a uniform distance from the pile. The freshwater-brine transition is at an oblique angle. There is heterogeneity and anisotropy. It would be good to visualize all of these things across the site. A visualization tool is a first step in the right direction. It becomes rapidly complicated due to all of these features.
  - The wetland is on the other side of the river. It seems like the river is at a natural low point during base flow, but the boundary condition flips every year. Maybe uranium gets pushed to the other side periodically. Previous suggestions about thermal data, fiberoptics, and geophysical methods are all ways to get a better grip on it.
  - The Leapfrog visual is cool, but the details are difficult. The contours are spherical, but the system is probably anisotropic.
  - The default remedy is natural flushing – implicit in that is where the flushing is expected to go. It goes to river. He wonders about that. There is a need to predict that, but we are at the point of changing the system by removing the pile. Potentially flushing will stop. It is hard to predict while making a huge change to the system. If the site floods, are they going to build a berm or dam?

- He has questions about the plume and monitoring network. The downstream edge of the plume does not seem delineated. The plume goes to the river and then the contours stop. He assumes that is the reporting boundary. Are there clean wells with no contamination on the edge of the plume? There are a narrow set of wells that are located between the pile and the river.
- He noted the tailings were initially a slurry, which sounds initially coarse. Once it is slurried, the fines will plug it up. He assumes that for the first few years water went into the formation, which is the source of the legacy plume.
- It is best to start simple then work our way up with modeling. Permeability or something other than conductivity will be needed. Conductivity is not adequate because of the brine.

- Brian added that the point about the dynamic environment giving free signals was well made. The idea is to see if there is information in these signals.
- Andy stated he cannot emphasize the transient issue enough. For example, the rising and falling of river is almost like saltwater intrusion or tides. The model will need to deal with density dependence; he does not think MODFLOW is the answer. The model will also need to deal with a transient water table.
- Fred commented that MODFLOW 6 can handle density driven flow. It encompasses former SEAWAT capabilities.
- Brian said we should try not to get into brands of models. Instead, we should describe features. To him, a type of platform is needed to make a quick and efficient model. Geologic and hydrologic visualization integration should be seamless. We are starting to get a list of site-specific needs.
- Gilles (LANL) shared his ideas:
  - Good work has been done by a good organization. It is very promising. The challenges are well-defined and can be amended with some guidance.
  - He is worried about how to fit this into a 2025 timeline. The team will need to reprioritize their focus and add potential new work.
  - Given the complexity and objectives, a transport model is unavoidable. It will need to incorporate things like surface complexation of uranium.
  - Identify best remediation practices and defense in depth for remediation measures.
  - Remediation by natural flushing will not necessarily work for uranium if the soil is contaminated. A model can constrain the problem and evaluate solutions

including four types of water – brine, freshwater, contaminated water, and uncontaminated water. It will also need to consider complexity for heterogeneity.
  - He believes redox conditions are important. Formation, speciation, toxicity, and anything to shore up the diversity of redox, pH, and water hardness and their transient behavior and location will be essential to getting a picture of remediation techniques.
  - It seems the project may be relying on natural flushing. It will get partly there; it already has. However, some assumptions might be incorrect over the long run as the system will evolve and potentially deteriorate. Natural flushing does not inherently address the potential for secondary contamination.
  - He agrees it is best to help the system retain a natural state. Permeable reactive barriers and rerouting the Colorado River might go a long way.
- Brian added that it is difficult for the site to get to background conditions. It might be useful to go to a surrogate site and measure background conditions. The site can aim towards natural conditions.
- Ken (LBNL) shared his ideas:
  - He congratulated the Moab team and Jennifer. The presentations were helpful and really well-framed. Kudos.
  - Past is prologue. When it comes to the GCAP, uranium concentrations are very high, as high as any LM sites, like Shiprock. 6,000 parts per billion (ppb) uranium is big. The long-term evolution of flushing at LM sites is showing that decreases are slow and will never come close to reasonable alternative concentration levels (ACLs) or Uranium Mill Tailings Radiation Control Act (UMTRCA) limits within 100 years. The uranium issue will have to be accounted for distinctly from ammonia. Issues for ammonia are considerably different than for uranium. Microbes can oxidize ammonia then denitrification can remove nitrogen from the system.
  - Shifting conditions towards more oxic to enhance nitrification is fundamental. For ammonia, he does not view it as insurmountable. But natural flushing for uranium may be a non-starter given the concentrations.
  - Regarding Fred's comments, there is a need for better aquifer characterization and identifying heterogeneities for preferential flow paths. Finer-grained areas probably represent long sources. The methods Fred described are well-suited. LM is using some of them at Shiprock. Fred alluded to USGS work in the Matheson wetland. This demonstrated that the methods work in this area.

- Regarding hydrostratigraphy, the team should marshal resources to identify secondary sources, especially uranium. Uranium will be persistent and thorny. Targeted and appropriate remedial technologies should be used to disconnect and isolate the source from the aquifer system.

- Brian commented that the information provided by the collaboration will be used to plan field work and it does not need to be a complete description. With regard to apatite, there is some crossover from research conducted at the Old Rifle site. Geophysics is being done there to monitor injections.
- Ken said that the apatite experiment being conducted at Moab is a proof of principle. On a subsurface bioremediation project, a small business was used for nuclear magnetic resonance (NMR) and geophysical logging. They have been using borehole NMR and will be trying some surface measurements as well. They are setting the stage for identifying technologies.
- Brian commented that flushing of uranium is highly uncertain. It will be a challenge to meet the 100-year time frame. It brings up the idea of sequestration.
- Ken commented that technologies can be used to "armor" and isolate secondary sources. Installing pressure transducers is low-hanging fruit and is a very cheap way to constrain groundwater movement. The site should address this as soon as possible. This dovetails with free signal monitoring.
- Hansell (SRNL) shared his ideas:
    - Hansell thanked everyone and noted the presentations were good and contained lots of information.
    - This is a good opportunity to refine the conceptual site model and try to use historical monitoring data to understand attenuation mechanisms. The vertical and lateral extent of contamination should be delineated. A different approach should be used for modeling. Surface complexation modeling is a good idea for uranium. Chemical equations are used to model complexation and precipitation of different minerals instead of partitioning coefficient (K_d) values, which depend on pH, ionic strength, and concentration.
    - Regarding the toolbox of amendments, collaborations with universities could be useful. Florida International University is a collaboration partner. Humic amendment could be used for uranium, especially in areas with high concentrations of uranium; this amendment has shown very promising results. The implementation would have to be fine-tuned for Moab site conditions. It can also be used to reduce copper toxicity.
- Keaton (Geosyntec) shared his ideas:

- Keaton emphasized understanding geochemical dynamics at the freshwater-brine and characterizing uranium in the brine layer. As the interface fluctuates, solid-phase uranium may serve as a long-term source. Geochemical equilibrium modeling could be conducted and incorporated into the transport model. If the brine is reducing, then there is an opportunity for sequestration.
- Estimating the mass of the source is necessary, especially solid-phase uranium under the tailings area. Understanding the speciation of uranium is needed to understand its potential for mobilization.
- Because there may be redox zones within the aquifer, there is opportunity for redox cycling of uranium and iron. Uranium may be sequestered or coprecipitated with metal oxides.
- Compound-specific isotope analysis can be used to evaluate nitrogen transformations. Molecular biology tools should be used to quantity populations of nitrifying and annamox bacteria. Keaton previously researched these options and could not find labs that would accept the samples from the Moab site because the labs did not have a radioactive material license.
- The effects of climate change should be included in modeling scenarios. Over 100 years, the river might change drastically, so it is important to include. The geomorphology of the river has changed just in the past few decades. Understanding and including this in the model is important.
- Remedial options should take advantage of having the tailings in place over the next few years. Consider injecting clean water upgradient of the pile to expediate flushing. Extract the water and spray it on the tailings. This could be done to enhance natural flushing for the next few years.

- Brian commented that these ideas go to the heart of how to do the work. He tends to not think about enhanced flushing, but it is important to get a complete list. Thank you for that – it is super helpful.
- Andy had a comment regarding climate change. Is the Colorado River subject to reservoir discharge controls? Ken responded that it is only when the Bureau of Reclamation calls for releases. They are minor compared to releases from Lake Powell. Tony (UTFFSL) noted that there is also a diversion near Cameo, Colorado. Operations can cause 1,000 cubic feet per second (cfs) differences sometimes.
- Brian asked Tony how open he is to rerouting the Colorado River? Tony said there are a lot of layers in there. In the most basic sense, Utah Department of Natural Resources exists to preserve rivers as navigable, ensure water quality, and ensure habitats. It is easy to partner with DOE because the primary goals are habitat preservation and water quality, at least from the point of view as river administrator.

If the original channel were still around, it would get stuff out, but that is not the case. If UMTRA were interested in it, they could partner with his department. It would change the hydrology; the river would flatten out.

- Amoret commented that in regard to remediation, she would like to see what we can offer towards sunsetting the initial action. This relates to adaptive site management and the treatment train.
- Gilles commented about a new capping technology: non-cementitious material. Capping could be implemented to avoid infiltration where the tailings are or were located. Green ponds could be constructed with porous filters that contain uranium-sorbing components. Hydroxyapatite has been mentioned a lot but clays and iron oxide mixtures could also be considered. Several types of components can be combined to achieve different goals. Brian added that bone char has been considered elsewhere.
- Liz shared her ideas:
  - All of these ideas resonate with her. She will need to get a better handle on them.
  - Regarding the risk analysis with uranium, uranium concentration is very high, and uranium is discharging to the river. This may require a new risk analysis. One thing to look into is whether supplemental standards or alternate concentration limits can be defined.
  - Liz is intrigued about brine fluctuating and creating secondary source layers.
  - Liz keeps thinking about using data better, both historical and current data, such as thinking of ways to further characterize groundwater.
- Chris shared his ideas:
  - He is very impressed with the depth of knowledge and mix of skills in the group. He is very, very impressed. His comments are less technical and more practical.
  - The Sharepoint site will be the central repository. Everyone will be given access.
  - Chris has been thinking about comments from the NRC at the end of yesterday's meeting, which basically said the site will need a numerical fate and transport model. He does not think this is optional; the site will probably need to do that. This can be discussed in future meetings.
  - Regarding the 10,000 mg/L brine interface and where that number came from, he is not sure where it came from and if it was approved. Brian said that the threshold used is actually 35,000 mg/L. Chris said he would look into the approval. Brian noted the chemocline is relatively sharp around 35,000 mg/L. Mark added that the 10,000 mg/L comes from UMTRCA standards (supplemental

standards). A brine is equal to typical seawater, which is 35,000 mg/L. Chris said he would circle back with the correct numbers.

  - Modeling such a dynamic system is an opportunity to incorporate various flows into a comprehensive model, including visually.

- Gilles commented on the relationship of water bodies of different density. This is related to flow velocities, specifically as it relates to dispersion and dilution. Maybe isolation of the brine is equivalent to remediation if one knows that the chemistry is in favor of sorption. It will be diluted by advection.
- Kris commented that it seems like clearly a shallow and deep system. It seems like the shallow zone is mostly associated with flushing back and forth annually. It seems like the deep zone would be on a much longer time scale. Fluids infiltrated the deep zone historically and maybe added more fluids to the system while the pile was still there. The focus of the shallow zone is monitoring. It would be difficult to do natural flushing in the deep system. The deep system is also difficult to characterize.
- Gilles asked if the flow velocity of the deeper brine system is known.
- Al (RSI) commented that he has worked on a lot of these GCAP sites. Knowing something about the source term has to be the focus. There is a lot of data at the site. There may be value in preliminary 3D reactive modeling with variable density. His group uses an iterative ensemble smoother that calibrate hundreds of thousands of models. It allows one to look at uncertainty in input parameters and effects. Data worth analysis could be performed next.
- Ron (RSI) added that modeling is often saved to the end. By then, other things may be identified that might be more important than were initially thought. Sometimes predictions are not sensitive to certain complexities. This can be solved by doing modeling earlier and doing data worth analysis. A lot of LM lessons learned have been brought up around this topic. Residual and secondary sources are a real barrier to the 100-year natural flushing time frame. The site should start with using data that is already available; there are a lot of data. Historical data can be reevaluated and input into Leapfrog to use up front to analyze the source term, mass balance, and solid phase information.
- Andy noted it is important to characterize the source term. Everything hinges on that. The freshwater-brine interface will go up and down, and the source will respond to that. If contaminants are present, they will get mixed up there, similar to the brine interface. Regarding ammonia in the brine area, maybe the initial fluid was dense and that played into dynamics. His philosophy is models are a reservoir of our knowledge. Building a model puts everything on the same terms and units. Models are helpful in ferreting out historical data, interpreting the past, and then moving forward. He likes the idea of 3D visualizations. He urged caution with regard to how one interpolates

data over 3D. The results can go way off when only finite amounts of data are available.

- Brian commented that it is better to start modeling sooner versus later because of all the learning that is done during the process. Regarding Jennifer's question to gain more insight into deep contaminant distribution, other than drilling lots of wells down there, borehole logging could be used to profile ammonia in vicinity of existing and future boreholes. Neutron and gamma logging were done for chlorine in dense non-aqueous phase liquid (DNAPL) days. Nitrogen is not a great element for that but depending on the concentration we may be able to get profiles in existing wells. Kris added that logging might be useful to delineate brine and chloride in deeper wells.
- Andy commented that if we are actually able to collect water at different depths, then isotopic methods may be able to distinguish bodies of water more clearly. Correlations can be made. Ammonia should not be in older water.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Brian will take notes and coalesce them. Ideas will be captured in a matrix and sent out. The self-selection sheet will be sent out for participants to sign up for teams and topics. The process will be iterative. We want folks to work on what they care deeply about.
- Brian noted that the goal is not to dig into everything discussed today. As a team, we will try to figure out maybe a dozen things then develop narratives with those ideas. The final product is not a comprehensive plan of everything. We want to provide a resource that gives the site team the ability to add, course correct, or adjust as they move through their planned sequence of activities. We do not want to recreate the wheel. We are already moving pretty strongly in that direction.
- Brian asked participants to select their interests relatively quickly and provide input by early next week. Leaders will coordinate setting up calls.
- Jennifer reviewed the meeting schedule. The first full-team meeting will be held on September 20, 2022. Liz will send out invites for future meetings.
- Jennifer reminded everyone that the Sharepoint site will serve as the repository for all files related to the collaboration. Let her know if you do not have access.
- Jennifer thanked everyone for their participation and enthusiasm.
- The following action items were identified:
    - Mark with send along information about the early work on density driven transport.

- Brian will coalesce the notes on everyone's ideas.
- Liz will send out invites to future meetings.
- Participants should complete the self-selection survey and return to Brian and Jennifer by early next week.
- If anyone has trouble accessing the Sharepoint site, let Jennifer or Liz know.

Attachments: Meeting Agenda

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Geosyntec consultants

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 22, 2023

Subject: Meeting Notes, September 20, 2022
NNLEMS Collaboration, Meeting 1
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the September 20, 2022, meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration is organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting. A list of invitees is attached.

DOE LM: Mark Kautsky, **Bud Sokolovich**, **Diana Trettin**, **Chuck Denton**, David Shafer, Katie Mclain

DOE EM: **Christopher Pulskamp**, **Ming Zhu**, Matt Udovitsch

RSI EnTech (RSI): **Nick Kiusalaas**, **Al Laase**, Doc Richardson, **Ron Kent**

Moab Contractors: **Liz Moran**, **James Ritchey**, **Barbara Michel**, Ken Kisiel

NNLEMS: **Carol Eddy-Dilek (SRNL)**, **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, Hansell Gonzalez Raymat (SRNL), **Amoret Bunn (PNNL)**, **Frederick Day-Lewis (PNNL)**, **Gilles Bussod (LANL)**, **Andrew Tompson (LLNL)**, **Kris Kuhlman (SNL),** James Lee (LANL), Ken Williams (LBNL)

Nuclear Regulatory Commission (NRC): Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL]), Lucy Parham (Utah Division of Water Quality), **Gregory Kinsman (North Wind Portage)**, Michael Pardue (NWP), **Swaine Skeen (SKLS)**, Thomas Prichard (SKLS), Jessica Thatcher (Grand County), **Christian Johnson (PNNL)**, Tom Bachtell (SKLS), Simona Murph (SRNL), Thomas Metschies

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING OVERVIEW

- Jennifer Nyman (Geosyntec) welcomed the attendees and reviewed the meeting agenda. The meeting agenda is attached.
- Jennifer and Liz Moran (Moab) reviewed the communication structure for the collaboration. Meeting materials will be uploaded to a Sharepoint site that collaboration participants will have access to. The collaboration will include a total of 13 weekly meetings that will alternate between full-team meetings and working group meetings.

REVIEW OF FOCUS AREAS

- Jennifer and Brian Looney (SRNL) introduced the three working group focus areas and reviewed the charge of each team:
  - Team 1: GCAP development status, requirements, and path forward
    - Team Lead: Amoret Bunn (PNNL), Jennifer Nyman (co-lead)
  - Team 2: Groundwater contamination-related topics
    - Team Lead: Andy Thompson (LLNL)
  - Team 3: Potential DOE response actions to include in the GCAP
    - Team Lead: Gilles Bussod (LANL, co-lead), Brian Looney (co-lead)
- Based on the self-selection survey that participants submitted to Brian ahead of this meeting, participants were assigned one or more teams to participate in. The team assignments are attached.
- Brian provided a high-level overview of the collaboration approach. The collaboration will not provide a comprehensive plan for Moab to arrive at a

successful end state. The objective of the collaboration is to develop ideas for tools to give the Moab team to refine/optimize their remedial strategy. For example, the collaboration should focus on latest technologies and clever ideas for the site team to incorporate into the remedial strategy. The primary products of the collaboration will be descriptive narratives, one for each idea/recommendation, which will be grouped within the three teams. One objective is to down select as a team a group of ideas that are actionable. A second objective is to affirm or augment the Moab team's plans.

- Andy asked if there is a risk of "stovepiping"? Brian said there will be room for cross-discussion, and there will be participants on multiple teams.
- Amoret asked if there are any changes to regulatory requirements since 2005? Liz replied that there have been aquatic risk updates, as indicated in 2018 Biological Opinion. Liz will check if any other regulatory requirements have been updated.
- Brian presented the long list of recommendations that was generated during Day 2 of the collaboration kickoff. The recommendations are based off participants' first impressions of the site. The long list of recommendation is attached.

REVIEW OF TEAM 1 LONG LIST OF RECOMMENDATIONS

- Amoret suggested that the risk criteria should be clearly defined. Clarification will help with development of options and end states.
- Jennifer wondered if there is potential for compensatory mitigation – other actions elsewhere that could help address impacts to endangered species habitat. Brian noted that one idea is to reroute the river and keep the protective areas. Jennifer clarified that compensatory mitigation is more like fish population augmentation, such as establishment of a fishery.
- Amoret noted to be careful with respect to changing the channel. The young of year fish move like particles; they are not swimming.
- Brian asked about the risk of uranium. Andy responded that uranium is part of a radioactive decay chain. Team 1 recommendations can acknowledge there is production of radioactive daughter products productions and explain why they are not an issue with respect to risk.
- Gilles noted that because of heterogeneity, mobility of uranium is based on changing conditions, like climate, input of water, etc. He reminded the group that groundwater is coming up into the river.
- Chris Pulskamp (EM) noted that, regarding the end state of the site, soil will likely need to be for unrestricted/residential end use. Drilling of groundwater wells is not likely.

REVIEW OF TEAM 2 LONG LIST OF RECOMMENDATIONS

- There was a 100% consensus that three dimensional (3D) numerical modeling is needed for development of the GCAP. It was noted that the LM team does a good job of incorporating 3D visualizations/models into hydraulic/transport models.
- Brian suggested adding reduced order models into the flushing model, perhaps.
- Multiple participants noted that the residual sources beneath the tailings pile and in the vadose zone need to be characterized. This could be done by solid-phase analyses that quantify solid-phase speciation of uranium, such as sequential extractions.
- Andy asked if the tailings are currently a source. Brian suggested a radon soil gas survey could be used to investigate this.
- Al (RSI) noted that for LM sites, a design study would be performed to collect cores from the surface to bedrock in the source area and outside the source area to get an understanding of where and how much contamination is present. 3D visualization programs can then be used to calculate a source mass. Andy agreed with this suggestion.
- The group discussed how to evaluate mass transfer from the brine zone to the freshwater zone. Brian said he does not have a good answer; perhaps tracers can be used. Andy suggested age dating—the shallow water may be younger.
- Keaton (Geosyntec) noted that the transition zone between the freshwater and brine zones may act as a long-term source, similar to how vadose zone can be long term secondary sources at other sites. Geochemical equilibrium modeling and batch reactor studies can be used to understand the geochemical processes of the system. The redox state of uranium in the subsurface is also unknown; uranium mobility is, in part, related to the redox state of uranium.
- Kris (SNL) does not believe the brine formation is old. The groundwater system would naturally stratify, and density is a good stratifier.
- Everyone agreed that a numerical model is needed. The model should include mixing and release from secondary sources.
- Fred (PNNL) suggested using geophysical methods to identify depth to brine. He is interested in the dynamics of the freshwater-brine interface. Development of a conceptual cartoon and a preliminary numerical model can be used to assess how much geophysical characterization to do.
- Liz noted that a subsurface salt cavern was used as a propane storage facility nearby the site.

- Kris suggested consideration of passive geophysical methods for long-term monitoring, such as self-potentials.

RECOMMENDATION DEVELOPMENT PROCESS

- Brian reviewed the recommendation development process:
    - A "pitch sheet" will be developed for each idea included in the long list of initial impressions. Pitch sheets are 1-2 page summaries of the idea. The pitch sheets will be used to present the idea to the team for discussion and review.
    - If the team downselects the pitch sheet for further consideration, the idea will be developed into a "narrative". Narratives are a 4-5 page summary of the idea and include more detail than a pitch sheet, including details on implementation and suitability for Moab site conditions. The author of the pitch sheet will be responsible for writing the narrative.
    - Each participant should generate a list of ideas and send them to Brian before the next meeting. Participants should be prepared to generate a pitch sheet for each idea submitted.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer thanked participants for their time and attention. Participants were reminded of the schedule; teams will meet separately next week to discuss the long list of ideas and assign authors to each idea pitch sheet.
- The following action items were identified:
    - Liz will check if any other regulatory requirements have been updated.
    - Each participant should generate a list of ideas related to their team's focus area and send them to Brian before the next meeting.

Attachments: Draft Long List Based on Initial Impressions from the Kick-off Call, Participant Contact Information and Team Assignments

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Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Meeting 1
Moab UMTRA Site
September 20, 2022

All meeting times shown in Mountain Time

Planned Attendees

DOE-LM: Mark Kautsky, David Shafer

DOE-EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

Meeting Moderator: Jennifer Nyman (Geosyntec)

RSI: Nick Kiusalaas, Al Laase, Doc Richardson, Ron Kent

SKLS: Liz Moran, James Ritchey

Network of National Laboratories for Environmental Management and Stewardship: Carol Eddy-Dilek (SRNL), Brian Looney (SRNL), Katie Muller (PNNL), Hansell Gonzalez Raymat (SRNL), Amoret Bunn (PNNL), Frederick Day-Lewis (PNNL), Gilles Bussod (LANL), Andrew Tompson (LLNL), Kris Kuhlman (SNL), Ken Williams (LBNL)

NRC: Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: Keaton Belli

Observers/Attendees: Tony Mancuso (UT FFSL), Lucy Parham (UT Div. of Water Quality), Gregory Kinsman (NWP), Michael Pardue (NWP), Swaine Skeen (SKLS), Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS)

Agenda

(All meeting times are approximate)

10:00 – 10:05	**Meeting Overview (Jennifer Nyman)**
10:05 – 10:10	**Communications (Jennifer Nyman, Liz Moran)**

- Sharepoint site
- Additional information requests
- Group meeting milestones
- Working group meetings

10:10 – 10:15	**Review of Focus Areas (Brian Looney, Jennifer Nyman)**
10:15 – 11:15	**Long List and Additional NNLEMS Brainstorming (Brian Looney)**

- NNLEMS approach and recommendations
- Discussion
- Note anything to be added
- Information needs (data, reports, etc.)

11:15 – 11:25	**Recap, Schedule Review, and Action Items (Jennifer Nyman)**

Meeting to be held Microsoft Teams

The Moab UMTRA Site will have 7 follow-up full team meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The tentative dates for the focus area technical meetings are also listed below. There will be three focus groups that will meet at separate times. The meetings will be scheduled to last 1 ½ hours:

- Tuesday 27 September, 1000am/1200pm – Focus Area Technical Meeting (not moderated)
- **Tuesday 4 October, 1000am – Full Team Meeting (moderated)**
- Tuesday 11 October, 1000am/1200pm – Focus Area Technical Meeting (not moderated)
- **Tuesday 18 October, 1000am – Full Team Meeting (moderated)**
- Tuesday 25 October, 1000am/1200pm – Focus Area Technical Meeting (not moderated)
- **Tuesday 1 November, 1000am- Full Team Meeting (moderated)**
- Tuesday 8 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 15 November, 1000am- Full Team Meeting (moderated)**
- Tuesday 29 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 6 December, 1000am- Full Team Meeting (moderated)**
- Tuesday 13 December, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 20 December, 1000am- Full Team Meeting/Wrap-up (moderated)**

Moab – NNLEMS collaboration

Draft Long List based on initial impressions from the kick-off call

Synopsis

This list is based on team discussion and subject to adjustment and refinement moving forward. Please note, that our goal is to provide consensus recommendation and opportunities for the Moab team – not to actually do the detailed analysis. So, if we urge consideration of something like surface complexation modeling, we need to dig in enough to see where they are on that topic and identify a few key steps needed to implement the suggestion… not to actually perform a detailed evaluation the heterogeneous and dynamic geochemistry at the site, the mineralogy, the solution matrix. This annotated version includes some of the detailed discussion points made during the call so that folks can see where some of their ideas were captured. The volunteer sheet only includes the bold lines. We are asking for folks to volunteer to contribute and lead on topics – the contributions will be short narratives where your idea is fleshed out in a few (2 to 5) pages.

1.Assess GCAP development status, requirements, and path forward:

Understanding the status and path forward for the GCAP is a community activity that started on the kickoff call. There were a few recurring ideas and recommendations that justify narrative development and focus by team members. These long list topics generally related to the need for risk-based strategies that are tied to end states that are beneficial to stakeholders and support concurrence by regulators. Several comments urged consideration of adaptive management strategies, combined remedies and inclusion of protective institutional controls.

General shared group objectives under this category included: development of a common understanding of GCAP requirements (what is sufficient and necessary), key aspects of the site conceptual models, strategic framework for understanding spatial and temporal conditions (key zones, zone interfaces and mass transfer), and governing regulatory frameworks (NUREG 1620 and 1724). The short 2025 timeline will be challenging and further supports the need for a staged strategy where each period has specific measurable objectives and a rubric to support decisions for transition over time as the site evolves and is cleaned up.

Long list topics for adoption:

- **Supplemental state-of-art and state-of practice risk tools and approaches**
    - ammonia and potential impacts to biota and critical habitats, seasonality and relationship to sensitive species lifecycles
    - biotic ligand modeling (Cu and Se)
    - U risk (high on site and may impacts supplemental standards and ACLs)
- **Potential End State Alternatives**
    - Role of institutional controls
    - Beneficial use to the community (access, beneficial reuse, targeted institutional controls and acceptable risks)
- **Options for combined remedies and adaptive site management**

    - Mass balance-based strategy and implications of enhanced removal versus selective areas of sequestration
    - Strategies that overcome geologic complexity, heterogeneity and temporal dynamics

2.Assess groundwater contamination related topics

This is one of the two major technical topical areas. There was consensus support and validation of the amount/quality/success of the work of the Moab team. Several opportunities and themes emerged from the discussions – primarily in the areas of modeling, characterization and monitoring to support refining the site conceptual model and providing key knowledge to select and optimize future environmental responses/management. There was strong support that a numerical model is needed (specifically a model that can effectively simulate the brine zone and the seasonal & spatial dynamics). Some of these recommendations could be cost effectively performed by university partners or students (next generation).

- **3D numerical model for site geology and hydrogeology**
    - Recommend features of the platform and model to maximize efficiency and value
        - Modern visualization platform that allows rapid and seamless integration of geologic knowledge and hydrologic simulation (e.g., a combination of tools that may include EVS, GMS, visual mudflow, groundwater vistas, and including sub-models that can address key aspects of the brine behavior and interactions with the overlying water such as SEAWAT or possibly Modflow 6).
        - Consider important role of boundary conditions and seasonal dynamics in the selection and implementation of the model
        - Consider how the model will handle data gaps and how it can be used to inform future characterization and monitoring to focus on those that are most important -- LM (currently using EVS and integration with GPS and USGS models) urged doing this type of model sooner rather than later
- **Reduced order models**
    - Opportunities to refine current flushing models and define the role of this type of model to environmental and legacy management(focusing on emerging system behaviors and the net fluxes over time)
- **Source Term** -- Tools and techniques to better understand the location and projected releases of residual and secondary sources (that will remain after the tailings are relocated)
    - Data that can be incorporated into the numerical and reduced order models
- **Geochemistry and isotopes** -- Tools and techniques to address important contaminant behaviors
    - Surface complexation models
    - Ionic strength impacts (e.g., solubilization of natural uranium) and redox impacts (e.g., spatial and temporal changes/mixing)
    - Extend U isotopes and offspring evaluation
    - Apply molecular and biological tools to assess microbial community (focus on enzymes and organisms involved in nitrogen cycling and uranium redox reactions)
    - Evaluate other tracers and age dating tools (waste related, stable isotopes, H3/He3, etc.)

- **Mass transfer associated with brine interface** and the up and down movement of the interface in response to river stage and extraction/injection and other seasonal/climate and anthropogenic factors
- **Analysis of system responses to dynamic site conditions (free signals)**
    - This may be low hanging fruit and several participants highlighted related journal articles and reports
    - May be important in understanding key details of flow in the vicinity of the Colorado River (on both sides of the river)
    - Consider temperature sensors and imaging tools such as IR sensors and fiber optic systems
- **Deep (brine zone) "legacy" contamination** – Technologies options and opportunities to apply innovative characterization to fill in data gaps
    - Borehole logging to generate profiles in existing and new wells (e.g., neutron-gamma elemental logging)
    - Push pull tests
    - Integrated borehole flowmeter testing
- **Climate change and other uncontrolled factors**
- **Data gaps in site geology and hydrogeology**
    - Geophysics (not otherwise captured in above)

3.Assess potential DOE response actions to include in GCAP

A number of innovative ideas for DOE management and response actions were provided. These included the entire range of protective actions (enhanced removal, enhanced sequestration, flushing, natural attenuation, pump and treat, boundary condition control and others. A coordinated strategy will be needed and selecting technologies that are synergistic and (preferably) technologies that are compatible with natural conditions at the site. The group discouraged combined-coincident use of technologies that have inconsistent goals (e.g., enhance flushing and enhanced sequestration). The group urged that the collateral impacts of the technologies be considered (e.g., impacts on both U and NH_3/NH_4 along with possible changes on other constituents such as As, Se, etc.)

- **Passive strategies**
    - Flushing
    - Natural attenuation (consider EPA guidance documents on attenuation of inorganics)
- **Amendments for in situ enhanced sequestration or enhanced flushing** (used to sequester residual source material or to create a permeable treatment zone or to enhance removal)
    - Apatite (ongoing and affirmed)
    - Humate
    - Lixiviants and similar solution mining concepts
    - Heat
    - Silica gel and other materials for isolating contaminants and clogging pores
- **NH_3/NH_4 bioremediation**
- **Permeable reactive barrier**
    - Solid apatite and phosphate minerals
    - Bone char

    - Other - iron/ iron oxides / clays / organoclays
    - Configurations (emplaced barrier or blending)
- **Boundary condition controls**
    - Groundwater bypass
    - Move channel of Colorado River
    - Green capping to control and direct infiltration
- **Limited-term activities to mitigate risk and release of contaminants**
    - Pump with treat and or reinjection
    - Evaporation Ponds
- **Monitoring emplacement and performance of actions**
    - Geophysics – NMR, ERT, etc.
    - Other

Organization	Particpant	Email Address
DOE/LM	Mark Kautsky	mark.kautsky@lm.doe.gov
	Bud Sokolovich	bud.sokolovich@lm.doe.gov
	Diana Trettin	diana.trettin@lm.doe.gov
	Chuck Denton	chuck.denton@lm.doe.gov
	David Shafer	david.shafer@lm.doe.gov
DOE/EM	Chris Pulskamp	christopher.pulskamp@emcbc.doe.gov
	Ming Zhu	ming.zhu@em.doe.gov
	Matt Udovitsch	matthew.udovitsch@emcbc.doe.gov
UMTRA Contractors	Liz Moran	liz.moran@moabem.doe.gov
	James Ritchey	james.ritchey@moabem.doe.gov
GeoSyntec	Jennifer Nyman	jnyman@geosyntec.com
	Keaton Belli	kbelli@geosyntec.com
RSI	Nick Kiusalass	nicholas.kiusalaas@lm.doe.gov
	Al Laase	Al.Laase@lm.doe.gov
	Doc Richardson	doc.richardson@lm.doe.gov
	Ron Kent	ron.kent@lm.doe.gov
National Labs	Carol Eddy-Dilek	carol.eddy-dilek@srnl.doe.gov
	Brian Looney	brian02.looney@srnl.doe.gov
	Katie Muller	katherine.muller@pnnl.gov
	Hansell Gonzalez Raymat	hansell.gonzalez-raymat@srnl.doe.gov
	Amoret Bunn	amoret.bunn@pnnl.gov
	Frederick Day-Lewis	frederick.day-lewis@pnnl.gov
	Gilles Bussod	gbussod@lanl.gov
	Andrew Tompson	tompson1@llnl.gov
	Kris Kuhlman	klkuhlm@sandia.gov
	James Lee	jamesedlee@lanl.gov
	Ken Williams	khwilliams@lbl.gov
NRC	Doug Mandeville	douglas.mandeville@nrc.gov
	John Saxton	john.saxton@nrc.gov
	Bill Von Till	bill.vontill@nrc.gov
Observers	Tony Mancuso	tmancuso@utah.gov
	Lucy Parham	lparham@utah.gov
	Gregory Kinsman	gkinsman@northwindgrp.com
	Michael Pardue	mpardue@northwindgrp.com
	Swaine Skeen	jskeen@skls-llc.com
	Thomas Prichard	thomas.prichard@moabem.doe.gov
	Jessica Thatcher	jthacker@grandcountyutah.net
	Christian Johnson	cd.johnson@pnnl.gov
	Ken Kisiel	ken.kisiel@moabem.doe.gov

Team 1	Amoret Bunn	amoret.bunn@pnnl.gov
	Jennifer Nyman	jnyman@geosyntec.com
	Brian Looney	brian02.looney@srnl.doe.gov
	Andy Tompson	tompson1@llnl.gov
	Gilles Bussod	gbussod@lanl.gov
	Al Laase	Al.Laase@lm.doe.gov
	Liz Moran	liz.moran@moabem.doe.gov

Team 2	Andy Tompson	tompson1@llnl.gov
	Gilles Bussod	gbussod@lanl.gov
	Kris Kuhlman	klkuhlm@sandia.gov
	Fredrick Day Lewis	frederick.day-lewis@pnnl.gov
	Katie Muller	katherine.muller@pnnl.gov
	Keaton Belli	kbelli@geosyntec.com
	Hansell Gonzales-Raymat	hansell.gonzalez-raymat@srnl.doe.gov
	Brian Looney	brian02.looney@srnl.doe.gov
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	Ron Kent	ron.kent@lm.doe.gov
	James Lee	jamesedlee@lanl.gov
	Liz Moran	liz.moran@moabem.doe.gov
	Chris Pulskamp	christopher.pulskamp@emcbc.doe.gov
	James Ritchey	james.ritchey@moabem.doe.gov

Team 3	Giles Bussod	gbussod@lanl.gov
	Brian Looney	brian02.looney@srnl.doe.gov
	Fredrick Day Lewis	frederick.day-lewis@pnnl.gov
	Amoret Bunn	amoret.bunn@pnnl.gov
	Katie Muller	katherine.muller@pnnl.gov
	Andy Tompson	tompson1@llnl.gov
	Kris Kuhlman	klkuhlm@sandia.gov
	Ken Williams	khwilliams@lbl.gov
	Al Laase	Al.Laase@lm.doe.gov
	Hansell Gonzales-Raymat	hansell.gonzalez-raymat@srnl.doe.gov
	Doc Richardson	doc.richardson@lm.doe.gov
	Chris Pulskamp	christopher.pulskamp@emcbc.doe.gov
	Liz Moran	liz.moran@moabem.doe.gov

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 22, 2023

Subject: Meeting Notes, September 27, 2022
NNLEMS Collaboration, Meeting 2
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the September 27, 2022, meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration is organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE), Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting.

DOE LM: Mark Kautsky, Bud Sokolovich, **Diana Trettin**, Chuck Denton, David Shafer, Katie Mclain

DOE EM: **Christopher Pulskamp**, Ming Zhu, Matt Udovitsch

RSI EnTech (RSI): **Nick Kiusalaas**, Al Laase, **Doc Richardson**, **Ron Kent**

Moab Contractors: Liz Moran, **James Ritchey, Barbara Michel,** Ken Kisiel

NNLEMS: Carol Eddy-Dilek (SRNL), **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, Hansell Gonzalez Raymat (SRNL), **Amoret Bunn (PNNL)**, **Frederick Day-Lewis (PNNL)**, **Gilles Bussod (LANL)**, **Andrew Tompson (LLNL)**, **Kris Kuhlman (SNL)**, James Lee (LANL), Ken Williams (LBNL)

Nuclear Regulatory Commission (NRC): Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL]), Lucy Parham (Utah Division of Water Quality), **Gregory Kinsman (North Wind Portage [NWP])**, Michael Pardue (NWP), **Swaine Skeen (SKLS)**, Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS)

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING OVERVIEW AND REVIEW OF COLLABORATION APPROACH

- Jennifer (Geosyntec) welcomed participants to the meeting and reviewed the meeting agenda. The meeting agenda is attached.
- Brian (SRNL) reviewed a high-level summary of the NNLEMS collaboration approach. The primary objective is to develop actionable recommendations to support development of a defensible GCAP for the Moab site. Three focus area teams will work to develop actionable recommendations for the Moab site. First, teams will develop a long list of recommendations. For each recommendation on the long list, a pitch sheet that summarizes the recommendation in 1–2 pages will be developed. Teams will then down select recommendations on the long list based on implementability and suitability for Moab conditions to generate a short list. For each recommendation on the short list, a 4–5-page narrative will be developed that provides more detail on how the recommendation will be implemented at the Moab site.
- Since the last meeting, Brian updated the long list of recommendations with additional ideas that were sent to him. Brian noted that the long list is in good shape. The updated long list is attached.
- Next steps will include identifying ideas that are a good match to the Moab site and are worthy for consideration.
- Brian will send out a template that participants should use to generate a pitch sheet for each of their ideas. He will also send out example pitch sheets for groundwater bypass and reduced order flushing models. The pitch sheet template is attached.

FOCUS AREA ASSIGNMENTS, DISCUSSION AND LEADERSHIP

- Brian presented the team assignments. Assignments were based on the self-selection survey submitted to Brian by each participant. Chris (EM), Liz (Moab), and Mark (LM) will each be assigned to a separate focus area team. A list of team assignments and roles is attached.
- Brian clarified the individual level of contribution of collaboration participants. Each participate is expected to author at least one pitch sheet and narrative as part of their primary team assignment. If participants chose to be a part of more than one team, then their role on the secondary team may be to only provide comments/feedback on pitch sheets and narratives.
- Participants who submit an idea for the long list should be prepared to develop a pitch sheet for the idea. If the idea is selected for the short list of recommendations, then the author of the pitch sheet will be the primary author of the narrative. The broad group can also contribute to the narrative before it is finalized.
- Andy (LLNL) asked if the pitch sheets will survive/be documented. Brian confirmed that pitch sheets will be preserved.
- Brian noted that each team will present their pitch sheets to the full group for discussion. This may generate new ideas that will then be developed into additional pitch sheets/narratives. A goal is to down select ideas for the short list in an orderly, calm fashion.
- Each participant was asked to come up with three to five ideas worth talking about at the next meeting. Each participant should send ideas (and pitch sheets if they have time to draft them) to their team leads.
- The updated long list of ideas, team assignments, and participant email addresses will be sent out to collaboration participants. The updated long list of ideas is attached.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer thanked the participants for their time and contributions.
- The following action items were identified:
    - Jennifer will send out the updated long list of ideas and team assignments to collaboration participants.
    - Liz (SKLS) will send out a compiled list of participant email addresses to collaboration participants.

- Each participant should come up with three to five ideas worth discussing at the next meeting. Participants can begin drafting pitch sheets if they have time. Participants should send ideas and any pitch sheets that have been developed to their team lead.

Attachments: Meeting Agenda; Pitch Sheet Template; Updated Long List Based on Initial Impressions from Kickoff Call; List of Team Assignments and Roles

* * * * *

Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Meeting 2
Moab UMTRA Site
September 27, 2022

All meeting times shown in Mountain Time

Planned Attendees

DOE-LM: Mark Kautsky, David Shafer

DOE-EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

Meeting Moderator: Jennifer Nyman (Geosyntec)

RSI: Nick Kiusalaas, Al Laase, Doc Richardson, Ron Kent

SKLS: Liz Moran, James Ritchey

Network of National Laboratories for Environmental Management and Stewardship: Carol Eddy-Dilek (SRNL), Brian Looney (SRNL), Katie Muller (PNNL), Hansell Gonzalez Raymat (SRNL), Amoret Bunn (PNNL), Frederick Day-Lewis (PNNL), Gilles Bussod (LANL), Andrew Tompson (LLNL), Kris Kuhlman (SNL), Ken Williams (LBNL)

NRC: Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: Keaton Belli

Observers/Attendees: Tony Mancuso (UT FFSL), Lucy Parham (UT Div. of Water Quality), Gregory Kinsman (NWP), Michael Pardue (NWP), Swaine Skeen (SKLS), Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS)

Agenda

(All meeting times are approximate)

10:00 – 10:05 **Meeting Overview (Jennifer Nyman)**

10:05 – 10:10 **NNLEMS Overall Approach (Brian Looney)**

10:10 – 10:40 **Focus Area Assignments, Discussion, and Leadership (Brian Looney, Jennifer Nyman)**

10:40 – 11:00 **Clarification of Individual Levels of Contribution (Brian Looney)**

- Commenting, reviewing
- Owning an idea and writing a narrative

11:00 – 11:30 **Assignment of Topics and Summary Sheets (Brian Looney)**

11:30 – 11:40 **Check in with NRC, Chris P. (Jennifer Nyman)**

11:40 – 11:50 **Recap, Schedule Review, and Action Items (Jennifer Nyman)**

- Focus area meetings next week

Meeting to be held Microsoft Teams

The Moab UMTRA Site will have 7 follow-up full team meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The tentative dates for the focus area technical meetings are also listed below. There will be three focus groups that will meet at separate times. The meetings will be scheduled to last 1 ½ hours:

- **Tuesday 4 October – Focus Area Technical Meetings**
- **Tuesday 18 October, 1000am – Full Team Meeting (moderated)**
- Tuesday 25 October, 1000am/1200pm – Focus Area Technical Meeting (not moderated)
- **Tuesday 1 November, 1000am- Full Team Meeting (moderated)**
- Tuesday 8 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 15 November, 1000am- Full Team Meeting (moderated)**
- Tuesday 29 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 6 December, 1000am- Full Team Meeting (moderated)**
- Tuesday 13 December, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 20 December, 1000am- Full Team Meeting/Wrap-up (moderated)**

Criterial for Collaboration Products

- Actionable recommendations
- Address Debbie Barr's charge questions – Whit id DOE doing that they should continue/stop/augment?
- The objectives for each topic area are annotated on the following series of slides

Previous Criteria Included (Based om LM)

- Feasibility, ease of implementation
- Short-term implementation
- Maturity, reliability, effectiveness
-
- Meeting of regulatory requirements
- Reduction in uncertainty

  Moab-specific criteria could include:
- Schedule – short-,mid-, long-term designation (implementation can extend past UMTRA project)
- Meeting regulatory requirements
- GCAP approval

Moab – NNLEMS collaboration

Draft Long List based on initial impressions from the kick-off call

Synopsis

This list is based on team discussion and subject to adjustment and refinement moving forward. Please note, that our goal is to provide consensus recommendation and opportunities for the Moab team – not to actually do the detailed analysis. So, if we urge consideration of something like surface complexation modeling, we need to dig in enough to see where they are on that topic and identify a few key steps needed to implement the suggestion… not to actually perform a detailed evaluation the heterogeneous and dynamic geochemistry at the site, the mineralogy, the solution matrix. This annotated version includes some of the detailed discussion points made during the call so that folks can see where some of their ideas were captured. The volunteer sheet only includes the bold lines. **We are asking for folks to volunteer to contribute and lead on topics – the contributions will be short narratives where your idea is fleshed out in a few (2 to 5) pages.**

1. **Assess GCAP development status, requirements, and path forward:**

Understanding the status and path forward for the GCAP is a community activity that started on the kickoff call. There were a few recurring ideas and recommendations that justify narrative development and focus by team members. These long list topics generally related to the need for risk-based strategies that are tied to end states that are beneficial to stakeholders and support concurrence by regulators.

Several comments urged consideration of adaptive management strategies, combined remedies and inclusion of protective institutional controls.

General shared group objectives under this category included: development of a common understanding of GCAP requirements (what is sufficient and necessary), key aspects of the site conceptual models, strategic framework for understanding spatial and temporal conditions (key zones, zone interfaces and mass transfer), and governing regulatory frameworks (NUREG 1620 and 1724). The short 2025 timeline will be challenging and further supports the need for a staged strategy where each period has specific measurable objectives and a rubric to support decisions for transition over time as the site evolves and is cleaned up.

Long list topics for adoption:

- **Supplemental state-of-art and state-of practice risk tools and approaches**
    - ammonia and potential impacts to biota and critical habitats, seasonality and relationship to sensitive species lifecycles
    - biotic ligand modeling (Cu and Se)
    - U risk (high on site and may impacts supplemental standards and ACLs)
- **Potential End State Alternatives**
    - Role of institutional controls
    - Beneficial use to the community (access, beneficial reuse, targeted institutional controls and acceptable risks)
- **Options for combined remedies and adaptive site management**
    - Mass balance-based strategy and implications of enhanced removal versus selective areas of sequestration
    - Strategies that overcome geologic complexity, heterogeneity and temporal dynamics
    - Rerouting river bed away from site boundary to mitigate contamination of biota and critical habitats

2.Assess groundwater contamination related topics

This is one of the two major technical topical areas. There was consensus support and validation of the amount/quality/success of the work of the Moab team. Several opportunities and themes emerged from the discussions – primarily in the areas of modeling, characterization and monitoring to support refining the site conceptual model and providing key knowledge to select and optimize future environmental responses/management. There was strong support that a numerical model is needed (specifically a model that can effectively simulate the brine zone and the seasonal & spatial dynamics). Some of these recommendations could be cost effectively performed by university partners or students (next generation).

- **GB: Conceptual Model**
  - Conceptualization of processes important to the characterization and description that captures the principal dynamic hydrologic and chemical processes at work that are required of a site process model needed to predict contaminant migration (primary and secondary sources).
- **3D numerical model for site geology and hydrogeology**
  - Recommend features of the platform and process model to maximize efficiency and value
    - Modern visualization platform that allows rapid and seamless integration of geologic knowledge and hydrologic simulation (e.g., a combination of tools that may include EVS, GMS, visual mudflow, groundwater vistas, and including sub-models that can address key aspects of the brine behavior and interactions with the overlying water (such as SEAWAT or possibly Modflow 6).
    - Numerical model that intrinsically incorporates basic first order reactive chemistry and transport phenomena associated with fluid-rock interactions (Uranium sorption capacity). Consider important role of boundary conditions and seasonal dynamics in the selection and implementation of the model.
    - Consider how the model will handle data gaps and uncertainties and how it can be used to inform future characterization and monitoring to focus on those that are most important -- LM (currently using EVS and integration with GPS and USGS models; **AVO and GPR also useful**) urged doing this type of model sooner rather than later
- **Reduced order models**
  - Opportunities to refine current flushing models and define the role of this type of model to environmental and legacy management (focusing on emerging system behaviors and the net fluxes over time)
- **Source Term** -- Tools and techniques to better understand the location and projected releases of residual and secondary sources (that will remain after the tailings are relocated), including source terms derived from tailings that are now in the subsurface.
  - Any and all data that can be incorporated to constrain and improve the numerical and reduced order models
- **Geochemistry and isotopes** -- Tools and techniques to address important contaminant behaviors
  - Simple surface complexation data and models appropriate for the site

    - Ionic strength impacts (e.g., solubilization of natural uranium) and redox impacts (e.g., spatial and temporal changes/mixing; effects on U-sorption capacity)
    - Extend U isotopes and offspring evaluation
    - Apply molecular and biological tools to assess microbial community (focus on enzymes and organisms involved in nitrogen cycling and uranium redox reactions)
    - Evaluate other tracers and age dating tools (waste related, stable isotopes, H3/He3, etc.)
- **Mass transfer associated with brine interface** and the up and down movement of the interface in response to river stage and extraction/injection and other seasonal/climate and anthropogenic factors
- **Analysis of system responses to dynamic site conditions (free signals)**
    - This may be low hanging fruit and several participants highlighted related journal articles and reports
    - May be important in understanding key details of flow in the vicinity of the Colorado River (on both sides of the river) and the importance of Mountain Front Recharge
    - Consider temperature sensors and imaging tools such as IR sensors and fiber optic systems
- **Deep (brine zone) "legacy" contamination** – Technologies options and opportunities to apply innovative characterization to fill in data gaps
    - Borehole logging to generate profiles in existing and new wells (e.g., neutron-gamma elemental logging)
    - Push pull tests
    - Integrated borehole flowmeter testing
- **Climate change and other uncontrolled factors**
    - Transport simulations tied to transient changes in precipitation and infiltration due to climate
- **Data gaps in site geology and hydrogeology**
    - Geophysics (not otherwise captured in above, AVO, GPR)
    - Down hole borehole characterization, logging and core recovery

3.Assess potential DOE response actions to include in GCAP

A number of innovative ideas for DOE management and response actions were provided. These included the entire range of protective actions (enhanced removal, enhanced sequestration, flushing, natural attenuation, pump and treat, boundary condition control and others. A coordinated strategy will be needed and selecting technologies that are synergistic and (preferably) technologies that are compatible with natural conditions at the site. The group discouraged combined-coincident use of technologies that have inconsistent goals (e.g., enhance flushing and enhanced sequestration). The group urged that the collateral impacts of the technologies be considered (e.g., impacts on both U and NH3/NH4 along with possible changes on other constituents such as As, Se, etc.)

- **Passive strategies**
  - Flushing
  - Natural attenuation (consider EPA guidance documents on attenuation of inorganics)
  - Contaminant dilution and dispersion in saturated zones?
- **Amendments for in situ enhanced sequestration or enhanced flushing** (used to sequester residual source material or to create a permeable treatment zone or to enhance removal)
  - Apatite (ongoing and affirmed)
  - Humate
  - Zeolites
  - Iron shavings
  - Lixiviants and similar solution mining concepts
  - Heat
  - Silica gel and other materials for isolating contaminants and clogging pores
- **NH3/NH4 bioremediation**
- **Permeable reactive barriers/filters with amendments for U-sorption**
  - Solid apatite and phosphate minerals
  - Montmorillonitic Clays
  - Bone char
  - Other - iron/ iron oxides / clays / organoclays
  - Configurations (emplaced barrier or blending)
- **Boundary condition controls**
  - Groundwater bypass
  - Move channel of Colorado River
  - Green surface capping of tailings site post 2025 removal to control and direct infiltration
- **Limited-term activities to mitigate risk and release of contaminants, and attenuate source terms**
  - Segregation: enhanced removal of U by GW pumping/filtration and re-injection of non-contaminated water and off-site disposal of filtered contaminant?
  - Pump with treat/filter
  - Evaporation Ponds
- **Monitoring emplacement and performance of actions**
  - Geophysics – NMR, ERT, AVO etc.
  - Other

Pitch Sheet for Ideas to Support Moab NNLEMS Groundwater Collaboration

(total length about a page plus a graphic if helpful)

Topic: {Title}

Long-List Item Addressed / Objectives: Long List item -- How technology addresses site challenges and/or reduces identified risks. Identify what specific challenge is being addressed by implementing the idea/action/recommendations. Identify the role of the action in resolving uncertainties and how implementation would reduce risk drivers for Moab groundwater.

Description: Short description of the idea or technology

Graphic(s): if appropriate to help convey idea and potential

Match to Moab Conditions: Is the technology well suited to Moab site specific conditions and geometry?

Implementability: a few bullets that capture key topics related to complexity, feasibility, cost and maturity

Timeframe: short term (1 to 2 years), mid term or long term

Technology Inter-Relationships: Identify the potential for added value compared to alternative technologies/strategies that might serve the same role/function. Identify if the technology or strategy supports/leverages planned site activities or other technologies that are already being considered in the baseline – or – if the approaches work against any specific plans/considerations.

Synopsis and Consensus: draft a provisional consensus after discussion

Focus Area team participants

Team 1 (GCAP, risk, path forward)

Amoret Bunn (co-lead, narrative)
Jennifer Nyman (co-lead)
Liz Moran (comment)
Brian Looney (narrative)
Andy Thompson (stay in touch, crossover)
Gilles Bussod (stay in touch)
Al Laase (comment)

Team 2 (assessment, groundwater contamination)

Andy Thompson (co-lead)
Liz Moran (co-lead, comment)
Chris Pulskamp (comment)
James Richey (comment)
Gilles Bussod (narrative)
Kris Kuhlman (narrative)
Fredrick Day Lewis (narrative)
Katherine Muller (narrative or comment)
Keaton Belli (narrative)
Hansell Gonzales-Raymat (comment)
Brian Looney (narrative)
James Lee (narrative)
Al Laase (comment)
Ron Kent (comment)

Team 3 (response actions)

Chris Pulskamp. (co-lead)
Brian Looney (co-lead; narrative)
Gilles Bussod (narrative)
Fredrick Day Lewis (comment or narrative)
Amoret Bunn (stay in touch, crossover)
Katherine Muller (narrative or comment)
Andy Thompson (stay in touch, crossover)
Kris Kuhlman (narrative)
Ken Williams (comment)
Al Laase (comment)
Hansell Gonzales-Raymat (narrative)
Doc R (comment)

Geosyntec consultants

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 22, 2023

Subject: Meeting Notes, October 11, 2022
NNLEMS Collaboration, Meeting 3
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the October 11, 2022, meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration is organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting.

DOE LM: Mark Kautsky, **Bud Sokolovich, Diana Trettin**, Chuck Denton, David Shafer, **Katie Mclain**

DOE EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

RSI EnTech (RSI): **Nick Kiusalaas**, Al Laase**, Doc Richardson**, **Ron Kent**

Moab Contractors: **Liz Moran**, **James Ritchey,** Barbara Michel, Ken Kisiel

NNLEMS: **Carol Eddy-Dilek (SRNL)**, **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, **Hansell Gonzalez Raymat (SRNL)**, **Amoret Bunn (PNNL)**, **Frederick Day-Lewis (PNNL)**, **Gilles Bussod (LANL)**, **Andrew Tompson (LLNL)**, Kris Kuhlman (SNL), James Lee (LANL), Ken Williams (LBNL)

Nuclear Regulatory Commission (NRC): **Doug Mandeville**, John Saxton, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL]), Lucy Parham (Utah Division of Water Quality), **Gregory Kinsman (North Wind Portage [NWP])**, **Michael Pardue (NWP)**, **Swaine Skeen (SKLS)**, **Thomas Prichard (SKLS)**, Jessica Thatcher (Grand County), **Christian Johnson (PNNL)**, Tom Bachtell (SKLS)

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING OVERVIEW AND REVIEW OF COLLABORATION APPROACH

- Jennifer (Geosyntec) welcome participants to the meeting and reviewed the meeting agenda. The meeting agenda is attached.
- Brian (SRNL) reminded participants of the collaboration approach: development of a long list of ideas, develop pitch sheets for each idea on the long list, down select ideas that are suitable for further consideration to a short list, and develop narratives for each short list recommendation.
- Brian reminded participants that pitch sheets are due this week. They should be sent to the respective team lead.

TEAM REPORT-OUTS

- Each team lead was asked to give a progress update on the long list of ideas that their team has been developing and the status of their team's pitch sheets.
- Amoret (PNNL) presented an update on Team 1:
    - Team 1 is focused on brainstorming diverse DOE actions for assessing GCAP development status, requirements, and path forward. Approximately 8-10 ideas have been added to the long list. Two pitch sheets have been completed.
    - Team 1 ideas are organized into several categories:
        - Supplemental state-of-art and state-of practice risk tools and approaches
        - Potential end state alternatives
        - Options for combined remedies and adaptive site management
    - Several Team 1 ideas relate to the Team 2 and Team 3 focus areas. Team 1 participants can partner with the other teams to develop these ideas.

- Several Team 1 ideas seem very promising, such as incorporation of adaptive site management into the Moab remedial management strategy and performing a mass balance and attenuation assessment to support natural flushing as a remedy component in the GCAP. Narratives will likely be generated for these ideas.

- Brian pointed out that NRC and DOE GCAP documents do not include adaptive site management. The team will need to consider how to dovetail this approach with NRC guidance. Brian thinks adaptive site management is a positive idea.
- Brian presented an update on Team 3:
  - Team 3 is focused on brainstorming diverse DOE response actions for consideration in GCAP development and to support an overarching adaptive site management strategy. Approximately 20 total ideas have been submitted for the long list. Five pitch sheets have been completed so far.
  - Ideas have been organized into several categories:
    - Passive strategies
    - Amendments for in situ enhanced sequestration or enhanced flushing
    - Ammonia bioremediation
    - Permeable reactive barriers/filters with amendments for uranium sorption
    - Boundary condition controls
    - Limited-term activities to mitigate risk and release of contaminants, and attenuate source terms
    - Monitoring emplacement and performance of actions
  - Andy (LLNL) suggested acknowledging impacts of climate change on the response actions. He volunteered to write this up as a pitch sheet.
- Andy presented an update on Team 2:
  - Team 2 is focused on brainstorming actions that provide insight and support for understanding the state of groundwater contamination and forecasting its future evolution under both natural and remedial action conditions.
  - Ideas on the long list are broadly organized into several categories:
    - Conceptual and numerical model formulation
    - Improved source term characterization
    - Boundary condition assessments
    - Geochemical and isotopic characterization

        - Climate change impacts
    - Andy presented a high-level review of Team 2's long list.
    - Brian noted that regarding numerical modeling, the pitch sheet/narrative should not go into too much detail. Team 2 should discuss scenarios and desired capabilities of the numerical model rather than a full detailed plan for generating a numerical model.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer reviewed the schedule for the upcoming collaboration meetings. Teams will meet individually next week, the week of October 17, 2022. The next full team meeting is scheduled for October 25, 2022.
- Jennifer reminded collaboration participants to draft pitch sheets for their ideas and send them to their team leads.
- Jennifer opened the floor to the Moab site team to provide initial impressions of the collaboration. Liz (Moab) said that she is interested to learn more about adaptive site management. Liz noted that the Utah Colorado River Management Plan discusses climate change, which is relevant for some of the Team 2 and Team 3 ideas.
- Jennifer thanked participants for their time and participation.
- The following action items were identified:
    - Collaboration participants should draft a pitch sheet for each of their ideas and submit them to their team lead.

Attachments: Meeting Agenda

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Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Meeting 3
Moab UMTRA Site
October 11, 2022

All meeting times shown in Mountain Time

Planned Attendees

DOE-LM: Mark Kautsky, David Shafer

DOE-EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

Meeting Moderator: Jennifer Nyman (Geosyntec)

RSI: Nick Kiusalaas, Al Laase, Doc Richardson, Ron Kent

SKLS: Liz Moran, James Ritchey

Network of National Laboratories for Environmental Management and Stewardship: Carol Eddy-Dilek (SRNL), Brian Looney (SRNL), Katie Muller (PNNL), Hansell Gonzalez Raymat (SRNL), Amoret Bunn (PNNL), Frederick Day-Lewis (PNNL), Gilles Bussod (LANL), Andrew Tompson (LLNL), Kris Kuhlman (SNL), Ken Williams (LBNL), James Lee (LANL)

NRC: Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: Keaton Belli

Observers/Attendees: Tony Mancuso (UT FFSL), Lucy Parham (UT Div. of Water Quality), Gregory Kinsman (NWP), Michael Pardue (NWP), Swaine Skeen (SKLS), Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS)

Agenda

(All meeting times are approximate)

10:00 – 10:05 **Meeting Overview (Jennifer Nyman)**

10:05 – 10:10 **NNLEMS Current Approach (Brian Looney)**

- Pitch sheets due *this week*

10:10 – 11:10 **Team Report-Outs (Amoret Bunn, Andy Tompson, Brian Looney)**

- Team discussion and progress
- Long list of ideas/topics
- Status of pitch sheets

11:10 – 11:15 **Check in with NRC, Chris P. (Jennifer Nyman)**

11:15 – 11:25 **Recap, Schedule Review, and Action Items (Jennifer Nyman)**

- Focus area meetings next week: evaluate pitch sheets and select topics for short list
- Next Full Team Meeting: review short lists, gain consensus

Meeting to be held Microsoft Teams

The Moab UMTRA Site will have full team meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The tentative dates for the focus area technical meetings are also listed below. There will be three focus groups that will meet at separate times. The full team meetings will be scheduled to last 1½ hours:

- **Tuesday 18 October – Focus Area Technical Meetings**
- **Tuesday 25 October, 1000am – Full Team Meeting (moderated)**
- **Tuesday 1 November, 1000am – Full Team Meeting (moderated)**
- Tuesday 8 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 15 November, 1000am – Full Team Meeting (moderated)**
- Tuesday 29 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 6 December, 1000am- Full Team Meeting (moderated)**
- Tuesday 13 December, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 20 December, 1000am- Full Team Meeting/Wrap-up (moderated)**

Geosyntec consultants

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 23, 2023

Subject: Meeting Notes, November 1, 2022
NNLEMS Collaboration, Meeting 4
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the November 1, 2022, meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration is organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

DOE LM: Mark Kautsky, Bud Sokolovich, Diana Trettin, Chuck Denton, David Shafer, Katie Mclain

DOE EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

RSI EnTech (RSI): Nick Kiusalaas, Al Laase, Doc Richardson, Ron Kent

Moab Contractors: Liz Moran, James Ritchey, Barbara Michel, Ken Kisiel

NNLEMS: Carol Eddy-Dilek (SRNL), Brian Looney (SRNL), Katie Muller (PNNL), Hansell Gonzalez Raymat (SRNL), Amoret Bunn (PNNL), Frederick Day-Lewis (PNNL), Gilles Bussod (LANL), Andrew Tompson (LLNL), Kris Kuhlman (SNL), James Lee (LANL), Ken Williams (LBNL)

Nuclear Regulatory Commission (NRC): Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: Keaton Belli

Observers/Attendees: Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL]), Lucy Parham (Utah Division of Water Quality), Gregory Kinsman (North Wind Portage [NWP]), Michael Pardue (NWP), Swaine Skeen (SKLS), Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS)

Meeting Moderator: Jennifer Nyman (Geosyntec)

MEETING OVERVIEW

- Jennifer reviewed the meeting agenda. The meeting agenda is attached.
- Brian (SRNL) reminded participants of the collaboration approach: development of a long list of ideas, develop pitch sheets for each idea on the long list, down select ideas that are suitable for further consideration to a short list, and develop narratives for each short list recommendation.
- All pitch sheets should be drafted this week.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer asked each team to provide a progress update, including the status of pitch sheets and recommendations for which pitch sheets to turn into narratives. She noted that recommendations that are developed into narratives should be actionable.
- Amoret (PNNL) presented a progress update for Team 1:
  - Three items were provisionally identified for narrative development:
    - Ammonia and potential impacts to biota and critical habitats, seasonality and relationship to sensitive species lifecycles
    - Adaptive site management
    - Mass balance-based strategy and implications of enhanced removal versus selective areas of sequestration
  - The following items will be incorporated/subsumed into the adaptive site management narrative:
    - Risk-based decision points that address ammonia and groundwater/surface water interface (critical habitat) in the short term
    - Risk control that addresses changes in groundwater contamination and dynamics of contamination with remedial action

- Andy (LLNL) presented a progress update for Team 2:
  - Pitch sheets were organized into the following categories:
    - Conceptual site model development
    - 3D models for hydrogeology, flow, and transport
    - Reduced order models
    - Source term characterization
    - Deep legacy brine source term characterization
    - Mass transfer behavior at bride or stream interface
    - System responses to dynamic site conditions (free signals)
    - Geochemistry and isotopes
    - Climate change and other uncontrolled factors
  - In total, 21 pitch sheets were developed for Team 2.
  - Team 2 is still working through how to combine the pitch sheets and deciding on which ones to develop into narratives.
- Brian (SRNL) presented a progress update for Team 3:
  - Nine items were provisionally identified for narrative development:
    - Natural attenuation
    - Amendments for in situ sequestration
    - Source zone clogging
    - Solid Amendments for Treatment of uranium and ammonium
    - Deployment Techniques for emplacing solid amendments
    - Groundwater bypass
    - Reconfigure Moab Wash and/or Colorado River
    - Green surface capping over areas of residual subsurface sources
    - Limited pump & treat with strategic reinjection
  - Brian briefly reviewed the nine items and how the technologies may be implemented at the site.
- Brian summarized a potential strategy to incorporate adaptive site management into the Moab remedial strategy. The following sequencing was presented:

- Complete removal and relocation of tailings
- Restore braided stream and native ecosystem in Moab Wash
- Perform targeted site characterization to address data gaps
- Refine site conceptual model and construct numerical model
- Develop a phased GCAP that integrates flushing with targeted areas of sequestration – consider defense in depth approach
- Control mass flux to mitigate risk (may include hydraulic controls with clean water, limited pump and treat, adjustments to Moab Wash Restoration, targeted green capping, strategic use of large volumes of treated water for contaminant sequestration, etc.)
- Discontinue pump-and-treat and implement passive actions that provide technically defensible-protective risk management

- Brian presented a template for developing narratives for each of the actionable recommendations. The recommended length for each narrative is two to six pages, with a nominal goal of three to four pages. The narrative should summarize key information and can use both narrative and bullet or table formats. Eleven sections are included in the template: title, objectives, description, graphics, match to Moab conditions, implementability, exemplars/references, technology inter-relationships, sequencing prerequisites and data gaps/needs, timeframe, and synopsis and consensus. The narrative template is attached.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer reviewed the schedule for upcoming collaboration meetings. Next week, teams will meet individually. The goal of the team meetings will be to achieve consensus on the short list of actionable recommendations. The next full team meeting is scheduled for November 15, 2022.
- Jennifer reminded everyone that participants should finish polishing pitch sheets and start drafting narratives for the pitch sheets that have been confirmed for the short list. The narrative template will be distributed to collaboration participants.
- The following action items were identified:
  - Participants should finish polishing pitch sheets and start drafting narratives for the pitch sheets that have been confirmed for the short list**.**
  - Brian will email the narrative template to participants.

Attachments: Meeting Agenda; Narrative Template

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Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Meeting 4
Moab UMTRA Site
November 1, 2022

All meeting times shown in Mountain Time

Planned Attendees

DOE-LM: Mark Kautsky, David Shafer

DOE-EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

Meeting Moderator: Jennifer Nyman (Geosyntec)

RSI: Nick Kiusalaas, Al Laase, Doc Richardson, Ron Kent

SKLS: Liz Moran, James Ritchey

Network of National Laboratories for Environmental Management and Stewardship: Carol Eddy-Dilek (SRNL), Brian Looney (SRNL), Katie Muller (PNNL), Hansell Gonzalez Raymat (SRNL), Amoret Bunn (PNNL), Frederick Day-Lewis (PNNL), Gilles Bussod (LANL), Andrew Tompson (LLNL), Kris Kuhlman (SNL), Ken Williams (LBNL), James Lee (LANL)

NRC: Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: Keaton Belli

Observers/Attendees: Tony Mancuso (UT FFSL), Lucy Parham (UT Div. of Water Quality), Gregory Kinsman (NWP), Michael Pardue (NWP), Swaine Skeen (SKLS), Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS)

Agenda

(All meeting times are approximate)

10:00 – 10:05 **Meeting Overview (Jennifer Nyman)**

10:05 – 10:10 **NNLEMS Current Approach (Brian Looney)**

10:10 – 11:15 **Team Report-Outs (Amoret Bunn, Andy Tompson, Brian Looney)**

- Team discussion and progress
- Status of pitch sheets
- Recommendations for narratives; "actionable" as an important criterion

11:15 – 11:20 **Review of Narrative Template (Brian Looney)**

11:20 – 11:25 **Check in with NRC, Chris P. (Jennifer Nyman)**

11:25 – 11:30 **Recap, Schedule Review, and Action Items (Jennifer Nyman)**

- Focus area meetings or full team meeting next week
- Consensus on short list
- Start narratives/polish pitch sheets as applicable

Meeting to be held Microsoft Teams

The Moab UMTRA Site will have full team meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The tentative dates for the focus area technical meetings are also listed below. There will be three focus groups that will meet at separate times. The full team meetings will be scheduled to last 1½ hours:

- Tuesday 8 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 15 November, 1000am – Full Team Meeting (moderated)**
- Tuesday 29 November, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 6 December, 1000am – Full Team Meeting (moderated)**
- Tuesday 13 December, 1000am/1200pm- Focus Area Technical Meeting (not moderated)
- **Tuesday 20 December, 1000am – Full Team Meeting/Wrap-up (moderated)**

Template for Topical Narratives to Support Moab–NNLEMS Groundwater Collaboration

Template draft 1 10-27-2022

These will be generated for each item on the short list

Recommended length for each idea is 2 to 6 pages (3-4 pages nominal, 6 pages max)

Strategy is to summarize key information – can use both narrative and bullet or table formats

The template includes:

Title – name of the idea for our discussion and report

Objectives: How technology addresses site challenges and/or reduces identified risks – length = a few sentences to a paragraph/page

Description: Short description of the idea or technology -- length = a few sentences up to a page

Graphic: if appropriate to help convey idea and potential impacts -- length = 1 page or less

Match to Moab Conditions: is the technology well suited to Moab site specific conditions and geometry and goals – length = a few sentences to a paragraph/page

Implementability: complexity, cost, actionable, maturity/technology readiness level (TRL) – length = a few sentences to a paragraph/page

Exemplars/References: provide specific examples of use, references to journal articles or reports with key information or case studies if available – length = a paragraph/page

Technology Inter-Relationships: identify where this would fit in to the baseline and compare to alternative strategies for meeting the objective – length = a few sentences to a paragraph/page

Sequencing prerequisites and data gaps/needs – length = a few sentences to a paragraph

Timeframe: identify timeframe bin from listed choices -- length = a few sentences

Synopsis and Consensus

An annotated version of the template with more description is provided below:

Topic: {Title}

Objectives: How technology addresses site challenges and/or reduces identified risks – length = a few sentences to a paragraph/page. Identify what specific challenge is being addressed by implementing the idea/action/recommendations, Identify the role of the action in resolving uncertainties and how implementation would reduce risk drivers or support the GCAP for Moab groundwater

Description: Short description of the idea or technology -- length = a few sentences up to a page {one to four paragraphs – link to one or a few graphic depiction(s) below if helpful}

Graphic(s): if appropriate to help convey idea and potential impacts -- length = 1 page or less {include if it helps in conveying information succinctly}

Match to Moab Conditions: is the technology well suited to Moab site specific conditions and geometry and goals – length = a few sentences to a paragraph/page

Implementability: complexity, actionable, cost, maturity/TRL – length = a few sentences to a paragraph/page. Note that maturity can be succinctly captured using TRL (1 is basic science, 2-4 are generally lab studies with the higher numbers capturing more realistic scenarios and lab pilot tests, 5-7 represent technologies with some small scale to full scale field testing, and 8 to 10 represent available to commercial and widely available technologies)

Exemplars/References: provide specific examples of use, references to journal articles or reports with key information or case studies if available – length = a paragraph/page

Technology Inter-Relationships: identify where this would fit in to the baseline and compare to alternative strategies for meeting the objective – length = a few sentences to a paragraph/page. Identify the potential for added value compared to alternative technologies/strategies that might serve the same role/function. Identify synergies or antagonists and potential groupings of ideas. Identify if the technology or strategy supports/leverages planned site activities or other technologies that are already being considered in the baseline – or – if the approaches work against any specific plans/considerations

Sequencing - Prerequisites and Data Gaps/Needs – length = a few sentences to a paragraph. Use a bullet list or graphic if helpful. Include some initial thoughts on the next steps needed if the Moab team wants to incorporate this into their programmatic baseline.

Timeframe: identify timeframe bin from listed choices -- length = a few sentences. Timeframe bins are as follows →

- Tier 1 (timeframe 1 to 2 years) -- Can be done with existing data or infrastructure or with data or infrastructure that can be rapidly and inexpensively collected/deployed. Examples would be techniques that re-evaluate or mine existing datasets, new analyses that can be done by collection and analysis of samples from existing wells, data that can be harvested from other sources such as USGS, NWS, USDA, USFS, data repositories or commercial services (satellite imagery). Tier 1 activities could also be used for the first phases of potential future activities such as larger characterization or monitoring efforts or remedies to be considered for inclusion in the adaptive site management plan – this would be things like the forward modeling of geophysics or preliminary modeling of ideas for groundwater bypass or permeable reactive barriers.
- Tier 2 (timeframe 1 to 3 years) – Requires implementation of a significant field effort and collection of new data or installation of new infrastructure – but potential for rapid implementation (for example, by dovetailing with existing plans for field activities or field campaigns such as the apatite field test). Specific examples might be implementation of a large scale geophysics survey or installation of infrastructure for long term geophysical monitoring.
- Tier 3 (timeframe 3 to 10 years) – These would not be implementable to support GCAP development but the timeframes would be needed by the Moab team to allow them to plan and sequence the proposed activities in the GCAP.
- Tier 4 (timeframe > 10 years)

Synopsis and Consensus: length = 1 to 3 sentences. Capture input from the broader group.

Geosyntec consultants

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 23, 2023

Subject: Meeting Notes, November 15, 2022
NNLEMS Collaboration, Meeting 5
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the November 15, 2022, meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration is organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting.

DOE LM: Mark Kautsky, Bud Sokolovich, **Diana Trettin**, Chuck Denton, David Shafer, Katie McLain

DOE EM: Christopher Pulskamp, Ming Zhu, Matt Udovitsch

RSI EnTech (RSI): **Nick Kiusalaas**, **Al Laase**, **Doc Richardson**, **Ron Kent**

Moab Contractors: **Liz Moran**, **James Ritchey, Barbara Michel, Ken Kisiel**

NNLEMS: Carol Eddy-Dilek (SRNL), **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, **Hansell Gonzalez Raymat (SRNL)**, **Amoret Bunn (PNNL)**, Frederick Day-Lewis (PNNL), Gilles Bussod (LANL), Andrew Tompson (LLNL), **Kris Kuhlman (SNL)**, Ken Williams (LBNL), James Lee (LANL)

Nuclear Regulatory Commission (NRC): Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL]), Lucy Parham (Utah Division of Water Quality), **Gregory Kinsman (North Wind Portage [NWP])**, Michael Pardue (NWP), **Swaine Skeen (SKLS)**, **Thomas Prichard (SKLS)**, Jessica Thatcher (Grand County), **Christian Johnson (PNNL)**, Tom Bachtell (SKLS)

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING OVERVIEW

- Jennifer (Geosyntec) welcomed everyone to the meeting and reviewed the meeting agenda. The meeting agenda is attached.
- Brian (SRNL) provided a recap of the collaboration approach. The first phase was generating a long list of ideas. Phase 1 was open and allowed creativity. The second phase is generating the narratives for actionable recommendations on the short list. Narratives should include an objective, a summary of the actionable recommendation, and information for the team to consider. The next phase involves consolidation of the narratives from the three teams into cohesive recommendations for the Moab site.
- The goal over the next week is to finalize the narratives. The narratives should be crisp, short, and formulaic with the same sequence of info.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer asked each team to present a progress update.
- Jennifer presented a progress update for Team 1:
  - Modeling and dynamics were added to the adaptive site management narrative.
  - Amoret (PNNL) reviewed the topic of risk.
  - The mass balance evaluation narrative was moved to Team 3 and consolidated with the recommendation to pursue natural flushing.
- Brian presented a progress update for Team 2:
  - All of the pitch sheets generated for Team 2 were combined and incorporated into nine narratives. The nine narratives were summarized into four actionable categories:
    - Model development and support

        - Physical sampling, monitoring, and characterization
        - Flow sampling, monitoring, and characterization
        - Geochemical sampling, monitoring, and characterization
    - Narratives for borehole assessments and river groundwater interface measurements will serve as menus of technologies for consideration by the Moab team.
    - Brian commented that it was amazing to consolidate 20 pitch sheets into nine narratives.
- Team 2 participants presented a summary of each Team 2 narrative:
    - Ron (RSI) presented an overview of the numerical modeling narrative. A number of pitch sheets were combined and incorporated into this narrative. There is a very strong consensus that numerical modeling would be needed for site. Having the recommendation from NNLEMS to develop a numerical model has helped to move that forward on LM sites. A lot of modeling has been done on LM sites, and the narrative will acknowledge the success of modeling at other sites. The narrative will not dictate software to use but will highlight things that are important that deserve special consideration. The narrative will go into some implementation details and crossover with other technologies. A 3D visualization platform and modeling software can be closely connected and can work together. The narrative includes some ideas of how numerical modeling could be used that might not have been previously considered, such as data worth analysis and a 2D cross-sectional model. The CSM is closely linked to numerical modeling.
    - Brian noted that the numerical modeling narrative is structured in a way to answer questions that will come up for the site. It is the "brightest green" recommendation that has come out of these discussions so far.
    - Amoret asked if the numerical model will also include other characteristics like pH and ammonia. Ron replied that the narrative is open ended. The narrative recommends modeling of flow system and transport for ammonium and uranium. The narrative mentions that more complex geochemical model that includes pH and other water chemistry is a possibility. Amoret hopes to talk further about this between teams. Brian commented that the key for numerical modeling is to identify Moab-specific conditions like the brine interface, the relationship with the river, and the kinds of questions that will be asked of the model. Including more advanced geochemistry in the model is one of the kinds of questions. This can go into criteria that the site uses to select the model. Brian thinks that a full geochemical model might be too robust of a recommendation, but mass balance is important. The ability of the model to project something about pH is reasonable.

- Keaton (Geosyntec) is focusing on the geochemical evaluation narrative. The narrative focuses on three main areas. The first area is solid-phase speciation of uranium within solids. Past work has characterized total uranium in soil, but understanding the phase is going to help refine the source term of any type of modeling or prediction. The second area is redox characterization. The brine layer may be more reducing than the freshwater zone. Understanding how those redox processes might affect mobility is critical. Uranium mobility is greatly determined by redox state. It is recommended to address these two topics with sampling and sequential extractions of site soils. Geochemical equilibrium modeling can be used as an estimate of redox state, but it is not reliable for decisions. The third area is the freshwater/brine interface. It plays a really important role in geochemical processes but has been typically overlooked because sites are often in freshwater. Probing into how ionic strength impacts geochemical processes is important to determining the fate of uranium. Geochem equilibrium modeling can be used to evaluate ionic strength effects. Ultimately, column studies could be used to assess the brine transition zone and the effects of fluctuating depth.
- Kris (SNL) is preparing the transient monitoring narrative, which is very similar to the pitch sheet. The narrative includes clear statements about kind of data involved in it and points to literature on the topic. This narrative also relates to the modeling narrative. The narrative includes a list of suggestions and considerations and is pretty straightforward.
- Brian said that Fred (PNNL) is preparing the narrative on surface water/groundwater interface measurements. It includes three different ways characterize the surface water/groundwater interface.
- Brian is preparing the reduced order model narrative, which is almost complete. It includes ways to estimate the remedial time frame for natural flushing. It affirms what the site has done already.
- Brian is preparing the narrative on isotopes and tracers. It recommends young water dating techniques to determine the relative age of the brine and overlying freshwater zone to get an idea of relative flow of the two zones. This will increase certainty in the conceptual site model.
- Brian and Keaton are preparing the narrative on molecular biology tools. This narrative focuses on examining the subsurface ecology and evaluating microbial transformations of ammonia.
- Brian is preparing the narrative on soil gas surveying. This narrative focuses on measurements of gases in the soil that are associated with uranium (i.e., radon and daughters) and ammonia (i.e., various nitrogen gases). Brian prepared a figure that summarizes the biogeochemical cycling of nitrogen and shows which

nitrogen species are gasses and the key enzymes that perform the transformations. Enzymatic analyses can provide a snapshot of microbial transformations. Soil gasses can be measured to get an idea of which nitrogen transformations are occurring. Brian commented that if participants have a powerful image that pulls together information on a narrative in a simple and compelling way, they are encouraged to include it. David (LM) asked if any sites where ammonia was a major contaminant or sites where processing of ore resulted in ammonia in groundwater were included with the high-risk site working groups for priority LM sites. Brian responded that Monument Valley had ammonia and Tuba City had nitrate. Some language in the narrative came from Monument Valley.

- Jennifer asked if the Team 2 recommendations were prioritized or a menu of options. Brian responded that Team 2 is more of a menu. As narratives are generated, the team will go through sequencing and will need to do some prioritization. Team 2 will bin together some things that are crucial to the site and things that are useful and to be considered. Fred's narrative includes a recommendation to get more information (e.g., a field pilot) then the team can select from a menu of options for characterization.
- Liz (Moab) requested that the most highly recommended items be highlighted. There will be a lot for the team to consider. It would be very helpful to have recommendations related to numerical modeling prioritized. She appreciates all the work and is excited to sift through the recommendations.
- Brian presented a progress update for Team 3:
  - Actionable recommendations developed by Team 3 are more of a menu of technologies that will be provided to DOE to be blended into a remedy for the site. Nine narratives are being prepared for Team 3.
- Team 3 participants presented a summary of each Team 3 narrative:
  - Katie (PNNL) is preparing the narrative for solid-phase amendments. Amendments will target sequestration of uranium, ammonia, or both. A benefit of solid amendments it that one can get a lot of mass into the subsurface compared to liquid injections. The narrative has split the amendments into different classes, including phosphate (apatite), clay, zero-valent iron, and tin apatite (which is not commercially available like the others). Brian provided some custom blend ideas that can treat both contaminants. Most of the amendments are commercially available. The narrative includes recommendations for some batch and column testing to get a better handle on effectiveness, rates, and potential for desorption/reoxidation.
  - Katie is also preparing a second narrative that focuses on how to get the amendments into the subsurface. The narrative includes injection of small-sized particulate amendments (suspension or slurry), injecting into subsurface in

existing wells, and direct push injections. A permeable reactive barrier is also possible. Amendments can also be physically emplaced in the subsurface via trenching or soil mixing. Deployment techniques have high technology readiness levels and are mature.

- Hansell (SRNL) is preparing the narrative on in situ sequestration, which combines three pitch sheet ideas: phosphate calcium solution to create an apatite barrier for uranium; in situ precipitation of ammonium via injection of a phosphate solution to precipitate struvite minerals; and humic solutions to create permeable reactive barriers for uranium and possibly ammonium. Deployment would be injecting reagents into subsurface, and the narrative will include a description of deployment options. This is a mature technology that has been used at Old Rifle and Hanford.
- Brian is preparing narratives for groundwater bypass, natural attenuation, and Moab Wash reconfiguration. He has mentioned these in previous meetings.
- Gilles is preparing a narrative for green surface capping.

- Brian reminded participants to use the template when preparing narratives and to try and keep to the suggested length (3 to 4 pages, maximum of 6).
- Brian is working on prioritizing and sequencing the recommendations. Modeling will be a key part of the sequencing. Brian commented that adaptive site management is essentially thinking about the site in a way in space and time and doing the right thing to get to intermediate and final end states.
- Brian presented multiple slides that depict a timeline of implementation of the collaboration recommendations. Development of a numerical model is front loaded and should be performed in the near-term so it can be used to identify remedial strategies for the GCAP. The numerical model can be conceptualized as a "GCAP Basis Model" that is used to make decisions about which response actions to include in the GCAP, followed by a "GCAP Adaptation Model" that is used make decisions in the future about when to transition the remedy from active and passive phases (adaptive site management). Recommendations for additional site characterization (Team 2) will mostly be implemented in the near term to inform development of the GCAP Basis Model.
- Amoret asked if there is a difference between a solid line and dots on Brian's slides. Brian intended the solid line to represent an official period, whereas the dots represent continued activity that cannot be described yet. Amoret asked if narrative authors should include periodic updates in the narratives. That is, should narrative authors describe when an update should happen? Brian said that narratives do not have to say exactly when an update should happen, but they should say there should be a plan for updates.

- Participants were reminded to complete their narratives and submit them to their team lead by Friday, November 18.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer reviewed the schedule for upcoming collaboration meetings. There are no meetings next week due to the Thanksgiving holiday. Teams will meet individually the week of November 28, 2022. The next full team meeting is scheduled for December 6, 2022.
- Liz commented that she likes the path the teams are on and is happy with the results of the collaboration so far.
- The following action items were identified:
    - Participants will complete their narratives and submit them to their team lead by Friday, November 18.

Attachments: Meeting Agenda

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Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Meeting 5
Moab UMTRA Site
November 15, 2022

All meeting times shown in Mountain Time

Agenda

(All meeting times are approximate)

10:00 – 10:05 **Meeting Overview (Jennifer Nyman)**

10:05 – 10:10 **NNLEMS Current Approach (Brian Looney)**

10:10 – 10:40 **Team Report-Outs (Amoret Bunn, Andy Tompson, Brian Looney)**

- Team discussion and progress
- Status of narratives

10:40 – 10:45 **Review of Narrative Template (Brian Looney)**

10:45 – 11:15 **Integration and Sequencing of Recommendations (Brian Looney)**

- Discussion/Input from group

11:15 – 11:25 **Check in with NRC, Chris P. (Jennifer Nyman)**

11:25 – 11:30 **Recap, Schedule Review, and Action Items (Jennifer Nyman)**

- *Complete narratives* by Friday, November 18 and send to team leads

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Meeting to be held Microsoft Teams

The Moab UMTRA Site will have full team meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The tentative dates for the focus area technical meetings are also listed below. There will be three focus groups that will meet at separate times. The full team meetings will be scheduled to last 1½ hours:

- Tuesday 29 November, 1000am/1100am- Focus Area Technical Meeting (not moderated)
- **Tuesday 6 December, 1000am – Full Team Meeting (moderated)**
- Tuesday 13 December, 1000am/1100am- Focus Area Technical Meeting (not moderated)
- **Tuesday 20 December, 1000am – Full Team Meeting/Wrap-up (moderated)**

Geosyntec consultants

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 24, 2023

Subject: Meeting Notes, December 6, 2022
NNLEMS Collaboration, Meeting 6
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the December 6, 2022, meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration is organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting.

DOE LM: Mark Kautsky, **Bud Sokolovich, Diana Trettin, Chuck Denton**, **David Shafer, Katie Mclain**

DOE EM: **Christopher Pulskamp**, **Ming Zhu**, Matt Udovitsch

RSI EnTech (RSI): Nick Kiusalaas, Al Laase, Doc Richardson, **Ron Kent**

Moab Contractors: **Liz Moran**, **James Ritchey,** Barbara Michel, Ken Kisiel

NNLEMS: Carol Eddy-Dilek (SRNL), **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, Hansell Gonzalez Raymat (SRNL), **Amoret Bunn (PNNL)**, **Frederick Day-Lewis (PNNL)**, **Gilles Bussod (LANL)**, **Andrew Tompson (LLNL)**, **Kris Kuhlman (SNL)**, Ken Williams (LBNL), James Lee (LANL)

Nuclear Regulatory Commission (NRC): Doug Mandeville, John Saxton, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL]), Lucy Parham (Utah Division of Water Quality), **Gregory Kinsman (North Wind Portage [NWP])**, Michael Pardue (NWP), **Swaine Skeen (SKLS)**, Thomas Prichard (SKLS), Jessica Thatcher (Grand County), Christian Johnson (PNNL), Tom Bachtell (SKLS), Brady Lee

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING OVERVIEW

- Jennifer (Geosyntec) welcomed everyone to the meeting and reviewed the meeting agenda. The meeting agenda is attached.
- Brian (SRNL) reviewed the approach for prioritizing and sequencing the recommendations. The goal is not to present old material. The goal is to present interesting material and the process. Team 2 recommendations will be prioritized. Team 1 recommendations are overarching. Team 3 recommendations serve as a menu of technologies and resources for the Moab team to consider in the future.

TEAM STATUS UPDATES

- Jennifer asked each team to present a progress update.
- Amoret (PNNL) presented a progress update for Team 1:
  - Team 1 recommendations focus on overarching issues. Some of these relate to recommendations from Teams 2 and 3 and the dynamic issues of the site.
  - Amoret likes the figure showing how critical habitats along the bank of the Colorado River have changed over time. There used to be multiple critical habitats, but these have shrunk over time as the river morphology has changed. Teams 2 and 3 can help the site address how the river morphology changes over time.
  - Adaptive site management is the primary recommendation of Team 1. Site objectives represent spatial and temporal issues of today and those that are changing with natural attenuation and remediation. Because of this, it is very important to refine the conceptual site model.
  - Amoret presented a conceptualization of the site as multiple spatial zones that will require different remedies to address the site objectives. This is only a concept and the figures do not necessarily apply to the current site status. The idea is to

separate the site into multiple zones. The zones provide a means to address how recommendations will relate to the site and the conceptual site model. It is a way to organize preliminary/interim objectives for the site according to adaptive site management.

  - Brian explained the various zones that were proposed and how they relate to the adaptive site management concept. Adaptive site management has been previously accepted by the Fish and Wildlife Service and DOE, including for the Columbia River. Stakeholders have found this approach to be acceptable at other sites.

- Jennifer commented that adaptive site management may sound open-ended but can include decision points and performance metrics for changing the remedy over time.
- Chris (EM) had some programmatic comments to incorporate in the spatial zone concept. For example: Moab Wash, LM eventually taking over the site, and how the 60% and 90% design process for the evapotranspiration cover at the disposal cell would fit into adaptive site management. There are currently contractual obligations for contractor to submit those. They may need to look at timeframe and what makes sense. Liz (UMTRA) said one example is a National Environmental Policy Act (NEPA) document, which requires a public comment period. Amoret thinks she has one for Columbia River management. She will send it to Liz. Brian commented that remediation at Savannah River Site was performed before the adaptive site management concept was developed. They have a different NEPA scenario. They did a site-wide groundwater Environmental Impact Statement (EIS). He does not have a good example that is applicable to Moab.
- Andy (LLNL) presented a progress update for Team 2:
  - Nine actionable recommendations were organized into the following categories:
    - Model development and support
    - Physical sampling, monitoring, and characterization
    - Flow sampling, monitoring, and characterization
    - Geochemical sampling, monitoring, and characterization
  - Andy presented a summary of each of the nine actionable recommendations
- David (LM) commented that LM has had work going on for 10 years regarding uranium from springs that emerge from the Mancos Shale in the Colorado Plateau. At one time they were looking at total uranium instead of isotopes. They made assumptions that uranium was from mills and mines, but people like Ray Johnson around 2011 started seeing significant differences with respect to isotopes of uranium (the assumption of secular equilibrium was wrong). They observed a different

signature of uranium that originated in Mancos Shale and had long travel times versus uranium from mill processing or ore processing. That led to looking at a series of other types of stable isotope ratios as supporting indicators. The isotope recommendation of Team 2 reminded him of that work. It might be useful to look back at that work.

- Andy commented that they looked at uranium isotopes in Southern Nevada. U-238 and U-234 were way out of equilibrium in water, for all sorts of reasons. By looking at uranium isotopic composition, one can see how ratios carry through and whether they have distinct signatures, similar to environmental forensics. There is a group at LLNL that deals with forensics. They have looked at (in other countries) signatures of uranium ore that comes out of mines with respect to source identification. The site may have uranium from many different sources.
- David is happy to send a couple of references along. He has dealt with this at three or four mill and mining sites. Different organizations, such Navajo Nation, Nuclear Regulatory Commission, and United States Geological Survey, do not always agree, but there is general agreement on some of those isotopic ratios as indicators of source.
- Brian co-authored the isotope narrative with Keaton (Geosyntec). Moab has previously measured uranium isotopes in groundwater. He will upgrade the discussion and references to LM sites in the narrative. The site team does not need to look into where the ores came from but rather into natural signals.
- Brian noted that the Team 2 recommendations will be prioritized. They will identify top priority recommendations and then 3–5 additional things to perform in the near term. Priorities will focus on ones with the most potential to impact the site. Brian said that Jennifer may want to include more recommendations, including from the secondary source investigation that is starting in Spring 2023.
- Brian provided a progress update for Team 3:
    - The primary Team 3 recommendation will be to consider response actions from the menu of options that Team 3 has generated. Multiple response actions that vary in space and team will be needed to achieve closure (relates to incorporation of adaptive site management recommendation of Team 1).
    - Brian reviewed the narratives developed by Team 3.
- David commented in the Teams chat: "Here is a link to an article by Kamp and Morrison (2014) : https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/2525475"
    - This article uses isotopic characterization to distinguish between mill-related and natural uranium in groundwater

- Amoret commented in the Teams chat: "Liz - for the list of solid amendments for treatment of U and NH4, we can help connect you with references from the Hanford Advisory Board, Tribal consultation, Natural Resources Trustees on their questions and responses about how the amendments at Hanford have address aquatic resources. These are not formal documents but could help make connections with stakeholders and regulators."
- Brian commented that a scoping analysis should be considered. He may be calling folks if more clarity or information is needed.
- Andy asked people to update the narrative file names with "v2." Liz added a v2 folder to each team folder on the Sharepoint site.
- Brian asked Team 2 members to list the highest priority Team 2 recommendation and then up to 5 other that should be prioritized in the near-term. Team 2 members were asked to comment whether the site team should consider these recommendations in next year's effort. The goal of this exercise is to get consensus on the priorities of the Team 2 recommendations.
  - Brian said that modeling is the most important. The site needs to make modeling a priority. A river survey is a top priority for next year. A soil gas scoping event should be considered for next year. Other priorities are tracers, geochemistry studies, and borehole logs (next year or not).
  - Andy agrees that numerical modeling is the first priority. He is a fan of borehole and geophysical assessments and geochemical assessments. These should be done next year. Isotopic and sediment/water interface measurements are his third priority. Transient work and climate change are near to his heart and would not take a lot of work. Climate work will fold into the model. Transient measurements are an easy thing to do and are useful.
  - Fred (PNNL) ranked numerical modeling first. Borehole geophysical surveys are useful for siting other things that will happen and are low-hanging fruit. The same goes for some of the sediment/water interface work. Using hand probes, etc. is very easy and low cost. Transient signals recommendation – analyzing data already available – is easy in year 1.
  - Ron (RSI) said modeling is the top priority. It will be difficult to get the GCAP approved without a 3D numerical model. His next priority is borehole measurements, followed by characterizing residual source mass. Source mass characterization was critical at Monticello. Because of the importance of fish habitats, sediment/water measurements should also be prioritized.
  - Gilles (LANL) agreed that modeling is the top priority. A caveat is that his second priority is any characterization data which includes borehole geophysics or a

borehole where one can do geophysics but also sample the chemistry of the water and possibly sample to know lithology. Numerical modeling also means data that feeds that model. Anything related to the water interface will be important for completing geophysics.

- Kris (SNL) said sediment/water interface measurements are the most important and should go first to collect data for the model. Geophysical characterization is his second priority. Free transient signal is another type of modeling with different dimensionality—it could be lumped with modeling as his third priority. The right data is needed, or else modeling is open-ended. Data is critical.
- Keaton said that modeling is first. Secondary priorities should be efforts to enhance characterization for modeling, for example borehole characterizations, geochemical analysis, and transient aquifer modeling. These should be emphasized in the next year.
- Al (RSI) agreed with Keaton. The right information is needed for the model. Geochemistry is important, then borehole and geophysical evaluations, and then free signals. Then sediment/water interface, which is also important.
- Katie (PNNL) echoed everyone else. Numerical model development is first, followed by site characterization activities.
- Liz said modeling is the first priority, but there is work to be done before getting there. Secondary source characterization is also a priority.
- Chris (EM) concurred with what other individuals have said. He now has a better idea of characterization activities, which includes modeling.
- Gilles commented that the borehole assessment is driven, in part, by understanding the brine/freshwater interface.
- Jennifer pointed out the importance of understanding whether the brine layer contributes significant mass flux to the overlying groundwater. Brian responded that age dating and/or isotopic analysis may be important for that.

- Brian presented slides that summarize the sequencing of recommendations. He will go through the final narratives and see if enough information is included to flush out the sequencing. The goal is to give the Moab team a robust product that fits together on multiple levels. The spatial zonation concept will be included as a notional idea—the idea is not set in stone but is a representative example for the site team to consider.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer reviewed the schedule for upcoming collaboration meetings. Teams will meet individually the week of December 12, 2022. The next and final full team meeting is scheduled for December 20, 2022.
- Chris commented that an amazing amount of work has been put into this effort. He could not be more grateful for the expertise and innovation that everyone has contributed.
- The following action items were identified:
    - Amoret will send an example NEPA document for Columbia River management to Liz.

Attachments: Meeting Agenda

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Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Meeting 6
Moab UMTRA Site
December 6, 2022

All meeting times shown in Mountain Time

Agenda

(All meeting times are approximate)

10:00 – 10:05 **Meeting Overview (Jennifer Nyman)**

10:05 – 10:10 **NNLEMS Current Approach (Brian Looney)**

- Scope, scale, implementation details

10:10 – 11:00 **Team Report-Outs (Amoret Bunn, Andy Tompson, Brian Looney)**

- Team discussion and progress
- Narratives complete
- Prioritization for Team 2 recommendations

11:00 – 11:15 **Integration/Sequencing of Recommendations (Brian Looney, if needed)**

11:15 – 11:25 **Check in with NRC, Chris P. (Jennifer Nyman)**

11:25 – 11:30 **Recap, Schedule Review, and Action Items (Jennifer Nyman)**

- Add scope, scale, implementation details to narratives

Meeting to be held Microsoft Teams

The Moab UMTRA Site will have full team meetings, listed below, to develop risk-reduction recommendations, which will be finalized into one report. The tentative dates for the focus area technical meetings are also listed below. There will be three focus groups that will meet at separate times. The full team meetings will be scheduled to last 1½ hours:

- Tuesday 13 December, 1000am/1100am- Focus Area Technical Meeting (not moderated)
- **Tuesday 20 December, 1000am – Full Team Meeting/Wrap-up (moderated)**

Geosyntec consultants

1111 Broadway, 6th Floor
Oakland, California 94607
PH 510.836.3034
www.geosyntec.com

Memorandum

Date: February 24, 2023

Subject: Meeting Notes, December 20, 2022
NNLEMS Collaboration, Meeting 7
Moab UMTRA Project Site

Geosyntec Consultants, Inc. (Geosyntec) has prepared meeting notes to summarize the December 20, 2022, meeting of the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Collaboration for the Moab UMTRA Project (Moab) Site. The collaboration is organized by the Savannah River National Laboratory (SRNL) in partnership with the Department of Energy (DOE) Office of Environmental Management (EM), DOE Office of Legacy Management (LM), DOE contractors, NNLEMS, and Geosyntec. The NNLEMS consists of subject matter experts from SRNL, Pacific Northwest National Laboratory (PNNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and Lawrence Berkeley National Laboratory (LBNL). The objective of the collaboration is to develop actionable recommendations for acquiring data and closing data gaps in support of developing a defensible Groundwater Compliance Action Plan (GCAP) for the Moab site.

The meeting notes are summarized below by general agenda item, followed by a summary of action items.

INVITED ATTENDEES

Names shown in bold were identified as attending the meeting.

DOE LM: **Mark Kautsky**, Bud Sokolovich**, Diana Trettin, Chuck Denton, David Shafer, Katie Mclain**

DOE EM: **Christopher Pulskamp**, Ming Zhu, Matt Udovitsch

RSI EnTech (RSI): **Nick Kiusalaas**, **Al Laase**, **Doc Richardson**, **Ron Kent**

Moab Contractors: Liz Moran, **James Ritchey**, Barbara Michel, Ken Kisiel

NNLEMS: Carol Eddy-Dilek (SRNL), **Brian Looney (SRNL)**, **Katie Muller (PNNL)**, **Hansell Gonzalez Raymat (SRNL)**, **Amoret Bunn (PNNL)**, **Frederick Day-Lewis (PNNL)**, **Gilles Bussod (LANL)**, **Andrew Tompson (LLNL)**, **Kris Kuhlman (SNL)**, **Ken Williams (LBNL)**

Nuclear Regulatory Commission (NRC): **Doug Mandeville**, John Saxton, Bill Von Till

Geosyntec: **Keaton Belli**

Observers/Attendees: **Tony Mancuso (Utah Division of Forestry, Fire, and State Lands [UT FFSL])**, Lucy Parham (Utah Division of Water Quality), Gregory Kinsman (North Wind Portage [NWP]), Michael Pardue (NWP), **Swaine Skeen (SKLS)**, **Thomas Prichard (SKLS)**, Jessica Thatcher (Grand County), **Christian Johnson (PNNL)**, Tom Bachtell (SKLS), James Lee (LANL)

Meeting Moderator: **Jennifer Nyman (Geosyntec)**

MEETING OVERVIEW

- Jennifer (Geosyntec) welcomed the participants to the final meeting of the NNLEMS collaboration and reviewed the meeting agenda. The meeting agenda is attached. This meeting is primarily focused on refining and finalizing narratives to support implementation of a portfolio of technologies and strategies.
- Brian (SRNL) reviewed the current approach to the collaboration:
  - Three teams were developed that focused on specific topics:
    - Team 1 – GCAP development topics including regulatory and stakeholder topics, and risk science. Led to a focus on adaptive site management and end state goals.
    - Team 2 – Modeling and Characterization. Many ideas to be discussed in more detail later in the meeting.
    - Team 3 – Remediation and site management technologies and strategies. Developed a menu of technologies for consideration by Moab with application to meet mid-term and long-term objectives.
- Amoret (PNNL) provided a summary of Team 1's recommendations. Adaptive site management was the primary recommendation of Team 1. Adaptive site management is accepted with regulators, including Fish and Wildlife Service. It allows the site to return and reassess changes in the environment and update the conceptual site model and end state goals as improvements occur.
- Andy (LLNL) provided a summary of Teams 2's recommendations. Team 2 developed nine narratives that represent actionable recommendations focused on site characterization and addressing data gaps. The recommendations represent a triangle of interlocking topics: conceptualization, computer models for forecasting, and

collecting data to support those efforts. The latter was reaffirmed as very important – with new ways to get new data.

- Brian provided a summary of Team 3's recommendation. Team 3 developed nine narratives that represent a menu of response actions that the Moab team can select from in the future to achieve site objectives. These should be seen as a resource for defining a remedy once site characterization is complete.
- Brian presented consensus statements he developed that summarize the recommendations of the collaboration. The consensus statements are attached.
- The first consensus statement is "GCAP decisions and development will require support using numerical modeling." This was a universal consensus from the NNLEMS, NRC, others, and the Moab team.
- Andy asked if there is anything in the consensus statements with regard to data supporting the model itself. Brian responded yes. The idea is in the triangle—models require data to look forward and for credibility. The data serve dual purposes, to verify and validate the model. Ron said he agreed with the consensus statement and noted that the narrative has a lot more detail. The consensus statement captures the key points. The narrative has a section on the CSM, which is sort of mentioned in the consensus statement, because we have to understand the key structures of the site to develop a model. The consensus statement captures the modeling recommendation overall.
- Gilles (LANL) noted that there is a feedback loop—the modeling supports adaptive site management and characterization/monitoring.
- The second consensus statement is "Moab is a 'complex site', and the collaboration recommends developing a GCAP that is consistent with the challenges and emerging science and policy for such sites."
- Jennifer noted that the current remedy is interim. An objective of this statement is to think ahead to the end state and consider the various steps to get there.
- The third consensus statement is "Additional characterization is needed to inform GCAP development and to support selection and implementation of most effective technologies to use for later temporal stages of the GCAP remedy."
- Andy commented that he likes how the Team 2 recommendations are grouped together: physical, flow, and geochemistry. They all complement each other. Brian noted that we are going to recommend encouraging a portfolio of actions. Are all three needed? He thinks so. Andy said people will gravitate to geochemistry right away, with uranium mobility in groundwater, redox processes, and sorption. Discharge of contaminants to the river is a unique opportunity. The river proximity

impacts subsurface hydraulics and provides gives good opportunities for additional characterization.

- Gilles noted that under consensus statement 3, the road infrastructure piece should be termed "Environmentally Sustainable Road Infrastructure" otherwise - there is nothing new about suggesting road infrastructure as it will be implemented using old techniques that are not "green" (high carbon footprint).
- Brian reviewed the spatial/temporal zones and the associated objectives. Each spatial zone has characteristic features, with associated objectives. The zones are built around the conceptual site model. A temporal framework might be built around river protection in near-term.
- Brian noted that the cross-sectional conceptual site model shows great-quality work has been going on for a long time. Key conceptual features are included in the cross section. Gilles commented that the conceptual model does not capture mountain front recharge. Andy noted that it should, not to worry. Kris (SNL) commented that it might be good to add a note there is probably a fair amount of flow in and out of the third dimension on this cross section.
- Andy asked if there is a section with regard to water inputs, such as mountain recharge and infiltration. He wondered if it is useful to acknowledge inputs and outputs. Are they matched? Is the brine zone isolated? This hypothesis could be tested with techniques. With cross-sections, there is a concern that it is not infinite in third dimension. The cross sections need to match salinity and volumetric flows. Brian likes that idea; he will add something showing recharge and a flow line that goes down through the brine zone. Brian noted that Fred's (PNNL) suggestion of probe samplers in the river and tracers should be helpful.
- Ken (LBNL) added a comment to the Team chat: "@All: Don't forget about this extremely relevant paper in terms of looking at preferential fresh vs. brine groundwater discharge zones along the stretch of Colorado River running past the Moab site: https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwat.12866"
- Brian said that Jennifer and he are reading every narrative and pulling out timing recommendations. They will run back by the narrative authors to get concurrence. The goal is to consider the recommendations in time and put together a timeframe where they have an insertion point. Brian will be working on putting together a more precise timeline over the next few weeks.
- Brian said that he did a little estimation of scoping, but not as much as LM. He will go through the narratives with that in mind and run it back by the authors. The Moab team needs that kind of information to plan the program and select among the recommendations.

- A number of recommendations enhanced the baseline. Small things may be done as part of the baseline characterization. The Moab team is relatively small and resource limited. To date they have focused on tailings relocation. An additional recommendation is a baseline resource addition, like another full-time employee, to handle site characterization and GCAP activities.
- The floor was opened up for comments regarding generation of a site characterization portfolio.
- Fred commented that push probe and infrared camera tools are great and can be used to site vertical temperature probes and flux chambers. Inland, surface and borehole geophysics could be done fairly soon, but probably more planning is involved. It is important to stage that properly. Borehole geophysics characterization should be intentional. Brian supported performing geophysics in existing wells. Fred agreed.
- Kris commented that zone 4 in Brian's zonation of the site is critical because it is a discharge point to the Colorado River. There is a unique opportunity when things are up at surface, so characterization should be done in space and in time. Thermal cameras can be used to detect differences and monitoring at multiple times. What is found can then be traced back further inland into the system. Regarding zone 1 (beneath the tailings), has the contamination that leached from the tailings been characterized from early days? If the slurry or process waters were documented, then one can get an idea of the density. He imagines contamination may be floating on top of a brine layer. This may be hard to characterize. It might be a thin lens. It will depend on the water budget for the system.
- Ron (RSI) noted that characterization has been really important for LM sites, especially with regard to quantifying the source term. There is a need to quantify the mass balance of secondary sources. Geochemical characterization in boreholes is important. The Monticello site required source controls. Regarding free transient signals, the sooner they are measured, the more value; it is simple to do.
- Keaton (Geosyntec) recommended prioritizing anything that supports development of model. Free signals (installing transducers) are low-hanging fruit. From a geochemistry perspective, the site is already considering column tests to look at pore volume flushing of uranium to achieve cleanup goals. The scope can be expanded to evaluate the effect of ionic strength and salinity on geochemical processes (zone 3). Solids interact with both fresh and saline water.
- Nick (RSI) recommended considering installing a SOARS station. If it was discussed already, he missed it.
- Hansell (SRNL) noted that sensors for conductivity could easily be installed in existing wells.

- Amoret noted that the breadth of technologies is really important. Understanding contaminants of concern with water chemistry is critical to understanding ecological risk. Breadth of technologies is also important with respect to discussions with regulators. Technologies should be matched with zones. A matrix would allow site management to understand what is important first then adapt as needed. Regarding inputs and outputs, a flux and mass balance evaluation would help assess how well the conceptual site model is working.
- Andy commented that understanding the fate of the saltwater body (brine zone) is important. Tracers can be used to identify age and reconcile that with salinity measurements from boreholes. Understanding how much of the brine zone participates in water movement helps in understanding the whole story. Deep boreholes may be needed. Are there transients in the deep brine zone?
- Gilles commented that deeper borehole studies may be required sooner than later for understanding the groundwater flow model.
- Brian likes what everyone has been saying. Tracers, isotopes, and age dating are critical for zone 1D. Information on possible flux at interface between brine and overlying intervals should also be gathered. A top recommendation is river surveying for protecting critical habitats. We should see if the soil gas survey has any value. It can be used to map residual shallow source material for not much effort. Some geophysical logging techniques should be scoped, including electromagnetic induction (EMI), which will tell something about brine interface. These can be tracked seasonally.
- Nick suggested looking for correlations between conductivity and contaminant concentrations. A correlation would allow transient monitoring. Andy added that correlations between groundwater age and salinity can also be evaluated.
- Doug (NRC) said that he has nothing to add.
- Tony (UTFFSL) thanked the group for their insight. It has been interesting to watch. He noted that they are very curious about the interface of Colorado River surface water and brine. There are a couple caveats. Whatever is installed cannot obstruct navigability of the river and must allow for passage of large boats. He can work together with the Moab team down the road. His agency issues permitting for all kinds of monitoring implements, and he can help the team work through them.
- Ken added a comment in the Teams chat: "@All: We will soon have a suite of borehole NMR logging measurements in multiple wells in the area of the former uranium plume study area in the northeastern part of the site. These will be made available to the broader group to assess their use in constraining hydrogeologic parameter estimation and pore size distributions across different facies types"

- Brian said that there are two paths forward: 1) review of narratives for resources and sequencing/scheduling; and 2) preparing the report. If anyone has feelings or lessons learned from the collaboration process, communicate them to Jennifer or Brian.

WRAP-UP, SCHEDULE REVIEW, AND ACTION ITEMS

- Jennifer thanked everyone for participating in the collaboration and opened it up to the Moab team for final comments.
- Chris (EM) thanked everyone. The collaboration is a great step forward. He hopes to include some participants in steps going forward. Brian added that Chris can reach out to the national labs; they have a lot of expertise.
- The following action items were identified:
  - Brian will review narratives and add any additional resource or information regarding sequencing.
  - Jennifer will draft the report and send it out for review when it is ready.

Attachments: Meeting Agenda

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Meeting Agenda

Network of National Laboratories for Environmental Management and Stewardship Collaboration Meeting 7
Moab UMTRA Site
December 20, 2022

All meeting times shown in Mountain Time

Agenda

(All meeting times are approximate)

10:00 – 10:05	**Meeting Overview (Jennifer Nyman)**
10:05 – 10:10	**NNLEMS Current Approach (Brian Looney)**
10:10 – 10:50	**Integration and Synthesis (Brian Looney)**
	- Consensus Statements - Spatial/Temporal Zones and Associated Objectives - Integration/Sequencing of Recommendations - Resource Loading and Enhanced Baseline
10:50 – 11:15	**Spatial Zones – Round Robin Input (All)**
	- Provide a specific recommendation for one of the spatial zones
11:15 – 11:25	**Check in with NRC, Chris P. (Jennifer Nyman)**
11:25 – 11:30	**Recap, Schedule Review, and Action Items (Jennifer Nyman)**

Meeting to be held Microsoft Teams

Consensus Statements from the Collaboration

GCAP decisions and support will require support using numerical modeling – implementation of a numerical model that simulates the key site-specific processes and structures that control Moab plume behaviors is essential to underpin the technical basis of the GCAP and support environmental and legacy management decisions.

Moab is a "complex site" and the collaboration recommends developing a GCAP that is consistent with the challenges and emerging science and policy for such sites.

- A one-step GCAP based on single technology in unlikely to provide effective and efficient risk management.
- The Moab collaboration process consensus recommendation is to develop a combined remedy with time-phased and site-specific objectives – for example, mid-term performance objectives to manage and reduce risks to the Colorado River, and longer term objectives to achieve UMTRCA target groundwater concentrations throughout the entire useable aquifer.
- Central to the recommended combined remedy is a strategy of matching technologies in time and space to maximize effectiveness and optimize performance. Spatial matching could consider the nature of contamination in different areas of the site and use technologies that address the specific conditions. Temporal matching could focus on active remedies to mitigate mid-term risks and transition to passive or semi-passive remedies based on conditions.
- The combined remedy should be structured to meet groundwater objectives over timeframes envisioned in UMTRCA and consider actions such as institutional controls (e.g., limiting use of groundwater) that are considered an integral component of the GCAP.
- The combined remedy strategy should include contingencies and framework criteria for transitioning technologies.
- Notional exemplars of spatial zones and temporal stages were developed by the collaboration for use as a resource by the Moab team, regulators and stakeholders.

Additional characterization is needed to inform GCAP development and to support selection and implementation of most effective technologies to use for later temporal stages of the GCAP remedy.

- Key data gaps remain that limit the effective selection, development and implementation of groundwater remedies.
- A portfolio of phased and targeted characterization activities will be needed to address the data gaps.
- Selection and implementation of the characterization portfolio should address:
    - Key uncertainties associated with each of the framework spatial zones identified to support adaptive site management (ASM) and the interfaces between the special zones – for example, for the residual contamination in the deep subsurface brine zone, the primary focus could be (i) on whether the contamination is migrating or staying in place and (ii) quantifying future predictions on the source mass flux away from the brine zone to the more active overlying aquifer zone.
    - Timing the implementation of insertion points in the target schedule to support GCAP development, modeling data needs, and timeframes for decision making. For example, supporting the initial development of the GCAP that includes mid-term actions and

longer-term decisions and actions. In some cases, this might include an early scoping deployment, followed by more comprehensive data collection if needed, and/or redirection if the scoping work results in promising and useful results that are actionable.

- Early recommended characterization activities for the portfolio include:
  - borehole related activities such as geophysical logs (electromagnetic induction and others), geochemical evaluations on core material and groundwater, and scoping evaluation of stable isotopes and tracers in groundwater.
  - Scoping survey for the Colorado river using probes and thermal techniques.
  - Scoping soil gas surveys.
  - Scoping analysis of temporal signals in the subsurface.
  - Site road infrastructure construction to accommodate Restoration activities.
- Longer-term characterization recommendations for consideration by the Moab team include those listed above and other methods – selection and implementation of the out-year portfolio composition should be guided by early scoping results. For example, some of the stable isotopes, tracers, soil gas or riverbed analytes may not provide clear or useful/actionable information. In this case, some of these items could be dropped or redirected to maximize the value of the longer-term characterization efforts.

APPENDIX B:
Table of Long List Recommendations

Table B-1
Long List Preliminary Recommendations
Moab UMTRA Project Site
Grand Country, Utah

Recommendation	Objectives	Description	Is the technology well-suited to conditions at the Moab site?	Implementability	Time Frame	Technology Inter-Relationships	Retained for Short List?
Team 1: GCAP Development Status, Requirements, and Path Forward							
Adaptive Site Management	Move the site towards closure, while accounting for significant uncertainty in site conditions, and the possible groundwater remedy, including a combination of approaches/technologies, both in conjunction and in phases, because of certain challenges (mixture of COCs with different behavior, depth of contamination, complexities of the brine, dynamics of interactions with the river, etc.). Significant new information will likely be gained during remedy implementation, and it can be used to adapt and optimize the remedy.	The ITRC defines adaptive site management as a comprehensive, flexible, and iterative process of remediation management that is well-suited for complex sites, where there is significant uncertainty in remedy performance predictions. Adaptive site management includes periodically evaluating and adjusting the remedial approach, which may involve multiple technologies at any one time and changes in technologies over time. The CSM is refined using information gained from remedy performance. Site remediation managers adapt or adjust the selected remedy over time in response to remedy performance. These adjustments keep the remedy on track to meet interim objectives. Interim objectives and associated performance metrics may reflect a variety of goals.	The complexity of site conditions may be better addressed with adaptive site management than a linear remedial approach. While it is not explicitly addressed by existing guidance and requirements, it is also not precluded.	The PEIS and NRC guidance do not envision an adaptable remedy, but it is technically feasible. Adaptive site management is increasingly gaining acceptance and use for complex sites. For Moab, the approach should incorporate institutional controls and be driven by potential beneficial end uses. Concern may be raised that the remedy would be open-ended. An adaptive remedy, though, can be well-defined, for example by identifying and clarifying, and seeking approval on decision points, their inputs, and follow-on actions, and by indicating how the approach will meet requirements and standards.	Short- to medium-term (2 to 3 years), for the GCAP.	This idea is consistent with the remedial approaches being considered by Team 3.	Yes
Biotic Ligand Models	Refine the technical basis for ecotoxicity target concentrations by incorporating chemical speciation – accounting for the relative toxicity of different species and the formation of complexes and the chemical matrix in surface water at the exposure location. The effort would provide robust risk reduction (protection of species and ecosystem function) and allow refinement of goals based on site specific conditions.	Setting ecological protection standards for streams involves testing of contaminants to determine impacts on the survival and sustainable reproduction of key ecosystem species such as zooplankton and fish. These studies result in setting of AWQC. In 2007, USEPA formalized the use of a simplified "biotic ligand model" (BLM) in the 2007 update for Copper Aquatic Life Ambient Freshwater Quality Criteria. The dominant matrix parameters that influence BLM based copper criteria are pH, dissolved organic carbon ("humic acid"), and (to a lesser extent) other interacting cations and anions. Copper is currently the only element for which the BLM is formally accepted. Nonetheless, the technical basis and general principle of the BLM are compelling – identifying the principal mechanism(s) of toxicity, assessing the relationship of contaminant speciation in the water matrix to the identified toxicity, and incorporating site-specific conditions to determine speciation and adjust the determination of acceptable levels. Other contaminants of concern at Moab may benefit from a similarly structured ecotox evaluation.	This is a conceptually interesting idea to refine ecotox standards while assuring protection of critical habitats and species at critical times of the year. However, the BLM is not currently in place for COCs at Moab (e.g., ammonium, uranium). Further, the amount (and direction) of adjustment in target ecotox concentrations is unknown and potentially not significant (e.g., less than a factor of 2).	Potentially implementable, but low TRL (approximately 4 or 5) since this strategy is not currently included and accepted by regulators.	Medium-term. This approach would require some calculations and possibly laboratory and pilot studies in the next few years.	For optimum performance, this concept would need to be considered and implemented with simultaneous evaluation of other GCAP development and risk reduction strategies.	No. Could be considered in the future by the Moab team as they finalize eco toxicity targets.
Team 2: Groundwater Contamination-Related Topics							
2-Dimensional Cross-Sectional Scoping Assessment of Brine Interface Dynamics	1) Develop a numerical, cross-sectional, model-based tool to aid in the assessment of brine interface dynamics, and 2) develop an assessment of groundwater age based upon 3H/3He dating techniques applied to samples collected at different depths in the system.	A 2D cross sectional model that incorporates density dependent flow and an ability to track a transient water table may be able to 1) explain the groundwater dynamics going on, 2) examine how mixing occurs across the interface, 3) demonstrate the depths to which shallow, recently recharged groundwater can penetrate, 4) assess dynamical shifts in groundwater flow directions and rates associated with river stage or hydraulic effects imposed by remedial strategies, 5) estimate the degrees to which the fresh and/or saline portions of the aquifer discharge directly into the river, 6) estimate the degree to which the aquifer flows on one side of the river are connected to the opposite side, 7) examine hypotheses about the origin of the deeper ammonia plume, and, most in a broader sense, 8) help set the stage for more complex, time consuming 3D calculations to be performed elsewhere. The ability to incorporate solid phase dissolution (of salt), as a means to understand the importance of this effect, may also be considered.	This recommendation is specific to the Moab site and addresses the fluctuating chemocline in the saturated zone beneath the site.	The approach will require access to numerical groundwater flow and transport models capable of addressing density-dependent flow, tracking water table surfaces, and (potentially) handling solid phase (salt) dissolution processes. In addition, it will require access to groundwater sampling techniques (that isolate groundwater from atmospheric exposure) and an associated a laboratory capable of analyzing 3H and 3He compositions in these samples.	Short- to medium-term.	The added value here links into myriad source term and interfacial mass questions, conceptual model topics, and 3D numerical model topics.	Yes. Consider with other numerical modeling recommendations.
3-Dimensional Numerical Model Considerations	Configure and calibrate a 3D numerical groundwater flow and contaminant transport model, and use it to forecast contaminant plume evolution and evaluate the effectiveness of potential compliance strategies.	Evaluation of the suitability of potential compliance strategies for the Moab site requires forecasting contaminant migration under different site management scenarios. Example forecasts of interest include remediation timeframes and future concentrations at points of compliance and points of exposure. Forecasts such as these are typically developed for several site management scenarios, including passive (e.g., natural flushing or ACLs) and active (e.g., groundwater extraction or amendment injection) compliance strategies. Developing appropriate forecasts requires application of mathematical models, which can be simple or complex. Given the hydrogeologic complexities at the Moab site, a sophisticated 3D numerical model will likely be necessary to make defensible forecasts that can be used to justify a groundwater compliance strategy for the site. The Moab site has a long history of using 3D numerical groundwater flow and contaminant transport models to support site management decisions, and continued application of these models for GCAP development is recommended.	3D numerical models have already been used for many years at the Moab site, and they are capable of simulating the complex site conditions at Moab.	The level of effort to complete modeling to support a GCAP will depend on whether an existing model for the site is adequate (with a minor or major update) or a new model is needed. The model will likely need the ability to simulate variable-density flow. Previous models at the site have been built with FEFLOW and SEAWAT, both of which can simulate density-dependent flow and multispecies transport.	Short-, medium-, and long-term (modeling can be performed at different project stages).	Data collected during site characterization activities proposed in the site assessment topical area can be used for model configuration and calibration. This includes information collected on contaminant sources, geochemical processes, biological activity, the brine or river interface, and transient signals. The results of reduced-order models or cross-sectional models can also be helpful for configuration of a 3D numerical model. The model can be used to compare approaches suggested in the response action topical area, and these comparisons can be made under different climate change scenarios.	Yes. Consider with other numerical modeling recommendations.

Table B-1
Long List Preliminary Recommendations
Moab UMTRA Project Site
Grand Country, Utah

Recommendation	Objectives	Description	Is the technology well-suited to conditions at the Moab site?	Implementability	Time Frame	Technology Inter-Relationships	Retained for Short List?
3-Dimensional Visualization to Support Refinement of the CSM and Construction of Numerical Models	1) Understand the state of groundwater contamination; and 2) forecast its future evolution under both natural and remedial action conditions.	3D visualization frameworks are used increasingly to support development of CSMs and facilitate construction of numerical models. Tools are needed to organize and visualize geologic information (e.g., geologic contacts, faults, and other structures) and build GFMs, which are essential components of CSMs. Visualization is critical to using GFMs to inform the construction of grids or meshes and definition of cell or element property values (e.g., permeability, porosity, initial concentration) for simulation models of flow and transport. A number of commercially available, public-domain, and open-source codes exist with capabilities for 3D visualization and management of spatial databases.	Software technology for 3D visualization, GFM development, and construction of simulation models are well designed to accommodate a broad range of sites and thus are well suited to Moab condition.	Implementation is straightforward with potential costs ranging from zero dollars (open-source options) to tens of thousands of dollars for software licenses (commercial software). Ultimately, implementation will facilitate model development and thus be cost-saving. Multiple tools may be required to satisfy project needs, and different tools offer different sets of capabilities.	Short-term (1 to 2 years).	The proposed technology will support development of the CSM, facilitate new insight into the controls on flow and transport, and the spatial distribution of groundwater contamination. Work to implement the technology at Moab will support planned site activities on tasks related to modeling (conceptual and quantitative). Selection of software tools should be coordinated with tasks related to modeling, to ensure seamless interaction between the GFM, CSM, and development of predictive models of flow and transport.	Yes. Consider with other numerical modeling recommendations.
Alternative Reduced Order Models to Project Flushing Time Frame	Diversify the technical basis for projecting the timeframes for groundwater flushing and/or remediation using simplified "reduced order models." This would aid in bounding flushing timeframe, which is particularly relevant to UMTRCA GCAP development. Diversifying the nature and types of modeling tools may be helpful in providing stakeholders/regulators with transparent and understandable information.	"Reduced order models" are often a useful adjunct to more complex numerical models – these models can assist in stakeholder communication because they are simple and straightforward to describe. When projecting contaminant flushing, many reduced order models mimic first order exponential decay. However, models may exhibit more pronounced "tailing" (e.g., due to mass transfer limitations and slow release from residual and secondary sources). Example models from the literature include stretched exponential and power functions. Recent projections of flushing timeframes for Moab groundwater use a simplified reduced-order model, the output of which resembles a exponential decay (e.g., matching a small 1D column) rather than accounting for the complexities of mass transfer and multiple residual sources and the associated fluxes.	This technology is suited to prediction of flushing and the decline in concentration in wells in the Moab plume. However, application might be limited by short period of data, changing conditions (i.e., clean water injections, groundwater extraction and tailings removal), and lack of information on the residual and secondary sources and associated projections of source mass fluxes. These challenges might limit application of reduced order models and require a 3D numerical modeling.	Relatively straightforward to perform scoping evaluation. May be suitable for collaboration with a university or implementation with the assistance of students.	Short-term (1 to 2 years).	Simple and straightforward. Would provide results and output relatively fast compared to waiting for the 3D numerical model.	Yes. Consider with other numerical modeling recommendations.
Borehole Logging	1) Understand the state of groundwater contamination; and 2) forecast its future evolution under both natural and remedial action conditions.	Borehole geophysical logging is a routine component of site characterization. Numerous logging methods provide information on diverse physical and chemical parameters, which in turn provide insight into aquifer properties, water quality/chemistry, and geologic structure. Borehole logging tools include EMI, natural gamma, self potential, normal resistivity, fluid conductivity/temperature, caliper, sonic, acoustic televiewer, optical televiewer, neutron porosity, NMR, and BHF. Synergy results from joint interpretation of multiple logs, hence a suite of logs is commonly collected in the same field campaign. Of particular relevance to site investigations at Moab are EMI, fluid conductivity, NMR, and BHF. EMI can be used to infer pore-fluid salinity, particularly when combined with other logs that help control for lithology. NMR results can be used to estimate hydraulic conductivity. BHF can be used to estimate transmissivities and hydraulic heads of different aquifer layers (or fractures) using simple graphical analysis and manual calibration or regression analysis. We recommend consideration of logging as part of site investigations. Furthermore, any plans for future drilling should be coordinated with plans for logging.	In general, site conditions at Moab are suitable for logging; however, well construction does limit which tools can be used; e.g., steel casing precludes the use of EMI tools, and BHF can only be used to estimate transmissivity and head in screened intervals or open intervals. The dimensions and material within the drilling annulus around the well casing can also pose issues to certain logging tools.	Borehole logging is straightforward to implement. Logging services are available from numerous vendors nationwide. Certain advanced logging techniques (e.g., NMR, BHF) are less common in the environmental industry.	Short-term.	Will require integration with efforts to develop spatial databases and capabilities for 3D visualization at Moab. Borehole logging should be coordinated with any plans for surface geophysics and drilling to enable comparison of different datasets and relation of geophysical and other properties. Logging results should be used to inform CSM development which will require inclusion in visualizations and consideration when constructing and refining the hydrogeologic framework model. Logging may provide information relevant to focused investigations into critical components of the CSM, such as 1) matrix diffusion, for which NMR may provide insight (i.e., pore size distribution and mobile/immobile porosity), and 2) the spatial distribution of brine distribution, for which EMI may prove useful.	Yes. Consider with other borehole and geophysical survey methods.
Climate Change and Other Uncontrolled Factors	Develop an explicit list of quantitative factors pertinent to the Moab site that could be altered by climate change and other factors (e.g., Colorado river stage, reduced precipitation), formulate one or more processes for identifying where these factors enter into evaluation strategies (e.g., computer model boundary conditions, modifications to river course), estimating potential changes in these factors that could be attributable to climate change, and incorporating such changes, or acknowledging their existence, in subsequent design and prioritization of contaminant management or remediation strategies over their relevant lifetimes.	This topic is focused on climate change and other uncontrollable factors that may impact hydrologic processes occurring in areas surrounding the Moab Tailings site, including the flows in the Colorado River. These should be considered in the quantitative design and prioritization of contaminant management or remediation strategies. Specific considerations may include: Reduced average river flows in the Colorado river attributable to warming temperatures, reduced precipitation in the upper Colorado watershed, and altered patterns of river diversion associated with climate change and greater upstream withdrawals; generally reduced amounts of rainfall that contribute to aquifer recharge processes at the Moab site proper and in upgradient locations bounding its perimeter or along Moab Canyon; higher "surge" like events associated with short but significant rainfall events that affect the river (e.g., spiked flow rates, higher stages, flooding events), the Moab site proper, or in upgradient areas like Moab Canyon; and drier conditions associated with warming temperatures and declines in precipitation which may influence the vitality or longevity of vegetation in or near the site, or which may influence potential for wildfire and wildfire-related impacts to the ecosystem or related hydrologic processes.	This recommendation is applicable to the Moab site because the remedial time frame is likely to be in the range of decades to centuries.	The approach is limited in that precise quantitative forecasts of potential changes (e.g., amounts, variability, timing) in the factors outlined above remain a matter of research that goes beyond the scope of this work. What is imagined here is 1) the acknowledgment of these changes (minimally), 2) model incorporation of nominally-altered boundary conditions (or related parametric or process related inputs) that are reflective of climate change impacts, and/or 3) evaluation of response or response sensitivities in the predictions due to these changes.	Medium- to long-term.	The added value here can be applied, potentially, to all assessments that have quantitative links to variables affected by climate change.	Yes

Table B-1
Long List Preliminary Recommendations
Moab UMTRA Project Site
Grand Country, Utah

Recommendation	Objectives	Description	Is the technology well-suited to conditions at the Moab site?	Implementability	Time Frame	Technology Inter-Relationships	Retained for Short List?
Data Worth Analysis	Use a preliminary version of the numerical groundwater flow and contaminant transport model to quantitatively assess the value of proposed data collection efforts. Data worth analysis focuses efforts on collecting data that will be most informative for making key site management decisions, thereby improving the efficiency of efforts to reduce risk.	Data worth analysis approximates the reduction in predictive uncertainty that can be achieved by incorporating new data into a numerical model, and it is generally performed using efficient first-order, second-moment Bayesian analysis methods (i.e., Schur's complement). It can be performed before new data are collected and before the model is calibrated. Traditionally, groundwater modeling is performed after the conclusion of data collection activities. The proposed approach reverses this order, with preliminary configuration of the groundwater model occurring before new data are collected. This reordering of work processes enables the model to be used for data worth analysis. Besides enabling a formal data worth analysis, configuring the groundwater model early in the schedule has other benefits. These additional benefits include 1) a less formal identification of data gaps that occurs naturally during model configuration and 2) potential implementation of a "forecast first" modeling workflow to determine an appropriate model configuration (for example, determining if the model could achieve its objectives using a simple steady-state mode of operation or if a more complex transient flow simulation would be necessary).	The initial long-list generated by the NNLEMS collaboration for the Moab site includes numerical modeling and multiple site characterization activities, so data worth analysis (i.e., using a numerical model to assess the value of various data collection activities) is applicable.	Data worth analysis requires minimal additional effort because a key to its implementation is simply rearranging scheduled activities so that groundwater modeling is performed early in the schedule instead of at the end. Additional effort is limited to 1) using the configured groundwater model to perform data worth analysis, and 2) revising the groundwater model after data collection is complete. Data worth analysis is a mature technology with software implementations available in the PEST software suite and pyEMU. These tools are model-independent (i.e., they work with any modeling code and are not specific to any particular modeling software, such as MODFLOW).	Short-term.	This activity leverages the 3D numerical model that has been proposed for the site to assess the value of data collection activities that are proposed for the site.	Yes. Consider with other numerical modeling recommendations.
Distributed Temperature Sensing for Detection and Monitoring of Seepage, to Support Sampling and Real-Time Operations for In-Stream Dilution	1) Understand the state of groundwater contamination; and 2) forecast its future evolution under both natural and remedial action conditions.	Stream/aquifer interaction at the Moab site is highly dynamic, with rapidly changing flux. There is a need to identify locations of focused discharge to the river in real-time to operate the in-stream dilution system and mitigate contaminant impacts to aquatic species. Additionally, understanding the spatial and temporal distribution of seepage is critical to providing hydraulic context for interpretation of sampling in or near streams. FO-DTS is a promising and potentially cost-effective technology to support these objectives.	FO-DTS measurements are local to the fiber-optic cable, which is only millimeters in diameter; thus, detection or mapping of focused seeps requires deployment of multiple cables or deployment of a cable on a grid. When deployed at the sediment/water interface, the utility of FO-DTS is limited in fast stream flows and (or) deeper water, where the in-stream mixing masks the thermal signal of discharging water. These limitations should be assessed under the conditions required at the site.	FO-DTS instruments cost ~$20-60K and cables cost ~$6/m. Software for data analysis and visualization includes instrument-specific software as well as public-domain codes for visualization and simple statistical analysis.	Short-term (1 to 2 years).	FO-DTS can be used in a multi-method characterization and monitoring strategy. FO-DTS provides continuous data collection in time but only along cables. TIR imaging can provide images of a large area, thus filling gaps between cables.	Yes. Consider with other surface water-groundwater interface measurements.
Evaluation of Geochemical Processes at the Brine-Freshwater Transition Zone	Understand how geochemical processes affecting uranium in the brine zone and how the fluctuating depth of the brine-freshwater transition contributes to uranium mobility/sequestration.	The following approaches could be used to evaluate the geochemical processes impacting uranium in the brine-freshwater transition zone: geochemical equilibrium modeling use freshwater and brine groundwater composition could be used to easily examine the impact of ionic strength of uranium sorption to solids and solubility of uranium minerals; batch and/or column tests could be used to evaluate the impact of changing ionic strength on uranium mobility by collecting soil from the brine-freshwater transition zone for use in a batch reactor or flow-through column; and the above processes could be incorporated into a reactive transport model to simulate the time to achieve the groundwater standards under different remedial scenarios.	These analyses address the unique chemocline that is present beneath the Moab site.	Geochemical equilibrium modeling is extremely simple and low cost. Treatability testing is simple, but it would cost far more to implement. Treatability testing would require mobilizing a drill rig to collect site soil and groundwater.	Short-term.	These analyses are necessary to support development of a comprehensive CSM. These processes will need to be incorporated into a reactive transport model to estimate remedial time frame under different scenarios. The flux of uranium to/from the brine aquifer to the freshwater aquifer is a current data gap.	Yes. Consider with other geochemical evaluation recommendations.
Evaluation of Solid-Phase Uranium Speciation	Characterize solid-phase uranium speciation (e.g., sorbed, precipitated, co-precipitated/incorporated, oxidized/reduced) within the vadose zone, saturated zone, and within the freshwater and brine zones.	Characterization of solid-phase speciation of uranium (e.g., sorbed, precipitated, co-precipitated/incorporated, oxidized/reduced) is needed to quantify the mass of solid-phase uranium present at the site and its potential for remobilization. Characterization would target soils beneath the current tailings pile and soil within the brine aquifer. Particularly, the redox state and speciation (precipitated, sorbed, incorporated/co-precipitated) of uranium within the brine zone remains unknown. Once tailings are removed, solid-associated uranium is expected to act as a long-term source of uranium to groundwater. An accurate estimation of uranium mass, both solid phase and dissolved, is necessary to identify and design remedial alternatives. An inaccurate estimation of source term mass will propagate down to estimations of remedial time frame, risk, and remedial design. Analytical techniques to consider include solid-phase extractions of soil samples, X-ray absorption spectroscopy, and X-ray photoelectron spectroscopy.	These analyses are appropriate for the Moab site. Sequential extractions could be performed at a laboratory with a radioactive materials license. XAS would need to be performed at a synchrotron beamline, which are operated by the DOE.	Sequential extractions are relatively simple to implement and can be performed at a standard commercial analytical lab with a rad license. Cost is typical of analytical costs for standard analyses. Labor costs are higher due to extensive manipulation of the samples. This approach is mature and has been used at other DOE sites, including Monticello. To evaluate redox conditions, special sampling protocol will need to be used to ensure that samples do not oxidize between sampling and analysis. Furthermore, XAS analyses are very complex and require trained technicians for preparation and analysis of the data. Moab could partner with academic institutions or national lab scientists to perform these analyses.	Short-term.	This information is necessary for a complete understanding of the geochemical processes driving uranium mobility at the site and development of a complete CSM. Additionally, quantifying solid-phase uranium and speciation in the brine zone will be necessary to accurately estimate the source term of uranium, which impacts estimates of remedial time frame and remedial design.	Yes. Consider with other geochemical evaluation recommendations.
Flux Chambers	Consider installing flux chambers in the Colorado River to directly measure flux of contaminants and to provide information on patchy-ness of contaminant discharge and extent of the discharge.	Flux chambers have been well documented in the literature and demonstrated by USGS and others. These are relatively simple to deploy, consisting of a chamber/box that is sealed into the sediment with systems to allow natural influx of water from the sediments and allow sampling of the chamber water over time. Flux chambers could be used to specifically characterize critical habitats, placed in a transect across the river to see the pattern of influx and the extent of plume impact across the river, to assess fluxes under varying river stage conditions (i.e., conditions that reverse direction and relative influx during varying "low stages"), and (if specific-important flow lines or seeps are identified,) characterize the contaminant influx along these preferential flow paths.	This concept is potentially matched to Moab conditions as a tool to understand source mass flux patterns in the Colorado River. Data on critical habitats might be interesting but may not be actionable (how it could be used or interpreted). Data on spatial pattern of fluxes might be useful in refining the conceptual model.	This technology is implementable, but would require time and labor to deploy (chambers often stay in place for several days or weeks). May be a fruitful project to perform in collaboration with a local university, high school or other STEM opportunity.	Long-term (>3 years).	Supports conceptual model and numerical model and provides information related to underflow and river dynamics.	Yes. Consider with other surface water-groundwater interface measurements.

Table B-1
Long List Preliminary Recommendations
Moab UMTRA Project Site
Grand Country, Utah

Recommendation	Objectives	Description	Is the technology well-suited to conditions at the Moab site?	Implementability	Time Frame	Technology Inter-Relationships	Retained for Short List?
Focused Evaluation of Brine Impacts to Uranium Geochemistry and Mineral Solubility	Assess the potential effects of high ionic strength and potential relationships with uranium solubility and uranium concentration. Depending on scoping calculations and initial results, refine the conceptualization to include potential ionic strength effects and co-contributions of anthropogenic and natural uranium to measured values in groundwater samples from different depths and locations.	The emergent solubility of uranium minerals (mg/L total uranium in solution) can be influenced by ionic strength (e.g., Lemire 1988 – at AECL). Specifically, at high ionic strengths (similar to the brine interval at Moab), uranium concentrations in simulated high ionic strength groundwater increased by a factor >10x when the water was equilibrated with geologic materials containing natural uranium minerals. This raises the possibility that some of the elevated uranium measured in the deeper samples from Moab could potentially be impacted by solubilization of natural uranium minerals (or impacted by higher solubility of Mill related diagenetic uranium minerals when compared to the overlying lower ionic strength groundwater). The specific recommendations for this topic are straightforward: 1) Include this objective in planned geochemical modeling runs (e.g., using Geochemist's workbench, Phreeqc, Minteq, or other) focusing on uranium behavior over a range of site-specific geochemical conditions representative of the range of ionic strength (brine concentration) and including expected natural uranium mineral phases present in the sediments 2) revisit the data from previous uranium isotope studies with a focus on differences in uranium isotope signatures (brine versus upper zones) and to determine if sufficient isotope data were collected to represent the range of ionic strength 3) (if additional isotope samples are needed to supplement past survey) , perform some additional U isotope profiling to fill in data gaps 4) incorporate information into the site conceptual model to include this factor/nuance in the adaptive site management planning for Moab.	This concept is matched to specific and relatively unique conditions at Moab – namely the presence of a chemocline and an ionic strength gradient as a function of depth in the underlying groundwater. Understanding the first and second order effects of this important constraint may be crucial in planning and implementing a practical-technically-based GCAP.	Relatively straightforward to perform scoping evaluation. May be suitable for collaboration with a university or implementation with the assistance of students.	Short-term (1 to 2 years).	Simple and straightforward. Would provide results and output relatively fast compared to waiting for the 3D numerical model. Results would be useable in refining the conceptual model, the numerical model and (potentially) the scope and scale of target uranium for remediation.	Yes. Consider with other geochemical evaluation recommendations.
Free Transient Signal Analysis	Understand the significant annual transient reversals that exist in the shallow Moab groundwater system. These natural perturbations driven by river stage can be used to better understand the system, since nature is providing a "free" signal. The signal is monitored and the response of the system is deconvoluted.	Historical long-term monitoring should be augmented by expanded current monitoring of the transients in the system (e.g., temperature, salinity, ORP, pH). Characterization of the signals might require high-frequency monitoring to catch the highest and lowest stages of the river and the timing of the associated groundwater system. To understand inter-year variability, long-duration monitoring is needed over multiple years. Some of the free signal may be easy to interpret, while other signals may require a detailed site model to interpret. It seems a detailed site groundwater flow and energy/solute transport model is inevitable, so these transient data sets will be useful to calibrate the model.	This recommendation is suitable for the Moab site because of the fluctuating stage of the Colorado River, which the site is adjacent to.	Groundwater monitoring is already performed semiannually. Implementation of this recommendation would involve increasing the frequency of monitoring. Transducers could be used to collected high-frequency measurements of pH, conductivity, and water level in existing monitoring wells.	Short- to long-term.	Additional transient forcing imposed on the system may change the natural periodicity of the system. Man-made transient signals from active remediation methods may add their own transient signals to the system. See "passive geophysical monitoring" for some possible additional signals to add going forward.	Yes
Geophysical Surveys for Mapping Brine	1) Understand the state of groundwater contamination; and 2) forecast its future evolution under both natural and remedial action conditions.	The depth to the brine interface across the site is poorly understood yet a required model input for simulation of flow and transport. Electromagnetic induction and electrical geophysical surveys were used across the river to characterize the shallow spatial distribution or brine. Electromagnetic induction and related electromagnetic and electrical methods are promising approaches to characterization of the brine interface under the Moab site.	The effectiveness of electrical and electromagnetic investigations in the wetland across the river from the Moab Site indicate a high probability of success. electromagnetic surveys can cover large areas using ATV-towed setups for both small frequency-domain tools (e.g., Gelectromagnetic-2, DUALelectromagnetic) and larger time-domain tools (e.g., tTelectromagnetic). A combination of tools may be required to map the interface across the site.	Electromagnetic and electrical geophysical technologies are mature and geophysical services can be contracted. Implementation concerns for electromagnetic geophysics include the effects of infrastructure. electromagnetic data are strongly influenced by the presence of steel pipes and electrical utilities above or below ground. Electrical methods are less sensitive to infrastructure but slower to collect over large areas. Prior to conducting any geophysical surveys, it is advisable to perform synthetic modeling (aka 'pre modeling') based on hypothetical scenarios for anticipated target depths and subsurface properties and structures. Such pre modeling exercises can provide the basis for go/no-go decisions on surveys and also provide insight into resolution to facilitate interpretation of results.	Short-term (1 to 2 years).	TIR (and possibly different TIR devices) can be used in a multi-method characterization and monitoring strategy. If continuous data collection is required, TIR cameras can be mounted at a site, or else TIR surveys can be triggered by other continuous data, e.g., water level monitoring, distributed temperature sensing, or water quality monitoring.	Yes. Consider with other borehole and geophysical survey methods.
Isotope and Tracer Opportunities	Assess the potential for using natural and anthropogenic tracers (stable and radionuclides) and age dating tools to refine conceptual model of flow and improve interpretation of the interaction of the brine zone with the overlying more active flow zone. Uranium isotopes can also be used to distinguish between sources of uranium (e.g., natural versus anthropogenic).	Tracers are a potentially useful technology to inform and improve the Moab CSM. A variety of intrinsic tracers have been used to trace, age data, and discern the history of young waters such as the water in the Rifle disposal cell. Young water tracers include stable isotopes of hydrogen and oxygen, tritium and helium 3, chlorofluorocarbons and sulfur hexafluoride. While speculative, there is a potential for standard young water tracers to elucidate the interactions between the brine and the overlying water layer. The most promising of the young water tracers may be those that most closely track with the water molecule – i.e., stable isotopes of hydrogen and oxygen (representing the evaporation history of the water) and tritium (because of its ease of measurement and primary form within the water molecule in the environment).	This concept may provide information to support interpreting mass transfer at the brine interface.	Relatively straightforward to perform scoping evaluation. May be suitable for collaboration with a university or implementation with the assistance of students.	Short-term (1 to 2 years).	Could provide results and output over the next year – requires setting up contract or collaboration. Results would be useable in refining the conceptual model and the numerical model.	Yes. Consider with other isotope and tracer recommendations.
Molecular Biology and Isotope Techniques to Evaluate Biological Ammonia Degradation (Nitrification)	Quantify the degree to which biological ammonia oxidation (nitrification) contributes to attenuation of the groundwater ammonia plume.	Molecular biology and isotope techniques could be used to confirm the occurrence and degree of microbial ammonia oxidation. Soil and/or groundwater samples can be analyzed for genetic markers of nitrifying microbes. These analyses provide a yes/no answer to whether microbial populations capable of this respiration pathway are present. Batch incubations or CSIA of 15N in ammonia can be used to better quantity the degree to which nitrification is occurring.	Preliminary evidence of biological ammonia degradation (nitrification) has been identified during site characterization (measurement of nitrate in groundwater).	Commercial measurement of genetic markers for nitrification in soil samples is not common. CSIA of 15N in ammonia is more common – there are numerous university labs that offer this service. However, the laboratories identified to date do not have a rad license, so they cannot handle material from Moab. An academic laboratory that can perform these analyses may be possible.	Short-term.	This data would support development of a more complete CSM, which is necessary to accurately estimate the remedial time frame under different remedial scenarios.	Yes. Consider with other isotope and tracer recommendations.

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Soil Gas Surveys to Refine Residual Source Area	Provide a rapid low-cost option for refining areas that contain significant residual or secondary sources of uranium and ammonium in the vadose zone and shallow groundwater. The overarching goal is to provide information to help focus the deployment of source control technologies (e.g., where capping or amendments might be beneficial).	Soil gas surveys are commonly applied in characterizing VOCs such as chlorinated solvents and hydrocarbons. In these surveys, the pattern of vapor phase concentrations in gas collected from a grid of sample locations is diagnostic of the location of residual contaminant and geologic features such as preferential flow paths. Similar to VOCs, the uranium daughters include a gas phase constituent (radon), and gas phase ammonia may be an indicator for residual ammonium (subject to potential pH limitations). Normally, a soil gas survey is performed rapidly by rapidly installing a grid of holes using a sliding hammer or similar field tool, inserting a sample probe into each hole, and collecting a gas sample for analysis. In the case of Moab, the analysis could be performed in the field using simple field gas monitors for radon and ammonia. For Moab, a grid of several hundred locations could be defined and samples collected and analyzed in a week.	This strategy may have short term application to Moab conditions and needs. Simple and low cost with the potential to provide actionable information – uniquely well matched to site specific COCs.	Implementable using standard practice.	Short-term.	Several, including source control technologies and adaptive site management strategies.	Yes
Thermal Infrared Imaging for Detection and Monitoring of Seepage to Support Sampling and Real-Time Operations for In-Stream Dilution	1) Understand the state of groundwater contamination; and 2) forecast its future evolution under both natural and remedial action conditions.	Stream/aquifer interaction at the Moab site is highly dynamic, with rapidly changing flux. There is a need to identify locations of focused discharge to the river in real-time to operate the in-stream dilution system and mitigate contaminant impacts to aquatic species. Additionally, understanding the spatial and temporal distribution of seepage is critical to providing hydraulic context for interpretation of sampling in or near streams. TIR imaging is a promising and potentially cost-effective technology to support these objectives.	The limitations of TIR derive from its sensitivity to the water surface, i.e., the skin (< 0.1 mm, Aboldt et al., 2018). The utility of TIR is therefore limited 1) in fast stream flows and (or) deeper water, where the in-stream mixing masks the thermal signal of discharging water, and 2) when discharging water is relatively cold and therefore less buoyant. These limitations should be assessed under the conditions required at the site.	TIR instruments range in cost from ~$100 (an add-on to mobile phones) to a few thousand dollars for handheld cameras, to tens of thousands of dollars for cameras that integrate with GPS and are designed for deployment from drones. Initially, handheld cameras could be assessed, with a possibility for deployment of drones in the future if determined to be effective and cost-effective.	Short-term (1 to 2 years).	TIR (and possibly different TIR devices) can be used in a multi-method characterization and monitoring strategy. If continuous data collection is required, TIR cameras can be mounted at a site, or else TIR surveys can be triggered by other continuous data, e.g., water level monitoring, distributed temperature sensing, or water quality monitoring.	Yes. Consider with other surface water-groundwater interface measurements.
Conceptual Hydrologic Model	Obtain defensible predictions of contaminant migration and map the future risks to the public and the environment by capturing all available first order data important to the characterization and description of the principal dynamic hydrologic and biochemical processes at work that are required of a site process model needed to predict contaminant migration of primary and secondary sources.	This model represents the starting point for imagining, identifying, describing, prioritizing and integrating complex, often non-linear, heterogenous processes important to the characterization of subsurface and surface flow and transport processes. It is fundamental to understanding the variables that control contaminant migration from a legacy waste site to the surrounding environment and predicting the effects and interactions between remediation solutions and their risks. The conceptualization of major operative hydrogeologic, geochemical and biological mechanisms that often occur in parallel is a reiterative activity, essential to the gradual development and integration of all first order hydrogeologic, bio-geochemical and geostatistical near-surface and subsurface models.	This recommendation is appropriate for the Moab site due to the unique geologic and hydrogeologic features of the site. How these features impact contaminant transport is not entirely characterized.	This recommendation could be implemented using historical site data. If additional data gaps are identified, then additional data could be collected (e.g., groundwater sampling, soil borings, surface geophysical techniques).	Short- to medium-term and long-term.	For optimum performance, this activity would need to be considered and implemented as a proposed approach to incorporating inputs from all Moab teams for site characterization data, technical recommendations (e.g., groundwater bypass and other clean water injection strategies), visualization platforms and other sub-models into a dynamic temporally and spatially dependent numeric model that can be used to 1) quantitatively and geostatistically assess the major hydrogeochemical operative mechanisms present at the site, and 2) serve as input to a performance assessment model and guide the management of site remediation protocols in light of evolving boundary conditions and climatic conditions.	Yes. Consider with other numerical modeling recommendations.
Vertical or Angled Boreholes	Potentially develop one or more new vertical or angled boreholes on the site to support characterization, hydraulic monitoring, or contaminant sampling activities. They are envisioned to augment / complement the existing borehole network.	Specific roles of these boreholes are envisioned to include: Geologic characterization of the formation over (shallow or potentially significant) depths with respect to physical or geochemical properties, hydrostratigraphy, mineralogy, etc., through the collection of cores and/or through providing access to geophysical, thermal, or flow-based logging tools (see other pitch sheets); providing multiple vertical access locations suitable for developing cross-well hydraulic or geophysical (e.g., tomography) tests that can be used to identify specific formation properties or other response characteristics; chemical characterization and monitoring of formation fluid levels and fluid compositions (contaminants, salinity) over (potentially significant and multiple) depths as a means to identify contaminant source terms (e.g., ammonia distribution) or monitor and identify brine profiles over depth (see source term pitch sheets); and consideration of the development of one or more angled chemical sampling boreholes as a way to emplace monitoring points beneath the current tailings pile that may be sampled while the tailings pile is still present.	This recommendations is suitable for the Moab site due to the need to characterize soil and groundwater beneath the tailings pile. The tailings pile is an area of active surface remediation, and therefore, subsurface access may be limited.	The approach is quite general and encompassing but limited in terms of costs and the need for careful upfront design. Boreholes in general can serve a multitude of needs and new boreholes must be considered in terms of their "value added" as related to 1) providing new characterization options (e.g., logging; cross well testing), 2) availing access to new locations (deeper spots, angled underneath tailings pile), 3) augmenting the existing network, and 4) compatibility to serve multiple needs (technology instrumentation) at the same time.	Short- (for characterization) to long-term (for monitoring).	The added value here is connected to the 1) application of multiple proposed technologies or demonstrations, e.g., conceptual model development, borehole logging, source term identification, monitoring of contaminant plume evolution, movement and dilution, or opportunities for numerical model validation, and 2) augmentation and strengthening of the existing borehole and monitoring network.	Yes. Consider with other borehole and geophysical survey methods.

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Team 3: Potential DOE response actions to include in the GCAP							
Mass Balance and Attenuation Assessment	1) Supplement current efforts to provide technically-defensible water balance, and 2) structure the evaluation using multiple lines of evidence as described in EPA and ITRC guidance documents. The overarching goal is to aid DOE in determining the potential role of attenuation processes in limiting the flux of contaminants to the Colorado River with a related goal to, conversely, assess if attenuation processes sequester contaminants and to better project the mass flux over time in the future and the flushing/remediation timeframes.	MNA is an environmental management strategy that relies on a variety of attenuation processes to transform or immobilize contaminants. MNA is appropriate at sites where contamination poses relatively low risks, the plume(s) are stable or shrinking, and the natural attenuation processes are projected to achieve remedial objectives in a reasonable timeframe. The conceptual model of natural attenuation as a mass balance between the loading (mass flux from residual contamination in the subsurface) and attenuation of contaminants in the plume is a powerful framework for understanding, documenting, and managing MNA. Importantly for Moab, assessing attenuation using the lines of evidence that are described in detail in the 2015 USEPA guidance for inorganic contaminants and radionuclides would provide DOE information to support incorporation of a final MNA stage in a combined remedy as part of adaptive site management and would provide insight about the role of natural processes in slowing contaminant flushing. For example, whether uranium solids or ammonium solids are present in the subsurface serving as secondary sources as they dissolve over time.	The complex chemistry of Moab would benefit from the structured multiple lines of evidence approach and from an attempt to improve the mass balance and water balance.	Implementable using standard engineering.	Short- to medium-term; would require some laboratory and pilot studies in the next few years.	Strong interrelationship with geochemical studies and geochemical examination of core sediments.	Yes
Assess Response of System to Response Actions	Use geophysical methods to monitoring emplacement and performance of response actions.	Given the transient nature of the system, geophysical methods must either have regular periodic surveys (data collected in space at a given time) or must be collected at a single location through time (e.g., well or surface time series). Passive hydrogeophysical methods are useful because they capitalize on the transients that exist in the system, and don't require regularly "stimulating" the system. Monitoring self potential, thermal, gravity, and synthetic aperture radar signals should be considered as ways to passively monitor the transient signals in the system over long periods of time.	All these methods should work well with the current Moab site. They are relatively easy to impalement, and could augment more traditional geophysical data (e.g., seismic, electromagnetics).	All the methods are relatively inexpensive and could be implemented in a passive way to monitor key areas without disturbing them or requiring constant human intervention (once installed).	Short- to long-term.	Relates to free transient signal recommendation from Team 2.	No
Clogging Amendments	Hydraulically isolate the residual contamination and reduce the source mass flux to the surrounding groundwater.	A number of technologies are potentially viable (silica gel, polymers, polymer foams, heat/wax, flowable grouts, etc.). This class of technology, often using silica gel or "water glass," has been used by DOE and internationally (e.g., Fukushima) for isolating groundwater from potential contamination source. The technology would require characterization information that demonstrated reasonably small areas of high, or significant residual contamination along with modeling that demonstrates that isolating or armoring the contamination would provide benefit to the adaptive site management and risk management for Moab. This technology, since it can use injectable amendments has the potential to be used at depths greater than soil blending or deep soil mixing. Silica gel is the most standard pore clogging material, however innovative technologies such as heat and paraffin wax or polymers could also be considered.	This concept is potentially matched to Moab conditions as a tool to control source mass flux..	This technology requires a number of prerequisites and could be considered in the future if appropriate targets of residual source contamination are identified.	Long-term (>3 years).	Fits in to the in-situ sequestration line of inquiry and inter-related with other implementation ideas such as liquid injection, PRBs and solid injection/fracking. The technology ideas specifically overlap with the green capping methods.	Yes
Enhanced Flushing	Assess the potential for deploying speeding up the flushing of key contaminants to provide support to a flushing based GCAP strategy.	Enhanced flushing and removal of uranium has been documented in the literature, primarily from the perspective of uranium solution mining. These systems use lixiviants (carbonate and complexing agents) to solubilize uranium and allow it to be removed rapidly in high concentration solutions. Uranium solution mining requires robust engineering controls to assure that the mobilized uranium is effectively captured. This is often accomplished by overpumping – in the case of Moab this would generate water requiring treatment. Note that there is minimal literature on chemical lixiviants and solution-based strategies to enhance the flushing of ammonium. Assuming that such solutions could be developed, effective capture would be critical since the ammonium efflux to the Colorado River is already near ecologically significant levels during key times of the year.	This concept, using chemical solutions to enhance flushing, is not well matched to Moab. The available information related primarily to uranium mining and not analogous to Moab conditions. Further, there are significant risks associated with enhanced flushing if robust capture is not successful.	Implementation of chemical or solution-based enhanced flushing would be challenging.	Long-term (>3 years).	Fits in to the Team 1 adaptive site management planning. Consistent with traditional GCAP flushing-based decision-making.	No
Enhanced Pond Evaporation	Provide an option for controlling pumped groundwater following tailings relocation prior to long term sustainable (passive) management strategies. The overarching goal is to limit plume expansion (e.g., limit efflux of ammonium, uranium, and other contaminants) to the Colorado River as long-term passive solutions are developed and implemented.	Currently, contaminated water is being pumped and dispositioned away from the river – used as dust suppression during tailings removal and relocation operations. As the tailings relocation is completed, dust suppression water needs will decline. A pond reasonably sized to fit into Moab would limit the flow rate of any pumping system – and thus limit the effectiveness of contaminant interception and plume control. For example, seasonal winter conditions would limit the practical operating period for evaporation. The specific objective of this pitch sheet is to explore options to maximize transfer of water to the atmosphere and to explore concepts to extend the practical seasonal operational timeframe. Several options are identified as seed concepts for evaluation, including 1) insulation/floating cover, 2) fountains, 3) rain diversion cover and/or air circulation, 4) expanded pond surface area, and 5) increased pond depth. Of these concepts, the most promising based on triage are use of solar fountains and possibly floating covers.	This strategy is may have short term application to Moab conditions and needs.	Hypothetically implementable using standard practice, but may encounter challenges to success associated with site specific water chemistry, space and logistics.	Short- to medium-term.	Several, including adaptive site management.	No

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Geophysical Monitoring to Assess Response of System to Response Actions	Monitor engineered perturbations to the system related to remediation performance and/or hydraulic manipulations of the aquifer/river interaction using geophysical techniques.	Geophysical methods that are used to monitor time-varying subsurface conditions include ER, SP, IP, frequency- and time-domain electromagnetic, seismic refraction and reflection, nuclear magnetic resonance, ground-penetrating radar, gravity, and thermal. Given the objectives and hydrologic conditions at Moab, the most promising approaches for monitoring emplacement and performance actions include 1) ER, 2) SP, 3) IP, 4) electromagnetic, and 5) thermal methods. The ultimate selection will depend on future decisions, but these methods are broadly applicable to processes of interest.	All of the methods discussed are suited to conditions at Moab to varying degrees. Underground infrastructure (e.g., pipes, tanks, structures) pose challenges to electrical and electromagnetic methods. Overhead powerlines are also problematic for electromagnetic methods.	Geophysical methods are inexpensive relative to drilling wells and capable of filling in gaps in space (and possibly time) between conventional sampling. Time-lapse geophysical monitoring can be achieved through continuous, long-term installations or by repeat site visits and periodic data acquisition. The latter is more cost effective for shorter deployments, and the former more cost-effective for long-term deployments. ER, IP and SP are suitable for long-term installations and near-real time delivery of results (Figure 1), whereas methods that require movement of transmitters and receivers (electromagnetic) or other labor (e.g., triggering seismic sources) are more difficult to implement in continuous operation.	Short- to long-term.	Geophysical monitoring and characterization are most effective when coordinated with conventional monitoring and characterization. Geophysics cannot substitute for direct measurements and require calibration and ground truth. In some cases, geophysical investigations provide valuable insight to guide conventional sampling, e.g., the siting of wells. In other cases, geophysics can fill gaps in space and/or time between direct measurements. For these reasons, geophysical monitoring is necessarily inter-related with conventional sampling and hydraulic testing campaigns; furthermore, geophysical investigations should be planned so as to facilitate the use of results in modeling efforts, through coordination with teams involved in 3D visualization, CSM development, and numerical modeling.	No
Groundwater Bypass	Modify hydrologic boundary conditions to isolate contaminated water and stagnate plume – limiting efflux to the Colorado River. This concept physically connects the upgradient (uncontaminated water) to the near-river zone using piping infrastructure to provide a passive and sustainable modification for risk reduction.	Install wells that connect the clean upgradient groundwater to the subsurface area along the river. This would reduce upgradient head and increase downgradient head, thus reducing driving force of water moving though the contaminated area. This provides passive isolation or partial stagnation of the contaminants. This has the potential to significantly reduce the flux of contaminants to the river and to critical habitats.	This technology may be suited to Moab. Note that bypass is not compatible with flushing and would not be used if contaminant flushing and removal are the core strategies in the GCAP. Bypass would be a useful and perhaps key passive/semipassive technology if the core strategy(-ies) in the GCAP are contaminant sequestration and control of the releases and mass flux to the Colorado River and Critical Habitats.	Relatively straightforward to implement. Initial step would be to simulate options using a numerical model.	Medium- to long-term.	Simple and straightforward. Works well with all sequestration ideas. Does not work with flushing or enhanced flushing concepts.	Yes
In Situ Hydroxyapatite Formation for Uranium Sequestration	Enhance the attenuation of uranium in the subsurface by forming an in situ permeable reactive barrier (PRB) that can intercept and remove contaminants as the groundwater plume passes through the reactive barrier.	A hydroxyapatite barrier is constructed by injecting a solution containing calcium citrate and sodium phosphate into the subsurface. As the indigenous soil microorganisms biodegrade the citrate, the calcium is released and reacts with the phosphate to rapidly form hydroxyapatite in situ (Eq. 1). Hydroxyapatite is very stable and highly insoluble in water, and contaminants (particularly uranium) are removed upon contact with the barrier though several mechanisms including sorption, surface complexation, substitution into the apatite structure by ion exchange, and formation of sparingly soluble uranium phosphate minerals.	The hydroxyapatite would be a viable treatment for uranium sequestration based on the groundwater pH (circumneutral) which is optimal for the formation of hydroxyapatite in situ. Care should be taken in the selection of the location (preferred at locations with lower permeability) for the installation of the PRB as it is required a certain period of time for the liquid amendments to interact and form hydroxyapatite.	This technology has been tested at Hanford site in 2008 to create a permeable reactive barrier for immobilization of strontium-90 at the Hanford Site, showing a 90% reduction in Sr-90 concentrations after 1 year of treatment. In 2017, a field pilot testing was conducted at the Old Rifle to test the performance of the apatite PRB for uranium remediation where it has shown positive results in maintaining uranium concentrations below UMTRCA levels (44 ppb). Currently, a test pilot for the in situ apatite amendment is being tested at the Moab site for uranium remediation.	Short-term.	This technology could work in parallel with other proposed technologies such as the use of phosphate injections to induce precipitation of struvite type minerals for the sequestration of ammonium.	Yes. Consider with other solid amendment recommendations.
In Situ Struvite Precipitation for Sequestration of Ammonia	Reduce ammonium solubility/ mobility ("immobilization" or "sequestration") to limit the flux to the Colorado River.	The strategy would be to inject reagent chemicals to encourage precipitation of Struvite – an idea that may be combined with the in situ apatite technologies already being tested at Moab. Ammonium tends to form soluble salts, thus limiting the potential applicability in situ sequestration concepts. The exception for ammonium is the formation of struvite type minerals in the presence of phosphate and another cationic element such as magnesium, nickel, barium, or others. The pKsp for struvite is in the range of -12 to -13. This strategy may be synergistic with technologies for in situ apatite generation (i.e., adding phosphate, calcium, and other reagents). Scoping calculations suggest that site conditions are near solubility for struvite type minerals and that conditions conducive to precipitation could be generated by injection of fluids containing phosphate and key accessory elements. Under the correct conditions, such mineral phases have potential to limit future release of ammonium to the active groundwater system.	This technology could be suitable for the Moab site to treat source zones. Due to the massive amount of ammonia used during milling operations at the site, this approach may not be suitable to treat the entirety of ammonium-impacted groundwater.	Implementable using standard engineering. Has not been used full scale but based on standard chemistry and literature documenting struvite formation in wastewater, biological, and industrial (process) systems.	Long-term (would require some laboratory and pilot studies in the next few years).	For optimum performance, this concept would need to be considered and implemented with simultaneous evaluation of uranium sequestration technologies. Concept is not viable if natural or enhanced flushing are central to the overarching GCAP strategy.	Yes. Consider with other solid amendment recommendations.

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Injection of Humate amendments for Uranium Sequestration	Enhance the sequestration of uranium and possibly ammonium in the subsurface by forming an in situ humic PRB that can intercept and sequester contaminants as the groundwater plume passes through the reactive barrier.	The formation of an in situ humic permeable reactive barrier is accomplished by: 1) injecting a humate solution to form a coating on the mineral surfaces, 2) injecting a humate solution followed by the injection of an acid or salt solution (Al(III), Fe(III)) to cause precipitation of humic substances, or 3) by employment of modified humate derivatives that provides higher adhesive affinity for mineral surfaces due to the formation of covalent Si-O-Si bonds. A humic PRB would limit uranium and ammonium discharges into the Colorado River. In addition, humic substances influence in the bioavailability of heavy metals by forming strong complexes, limiting the availability of free metal ions to interact with organisms, and reducing metal toxicity (e.g., copper).	Initial testing would be required to evaluate if Moab field conditions are optimal for the creation of a humic permeable reactive barrier. It is anticipated that humic sorption onto aquifer sediments will be moderate since Moab's groundwater pH is characterized for being between 6.57 – 7.67 while humate sorption on aquifer sediments tend to be higher at acidic pH and much lower at alkaline pH.	Since humates are nontoxic and water soluble, they can be easily introduced in the subsurface to create humic PRBs. There is no need for soil excavation, trenching, etc. This reduces the cost of operation and Raw humic materials have a low cost and commercially available. This technology was piloted at SRNL in 2013 and was successful at decreasing dissolved uranium concentrations in groundwater.	Medium-term. Would require laboratory and pilot studies.	Humates are polyfunctional and may operate many roles at the same time. Not only to enhance the sequestration of uranium and possibly ammonium in the subsurface, but it also provides a detoxification pathway to reduce the bioavailability of heavy metals (e.g., copper) to aquatic organisms.	Yes. Consider with other solid amendment recommendations.
Injection of Solid-Phase Amendments	Sequester uranium via the injection of solid-phase amendments to provide source zone treatment or a reactive zone to treat contaminants as they flow downgradient.	Solid phases to consider include hydroxyapatite and zero-valent iron. Hydroxyapatie sequesters uranium via sorption on the hydroxyapatite surface, precipitation of uranyl phosphate mineral phases, and incorporation into the apatite mineral. ZVI sequesters uranium through reduction and precipitation of U(IV) minerals, adsorption and co-precipitation onto and within ZVI corrosion products, such as iron oxides. Solid phase amendment materials could be injected into the subsurface either to provide source zone treatment or a reactive zone to treat contaminants as they flow downgradient. Particle size is the major factor that controls injection and delivery.	Injection of solid phase particulates should be feasible under most conditions. Site specific amendment delivery and distribution requirements can often be met through engineered design considerations (i.e., number and location of injection points). The properties of the solid phase amendment will determine the feasible delivery strategies.	Some considerations for injection of solid phase amendments include: How will the subsurface be accessed (e.g., injection points, existing wells, trenches, fracturing, surface infiltration)? Does the amendment require a delivery aid for successful subsurface distribution? What are the conditions of the targeted zone that will influence treatment and delivery (heterogeneities, permeability, preferential flow paths, pH, moisture content, soil texture, etc.)? How much amendment mass is required for successful treatment? How far can the amendment be distributed? How quickly does the amendment react? Are secondary effects of amendment (and/or carrier fluid) that need to be considered for the site?	Short- to medium-term.	Successful delivery of solid phase amendments will depend on the size of available amendment particulates, amendment properties, treatment requirements, and subsurface properties.	Yes. Consider with other solid amendment recommendations.
Interim Pump and Treat	1) Provide a limited term option for controlling pumped groundwater following tailings relocation prior to long term sustainable (passive) management strategies, and 2) develop strategy to manage water in the scenario where dust suppression is no longer needed. The overarching goal is to limit plume expansion (limit efflux of ammonium uranium and other contaminants) to the Colorado River as long-term passive solutions are developed and implemented.	Currently, contaminated water is being pumped and dispositioned away from the river – used as dust suppression during tailings removal and relocation operations. As the tailings relocation is completed, dust suppression water needs will decline. However, it may take many years to refine and implement long term passive plume management and risk reductions strategies (such as in situ sequestration, permeable reactive barriers, groundwater bypass, and others). During this period, some active pumping-based plume control may be needed or considered by the Moab team. Developing a pathway for the pumped water as well as integrating the pumping objectives into an overall GCAP plan for the site are keys to supporting such an interim pump and treat. There are a number of potential water disposition (treatment) options for Moab contaminants and bulk water chemistry. A notable example scenario for water treatment and disposition would be to apply air stripping to remove ammonia and a mineral based sequestration for uranium.	This strategy is a reasonable match to the challenging Moab conditions such as mixed contaminants in water with intermediate levels of specific conductance.	Implementable using standard engineering. Would require significant investment to implement.	Medium-term (would require some near-term focus and effort to implement in time to coincide with the completion of the tailings relation in 2025).	Strong interrelationship with development of an adaptive site management strategy Including combined and sequential remedies) and closely connected to in situ sequestration efforts (apatite, humate and struvite).	Yes
Permeable Reactive Barrier Amendments	Install a PRB filled with solid phase amendment material parallel to the river to create a reactive treatment zone to either degrade, precipitate or sorb mobile contaminants and decrease the overall mass flux entering the river.	Large particulate amendments are commonly employed as PRBs, where either a direct reaction (or indirect through release of a reactive agent) between the amendment and the contaminant occurs or subsurface conditions that define contaminant mobility are altered (pH, Eh) creating a subsurface treatment zone. PRBs can be created by various methods such as soil mixing, trenching, amendment injections, etc. PRBs can be designed to have higher permeability than the surrounding formation to promote flow through the PRBs reactive zone (e.g., funnel and gate design).	This technology may be suitable for Moab site. Need to understand the mobile contaminant phases and the biogeochemistry and to identify which solid phase amendment might be applicable to the Moab site.	PRBs are relatively straightforward to design and implement. Some design considerations would include the location, barrier thickness, resulting treatment longevity, and potential secondary effects (e.g., alterations to the pH/Eh of the subsurface and groundwater, amendment byproducts). Initial step would be to simulate options using a numerical model. Some additional considerations include the potential for desorption and contaminant release over time and the potential for clogging by mineral precipitation and passivation by formation of corrosion products (Fuller et al., 2003).	Short- to medium-term.	Simple and straightforward. Works well with all sequestration ideas.	Yes. Consider with other solid amendment recommendations.
Phytoevapotranspiration (Irrigation)	Provide an option for controlling pumped groundwater following tailings relocation prior to long term sustainable (passive) management strategies. The overarching goal is to limit plume expansion (limit efflux of ammonium uranium and other contaminants) to the Colorado River as long term passive solutions are developed and implemented.	Currently, contaminated water is being pumped and dispositioned away from the river – used as dust suppression during tailings removal and relocation operations. As the tailings relocation is completed, dust suppression water needs will decline. However, it may take many years to refine and implement long term passive plume management and risk reductions strategies (such as in situ sequestration, PRBs, groundwater bypass, and others). During this period, some active pumping-based plume control such as irrigation and phytoevapotranspiration may be needed or considered by the Moab team. Using pumped water for irrigation to take up ammonium may not be optimal for Moab because of a number of constraints: the high specific conductance (salt) levels is not compatible with sustainable irrigation standards (see below), there is limited land area for irrigation planting, and the planned restoration of the Moab Wash braided stream ecosystem is not compatible with plantings needed for irrigation.	This strategy is a poorly matched to Moab conditions and needs.	Hypothetically implementable using standard practice, but likely to encounter challenges to success associated with site-specific water chemistry, space and logistics.	None.	Eliminate from further evaluation due to poor match to Moab conditions.	No

Recommendation	Objectives	Description	Is the technology well-suited to conditions at the Moab site?	Implementability	Time Frame	Technology Inter-Relationships	Retained for Short List?
Reconfigure Channel of Colorado River	Reconfigure the channel to protect critical habitat from the efflux of contaminants from Moab groundwater.	The current channel represents an anthropogenically modified river course that was engineered slightly to bring the Colorado River closer to the millsite (to provide easy access to water for milling and sluicing operations). The current "modified-engineered" river path resembles a mature oxbow. A technically defensible strategy for reducing risk and protecting human and ecosystem health would be to 1) reconfigure/restructure the channel to provide more robust and stable critical habitat located in zones where there is minimal hyporheic impact from Moab plume groundwater, or to 2) reroute the channel to follow a more natural historical path – thus increasing the distance between the former millsite and the river (providing additional space for implementing remedial action). In the rerouting scenario, the current river channel could be beneficially used as a component for deployment of a permeable reactive barrier that would intercept and reduce the long term flux to the River. Note that a project is already planned for restoration of the Moab wash (inlet and braided channel entering Colorado river in the area of the former millsite) to be more representative of pre-millsite conditions. Potential reconfiguration options could be coupled with this already planned activity.	This idea could be explored with regulators and subject matter experts from the state of Utah. The simple reconfiguration might be challenging because the current anthropogenically modified river channel is not stable and is subject to hyper-natural erosion and deposition. The more aggressive rerouting would require significant planning and time and close coordination with regulators and the public.	Implementable using standard engineering and ecological principles.	Long-term.	For optimum performance, this concept would need to be considered and implemented with simultaneous evaluation and consideration of other boundary conditions controls (e.g., groundwater bypass and other clean water injection strategies).	Yes
Soil Blending and Deep Soil Mixing	Assess the potential for deploying solid amendments using soil blending or mixing. This is a commercially available strategy that provides the ability to deploy reagent amendments and ensure effective contact of reagent amendments and contamination.	Soil blending and deep soil mixing have been used to support a range of remediation technologies including steam and hot air stripping of volatile contaminants (with a collection hood), in situ chemical oxidation and reduction, installing PRBs, installing barrier walls (funnel and gate systems), and limiting water flow through contaminated zones. The principal advantage of blending and mixing is assuring reasonable and effective contact of the treatment reagents with the contaminants. Many of the chemical treatments rely on short term destruction within the mixed volume – typically, field data have demonstrated 98% to >99% destruction. There are a number of systems for performing the blending/mixing with nominal deployment depths of around 25 feet and maximum depths up to 70 to 90 feet. A second advantage of blending and mixing is the ability to incorporate large quantities of reagents – tons of reagents can be added as solids and mixed in instead of dissolving in water for injection.	This concept is potentially matched to Moab conditions as a tool to deploy sequestering solids or component amendments. The technology is limited in depth so that deployment of reagents would need to be performed in areas where the target material in nominally within 25 to 50 feet of the ground surface (or benched surface). The technology might have most advantageous use in areas where there is residual contamination in the vadose zone and shallow groundwater such as under the former tailing pile following the relocation activities.	Implementable using commercial technology – but costs may be relatively high compared to injection of liquids. Significant testing needed.	Long-term (>3 years).	Fits in to the in situ sequestration line of inquiry and inter-related with other implementation ideas such as liquid injection, PRBs and solid injection/fracking.	Yes. Consider with other solid amendment recommendations.

Table B-1
Long List Preliminary Recommendations
Moab UMTRA Project Site
Grand Country, Utah

Abbreviations:

ACL	alternate concentration level
AWQC	ambient water quality criteria
BHF	borehole flowmeter
COC	contaminants of concern
CSIA	compound-specific isotope analyses
CSM	conceptual site model
DOE	US Department of Energy
EMI	electromagnetic induction
ER	electrical resistivity
FO-DTS	fiber-optic distributed temperature sensing
GCAP	groundwater compliance action plan
GFMs	geologic framework models
IP	induced polarization
ITRC	Interstate Technology Resource Council
mg/L	milligrams per liter
MNA	monitored natural attenuation
NMR	nuclear magnetic resonance
NNLEMS	Network of National Laboratories for Environmental Management and Stewardship
NRC	United States Nuclear Regulatory Commission
ORP	oxidation reduction potential
PEIS	Programmatic Environmental Impact Statement
ppb	parts per billion
PRB	permeable reactive barrier
SP	self potential
SRNL	Savannah River National Laboratory
TIR	thermal infrared
TRL	technology readiness level
UMTRCA	Uranium Mill Tailings Radiation Control Act
USEPA	US Environmental Protection Agency
USGS	US Geological Survey
VOC	volatile organic compound
XAS	x-ray absorption spectroscopy
ZVI	zero-valent ion

Sources:

Aboldt et al. 2018.
Fuller et al. 2003.

APPENDIX C:
Narratives for Short List Recommendations

TEAM 1

GCAP Development, Requiements, and Path Foward

Topic: Adaptive Site Management

Objectives:

The groundwater remedy for the Moab UMTRA Site may be a combination of approaches/technologies, both in conjunction and in phases, because of certain challenges (mixture of COCs with different behavior, depth of contamination, complexities of the brine, dynamics of interactions with the river, etc.). Uncertainty in site conditions and the dynamics of the Colorado River limit the predictive accuracy of hydrologic models; climate change exacerbates the uncertainty. Significant new information will likely be gained during remedy implementation, and it can be used to adapt and optimize the remedy.

Description:

Adaptive site management is a comprehensive, flexible, and iterative process of remediation management that is well-suited for complex sites, where there is significant uncertainty in remedy performance predictions (ITRC, 2017). Adaptive site management includes periodically evaluating and adjusting the remedial approach, which may involve multiple technologies at any one time and changes in technologies over time. The conceptual site model (CSM) is refined using information gained from remedy performance.

Site remediation managers adapt or adjust the selected remedy over time in response to remedy performance. These adjustments keep the remedy on track to meet interim objectives. Interim objectives and associated performance metrics may reflect a variety of goals.

A typical site objective is to restore groundwater to beneficial use (ITRC, 2017). For the Moab site, beneficial use considerations include access, targeted institutional controls, and acceptable risks for land and water use, including use of the river habitats by endangered species. The anticipated end use of the site will influence selection of combinations of remedial approaches and their sequencing.

Under adaptive site management, institutional controls (ICs) and land use controls (such as deed restrictions and fencing) are typically used to prevent exposure over the long term. UMTRCA regulations require the use of institutional controls for passive restoration remedies. In Long-Term Contaminant Management Using Institutional Controls, ITRC (2016) identified critical elements of effective IC management programs based on successes from established state and federal regulatory programs.

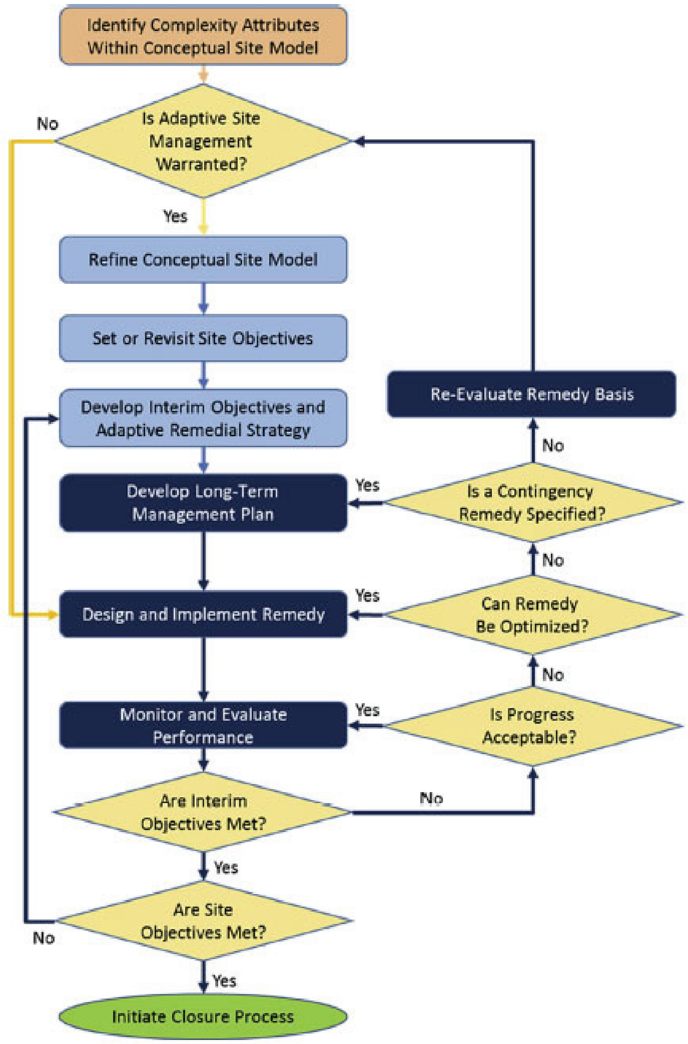


Figure 1. The Adaptive Site Management Process (Price et al., 2017).

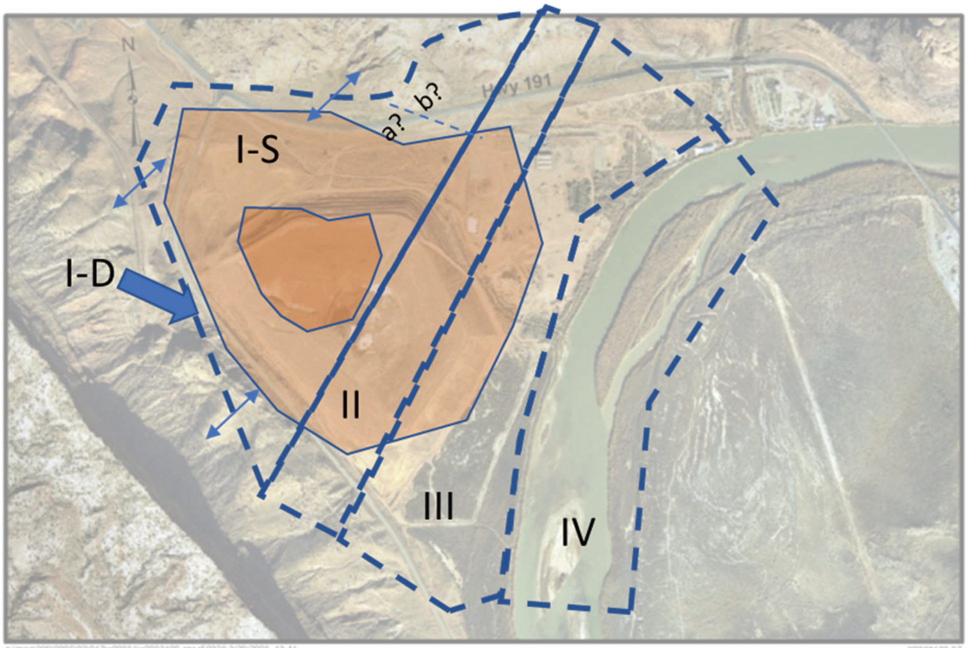
Match to Moab Conditions:

The complexity of site's conditions may be better addressed with adaptive site management than a single prescriptive remedy. While adaptive site management is not explicitly addressed by existing UMTRA/NRC guidance and requirements, it is also not precluded.

Based on the conceptualization of Moab, an eventual adaptive site management strategy will need to address several spatial zones – each having unique environmental risk management goals/objectives – and several target timeframes. Figure 2 is a hypothetical example designating zones. This designation is focused on a primary interim and long-term objective of protecting the Colorado River. The depiction is only one notional possibility and is provided only as an example of the process. For example, in the area(s) of former uranium and ammonium sources, there is an emphasis for the shallow active aquifer zone toward midterm actions to remove or control source mass flux using sequestration or flushing, and long-term transition to enhanced attenuation. The emphasis for transition and buffer zones is providing reliable (defense in depth) control of source mass flux to the river and assuring that remedial actions do not result in river impacts. For the notional zones depicted in Figure 2, the following provides a more detailed summary of objectives and brainstorming thoughts:

- I-S – Residual Source Zone (shallow) -- isolate and stabilize/sequester residual source material in the vadose zone and shallow groundwater. This could be done using mid-term activities such as injecting or blending sequestering or pore clogging reagents (or enhanced flushing reagents) combined with engineered controls of infiltration and drainage such as lithification technologies or braided drainage channels that minimize infiltration in areas of residual sources.
- I-D – Residual Source Zone (deep/brine) -- Isolate and/or document acceptable source mass flux.
- II – Transition Zone -- control source mass flux by using interim pump and treat and longer term using PRBs or other technology to reduce source mass flux to an acceptable level.
- III – River Protection Buffer Zone -- area where river fluctuations will flush and rinse contaminants. The designation of this zone helps assure that engineered remedial actions do not have adverse collateral impacts on the river and hyporheic zone. This zone could also be used for interim enhanced flushing during designated times of the year where there are no sensitive species present or potential impacts on critical habitats.
- IV – River Management Zone -- river area where critical habitats are monitored and water is managed to protect sensitive species during key times of the year.

Developing this type of strategy as part of the GCAP process provides a platform for clear communication about the objectives of the activities in both space and time and provides the basis for proposing timeframes for transitioning from active to passive remediation technologies and strategies. This paradigm also helps guide the plans for characterization since a key aspect of the characterizations would be to support and provide a technical basis for the delineation of the proposed zones.



I-S Residual Source Zone (shallow)
I-D Residual Source Zone (deep/brine)
II Transition Zone
III River Protection Buffer Zone
IV River Management Zone

Notes – depicted shading is notional and not based on data – it is intended to demonstrate how information on potential residual sources could be leveraged to inform adaptive site management

Figure 2. Notional example of spatial zonation to support an adaptive site management strategy.

Implementability:

The Programmatic Environmental Impact Statement and NRC guidance do not envision an adaptable remedy, but it is technically feasible. Adaptive site management is increasingly gaining acceptance and use for complex sites. For Moab, the approach should incorporate institutional controls and be driven by potential beneficial end uses.

Concern may be raised that the remedy would be open-ended. An adaptive remedy, though, can be well-defined, for example by identifying, clarifying, and seeking approval on decision points, their inputs, and follow-on actions, and by defining how the approach will meet requirements and standards.

The technology readiness level (TRL) is estimated as 8.5. Adaptive site management has been accepted by regulatory agencies and is quickly increasing in recognition as it is proposed for complex sites.

Exemplars/References:

ITRC (Interstate Technology & Regulatory Council). 2017. Remediation Management of Complex Sites. RCMS-1. Washington, D.C.: Interstate Technology & Regulatory Council, Remediation Management of Complex Sites Team. www.itrcweb.org.

John Price, Carl Spreng, Elisabeth L. Hawley, Rula Deeb. 2017. Remediation management of complex sites using an adaptive site management approach. Journal of Environmental Management, 204(2017): 738-747.

Technology Inter-Relationships:

The general GCAP process typically is presumed to be linear; a remedy is selected and then implemented. Adaptive site management could be implemented as an approach during GCAP development, though, and incorporate options for remedy optimization as cleanup progresses. The remedy options could include those developed by Team 3. Team 2 is recommending numerical flow and transport modeling. Characterization and remedy selection activities can be informed by and iterated with numerical modeling. Similarly, numerical models can be refined and enhanced as data are collected during the remedy selection and implementation processes.

An adaptive site management approach includes upfront and early agreement on remedy transitions, thereby laying the groundwork for efficient transitions. The approach also acknowledges uncertainties and allows for updates to the conceptual site model as the remedy progresses, which supports optimization and efficiency.

Sequencing - Prerequisites and Data Gaps/Needs:

Principles of adaptive site management could begin to be used by the site team immediately. The framework explicitly includes revisions and continual updates, so the approach can be adjusted and revised as appropriate.

Timeframe:

Tier 1 (timeframe 1 to 2 years) -- Can be done with existing data or infrastructure or with data or infrastructure that can be rapidly and inexpensively collected/deployed. Adaptive site management can be used in the development of the GCAP.

Synopsis and Consensus:

The approach has the support of the working group, and no significant concerns have been raised about its application.

TEAM 2

Groundwater Contamination-Related Topics

Topic: Numerical Model Development

Long List Item / Objectives:

Team 2 – 3D Numerical Model for Hydrogeology, Flow, and Transport—Configure and calibrate a 3D numerical groundwater flow and contaminant transport model, and use it to forecast contaminant plume evolution and evaluate the effectiveness of potential compliance strategies. An appropriate numerical model will support the development of a defensible Groundwater Compliance Action Plan (GCAP) that is acceptable to regulators and stakeholders.

Description:

Evaluation of the suitability of potential compliance strategies for the Moab site requires forecasting contaminant migration under different site management scenarios. Example forecasts of interest include remediation timeframes and future contaminant concentrations at points of compliance and points of exposure. Forecasts such as these are typically developed for several site management scenarios, including passive (e.g., natural flushing or alternate concentration limits) and active (e.g., groundwater extraction or amendment injection) compliance strategies. Developing appropriate forecasts requires application of mathematical models, which can be simple or complex. Given the hydrogeologic complexities at the Moab site, a sophisticated 3D numerical model will likely be necessary to make defensible forecasts that can be used to justify a groundwater compliance strategy for the site. The Moab site has a long history of using numerical models to support site management decisions (DOE 2003, DOE 2012, DOE 2016), and continued application of these models for GCAP development is recommended (Figure 1).

The conceptual site model (CSM) is the starting point for a numerical model. The CSM describes processes controlling groundwater movement and contaminant migration at a site, and it highlights key site features that need to be represented in a numerical model to achieve project objectives. Misunderstandings in the CSM become misspecifications in the numerical model, potentially causing inaccurate forecasts that could lead to poor site management decisions. The Moab site has a mature CSM (Figure 2); the Site Observational Work Plan (SOWP) describes the original CSM (DOE 2003). CSM development is an iterative activity, and the CSM should be updated to incorporate new information as it becomes available. Before initiating numerical modeling, the CSM should be reviewed and refined, as necessary. CSM review includes a thorough reevaluation of historical data, identification of data gaps, and refinement of the conceptualization as data gaps are addressed. This process can be aided by 3D visualization tools, such as Seequent's Leapfrog software (Figure 3), which was recently used to perform geologic and plume modeling for the Moab site.

The current CSM for the Moab site emphasizes several complex processes that might control the distribution of contaminants. The following processes and features described in the CSM should be reviewed, and appropriate representations should be considered during development and application of a 3D numerical model:

- The brine interface, including variable-density flow and interfacial mass transfer
- Residual and secondary contaminant sources, including vadose zone sources and the deep legacy brine plume—experience at LM sites suggests that residual and secondary sources can be the primary driver of remediation timeframe, and not including these sources in simulations leads to remediation timeframe forecasts that are too optimistic
- Transient processes, especially relating to seasonal fluctuations of Colorado River stage and the consequent shifts in groundwater flow directions
- Interactions with the Colorado River, including possible flow beneath the river and brine discharge to the river
- Inflows from precipitation-based recharge or from adjacent bedrock aquifers, accounting for alternate permeability models describing the Moab fault
- Key biogeochemical processes, including biological ammonia degradation and the impact of brine zone fluctuations/changing geochemistry on uranium mobility
- Heterogeneity of the aquifer's hydraulic and geochemical properties

Determining an appropriate level of complexity to represent these processes and features is a challenge (Doherty and Moore 2019). A model that is too complex becomes unmanageable because of lengthy run times and numerical instability. Complex models are also more difficult to parameterize, often requiring input information that is not available or not readily obtainable. On the other hand, an oversimplified model will fail to reasonably represent important processes, resulting in unacceptable bias in model predictions. Development of data quality objectives (DQOs) is recommended to ensure that data generated during site characterization and modeling activities are adequate to support decisions (EPA, 2000). Preliminary modeling with uncertainty analysis can also help determine an appropriate level of complexity for a 3D numerical model. This preliminary modeling may include development of simple, focused models to improve understanding of specific aspects of the system. Preliminary modeling could also include testing alternative configurations of the full 3D numerical model to gauge the sensitivity of model predictions to various simulated processes, following the forecast-first approach to modeling (White 2017).

A proposed application of the first approach (i.e., using a simple, focused model) for the Moab site is development of a cross-sectional model to aid in the assessment of brine interface dynamics. A 2D cross-sectional model that incorporates density-dependent flow and simulates transient conditions may improve understanding of several of the processes identified in the bulleted list above, especially with regard to the brine interface and transient interactions with the Colorado River (Figure 4). Cross-sectional models have the advantage that they are relatively straightforward to set up and have fast run times; however, cross-sectional models are limited and generally cannot replace 3D numerical models. For example, a 2D profile model is not appropriate for simulating the effect of groundwater extraction wells on the system because pumping induces radial flow, violating the assumption of flow being parallel to the profile (unless the model is constructed as an axisymmetric profile, which would not be the case for Moab). Rather, a 2D model could help to quickly determine how to adequately represent the brine interface and seasonal processes in the full 3D numerical model. A 2D cross-sectional modeling approach was applied previously at the Moab site for this purpose, and the results are described in Appendix D of the SOWP (DOE 2003). Moreover, a 3D variable-density flow model with monthly stress periods was previously developed for the site (DOE 2012, DOE 2016). These previous modeling efforts should be reviewed, and updated 2D cross-sectional modeling may be performed if the review suggests that a revised profile model would be beneficial.

If preliminary modeling is performed prior to additional data collection, then a preliminary version of the 3D numerical model can be used for data worth analysis (Doherty 2015, Fienen et al. 2010, White et al. 2016). Data worth analysis approximates the reduction in predictive uncertainty that can be achieved by incorporating new data into a numerical model (Figure 5), and it is generally performed using efficient first-order, second-moment (FOSM) Bayesian analysis methods (i.e., Schur’s complement). It can be performed before new data are collected and before the model is calibrated. Data worth analysis focuses efforts on collecting data that will be most informative for making key site management decisions, thereby improving the efficiency of efforts to reduce risk. Examples of questions that can be addressed using data worth analysis with groundwater models include the following: Where should new monitoring wells be installed to improve plume delineation under current and future site conditions? How will collection of sediment core samples beneath the tailings pile improve predictions of remedial time frames? How will a field program to refine hydraulic conductivity estimates improve evaluation of groundwater extraction system performance?

The 3D numerical model will be calibrated and its forecasts finalized once CSM review, preliminary modeling, and data collection are complete. Even when advanced site characterization data are available to constrain a groundwater flow and contaminant transport model, the model forecasts remain highly uncertain; therefore, a robust uncertainty analysis is also recommended. Examples of uncertainty analysis methods that could be applied at the site include traditional Monte Carlo, null-space Monte Carlo (Tonkin and Doherty 2009), iterative ensemble smoothers (White 2018), FOSM Bayesian methods (White et al. 2016), and Markov chain Monte Carlo. Stochastic model simulations provide a quantitative basis for risk management, improving management decisions and minimizing risk.

The level of effort to complete modeling (including preliminary modeling, potentially involving a 2D cross-sectional model) to support a GCAP will depend on whether an existing model for the site is adequate (with a minor or major update) or a new model is needed. Significantly less effort is required if the existing models can be adapted to meet current needs. The model will likely need the ability to simulate variable-density flow. Previous models at the site have been built with FEFLOW and SEAWAT, both of which can simulate density-dependent flow and multispecies transport. SEAWAT was built from the MODFLOW and MT3DMS codes. If future modeling for the Moab site is performed using the MODFLOW family of codes, the project team should consider updating the model to a newer version of MODFLOW that includes a variable-density flow formulation and unstructured grids (i.e., MODFLOW-USG or MODFLOW 6). A modern graphical user interface (GUI) can limit the effort needed to update from an older version of MODFLOW to a newer version. The model may require advanced geochemical reaction simulation capabilities (for example, if simulated remediation scenarios involve amendment injection to sequester contaminants by forming a mineral precipitate). FEFLOW has these capabilities using its piChem plugin, and PHT-USG (PHREEQC coupled with MODFLOW-USG) is an option within the MODFLOW family of codes for 3D geochemical modeling with density-dependent flow.

Pre- and post-processing of model inputs and outputs is greatly facilitated by a well-designed GUI. Moreover, 3D visualization capabilities within a GUI enhance the interpretation and communication of model results. FEFLOW includes a GUI with 3D visualization capabilities. Groundwater Vistas, Visual MODFLOW, and GMS are popular GUIs for the MODFLOW family of codes (including SEAWAT). GMS and Visual MODFLOW Flex both include advanced 3D visualization capabilities. The Leapfrog 3D visualization software that was recently applied at the Moab site is capable of importing from and exporting to FEFLOW, MODFLOW, and MT3DMS in structured and unstructured grid or mesh formats. Leapfrog can also export models to Groundwater Vistas. Leveraging the existing Leapfrog model by interfacing it with a specialized groundwater flow modeling GUI will facilitate construction of the 3D numerical model, reducing the overall level of effort needed for implementation.

Graphic(s):

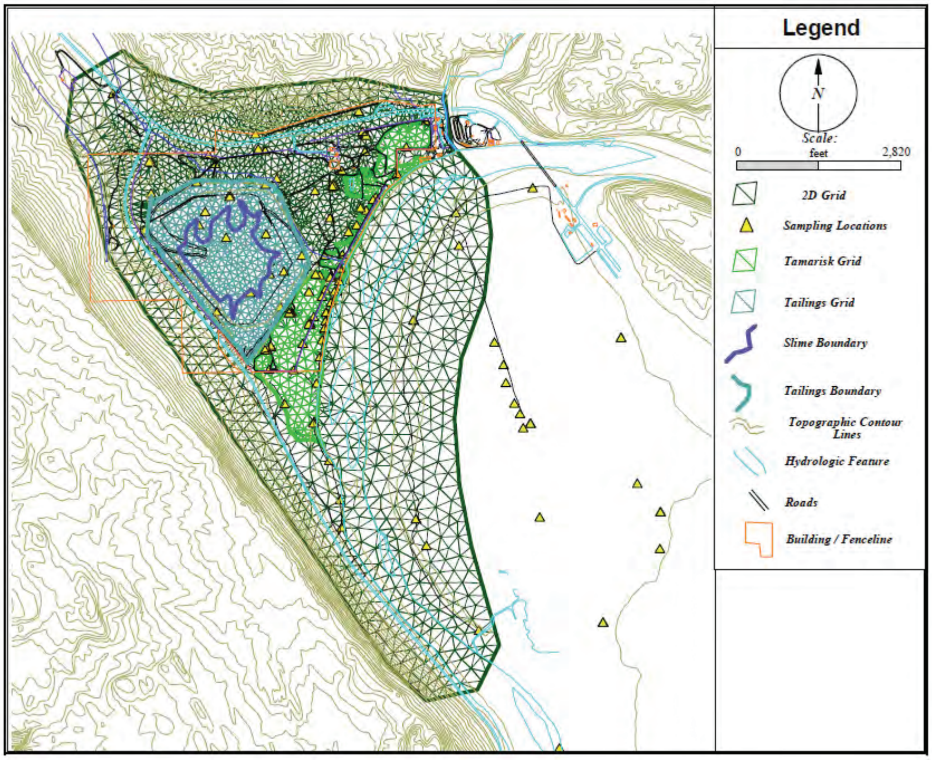


Figure 1. Finite element mesh used in the 2003 Moab flow and transport model (DOE 2003).

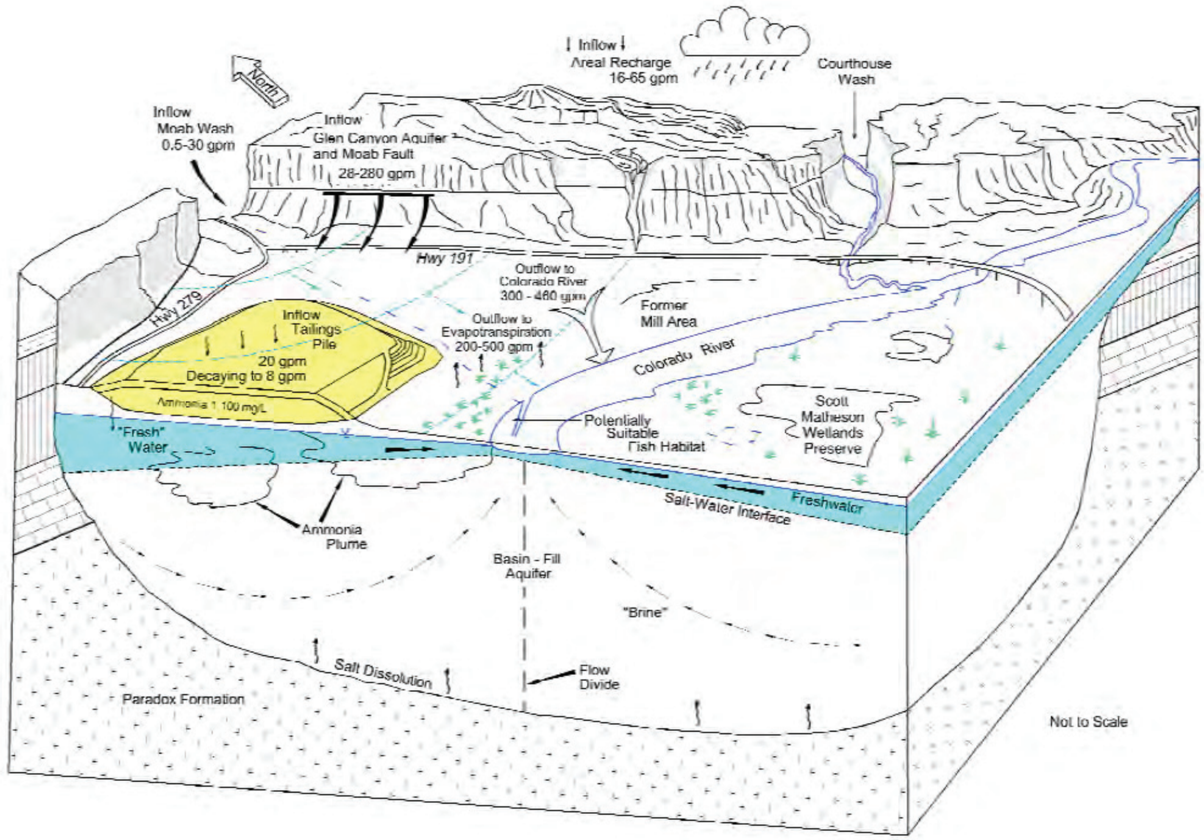


Figure 2. Pictorial CSM for the Moab Site (DOE 2003).

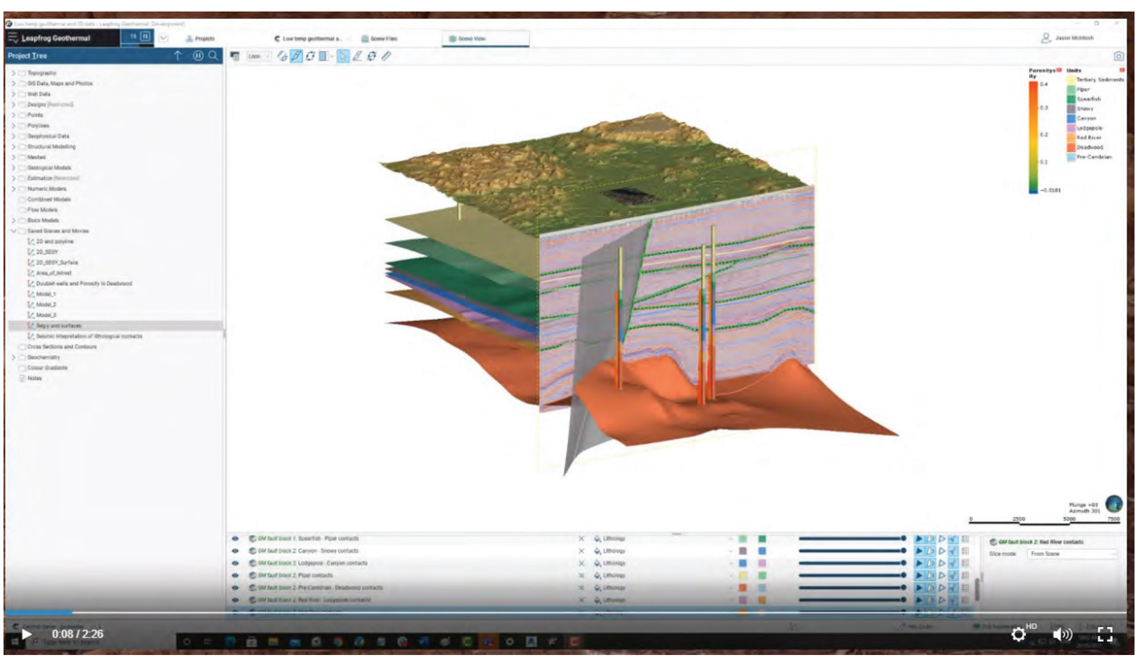


Figure 3. Graphic illustrating Leapfrog's capabilities for 3D visualization of geologic information.

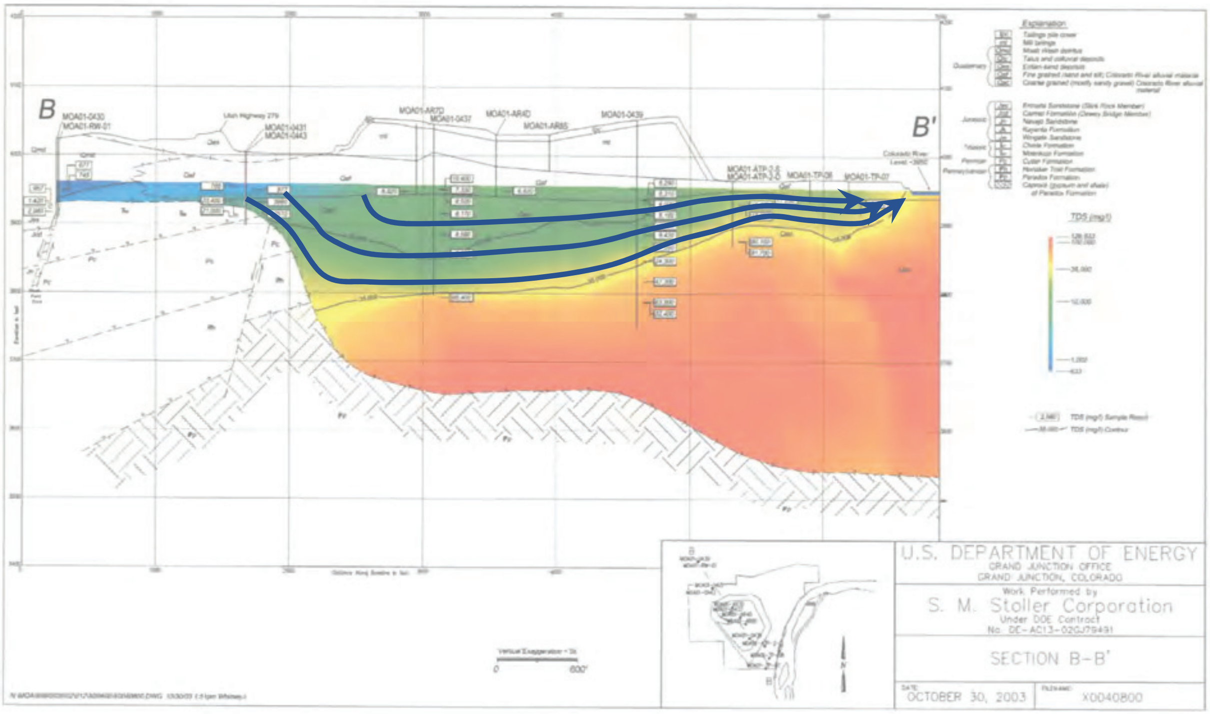


Figure 4. Conceptual cross-sectional flow paths along the brine interface (DOE 2003).

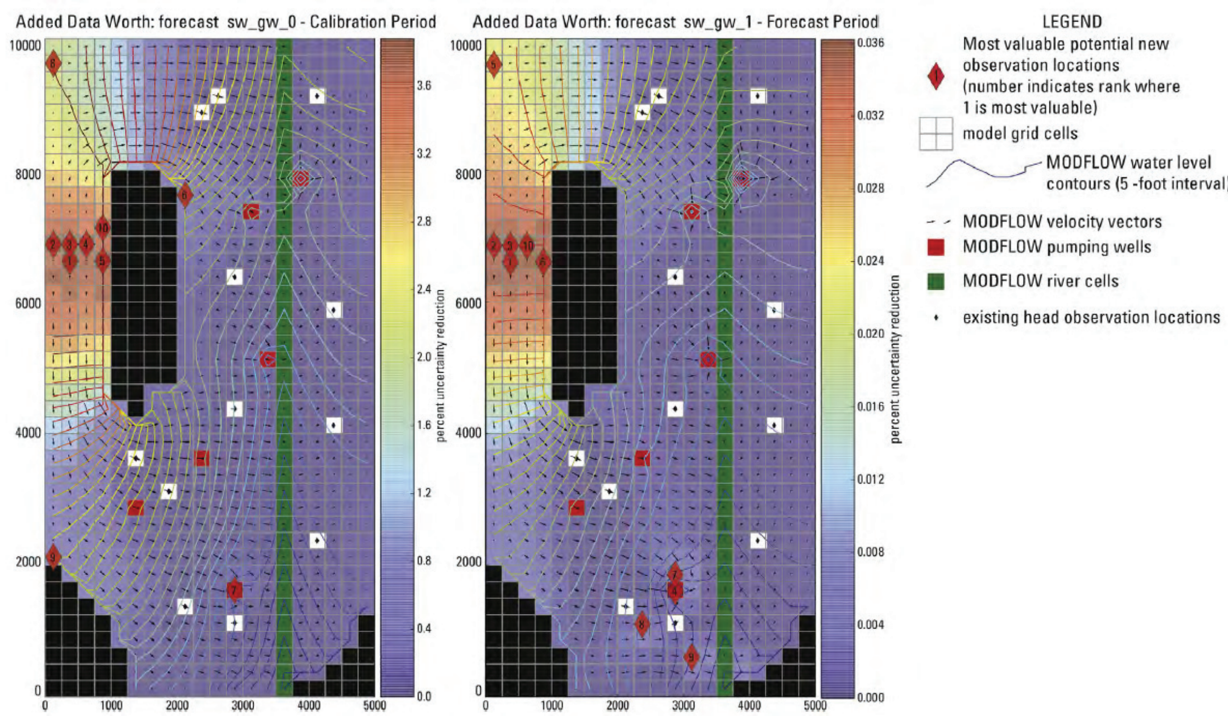


Figure 5. Example of data worth analysis using MODFLOW and pyEMU (White et al. 2016).

Match to Moab Conditions:

3D numerical models have already been used for many years at the Moab site (DOE 2003, DOE 2012, DOE 2016). They are capable of simulating the complex site conditions at Moab and can meet project needs by forecasting the performance of potential compliance strategies. Cross-sectional modeling has also been performed previously at the Moab site to improve understanding of how transient interactions with the Colorado River and the brine interface influence contaminant transport processes (DOE 2003). Because multiple site characterization activities have been proposed for the Moab site by the NNLEMS collaboration, using the model for data worth analysis is also applicable.

Implementability:

As described above, a mature CSM is available for the Moab site, and numerical modeling has been used at the site for many years. Public and commercial software capable of simulating the conditions at Moab (including variable-density flow) is readily available and widely used and has already been applied at the site. Software for uncertainty analysis and data worth analysis is also readily available (Doherty 2015, White et al. 2016, White 2018), and these analyses can be performed efficiently with modern computing resources. If the modeling is performed using proprietary software such as FEFLOW, then licensing expenses need to be considered. If the modeling uses publicly available software from the USGS or the national labs, then there is not a licensing expense; however, publicly available modeling software is generally run using a commercial GUI that does have licensing fees.

Data worth analysis requires minimal additional effort because a key to its implementation is simply rearranging scheduled activities so that groundwater modeling is initiated early in the schedule instead of at the end. Additional effort is limited to (1) using the configured groundwater model to perform data worth analysis and (2) revising the groundwater model after data collection is complete.

The technology readiness level (TRL) for numerical modeling is 8–10, depending on the sophistication of the modeling approach. More advanced methods for modeling (e.g., reactive transport modeling with PHT-USG or stochastic simulations with an iterative ensemble smoother) are not as widely applied as simpler models (e.g., deterministic models with single-species transport and linear sorption isotherms). Nevertheless, public and commercial software and technical support are available even for the more advanced modeling techniques that might be used for the Moab project.

Exemplars/References:

DOE (U.S. Department of Energy), 2003. *Site Observational Work Plan for the Moab, Utah, Site*, GJO-2003-424-TAC, December.

DOE (U.S. Department of Energy), 2012. *Moab UMTRA Project 2011 Ground Water Program Report*, DOE-EM/GJTAC2041, May.

DOE (U.S. Department of Energy), 2016. *Moab UMTRA Project 2015 Ground Water Program Report*, DOE-EM/GJTAC2202, May.

Doherty, J., 2015. *Calibration and Uncertainty Analysis for Complex Environmental Models, PEST: Complete Theory and What it Means for Modelling the Real World*, Watermark Numerical Computing, Brisbane, Australia.

Doherty, J., and C. Moore, 2019. "Decision Support Modeling: Data Assimilation, Uncertainty Quantification, and Strategic Abstraction," *Groundwater*, 58 (3): 327–337.

Fienen, M.N., J.E. Doherty, R.J. Hunt, and H.W. Reeves, 2010. *Using Prediction Uncertainty Analysis to Design Hydrologic Monitoring Networks: Example Applications from the Great Lakes Water Availability Pilot Project*, Scientific Investigations Report 2010-5159, U.S. Geological Survey, Reston, Virginia.

Ma, R., C. Zheng, C. Liu, J. Greskowiak, H. Prommer, and J. M. Zachara, 2014. "Assessment of controlling processes for field-scale uranium reactive transport under highly transient flow conditions," *Water Resources Research*, 50: 1006–1024.

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Thornton, M. M., and A. M. Wilson, 2007. "Topography-driven flow versus buoyancy-driven flow in the U.S. midcontinent: implications for the residence time of brines," *Geofluics*, 7: 69–78.

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White, J.T., 2017. "Forecast First: An Argument for Groundwater Modeling in Reverse," *Groundwater*, 55 (5): 660–664.

White, J. T., 2018. "A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions," *Environmental Modelling & Software*, 109: 191–201.

Zachara, J. M., X. Chen, C. Murray, and G. Hammond, 2016, "River stage influences on uranium transport in a hydrologically dynamic groundwater-surface water transition zone," *Water Resources Research*, 52: 1569–1590.

Technology Inter-Relationships:

Iterative updating of the CSM and the 3D numerical model will play an important role in the adaptive site management approach proposed by Team 1, many of the site characterization technologies proposed by Team 2 can be evaluated using the model through application of data worth analysis, and the predicted performance of various remediation strategies proposed by Team 3 can be compared using the model as well.

Sequencing - Prerequisites and Data Gaps/Needs:

The CSM should be reevaluated and refined (as necessary) before updating the numerical model. If the model will be used for data worth analysis to vet proposed data collection strategies, then preliminary modeling should begin immediately, before additional data are collected. Otherwise, the modeling should begin after data collection supporting GCAP development is complete, and after the new data are incorporated into the CSM. In either case, model calibration and finalization of model forecasts should be completed after data gaps have been addressed. The forecasts of the calibrated model can then be used to help select a groundwater remedy for the GCAP. Subsequently, the model may be updated periodically at key decision points as part of an adaptive site management strategy.

Timeframe:

Tier 1 (timeframe 1 to 2 years) -- Can be done with existing data or infrastructure or with data or infrastructure that can be rapidly and inexpensively collected/deployed. Numerical modeling can be used in the development of a GCAP.

Synopsis and Consensus:

There was a strong consensus among the NNLEMS collaboration participants that a 3D numerical model with an appropriate level of complexity will be needed to justify a groundwater compliance strategy for the Moab site.

Topic: Sediment/Water Interface Measurements

Long List Item / Objectives:

Team 2: (1) Understanding the state of groundwater contamination; and (2) forecasting its future evolution under both natural and remedial action conditions. The objective of work under this topic is to characterize and monitor the spatial and temporal distribution of flux (chemical constituents and water) across the sediment/water interface. Stream/aquifer interaction at the Moab site is highly dynamic, with rapidly changing flux across the sediment/water interface. Implementation will enable identification of the locations and timing of focused discharge to the river in real-time to operate the in-stream dilution system and mitigate contaminant impacts to aquatic species. Additionally, this work will provide hydraulic context for interpretation of sampling in or near the River.

Description:

The technologies considered include: (1) flux chambers (FC), (2) direct probes (DP), (3) fiber-optic distributed temperature sensing (FO-DTS), (4) thermal infrared (TIR) imaging, and (5) vertical temperature profiles (VTPs). Whereas DP and FC represent technologies for direct measurement of fluid and (or) sediment properties, FO-DTS, TIR and VTPs indirectly measure flux based on the thermal signature of seepage.

Flux chambers (Figure 1) have been well documented in the literature and demonstrated by USGS and others (Rosenberry et al., 2020). The most basic are relatively simple and easy to deploy; they consist of a chamber or box that is pressed into the sediment to allow natural influx (or efflux) of water (in terms of specific discharge) from (to) the sediment. Water volume and possibly chemistry are sampled periodically. Flux chambers could be used to specifically characterize critical habitats, placed in a transect across the river to see the pattern of influx and the extent of plume impact across the river, to assess fluxes under varying river stage conditions (i.e., conditions that reverse direction and relative influx during varying “low stages”), and (if specific-important flow lines or seeps are identified,) characterize the contaminant flux along these preferential flow paths.

A number of different DP technologies are available for studies of the sediment/water interface, e.g., the MHE PushPoint Samplers (Figure 2) which are small, low-cost, and can be installed manually in soft sediments. Larger diameter drive-point piezometers are available from AMS, and mini piezometer setups are available from Solinst and other companies. All of these devices can be used to sample pore water from, or measure hydraulic head in, the streambed. For example, the MHE PushPoints can be sampled using syringe or peristaltic pumps.

FO-DTS instruments (Selker et al., 2006) are capable of measuring temperature with sub-meter resolution and precision <0.1℃, at sub-minute sampling, along cables extending several kilometers. The fiber-optic cables serve as both measurement device and means of transmitting data to a control unit at the end of the cable. Suitable for long-term, continuous monitoring, FO-DTS has been used to infer the spatial and temporal distribution seepage, including at highly dynamic sites such as Hanford (e.g., Slater et al., 2010; Mwakanyamale et al., 2013). Seeps appear as either cold or warm anomalies (Figure 3) depending on the contrast between surface water and discharging groundwater, which varies seasonally. Cables can be deployed at the sediment/water interface or below the interface (e.g., Briggs et al., 2013).

TIR is used increasingly to map locations of seepage to streams in both research and practice, from handheld devices and drones, over a wide range of spatial scales (e.g., Torgeson et al., 2001; Loheide and Gorelick, 2006; Deitchman and Loheide, 2009; Briggs et al., 2013; Harvey et al., 2019). Seeps appear as either cold or warm anomalies (Figure 1) depending on the contrast between surface water and discharging groundwater, which varies seasonally. Handheld TIR cameras offer centimeter-scale resolution and thermal sensitivities <0.05℃.

VTPs are used to quantify specific discharge (upwelling or downwelling) through analysis of time series of temperature measured at different depths in the streambed (e.g., Lapham, 1989. Thermal changes at the streambed (e.g., from diel heating/cooling) propagate into the streambed to varying degree depending on the direction and magnitude of discharge. Through signal extraction or calibration of heat-transport models, the flux can be inferred. Public-domain and freeware software packages are available for several of these methods, including the USGS Windows-based 1DTempPro (Voytek et al., 2013; Koch et al., 2016, Figure 4), the Matlab-based VFLUX code from Syracuse University (Gordon et al., 2012), and the USGS tempest1d Python library. VTPs can be automated using commercially available probes (e.g., TRodX from AlphaMach) or assembled from off-the-shelf components including thermistors and data loggers.

Graphic(s):

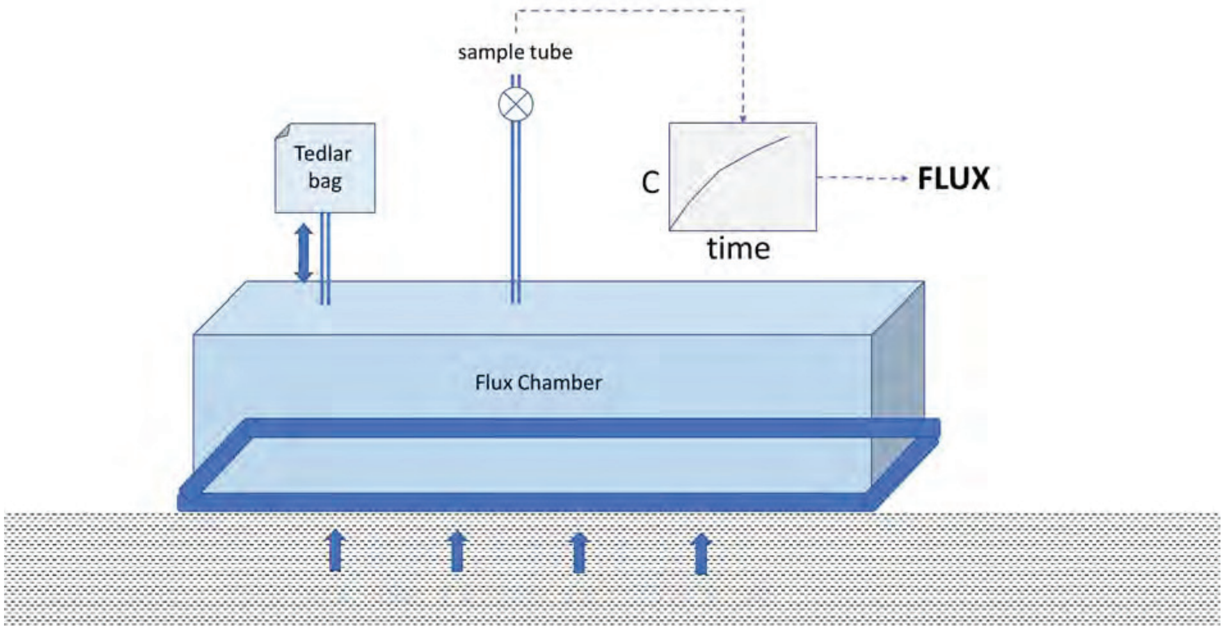


Figure 1. Simplified sketch of a flux chamber – these can be made more complex if needed.

Figure 2. (a) Installation of a MHE PushPoint Sampler, and **(b)** sampling using a syringe pump. http://www.mheproducts.com/insertion.jpg .

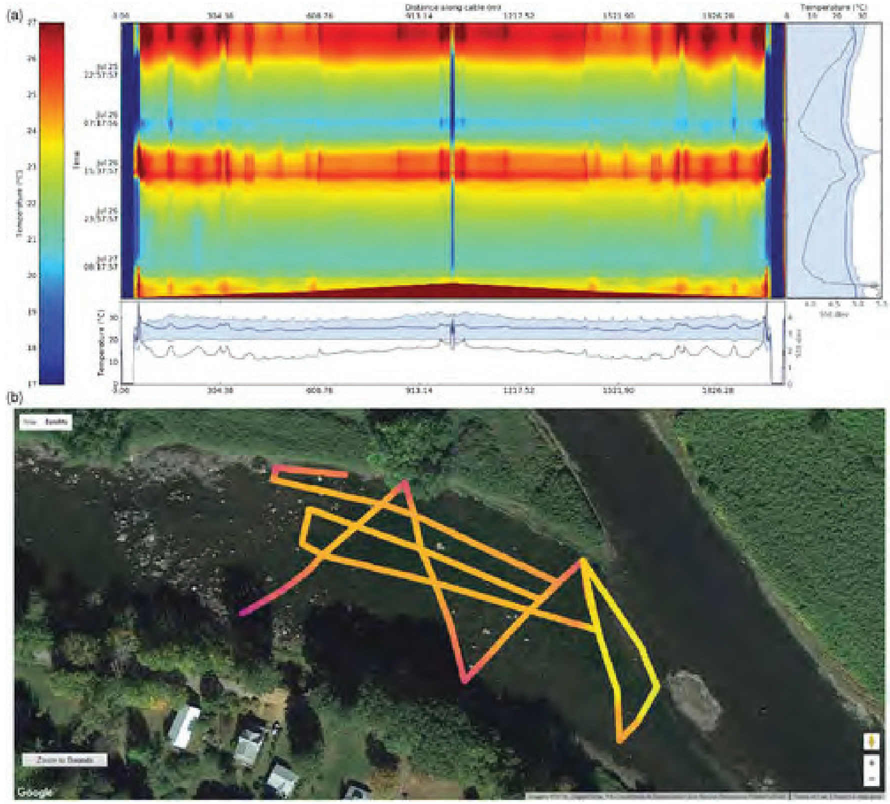
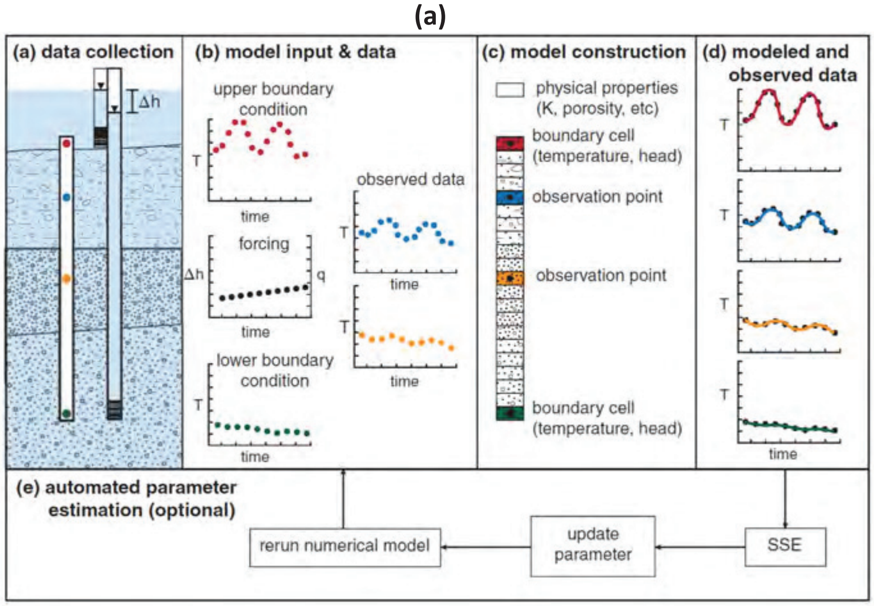


Figure 3. (a) FO-DTS data displayed as temperature (color) vs. distance along cable (x axis) and time (y axis), along with summary statistics in space and time; and **(b)** overlay of FO-DTS temperature on a base image from Google Earth using the DTSGUI software (Domanski et al., 2019).

(a)



(b)

Figure 4. (a) Workflow of the user friendly, Windows-based 1DTempPro code available in the public-domain from USGS for analysis of VTP data to infer specific discharge through a streambed (from Koch et al., 2016); and **(b)** photograph of TRodX, a commercially available VTP probe (https://nevada.usgs.gov/TROD/measurements.html) .

Match to Moab Conditions:

The FC concept is potentially matched to Moab conditions as a tool to understand source mass flux patterns in the Colorado River. Data on critical habitats might be interesting but may not be actionable. Data on spatial pattern of fluxes might be useful in refining the conceptual model.

The DP approach is well suited to deployment at Moab, although the specific technology may require limited field testing to determine, as there are tradeoffs between cost and durability, and some technologies (e.g., the MHE PushPoint samplers) require soft sediments for installation, while others are more robust and can be driven in by slide hammers or augers.

FO-DTS measurements are local to the fiber-optic cable, which is only millimeters in diameter; thus, detection or mapping of focused seeps requires deployment of multiple cables or deployment of a cable on a grid. When deployed at the sediment/water interface, the utility of FO-DTS is limited in fast stream flows and (or) deeper water, where the in-stream mixing masks the thermal signal of discharging water. These limitations should be assessed under the conditions required at the site.

The limitations of TIR derive from its sensitivity to the water surface, i.e., the skin (< 0.1 mm, Aboldt et al., 2018). The utility of TIR is therefore limited (1) in fast stream flows and (or) deeper water, where the in-stream mixing masks the thermal signal of discharging water, and (2) when discharging water is relatively cold and therefore less buoyant. These limitations should be assessed under the conditions required at the site.

VTP installation can be challenging in rocky or armored beds but otherwise is straightforward. Data analysis becomes problematic in the presence of extreme upwelling conditions (> ~3 m/day), where streambed temperatures converge and sensitivity to discharge is lost. In settings subject to extreme upwelling, active heating has been used, but active heating is not implemented in commercially available technologies.

Implementability:

The use of FCs is well established, with assembly of basic setups possible using COTS parts (TRL 9-10). Data collection using FCs can be labor-intensive. DPs also are well established and available from multiple vendors, with designs available for different site conditions (TRL 10). FO-DTS is used widely in the scientific community and increasingly by industry. FO-DTS equipment costs (~$40-60K) have come down dramatically over the last decade, and rentals are possible (TRL 8-9). Software for FO-DTS data analysis and visualization includes instrument-specific software as well as public-domain codes for visualization and simple statistical analysis (Domanski et al., 2019). TIR instruments range in cost from ~$100 (an add-on to mobile phones) to a few $K for handheld cameras, to a few 10's of $K for cameras that integrate with GPS and are designed for deployment from drones. Initially, handheld cameras could be assessed, with a possibility for deployment of drones in the future if determined to be effective and cost-effective. VTPs are easily implemented using commercially available technology for <$2K per site, and less with assembled components. Data analysis is possible with free and well-documented software.

Exemplars/References:

Briggs, M.A., Voytek, E.B., Day-Lewis, F.D., Rosenberry, D.O., and Lane, J.W., 2013, Understanding Water Column and Streambed Thermal Refugia for Endangered Mussels in the Delaware River, Environmental Science & Technology, 47 (20), 11423-11431, DOI: 10.1021/es4018893.

Domanski, M., Quinn, D., Day-Lewis, F.D., Briggs, M.A., Werkema, D. and Lane, J.W., Jr. (2020), DTSGUI: A Python Program to Process and Visualize Fiber-Optic Distributed Temperature Sensing Data. Groundwater, 58: 799-804. https://doi.org/10.1111/gwat.12974

Gordon, R.P., L.K. Lautz, M.A. Briggs, and J.M. McKenzie, 2012, Automated calculation of vertical pore-water flux from field temperature time series using the VFLUX method and computer program. Journal of Hydrology 420–421: 142–158.

Koch, F. W., Voytek, E. B., Day-Lewis, F. D., Healy, R., Briggs, M. A., Lane, J. W. and Werkema, D., 2016, 1DTempPro V2: New Features for Inferring Groundwater/Surface-Water Exchange. Groundwater, 54: 434-439. doi:10.1111/gwat.12369

Lapham, W., 1989, Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity. U.S. Geological Survey Water Supply Paper 2337, 35. Reston, Virginia: USGS.

McAliley, W. A., Day-Lewis, F. D., Rey, D., Briggs, M. A., Shapiro, A. M., and Werkema, D., 2022, Application of recursive estimation to heat tracing for groundwater/surface-water exchange. Water Resources Research, 58, e2021WR030443. https://doi.org/10.1029/2021WR030443.

Mwakanyamale, K., L. Slater, F. Day-Lewis, M. Elwaseif, and C. Johnson. 2012. Spatially variable stage-driven groundwater-surface water interaction inferred from time-frequency analysis of distributed temperature sensing data. Geophysical Research Letters 39: L06401. https://doi.org/10.1029/2011GL050824

Rosenberry, D.O.; Duque, C.; Lee, D.R. History and evolution of seepage meters for quantifying flow between groundwater and surface water: Part 1—Freshwater settings. Earth Sci. Rev. 2020, 204, 103168.

Selker, J. S., N. van De Giesen, M. Westhoff, W. Luxemburg, and M. B. Parlange (2006), Fiber optics opens window on stream dynamics, Geophys. Res. Lett., 33, L24401, doi:10.1029/2006GL027979.

Slater, L. D., D. Ntarlagiannis, F. D. Day-Lewis, K. Mwakanyamale, R. J. Versteeg, A. Ward, C. Strickland, C. D. Johnson, and J. W. Lane Jr. (2010), Use of electrical imaging and distributed temperature sensing methods to characterize surface water–groundwater exchange regulating uranium transport at the Hanford 300 Area, Washington, Water Resour. Res., 46, W10533, doi:10.1029/2010WR009110.

Voytek, E.B., A. Drenkelfuss, F.D. Day-Lewis, R. Healy, J.W. Jr. Lane, and D. Werkema, 2013, 1DTempPro: Analyzing temperature profiles for groundwater/surface-water exchange. Groundwater 52, no. 2: 298–302. DOI:10.1111/gwat.12051.

Technology Inter-Relationships:

Depending on the goals, FCs, DPs, FO-DTS and TIR can provide complementary or redundant information. All of these methods can provide information about the spatial and temporal distributions of water flux. FCs provide quantitative measurements of water flux (as specific discharge), whereas FO-DTS and TIR provide qualitative information. FCs are capable of measuring bi-directional flux across the sediment/water interface, whereas the thermal methods normally can detect only discharge to surface water. Chemical sampling is possible using either FCs or DPs. VTPs are generally easier to implement than FCs but provide less direct information. All of the technologies considered here for characterization and monitoring at the sediment/water interface support refinement of the conceptual site model in terms of underflow and river dynamics, as well as development of a numerical model.

Sequencing - Prerequisites and Data Gaps/Needs:

These technologies or a subset of them could be implemented in the next 1-3 years.

Timeframe:

- Tier 1 (timeframe 1 to 2 years) – Technology selection, planning, and pilot testing of FC, DP, FO-DTS, VTPs, and (or) TIR. Initial efforts (stage 1) should focus on DP and TIR, which are cost-effective and easily implemented. Based on results from DP and TIR, limited sites could be selected for FCs for short-term deployment and VTPs for long-term deployment (stage 2). Long-term monitoring could be performed (stage 3) using VTPs and FO-DTS sited based on results from stages 1 and 2.
- Tier 2 (timeframe 1 to 3 years) – Field deployment of FC, DP, FO-DTS and (or) TIR at the site.

Synopsis and Consensus:

Capture input from the broader group.

Topic: Geochemical Evaluation of Mineral Solids and Uranium Geochemistry

Long List Item / Objectives:

Once tailings are removed, solid-associated uranium in the subsurface (vadose and saturated zones) is expected to act as a long-term source of uranium to groundwater. However, only a fraction of solid-phase uranium is likely to be mobilized from the solid phase to groundwater because the recalcitrance of solid-phase uranium species varies. Therefore, a quantitative understanding of solid-phase uranium speciation is necessary to design an effective remedy and predict the remedial time frame under different remediation scenarios. Additionally, design of a remedy and prediction of a remedial time frame require a comprehensive understanding of geochemical processes that control the mobilization of solid-phase uranium to groundwater. The objective of this topic is to quantify solid-phase uranium speciation (e.g., sorbed, precipitated, co-precipitated/incorporated, oxidized/reduced) and characterize geochemical processes that influence uranium mobility, particularly in the freshwater-brine transition zone, which has not been the focus of past site characterization efforts.

Description:

Solid-phase extractions are commonly used to quantity solid-phase metal speciation. Solid-phase extractions involve exposing a solid to an extractant solution (e.g., in a batch reactor bottle) that is designed to dissolve/release a particular solid phase. The extractant solution is then analyzed for the analyte of interest to quantify the mass that was initially present in the target phase. Sequential extractions, a particular type of solid-phase extractions in which solids are sequentially exposed to increasingly strong extractant solutions, target multiple solid phases and are useful when evaluating the recalcitrance of an analyte to remobilize from the solid phase (Tables 1 and 2). Solid-phase extractions are commonly used in academic research and can be performed by environmental testing laboratories. Soil samples collected using common environmental drilling techniques (e.g., direct push, sonic drilling) could be sent to an environmental lab for sequential extraction analysis.[1] Characterization of solid-phase uranium speciation should focus on soil within the vadose zone, freshwater saturated zone, and freshwater-brine transition zone. Previous site characterization efforts have quantified total solid-phase uranium in the vadose and freshwater saturated zones, but the speciation of solid phase uranium was not evaluated.

Uranium mobility is highly dependent on redox state; oxidized U(VI) as the uranyl ion (UO_2^{2+}) is highly soluble, whereas reduced U(IV) as the uranous (U^{4+}) ion tends to precipitate from solution in the absence of organic complexing ligands. The brine zone is thought to be more reducing than the aerobic freshwater zone, and therefore, understanding the redox speciation of uranium and processes which impact uranium redox transformations, particularly in the

[1] Any laboratory handling tailings-impacted soil or groundwater from the Moab UMTRA Project site will need to have a radioactive materials license to handle the samples.

freshwater-brine transition zone, will be important for developing a comprehensive geochemical conceptual site model. Advanced analytical techniques, such as X-ray adsorption spectroscopy (XAS) and X-ray photoelectron spectroscopy (XPS), can be used to quantify the redox state of solid-phase uranium. XPS analyzes uranium exposed on a solid surface, whereas XAS analyzes a bulk sample. Sequential extractions may also be used to evaluate redox state – results using anaerobic extraction solutions can be compared to aerobic extraction solutions to determine the concentration of reduced species by difference. Reduced uranium is easily oxidized in the presence of oxygen, and therefore, special sampling protocols would need to be implemented to ensure that the redox state of uranium is maintained during soil sample collection, transportation of the lab, and subsequent analysis. For example, soil samples could be sealed in an air-tight jar (e.g., mason jar) with a Thermo Scientific AnaeroPouch™ sachet, which contains a catalyst that consumes oxygen within the jar and generates an aerobic atmosphere. Finally, geochemical equilibrium modeling could be used to estimate uranium redox state in the brine aquifer using existing groundwater monitoring data. Geochemical modeling software assumes that the system is at redox equilibrium (a large assumption), and therefore, this approach would provide an estimate and would not be suitable for making remedial decisions.

A unique geochemical feature within the aquifer beneath the Moab site is the saturated brine zone, where dissolution of bedrock generates groundwater with extremely high ionic strength. Ionic strength influences adsorption, mineral solubility, and reaction kinetics, processes which influence the mobility of uranium at the site. For example, under conditions of high ionic strength, mineral solubility is increased and adsorption is diminished. At Moab, the depth of the brine zone fluctuates seasonally as a function of river stage–when the river stage is high, the brine layer is suppressed, and when the river stage is low, the elevation of the brine surface increases. Geochemical processes that mobilize solid-phase uranium within the freshwater-brine transition zone may occur seasonally (Figure 1). The temporal nature of these processes may explain seasonal changes in groundwater uranium concentrations that have been observed previously.

The following approaches could be used to evaluate the geochemical processes impacting uranium in the brine-freshwater transition zone:

1) Geochemical equilibrium modeling of the freshwater and brine zones could be used to easily examine the potential impact of ionic strength on uranium sorption to solids and solubility of uranium minerals. This evaluation is recommended as a first step to determine the significance of changes in ionic strength on solid-phase uranium mobilization and if additional sampling and laboratory testing are needed. Because the solid-phase speciation of uranium is unknown, hypothetical uranium solid phases (e.g., uranium adsorbed to iron oxides, oxidized and reduced uranium-bearing minerals) would be equilibrated with groundwater from the freshwater and brine zones. Data analysis would include comparisons of dissolved uranium concentrations under

freshwater and brine conditions and identifying whether precipitation of uranium-bearing minerals is possible (i.e., minerals are supersatured). Minimum data requirements for this approach include groundwater composition of the freshwater and brine zones, including pH and concentrations of uranium, ammonia, and major cations (sodium, potassium, magnesium, calcium) and anions (chloride, sulfate). Additional analytes that impact uranium mobilization and would be useful to include in the evaluation are carbonate (alkalinity), phosphate, and redox indicator species (dissolve oxygen, nitrate, sulate, dissolved iron and manganese). If historical groundwater monitoring data is not available for these analytes, then additional samples could be collected. This effort could take a week (up to 16 hours of labor) if historical data is used. If additional sampling is needed, then the effort could take one or two months.

2) Batch and/or column tests could be used to evaluate the impact of changing ionic strength on uranium mobility by collecting soil from the brine-freshwater transition zone for use in a batch reactor or flow-through column. Influent to the column would be alternated between groundwater from the freshwater zone and the brine zone. Uranium and other geochemical parameters would be monitored in the effluent to evaluate the extent to which ionic strength mobilizes uranium. This effort, including sample collection and laboratory testing, would take a few months.

The above activities would inform the degree to which fluctuations in the brine zone depth and impacts of ionic strength on uranium geochemistry should be incorporated into a reactive transport model.

Graphic(s):

Example sequential extraction sequences:

Table 1. Sequential extraction sequence used at the Nuclear Metals Inc. Superfund Site.

Extraction	Target Phase	Extraction Solution	Time (hours)	Temperature (°C)
Step 1	Weakly sorbed/exchangeable	1.0 M magnesium chloride in 10 mM NTA, pH 4.5	1	22
Step 2	Strongly sorbed/weak acid extractable	1.0 M sodium acetate, pH 5 with acetic acid	8	22
Step 3	Iron- and manganese-associated	40 mM hydroxylamine hydrochloride in 25% acetic acid	6	96
Step 4	Uranium-phosphate minerals and recalcitrant fraction	25% hydrochloric acid, 75% nitric acid	To Completion	90

Note: Adapted from: Salome, K.R., Beazley, M.J., Webb, S.M., Sobecky, P.A., and Taillefert, M. 2017. *Biomineralization of U(VI) phosphate promoted by microbially-mediated phytate hydrolysis in contaminated soils*. Geochim. et Cosmochim. Acta 197, 27-42.

Table 2. Example sequential extraction sequence to target various uranium oxidation states.

Extraction	Target Phase	Extraction Solution
Step 1	Aqueous	Anerobic groundwater
Step 2	Adsorbed/exchangeable	Anaerobic 0.5M $Mg(NO_3)_2$
Step 3	Reduced, easily oxidized	Aerobic 0.5M $Mg(NO_3)_2$
Step 4	Carbonate precipitates	pH 2.3 acetic acid
Step 5	Precipitated (silicates, oxides, others)	8M HNO_3 at 95°C

Note: Steps 1 and 2 could be considered "mobile". Steps 3 could be considered "temporarily immobile". Steps 4 and 5 could be considered "immobile".

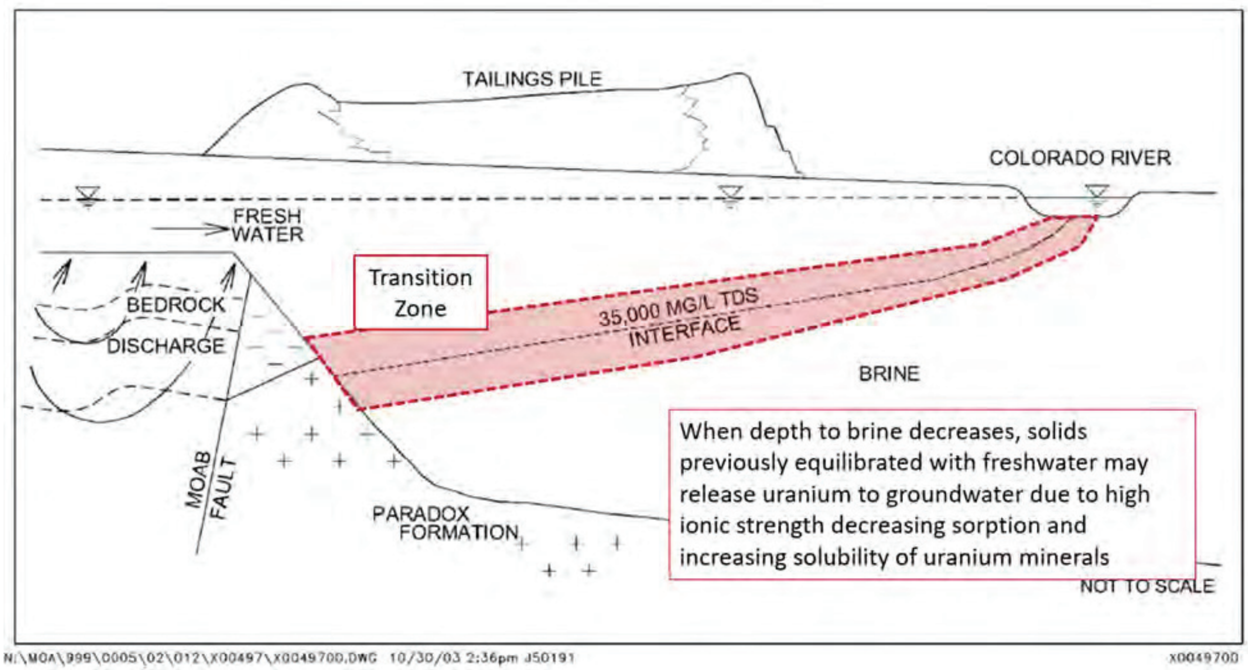


Figure 1. Illustration of how geochemical processes within the freshwater-brine transition zone may impact mobilization of uranium from the solid phase to groundwater.

Match to Moab Conditions:

The geochemical analyses described above are appropriate for the Moab site. Sequential extractions and column/batch testing using soil and groundwater from the freshwater zone are planned for early 2023. A radiological materials license is required by the laboratory to handle tailings-impacted soil and groundwater collected from the site. More advanced analytical techniques would likely need to be performed at a specialized facility. XAS would need to be performed at a synchrotron beamline, which are operated by the DOE.

Implementability:

All of the technologies presented herein are commonly used in academic research settings or during characterization of contaminated sites. Geochemical equilibrium modeling is extremely simple, low cost, commercially available, and would not require collection of additional soil and groundwater samples. Laboratory analyses, including sequential extractions, advanced solid-phase analytical techniques, and column/batch testing, would require collection of site soil and groundwater, which is obtainable at Moab.

Sequential extractions can be performed at a standard commercial analytical lab with a radioactive material license. Analytical costs are typical of standard analyses. Labor costs are higher due to extensive manipulation of the samples. This approach has been used at other Superfund and DOE sites, including the Monticello Mill Tailings Site in Monticello, Utah. To evaluate redox conditions, special sample protocols will need to be used to ensure that samples do not oxidize between sampling and analysis. XAS and XPS analyses would require trained technicians for preparation and analysis of the data. XAS analysis at DOE synchrotron facilities is free but requires submitting a proposal for consideration. XAS analysis time is very competitive, but because the facilities are operated by the DOE, it might be obtainable. XPS analysis could be performed at a commercial laboratory. Moab could partner with academic institutions or national lab scientists that have performed these analyses before (e.g., John Barger, Ken Williams). Each of these technologies has a technology readiness level of 10.

Exemplars/References:

The DOE Monticello Mill Tailings Site is an excellent example of using solid-phase sequential extractions and column tests to elucidate geochemical processes controlling uranium mobility and incorporating these finding into a reactive transport model. The following reports describe the geochemical investigation and the incorporation of geochemical data into a reactive transport model:

DOE. 2020. Monticello Mill Tailings Site Operable Unit III Geochemical Conceptual Site Model Update, LMS/MNT/S26486, Office of Legacy Management. July.

DOE. 2021. Monticello Mill Tailings Site Operable Unit III, Groundwater Flow and Contaminant Transport Model Report, LMS/MNT/S30707, Office of Legacy Management. June.

The following report discusses the effects of ionic strength on uranium mineral solubility:

Lemire, R.J., 1988. *Effect of High Ionic Strength Groundwater on Calculated Equilibrium Concentrations in the Uranium-Water System*, Report No. AECL-9549, Atomic Energy of Canada Limited, Pinawa, Manitoba.

Technology Inter-Relationships:

Quantifying the mass of solid-phase uranium with the potential to remobilize to groundwater and the geochemical processes which influence remobilization is necessary to develop a complete conceptual site model, predict the remedial time frame, and design an effective remedy. Because selection of natural flushing as a groundwater remedy requires a reactive transport model to demonstrate remedial time frame, these processes would need to be incorporated into the model for the site. A data worth analysis has been recommended, which could be used to identity which geochemical data gaps have the highest influence on model predictions.

A secondary source evaluation happening in early 2023 will include soil and groundwater sampling within the saturated freshwater zone, followed by sequential extraction of soil samples to quantify solid-phase uranium speciation and column tests to evaluate remobilization of solid-phase uranium to groundwater. Future characterization could focus on the freshwater-brine transition zone and vadose zone. Past site investigations have identified a substantial amount of sequestered uranium in the vadose zone, which may be remobilized to groundwater during rain events via infiltration. However, the solid-phase speciation of this secondary source remains unknown, so it is unclear how much of this uranium pool may eventually be transported to groundwater.

Sequencing - Prerequisites and Data Gaps/Needs:

Geochemical equilibrium modeling is recommended as a first step to evaluate the degree to which changes in ionic strength impact sequestration (uranium adsorption and mineral precipitation/dissolution) and the predicted redox state of uranium under site conditions. As noted above, historical groundwater monitoring data could be used as input to the geochemical modeling software. If historical groundwater monitoring data is not available for the necessary analytes (pH, uranium, major cations and anions; additional preferred analytes include redox indicator species, phosphate, and carbonate) then groundwater samples would need to be collected. If ionic strength is found to significantly affect uranium sequestration, then laboratory studies using site soil and groundwater are recommended.[2]

Soil and groundwater sampling would be needed to support laboratory testing on the effects of ionic strength on uranium mobilization. Batch reactor studies are cheaper than column studies and could therefore be used to decide if column tests are necessary (i.e., if the effect of high ionic strength on uranium mobilization is negligible under batch conditions, it is likely negligible under flow conditions). If the effect of fluctuating ionic strength is deemed significant,[2] then column tests are recommended to evaluate these processes under flow conditions. Column testing would likely be necessary to incorporate results into a reactive transport model.

Refining the estimate of solid-phase uranium (vadose and saturated zone soils) with the potential for remobilization will be necessary regardless of whether the above laboratory studies are needed. Soil samples to determine solid-phase uranium speciation and oxidation state by sequential extractions or other advanced analytical techniques could be collected

[2] A data worth/sensitivity analysis using a reactive transport model could be used to evaluate whether the predicted effect of ionic strength on uranium mobilization would impact the remedial time frame. Alternatively, the batch flushing model may be used to evaluate the effect of these process on remedial time frame using a simplified/less mechanistic approach.

simultaneously with the bulk soil and groundwater samples to support the laboratory studies described above.

The geochemical evaluations described above are recommended to commence before or concurrently with the development of a reactive transport model. A data worth/sensitivity analysis could be used to evaluate which geochemical processes have the largest impact on the remedial time frame and, therefore, should be prioritized during additional site characterization and laboratory studies.

Timeframe:

The time frame for this topic is considered Tier 2 (time frame of 1 to 3 years). Existing groundwater monitoring data could be used to perform geochemical equilibrium modeling. Sequential extractions, advanced solid-phase analytical techniques, and column/batch reactor testing would require a field event to collect additional soil and groundwater samples from the site.

Synopsis and Consensus:

An accurate understanding of the source term (i.e., mass of uranium that has the potential to mobilize from the solid phase to groundwater) and geochemical processes impacting uranium remobilization will be essential to predict the remedial time frame of the site and to design an effective remedy.

Topic: Isotope, Tracer and Molecular Biological Tools

Long List Item / Objectives:

Team 2 – Geochemistry and Isotopes and Molecular-Biological Tools-- Assess the potential for using natural and anthropogenic tracers (stable isotopes and radionuclides), age dating tools, and molecular biological tools to refine conceptual models of flow and subsurface microbial ecology and to improve interpretation of the interaction of the brine zone with the overlying more active flow zone.

Description:

Tracers and molecular biological tools are a potentially useful technologies to inform and improve the Moab site conceptual model. A variety of intrinsic tracers have been used to trace, age date, and discern the history of young waters such as the water in the Rifle disposal cell (see review by the USGS -- https://pubs.usgs.gov/fs/FS-134-99/pdf/fs-134-99.pdf). Young water tracers include stable isotopes of hydrogen and oxygen; tritium and helium 3; chlorofluorocarbons; and sulfur hexafluoride. While speculative, there is a potential for standard young water tracers to elucidate the interactions between the brine and the overlying water layer. The most promising of the young water tracers may be those that most closely track with the water molecule – i.e., stable isotopes of hydrogen and oxygen (representing the evaporation history of the water) and tritium (because of its ease of measurement and primary form within the water molecule in the environment). A short synopsis for each of the key young water tracer categories is provided below.

- Stable isotopes of hydrogen and oxygen provide an intrinsic metric for the evaporation history of groundwater and surface water. Preferential evaporation of lighter isotopes results in a shift of the isotope ratios toward heavier isotopes (e.g., ^{16}O toward ^{18}O and ^{1}H toward ^{2}H or D (i.e., deuterium)). Typically, the quantitative degree of the shift compared to an accepted standard (calculated in parts per 1000 and designated δH or δO) are plotted with δH on the x axis and δO on the y axis. Rainfall falls on the meteoric water line (with seawater near the upper right), which is approximated by the equation $dD \cong 8.13d^{18}O + 10.8$. Waters that have been subject to localized intensive evaporation (such as a tailings pond) would fall to the right of the meteoric water line.
- A similar tracer scenario can be developed based on measurements of tritium in groundwater. The atmospheric concentrations of tritium (input signal) have varied through the years due to aboveground nuclear testing, seasonal atmospheric mixing (lower in winter and higher in summer), and radioactive decay with a relatively short half-life (circa 12 years) – the radioactive decay forms a stable gaseous daughter product (^{3}He). Figure 1 below shows example data for tritium measurements in the atmosphere for a period of five decades, from the early 1950s to the early 2000s. Performing scoping measurements of tritium with low ambient environmental level

detection limits would be reasonable and prudent. A laboratory capable of reliable and reproducible measurements at trace activity levels (well below human health standards) is needed. In practice, the laboratories that perform stable isotope evaluations also perform low-level tritium measurement so that these scoping efforts could be organized relatively efficiently.

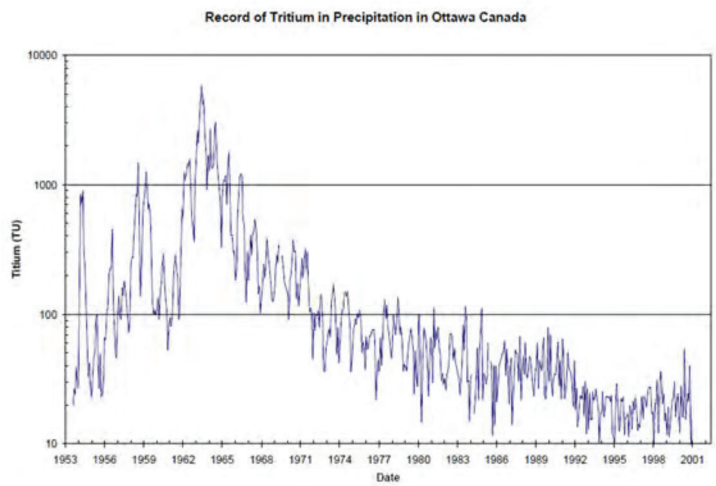


Figure 1. Tritium in precipitation at Ottawa Ontario Canada as measured by AECL in composite monthly samples and reported in the IAEA database.

Chlorofluorocarbons and related compounds have varied significantly over the past several decades (in response to ozone depletion measurements and responding limits, bans, and regulations (Figure 2). Some notable changes in chlorofluorocarbon regulations and measured response in the atmosphere correspond to the period during which Moab operated.

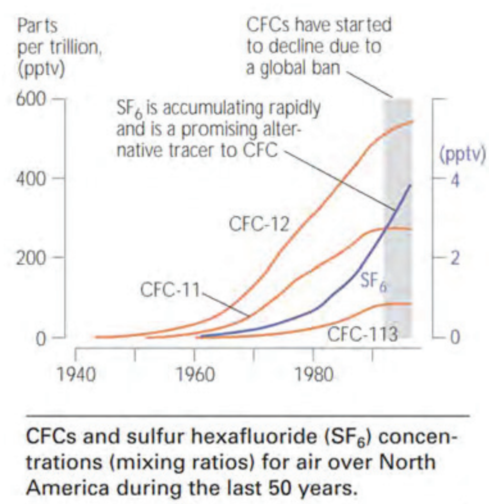


Figure 2. Concentrations of chlorofluorocarbons in the atmosphere from 1940 through 2000.

Molecular Biological Tools (MBTs) are available to identify and quantify – "profile" – the subsurface microbial community and microbial ecology. For microorganisms that influence nitrogen, there are several potential pathways that govern the transformation of key species under a range of biogeochemical conditions. Figure 3 summarizes the known nitrogen pathways, the sequence of transformations and the associated enzymes. MBTs target the genes that encode these enzymes and provide data on their presence and quantity. The presence of a gene that encodes a particular enzyme in significant amounts indicates that the microbial population is capable of the associated nitrogen transformation and the transformation may be active. A snapshot of MNT measurements using MBTs such as quantitative polymerase chain reaction (qPCR) and similar quantitative array measurements would provide useful and actionable information. For example, if there are significant microorganisms present that would result in transformation and loss of ammonium, then additional focus on attenuation-based remedies could be developed to support a long-term end state. In Figure 3, gaseous species are identified using a gold color. These are potential targets for inclusion in soil gas surveys – the presence of N_2O and NO would provide confirmatory lines of evidence that ammonium transformation pathways identified using MBTs are active. Note that MBTs are commercially available and reasonably priced. However, these analyses may be difficult to access for radioactively contaminated samples – in some cases, onsite extraction of the DNA to separate the MBT sample from uranium and other radionuclides in the groundwater has been used to overcome this limitation.

If the qPCR or quantitative array data indicate significant microbial nitrogen transformation may be occurring, follow up confirmation and studies could be considered by the Moab team – for example, Compound-specific isotope analysis (CSIA) and batch reactor experiments. CSIA of N^{15} in ammonia can also be used to confirm biological ammonia transformations. Enzymes preferentially use lighter ammonia isotopes, and therefore, the remaining pool of ammonia trends toward heavier nitrogen isotopes if ammonia degradation is active. This approach would involve collection of groundwater samples along the groundwater flow path for analysis of N15 in ammonia. This technology is less mature and may be higher cost compared to traditional DNA and enzyme focused MBTs. A commercial isotope lab with a radioactive materials license would be required.

Simple batch reactor experiments can also be used demonstrate ammonia degradation and provide scoping estimates on processes and rates. Ammonia is consumed via nitrification, an aerobic process, and anaerobic oxidation in the absence of oxygen (Figure 3). Nitrification is thought to be the primary ammonia degradation mechanism in the freshwater zone because it is largely aerobic. Batch reactors could consist of groundwater sparged with air, and ammonia and nitrification products (nitrate and nitrite) would be measured over time. Kinetics of ammonia degradation may be able to be obtained from these types of experiments. These experiments would require a careful site specific design.

Graphic(s):

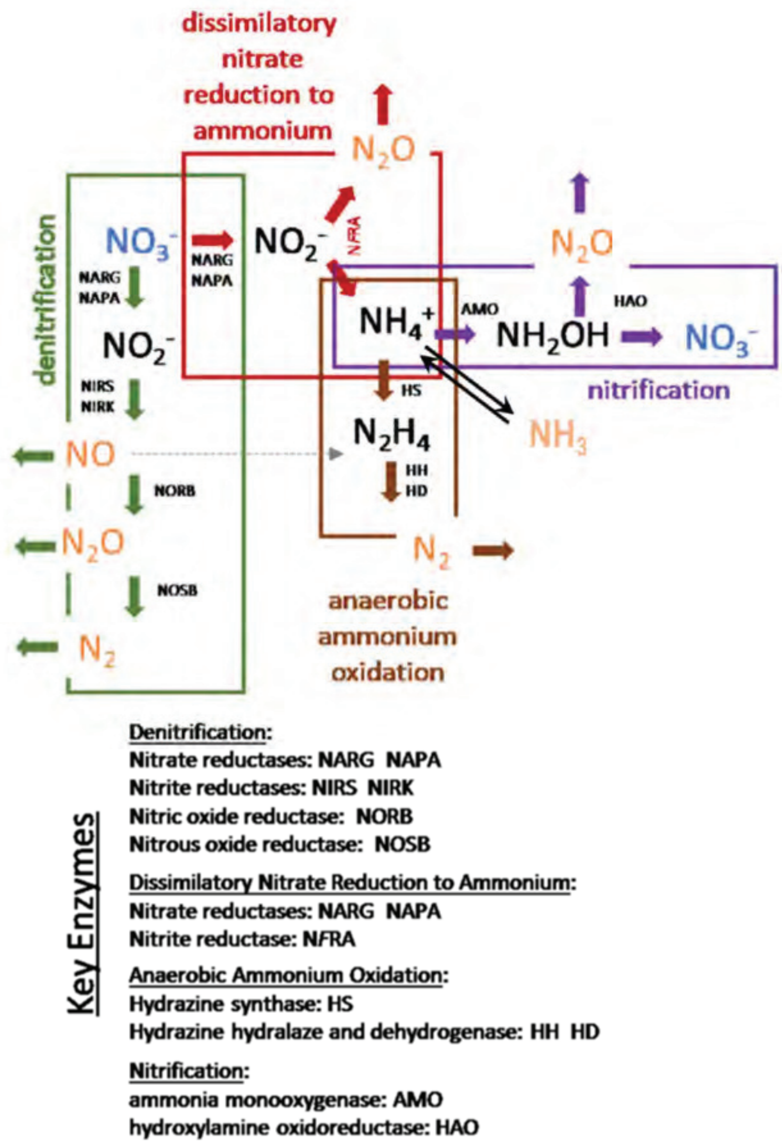


Figure 3. Biological nitrogen transformation pathways and associated key enzymes.

Match to Moab Conditions:

This concept may provide information to support interpreting mass transfer at the brine interface and assist in understanding key microbial ecology conditions and potential nitrogen transformations.

Implementability:

Relatively straightforward to perform scoping evaluation. TRL for isotope studies and MBTs is intermediate - TRL approximately 5 to 7. May be suitable for collaboration with a university or implementation with the assistance of students. May be challenges in identifying laboratory that can accept samples containing radioactivity at TENORM (Technologically Enhanced Naturally Occurring Radioactive Material) levels. There is potential to collaborate with USGS or universities to perform the analyses. An informal survey of available laboratories yielded the following information:

USGS laboratories can analyze outside and other agency samples for many of the recommended tracers and stable isotopes (but no official information is provided on radioactive samples or levels). Assuming collaboration with the following two separate USGS laboratories:

- Groundwater Dating Laboratory… CFCs and SF6 ($900 per sample including spreadsheet with date estimate)
- Stable isotope lab… low level tritium ($400); 3He/4He ($400 or alternatively $720 if including Ne, Ar, Kr and Xe); delO/delH stable isotope evaluation for $100; ammonium 15N/14N for $500; sulfate S-34/S-32 for $200 (underlined items that are not provided at the university labs listed below)

University of Miami "The Tritium Laboratory"

- CFC-11, CFC-12, CFC-113, and SF6 for $200 per samle
- Tritium for $200 (circa >3 TU) to $400 (circa >0.1 TU) per sample depending on activity

University of UT Noble Gas Lab (this lab has a fairly comprehensive set of capabilities -- ie., most everything except delO/delH and ammonium 15N/14N).

- Tritium for $400
- Ar, Kr, Xe, Ne, 4He, 3He/4He ratio $300 to $500 depending on options
- CFC-11, CFC-12 and CFC-113 $210
- SF6 $210

In this narrative, we also discuss performing some additional U isotope analyses in portions of the site where data are limited (e.g., brine wells). A number of labs are set up for that analysis using ICP-MS (including National Laboratories such as LBNL, various universities and others). A nominal cost per sample could be in the $400 range.

Thus, a reasonable selection of tracers and dating parameters might include tritium, 3He/4He, CFCs, SF6, and uranium isotopes as an initial set – if including the USGS stable isotopes lab in the collaboration one could add ammonium N13/N14, and delH/delO. The cost for analyses would be approximately $3000 per sample. Assuming $60K for the sample analysis and $50K field costs maybe included in enhanced baseline for a total of about $110K.

The first step is determining if the samples can be accepted into any or all candidate labs…

Sequencing prerequisites and data gaps/needs:

This work could be performed as a snapshot and coordinated with a planned sampling event. Some planning is required (contracting and assuring ability of lab to accept samples containing low levels of TENORM radionuclides) so that this activity would be Tier 2.

Timeframe:

Short term (1 to 3 years).

Technology Inter-Relationships:

Could provide results and output over the next year – requires setting up contract or collaboration. Results would be useable in refining the conceptual model and the numerical model.

Synopsis and Consensus:

Consider these tools to refine and enhance the conceptual model and to support understanding potential attenuation of ammonium.

Topic: Soil Gas Surveys to Refine Residual Source Areas

Long List Item / Objectives:

Team 2 – Improved Source Term Characterization -- Objectives are to provide a rapid low-cost option for refining areas that contain significant residual or secondary sources of uranium and ammonium in the vadose zone and shallow groundwater. The overarching goal is to provide information to help focus the deployment of source control technologies (e.g., where capping or amendments might be beneficial).

Description:

Soil gas surveys are commonly applied in characterizing volatile organic compounds (VOCs) such as chlorinated solvents and hydrocarbons. In these surveys the pattern of vapor phase concentrations in gas collected from a grid of sample locations is diagnostic of the location of residual contaminant and geologic features such as preferential flow paths. Similar to VOCs, the uranium daughters include a gas phase constituent (radon), and gas phase ammonia may be an indicator for residual ammonium (subject to potential pH limitations). Normally, a soil gas survey is performed rapidly by rapidly installing a grid of holes using a sliding hammer or similar field tool, inserting a sample probe into each hole, and collecting a gas sample for analysis. In the case of Moab, the analysis could be performed in the field using simple field gas monitors for radon and ammonia.

The use of radon (and radon daughter) signals as an indicator of localized uranium source material has been documented. For example, in Figure 1 below, a bismuth 214 anomaly was measured in an aerial gamma survey; upon further evaluation, the anomaly was linked to a subsurface (natural) deposit of uranium (Figure 2) and the upward migration of radon (the radon was decaying with a short half-life resulting in the observed signal –Figure 3). There are several case studies that document use of radon soil gas and soil flux surveys to delineate residual mill- and tailings-related uranium/radium contaminant source areas in soil and shallow groundwater. For example, Karp (1988) used soil gas and soil flux data to generate maps of residual sources associated with areas of former/removed or current tailings as well as areas where tailings were moved into Grand Junction for use as fill material (see example maps in Figure 4). (reference - Karp, K.E., 1988. Detecting Buried Radium Contamination Using Soil Gas and Soil Flux Radon Measurements, Report No. UNC/GJ-41(TMC), US DOE Grand Junction Projects Office, Grand Junction CO),

The ammonia testing a somewhat more speculative because almost all of the ammonia/ammonium should be protonated at the pH observed in the field (e.g., 7 to 8 nominal). However, due to the large ammonia/ammonium inventory and the ease of field detection, collecting gas samples for analysis is reasonable and has the potential to identify the most significant areas of residual ammonia/ammonium source material. Other cautions based on historical experience include – plan sampling during periods of relatively low barometric pressure (supports best quality samples due to a net exhalation from the soil to the atmosphere), use soil probes that are reasonably well sealed to avoid annular leaks of outside air, if possible collect data for other indicator gases that are easily measured (e.g., CO2, O2, NO, N2O – since these might be indicative of nitrogen cycling in the subsurface ecosystem), and record potential factors that might impact results (e.g., pH of underlying groundwater, meteorological conditions, etc.).

For Moab, a grid of several hundred locations could be defined and samples collected and analyzed in 5 to 10 days. p

Graphic(s):

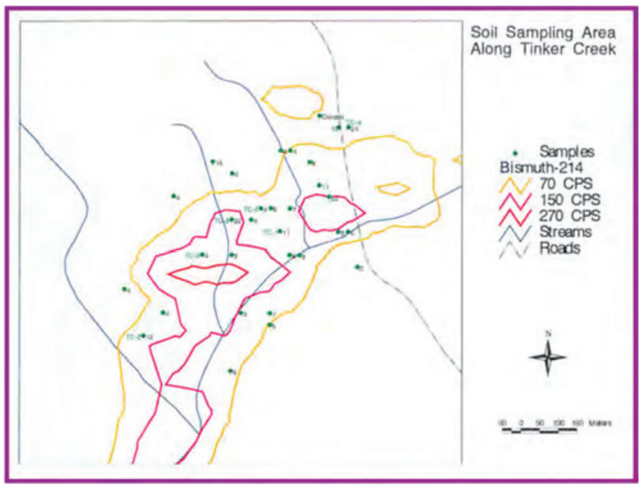


Figure 1. Observed anomaly in example study.

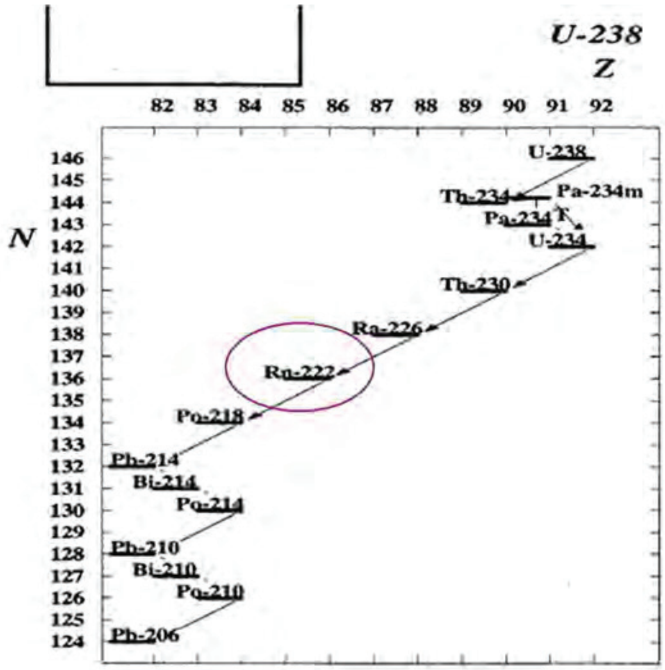


Figure 2. Documentation of radon gas as a potential tracer of opportunity.

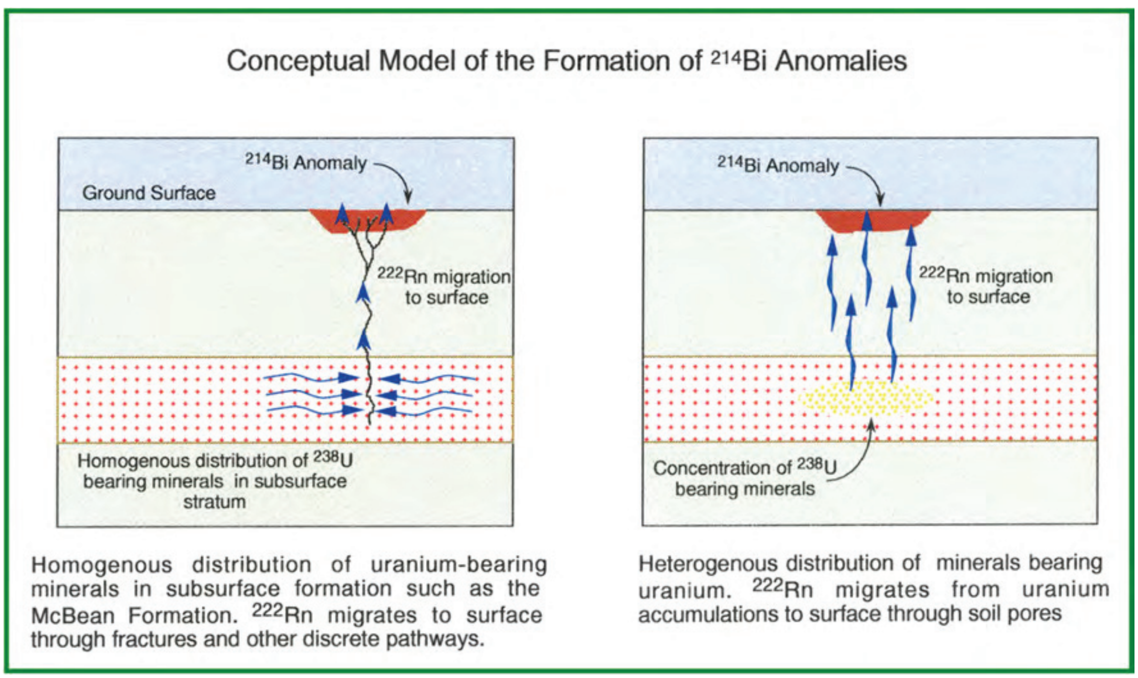


Figure 3. Two alternative conceptual models developed for example anomaly.

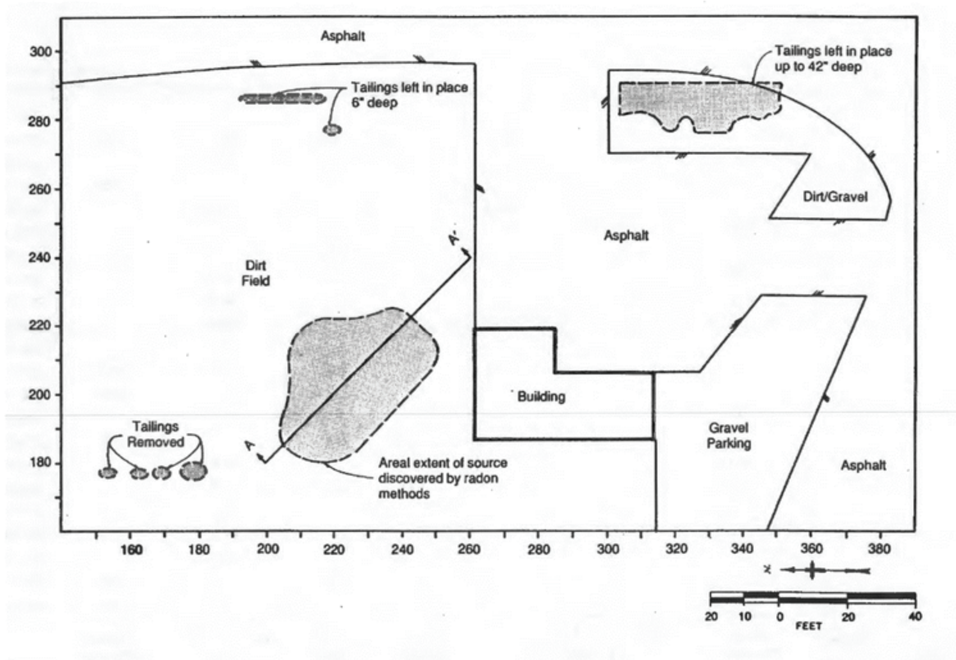


Figure 4. Example map of residual radionuclide contamination (shaded areas) associated with mill tailings and mill operations – map was generated based on radon soil gas and soil flux surveys

Match to Moab Conditions:

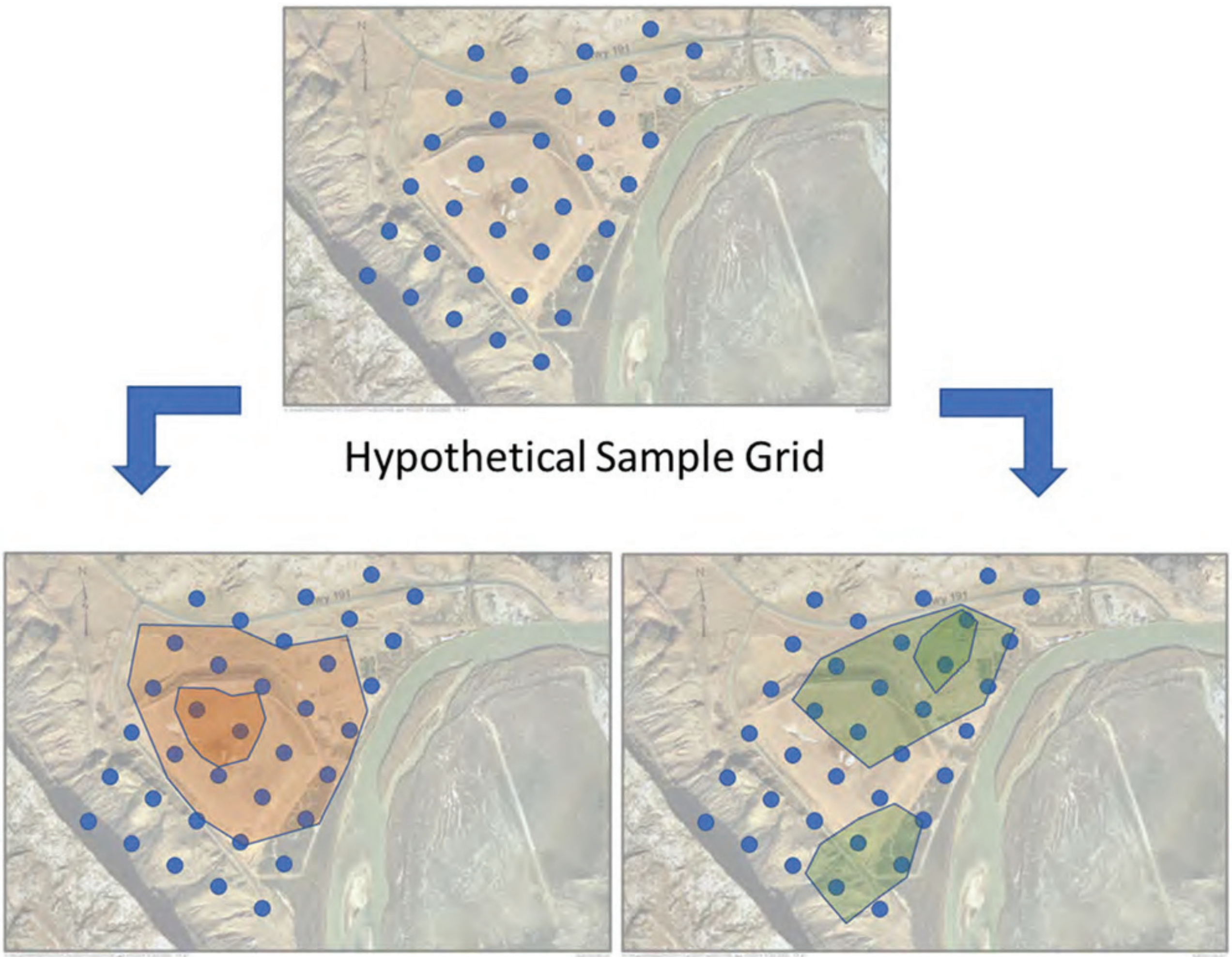
This strategy may have short term application to Moab conditions and needs. Simple and low cost with the potential to provide actionable information – uniquely well matched to site specific contaminants of concern. The deployment could be done by the Moab team or by a university or contractor.

Implementability:

Implementable using standard practice using available equipment and data mapping tools - TRL 7 to 8.

Sequencing prerequisites and data gaps/needs:

This concept could be implemented quickly and easily. The work can be performed using standard equipment such as a sliding hammer, temporary gas probes, and small gas sampling pump (sampling equipment approximately $10K), along with portable gas monitors/sensors configured to measure diagnostic gases such as (example field instruments are noted parenthetically): radon (e.g., Durridge RAD7 Radon Detector – approx. $15K), NH_3, N_2O, NO, O_2, CO_2, and CH_4 (e.g., one or two custom configured MSA Altaie 5x multigas detectors – approx. $5000 each). Figure 4 depicts a hypothetical sampling grid and the type of data that might be generated by a soil gas survey (note that this figure is for demonstration purposes only and does not represent real data. Areas where uranium related gases are focused might indicate zones where there may be residual shallow U source materials. Similarly, areas where ammonia or other nitrogen related gases are detected would provide insights about residual ammonium sources materials and transformation processes. This type of field activity can be performed quickly (e.g., 1 to 2 week(s)). The results would be sensitive to physical and environmental factors such as depth to water, subsurface clay layers or barriers, barometric pressure (recommend sampling when barometric pressure is low), and geochemical conditions such as pH. The scoping (qualitative) data has the potential to guide future more detailed sampling activities and to assist in designing environmental response actions (e.g., by identifying areas where infiltration might be discouraged or encouraged to meet GCAP objectives during the Moab Wash restoration).



Hypothetical Data for gas phase U source surrogates (e.g., radon)

Hypothetical Data for gas phase N source and transformation surrogates (e.g., NH_3 or N_2O)

Figure 4. Hypothetical implementation of soil gas survey concept depicting the type of data that might be generated (depictions are illustrative only and not based on actual data).

Timeframe:

Simple to implement – could be performed in the short term (Tier 1 or Tier 2) to provide actionable information for a number of related activities.

Technology Inter-Relationships

Would inform target areas for source control technologies and adaptive site management strategies. Could be used to refine Moab Wash Restoration design.

Synopsis and Consensus:

Consider for further evaluation if Moab team feels that it may be of value.

Topic: Transient Aquifer Monitoring

Long List Item / Objectives:

Transient Aquifer Monitoring (free transient signal). Significant transient reversals (driven largely by river stage) exist in the shallow Moab groundwater system. These transients can be used to understand the system, as nature is providing a “free” signal, we only need monitor it at sufficient temporal resolution to deconvolve the response of the system. Compared to the deeper, more likely stagnant saline groundwater system, the river infiltration to the shallow aquifer is likely at a different temperature, salinity (density and electrical conductivity), dissolved oxygen content, pH, etc. The results of this type of analysis (depending on the types of data used) could be used to help inform groundwater sampling, as it may help understand when river vs. groundwater would be dominant at each location.

Description:

This narrative includes two main aspects. First, the continued or improved collection of high-frequency signals over multiple years (ideally using multiple data types). Second the use of these signals to calibrate a flow and transport model (the focus of other narratives) and develop a reduced-order frequency-domain model.

Collecting pressure, temperature, and electrical conductivity in multiple boreholes at a relatively high frequency (i.e., hourly, or higher) would result in an informative dataset for supplementing this analysis. Temperature at the surface, or at shallow depths below the river, would also be a good signal to help quantify when the river is gaining or losing at each physical location.

Some free signals will likely be easier to interpret (groundwater levels), while other signals may require a more detailed site model to interpret (chemistry). The development of a detailed site groundwater flow model with energy/solute transport is inevitable, so performing these simpler analyses first is a key step in understanding and preparing the transient data sets to be calibration targets for the model.

The groundwater flow system has a spatial steady-state component (i.e., Darcy’s law) that is proportional to permeability, and a transient storage component that is proportional to compressibility and porosity. The groundwater flow system constrains the porewater velocity, which drives thermal convection (temperature pulse) and solute advection (salinity redistribution and reactive transport). Getting the pressure transient wrong will result in an incorrect velocity and given the shallow groundwater flow system flips from gaining to losing each year, not just the magnitude but the velocity direction may be wrong without careful calibration.

A reduced-order harmonic analysis of some of the signals may be possible (focusing on the average change in amplitude and phase shift between source and response, rather than individual details of multiple timeseries), following an approach like that used with other periodic driving forces like barometric pressure or earth tides investigations (e.g., Rojstaczer, 1988; Rojstaczer & Agnew, 1989; Rojstaczer & Riley, 1990; Rojstaczer & Tunks, 1995; Cutillo & Bredehoeft, 2010). In the case of the Moab site, the driving force (river stage) and key river characteristics (e.g., electrical conductivity, temperature, pH, and turbidity) are possibly available up- and down-stream at high frequency (~15-minute data, see **Figure 1**). Both reduced-order physical and purely correlative models can be developed between the signal in the river (i.e., driving force) and the response of the shallow or deep groundwater system (i.e., pressure, salinity, and temperature). These models can be developed in the time domain or in the frequency domain using Fourier and/or wavelet transforms. Special care will be needed if the datasets are not uniformly sampled (e.g., missing data or non-uniformly measured points); “fast” transform methods may not be available for real-word data, but other transforms should still work with arbitrary data without the need to re-sample or interpolate (both of which reduce the quality of the data). Both the physical and correlative types of analyses would complement a traditional spatially resolved time-domain flow/transport numerical model. It may also be possible to see the effect groundwater has on the river, especially using parameters like electrical conductivity (EC), if saline groundwater is discharging to the river (**Figure 1** shows upstream EC data). Monitoring Colorado River fluid electrical conductivity and temperature at a high frequency immediately up- and down-stream from the site might help to quantify the total discharge of deep saline groundwater at the site (and might also be leveraged to provide excellent calibration targets for numerical models). Finding an appropriate location for this monitoring point would require careful consideration, since the river is likely not well-mixed over short distances.

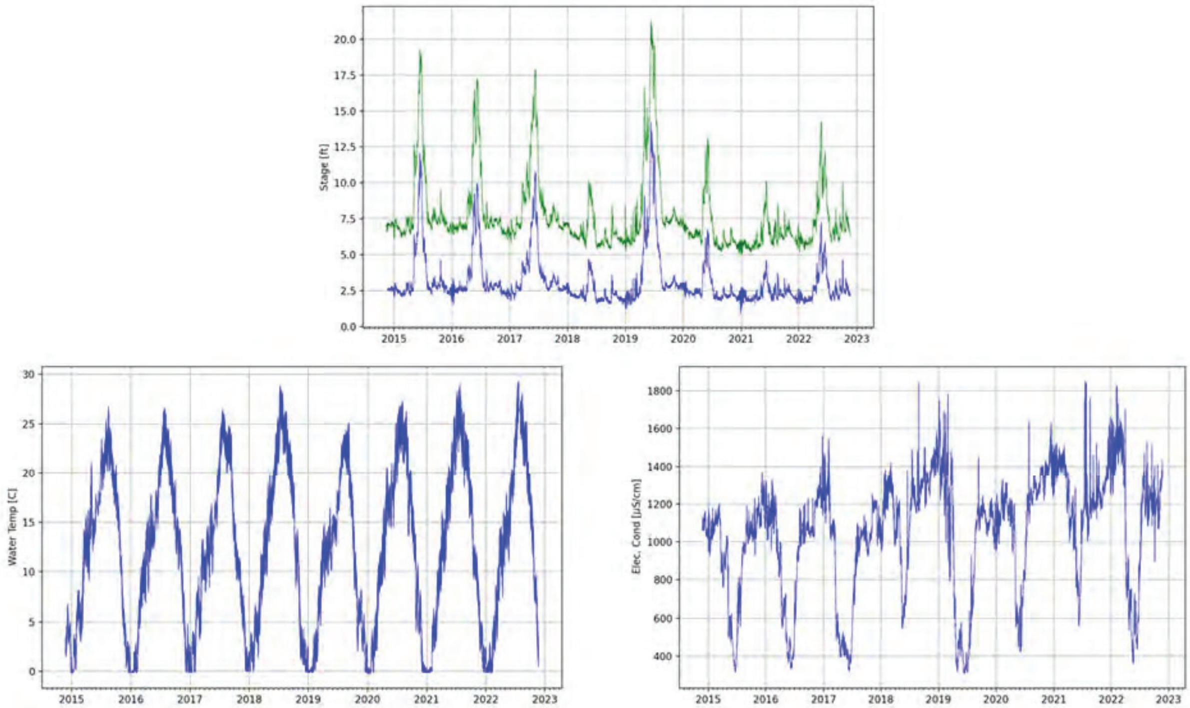


Figure 1. 15-minute USGS streamflow data from upstream (blue, Cisco UT 09180500) and downstream (green, Potash UT 09185600) Colorado River monitoring sites.

A possible avenue for investigation is to see if signals observed in the deeper groundwater system have a different transient nature (high-frequency shallow fluctuations vs. possibly annual or longer deeper fluctuations). This could help inform how long it may take to clean up deep contamination in the aquifer using a passive approach. One limitation is that this approach requires relatively long or high-frequency datasets, which may not be available yet. The deeper system likely filters out high-frequency oscillations present in the shallow system (diffusion alone is a low-pass filter, but advection may still allow through high frequencies. One question to ask: Is the deep system diffusion-dominated, or possibly some advection from shallow fluctuations impacts observations at depth? – see example plot comparing two wells and the river stage in **Figure 2**).

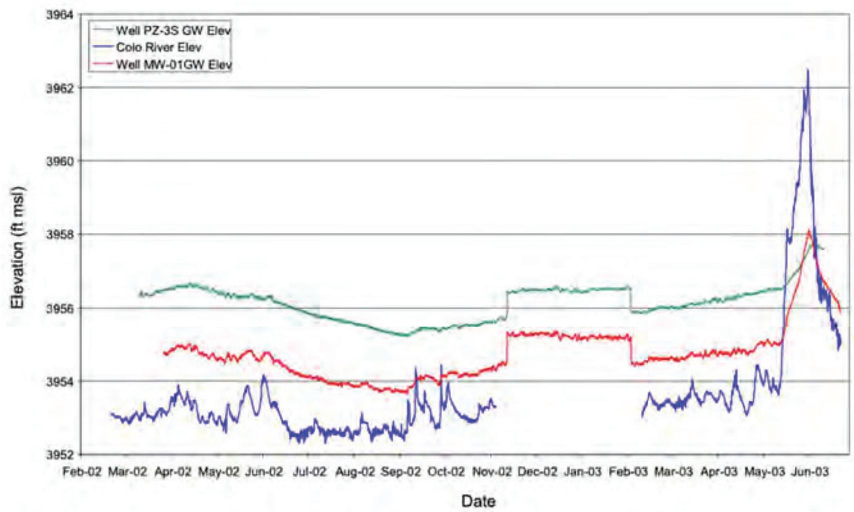


Figure 5–8. Wells SMI-MW01 and SMI-PZ3S Ground Water Elevations and Comparable Colorado River Elevations in 2002 and 2003

Figure 2. Illustration of river stage and groundwater levels in two nearby wells (from Site Observational Work Plan, 2003).

Match to Moab Conditions:

This narrative doesn't describe a technology. It is more a call to observe and analyze the significant transient signal that is occurring at the site, with the hope of better constraining and calibrating site numerical models (both traditional time-domain distributed models and reduced-order frequency domain models). If numerical models developed for the site cannot describe the observed annual transients, it will be impossible to consider them to be predictive into the future. The method could be adapted to many types of transient data (e.g., hydrological or geophysical), if they are collected at a high enough temporal frequency.

Implementability:

Collecting high-frequency data is not a technology with a TRL, but the method does require some analysis approaches that may not be typically or already applied to these data. Keep collecting the data that is already being collected (river data at USGS monitoring locations up- and down-stream of the site and depth-specific water levels, salinity, and temperature), but ensure high enough frequency is being collected (e.g., 1 to 4 data points per year at a location is not enough) and ensure datasets are long enough to understand the variability between years. It may take time to interpret the data, but any new data needs to start being collected as soon as possible.

Exemplar/References:

There are several applications in the literature of frequency-domain analysis of groundwater and surface water signals. Some are associated with statistical-type analysis of frequency-domain signals (Acworth et al., 2015; Guillaumot et al., 2022; Spongberg, 2000; Wallace et al., 2018), while others are associated with physically based frequency-domain models (Cutillo et al., 2011; Rasmussen et al., 2003; Rojstaczer, 1988; Rojstaczer & Agnew, 1989; Rojstaczer & Riley, 1990; Rojstaczer & Tunks, 1995).

The approach may be extendable to several different kinds of data, including pressure signal (a diffusive hydrological signal), to thermal or geochemical (an advective signal).

Acworth, R.I., G.C. Rau, A.M. McCallum, M.S. Andersen & M.O. Cuthbert (2015). Understanding connected surface-water/groundwater systems using Fourier analysis of daily and sub-daily head fluctuations. *Hydrogeology Journal, 23*:143-159. https://doi.org/10.1007/s10040-014-1182-5

Cutillo, P.A., & J.D. Bredehoeft (2011). Estimating aquifer properties from the water level response to earth tides. *Groundwater*, *49*(4):600-610. https://doi.org/10.1111/j.1745-6584.2010.00778.x

Guillaumot, L., L. Longuevergne, J. Marçais, N. Lavenant & O. Bour (2022). Frequency domain water table fluctuations reveal impacts of intense rainfall and vadose zone thickness on groundwater recharge. *Hydrology and Earth System Sciences, 26*:5697-5720. https://doi.org/10.5194/hess-26-5697-2022

Rasmussen, T.C., K.G. Haborak & M.H. Young (2003). Estimating aquifer hydraulic properties using sinusoidal pumping at the Savannah River site, South Carolina, USA. *Hydrogeology Journal*, *11*(4):466-482. https://doi.org/10.1007/s10040-003-0255-7

Rojstaczer, S. (1988). Determination of fluid flow properties from the response of water levels in wells to atmospheric loading. *Water Resources Research, 24*(11):1927-1938. https://doi.org/10.1029/WR024i011p01927

Rojstaczer, S., & D.C. Agnew (1989). The influence of formation material properties on the response of water levels in wells to Earth tides and atmospheric loading. *Journal of Geophysical Research: Solid Earth*, *94*(B9):12403-12411. https://doi.org/10.1029/JB094iB09p12403

Rojstaczer, S. & F.S. Riley (1990). Response of the water level in a well to Earth tides and atmospheric loading under unconfined conditions. Water Resources Research, 26(8):1803-1817. https://doi.org/10.1029/WR026i008p01803

Rojstaczer, S., & J.P. Tunks (1995). Field-based determination of air diffusivity using soil air and atmospheric pressure time series. *Water Resources Research*, *31*(12):3337-3343. https://doi.org/10.1029/95WR02115

Spongberg, M.E. (2000). Spectral analysis of base flow separation with digital filters. *Water Resources Research, 36*(3):745-752. https://doi.org/10.1029/1999WR900303

Wallace, C.D., A.H. Sawyer & R.T. Barnes (2018). Spectral analysis of continuous redox data reveals geochemical dynamics near the stream-aquifer interface, *Hydrological Processes, 33*:405-413. https://doi.org/10.1002/hyp.13335

Technology Inter-Relationships:

This passive approach will work well with basically any approach, but it may work especially well with temperature or salinity observations in the river or riverbed (i.e., the source/outflow signal). Any additional transient forcing imposed on the system (i.e., cleanup efforts) will also likely change the natural periodicity of the system. Man-made transient signals from active remediation efforts may add their own transient signals to the system.

Sequencing – Prerequisites and Data Gaps/Needs:

Historical monitoring should be augmented by expanded (to the degree possible) higher-frequency monitoring of the transients in the system. Characterization of the signals might require high-frequency monitoring to catch the response of the groundwater system due to the highest and lowest stages of the river. To understand inter-year variability (i.e., wet vs. dry years, local flooding, Moab wash vs. Colorado River), long-duration monitoring is needed over multiple years.

This approach could be applied immediately (days to weeks, tier 1) on existing data and could be applied to new data as they are collected (e.g., downhole temperature and conductivity, or riverbed temperatures). The analysis may be used to understand data before using them as calibration targets in larger, gridded 3D numerical models (tier 2-3). The data would also be useful for testing lower-dimensional models (i.e., cross-sectional models), to see if they capture the transients in the system adequately. If a model can't capture the back and forth transient signal in the system, it will be hard to make meaningful predictions with certainty.

Topic: Borehole and Geophysical Assessments

Long List Item / Objectives:

Team 2: (1) Understanding the state of groundwater contamination; and (2) forecasting its future evolution under both natural and remedial action conditions. The objective of work under this topic is to characterize (1) the spatial distribution of subsurface contamination at the Moab site, and (2) the physical and chemical properties controlling fate and transport at the site. New boreholes, borehole logging, and surface geophysical surveys have potential to improve the current understanding of the state of groundwater contamination and subsurface conditions at the Moab; this information is critical to forecasting contaminant fate and transport and remedy performance. Implementation will reduce uncertainties associated with (1) contaminant distribution, (2) soil and aquifer properties and the hydrogeologic framework, and (3) brine distribution. Implementation will thereby reduce risk drivers and support the GCAP.

Description:

Characterization approaches are divided into (1) installation of new boreholes, either vertical or angled, (2) borehole logging, and (3) geophysical surveys for subsurface salinity distribution.

New boreholes would support geologic characterization of the formation over (shallow or potentially significant) depths with respect to physical or geochemical properties, hydrostratigraphy, mineralogy, etc., through the collection of cores and/or through providing access to geophysical, thermal, or flow-based logging tools. Furthermore, additional boreholes would providing new opportunities for cross-well hydraulic or geophysical (e.g., tomography) tests that can be used to identify specific formation properties or other response characteristics. New boreholes would also allow for chemical characterization and monitoring of formation fluid levels and fluid compositions (contaminants, salinity) over (potentially significant and multiple) depths as a means to identify contaminant source terms (e.g., ammonia distribution) and (or) monitor and identify brine profiles over depth. Well design components may include multi-level sampling (e.g., nested piezometers) and/or pressure transducer instrumentation packages. One or more angled chemical sampling boreholes could serve to enable monitoring beneath the current tailings pile while the tailings pile is still present.

Borehole geophysical logging is a routine component of site characterization. Numerous logging methods provide information on diverse physical and chemical parameters, which in turn provide insight into aquifer properties, water quality/chemistry, and geologic structure (Keys, 1990). Borehole logging tools include electromagnetic induction (EMI), natural gamma, self potential, normal resistivity, fluid conductivity/temperature, caliper, sonic, acoustic televiewer, optical televiewer, neutron porosity, nuclear magnetic resonance (NMR), and borehole flowmeter (BHF). Synergy results from joint interpretation of multiple logs, hence a suite of logs is commonly collected in the same field campaign. Of particular relevance to site investigations at Moab are EMI, fluid conductivity, NMR, and BHF. EMI can be used to infer pore-fluid salinity (Stumm and Como, 2017), particularly when combined with other logs that help control for lithology (e.g., natural gamma). NMR results can be used to estimate hydraulic conductivity (e.g., Kendrick et al., 2021). BHF can be used to estimate transmissivities and hydraulic heads of different aquifer layers (or fractures) using simple graphical analysis and manual calibration or regression analysis (e.g., Day-Lewis et al., 2011; Barbosa et al., 2019). Plans for drilling new boreholes should be coordinated with plans for logging, as well design (e.g., casing material, well diameter, backfill material) limit which logging tools can be used in the well.

EM and electrical geophysical methods have been used to characterize groundwater salinity in numerous investigations including recent work at the Scott M. Matheson Wetlands Preserve across the Colorado River from the Moab Site (Briggs et al., 2019) (Figure 1). EM technologies include time- and frequency-domain tools suitable for both shallow (<10 m) and deep (10-500 m) target depths. Small, frequency domain tools (e.g., the DUALEM or GEM2) that can be carried or towed behind an ATV or kayak are well suited to the former, whereas time-domain tools (e.g., the tTEM, WalkTEM, or ProTEM) are well suited to the latter. Electrical resistivity tomography, based on DC electrical conduction, is also effective at characterizing salinity and fresh/saltwater interface (e.g., Henderson et al., 2010).

Graphic(s):

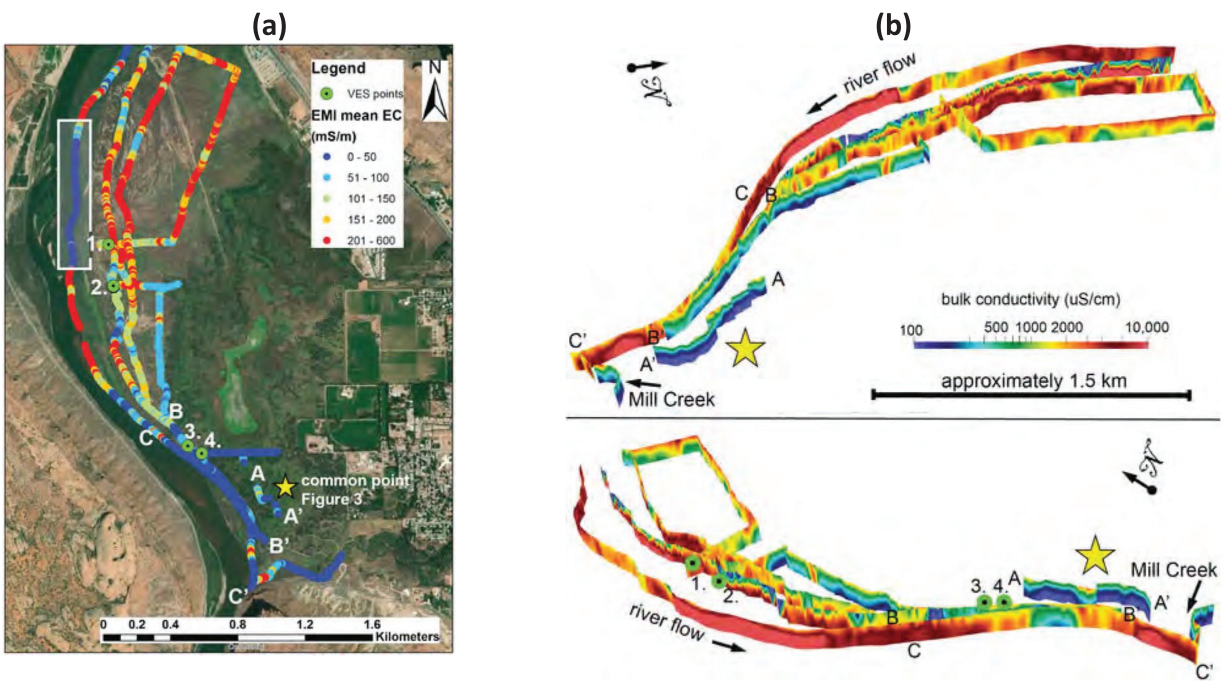


Figure 1. (a) Apparent bulk conductivity from the EM data indicating general patterns in the pore water conductivity of the upper approximate 5 m of sediment. The star indicates a common spatial point with Figure 1b, and he gray box encompasses waterborne EM data influenced by a deep section of channel. The approximate subsection transects of the

inverted EM data in Figure 1b are indicated (A-A′, B-B′, C-C′); and **(b)** Two visual perspectives of the EM inversions. From Briggs et al. (2019).

Match to Moab Conditions:

Site conditions at Moab are clearly conducive to installation of boreholes, although the best drilling methods and the practicality of angled boreholes may be affected by target depths, the intended use of the boreholes (e.g., sampling vs. logging), and site conditions. In general, site conditions at Moab are also suitable for logging; however, well construction does limit which tools can be used; e.g., steel casing precludes the use of EMI tools, and BHF can only be used to estimate transmissivity and head in screened intervals or open intervals. The dimensions and material within the drilling annulus around the well casing can also pose issues to certain logging tools.

The effectiveness of electrical and EM investigations in the wetland across the river from the Moab Site indicate a high probability of success. EM surveys can cover large areas using ATV-towed setups for both small frequency-domain tools (e.g., GEM-2, DUALEM) and larger time-domain tools (e.g., tTEM). A combination of tools may be required to map the interface across the site. Underground and above-ground infrastructure can pose challenges to EM and electrical geophysical surveys. EM data are strongly influenced by the presence of steel pipes and electrical utilities above or below ground. Electrical methods are less sensitive to infrastructure, but the data is slower to collect over large areas. Prior to conducting any geophysical surveys, it is advisable to perform synthetic modeling (aka ‘pre modeling’) based on hypothetical scenarios for anticipated target depths and subsurface properties and structures. Such pre modeling exercises can provide the basis for go/no-go decisions on surveys and also provide insight into resolution to facilitate interpretation of results.

Implementability:

Borehole installation technology is well established (TRL 10), although installation of angled boreholes is more costly and requires more specialized technology and services available from only a subset of drilling contractors (TRL 8-9). Borehole logging is straightforward to implement. Standard logging services are available from numerous vendors nationwide (TRL 10), although certain advanced logging techniques (e.g., NMR, BHF) are less common in the environmental industry (TRL 7-9). EM and electrical geophysical technologies are mature and geophysical services for surveys can be contracted (TRL 9-10); however, certain technologies and approaches require more specialized services or assistance from the research community, e.g., tTEM (TRL 7-8) and time-lapse monitoring (TRL 7-8).

Exemplars/References:

Barbosa, M.B., Terry, N., Day-Lewis, F.D., Bertolo, R. and Lane, J.W., Jr (2020), A New R Program for Flow-Log Analysis of Single Holes (FLASH-R). Groundwater, 58: 987-992. https://doi.org/10.1111/gwat.12994

Briggs, M.A., Nelson, N., Gardner, P., Solomon, D.K., Terry, N. and Lane, J.W. (2019), Wetland-Scale Mapping of Preferential Fresh Groundwater Discharge to the Colorado River. Groundwater, 57: 737-748. https://doi.org/10.1111/gwat.12866.

Day-Lewis, F.D., C.D. Johnson, F.L. Paillet, and K.J. Halford. 2011. A computer program for flow-log analysis of single holes (FLASH). Groundwater 49, no. 6: 926– 931

Elwaseif, M., Robinson, J., Day-Lewis, F.D., Ntarlagiannis, D., Slater, L., Lane, J.W., Minsley, B. and Shultz, G., 2016, A Matlab-Based Frequency-Domain Electromagnetic Inversion Code (FEMIC) with Graphical User Interface, Computers and Geosciences, 99, 61-71.

Henderson, R.D., Day-Lewis, F.D., Abarca, E. et al. Marine electrical resistivity imaging of submarine groundwater discharge: sensitivity analysis and application in Waquoit Bay, Massachusetts, USA. Hydrogeol J 18, 173–185 (2010). https://doi.org/10.1007/s10040-009-0498-z.

Kendrick, A.K., Knight, R., Johnson, C.D., Liu, G., Knobbe, S., Hunt, R.J. and Butler, J.J., Jr., 2021, Assessment of NMR Logging for Estimating Hydraulic Conductivity in Glacial Aquifers. Groundwater, 59: 31-48. https://doi.org/10.1111/gwat.13014

Keys, W.S., 1990, Borehole Geophysics Applied to Ground-Water Investigations, U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 2, Chapter E-2.

Stumm, F., and Como, M.D., 2017, Delineation of Salt Water Intrusion through Use of Electromagnetic-Induction Logging: A Case Study in Southern Manhattan Island, New York, Water 9 no. 631; doi:10.3390/w9090631

Technology Inter-Relationships:

The multi-method and multi-scale characterization effort calls for an integrated strategy to address information needs for modeling (conceptual and numerical) and remedy design. Drilling, logging and surface geophysics should be coordinated to enable comparison of co-located data to support calibration or ground truth of geophysical interpretations.

Boreholes in general can serve a multitude of needs and new boreholes must be considered in terms of their "value added" as related to (1) providing new characterization options (e.g., logging; cross well testing), (2) availing access to new locations (deeper spots, angled underneath tailings pile), (3) augmenting the existing network, and (4) compatibility to serve multiple needs (technology instrumentation) at the same time.

Capitalizing on the information from borehole geophysical logs will require integration with efforts to develop spatial databases and capabilities for 3D visualization at Moab. Logging results should be used to inform CSM development which will require inclusion in visualizations and consideration when constructing and refining the hydrogeologic framework model.

Sequencing - Prerequisites and Data Gaps/Needs:

The preferred sequence of efforts described under this narrative is (1) planning, pre modeling, and execution of surface EM and (or) electrical geophysical surveys; (2) identification of sites for new boreholes, design of borehole construction, and installation; (3) logging of existing and new boreholes. The surface geophysical surveys could provide information to support siting and design of boreholes, and collection prior to borehole installation could provide for cleaner data at the locations of new boreholes.

Timeframe:

- Tier 1 (timeframe 1 year) – Planning of geophysical surveys, pre modeling, and survey design; design and preliminary selection of sites for new boreholes.
- Tier 1 or 2 (timeframe 2 – 3 years) – Collection of surface geophysical data; installation of boreholes; collection of borehole logs.

Synopsis and Consensus:

Capture input from the broader group.

Topic: Alternative Reduced Order Models

Long List Item / Objectives:

Team 2 - Reduced Order Models -- Diversify the technical basis for projecting the timeframes for groundwater flushing and/or remediation using simplified “reduced order models” and “mass balance models. This would aid in bounding flushing timeframe and improve assessment of attenuation processes – topics that are directly relevant to UMTRCA GCAP development. Diversifying the nature and types of modeling tools may be helpful in providing stakeholders/regulators with transparent & understandable information.

Description:

“Reduced order models” are often a useful adjunct to more complex numerical models – these models can assist in stakeholder communication because they are simple and straightforward to describe. When projecting contaminant flushing, many reduced order models mimic 1st order exponential decay. However, models that exhibit more pronounced “tailing” (e.g., due to mass transfer limitations and slow release from residual and secondary sources) require more sophisticated mathematical treatment. Example models from the literature that better model this “tailing” include stretched exponential and power functions. Recent projections of flushing timeframes for Moab groundwater use a simplified reduced-order model whose output resembles an exponential decay (e.g., matching a small 1-D column) rather than accounting for the complexities of mass transfer and multiple residual sources and the associated fluxes.

The observed progression of a groundwater flushing or remedy performance composites multiple, complex and interacting processes, including: the quantity and behavior of primary and secondary sources, aquifer and fluid heterogeneity, mass transfer, biogeochemical interactions/processes, and (if active remedy is underway) remediation system design. While explicitly and comprehensively modeling such systems is challenging, there has been progress in projecting the emergent behavior of groundwater flushing/remediation progress using straightforward analytical expressions. The literature suggests that the simplest expressions (exponential or linear), when calibrated to early remediation system performance, will tend to underpredict flushing/remediation timeframe, do not adequately anticipate the typical observed “tail”, and will result in projected timeframes that progressively shift (longer) as more data are collected. However, recent applications of power functions and various enhanced exponential functions (stretched exponential and double exponential) have improved projections of observed-emergent flushing/remediation performance and timeframe. The basis for these models is that they better account for the residual source material that is present in different forms/settings and provide a theoretical basis for the projection – for example, the stretched exponential is often used to describe the discharge of a capacitor (a process that is somewhat analogous to the flushing of contaminant from a groundwater system).

The graphic depicts an example of these models applied to a groundwater pump and treat system. As shown, the power function, stretched exponential, and double exponential provide a significant improvement in matching the emergent-observed progress of remediation compared to a simple exponential projection. This is shown for the overall system (a - an area with multiple recovery wells) and for individual wells (b – an example well). Improved performance of the enhanced mathematical expressions is most significant when projections are made based only on early performance data (b) but improvement is also observed when calibrating to the entire data period (a).

Finally, development of mass balance models is valuable in assessing natural attenuation and flushing timeframe. These models explicitly consider source mass flux (and spatial distribution), attenuation processes in different zones of the plume footprint, and focused examination of mass flux at key interfaces (e.g., from groundwater to surface water or from the deeper brine zone to the shallow transport zone). For Moab, the zones developed to support the GCAP and adaptive site management would provide a useful framework for mass balance evaluation – the initial mass balance could be done with simplified reduced order modeling tools such as RemCHLOR and could be incorporated into the 3D numerical modeling by defining the interfaces for mass balance accounting.

Graphic(s):

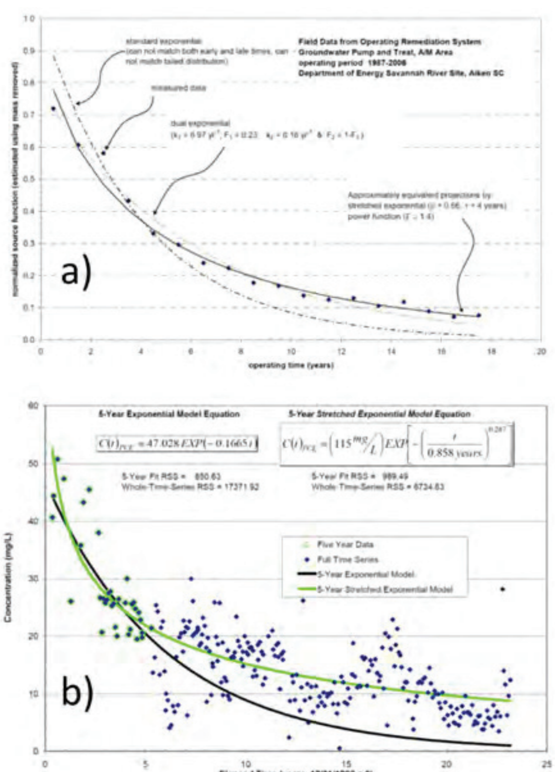


Figure 1. Example results for application of alternative analytical expressions for projection of the remediation progress for a groundwater pump and treat system operating in the A/M Area

of the DOE Savannah River Site – a) projections for the overall system, and b) projections of a single wells (RWM-1). Note that the simple exponential does not adequately project the “tail”. The expressions in graph (a) are calibrated to the entire 18-year period of record while the expressions in graph (b) are calibrated to the first 5 years of data.

Match to Moab Conditions:

This technology is suited to prediction of flushing and the decline in concentration in wells in the Moab plume. However, application might be limited by short period of data, changing conditions (i.e., clean water injections, groundwater extraction and tailings removal), and lack of information on the residual and secondary sources and associated projections of source mass fluxes. These challenges might limit application of reduced order models and require a 3D numerical modeling. A specific limitation is that the period of record is relatively short so that the degree of tailing is not yet fully quantifiable based on the data.

Implementability:

Relatively straightforward to perform scoping evaluation. May be suitable for collaboration with a university or implementation with the assistance of students. The initial implementation could be done as an extension of the current flushing modeling and be positioned as a method to provide context and bounds on potential flushing timeframes and attenuation processes.

Sequencing prerequisites and data gaps/needs:

This concept could be implemented quickly and easily. The work can be performed as an extension of the baseline effort and/or by collaboration with a university, students or National Laboratory.

Timeframe:

Short term (1 to 2 years).

Technology Inter-Relationships:

Simple and straightforward. Would provide results and output relatively fast compared to waiting for the 3D numerical model.

Synopsis and Consensus:

Consider implementation by the Moab team.

Topic: Climate Change and Other Uncontrolled Factors

Long-List Item Addressed / Objectives:

This topic is focused on climate change and other uncontrollable factors that may impact hydrologic processes occurring in areas surrounding the Moab Tailings site, including the flows in the Colorado River. These should be considered in the quantitative design and prioritization of contaminant management or remediation strategies, especially those that relate to flow rates and water quantities in the river. Specific considerations may include:

- Reduced average river flows in the Colorado river attributable to warming temperatures, reduced precipitation in the upper Colorado watershed, and altered patterns of river water consumption, river diversion and reservoir storage associated with climate change (e.g., Figure 1 and SWCA, et al., 2020; Villarini et al., 2009);
- Generally reduced amounts of rainfall that would contribute to aquifer recharge processes at the Moab site proper and in upgradient locations bounding its perimeter, along Moab Canyon, or in the Moab Wash (Figure 2); and
- Potentially higher “surge-like” or extreme events associated with short but significant rainfall events that affect the river (e.g., spiked flow rates, higher stages, flooding events), the Moab site proper, or in upgradient areas like Moab Canyon.
- Drier conditions associated with warming temperatures and declines in precipitation which may influence the vitality or longevity of vegetation in or near the site, or which may influence potential for wildfire and wildfire-related impacts to the ecosystem or related hydrologic processes.

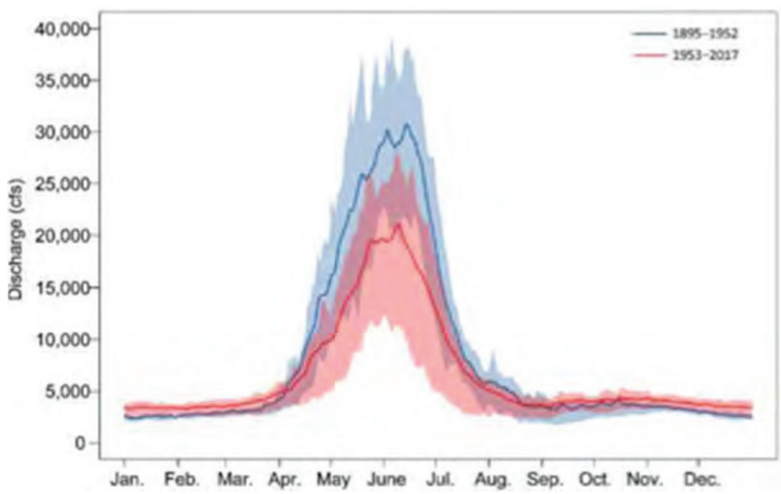


Figure 1. Annualized hydrograph for the Colorado River near Cisco, Utah (gage 09180500) for two different peak flow regime periods in the 20th century (SWCA, 2020; USGS, 2018). Shaded areas represent range of daily departures from mean flow curves as observed in the years comprising each period.

Description:

Over the past century, the rate of temperature increases in the Colorado River Basin as a result of climate change has been larger than anywhere else in the lower 48 United States. This has been associated with much of the observed declines in the Colorado river discharge observed since 2000 (Figure 1). Pertinent impacts at the Moab site may include reduced interannual flow rates and flood stages in the Colorado River, reduced levels of local precipitation, higher local temperatures (air and river water), and a potentially wider range of "one-off" or "extreme" events such as heavy storms (e.g., as were experienced in the last year in Death Valley and Yellowstone National Parks). Collectively, these effects may lead to different ranges or magnitudes of processes that are observed today and factored into remedial designs and strategies. Examples include:

- Changing flow patterns in the river and its braiding patterns (e.g., that may be pertinent in efforts focused on changing the river course) (Figure 2);
- Changing the degree and magnitude of hydraulic interactions occurring between the river and adjacent shallow groundwater (e.g., flow directions, rates, periods of effect);
- Different dilution effects associated with contaminant discharges into the river (e.g., into more stagnant, smaller volumes of river water);
- Modified biogeochemical processes in the river and channel proper (e.g., as a result of different temperatures or different volumes of water);
- Lowered levels of groundwater recharge in the shallow groundwater systems surrounding the Moab Site;
- Different mean and/or peak runoff rates in the Moab Wash (lower OR higher);
- Changing types or distributions of local surface vegetation;
- Altered surface runoff scenarios that may lead to suspended U sediment loads entering the river.

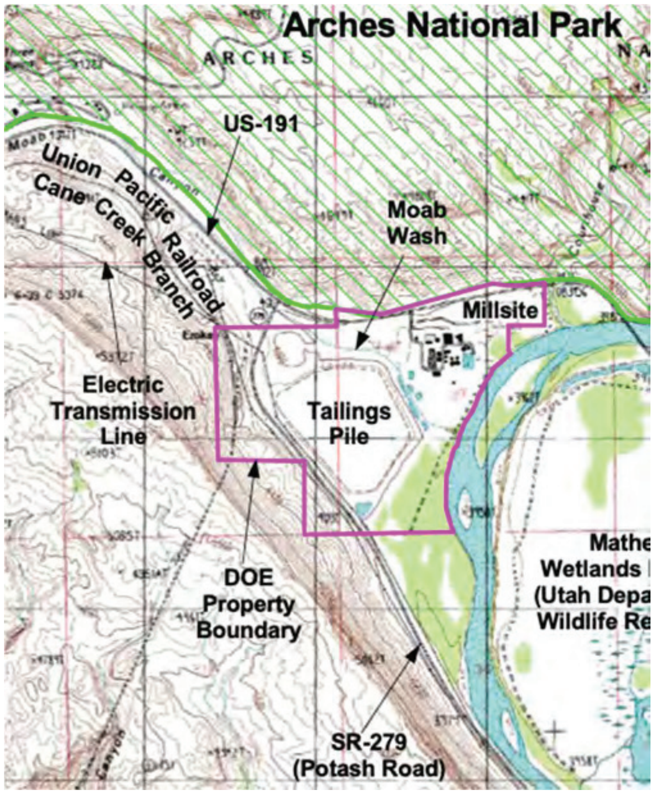


Figure 2. Site map of the Moab tailings site showing the braided Colorado River course, Moab wash.

The “technology” here is really one of reasoned anticipation: to develop an explicit list of quantitative factors pertinent to the Moab site that could be altered by climate change and other factors (e.g., as above), formulate one or more processes for identifying where these factors enter into evaluation strategies (e.g., computer model boundary conditions, modifications to river course), estimating* potential changes in these factors that could be attributable to climate change, and incorporating such changes, or acknowledging their existence, in subsequent design and prioritization of contaminant management or remediation strategies over their relevant lifetimes.

Match to Moab Conditions:

See above.

***Implementability**:

The approach is limited in that precise quantitative forecasts of potential changes (e.g., amounts, variability, timing) in the factors outlined above remain a matter of research that goes beyond the scope of this work. What is imagined here is (1) the acknowledgment of these changes (minimally), (2) model incorporation of nominally-altered boundary conditions (or related parametric or process related inputs) that are reflective of climate change impacts, and/or (3) evaluation of response or response sensitivities in the predictions due to these changes.

Timeframe:

Tier 1.

Technology Inter-Relationships:

The added value here can be applied, potentially, to all assessments that have quantitative links to variables affected by climate change.

References:

SWCA (Environmental Consultants), et al. (2020), Final Colorado River Comprehensive Management Plan (January), Utah Department of Natural Resources (Salt Lake City, UT)

U. S. Geological Survey (2018), USGS 09180500 Colorado River Near Cisco, UT, Time-series: Monthly Statistics. U.S. Department of the Interior. Accessed September 6, 2018 at: https://waterdata.usgs.gov/nwis/monthly/?search_site_no=09180500&agency_cd=USGS&referred_module=sw&format=sites_selection_links.

Villarini, G., F. Serinaldi, J.A. Smith, and W.F. Krajewski (2009) On the stationarity of annual flood peaks in the continental United States during the 20th century. Water Resources Research 45:1–17. DOI: 10.1029/2008WR007645.

TEAM 3

Potential DOE Response Actions to Include in the GCAP

Topic: Natural and Enhanced Attenuation

Long List Item / Objectives:

Team 1 – Options for combined remedies and adaptive site management -- The overarching goal is to aid DOE in determining the potential role of natural or enhanced attenuation processes in limiting the flux of contaminants to the Colorado River with a related goal to, conversely, assess if attenuation processes are holding up contaminants. This information will support projection of mass flux over time at key interfaces in the subsurface system and improve estimates of flushing/remediation timeframes. Objectives are to: a) supplement current efforts to provide technically-defensible water and mass balance, b) refine flushing conceptualization and timeframe to achieve remedial objectives, and c) to structure the evaluation using multiple lines of evidence as described in United States Environmental Protection Agency (EPA) and Interstate Technology Regulatory Council (ITRC) guidance documents.

Description:

Monitored natural attenuation (MNA) is an environmental management strategy that relies on a variety of attenuation processes to transform or immobilize contaminants. MNA is appropriate at sites where contamination poses relatively low risks, the plume(s) are stable or shrinking, and the natural attenuation processes are projected to achieve remedial objectives in a reasonable timeframe. The conceptual model of natural attenuation as a mass balance between the loading (mass flux from residual contamination in the subsurface) and attenuation of contaminants in the plume is a powerful framework for understanding, documenting, and managing MNA. EPA and ITRC guidelines encourage evaluation of attenuation based on multiple-tiered lines of evidence. These include (EPA, 1999; 2007; 2010; 2015; IRTC, 2010):

- Documentation of site-specific attenuation processes that reduce the quantity, toxicity, and/or mobility of contaminants,
- Explicitly accounting for the full range of contaminant sources (U and NH4), the potential for uranium mobilization, and the various mechanisms of uranium attenuation (mass balance)
- For the identified attenuation process, provide data related to attenuation rates and capacity/sustainability.

MNA remedies recognize dilution and dispersion as attenuation processes and allow for these to contribute to an MNA remedy; however, typical guidance generally does not support MNA remedies based solely on dilution and dispersion (EPA 2010 and 2015).

Importantly, for Moab, effort to assess attenuation using the lines of evidence as described in the 2015 EPA guidance for inorganic contaminants and radionuclides has the potential provide DOE information to support incorporation MNA of a final stage of a combined remedy -- as part of adaptive site management. As depicted in the Figure 1, the EPA guidance comprises three volumes – a general technical basis in volume 1 and contaminant specific guidance in volume 2 (non-radionuclides) and volume 3 (radionuclides). The information that would be most useful for Moab would be the general technical basis and the chapter on uranium. There is no specific information for ammonium in the EPA guidance, but there is a chapter on nitrate that would have useful information and insights – specifically related to nitrogen transformations, nitrogen speciation, and the potential for nitrogen containing gases to be lost from the system (e.g., NH_3, NO, N_2O, N_2). The potential for nitrogen transformation and attenuation can initially be assessed using the recommended molecular and biological tools and soil gas survey techniques described in sibling narratives. Similarly, initial uranium-specific attenuation assessments are provided in the sibling geochemical narratives.

Assessment of attenuation processes would also provide insight about the role of natural processes in slowing contaminant flushing (due to sorption or matrix diffusion, or other non-destructive attenuation mechanisms). For example, are uranium solids or ammonium solids present in the subsurface serving as secondary sources as they dissolve over time. Based on site conditions and features (e.g., contaminants already cropping out to Colorado River system and currently in trailing edge of plume lifecycle), natural attenuation is anticipated to have a limited role in the remediation of Moab groundwater. However, information on attenuation have the potential to improve the technical basis and defensibility of flushing projection, and development of potential enhanced attenuation strategies.

Graphic(s):

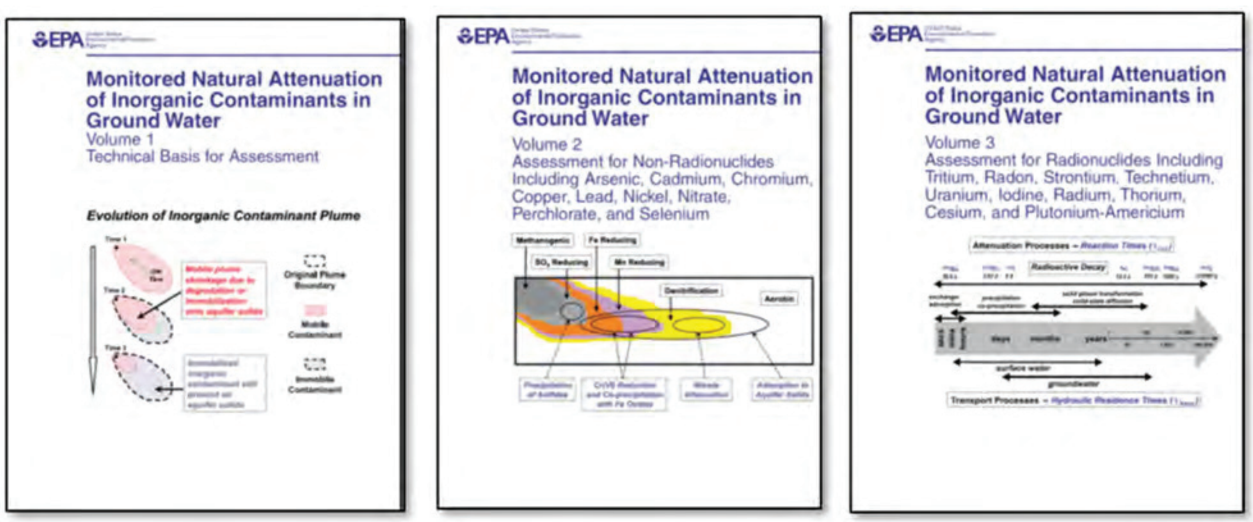


Figure 1. EPA guidance documents related to MNA of inorganics in groundwater.

Match to Moab Conditions:

The complex chemistry of Moab would benefit from the structured multiple lines of evidence approach and from an attempt to improve the mass balance and water balance.

Implementability:

Implementable using standard engineering. Recommend incorporation into baseline as a standard ("best practice") that would not require significant additional resources – recommend implementation of scoping MBTs, some of the geochemical studies, and the recommended modeling activities to support this baseline approach (specifically with attention to a mass balance framework and interpretation).

References:

Interstate Technology Regulatory Council (ITRC). 2010. A Decision Frameowrk for Applying Monitored Natural Attenuation Processes to Metals and Radionuclides in Groundwater. APMR-1. December.

United States Environmental Protection Agency (EPA). 1999. *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites,* OSWER Directive 9200.4-17P.21 April.

EPA. 2007. *Monitored Natural Attenuation of Inorganic Contaminants in Groundwater.* Volume 1 – Technical Basis for Assessment, EPA/600/R-07/139. October.

EPA. 2010. *Monitored Natural Attenuation of Inorganic Contaminants in Ground Water Volume 3: Assessment for Radionuclides Including Tritium, Radon, Strontium, Technetium, Uranium, Iodine, Radium, Thorium, Cesium, and Plutonium-Americium*, EPA/600/R-10/093. September.

EPA. 2015. *Use of Monitored Natural Attenuation for Inorganic Contaminants in Groundwater at Superfund Sites,* OSWER Directive 9283.1-36. August.

Sequencing prerequisites and data gaps/needs:

This concept could be implemented quickly and easily. The work can be performed within the baseline effort. May require implementation of some of the recommended laboratory and pilot studies in the related narratives (e.g., molecular and biological tools, and sequential extractions of core material).

Timeframe:

Short term (Tiers 1 and 2) to medium term (tier 3).

Technology Inter-Relationships:

Strong interrelationships with geochemical studies, tracers/MBTs and modeling narratives and recommendations.

Synopsis and Consensus:

Consider for incorporation into the baseline program.

Topic: Liquid Amendments for In Situ Sequestration

Long List Item / Objectives: Team 3 – Amendments for in situ enhanced sequestration -- Objectives are to reduce uranium and ammonium solubility/mobility and limit the flux of these contaminants to the Colorado River by injecting liquid amendments in the subsurface to create a permeable reactive barrier that will intercept and remove these contaminants from groundwater through in situ precipitation and/or sequestration. In addition, liquid amendments can be used to selective isolate known or to-be-identified secondary sources zones thereby limiting or greatly reducing their sustained and persistent contaminant loading to the aquifer system.

Description: Groundwater contamination at the Moab Site still persist and its discharges to the Colorado River poses a risk to human health and to endangered fish species. Since 2003, the site has been implementing an active remediation strategy by installing a configuration of extraction wells to intercept and reduce the amount of ammonia and uranium discharges to the river. Currently, the extracted water is used for dust suppression on the tailings pile. Once the tailing piles removal is completed, other disposition methods of the extracted water would be required to remove contaminants from the extracted water prior to disposal. In the long-term, this strategy would pose a significant cost; therefore, alternative and more passive remediation strategies are being considered at the site that could enhance the removal of contaminants, accelerate cleanup efforts, and reduce costs. In this document, we are focusing on three liquid amendments that can be injected in the subsurface to create a permeable reactive barrier to intercept and remove contaminants in situ, eliminating the need to extract-treat-dispose of water.

The first proposed approach is the creation of an in situ hydroxyapatite barrier in the subsurface to target uranium plume at the Moab site. This barrier is created by injecting a solution containing calcium citrate and sodium phosphate into the subsurface (**Figure 1**). As the indigenous soil microorganisms biodegrade the citrate, calcium is released and reacts with phosphate to rapidly form hydroxyapatite in situ (**Eq. 1**). Hydroxyapatite is very stable and highly insoluble mineral in water, and contaminants (particularly uranium) are removed upon contact with the barrier though several mechanisms including sorption, surface complexation, substitution into the apatite structure by ion exchange, and formation of sparingly soluble uranium phosphate minerals.

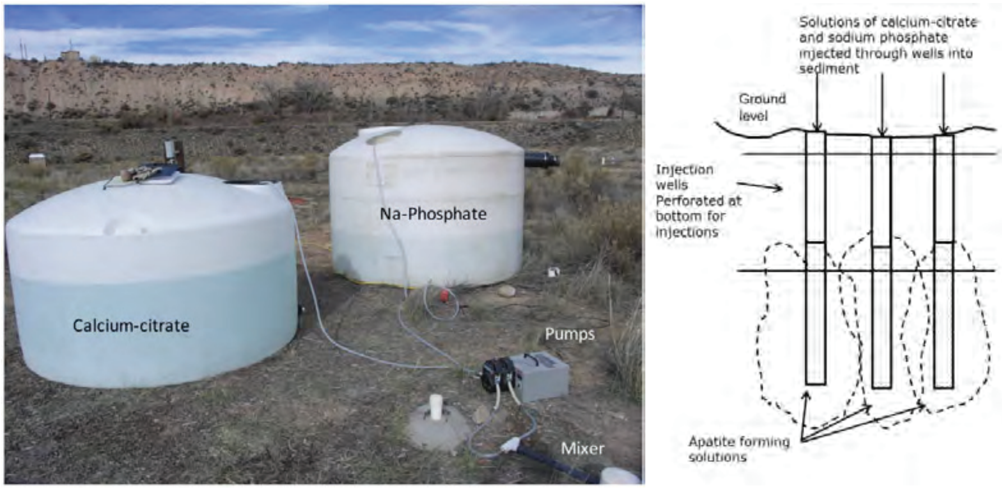


Figure 1. Injection of liquid reagents to create a hydroxyapatite reactive treatment zone in situ.

$$\text{calcium} - (\text{citrate})_2 + \text{sodium phosphate} \xrightarrow{\text{soil microorganisms}} \text{hydroxyapatite} \qquad \textbf{Eq. 1}$$

The second proposed approach is the injection of reagents in the subsurface to induce the precipitation of ammonium as struvite (**Figure 2**). This precipitation occurs when ammonium in the presence of phosphate and other cationic elements such as magnesium, nickel, barium combine in water at equal molar ratios to form struvite-type minerals (**Eq. 2**). Struvite has a low solubility in water with a pKsp of 13.36 with optimal pH for its precipitation in the range of 7.5 – 9.0. Scoping calculations suggest that site conditions are near solubility for struvite type minerals and that conditions are favorable for precipitation. Under the correct conditions, such mineral phases have potential to limit future release of ammonium to the active groundwater system.

This approach could be implemented in combination with technologies for in situ hydroxyapatite generation (i.e., adding phosphate, and other reagents). Care should be taking when adding calcium to the recipe as calcium ions can compete with magnesium ions for phosphate ions, resulting in the formation of hydroxyapatite instead of struvite minerals.

$$\mathrm{Mg^{2+} + NH_4^+ + H_nPO_4^{n-3} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O + nH^+ (n = 0{,}1 or 2)} \qquad \textbf{Eq. 2}$$

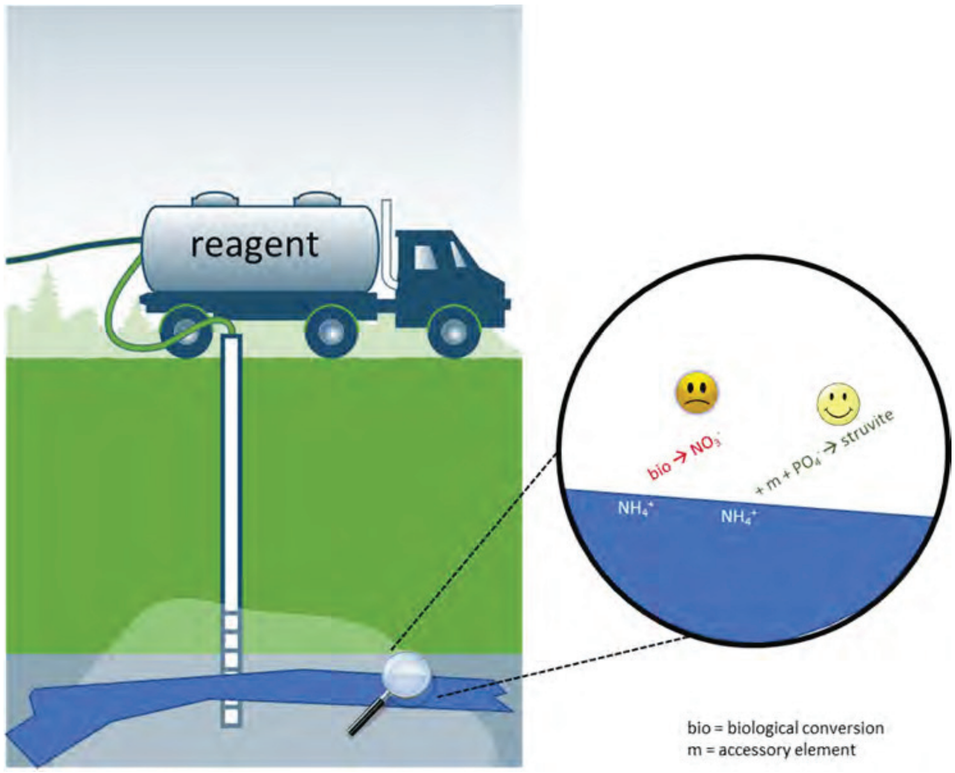


Figure 2. Injection of phosphate and magnesium reagents to induce precipitation of struvite minerals.

The third approach proposed to address uranium and possibly ammonium contamination is the in situ formation of a humic barrier. This barrier or reactive treatment zone is created by injecting a humate solution to form a coating on the mineral surfaces (**Figure 3**). Humates, also known as humic substances, are complex mixtures of heterogeneous organic compounds formed by biochemical and chemical reactions during the decay and transformation of plant and microbial remains. Humic substances are highly chemically reactive due to the presence of a variety of functional groups within their structure and yet recalcitrant with respect to biodegradation. The presence of carboxyl and phenol groups allows humic substances to form chelate complexes with metal cations (including uranium, ammonium and copper), greatly reducing their mobility, bioavailability and toxicity.

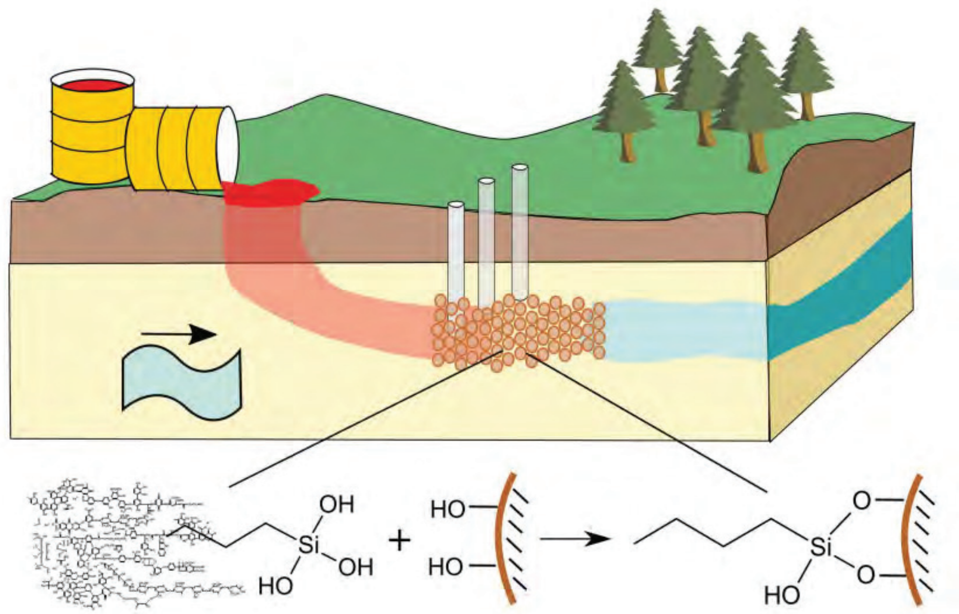


Figure 3. Example of an in situ passive installation of a humic permeable reactive barrier using injections of a humate and/or humic derivatives via a fence row of boreholes.

Match to Moab Conditions: The hydroxyapatite barrier would be a viable treatment for uranium sequestration based on Maob's groundwater pH (circumneutral) which is optimal for the formation of hydroxyapatite in situ. Care should be taken in the selection of the location (preferred at locations with lower permeability) for the barrier installation as it is required a certain time period for the liquid amendments to interact and form hydroxyapatite. Below is a summary of the optimal conditions for the formation of an in situ hydroxyapatite barrier:

- Groundwater pH between 6.9 and 9.0
- A relative slow groundwater flow rate to allow hydroxyapatite formation before the injected reagents are washed out from the injection points. Also, slow groundwater flow rate would allow uranium to interact and be immobilized by the PRB.
- An active microbial population for degradation of citrate.

The in situ precipitation of struvite minerals could be coupled with the hydroxyapatite strategy. Note that struvite precipitation would extend the timeframe of release and is potentially worthy of study since the presence of struvite minerals in current conditions might impact the flushing rate in an unrecognized manner. A second significant issue/challenge is the scale of the Moab challenge, specifically the potential mass of contaminants that were released during milling operations. Estimates for ammonia use ranged from around 5000 to 10000 lbs per day during milling and over 100000 lbs of ammonium have already been removed by pumping (over 5000 lbs of U have been removed). If stoichiometric amounts of reagents are needed for sequestration, then there may be practical challenges for deployment and possible adverse collateral impacts. These need to be assessed during any laboratory and pilot studies.

For the humate barrier, it will be required to conduct some preliminary lab experiments to evaluate the performance of humates on the removal of both uranium and ammonium under Moab site specific conditions prior to field pilot study. Moab's groundwater pH is characterized for being between 6.57 – 7.67 while humate sorption on aquifer sediments tend to be higher at acidic pH and moderate at neutral pH due to its solubility increases at basic pH. Depending on the humate material used (unrefined vs modified), different results in terms on sorption capacity can be obtained. Therefore, it is recommended to test some of these humate materials to obtain the best outcome during the deployment.

Implementability: The three proposed approaches can be implemented using standard engineering techniques. Since these are liquid amendments, the creation of a permeable reactive barrier is relatively simple and inexpensive compared to other methods of amendment deployment (e.g., trenching, excavation). Once the treatment zone is in place, no operational costs or maintenance is required. Sequestered contaminants are available for eventual excavation and removal, as warranted by the eventual groundwater compliance action plan for the site.

The hydroxyapatite technology has already been tested at two sites, and recently was also deployed at Moab site, so it has a higher TRL (6-8) compared to struvite precipitation (TRL 4-5) and humate technology (4-6) which may need some lab and field-scale testing.

Exemplars/References: The hydroxyapatite technology was tested at Hanford site in 2008 to create a permeable reactive barrier for immobilization of strontium-90. The study showed a 90% reduction in Sr-90 concentrations after 1 year of treatment. In 2017, a field pilot testing was conducted at the Old Rifle to test the performance of the hydroxyapatite PRB for uranium remediation, and the results were very positive with uranium concentrations below UMTRCA levels (44 ppb) for a period having exceeded 5+ years post-injection. Currently, a test pilot for the in situ apatite amendment is being tested at the Moab site.

For uranium remediation to supplement a series of successful batch incubation experiments that indicated the chemical formulation used at the Rifle, CO site was equally effective at reducing uranium concentrations from 2000-3000 ppb to <10 ppb when utilizing sediments and groundwater derived from the Moab, UT site.

The struvite precipitation strategy has not been used at a full scale but there is literature documenting struvite formation in wastewater, biological, and industrial (process) systems. Still, this approach requires some laboratory testing and pilot studies in the next few years.

The humate technology was evaluated at the Savannah River Site (SRS) by a single well injection test to evaluate whether humate is a viable amendment to enhance attenuation of uranium in the acidic portion of the groundwater contamination plume associated with the SRS F-Area Seepage Basins. The post-injection monitoring data showed that uranium attenuation was enhanced in the treatment zone. Uranium concentrations decreased by 32% compared to pre-test concentrations. An estimated 30-40 pore volumes of groundwater passed through the 1-

meter wide treatment zone during the test, so a full deployment with a much wider treatment zone would achieve sufficient uranium removal to achieve regulatory standards.

Technology Inter-Relationships: The hydroxyapatite technology and struvite precipitation could be combined and implemented simultaneously to target both uranium and ammonium contamination. Humate technology not only would serve to sequester uranium and possibly ammonium in situ, but it could also be used to provides a detoxification pathway to reduce the bioavailability of heavy metals (e.g., copper) to aquatic organisms. These three approaches will not be viable if natural or enhanced flushing are central to the overarching GCAP strategy.

Sequencing - Prerequisites and Data Gaps/Needs

Hydroxyapatite Barrier

Tier 1 (2023 - 2025) – The hydroxyapatite technology is currently being tested at the Moab Site. Batch incubation experiments indicated that chemical formulation used at the Rifle, CO site was equally effective at reducing uranium concentrations from 2000-3000 ppb to <10 ppb when utilizing sediments and groundwater derived from the Moab, UT site. Next steps are to: 1) focus on monitoring uranium concentrations in groundwater and evaluate hydroxyapatite barrier performance under Moab field conditions, and 2) perform laboratory experiments to optimize the baseline (Old Rifle) recipe for Moab groundwater conditions – specifically, studies that focus on elimination of added ammonium, simpler recipes that rely on the naturally higher levels of calcium in Moab groundwater, recipes that explore the potential for precipitation of struvite, potential non-phosphate amendments such as humates, and potential recipes that would be applicable to different areas of Moab groundwater (e.g., U dominant and ammonium dominant). The lab studies could be performed collaboratively with universities (e.g., FIU, or local universities) and/or National Laboratories.

Tier 2 (2025 - 2028) – If positive results are obtained from the pilot study, and it is observed that uranium concentrations, passing through the treatment zone, continue to have a decreasing trend, then consider implementing this strategy at a larger scale using optimized recipes. First, it should be focus on identifying potential locations (secondary sources) where the hydroxyapatite barrier can be used to isolate these areas to reduced and/or eliminate contaminant leaching to the aquifer system.

Tier 3 – 4 (2028 - 2038) – Continue monitoring the performance of the permeable reactive barriers to ensure uranium concentration in groundwater continue decreasing.

Struvite Precipitation

Tier 1 (2023 - 2024) – There are several studies documenting struvite formation in wastewater, biological, and industrial (process) systems, but no field scale deployment has been done for this approach. First, it is recommended to perform lab studies using groundwater samples to determine the quantity of each of the components (magnesium and phosphate) needed to induce the precipitation of ammonium to form struvite and be able to scale it up for field deployment. The recommended lab studies would be done in conjunction with the apatite recipe refinement studies described above.

Tier 2 (2024 - 2025) – If lab experiments show positive results and the team decides to include this approach in the GCAP, then it can be started with the process to initiate a pilot scale testing.

Tier 3 – 4 (2025 - 2035) The pilot scale testing will be initiated and monitored to evaluate its efficiency in reducing ammonium concentration inf groundwater.

<u>Humate Barrier</u>

Tier 1 (2023 - 2024) – First, some lab experiments need to be conducted to evaluate the humate technology on the removal of uranium and ammonium under Moab site specific conditions. The humate studies could be performed in conjunction with the apatite recipe refinement studies described above.

Tier 2 (2024 - 2025) – If lab experiments show positive results and the team decides to include this approach in the GCAP, then it can be started with the process to initiate a pilot scale testing.

Tier 3 – 4 (2025 - 2035) The pilot scale testing will be initiated and monitored to evaluate its efficiency in reducing uranium and ammonium concentration inf groundwater.

Synopsis and Consensus: Recommended for further evaluation.

Topic: Clogging Amendments

Long List Item / Objectives:

Team 3 – Amendments for in situ enhanced sequestration -- Assess the potential for deploying materials in identified source areas to hydraulically isolate the residual contamination and reduce the source mass flux to the surrounding groundwater.

Description:

A number of technologies are potentially viable (silica gel, polymers, polymer foams, heat/wax, flowable grouts, etc.). This class of technology, often using silica gel or "water glass", has been used by DOE and internationally (e.g., Fukushima) for isolating groundwater from potential contamination source. The technology would require characterization information that demonstrated reasonably small areas of high, or significant residual contamination along with modeling that demonstrates that isolating or armoring the contamination would provide benefit to the adaptive site management and risk management for Moab. This technology, since it can use injectable amendments has the potential to be used at depths greater than soil blending or deep soil mixing. Silica gel is the most standard pore clogging material, however innovative technologies such as heat and paraffin wax, polymers and/or foams could also be considered.

Graphic(s):

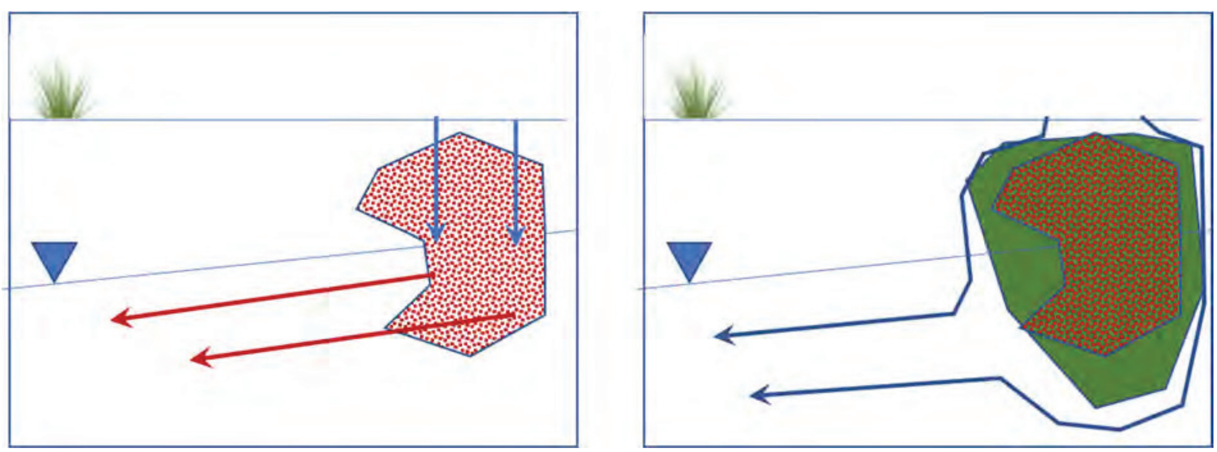


Figure 1. Simplified sketch of clogging if significant source area is identified.

Match to Moab Conditions:

This concept is potentially matched to Moab conditions as a tool to control source mass flux. The target zone to support adaptive site management would be in the vadose zone and shallow groundwater in areas where residual and secondary sources are present (e.g., Area I-S in the Adaptive Site Management Spatial Zone Map).

Implementability:

This technology requires a number of prerequisites and could be considered in the future if appropriate targets of residual source contamination are identified. Some of the technologies are commercially available (such as silica gels) with TRL in the 6 to 9 range and some (e.g., waxes) are less mature with TRL in the 3 to 6 range.

Sequencing Prerequisites and Data Gaps/Needs:

This is a surgical or targeted technique that requires detailed knowledge of the location (depth, spatial extent, boundaries and lithology of residual sources in the vadose zone and shallow groundwater. This technique is most applicable to residual sources that are present as a sorbed or solid phase in permeable strata and for reducing back diffusion from lower permeable strata (by forming a barrier at the surface. In general, this strategy is less promising than some of the other technologies but has the potential to be applicable if the Moab team identifies a promising deployment target. In that case, future deployment would require modeling of the potential impact of reducing the source mass flux via clogging, selection and testing of clogging amendments, and documentation of sustainability (amendment resilience over time). No near-term actions are proposed.

Timeframe:

Long term (>3 years).

Technology Inter-Relationships:

Fits in to the in situ sequestration line of inquiry and inter-related with other implementation ideas such as liquid injection, PRBs and solid injection/fracking. The technology ideas overlap with the green capping methods.

Synopsis and Consensus:

Recommend future consideration if data collection identifies an appropriate target area.

Topic: Solid Amendments for Treatment of Uranium and Ammonium

Long List Item / Objectives:

Team 3– Amendments for in situ enhanced sequestration.

Description:

The objective is to provide possible solid-phase amendments for the treatment of uranium and/or ammonium. Solid amendments can be added to the subsurface through various deployment methods to decrease aqueous plume concentrations or source areas/hot spots. Many solid-phase amendments target mobile uranium specifically either through sorption, reduction, or incorporation into the solid structure (or a combination of various mechanisms) (Table 1).

Table 1. Solid-Phase Amendments for Uranium and/or Ammonium Treatment

Amendment	Description	Contaminant	Notes	References	Example Products
Apatite Minerals	Apatite minerals mined and granulated for use in a PRB. Hydroxyapatite for uranium removal. Other commercially made products may also be available.	Uranium	Data on removal of uranium and other methods deployed as active capping materials in rivers and estuaries	Fuller et al., 2003; Lammers et al., 2017; Raicevic et al., 2006	
Fish Bones	Apatite derived from fish (recycled waste material from seafood processing). Other commercially made products may also be available.	Uranium	Several pilot studies, reports, and journal articles with data demonstrating removal of metals and uranium from aqueous solutions. Contaminants may be present in fish bones (e.g., Hg, Pb, other heavy metals, etc.)	Chattanathan et al., 2013; CH2M Hill, 2010 Fish bone apatite was jet injected at Hanford's 100-N Area (Szecsody et al., 2010)	http://www.pimsnw.com/ The nominal cost is approximately \$2 to \$10 per lb.
Bone Char	Apatite containing activated carbon derived from cow bones and used in large scale industrial processing applications.	Uranium	Granular bone char is an apatite-based solid processed in batches where bone solids are treated to 400-500°C in controlled-oxygen conditions. This is sufficient to remove most of the organic matter and results in a desirable apatite crystal structure for metal removal and a small amount of residual activated carbon. Bone char materials that are prepared from cow bones at higher or lower temperatures and/or without oxygen control have not performed as well for metals removal.	Fuller et al., 2003; Bargar, 2002	"Bone-Black": https://www.reade.com/products/bone-char-granular-bone-black The nominal cost is approximately \$2 to \$10 per lb.

Amendment	Description	Contaminant	Notes	References	Example Products
Activated Carbon & BioChars	Carbon-based adsorbent materials	Uranium, with potential for ammonium sorption	Low cost biochars can be made from a variety of source materials (e.g., switchgrass, wheat straw, cow manure) and further functionalized to provide additional sorption sites. Potential for contaminant breakthrough once the adsorption capacity has been reached, or contaminant desorption over time. If applied in a PRB, exhausted materials could be excavated and disposed of.	Dong et al., 2017, Kumar et al., 2011 (biochar) Mellah et al., 2006 (activated carbon) Sun et al., 2015 (graphene oxides) HNO_3 modified biochar (Jin et al., 2018)	
Clays	Clay materials (e.g., Zeolites, Montmorillonite, Kaolinite, Bentonite) as a sorbent for U(VI). Crystalline aluminosilicate materials for U(VI) uptake.	Uranium, with potential for ammonium sorption	High surface area and various functional groups on clay structures provide sites for contaminants to adsorb (including uranium). Adsorption is highly pH dependent due to the alteration of functional groups and surface charges. U(VI) sorption will be decreased in the presence of carbonate.	Morante-Carballo et al., 2021; Chisholm-Brause et al., 2001 Li et al., 2014 (Ammonium)	
Zero Valent Iron (ZVI) & Sulfur Modified Iron (SMI)	Reduction and precipitation of U(VI)	Uranium	ZVI is available in many different particle sizes (granular, micron, nano). Smaller particle sizes have higher reactivity. Primary removal mechanism is reduction, resulting in uranium precipitation; however, reduction is typically not seen as a permeant solution because remobilization can occur if reducing conditions are not sustained. ZVI has been deployed in PRBs in several uranium-contaminated aquifers.	Gu et al., 1998; Fuller et al., 2003	
Tin Apatite	The tin reduces the uranium, which is then sequestered within the solid apatite	Uranium	Limited testing. No field testing.	WRPS, 2012	No known commercially available product.
Custom Blends of Apatite-Forming Solids	Existing apatite formulations could be altered for a site-specific Moab blend to treat both uranium and ammonium	Uranium and Ammonium	Example formulation detailed below.		N/A

Custom Blend of Apatite-Forming Solids: Existing apatite formulations could also be altered for a site-specific Moab blend to treat both uranium and ammonium. For instance, the reagents used for liquid apatite formulation could instead be applied as solids or slurries and blended into the subsurface for apatite formulation. In this case, the liquid recipe (e.g., Old Rifle Site formulation) could be modified to address both uranium and ammonium as indicated in the notional/conceptual example below (molar ratio in solid amendments):

<u>Primary reagents</u>

- (1) NaH_2PO_4 (weak acid with pH in solution of 4 to 6 and pKa near 7) –to provide phosphate for apatite formation and struvite formation
- (0.2) $Mg(OH)_2$ (base with pH in DI water solution near 12) –to provide magnesium for struvite formation
- (0.3) CaO / $Ca(OH)_2$ (base with pH in DI water solution near 13) –to provide calcium for apatite formation

<u>Possible trace elements</u>

- 0.01 NaF or SnF_2 might support further stabilization of apatite/struvite phases – analogous to fluoride toothpaste
- 0.01 Ni might support further stabilization of apatite/struvite phases

<u>Makeup of final reagent amendment solid mix</u>

- filler material (sand, zeolite, etc.) if needed
- Additional calcium $Ca(OH)_2$ powder to bring blended reagent pH to approximately 8

Match to Moab Conditions:

Need to understand the mobile contaminant phases and the biogeochemistry and to identify which solid-phase amendment might be applicable to the Moab site.

Implementability:

Solid amendments could either be incorporated into the subsurface through either physical emplacement techniques or potentially injected if the amendment particle sizes are in the micron- to nano-size. Some additional considerations include the potential for desorption and contaminant release over time and the potential for pore clogging by mineral precipitation (Fuller et al. 2003).

Exemplars/References:

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Technology Inter-Relationships:

Interconnected with the deployment of solid materials for in situ remediation.

Timeframe:

Tier 1 (2023-2024) – Batch and column experiments aimed at quantifying the treatment effectiveness, capacity, and uptake rates (and desorption rates) of the solid-phase amendments with Moab soils, groundwater chemistry, expected groundwater velocities, and the range of expected contaminant concentrations to be encountered.

Using the laboratory-measured treatment effectiveness, preliminary calculations can be conducted to determine potential deployment strategies and configurations required for the treatment outcomes.

Synopsis and Consensus: Recommend future consideration.

Topic: Deployment Techniques for Emplacing Solid Amendments

Long List Item / Objectives:

Team 3– Amendments for in situ enhanced sequestration – The objective of this writeup is to provide information about techniques for emplacing solid-phase amendments in the subsurface for treatment of uranium and/or ammonium. Solid amendments can be added to the subsurface to decrease dissolved-phase concentrations in the aqueous plume or in source areas/hot spots.

Description:

There are several techniques to emplace and distribute solid-phase amendments in the subsurface for contaminant treatment, including but not limited to, injection of small particulates, soil mixing, trenching, jet grouting, and fracturing. Because the contaminant plumes at the Moab site are located primarily within permeable soils with high hydraulic conductivities, only deployment techniques suitable for such aquifer materials will be discussed here. More aggressive emplacement techniques typically utilized for low permeability zones, such as fracturing and jet grouting (e.g., Szecsody et al., 2010), will not be discussed.

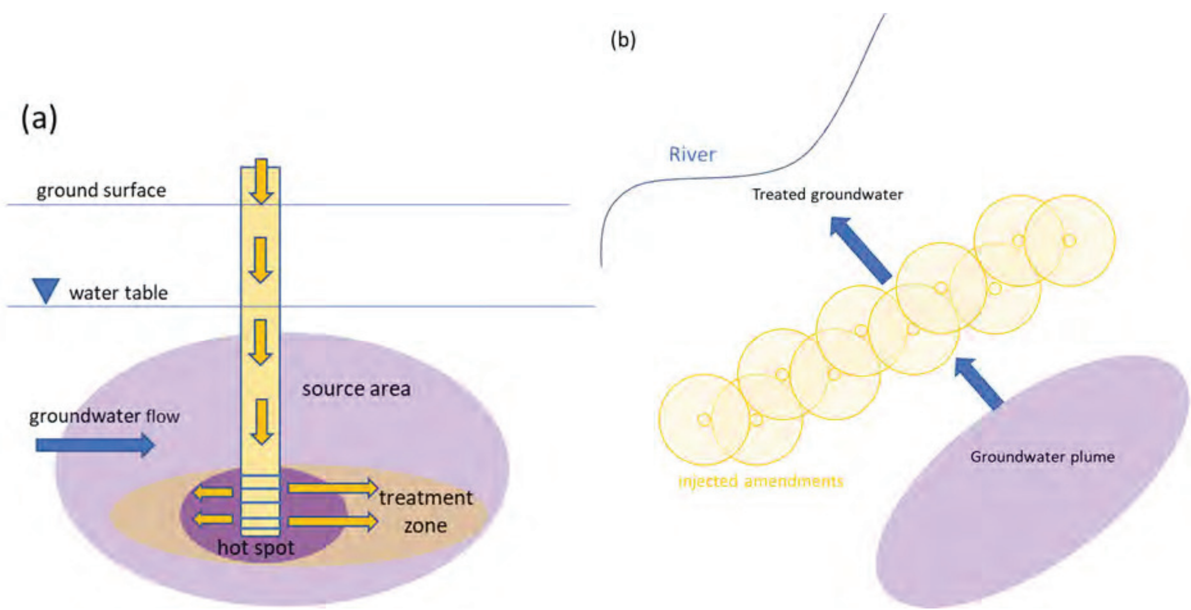
Injections: The particle size of the selected amendment will determine whether it can be injected effectively, because the amendment particle size is the primary factor that controls injection and delivery. Delivery by injection tends to only be applicable for micron to nano-size particles, depending on the nature of the porous media. The porous media grain size distribution, formation heterogeneities, amendment particle size and composition, injection fluid properties, and injected particle concentration, all greatly influence the achievable radius of influence (ROI) (i.e., the effectiveness of delivery/distribution). Delivery fluids (e.g., xanthan gum is commonly used to facilitate transport of zero valent iron [e.g., Vecchia et al., 2009]) can aid suspension and stability of amendment particles for improved injectability and in situ distribution. Laboratory testing would be needed to (a) determine the optimal amendment-delivery fluid formulation, and (b) quantify any loss of amendment reactivity that may occur when placed within the selected delivery fluid. If heterogeneity is present within the subsurface target zone, a shear-thinning delivery fluid (e.g., Zhong et al., 2013) could facilitate more uniform distribution of solid amendments throughout the treatment zone.

The high permeability soils expected at the Moab site lend themselves to multiple injection methods, including gravity feed or pressure injections into permanent wells, or direct push injections (Figure 1a). Standard boreholes/wells are flexible with respect to achievable depth, but direct push injections are typically recommended for shallower delivery depths, although direct push points can go to a maximum of 100 ft below ground surface (bgs). A network of injection wells could be used for volumetric treatment over a large area or to create a permeable reactive barrier (PRB) to intercept the dissolved groundwater contaminant plume at a designed location, for example before discharge into the Colorado River (Figure 1b). Other configurations could include a recirculation system where injection and extraction wells in a designed configuration (e.g., dipole, 5-spot, etc.) are used to enhance amendment distribution into the aquifer formation between the injection well(s) and extraction wells, while also controlling the plume migration by manipulating the groundwater hydraulics within the treatment zone (Figure 1c).

Trenching/Soil Mixing: Larger-sized solids (e.g., granular materials) require direct placement in the subsurface to create a reactive treatment zone, either volumetric or a PRB, through trenching or soil mixing (Figure 1d). Trenching involves excavating a specified path of designed width in the subsurface and then backfilling the trench with the reactive amendment. A funnel and gate system could be created to direct contaminated groundwater through the treatment zone (Figure 1e). Amendments can also be mixed directly into the subsurface to create a reactive zone. With soil mixing, the soil is mechanically mixed using soil blenders or large augers (Figure 2). This technique can be used to create a treatment zone covering the needed footprint, including volumetric treatment or along lines to achieve a PRB design.

The principal advantage of soil mixing is that effective contact of the treatment reagents with the contaminants is well assured. Multiple systems are available for performing the blending or mixing, with nominal deployment depths of around 25 ft and maximum depths up to 70 to 90 ft (Figure 2). For large jobs, typical treatment costs range from $50 to $100 per cubic yard of soil mixed/treated. There are some limitations and challenges surrounding physical mixing of amendments, including restrictions related to the depth and size of the mixing zone, inability to mix when the subsurface containing large, buried objects (e.g., cobbles, rocks, infrastructure), altering soil and groundwater flow properties, and potential for subsidence of the ground surface.

Graphic(s):



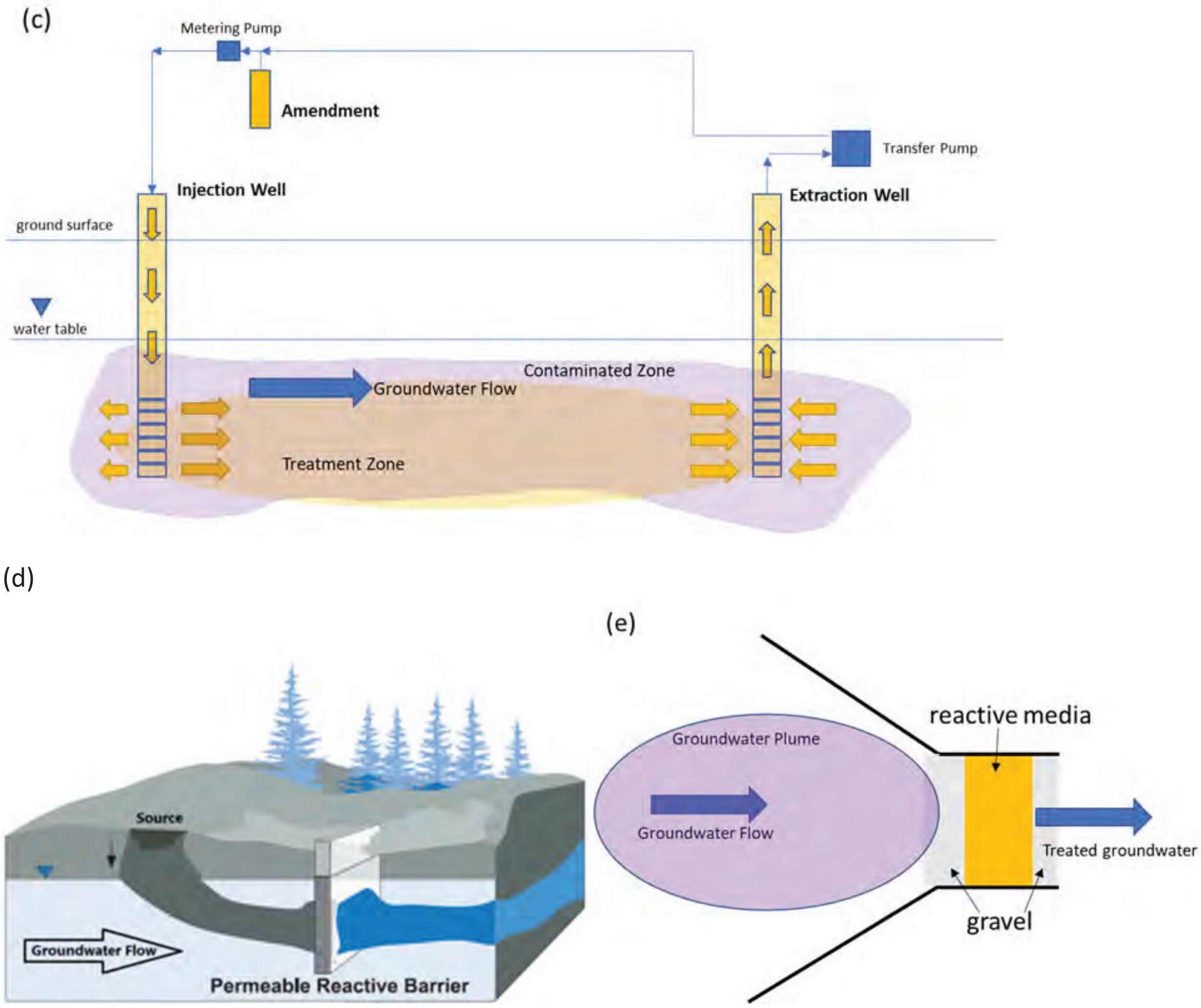


Figure 1. Solid Amendment Deployment Techniques. (a) Illustrative example of injection of solid-phase amendments for source area treatment or to distribute amendments throughout the subsurface, if a sufficient ROI can be achieved, (b) Multiple injection points used to create a large reactive treatment zone to treat flowing groundwater, (c) Illustration of a standard recirculation system to facilitate amendment distribution, while commonly employed for liquid amendments, such a method could also be used for suspensions of solid amendments (source: NAVFAC, 2013), (d) Illustration of a PRB for groundwater treatment (Source: https://www.enviro.wiki/index.php?title=Zerovalent_Iron_Permeable_Reactive_Barriers), and (e) illustration of a funnel and gate PRB system to direct groundwater flow through the reactive treatment zone.

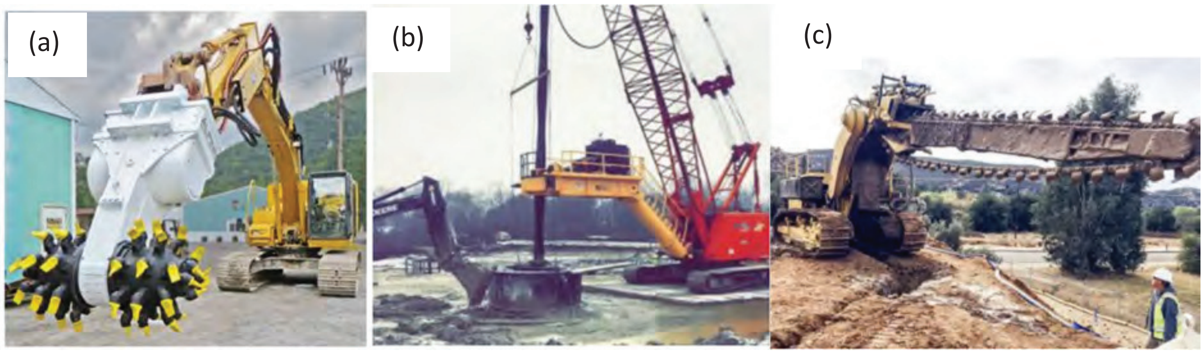


Figure 2. In Situ Soil Mixing. (a) Equipment used to mix to a depth of 25 ft (Source: Redox Tech), (b) Deep soil mixing where blending can be completed to 90 ft depth (Source: GeoSolutions) and (c) Trenching technique used to either blend or create a PRB trench to a nominal depth of 25 ft bgs (Source: GeoSolutions).

Match to Moab Conditions:

All deployment techniques would be well suited to address the shallower groundwater contamination at Moab (i.e., between 25 - 50 ft bgs) within the highly permeable sandy gravel valley fill. Soil mixing or direct push injections might be the most advantageous in areas where there is residual contamination in the vadose zone and shallower groundwater (less than around 100 ft bgs), such as under the former tailing pile following the relocation activities. Given that some of the groundwater plume may be located deeper than 100 ft bgs (and potentially down to 150 ft depths), if treatments at such depths was desired, this could be a major limitation, in particular for physical emplacement techniques (soil mixing or trenching), as they have depth limitations. If attempting to treat the groundwater plume, success would hinge on finding a suitable treatment location where the emplaced amendment or injected amendment ROI would intersect contaminated groundwater before it discharges into the Colorado River, while taking care not to unintentionally redirect the plume around or under the treatment zone. Any permeability loss due to the addition of amendment would need to be limited because it could also create or enhance flow conditions where groundwater would bypass the treatment zone.

Implementability:

Deployment of solid-phase particulates should be feasible under the conditions expected at the Moab site. However, the properties of the selected solid-phase amendment, treatment location (depth, spatial extent), amount of amendment required to address the desired aqueous concentration/flux reduction, and subsurface flow behavior will determine the feasible delivery strategies. Site-specific amendment delivery and distribution requirements can often be met through engineered designs. Gavaskar et al., (2000) provides guidance on PRB design. Obiri-Nyarko et al., (2014) detail a review of PRBs. Overall, solid-phase amendment deployment is mature and straightforward with high technology readiness level (TRL) levels.

Exemplars/References:

CLU-IN, Permeable Reactive Barriers, Permeable Treatment Zones, and Application of Zero-Valent Iron https://clu-in.org/techfocus/default.focus/sec/Permeable_Reactive_Barriers%2C_Permeable_Treatment_Zones%2C_and_Application_of_Zero-Valent_Iron/cat/Overview/

Gavaskar, A.N. B Gupta R.J. Sass and J Hicks. 2000. Design guidance for application of permeable reactive barriers for groundwater remediation. https://clu-in.org/conf/itrc/prgbll_061506/prb-2.pdf

Muller, K.A., Johnson, C.D., Bagwell, C.E. and Truex, M.J. (2021), Methods for Delivery and Distribution of Amendments for Subsurface Remediation: A Critical Review. Groundwater Monit R, 41: 46-75. https://doi.org/10.1111/gwmr.12418

Naval Facilities Engineering Command (NAVFAC) (2013) Best Practices for Injection and Distribution of Amendments.

Obiri-Nyarko, Franklin, S. Johana Grajales-Mesa, and Grzegorz Malina. "An overview of permeable reactive barriers for in situ sustainable groundwater remediation." Chemosphere 111 (2014): 243-259.

JE Szecsody, VR Vermeul, JS Fruchter, MD Williams, ML Rockhold, NP Qafoku, JL Phillips (2010) Hanford 100-N Area In Situ Apatite and Phosphate Emplacement by Groundwater and Jet Injection: Geochemical and Physical Core Analysis. PNNL-19524

Vecchia E.D., Luna, M., and Sethi, R. (2009). Transport in porous media of highly concentration iron micro- and nanoparticles in the presence of xanthan gum. Environ. Sci. Technol. 43: 8942-8947.

Zhong, L., Oostrom, M., Truex, M.J., Vermeul, V.R., and Szecsody, J.E. (2013). Rheological behavior of xanthan gum solution related to shear thinning fluid delivery for subsurface remediation. J. Hazard. Mater. 244-245:160-170.

Technology Inter-Relationships:

Interconnected to the site conceptual model and any flow and/or transport modeling. Also, directly connected to the solid-phase amendments suitable for uranium and/or ammonium treatment.

Sequencing - Prerequisites and Data Gaps/Needs

Timeframe:

Tier 1 (2023) –

- Determine suitable solid amendment(s) for uranium and/or ammonium at the Moab Site. Down select deployment techniques to ones that are compatible with the selected amendment.
- Conduct design scoping calculations to check for feasibility, including identification of the desired location and size (length, depth) of the treatment zone, and estimation of the amount of solid amendment required.
- Consider preliminary system design aspects to evaluate whether any significant complications for the Moab site may exist, such as:
    - Identification of any targeted zone conditions that may negatively influence treatment and delivery (i.e., heterogeneities, permeability, preferential flow paths, pH, soil texture, buried objects, etc.)
    - If injecting, estimate the expected ROI and corresponding required number of injection points to achieve the required treatment zone
    - If mixing, estimate the required locations/size of a soil mixing zone
    - Estimate the expected reaction rate of solid amendment with the COCs
    - Consider any potential secondary effects of amendment (and/or carrier fluid) (e.g., pH alterations)

Tier 2 (2024 - 2025) – Batch experiments testing the treatment effectiveness (capacity, uptake rate, desorption rates, etc.) of the solid amendments with soils, groundwater chemistry, groundwater velocities, and the range of expected contaminant concentrations to be encountered at the Moab site. If considering solid amendment injections, 1-D column studies should be completed to determine the mobility of the solid suspensions in Moab soils and under the expected flow and chemistry conditions.

Tier 3 (2025 – onward) – Pilot-scale testing at the Moab Site.

Synopsis and Consensus:

Recommend for future consideration.

Topic: Groundwater & River Water Bypass and Hydrologic Controls

Long List Item / Objectives:

Team 3 – Boundary Condition Control -- Modify hydrologic boundary conditions to isolate contaminated water – limiting efflux to the critical habitats in the Colorado River during periods of ecological sensitivity. This technology/strategy has the potential to significantly reduce the flux of contaminants to the river and to critical habitats. The Moab team is currently deploying this strategy using upstream river water – a creative and affirmed approach. This narrative explores if the concept can be supplemented, expanded or modified to make it even more effective.

Description:

This technology/strategy physically uses uncontaminated upgradient groundwater, treated groundwater, or upstream river water to beneficially alter hydrologic driving forces – target locations for deploying the water include the subsurface zones near the river and sensitive backwater habitats. Applications use piping and other engineered infrastructure to provide either active or passive/sustainable modification to the hydrologic boundaries/conditions for risk reduction. If information is developed that indicates that time dependent risk sensitivity in the river (e.g., periods where breeding is occurring in critical habitats) then the boundary condition control can be strategically operated based on seasons or conditions to (on) mitigate groundwater contaminant fluxes during periods of higher sensitivity/risk and (off) to allow maximum groundwater flushing during periods where there is lower sensitivity/risk. In a passive deployment the system could be turned off during periods of flooding where gradients are reversed.

Groundwater bypass and boundary conditions controls can be operated actively by pumping the water from the clean area to the target area or passively by simply connecting an area of clean upgradient/upstream water to the target location.

A passive strategy requires a reliable and sustainable head, or pressure, difference to provide the motive force for moving the water – when operating a groundwater bypass (“geosiphon”) in a passive mode, the system would lower upgradient head and increase downgradient head, thus reducing driving force of water moving though the contaminated area and providing passive isolation or partial stagnation of the contaminants. Based on the historical data, the available head for a passive strategy is nominally in the range of 10 ft. This relatively small head difference and significant seasonal flooding suggests that a passive-only groundwater bypass strategy may not be viable at Moab (but could be evaluated using the site model).

An active pumping strategy (using either clean upgradient groundwater, treated groundwater, or upstream river water) would be viable at Moab. Because this is an active strategy, the team might consider it to be an interim measure in the GCAP development – a technology to strategically protect critical habitats in the river as additional actions are implemented that provide passive or semipassive long term risk management.

Graphic(s):

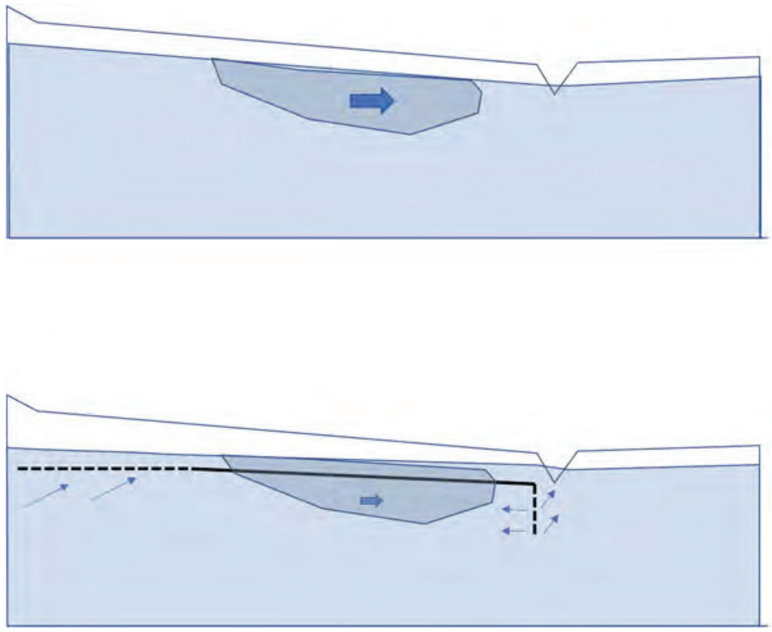


Figure 1. Notional-simplified depiction of baseline conditions above and groundwater bypass below – the water relocation could be done passively based on available head differences or actively using pumping. In this scenarios, the gradient and efflux of contaminated water and the associated contaminated mass are reduced by the action.

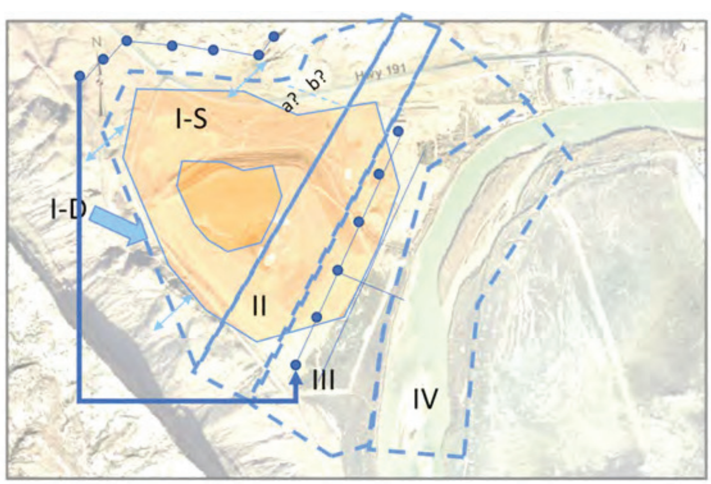


Figure 2. Example of some of the potential Moab Wash bypass and hydrological control Options and how these relate to notional adaptive site management spatial zones.

Match to Moab Conditions:

This technology is generally suited to Moab for an active bypass or boundary conditions modification system – Moab team is currently operating a system using upstream river water. Consideration of a passive deployment may not be viable for Moab -- requiring confirmation of sufficient and sustainable head and the ability to provide access and infrastructure. Note that strategies based on continuous bypass or near-river infiltration of clean water are not compatible with GCAP flushing since these actions slow the efflux contaminants from the groundwater. Thus, continuous flushing would not be used if contaminant flushing and removal are the core strategies in the GCAP. If the Moab site is divided into zones for optimizing technology matching, as part of an adaptive site management strategy, then the water from bypass or the river could be injected along the upgradient boundary of a target strip near the river to maximize flushing of that zone. Bypass and boundary condition modification would be a useful and perhaps key passive/semipassive technology if the core strategy(-ies) in the GCAP are: a) contaminant sequestration of residual and secondary sources, and/or b) control of the releases and mass flux to the Colorado River and Critical Habitats. Conditional or seasonal operation based on protecting critical habitats during sensitive periods would be a potentially useful management strategy and this type of temporal implementation could be done in combination with any core GCAP strategy.

Implementability:

Relatively straightforward to implement. Relatively mature using standard technology. Limited implementations based on passive bypass.

Sequencing prerequisites and data gaps/needs:

Initial step would be to simulate a range of options using the numerical model (tier 2). Recommend performing this type of simulation as soon as possible (coincident with the development of the model).

Timeframe:

Tier 2 for simulation, Tier 3 (medium term) for active systems to tier 4 (long term) for passive systems if viable.

Technology Inter-Relationships:

Simple and straightforward. Requires implementation of modeling recommendations. Works well with all sequestration ideas. Works well with adaptive site management and proposed zonation. Does not work with flushing only or enhanced flushing only GCAP concepts.

Synopsis and Consensus:

Consider including in portfolio.

Topic: Reconfigure Channel of Colorado River and Moab Wash

Long List Item / Objectives:

Team 3 – Boundary Conditions Controls -- Reconfigure channel or wash to protect critical habitat from the efflux of contaminants from Moab groundwater. Potential deployment scenarios include: a) restructuring the current channel/influents to provide spawning habitat during critical times of the year in areas that are unimpacted by the plume, or (alternatively) b) rerouting the channel further from the site (restoring a more natural river course and abandoning the current "artificial" channel location that was engineered to bring water closer to the mill site).

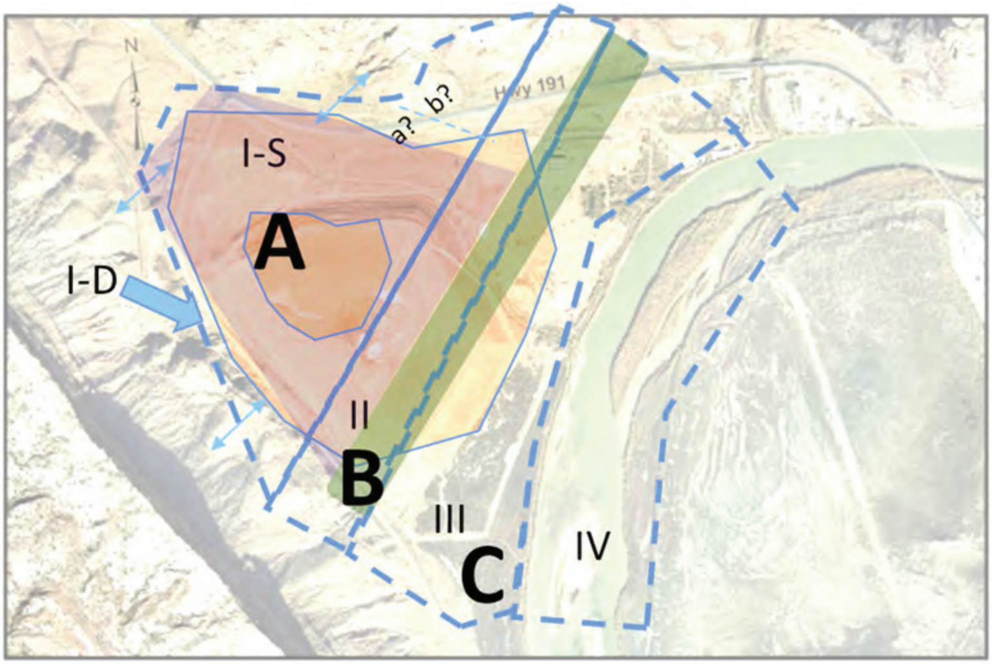
Description:

The current channel represents an anthropogenically modified river course that was previously engineered to bring the Colorado River closer to the millsite (to provide easy access to water for milling and sluicing operations). The current "modified-engineered" river path resembles a mature oxbow. Thus, the water flowing through this serpentine river stretch is actively eroding and depositing sediments resulting in dynamic and shifting zones of critical habitat. The Moab Wash which feeds the Colorado River in this reach has also been modified by mill operations and anthropogenic activities – eliminating the natural braided stream hydrologic system. Braided streams are active and evolving systems that respond to changing and fluctuating hydrologic conditions. The Moab site is currently planning to restore a natural braided stream character to the Moab Wash as part of the post-millsite transition activities. This activity provides another opportunity for risk reduction and mitigation – for example by biasing the inflows into areas where the clean surface water would have maximum beneficial impacts. Some of the technically defensible strategies for reducing risk and protecting human and ecosystem health would include a) reconfigure/restructure the channel to provide more robust and stable critical habitat located in zones where there is minimal hyporheic impact from Moab plume groundwater, or to b) reroute the channel to follow a more natural historical path – thus increasing the distance between the former millsite and the river (providing additional space for implementing remedial action). The engineering of the Moab Wash reconfiguration scenario would need to be done in the context of a dynamic and responsive braided stream system (e.g., allowing the braids to naturally meander in response to erosion and deposition while providing engineering that delivers water in a beneficial manner to the river and possibly providing engineered channels for extreme flooding conditions). One example of how the Moab Wash restoration could be coupled to the plans for Adaptive Site Management are depicted and described in Figure 2. In the rerouting scenario, the longer flow distance and time would provide a primary risk reduction mechanism, but secondary opportunities include beneficial use of the current river channel to support deployment of a permeable reactive barrier that would intercept and reduce the long term flux to the River.

A project is already planned for restoration of the Moab wash (inlet and braided channel entering Colorado river in the area of the former millsite) to be more representative of pre-millsite conditions. Potential reconfiguration options should be coupled with this already planned activity**.**

Graphic(s):

Figure 1. Premill aerial photo (1953).



Example of potential Moab Wash Reconfiguration Design Zones superimposed on notional spatial Adaptive Site Management Areas

A (purple) – Area where infiltration could be discouraged in areas of vadose and shallow groundwater contamination (areas with residual and secondary sources) to decrease source mass flux) – this could be done by creative design of the initial guiding of the braded stream system and/or by deploying lithification agents

B (green) – transition areas where a surface low or ponded area could be designed to buffer the flow of water, to provide water for flushing the shallow groundwater near the river, and to help assure even distribution of water to the near river braided stream system

C (clear) -- area configured to allow for a natural hydrodynamically controlled and evolving braded stream system

Figure 2. Example of Moab Wash Reconfiguration coupled to Adaptive Site Management.

Match to Moab Conditions:

This is a conceptually interesting idea that could be explored with the regulators & subject matter experts from the state of Utah. A simple reconfiguration might be challenging because the current anthropogenically modified river channel is not stable and is subject to hyper-natural erosion and deposition. This would challenge the deployment of stable critical habitat zones and result in the need to work against some of the dynamic processes that are currently active in the river channel. The more aggressive rerouting has the potential to provide a more stable channel with less dynamic erosion and redeposition. However the rerouting would require significant planning and time and close coordination with regulators and the public. The most viable option in the near to mid-term is considering the overall risk reduction goals in the design and implementation of the planned Moab Wash restoration.

Implementability:

Implementable using standard engineering and ecological principles.

Sequencing Prerequisites and Data Gaps/Needs:

The Moab team that is currently planning for the Moab Wash restoration needs to be provided information on erosion and deposition processes in the River, the location and dynamics of critical habitats, and protective criteria for these habitats, as well as how the influent water from the wash can interact to beneficially (or adversely) impact risks to the river. Consideration of this bullet list of information during the planned restoration activities is recommended. For the medium and long term, inclusion of modeling scenarios that envision other types of river reconfiguration and relocation are recommended. The extreme case of significant river relocation into the preserve area is unlikely, reducing the priority of this effort compared to some of the other technologies in the remediation portfolio. However, this strategy should remain in the portfolio for inclusion by the Moab team in the long term adaptive site management GCAP strategy if needed.

Timeframe:

Medium term (Moab Wash) -- long term (Colorado River).

Technology Inter-Relationships

For optimum performance, this concept would need to be considered and implemented with simultaneous evaluation and consideration of other boundary conditions controls (e.g., groundwater bypass and other clean water injection strategies).

Synopsis and Consensus:

Moderate to low priority but should remain in the portfolio.

Topic: "Green" Construction Technology for Surface-Capping, Flow Barriers, Channel Containment, Surface Ponds and High Load Capacity Road Infrastructure

Objectives:

Many of the Moab Site Restoration measures will require technological solutions that aim to control site- and near-field boundary conditions to help mitigate further contaminant migration to the accessible environment and serve as barriers, flow channels or ponds. In addition, access to Moab Restoration construction sites will require building access roads that can support heavy equipment and/or withstand a range of weather conditions and uses. To address the challenges of Moab Restoration, environmentally sound and cost-effective solutions are needed. This requires the use of "green" materials that are simultaneously non-toxic, mechanically strong and durable, as well as UV and freeze-thaw resistant, and cost effective. Traditional industrial standards utilize cementitious materials and fossil-fuel products such as tars, asphalts and plastic liners as building materials that cannot meet all requirements, are expensive to produce or maintain, and associated with a large carbon footprint due to transportation and/or greenhouse gas emissions. The objective here is to introduce a new cost-effective, low carbon footprint, "green" accelerated lithification technology LithTec™ that has been recently developed by the private sector and is adaptively engineered and shaped from locally sourced soils and rock aggregates, to form rock-hard materials on location.

Match to Moab Conditions:

The geology and soils in the Moab area are well suited for the soil and aggregate accelerated lithification process described. The LithTec™ process has been successfully applied to a range of materials from the Southwestern (TX, AZ, NM, CO, UT), Western (CA, WA), Southeastern (LA) and Eastern (NC, FL) United States [1]. Hawaii, New Mexico DOT and other projects are projected for 2023. This technology can be used to support the construction of several Moab Restoration projects and projected Adaptive Site Management (ASM) activities for different Restoration Zones [Figure 1]. Applications are suitable for, but not limited to, the following collaborative Team Narratives:

1) Building an environmentally sustainable road infrastructure for Moab Restoration Projects. This will support the mobilization of heavy equipment and vehicles during construction, monitoring and adaptive site management activities. This water-resistant lithified road surfacing and base course foundation technology can provide reliable site access, and suppress dust, mud and pothole formation. It is also cost effective compared to traditional road construction and maintenance [1] (All Site Area Zones).
2) Capping the Moab post tailings removal footprint with an impermeable LithTec™ Surface. This represents a "green" barrier to infiltration from surface precipitation, after removal of the U-mill tailings circa 2025 (ZONE A). The lithified earth cover is a

mechanically strong, and durable rock-hard layer designed with a low hydraulic conductivity (10-9 meters per second [m/s] to 10-10 m/s). It mitigates erosion triggered by extreme precipitation events and freeze-thaw conditions, suppresses dust formation, and acts as a barrier to surface water infiltration. In the case of mill tailings, it can be designed to block Ra-226 gamma radiation while allowing Radon-222 gas to vent upwards from the contaminated footprint surface at low concentrations that meet regulatory air quality standards and shield humans and animals from radiation exposure. This technology can help (i) mitigate the remobilization of subsurface contaminant plume(s) beneath the surface footprint of the mill tailings by water infiltration, as well as (ii) prevent the formation of new secondary contaminant sources, and (iii) mitigate surface erosion, and seasonal dust and mud formation.

3) Construction of a non-toxic barrier impermeable barrier wall in Transition Zone B. This vertical wall structure could reduce risk by mitigating subsurface transport of GW contaminants to the Colorado River. A trench can be filled with a lithified, bubble-free slurry of finely crushed local soil and aggregates as currently used to build algae biofuel ponds [4][5]. When fully water saturated, this LithTec™ slurry cures in place within 28 days into a very strong (UCS>10 MPa), non-toxic, crack-free single wall block with a very low saturated hydraulic conductivity (Ksat < 10-9 m/s).

4) The construction of containment channel(s) or other engineered infrastructure designs. These could provide either active or passive/sustainable modifications to the hydrologic boundaries/conditions for risk reduction, as presented by Team 1 [Groundwater Bypass and Hydrologic Controls] for the proposed restoration of the Moab wash into a former braided stream system (Figure 1, ZONE 1-Sa,b). A single LithTec™ channel or several channels can be built to accommodate changing flow rates and/or mitigate the effects of excess runoff from extreme precipitation events or Spring snowpack melting and flooding that would alter the braided stream morphology and potentially result in its destruction.

5) The construction of impermeable "green surface pond system" to support Limited Term Pump & Treat solutions. This narrative proposed by Team 3 would recover contaminated groundwater and pump it into containment ponds for treatment. For this option, LithTec™ Earthliners could replace plastic pond liners as an eco-friendly, impermeable, freeze-thaw and UV resistant pond liner system into which removable amendment screens could be placed for filtration and permanent removal of dissolved uranium (uranyl) and NH3/NH4 contaminants, and/or used as evaporative ponds for ammonia.

Description:

This technology was originally developed from 2011-2018 by Lithified Technologies-US, LLC to replace greenhouse gas producing cementitious and fossil fuel products currently used worldwide for infrastructure projects [1]. It has been successfully applied to commercial roadway reclamation projects (chip seal and basecourse) construction in the US over the past 5 years using different soils, volcanic cinders and aggregate rocks, clays, sands (Archuleta County, Pagosa Springs, CO; San Juan County, UT; Navajo Nation; NMDOT, Santa Rosa, NM; Union Pacific Railroad yards, CA). It has recently been approved for road reclamation by the Texas DOT (March, 2023). In addition to traditional road and reclamation basecourse applications [1][2], the LithTec™ product is being engineered and tested for other environmental and energy applications. Lithified Technologies, U.S. has also developed improved solutions for capping Abandoned Uranium Mines (EPA Region 9, Navajo Nation) [3], and in partnership with Los Alamos National Laboratory and The Santa Fe Community College (SFCC), NM, LithTec™ has successfully completed a combined laboratory/outdoor pilot study on algae biofuel production using LithTec™ Earthliner ponds in lieu of plastic pond liners [4][5]. In addition to being strong, non-toxic, impermeable, and UV and freeze-thaw resistant, LithTec™ Earthliners are lower maintenance, more durable, and 2x cheaper to manufacture [1].

The new lithification technology can be scientifically engineered for site-specific applications (Figure 2; Table 1) and can be implemented as a multilayered surface cover of lithified aggregate and soil mixtures and/or lithified impermeable slurries that combined can meet a range of mechanical, hydrologic, and environmental requirements (Figure 2, Table 1) [1]. Because the lithification process can be controlled to produce either permeable or impermeable materials these formulated products can be used to obtain “rock hard”, permeable products by cementation, with solid amendments (e.g., Zeolites±apatite±Fe^0, etc.) to filter out (adsorb) dissolved contaminants such as uranyl ions. For commercial roadways or access roads for example, LithTec™ formulations are engineered into two lithified layers with different mechanical properties [1][2]: a 6 - 12 inch locally sourced base course foundation, and a thin, strong surface layer that together provide mechanical strength, plasticity, and durability for heavy traffic loads. For agricultural and algae biofuel ponds, fine soil and aggregate slurries are molded in place and lithified to form non- toxic, impermeable, mechanically strong, UV and freeze-thaw resistant pond liners that replace plastic liners at a fraction of the cost.

Graphic:

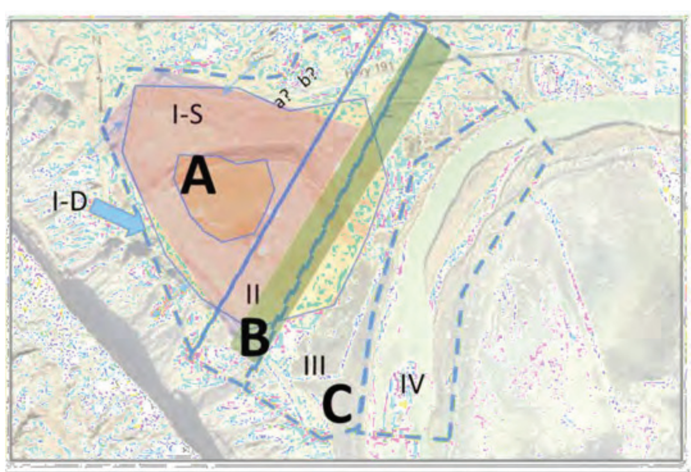


Figure 1. Moab site Zones superimposed on notional ASM areas I-S, II, III and IV.

- Zone A. Area where infiltration could be mitigated in areas of vadose and shallow GW contamination (w/ residual secondary sources) by capping tailing footprint surface (post removal) and/or restoration of braded stream configuration with additional channels for flooding controls.
- Zone B. Transition area between Zone A tailings footprint (near surface contamination) and Zone C that abuts the Colorado River. This low, potentially ponded Area could be used to mitigate the flow of contaminated water from the Moab tailings footprint site (Figure 1, Zone A) using a buried vertical barrier wall (green; ASM Area II) and/or serving as a clean water containment site in ponds for flushing the shallow groundwater near the river.
- Zone C. Area configured to allow for restored, hydrodynamically controlled end evolving braided stream system development.

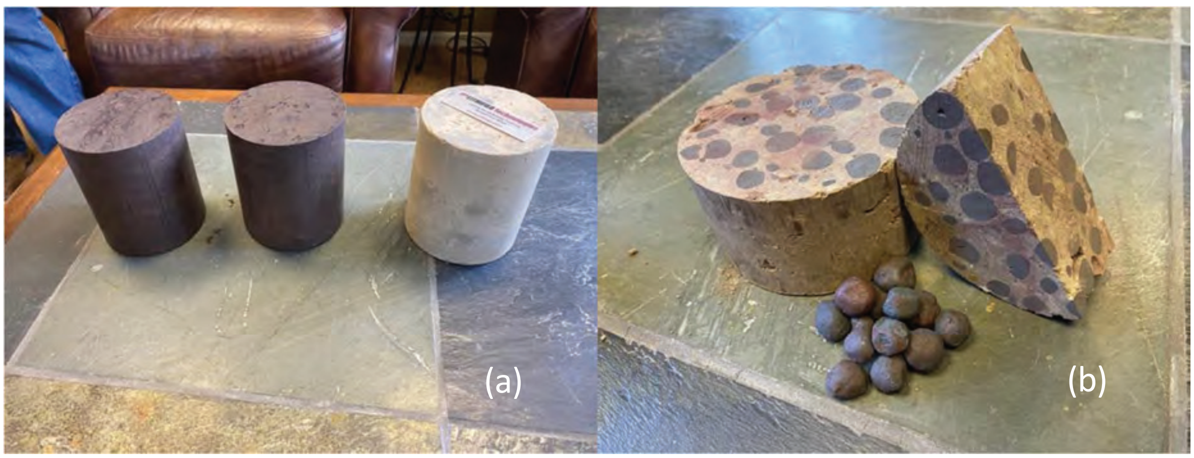


Figure 2. Examples of soil and aggregate lithification using the LithTec™ process. (a) Two lithified cylinders of Bauxite residue (dark brown cylinders), and Rio Tinto copper and gold tailings (tan cylinder). (b) Nucor Steel, lithified swampland soil of sand, silt and clay mixed with iron oxide balls from steel processing that had sunk into the mud. Results on the mechanical properties of the lithified cylinders in Figures 2(a) and 2(b) are shown in Table 1. (All samples have passed EPA Technical Procedure Tests for TCLP and SPLP, Synthetic Precipitation Leaching Procedure).

Table 1. Geotechnical Reports: LithTec™ Resilient Modulus (MR) and Compressive Strength (UCS) for lithified cylinders from various US Projects.

1. Cinder, AZ Project (volc. cinders): Stone fragment Gravel & Sand (ASHTO Class. A-1-b).
   - *Design Min. Req.:* M_R = 100,000 psi / *UCS* = 300 psi
   - *LithTec™ 5%:* M_R = **607,196** psi / *UCS* = 624 psi
2. NuCOR Project LT-US-022-00103 (swamp): Clayey Gravel & Sand (ASHTO Class. A-2-6).
   - *Design Min. Req.:* M_R = 100,000 psi / *USC* = 250 psi

- *LithTec™ 3%:* M_R = **455,320** psi / *USC* = 775 psi

3. Kennecott Rio Tinto Project UT-019-00102 (mine tailings): Silty soils (ASHTO Class. A-4).
   - *Design Min. Req.:* M_R = 100,000 psi / *UCS* = 300 psi
   - *LithTec™ 5%:* M_R = 569,017 psi / *UCS* = 500.7 psi
   - *LithTec™ 7%:* M_R = **920,235** psi / *UCS* = 707.4 psi

Match to Moab Conditions:

This "green" technology has been engineered to be flexible, environmentally sustainable, and simultaneously satisfy a large range of mechanical and hydrologic property requirements and environmental constraints. It is also well suited for on-site construction (low transportation carbon footprint), and its use of local soils and rock aggregates makes it cost effective as material transportation costs are minimal. The LithTec™ material could be used to meet several Moab Restoration needs including but not necessarily restricted to the applications described above. The lithification formula can be adapted to site specific mineral compositions and soil pH buffering capacities, and successfully used on silicate and carbonate rock aggregates, clays, silts, sands without, or with amendments to enhance uranium sorption capacity under saturated conditions (i.e., Kd >400L/kg, in pH ?7 buffered systems) [3][6].

Implementation:

Recent and current projects can be used as exemplars for the implementation of the LithTec™ lithification process to Moab Restoration activities. Though a novel technology, it is already successfully used in a number of US localities - with a range of soil and aggregate compositions – for road reclamation and construction, tailings capping (gold and copper mine tailings, Kennecott Copper mine, Rio Tinto, UT), and lithification of talc-like bauxite mine residues and clays (Kaiser Aluminum Bauxite), volcanic cinders (Flagstaff, AZ), and iron oxide balls (Nucor Steel, Charlotte, NC) [Figure 2a, b]. Based on the Technology Readiness Assessment Guide, Appendix F Tables [11] the TRLs for this technology are specific to the applications and subject to preliminary lab testing* (soil sampling, mechanical testing) [2][3][7][8][9]; and chemical analysis [10] for design prior to construction.

- TRL 8-9: LithTec™ chip seal or asphalt/concrete road surfacing and lithified road base foundation for high load capacity road construction for all seasons, wet and dry climatic conditions, and heavy vehicular use. Local dust and mud suppression for all Moab Zones (Figure 1) and surroundings.
- TRL 7-8*: LithTec™ Earthliner aggregate and soil lithification for post-mill tailings using "green" single or multilayer impermeable surface capping of Zone A (Ksat < 10-9 m/s) [4].
- TRL 6-7**: LithTec™ lithification of Moab aggregates and soils for impermeable, vertical "green" wall barrier construction in Zone B to mitigate subsurface GW contaminant

transport to Colorado River from Zone A.
**Lower TRL reflects the need for (i) design testing of stand-alone permeable barrier wall and, (ii) optimization of lithified slurried aggregate soil composition for optimal strength and low hydraulic conductivity.

- TRL 6*** : LithTec™ impermeable (Ksat<10-9 m/s) Earthliner pond for pump & treat of contaminated groundwater. The LithTec™ pond Earthliner technology has been successfully developed and tested in the laboratory over a period of nine months in 2021 [4], and in a subsequent continuous open air algae biofuel production pilot test in 2022, during the summer-fall-winter months [5].
***TRL is associated with designing an outdoor pilot test specific to the Moab site conditions to optimize the combined liner properties of mechanical strength, durability, low saturated hydraulic conductivity, and freeze-thaw resistance.

Technology Inter-Relationships:

Strong interrelationship with the development of an adaptive management strategy including combined and sequential remedies and connected to surface and in-situ sequestration goals.

Team 1 - Adaptive Site Management (ASM); Team 3 - Groundwater Bypass and Hydrologic Controls; River and Wash Reconfiguration; Interim Pump and Treat.

1) Containment and filtering in surface ponds associated with pumping/flushing (Zones B, C).
2) Barrier to infiltration from surface precipitation (Zone A).
3) Containment channel(s) construction in conjunction with the proposed restoration of the Moab wash into a former braided stream system (Zones B, C).
4) Construction of a non-toxic barrier wall in Zone B to help mitigate contaminant transport from Moab contaminated site boundaries (Zone A) to the Colorado riverbed (Zone C).
5) Site infrastructure construction of cost effective, "green" roads that allow vehicular access the site for Moab Restoration and monitoring (All Zones, Figure 1).

Sequencing Prerequisites and Data Gaps/Needs:

Tier 1 (2023) – In addition to laboratory testing and design, the on-site lithification of soil and rock aggregates for road construction will involve the use of trucks and heavy equipment to excavate surfaces, distribute the aggregate mix, and compact it.

In terms of barrier construction, 2-D scoping modeling is recommended for tailing footprint design and construction, as well as sampling and optimization of lithified formulation for Moab soil compositions using a proprietary formula tailored to produce an impermeable, rock-hard product that can be made and cured on-site.

In the case of barrier wall construction, this could involve producing the slurry in a nearby facility and delivering it to the site by truck, otherwise all materials are locally sourced within the Moab site area or nearby vicinity.

Tier 2 (2024 to 2025) – If one or several Lithified Earth applications are selected for inclusion in the phased GCAP, we recommend that existing sites be visited in the case of road construction applications and that implementation of a Pilot Project be used for the purpose of technology demonstrations.

Tier 3 (2025-2035) – In the case of barrier cover applications, an ongoing monitoring program should be implemented as part of an Adaptive Management Strategy.

Timeframe: (application dependent - need to contact company).

Road Infrastructure Applications (TRL 8-9): Tier 2 and Tier 4, immediately available. Timeframe depends on road specifications and weather and is commonly seasonally restricted to a 9 month period (Spring through Fall). Following on-site soil sampling, testing and analysis for road design (1month), roadbed preparation involves on-site excavation-reclamation/pulverization/mixing prior to lithification/compaction/surface emulsification. This roadbed prep activity averages to 3-4 weeks per mile and is followed by on-site lithification, compaction, and final road surfacing (1,000 ft/day). Road basecourse foundation and surface emulsion curing require an additional 24-48 hours.

Impermeable surface applications for capping, ponds, barriers, and channels (TRL 6-8): (Tier 2 and Tier 3)Timeframes are application-dependent, but the capping technology (TRL 7-8) is similar to the road infrastructure process in that it is multilayered and can accommodate large vehicular loads if requested (Tier 2; post 2025 tailings removal). The basecourse foundation can also accommodate amendments if required. Construction and curing times are identical and for optimal conditions the timeframe can vary anywhere from 2-4 years including a 1-year pilot test. The Lithified Earth barrier hydrologic, mechanical, and gas diffusivity properties are currently being quantitatively determined in laboratory studies in conjunction with model simulations to assess barrier performance.

Synopsis and Consensus:

Consider including lithified earth technology in portfolio and implementing road construction technology early on to support use of heavy vehicles on site and suppress mud and dirt formation.

Reference List:

Lithified Technologies Website and Geotechnical Reports: www.LithTec.com

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TRL: Technology Readiness Assessment Guide, Appendix F Tables. DOE G 413.3-4A, Approved 9-15-2011, U.S. Department of Energy Washington, D.C. 20585 www.directives.doe.gov

Topic: Interim Pump and Treat

Long List Item / Objectives:

Team 3 – Limited-term activities to mitigate risk and release of contaminants, and attenuate source terms -- Objectives are to: a) provide a limited mid-term option for controlling pumped groundwater following tailings relocation prior to long term sustainable (passive) management strategies, b) develop technology strategy to manage water in the scenario where dust suppression is no longer needed, and c) minimize secondary wastes and provide a source of water that can be used for minimizing plume discharges (boundary condition controls) and/or for deploying reagents for processes such as in situ sequestration. The overarching goal is to limit plume expansion (i.e., limit efflux of ammonium, uranium and other contaminants) to the Colorado River and provide contaminant removal and groundwater concentration reduction during the period in which long-term passive solutions are being developed and implemented.

Description:

Currently, contaminated water is being pumped and dispositioned away from the river – used as dust suppression during tailings removal and relocation operations. As the tailings relocation is completed, dust suppression water needs will decline. However, it may take many years to refine and implement long term passive plume management and risk reductions strategies (such as in situ sequestration, permeable reactive barriers, groundwater bypass, and others). During this period, some active pumping-based plume control may be needed or considered by the Moab team. Developing a pathway for the pumped water as well as integrating the pumping objectives into an overall GCAP plan for the site are keys to supporting such an interim pump and treat. There are a number of potential water disposition (treatment) options for Moab contaminants and bulk water chemistry. Notably, some options, such as using the water for irrigation to take up ammonium are not optimal because of a number of constraints: the high specific conductance (salt) levels are not compatible with sustainable irrigation standards, there is limited land area for irrigation planting, and the planned restoration of the Moab Wash braided stream ecosystem is not compatible with plantings needed for irrigation. There are some viable and commercially available technologies that have moderate to low operation and maintenance costs such as adding carbon substrates and removing ammonium in a biotreatment lagoon – however the startup costs for these or any other treatment-based pump and treat are significant, and all such strategies would generate secondary wastes that would require disposal. In the specific case of a biotreatment lagoon, integrating ammonium and uranium removal has been challenging (a challenge identified by Rocky Flats), and the quality of the treated water is not optimal for beneficial use in meeting related subsurface needs since the treated water tends to have relatively high levels of residual organic carbon and biomass.

Two treatment scenarios are described below – one focuses on complete treatment, and one focuses only on uranium treatment. Both scenarios would be designed with sufficient capture (water extraction) to provide interim control of the plume mass flux to the Colorado River. The complete treatment scenario would be significantly more expensive to build, operate and maintain, but provides more options for beneficial use of the treated water. A uranium only scenario is less costly but could be used to provide product water that could be used as the base for in situ sequestration reagents.

A notable example scenario for optimized water treatment and disposition might be to apply air stripping to remove ammonia and then use a mineral based sequestration for uranium on the remaining water (Figure 1). The air stripping process has been documented and is commercially available at scale – used to treat wastewaters from livestock and industrial operations. In this strategy, the ammonium would be separated from the uranium for separate handling and disposal. As depicted in Figure 1, the process involved increasing the pH (e.g., using CaOH, MgOH, NaOH or similar alkaline reagent to bring pH up to approximately pH 11 – this converts the ammonium to ammonia) and then stripping the ammonia gas from solution using air – the ammonia then treated separately in the gas (air) phase. Typical removal efficiencies of ammonium for commercial systems are in the range of 80%. In industrial and livestock operations, ammonium, in large amounts, may be scrubbed from the gas using acid. In these commercial applications, sulfuric acid is used resulting in a byproduct ammonium sulphate solution which is sold (e.g., fertilizer manufacturer) or disposed as a waste material. In the case of Moab, the ammonia concentrations are lower, and a more suitable treatment might be thermal-catalytic conversion of ammonia to nitrogen which can be released to the atmosphere. This catalytic process is more expensive to build (due to the high cost of the catalyst that contains precious metals) but this flowsheet eliminates the ongoing costs for handling and disposing of ammonium related wastes). Following air stripping, the water contains the remaining primary contaminant, uranium. After recovering heat and lowering the pH of the pumped water to a desired target (e.g., 8) the uranium could be removed from the ammonia-stripped water by contact with hydroxyapatite minerals, bone char or another bioapatite, or a number of other removal technologies – ion exchange might not be optimal for Moab because of the high specific conductance of the water at the site. Additional information on potential bioapatite amendments is provided below.

Two forms of bioapatite have shown promise for uranium removal from representative DOE groundwaters – 1) ApatiteII (fish bones and hard parts – see http://www.pimsnw.com/) and 2) granular (cow) bone char prepared for water treatment (see Figure 2). Granular bone char is used for water treatment (aquarium filters, industrial sugar syrup, etc.). Both of these materials have demonstrated effective removal of uranium – with data indicating better performance at higher pH. Granular bone char is an apatite-based solid that is consistent from batch to batch – bone solids are treated to 400-500C in controlled oxygen conditions. This is sufficient to remove most of the organic matter and results in a desirable apatite crystal structure for metal removal and a small amount of residual activated carbon. Bone char materials that are prepared from cow bones at higher or lower temperatures and/or without oxygen control have not performed as well for metals removal. An example material for consideration is Reade granular bone char (“Bone-Black” -- https://www.reade.com/products/bone-char-granular-bone-black). The nominal cost for both ApatiteII and granular bone char material is approximately $5 per lb. ($2 to $10 per lb. depending on quantity and packaging).

Following uranium removal, the treated water would be high quality and suitable for reinjection to help control plume migration. If this system was carefully designed, the treated water could be adjusted to support in situ sequestration or enhanced flushing. The treated water solution could easily be adjusted using phosphate and citrate and other components as needed to provide a chemical recipe similar to that being tested for uranium sequestration by hydroxyapatite and appropriate for ammonium sequestration as struvite. By integrating in this way, a strategy for interim pump and treat that is actively moving the site to a stable passive sequestration condition could be implemented. All these steps can be performed with commercially available equipment. Factors such as the potential for scaling should be considered in the design – so membrane-based processes might be problematic due the potential for pore clogging -- open channel designs that are easily cleaned could be emphasized.

The appended graphic is a conceptual diagram that depicts the treatment process described above. Preliminary calculations for a 100 gpm system (with information on ammonium stripping provided by Branch Environmental – a commercial vendor for ammonia stripping systems). Assuming that the water is well behaved during pH adjustment and heating and does not form significant amounts of solids for separate handling, the treatment system comprises three major unit operations: air stripping, air treatment and uranium removal along with a number of water handling and preconditioning steps. The air stripping requires preheating of the water to 40 C and pH adjustment to 11 followed by contact with air (16,000 cfm) in a stripping tower (20 ft tall). The air treatment requires preheating of the air to approximately 500 C and contact with a selective catalyst bed for converting the ammonia gas to nitrogen. The water containing uranium is pH adjusted (to approximately 8) prior to uranium removal using mineral or bioapatite (or a similar process) -- this will generate a uranium contaminated waste stream for disposal. Previous studies suggest realistic loading onto bioapatite in the range of 5000 mg U / Kg of media. The treated water would be suitable and available to support related GCAP objectives. The Capital cost for implementation of this system is significant (scoping estimate of $2,000K to $3,000K) and the operation and maintenance costs are in the moderate range (approximately $20 / 1000 gallons). The highest contributing costs would be energy, labor and disposal of the uranium waste stream. Energy costs in this scoping calculation were optimized using heat exchangers but the heating of the water and air would still require approximately 5 MBTU/hr (40% for the water and 60% for the air). If significant solids are generated in the water at any stage of the treatment, system costs and complexity would increase. Thus, consideration of this idea would benefit from near term geochemical modeling and laboratory ("jar") testing that would inform a more complete and robust design and support a more accurate cost estimate for implementation and for operation and maintenance.

Graphic(s):

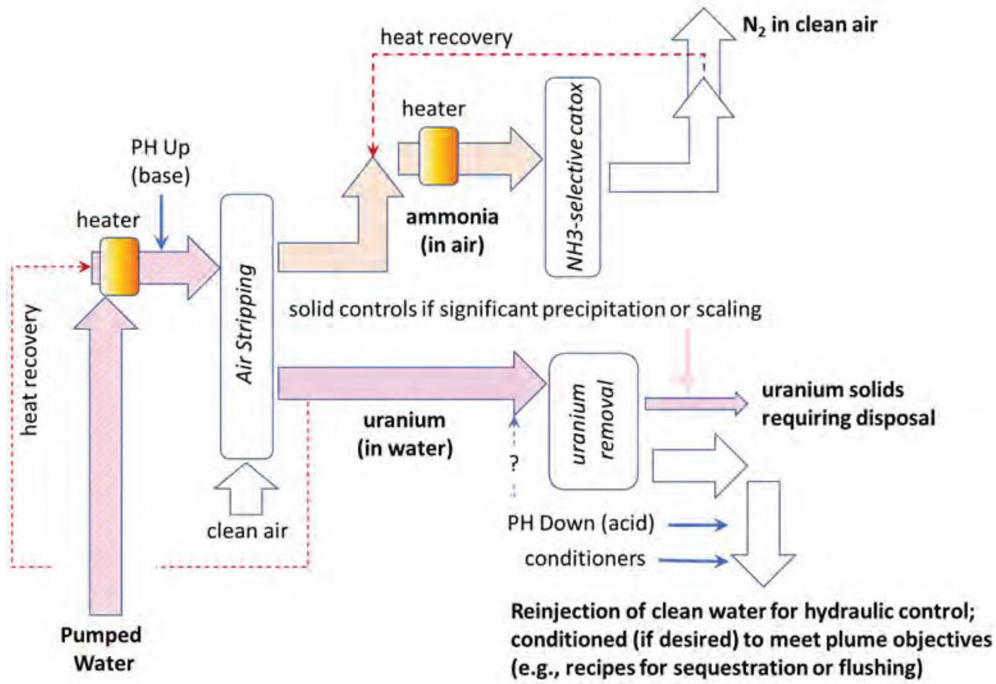

Figure 1. Simplified schematic of treatment system that focuses on separating ammonium from uranium, providing high quality water for beneficial related GCAP uses, and minimizing secondary wastes.

Figure 2. Two key exemplars of Bio-Apatite media – Apatite II (left) and Bone char (right).

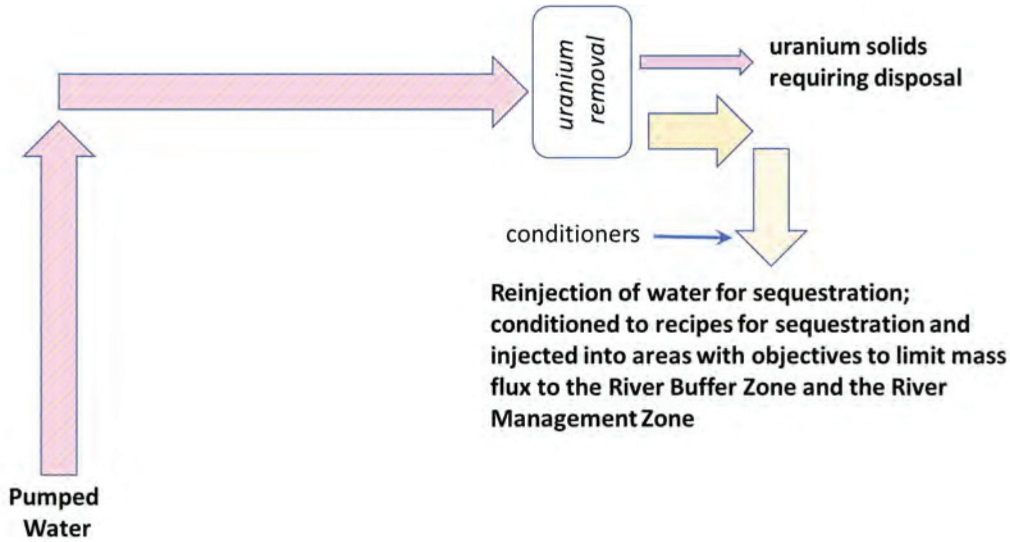

Figure 3. U-only Treatment Scenario using traditional facility-based deployment. This could also be done using surface impoundments with sorbents that are designed for removal and disposal as secondary waste.

Match to Moab Conditions:

This strategy is a reasonable match to the challenging Moab conditions such as mixed contaminants in water with intermediate levels of specific conductance. Further, this strategy provides: a) a possible tool to navigate a mid-term need for the site (providing some control on groundwater after the tailings removal is complete and dust control is no longer needed), b) a source of high-quality water that can be used to limit flux to the river or to sequester residual sources, and c) a treatment that minimizes secondary wastes.

Implementability:

Implementable using standard engineering. Would require significant investment to implement. Each unit operation has a relatively high TRL (6 to 9). A few data gaps need to be addressed before a final decision is made on this concept. Importantly, testing is needed to assess if solid precipitation or scaling of equipment will cause significant operational challenges.

Exemplars/References:

The use of ammonia stripping is well documented (see for example https://www.branchenv.com/) – example commercial systems of similar scale to Moab are depicted below (Figure 4):

Figure 4. Commercial air stripping tower (left) and catalytic oxidizer (right).

Uranium treatment options for similar water were previously evaluated for Rocky Flats (see: Looney, et al., 2019). Other relevant studies listed below have examined bioapatites including fish bones, generic “bone char phosphate” and mineral hydroxyapatite for uranium treatment.

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Technology Inter-Relationships:

Strong interrelationship with development of an adaptive site management strategy Including combined and sequential remedies) and potentially connected to in situ sequestration efforts (apatite, humate and struvite).

Sequencing - Prerequisites and Data Gaps/Needs

Tier 1 (2023) – Recommend scoping modeling of potential for solid mineral formation during treatment -- using a standard software package such as geochemist Workbench, PHREEQC, OLI, or similar. Recommend scoping laboratory "jar" testing including pH adjustment and heating to assure that water will not generate precipitates, solids and/or scale that would interfere with system operation. Recommend scoping testing of ammonia stripping performance and testing on Moab specific water conditions as a function of pH to evaluate uranium removal options and potential loading of uranium on alternative sequestration solids (supporting engineering estimates performance and material service life as well as operating and waste disposal costs). Use available groundwater models to evaluate alternatives for water extraction (location and flow rates) and water injection for plume control and or sequestration objectives.

Tier 2 (approximately 2024 to 2025). If concept is selected by site team for inclusion in the phased GCAP, perform project design and generate a procurement package for implementation following removal of the tailings.

Tier 3 to tier 4 (Approximately 2025 to 2035) – operate system while transitioning to long term passive strategy/strategies.

Synopsis and Consensus:

Consider implementing if active treatments are determined to be necessary as a medium-term transition need.

APPENDIX D:
Additional Resources

Topic: Enhanced Evaporation—Optimized Ponds and Wind/Solar Systems

Objectives: Team 3 – Limited-term activities to mitigate risk and release of contaminants, and attenuate source terms. Objectives are to provide an option for controlling pumped groundwater following tailings relocation prior to long-term sustainable (passive) management strategies. The overarching goal is to limit plume expansion (i.e., limit efflux of ammonium, uranium, and other contaminants) to the Colorado River as long-term passive solutions are developed and implemented.

Description: Currently, contaminated water is being pumped and dispositioned away from the river as dust suppressant during tailings removal and relocation operations. As the tailings relocation is completed, dust suppression water needs will decline. However, it may take many years to refine and implement long-term passive plume management and risk reduction strategies such as in situ sequestration, permeable reactive barriers, groundwater bypass, and others. During this period, some active pumping-based plume control, including enhanced evaporation, may be needed or considered by the Moab team. Enhanced evaporation can be technically achieved in a number of ways, including engineered systems such as the Wind-Aided Intensified eVaporation (WAIV) system, adding enhancements to evaporation ponds, or using irrigation and evapotranspiration (this third option is addressed in a separate narrative).

Engineered evaporation systems are available. One example, the WAIV, is described as a vertical evaporation pond. This system consists of a tower of vertical supports and fabric panels that provide a high density of wetted surface area maximizing evaporation in a small footprint (Figure 1). The systems have been used for solutions with relatively high total dissolved solid (salt) levels. The manufacturer claims many benefits including: lower cost compared to standard evaporation (evaporative energy from wind and sun not fuel); modular "units" (each with a small footprint, 80 feet by 20 feet and greater than 62,000 square feet of surface area); evaporates 2,000 to 5,000 gallons per day per unit; can be used for a range of water quality, such as leachate, reverse osmosis brine, oil and gas liquids, and industrial wastewaters; can be used in a range of climates; and not dependent on water treatment plant. However, the WAIV system has the potential to allow for limited dispersal of contaminants and requires use of chemicals for cleaning precipitated salts and scale from the panels. The cleaning solutions require disposition. Many of the challenges for enhanced engineered evaporation are similar to the challenges for enhanced pond evaporation as described below.

A pond reasonably sized to fit within the Moab site would limit the flow rate of any pumping system and thus limit the effectiveness of contaminant interception and plume control. For example, seasonal winter conditions would limit the practical operating period for evaporation. The specific objective of this narrative is to explore options to maximize transfer of water to the atmosphere and to explore concepts to extend the practical seasonal operational timeframe. Several options are identified as seed concepts for evaluation, including a) insulation/floating cover, b) fountains, c) rain diversion cover and/or air circulation, d) expanded pond surface area, and e) increased pond depth. Of these concepts, the most promising based on triage are use of solar fountains and possibly floating covers. Note that these ideas have potential adverse collateral impacts such as exposure to wildlife (ponds are attractive to waterfowl, amphibians, and fish), potential for airborne spread of contaminants, and potential for accumulation of contaminated scale (e.g., precipitates on floating covers).

This is a straightforward concept that has the potential to incrementally contribute to the disposition of pumped water from the site. A few example concepts are described below.

Solar fountains have the potential to provide enhancement in evaporation and can provide this increase within the limits of small pond footprints. Solar fountains can be implemented quickly for a low cost. Figure 1 depicts commercially available solar powered fountains and a photo of an installation. These systems pump during the day when the sun provides sufficient energy for operating and thus have simple installation and no battery costs or battery maintenance. The list price for a relatively large solar fountain including solar panels is < $10k (for the F1600). An optimized mist type evaporation system could be used, but those are notoriously unreliable due to the small openings and potential for clogging by high specific conductivity water and freezing during the winter. Another disadvantage of the mist system is the potential for wind to blow the aerosolized water out of the pond—the large drops in a standard fountain help mitigate this possibility. Multiple fountains could be implemented to provide additional evaporation as needed.

Floating covers would provide thermal insulation and have the potential to extend the seasonal operating timeframes (Figure 3). A floating cover would be used to maintain a generally higher pond temperature in both the summer and winter via solar heating and insulation and would minimize the period of surface freezing. A secondary benefit of the floating cover is that it would further discourage wildlife from interacting with the pond. Floating covers substantially reduce evaporation so that use of a floating cover would require co-deployment of a fountain system to recover lost evaporation from the open surface and to increase evaporation as needed to keep up with any increases in extraction rates. A potential disadvantage of the cover would be the formation of minerals on the upper surface (a crust of evaporite salt minerals) that would be unsightly and a potential exposure pathway. Floating covers are simply installed —the cover pieces (floating hexagons or balls) are dumped into the pond, and they spread out and self-arrange into the cover. The rough costs of the floating cover material are $250 per sq foot, including transportation. Table 1 and Figure 3 provide summary characteristics for some of the available floating cover materials and a description of one potential material for the evaporation pond are provided below.

Table 1. Example floating cover products.

PRODUCTS COMPARISON	ARMOR BALL®	ARMOR BALL® AQUA	HEXPROTECT®	HEXPROTECT® AQUA	HEXPROTECT MAX R	RHOMB 66
Surface coverage (up to)	91%	91%	99%	99%	99%	99%
Insulation (R factor)	++	+	++	+	+++++	+++
Heating cost reduction (up to)	75%	75%	85%	85%	85%	85%
Evaporation Reduction	++++	++++	++	++++	++++	+++++
Wind Resistant	+	++++	++	+++++	++	+++++
Buoyancy (per sq.ft)	–	–	–	–	–	–
Odor Control	✓	✓	✓	✓	✓	✓
Chemical Evaporation Reduction	✓	✓	✓	✓	✓	✓
Algae Reduction	✓	✓	✓	✓	✓	✓
Bird Deterrent	✓	✓	✓	✓	✓	✓
Snow & Ice Resistant	✓	✓	✓	✓	✓	✓
Quick Install	✓	✓	✓	✓	✓	✓
Maintenance Free	✓	✓	✓	✓	✓	✓
Life Expectancy	25+ Years	25+ Years	25+ Years	25+ Years	25+ Years	25+ Yea
Cost Estimate	$$$$$	$$$$$	$$$$$	$$$$$	$$$$$	$$$$$

Graphic(s):

Figure 1. Installed WAIV system. Wind and enhanced evaporation is enhanced in a small footprint using large surface area panels.

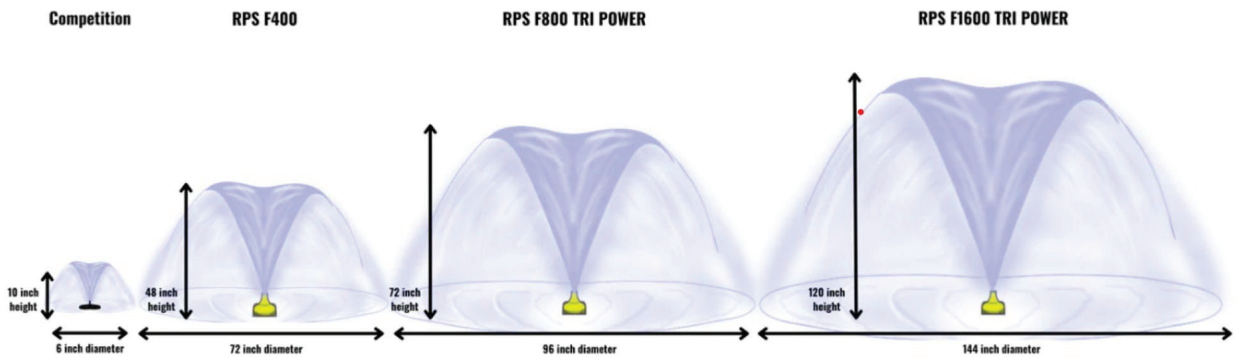

Figure 2. Example solar fountains models and an installed solar fountain.

The Hexprotect® hexagonal floating cover system ensures coverage of up to 99%. The resulting thermal insulation barrier combines the insulation factor of the air held in each tile with the poor heat conductivity of plastic. While the small air pockets between the tiles are not sealed, they also contribute to this insulation system, which dramatically reduces heat loss and light transfer. The cover also reduces liquid loss through evaporation and prevents odor problems.

The Hexprotect® floating cover, contrary to standard covers, does not represent an obstacle to static, moving or dipping equipment. The tiles can be easily pushed aside and the cover reforms itself as the basin and obstacles change configuration, as in a clarifier. In fact, the tiles will keep up with liquid level, rising, lowering and restacking themselves as needed.

The Hexprotect® floating covers are also an effective wildlife deterrent. When entirely covered, the body of water becomes unattractive to waterfowl and other wildlife such as deer. They simply don't recognize it as water.

Compared to netting, Hexprotect® floating covers are not sensitive to ice or snow damage and do not require any kind of support.

Figure 3. Deployment of a hexagonal floating cover product.

Match to Moab Conditions: This strategy may have short term application to Moab conditions and needs. The listed technologies provide the potential for supplemental pump-and-treat volume reduction to meet mid-term needs/objectives. However, all of the systems result in a concentrate stream and/or solid secondary waste that requires disposition. In addition to commercial high surface area systems (e.g., the WAIV system) items such as pond recirculators in evaporation ponds are potentially useful. Vendor literature suggests that pond evaporation efficiency could be improved by about 20% even in high TDS water using a simple pond recirculator. These technologies support a reduced pond footprint.

Implementability: Hypothetically implementable using standard practice but may encounter challenges to success associated with site-specific water chemistry, space, and logistics.

Timeframe: short- to medium-term

Technology Inter-Relationships: Several, including adaptive site management

Synopsis and Consensus: May not be an optimal match for Moab. However, consider for further evaluation if Moab team feels that it may be of value.

Topic: Irrigation and Phytoremediation

Objectives: Team 3 – Limited-term activities to mitigate risk and release of contaminants, and attenuate source terms. Objectives are to provide an option for controlling pumped groundwater following tailings relocation prior to long-term sustainable (passive) management strategies. The overarching goal is to limit plume expansion (i.e., limit efflux of ammonium uranium and other contaminants) to the Colorado River as long-term passive solutions are developed and implemented.

Description: Currently, contaminated water is being pumped and dispositioned away from the river as dust suppression during tailings removal and relocation operations. As the tailings relocation is completed, dust suppression water needs will decline. However, it may take many years to refine and implement long term passive plume management and risk reductions strategies, such as in situ sequestration, permeable reactive barriers, groundwater bypass, and others. During this period, some active pumping-based plume control including technologies such as irrigation/phytoremediation may be applicable. There are two major benefits of phytoremedation for water management at this site: 1) removal of ammonium as a macronutrient, and 2) maximized evapotranspiration to limit re-infiltration of water. Evapotranspiration uses solar energy to enhance evaporation and as the growth of biomass removes ammonium—phytoremediation is normally considered a green technology. Importantly, there are key risks that limit the use of irrigation for long-term water management: 1) the approach requires large amounts of land and may not be compatible with future land use plans, 2) the plants may contain low levels of contaminants such as uranium that can be taken up by insects and animals, 3) plants may require harvesting and disposal generating a secondary waste, and 3) the water quality in the aquifer may not support sustainable irrigation and soil health.

For irrigation, there is a large body of literature related to use of saline or brackish water and specific actions to allow sustainable use for plants; these account for the sensitivity of various plants, soil type, pH, and other factors. Several of the references were blended to create a table of approximate target levels for an irrigation scenario (Table 1). Note that Moab groundwater may not have sufficient quality (e.g., high TDS) for sustainable irrigation.

Table 1. Target water quality for irrigation

parameter	potentially acceptable range		
electrical conductivity	<1	3	mmho/cm
sodium absorption ratio (SAR)		<6	---
TDS	<300	1000	ppm
alkalinity	1	100	ppm as CaCO3 (desired range)
sulfate	<50	1000	ppm
arsenic	<0.1	2	ppm
beryllium	<0.1	0.5	ppm
boron	<0.5	2	ppm (alfalfa up to 5 ppm)
cadmium	<0.01	0.05	ppm
calcium	<50	200	ppm
chloride	<50	200	ppm
chromium	<0.1	1	ppm
cobalt	<0.05	5	ppm
copper	<0.2	5	ppm
fluoride	<1	15	ppm
iron	<5	20	ppm
lithium	<1	5	ppm
magnesium	<5	30	ppm
manganese	<0.2	10	ppm
molybdinum	<0.01	0.05	ppm
nickel	<0.2	2	ppm
potassium	<5	10	ppm
selenium	<0.02	0.02	ppm
sodium	0	50	ppm
vanadium	<0.1	1	ppm
zinc	<2	10	ppm

Abbreviations: ppm = parts per million, mmho/cm = milliohms per centimeter

Match to Moab Conditions: This strategy may have short term application to Moab conditions and needs. Irrigation has the potential for ammonium removal and as a supplemental pump-and-treat volume reduction technology to meet mid-term need/objectives.

Implementability: Hypothetically implementable using standard practice but may encounter challenges to success associated with site-specific water chemistry, space, and logistics.

Timeframe: short- to medium-term

Technology Inter-Relationships several including adaptive site management

Synopsis and Consensus: May not be an optimal match for Moab. However, consider for further evaluation if Moab team feels that it may be of value.