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REVIEWS AND APPROVALS

AUTHORS:

BRIAN LOONEY (Affiliate)
Digitally signed by BRIAN LOONEY (Affiliate)
Date: 2026.02.24 11:59:52 -05'00'

B. Looney, Savannah River National Laboratory **Date**

Ken Williams
Digitally signed by Ken Williams
Date: 2026.02.23 10:45:03 -07'00'

K. Williams, Lawrence Berkeley National Laboratory **Date**

Johnson, Christian
Digitally signed by Johnson, Christian
DN: cn=Johnson, Christian, ou=R3.L3, email=cd.johnson@pnnl.gov
Date: 2026.04.08 08:59:25 -07'00'

C. Johnson, Pacific Northwest National Laboratory **Date**

KRISTOPHER KUHLMAN (Affiliate)
Digitally signed by KRISTOPHER KUHLMAN (Affiliate)
Date: 2026.04.08 10:05:42 -06'00'

K. Kuhlman on behalf of M. Rigali, Sandia National Laboratories **Date**

EMILY FABRICATORE (Affiliate)
Digitally signed by EMILY FABRICATORE (Affiliate)
Date: 2026.02.17 13:13:37 -05'00'

E. Fabricatore, Savannah River National Laboratory **Date**

TECHNICAL REVIEW:

CAROL EDDY-DILEK (Affiliate)
Digitally signed by CAROL EDDY-DILEK (Affiliate)
Date: 2026.04.16 09:46:01 -04'00'

Carol Eddy-Dilek, Savannah River National Laboratory **Date**

APPROVAL:

ERIC PIERCE (Affiliate)
Digitally signed by ERIC PIERCE (Affiliate)
Date: 2026.04.16 10:35:01 -04'00'

Eric Pierce, Savannah River National Laboratory **Date**

Associate Laboratory Director, Environmental and Legacy Management

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Executive Summary

In 2019, the US Department of Energy (DOE) Office of Legacy Management (LM) initiated a series of structured collaborations between LM's staff & national strategic contractor and a consortium of DOE national laboratories (now known as the Network of National Laboratories for Environmental Management and Stewardship, NNLEMS) to support proactive management of its highest risk sites. The overarching goal of these "high risk site working groups" was to engage all participants to develop actionable recommendations that would reduce the identified risks. The consensus-based process evaluated the risks and baseline DOE-LM activities and provided affirmations along with recommendations to consider supplemental or replacement actions. The first high risk site working group focused on the former DOE mill and disposal site in Shiprock, NM. The high-risk site working groups were intended to foster a disciplined brainstorming process that encouraged appropriate incorporation of innovations into the DOE-LM program and to support DOE-LM stewardship goals and performance.

In 2024, DOE-LM management directed staff to assess the impacts of the collaborative high risk site working group process to determine if/how recommendations had been incorporated into the baseline and to assess the value of the collaborations to the DOE-LM program. To provide the requested information at an appropriate level of granularity, this retrospective evaluation on the Shiprock collaboration was performed. The retrospective evaluation was focused on evaluating the post-2020 activities, including the progress and performance for each of the topical recommendations from the 2019 collaboration.

For efficiency, the retrospective evaluation was performed by several key participants from the original 2019 collaboration. These individuals, representing multiple DOE national laboratories, were familiar with the site history, the high-risk site working group process and recommendations, and could represent the breadth and diversity of ideas from the teams that they led. Key to the success of the effort was the support of DOE-LM and the DOE strategic contractor team who provided detailed information about the actions and activities that occurred in the 2020 to 2024 timeframe. The NNLEMS acknowledges the DOE-LM and DOE-LM strategic partner who provided comprehensive and open information and communication to support the retrospective evaluation.

During the period from 2020-2024, the Shiprock DOE-LM team (managers, technical staff and subject matter experts, and collaborators such as the Applied Studies and Technologies (AS&T) Program) collaborated with National Laboratories, universities, subcontractors and the community to:

a) significantly and beneficially advance the environmental status and protections at the Shiprock Site,
b) reduce potential risks to the public and environment,
c) improve the technical basis for current and future actions and final GCAP development, and
d) successfully implement most of the recommended activities from the 2019 high risk site working group report (DOE-LM, 2020).

Notable progress included:

- Curated strategic plan for GCAP development for effective management of the site. To account for future adjustments in the GCAP support activities, the Shiprock team may want to consider the GCAP work plan to be a living document with planned periodic updates (e.g., every 2 to 3 years)
- Effectively worked with the Navajo Nation, stakeholders, community, and schools. Provided updates for key stakeholders (US Nuclear Regulatory Commission (NRC) and Navajo Abandoned Mine Lands Reclamation Department (Navajo AML) and Navajo Nation Leaders/community) including clear information on topics such as budget, and/or emerging data/model results, and other changing conditions.
- Worked with the Navajo Nation, regulators and stakeholders to respond to their highest priorities and to develop a full plan for decommissioning the evaporation pond implementing a strategy to reduce the footprint and environmental impacts of the pump and treat system.
- Implemented state of practice data management and visualization using Earth Volumetric Studio (EVS) software to support improved 3D conceptual model development, integration of data from drilling and boring data and geophysical surveys, generation of powerful and compelling images, and providing improved archival management of the data in a form that supports robust current use and future ingestion into emerging machine learning and artificial intelligence.
- Implemented state of practice geophysical surveys to delineate key subsurface features and heterogeneities that influence preferential flow paths and the fluxes of water and contamination from the terrace to the floodplain.
- Performed data mining information from past studies and historical information/data, as well as generating important topical reports for mill and non-mill contamination in terrace and floodplain groundwater, documenting background concentrations for the contaminants of concern (COCs).
- Successfully completed Phase 1 of drilling on the terrace and floodplain and planning for Phase 2 drilling campaign to include the waste area and additional terrace locations. The core materials and pore water were analyzed (geochemistry and contamination) and subjected to sequential leaching and other laboratory evaluations.
- Completed initial testing of alternative, innovative and/or supplemental data collection techniques such as passive fluxmeters and thermal imaging in the San Juan River.

The efforts and progress made by the Shiprock team between 2020 and 2024 were extensive and commendable. The Shiprock team (DOE-LM and LMS) provided high quality (state of practice and in some cases world-class) support to DOE-LM. The DOE-LM structure, with a nationwide strategic contractor that provides some centralization of technical and applied studies functions, is a significant factor contributing to the high level of performance. This structure allows the contractor to develop standardized tools and application paradigms that improve both the quality and efficiency of the work. For example, use of Earth Volumetric Studio (EVS) as a central tool for organizing and visualizing data at all of the major DOE-LM sites with subsurface contamination allows the team to consistently work up data, interface the data to numerical models and geographic information systems, integrate incoming data such as geophysics and borehole characterization data, and automate supporting statistical evaluations such as trend and plume

structure analysis and mass estimations. This standardization and ability to easily and seamlessly apply lessons learned across the entire portfolio of DOE-LM sites is a significant finding.

The retrospective review highlighted a seamless inclusion of the collaborative recommendations from the high-risk site working group that provided substantial value to the Shiprock Team. The original emphasis on a phased approach was useful – based on a focused strategy to resolve data gaps and challenges that contribute to key site risk factors. The initial working group emphasis on actionable recommendations (activities that can be performed cost-effectively in the near- to mid- term timeframe) facilitated the incorporation of recommended activities into the baseline plans for Shiprock. The associated success of the implementation resulted from the internal LMS infrastructure with local site subject matter experts with national centralized technical support personnel and the Applied Studies and Technologies (AS&T) Program. The NNLEMS retrospective review team recommends continued use of the centralized technical support and applied studies framework/structure, with sufficient resources allocated, to support current and future high levels of performance toward DOE-LM stewardship objectives.

Similarly, the DOE-LM outreach and stakeholder program currently is an exemplar of “best practices” that provides a model that can be valuable to the rest of DOE and other Federal Agencies. The DOE-LM skillset and organizational culture was clearly demonstrated at the Shiprock site to address Navajo Nation, stakeholder, regulator and STEM related topics.

Two major external events/factors impacted the implementation period from 2020 through 2024: 1) the COVID pandemic and 2) a stakeholder driven emphasis on replacing the aging evaporation pond. The COVID pandemic necessitating periods of remote work, telework, and virtual meetings, limiting the opportunities for interacting with stakeholders and regulators, and limiting the scheduling and performance of field work. The increased focus on the evaporation pond required DOE-LM to reallocate resources and reprioritize baseline activities. DOE-LM did an effective job in mitigating the adverse impacts of these external factors.

The status and key future recommendations for the various lines of inquiry are briefly summarized in table form within the document with a more complete discussion for each line of inquiry provided in the appendix.

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Acronyms and Abbreviations

3D	Three-Dimensional
AS&T	Applied Studies and Technology
COC(s)	Contaminant(s) of Concern
DOE	Department of Energy
EC	Electrocoagulation
EM	Environmental Management
ERT	Electrical Resistivity Tomography
Evap.	Evaporation
EVS	Earth Volumetric Studio
GCAP	Groundwater Compliance Action Plan
IC	Institutional Control
LBNL	Lawrence Berkeley National Laboratory
LM	Legacy Management
LMS	Legacy Management Support
LOI	Line of Inquiry
ML	Machine Learning
MLP	Multi-Layer Perceptron
NAML	Navajo Abandoned Mine Lands
NECA	Navajo Engineering Construction Authority
NLN	National Laboratory Network
NMR	Nuclear Magnetic Resonance
NNEPA	Navajo Nation Environmental Protection Agency
NNLEMS	Network of National Laboratories for Environmental Management and Stewardship
NNWCA	Navajo Nation Water Control Authority
NOLM	Nonoutlier Maximum
NRC	Nuclear Regulatory Commission

NUTA	Navajo Tribal Utility Authority
O&M	Operations and Maintenance
PFM	Passive Flux Meters
PNNL	Pacific Northwest National Laboratory
RFC	Random Forest Classifier
RO	Reverse Osmosis
SNL	Sandia National Laboratories
SOWP	Site Observational Wok Plan
SRNL	Savannah River National Laboratory
STEM	Science, Technology, Engineering, and Mathematics
TEM	Time-Domain Electromagnetic
UMTRA	Uranium Mill Tailings Remedial Action

Introduction

The US Department of Energy Office of Legacy Management (DOE-LM) provides stewardship and long-term monitoring maintenance and emergency response at former DOE mining, milling, and production sites across the nation, including the former ore milling, processing and disposal site in Shiprock, New Mexico ("Shiprock"). Shiprock is one of the highest risk sites in the DOE-LM portfolio. In 2019, DOE-LM initiated a collaboration with the DOE National Laboratories to consider the potential for implementing additional technology options to lower the identified "high risks". The evaluation focused on actionable and implementable ideas for consideration by DOE-LM (DOE-LM, 2020).

At Shiprock, the consensus recommendations focused on understanding the fluxes and driving forces for contaminants to move toward the San Juan River, understanding the nature, quantity, and extent of residual and secondary sources in the subsurface, and region-specific factors (baseline groundwater quality, desert ecosystem conditions, etc.). Some of the key recommendations focused on resolving critical data gaps required to meet regulatory guidance needs. The Shiprock team has been actively moving forward with follow-on work since the 2019/2020 National Laboratory collaboration.

One of the recommendations in the original report was to perform a periodic review to assist in fine tuning the planning and to identify if there are opportunities that were revealed by incoming information and data. This periodic review recommendation was specifically supported by the Nuclear Regulatory Commission (NRC) representatives who participated in the 2019-2020 process. This report details the review that was performed by Lawrence Berkeley National Laboratory (LBNL), Pacific Northwest National Laboratory (PNNL), Sandia National Laboratories (SNL), and Savannah River National Laboratory (SRNL) subject matter experts.

Background

High Risk Site Working Groups

In 2019, DOE-LM initiated a series of structured collaborations between LM's staff & strategic partner and a consortium of DOE National Laboratories (now known as the Network of National Laboratories for Environmental Management and Stewardship, NNLEMS) to support proactive management of its highest risk sites. The overarching goal of these "high-risk site working groups" was to engage all participants to develop risk reduction recommendations that are actionable and consensus-driven and that directly reduce risks in one or more of four risk categories – human health, regulatory, stakeholder, and institutional control (IC). The high-risk site working groups were intended to foster a disciplined brainstorming process that encouraged appropriate incorporation of innovations into the DOE-LM program and to improve the long-term stewardship of DOE sites.

The DOE-LM Shiprock site was selected to be the first site addressed using the collaboration initiative. Following Shiprock, several additional high-risk site working groups have been performed for DOE-LM sites and for the former DOE mill and disposal site in Moab, Utah (currently managed by the DOE Office of Environmental Management (EM) and on track for transition to LM). For Shiprock, the participants in the collaboration included DOE-LM management personnel, DOE-LM contractors and technical experts,

subject matter experts from various National Laboratories, Navajo Nation Abandoned Mine Lands Reclamation/Uranium Mill Tailings Remedial Action Department and Navajo Nation Environmental Protection Agency (NNEPA) representatives, Shiprock tribal government representatives, and regulators from NRC. The eight-week NNLEMS collaboration used an organized framework to ensure that proposed actions were developed with recognition of the context of current objectives and ongoing work at the Shiprock site. The process was based on three leading questions that were considered from the perspective of DOE-LM. Each of these is summarized below – more complete descriptions and information is provided in the full collaboration report (DOE-LM, 2020).

Affirm. What are we doing that we should keep doing? Examples of activities that were affirmed include: a) continuation of active pumping and evaporation until an alternative is developed and approved; b) update and revise Groundwater Compliance Action Plan (GCAP); c) decommission and replace aging evaporation pond; and d) continued Tribal, stakeholder, regulator and stakeholder engagement.

Replace. What are we doing that we should stop doing? Examples of activities that were recommended for replacement or discontinuing include: a) development and transmittal of final GCAP documents to the Navajo Nation or NRC without regular incremental engagement to allow for feedback and course correction, and b) development of ICs that unnecessarily restrict access to land and limit the potential for beneficial reuse and positive stakeholder engagement.

Supplement. What are we not doing that we should be doing? Examples of supplemental activities include: a) increased planning and data sharing briefings to stakeholders and regulators to foster strategic alignment and collaborative, dynamic decision making; b) working groups that include subject matter experts, regulators, and stakeholders to support GCAP development and to increase transparency and acceptance of developed plans, b) update site conceptual model focusing on flux and mass balance centered constructs; c) better understand and optimize the water balance; and d) facilitate educational opportunities and safe/beneficial reuse of impacted lands.

In 2024, DOE-LM management directed staff to assess the impacts of the collaborative high-risk site working group process to determine if/how recommendations had been incorporated into the baseline and assess the value of the collaborations to the DOE-LM program. To provide the requested information at an appropriate level of granularity, the resulting retrospective evaluation was focused on Shiprock as the first high-risk site working group (with the longest follow-on time period). In the original Shiprock NNLEMS collaboration, the various recommendations were organized into a summary chart with text that provided specific topical recommendations. The retrospective evaluation was focused on evaluating the post-2020 activities, progress, and performance for each of the tabulated topical recommendations.

Notably, two major events/activities impacted the implementation period from 2020 through 2024, the COVID pandemic and a stakeholder driven focus on replacing the aging evaporation pond. The COVID pandemic significantly impacted the Shiprock team, necessitating periods of remote work, telework, and virtual meetings, limiting the opportunities for interacting with stakeholders and regulators, and limiting the scheduling and performance of field work. DOE-LM did a commendable job in mitigating the adverse impacts of these external factors – the various topical narratives included in the retrospective evaluation

note impacts and mitigations related to the COVID pandemic and increased prioritization of the evaporation pond replacement (and associated water treatment needs).

Shiprock History and Cleanup Activities

Uranium and vanadium ore was milled and processed in Shiprock, New Mexico from 1954 through 1968. During operations, tailings and process water were released to the environment resulting in the infiltration of contaminants into the groundwater. The tailings piles and other contaminated materials have been consolidated and stabilized in a large on-site disposal cell.

A significant amount of high-quality characterization work has been performed at Shiprock by DOE and other agencies. Data from the Site Observational Work Plan (SOWP) and subsequent studies indicate the following:

a) the vadose zone and near-field groundwater beneath the former processing and tailings areas are contaminated with uranium, sulfate, and several other milling/disposal related contaminants,
b) contamination is moving in the groundwater in preferential flow paths toward the San Juan River – passing through a floodplain zone
c) the site hydrogeology is influenced by the arid site conditions and heterogeneities, and
d) floodplain and river interactions are dynamic and change in space and time.

Approach

The Shiprock high-risk site working group retrospective was performed by several topical teams. Each team was co-facilitated by a lead from a National Laboratory and a technical subject matter expert from the DOE-LM strategic contractor. To support an effective and efficient process, the original 2019 national laboratory team leads were engaged to work as a small group to perform the 2024-2025 Shiprock retrospective evaluation. Each original team lead was familiar with the 2019 deliberations and recommendations and was able to fully represent their original team.

The high-risk site collaboration generally affirmed the use of a spatial decision framework for GCAP development in which different areas are addressed by different groundwater compliance strategies (based on conditions and risk drivers). Specifically, the collaboration generally supported an initial spatial delineation defined in the 2002 proposed GCAP that focused on groundwater contamination in three distinct areas of the Shiprock disposal site: the west terrace, the east terrace, and the floodplain. Each of the three spatial areas were prescribed a different proposed groundwater compliance approach in 2002 as follows: 1) West Terrace - Supplemental Standards, 2) East Terrace - Active Remediation, and 3) Floodplain - Natural Flushing Supplemented by Groundwater Extraction (“Enhanced Natural Flushing”). A principal goal of the effort since 2002 has focused on implementing interim protections and refining plans and proposals for the GCAP to provide a protective and technically defensible plan that is concurred by NRC and accepted by the Navajo Nation and stakeholders. Central themes of the recommendations from the NNLEMS high risk site collaboration included a focus on refinement of the spatial zones and the transport of contamination – or “flux” – across key boundaries or interfaces between zones. For example, from the terrace to the floodplain, or from the primary or secondary sources into the underlying groundwater. Some of the technical topics of interest included baseline and contaminated water quality,

opportunities for closing data gaps, characterization of controlling heterogeneities and preferential flow paths, such as former arroyos, and implementation of tools and techniques to consolidate the information. Figure 1 depicts an annotated simplified cross section of the Shiprock site with key zones and interfacial fluxes noted by labels and arrows.

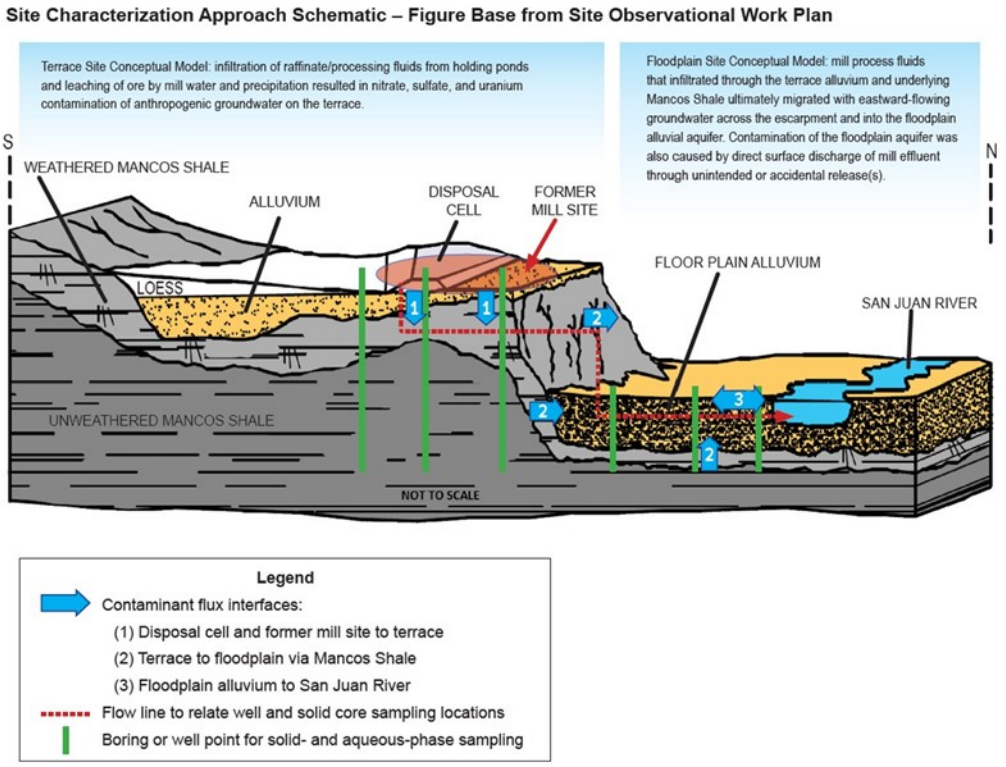

Figure 1. Depiction of the Geology, Source, and Receptor at the Shiprock Site Identifying Key Mass Flux.

For the current retrospective evaluation, the reviewers organized several lines of inquiry (LOIs) from the 2019 report as the framework for the retrospective evaluation. The review was then performed in a stepwise manner. First, subject matter experts from the Shiprock Site were contacted to collect information and documents on work performed between 2020 and 2024. Multiple meetings were held to collect information on the various technical and regulatory activities, and a virtual workshop was planned to facilitate a more comprehensive discussion and transfer of information. The original high-risk site working group represented a collaboration of DOE-LMS and five DOE National Laboratories (with briefings to NRC and the Navajo Nation agencies and leadership. The technical topical teams were co-chaired by an LMS subject matter expert (SME) and a National Lab SME. The co-chairs were responsible for facilitating their group brainstorming/deliberations and summarizing the results into actionable recommendations. The level of effort ranged from 50 for participating SMEs up to a nominal 100 hours for the co-chairs.

On January 14, 2025, the Laboratory Team held a short workshop to have a discussion and invited Shiprock researchers, DOE-LM headquarters, and NRC (Appendix B). The focus of the meeting was to talk through various LOIs developed by the Laboratory Team to respond to the requested report on progress made and additional recommendations. These lines of inquiry were grouped into three categories based on the previous recommendations:

- Overarching site characterization, modeling, and other actions to address GCAP data gaps
- Remedy progress, GCAP support, and compliance strategy
- Tribal, stakeholder, regulatory, and Science, Technology, Engineering, and Math (STEM) activities

During this three-hour workshop, a robust discussion was had on the significant progress made at the site which is detailed below. Following the workshop, data files and reports were organized by the Shiprock subject matter experts.

The review team recognizes and gratefully acknowledges the efforts of the DOE-LM Shiprock team and the technical experts within the DOE-LM strategic partner. The quantity and quality of the work performed at Shiprock in the 2020 to 2024 period was outstanding The Shiprock team workshop presentations and follow-up actions rapidly, efficiently and effectively provided clear and technically robust information to support the retrospective evaluation.

Lines of Inquiry

The selected lines of inquiry align with the recommendations in the 2019 Shiprock collaboration report. Those original recommendations were described in more detail in the 2019 report and a notional sequencing for potential implementation was developed by DOE-LM as part of the process. The organized lines of inquiry are shown in Table 1.

Table 1. Lines of Inquiry (LOIs).

Overarching LOI

1. Strategic management of GCAP development process

Site Characterization, Modeling, and Other Actions to Address GCAP Data Gaps - LOIs

1. Data mining and data review of historical information and reports
2. Apply Cost-Effective Surface and Borehole Geophysical Methods to Identify Preferential Contaminant Transport Pathways
3. Create new EVS 3D Model as a basis to support all aspects of the Shiprock efforts. Incorporate EVS visualizations into geohydrologic and geochemical models
4. Revise key reports, such as the Terrace Mill / Non-Mill Report
5. Implement additional drilling, borehole logging and core analysis and data collection activities
6. Complete pilot study of passive flux meters (with media that provide data on key COCs)
7. Improve estimated of water flux to San Juan River using thermal survey
8. Develop updated background concentrations with consensus from Navajo agencies for the terrace and floodplain and for areas influenced by artesian flowing well water, Arroyos, etc.

Remedy Progress, GCAP Support, and Compliance Strategy LOIs

1. Evaluate major efforts at Shiprock that focused on mitigating challenges associated with aging evaporation pond (ex-situ technologies)
2. Perform bench-scale tests for remedial technologies prioritized by the National Laboratory Network (NLN) collaboration and detailed literature review (in-situ technologies)

Tribal, Stakeholder, Regulatory, and STEM Activities LOIs

1. All Navajo Nation and Stakeholder Regulator and STEM Related LOIs

Discussion

Each of the lines of inquiry was evaluated and a summary narrative prepared (Appendix A). The narratives were prepared using the information from the workshop and post-workshop data sharing activities. For the narrative, the templated format followed the following outline:

- Title
- Summary of Original Recommendation and Objectives (target 0.5 to 1 page)
- Summary Review of Shiprock Activities and Progress (target 0.5 to 3 pages)
- Summary Assessment (target 0.5 to 1 page)

Each narrative ranged in length from 1 to 7 pages with a typical narrative length of 3 to 4 pages. The complete set of narratives is provided in Appendix A – these were not included in the main body of the report to aid in document flow and ease of reading. An image of an example narrative is provided in Figure 2, to provide the reader with context on the length, level of detail, and the nature of the evaluation and recommendations. The narratives represent consensus of the NNLEMS retrospective analysis team. Readers are encouraged to refer to the full narratives in the appendix to more fully understand the deliberations and recommendations.

Remediation –

1. Evaluate major efforts at Shiprock that focused on mitigating challenges associated with aging evaporation ponds (ex-situ technologies)

Summary of Original Recommendation and Objectives

This recommendation addressed the current and future regulatory, stakeholder and human health risks associated with the flux of contaminants in the groundwater underlying the Shiprock Disposal Site. The recommendation addressed both ex-situ technologies (i.e., associated with pump and treat) and in situ technologies and strategies. The activities and progress of these two categories are evaluated separately – this section focuses on ex-situ technologies.

At the time of the initial NNLEMS collaboration, water from the pump and treat system was dispositioned using evaporation in a large evaporation pond. The pond liner was approaching its design lifetime and there were concerns that liner failure would lead to leaks and releases. Potential leaking or failure of the aging pond liner was a recognized and high-profile risk driver for regulators, stakeholders DOE, and the Navajo Tribal Nation.

To address these risks, the NNLEM collaboration recommended a range of laboratory tests to assess the state of the existing pond liner (e.g., sampling and analysis of the amount of remaining UV protecting compounds in the existing liner) and (if sun exposed liner is nearing end of life) consideration of applying and overlay liner of fresh material in the upper portion of the pond that is exposed to sunlight. Further, the NNLEMS collaboration supported the LM engineering evaluation of alternatives to simple evaporation. The NNLEMS list of ex situ technologies included:

- Water Treatment
  - Membrane technologies (ultrafiltration, nanofiltration, reverse osmosis)
  - Ion exchange.
  - Distillation.
  - Electrocoagulation or chemical coagulation as a pretreatment.
  - Biological treatment media or bioreactor.
  - Media filtration.
  - Chemical sulfate removal.
- Water Management and Disposition
  - Evaporation (similar to ongoing remedial action).
  - Reinjection of treated water with or without oxidant addition (i.e., bicarbonate)
  - Phytoremediation, as a component of the compliance strategy.
  - Evapotranspiration (ET) disposal cell cover, as a component of the compliance strategy.

Summary Review of Shiprock Activities and Progress

Developing a path forward and working with the Navajo Nation, regulators and stakeholders to address the need for ongoing and future ex-site water treatment and disposition has been one of the top priorities for DOE over the past 5 years. Highlights of the activities are summarized below.

Figure 2a. Example Narrative Related to Replacing Aging Evaporation Pond (continued).

DOE's LM contractor performed and engineering alternatives analysis to identify the appropriate options for treating and dispositioning groundwater generated by future pump and treat operations. Navajo technical staff and leaders and regulators were regularly briefed on the evaluation progress and on the options.

The condition of the existing pond liner was assessed. The laboratory data confirmed that the liner was nearing end of life. Logistics and costs associated with disposal of the accumulated evaporative solids and liner replacement were included in the engineering evaluation.

When complete, the engineering evaluation focused on a combination strategy that includes active treatment, offsite disposal of secondary wastes, and onsite evaporation of a "low volume" concentrate discharge using a small-lined evaporation pond. The objective of treatment is to restore most of the water (e.g., 70 to 90%) for beneficial release to the environment. The objectives of the remaining actions are to cost effectively isolate and/or control risks from the contaminants removed from the contaminated groundwater and to responsibly disposition any additional secondary wastes generated during water treatment. The preferred technology combination includes sequential electrocoagulation (EC) and reverse osmosis (RO) for water treatment an evaporation (Evap) in a small footprint lined pond for distribution of the concentrated waste brine. The public supported the results of the engineering evaluation. Implementation of the RO/EC/Evap strategy is underway.

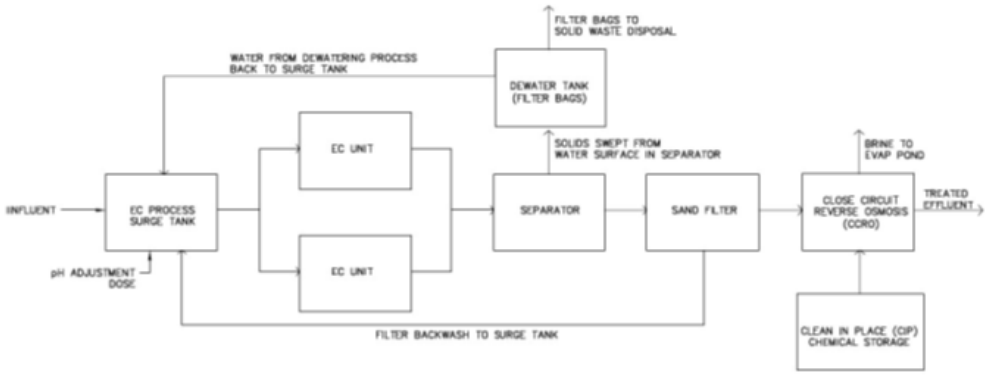

Figure xxx. Schematic diagram of ex situ treatment system being implemented by the Shiprock team.

The Shiprock team has developed a final ex situ groundwater treatment system design and implementation plan (report No. LMS/SHP/44869). This report addresses and documents system requirements, operations and maintenance (O&M), water treatment performance objectives and metrics, secondary waste generation and disposition, and potential risks associated with implementation and operation. In particular, the design and implementation plan generally recognizes the potential challenges associated with operating EC and RO systems on waters with high dissolved solids (sulfates and other salts) and the associated potential impacts on system maintenance and secondary waste generation. The Shiprock team considered analogous

Figure 2b. Example Narrative Related to Replacing Aging Evaporation Pond (continued).

commercial and technology performance experience related to treating fracking and similar geologic wastewater. The core treatment technologies EC and RO have been used for such treatment. The selected filter bag technology for separation of solids generated by the EC system is straightforward and appropriate. The Shiprock team commendably identified a complete offsite disposal pathway for generated secondary waste solids (a topic that is sometimes overlooked in the early design stages) and reasonably accounted for disposition of the brine/concentrate in a small footprint pond that, compared to the current large evaporation pond, is more acceptable to the nearby community. The Shiprock team also included reasonable estimates for future labor and O&M resources in the evaluation and planning.

Nonetheless, treatment of Shiprock groundwater will be challenging. Some of the key performance risks are geochemical in origin, including formation of excess precipitates in the EC and RO systems or in system piping/valves – the groundwater is already near solubility for some solids and precipitation may pose a problem as the groundwater is successively concentrated in the sequential process. This issue impacted the effectiveness, efficiency and success of the membrane-based groundwater treatment system at the DOE Tuba City AZ mill/disposal site (see SRNL-STI-2013-00619). During operation, the EC system will generate auxiliary aluminum oxide solids and controlling the quantity of these additional solids may be challenging during long term continuous operation. Finally, compared to other water treatment unit operations, EC systems are less common and therefore there is more uncertainty in the details of design and operations and more uncertainty in expected performance. To address these various challenges, system design should emphasize easy access for O&M and cleaning as well as operational flexibility to respond to the observed performance during a startup and shake out period. When selecting contractors for final design and implementation, it would be prudent for DOE to identify and select companies with a proven track record of successfully treating analogous or similar water such as produced water from fracking or similar geologic operations at a similar scale.

Summary assessment

Recommendation was fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team has done an exemplary job in advancing the ex-situ treatment planning and mitigating the associated risks. Communication with regulators, stakeholders and the technical and leadership representatives from the Navajo Nation were key to this progress. The potential concerns Identified above should be considered in developing the startup strategy for the system and in refining system operations over the first year or so of operation

Figure 2c. Example Narrative Related to Replacing Aging Evaporation Pond (continued).

The following findings are generally representative of the review narratives.

The Shiprock DOE-LM Team -- managers, technical staff and subject matter experts, and collaborators such as the Applied Studies and Technologies (AS&T) Program worked with National Laboratories, universities, subcontractors and the community to:

a) significantly and beneficially advance the environmental status and protections at the Shiprock Site,
b) reduce potential risks to the public and environment,
c) improve the technical basis for current and future actions and final GCAP development, and
d) successfully implement most of the recommended activities from the 2019 high risk site working group report (DOE-LM, 2020).

Notable progress included:

- Curated a strategic plan for GCAP development for effective management of the site. To account for future adjustments in the GCAP support activities, the Shiprock team may want to consider the GCAP work plan to be a living document with planned periodic updates (e.g., every 2 to 3 years) These updates should consider stakeholders, NRC, budget, and/or emerging data/model results, or other changing conditions.
- Effectively worked with the Navajo Nation, stakeholders, community, and schools.
- Responded to the highest priorities of the Navajo Nation, regulators and stakeholders by focusing on aging evaporation pond. Developed a full plan for decommissioning the evaporation pond, implementing a strategy to reduce the footprint and mitigate future environmental impacts of the pump and treat system.
- Implemented state of practice data management and visualization using Earth Volumetric Studio (EVS) software to support improved 3D conceptual model development, integration of data from drilling and boring data and geophysical surveys, generation of powerful and compelling images, and providing improved archival management of the data in a form that supports robust current use and future ingestion into emerging machine learning and artificial intelligence.
- Implemented of a range of state of practice geophysical surveys to delineate key subsurface features and heterogeneities that influence preferential flow paths and the fluxes of water and contamination from the terrace to the floodplain.
- Data mining information from past studies and historical information/data, as well as generating important topical reports for mill and non-mill contamination in terrace and floodplain groundwater, documenting background concentrations for the contaminants of concern (COCs).
- Successfully completing Phase 1 of drilling on the terrace and floodplain and planning for Phase 2 drilling campaign to include the waste area and additional terrace locations. The core materials and pore water were analyzed (geochemistry and contamination) and subjected to sequential leaching and other laboratory evaluations.
  Initial testing of alternative and innovative data collection techniques, such as passive fluxmeters and thermal imaging in the San Juan River.

Conclusions & Recommendations

The efforts and progress made by the Shiprock team between 2020 and 2024 were extensive and commendable. The Shiprock Team provided high quality (state of practice and in some cases world-class) support to DOE-LM. Most of the recommendations developed by consensus in the LM-NNLEMS high-risk site collaboration have already been implemented and others are in progress. The DOE-LM structure with a nationwide strategic contractor that provides some centralization of technical and applied studies functions is a significant factor contributing to the high level of performance. This structure allows the contractor to develop standardized tools and application paradigms that improve both the quality and efficiency of the work. For example, using EVS as a tool for organizing and visualizing data at all of the major DOE-LM sites with subsurface contamination allows the team to consistently work up data, interface the data to numerical models and geographic information systems, to integrate incoming data such as geophysics and borehole characterization data and automate supporting statistical evaluations such as trend and plume structure analysis and mass estimations. This standardization and ability to easily and seamlessly apply lessons learned across the entire portfolio of DOE-LM sites is a significant finding. The NNLEMS retrospective review team recommends continued use of the centralized technical support and applied studies framework/structure with sufficient resources allocated to support current and future high levels of performance toward DOE-LM stewardship objectives.

Similarly, the DOE-LM outreach and stakeholder program currently is an exemplar of “best practices” that provides a model that can be valuable to the rest of DOE and other Federal Agencies. The DOE-LM skillset and organizational culture was clearly demonstrated at the Shiprock site to address Navajo Nation, stakeholder, regulator and STEM related topics.

The status and key future recommendations for the various lines of inquiry are briefly summarized in Table 2.

Table 2. Summary of LOIs, Status, and Recommendations.

Green cells indicate fully fulfilled LOIs and yellow cells indicate partially fulfilled LOIs.

Overarching LOIs

Line of Inquiry	Status
1. Strategic management of GCAP development process	**Recommendation was fulfilled** – consider the GCAP work plan to be a living document; consider the provided list of specific future technical recommendations

Site Characterization Approaches to Address Data Gaps LOIs

1. Data mining and data review of historical information and reports	**Recommendation was fulfilled**
2. Apply Cost-Effective Surface and Borehole Geophysical Methods to Identify Preferential Contaminant Transport Pathways	**Recommendation was fulfilled** – consider the provided list of specific future technical recommendations
3. Create new EVS 3D Model as a basis to support all aspects of the Shiprock efforts. Incorporate EVS visualizations into geohydrologic and geochemical models	**Recommendation was fulfilled** – consider continued support and resources for this with a focus on how EVS fits within the DOE data management ecosystem.
4. Revise key reports, such as the Terrace Mill/Non-Mill Report	**Recommendation was fulfilled** – consider the provided list of specific future technical recommendations
5. Implement additional drilling, borehole logging and core analysis and data collection activities	**Recommendation was partially fulfilled** – continue with Phase 2 of the planned drilling and analysis. **In Progress**
6. Complete pilot study of passive flux meters (with media that provide data on key COCs)	**Recommendation was fulfilled** – if needed, consider alternative methods for estimating flux or deployments targeted to heterogeneities and potential preferential flow zones
7. Improve estimates of water flux to San Juan River using thermal survey	**Recommendation was partially fulfilled** – thermal imaging underperformed -- consider continuing work on this important topic using alternative methods; consider information and lessons learned from recent studies in the Colorado River adjacent to the DOE Moab site
8. Develop updated background concentrations with consensus from Navajo agencies for the terrace and floodplain and for areas influenced by artesian flowing well water, Arroyos, etc.	**Recommendation was partially fulfilled** – consider the provided list of specific future technical recommendations

Table 3. Summary of LOIs, Status, and Recommendations (continued).
Green cells indicate fully fulfilled LOIs and yellow cells indicate partially fulfilled LOIs.

Remedy Progress, GCAP Support, and Compliance Strategy LOIs

Line of Inquiry	Status
1. Evaluate major efforts at Shiprock that focused on mitigating challenges associated with aging evaporation ponds (ex-situ technologies)	**Recommendation was fulfilled –** consider the provided list of specific future technical recommendations
2. Perform bench-scale tests for remedial technologies prioritized by the NLN collaboration and detailed literature review (in-situ technologies)	**Recommendation was partially fulfilled –** consider the provided list of specific future technical recommendations **In Progress**

Tribal, Stakeholder, Regulatory, and STEM Activities LOIs

Line of Inquiry	Status
1. All Navajo Nation and Stakeholder Regulator and STEM Related LOIs	**Recommendations were partially fulfilled –** consider the provided list of specific future recommendations **In Progress**

References

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Department of Energy Office of Legacy Management. (DOE), 2022b. *Investigation of Non-Mill-Related Water Inputs to the Terrace Alluvium at the Shiprock, New Mexico, Disposal Site*, LMS/SHP/S14504, December 2022

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Department of Energy Office of Legacy Management. (DOE), 2024. Interim Treatment Plan for the Shiprock, New Mexico, Disposal Site, LMS/SHP/44869. August 2024

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Appendices

Appendix A: Assessment of Lines of Inquiry

Overarching LOI

This ROI focuses on the strategic management of the GCAP development activities and management of planning, sequencing and resourcing of the various activities including characterization needed to fill data gaps and modeling/engineering to mitigate risks.

Overarching LOI

1. Strategic management of GCAP development process

Narrative for the overarching LOI follows.

Overarching Recommendation

Strategic management of GCAP development process

Summary of Original Recommendation and Objectives

In the NNLEMS collaboration, a process for organized planning and sequencing of GCAP development efforts and the various activities for consideration that would provide a compelling policy and technical basis for the GCAP were included as a general overarching Shiprock recommendation. An initial listing of highest priority activities (and various branching options) was provided in the NNLEMS collaboration report. A key graphic in the collaboration report was a first iteration of schedule chart depicting sequenced activities – this graphic was envisioned and generated by the DOE-LM strategic contractor and this graphic served as a model for all future DOE-LM high-risk site working group reports (Shiprock was the inaugural LM-NNLEMS collaboration).

Summary Review of Shiprock Activities and Progress

Over the past five years, the nascent sequenced and prioritized activities described in the LM-NNLEMS collaboration were carefully considered, refined, expanded and built out. These strategic deliberations were combined with stakeholder and Tribal Nation inputs, as well as NRC GCAP requirements and NRC guidelines on GCAP content and how GCAPs will be reviewed. The initial LM-NNLEMS planning and schedule charts were updated to reflect the disciplined ongoing planning process, and the results are documented in DOE, 2022 (LMS/SHP/S28119 - Revised Groundwater Compliance Action Plan (GCAP) Work Plan Shiprock, New Mexico, Disposal Site, November 2022). This document represents a roadmap toward a viable and technically defensible GCAP. The sections of the Work Plan include:

- Background and historical information (including descriptions of past milling and disposal activities, general description of groundwater challenges and site conceptual model)
- Groundwater Compliance Considerations (including DOE-LM Strategies for Uranium Mill Tailings Radiation Control Act (UMTRCA) Sites, and Shiprock-specific GCAP Plan Strategic Approach)
- Summary of available data (including plume metrics and remediation progress, and contaminant occurrences and distributions for sulfate nitrate, uranium & other constituents)
- Analysis of Remediation Progress (including floodplain and terrace)
- Description of planned activities to close data gaps (including Data Quality Objectives, target needs and objectives, coordination of activities, boundaries of proposed studies, evaluation approaches and decision rules, methods and acceptance criteria)
- Develop Data Collection Plan
- Integrate existing data and build a preliminary flow, fate, and transport model
- Specific field campaign plans and schedules (including groundwater Isotopic analysis on floodplain and terrace, solid-phase geochemical sampling, uranium kinetic phosphorescence analyzer field testing, floodplain aquifer test, construction of flume in Bob Lee Wash and quantification of seeps, baseline aerial surveys including LiDAR, multispectral, & thermal, various innovative sensors and

meters, installation of piezometers and wells, passive flux meters, geophysical surveys, and other activities)

- GCAP response (including options for remedial technologies and ICs, coordination and consultation with external entities, sequestration studies, remedial alternatives evaluation

Preparation and documentation of the GCAP Work Plan was a significant and important activity for the Shiprock team. The resulting plan has been useful to facilitate communication with Navajo Tribal Leaders and Navajo technical experts. The plan will aid in preparing a GCAP with the highest potential for acceptance by the NRC. Further, when adjustments are needed in sequencing the GCAP work planning process supports organized rescheduling and other management changes. An example from the past five years was reallocating resources to accelerate the replacement of the evaporation pond in response to stakeholder inputs – this required delay of some of the drilling and sensor testing activities.

Figure 3 and Figure 4 are two examples from the GCAP Work Plan Report that depict key strategic programmatic implementation activities. Figure 3 is a groundwater compliance flowchart and Figure 4 is a tiered matrix of actions to close key data gaps.

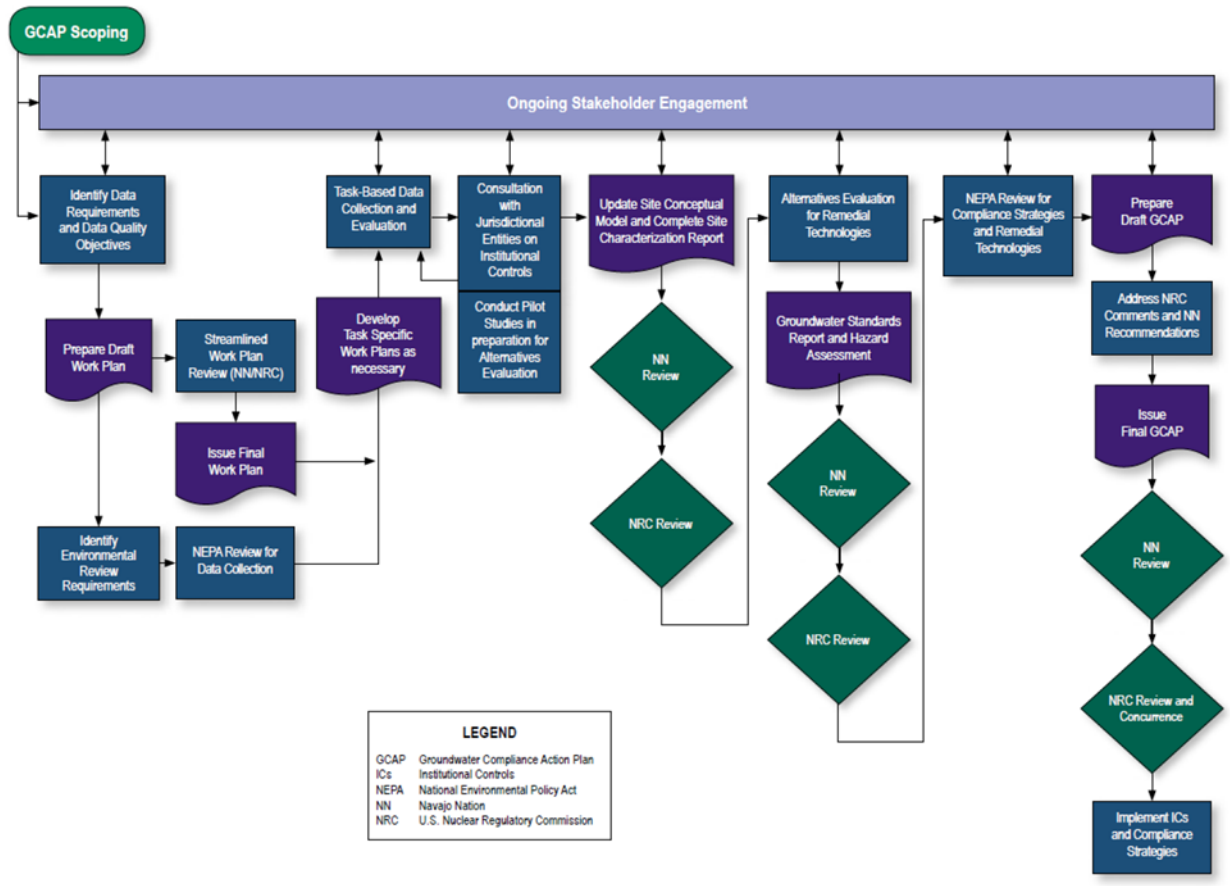

Figure 3. Shiprock Groundwater Compliance Flowchart.

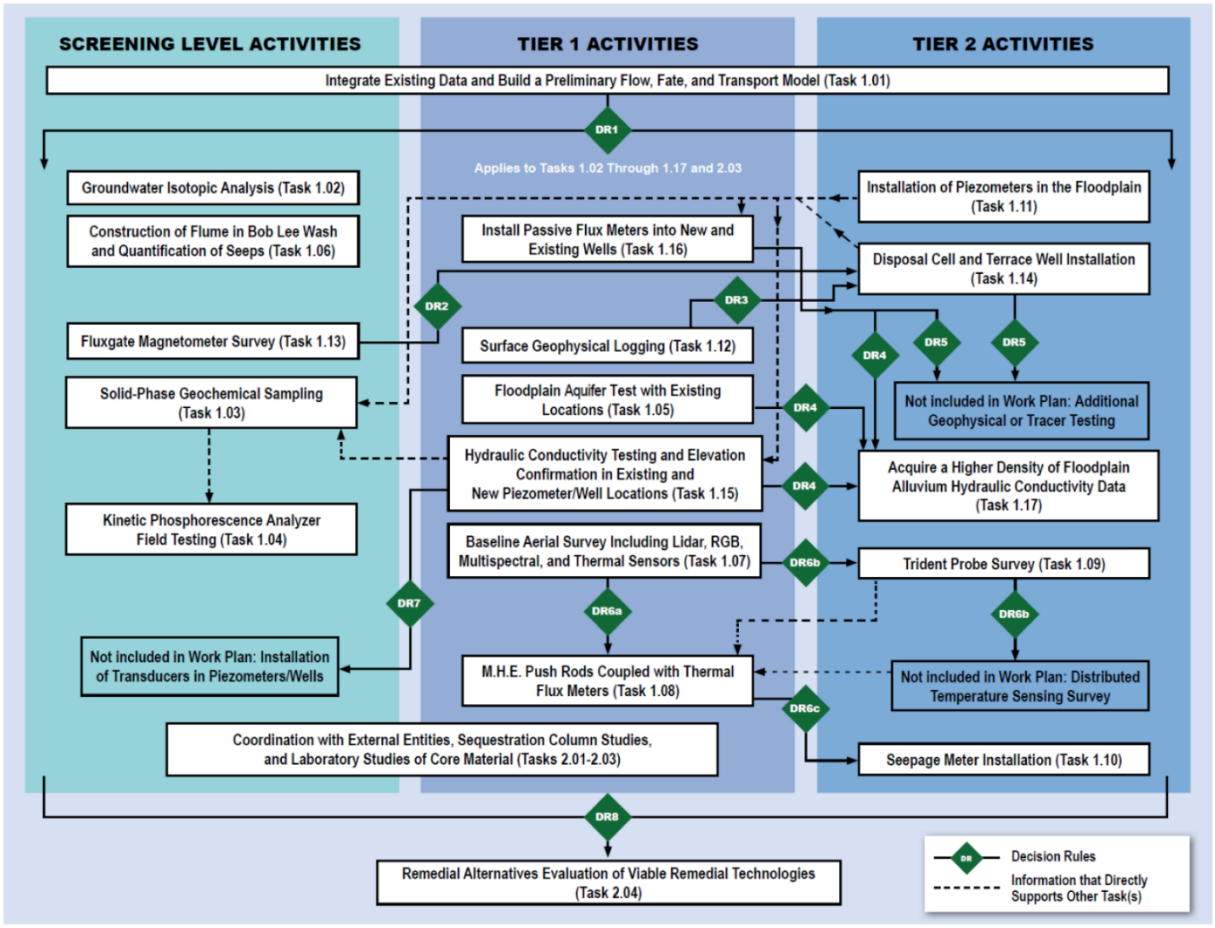

Figure 4. Shiprock Data Collection Tasks, Decision Rules, and Tier Assignments.

Summary Assessment

Recommendation was fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team has done an exemplary job in carefully managing, building out and documenting a strategic plan for GCAP development and effective management of the site. To account for future adjustments in the GCAP support activities, the Shiprock team may want to consider the GCAP work plan to be a living document with planned periodic updates (e.g., every 2 to 3 years) – these updates may be appropriate to effectively respond to stakeholders, NRC, budget changes, or emerging data/model results, or other changing conditions. Remaining topics originally discussed in the NNLEMS high risk site report recommendation should be considered in future work, including: 1) incorporate a wider range of tailings removal and ET cover scenarios in predictive simulations to evaluate the estimated effects of each effort on contaminant loading reduction at the site, 2) supplement with clear definition of collaborative decision points, and 3) develop strategy to communicate benefits and challenges relative to the estimated effects of different GCAP options.

Site Characterization, Modeling, and Other Actions to Address GCAP Data Gaps

This broad set of characterization LOIs focused on utilization of multiple approaches to close data gaps to support improvement of the site conceptual model and to provide an improved technical basis for finalizing the GCAP. Key to refining the site conceptual model is improving understanding of preferential pathways for contaminant transport. The recommendations addressed a range of strategies and tools including data mining, borehole and surface geophysical approaches and sampling of the subsurface and surrounding environment.

Site Characterization, Modeling, and Other Actions to Address GCAP Data Gaps - LOIs

1. Data mining and data review of historical information and reports
2. Apply Cost-Effective Surface and Borehole Geophysical Methods to Identify Preferential Contaminant Transport Pathways
3. Create new EVS 3D Model as a basis to support all aspects of the Shiprock efforts. Incorporate EVS visualizations into geohydrologic and geochemical models
4. Revise key reports, such as the Terrace Mill / Non-Mill Report
5. Implement additional drilling, borehole logging and core analysis and data collection activities
6. Complete pilot study of passive flux meters (with media that provide data on key COCs)
7. Improve estimated of water flux to San Juan River using thermal survey
8. Develop updated background concentrations with consensus from Navajo agencies for the terrace and floodplain and for areas influenced by artesian flowing well water, Arroyos, etc.

Narratives for the site characterization, modeling, and other actions for addressing GCAP data gaps LOIs follow.

Site Characterization Approaches

1. Data mining and data review of historical information and reports

Summary of Original Recommendation and Objectives

This recommendation was a general recommendation that encouraged the Shiprock team to maximize the value of previous and ongoing activities. Examples of topics that were highlighted for review are the documentation and data from the SOWP, the raw and processed data from previous geophysical studies, aerial survey reports, information from plant ecology & evapotranspiration studies, previous hydrological and biogeochemical characterization, and information developed in collaboration with the Navajo technical experts and local stakeholders. Specific recommended topics of interest to emphasize during the data review included Arroyos and Flowing Springs, general groundwater chemistry, and the flux of water and dissolved constituents from the terrace deposits into the floodplain and San Juan River.

Summary Review of Shiprock Activities and Progress

While this was not a formal activity over the past five years, the Shiprock team has been actively reviewing and incorporating historical information – documenting the results as part of several organized and referenceable reports. Examples of these reports include: LMS/SHP/S29390 *Reevaluation of Ammonia, Manganese, Selenium, and Strontium as Contaminants of Concern (COCs) for the Shiprock, New Mexico, Disposal Site*; LMS/SHP/S28979 *Investigation of Mill and Non-Mill Related Groundwater in the Floodplain at the Shiprock, New Mexico, Disposal Site;* and LMS/SHP/S14504 *Investigation of Non-Mill-Related Water Inputs to the Terrace Alluvium at the Shiprock, New Mexico, Disposal Site*. Notably, this historical information, along with new data and information, has also been captured in the evolving EVS model (discussed separately) – the EVS model serves as an archive and a tool for integrating and maximizing the value of historical, ongoing and future characterization activities and for providing the quantitative framework for future models.

Summary Assessment

Recommendation was fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team has done a commendable job in considering, capturing and incorporating historical information into documents and the EVS model and included the information into the deliberations and planning for GCAP development and effective management of the site. As future needs and directions are identified, additional options for beneficial use of the historical technical information should be considered. For example, future opportunities to better understand and leverage areas of preferential or focused flux that are controlled by features such as former Arroyos and other heterogeneities.

Site Characterization Approaches

2. Apply Cost-Effective Surface and Borehole Geophysical Methods to Identify Preferential Contaminant Transport Pathways

Summary of Original Recommendation and Objectives

This broad recommendation addressed the utilization of multiple characterization approaches to delineate locations for drilling and direct sampling at the Shiprock Disposal Site along with the generation of datasets capable of refining the site conceptual model through identification of preferential pathways for contaminant transport. The recommendation addressed the use of borehole and surface geophysical approaches to accomplish both objectives. The activities and progress of these two categories are evaluated separately, with this section focusing on synoptic geophysical approaches to refine the site conceptual model through identification of spatial variations in subsurface properties corresponding to locations of preferential contaminant flux.

The core objective of the recommended geophysics is to provide spatial (and temporal) information on subsurface structure and conditions to support a better understanding of heterogeneity and to identify the presence, location(s) and role that preferential flow paths are controlling contaminant fluxes in the system and, by extension, identify areas that might be viable for effective GCAP interventions and remediation.

Summary Review of Shiprock Activities and Progress

In support of the Groundwater Compliance Action Plan development at the Shiprock site and stemming directly from recommendations identified in the site assessment report, geophysical measurements were collected under the guidance and assistance of DOE-LM staff, their contractor personnel, and researchers from the Lawrence Berkeley National Laboratory with the following objectives:

- Identify the three-dimensional (3D) location of saturated fractures and preferential flow paths that transmit dissolved contaminants from the terrace to the floodplain
- Identify the 3D location of elevated/anomalous from background electrical conductivities indicative of the dissolved contaminant plume
- Support a 3D model that distinguishes the unsaturated alluvium, saturated alluvium, the more highly weathered and fractured upper portion of the Mancos Shale - hereafter referred to as the transmissive Mancos Shale, and competent Mancos Shale on the terrace and the floodplain. The 3D model will also incorporate the elevated electrical conductivities indicative of the dissolved contaminant plume

Geophysical imaging, paired with borehole logging, is particularly suitable to address these objectives, as it provides high-resolution images of subsurface geophysical properties that can be validated and translated into hydrological properties using borehole logging data. Activities at the Shiprock site in support of the recommended activities measured electrical and seismic properties of the ground. Electrical properties, and the electrical resistivity in particular, are highly sensitive to variations in the

composition of the sub-surface (e.g. sand and clay contents) and the conductivity of the pore fluid. At the site, contaminated groundwater is expected to have considerably higher electrical conductivity than clean groundwater, and hence contaminated fractures and preferential flow pathways are expected to show comparably low electrical resistivity. Similarly, sandy alluvium of the terrace and floodplain are expected to have significantly higher resistivity than the shale bedrock.

Data collected at the site highlighted areas of comparably low electrical resistivity in proximity to the evaporation pond, and at locations of expected or confirmed infilled arroyos, as well as in locations where contaminants were previously mapped on the floodplain. While no well data were available close to the evaporation pond, other areas of low resistivity aligned with monitoring wells where elevated uranium content was measured, indicating that indeed low resistivities relate to elevated contaminant content.

Seismic data were acquired to provide information on the thickness of the Quaternary layer and the thickness of the underlying, transmissive Mancos Shale. To achieve this, seismic P- and S-wave velocity data were obtained that provide information on subsurface structure and allow calculation of bedrock elastic properties. These elastic properties (i.e., the Poisson's ratio) highlighted a likely change in composition and/or stress state of the Mancos Shale, which showed an increase in rigidity towards the eastern corner of the site. The surface geophysical data highlighted areas of concern, in particular in the northern parts around the evaporation pond and the infilled arroyos thereby identifying locations of elevated contaminants and providing insights into potential migration pathways from the terrace to the floodplain, as evidenced by the current site conceptual model.

To establish a hydrostratigraphic model, surface and borehole geophysical data were assimilated using Machine Learning approaches. Resistivity-depth profiles obtained from Time-Domain Electromagnetic (TEM) measurements were extracted at 65 borehole locations and combined with the lithology logs and borehole location to create a training data set to predict lithology from measured resistivities. Multiple ML approaches were tested, including Random Forest, Gaussian Process, AdaBoost, Support Vector and Multi-layer Perceptron classifiers. Random Forest (RFC) and Multi-layer perceptron (MLP) classifiers provided the highest accuracy, and eventually a set of 10,000 RFC classifications were used to provide the lithology class with the highest probability.

Additional Electrical Resistivity Tomography (ERT) data were classified based on measured resistivity alone. This approach provided a prediction of the lithology at the TEM sounding locations and the ERT measurement lines. To provide a 3D hydrostratigraphic model of the entire site, layer depths were extracted and interpolated using kriging. To provide estimates of the hydraulic conductivity, relationships were established between measured electrical resistivity and hydraulic conductivity estimated from Nuclear Magnetic Resonance (NMR) borehole logging data. Linear relationships were developed that linked these two variables and applied to resistivity data to obtain a 3D distribution of site hydraulic conductivities. Quaternary deposits were identified to have the highest hydraulic conductivities, followed by the transmissive Mancos Shale. The competent Mancos Shale, as expected, was estimated to have the lowest hydraulic conductivity on average.

In aggregate, the work stemming from the site recommendations illustrated the utility of combined surface and borehole geophysical approaches for providing detailed information about the distribution of contaminants in the subsurface and in establishing a hydrostratigraphic model of the site that outlines the various layers and provides estimates of their hydraulic properties (Figure 5). While single fractures could not be identified, the mapped infilled arroyos are collocated with elevated uranium content both on the terrace and the floodplain and inferred to constitute a major flow pathway for contaminant migration from the terrace to the floodplain.

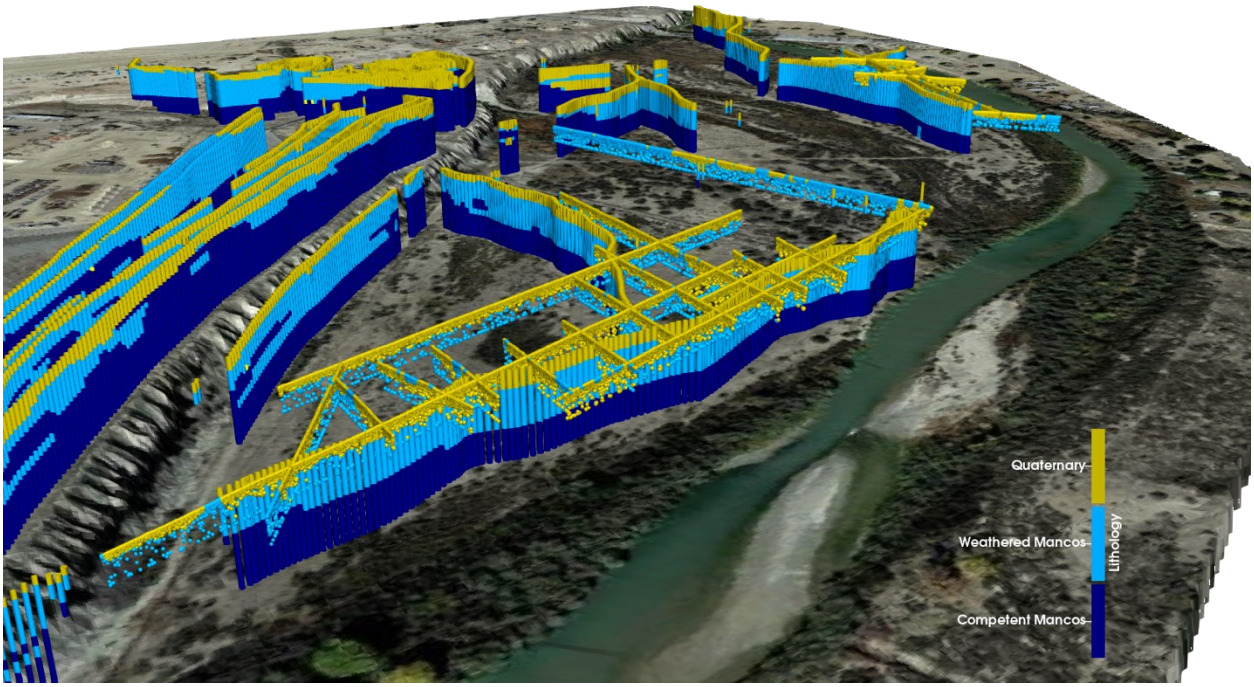

Figure 5. Hydrostratigraphic Delineation of High (Quaternary) to Low (Competent Mancos Shale) Permeability Lithofacies Types at the Shiprock Site Derived from a Combination of Surface and Borehole Geophysical Characterization Approaches.

The following provides some additional examples of geophysical progress at the Shiprock in the 2020-2024 period.

NMR data were collected in ten of the floodplain wells with two of these located along the base of the escarpment. The NMR data indicate a range of saturated hydraulic conductivity representative of unconsolidated alluvium, as well as strong gradients in conductivity both spatially and vertically. As exemplified in Figure 6, two floodplain wells (0859 and 1013) exhibit very different hydrologic properties in terms of total water content, percentage of mobile water, and saturated hydraulic conductivity, with the latter varying by more than 2-orders of magnitude between wells separated by 180 meters. While not yet constrained by more traditional hydrologic characterization approaches, such as slug & pumping tests, the geophysics data reveal the importance of floodplain heterogeneity in controlling local aquifer properties, such as transmissivity, that govern contaminant fluxes and extraction efficiency in areas of

groundwater withdrawal for plume management. Geophysical approaches can be performed for relatively low-cost with a high throughput to evaluate hydrologic properties in the floodplain extraction wells at the site, and when integrated with existing supporting hydrologic data, the combined approach is useful to support decision on the need and location of additional withdrawal wells to maximize capture efficiency.

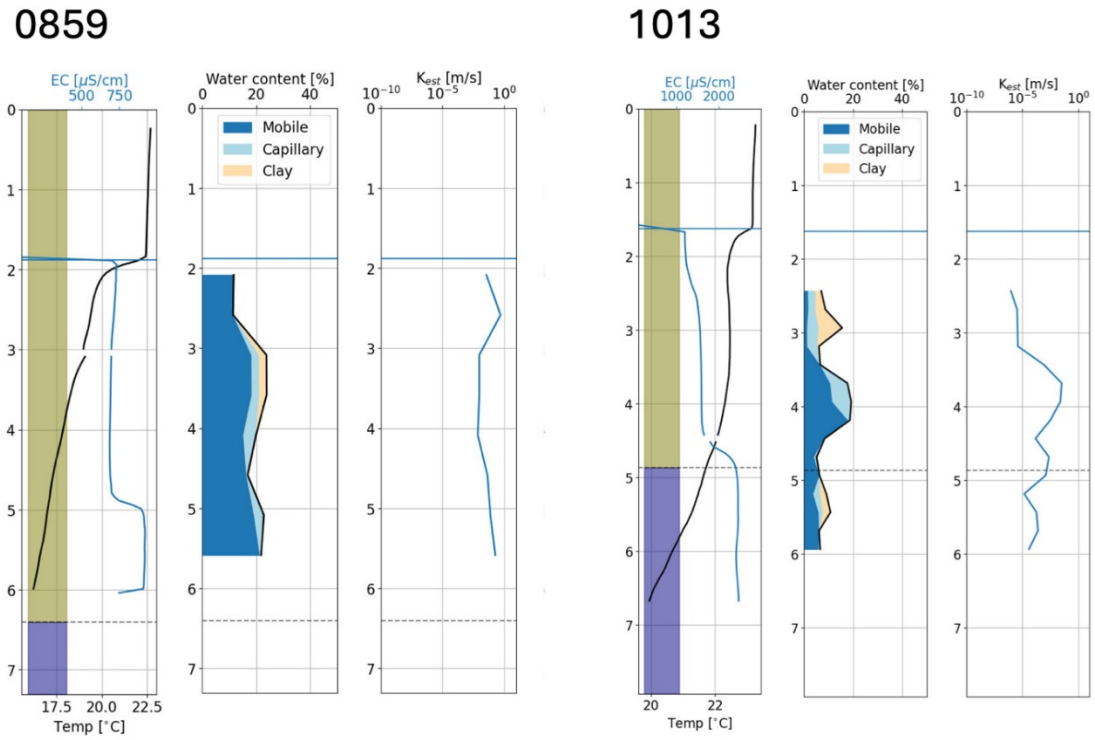

Figure 6. Borehole Logging Data from Shiprock, NM Floodplain Wells 0859 and 1013 Illustrating Thickness of Alluvium (Tan Shading), Fluid Conductivity and Temperature, Water Content and Type (Mobile, Capillary, Clay-Bound), and Saturated Hydraulic Conductivity (Note Different Vertical Depths for the Two Wells).

Summary Assessment

Recommendation was fulfilled in its entirety.

The Shiprock team overseeing the execution of this recommendation included staff from DOE-LM, their contracting personnel, and researchers from LBNL. The team worked in a highly effective and productive manner, producing data of high value to DOE-LM in support of refining the conceptual site model and improving subsurface material property delineation to enable ongoing and planned hydrostratigraphic modeling of the Shiprock site.

Site Characterization Approaches

3. Create new EVS 3D Model as a basis to support all aspects of the Shiprock efforts. Incorporate EVS visualizations into geohydrologic and geochemical models.

Summary of Original Recommendation and Objectives

This recommendation was a general recommendation that encouraged the Shiprock team to implement and extend data management and visualization resources for the site using state of practice tools. The objective of the effort would include: 1) improved 3D conceptual model development, 2) integration of data from drilling and boring data and geophysical surveys for effective use, 3) generation of powerful and compelling images, 4) integration of the information into numerical and predictive modeling, and 5) provision of improved archival management of the data in a form that supports robust current use and future ingestion into emerging machine learning and artificial intelligence.

Summary Review of Shiprock Activities and Progress

The Shiprock team has actively deployed state of practice data management and data visualization using EVS software to support the listed site objectives. Notably, the effort has provided a platform for improving the spatial and temporal understanding of contaminant fluxes across key interfaces beneath and downgradient of the Shiprock Site as described in the initial NNLEMS recommendation report (Figure 7).

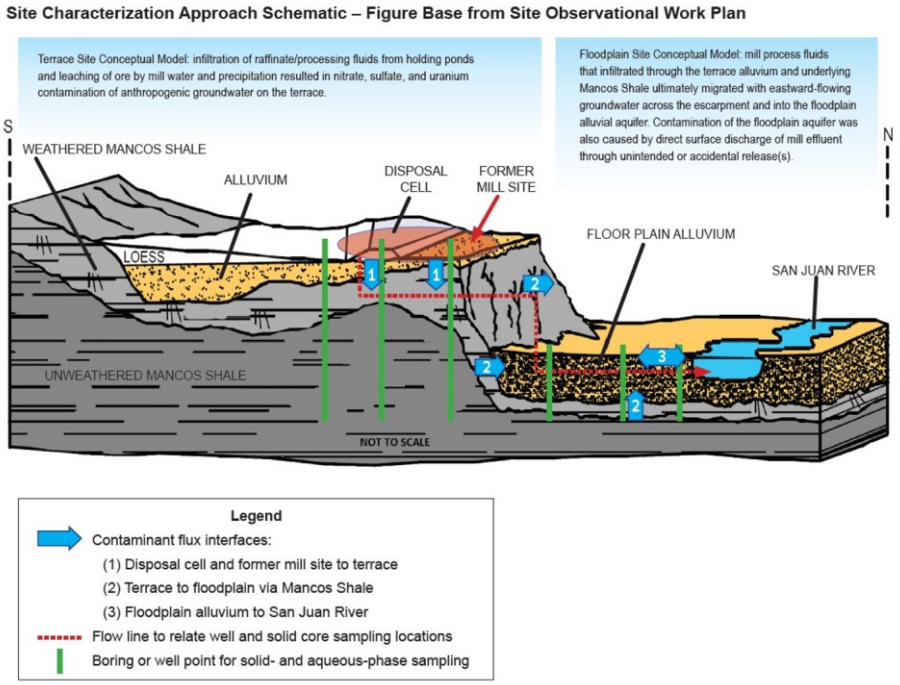

Figure 7. Depiction of the Geology, Source and Receptor at the Shiprock Site Identifying Key Mass Flux Interfaces.

Figure 8 depicts example Shiprock data presented using 3D imaging software, demonstrating the effectiveness of the approach in communicating large amounts of complex data in images (and videos if time data or projections are available).

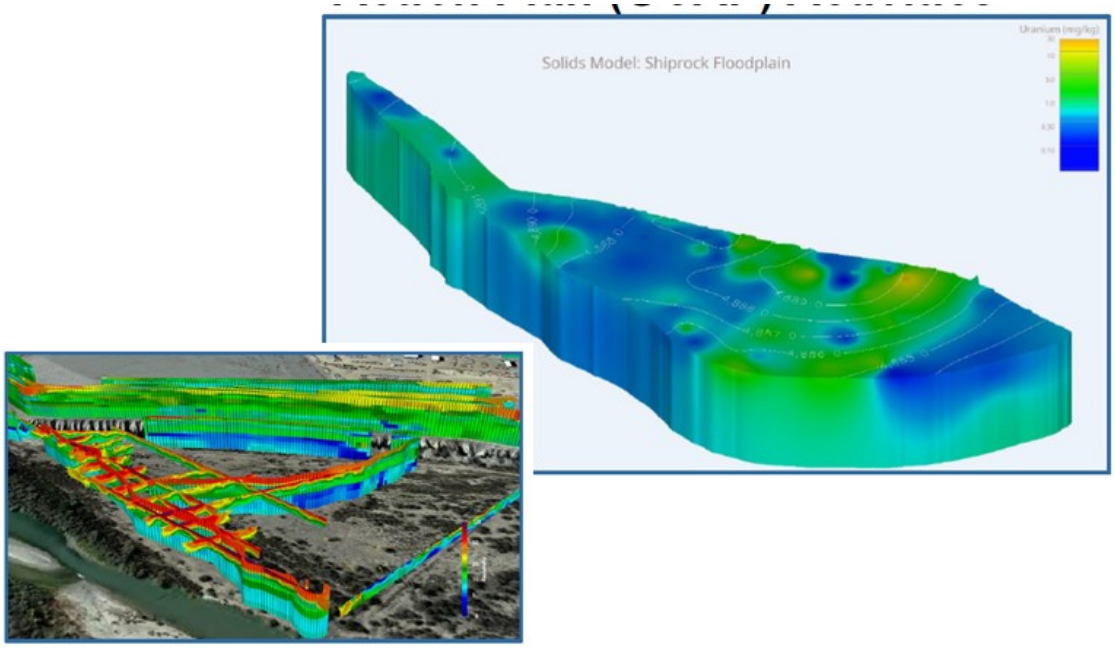

Figure 8. Example Graphics Depicting Soil Properties Measured from Borehole Samples (Upper Right) and Information from Geophysical Studies (Lower Left).

Significantly, because DOE-LM has a nationwide strategic contractor for its sites and centralization of technical support and applied studies, they have adopted EVS as a standard platform that is being used at all their major sites with subsurface contamination challenges. This standardization has allowed them to develop efficient and effective workflows and to provide a very high level of performance. DOE-LM contractors are currently providing best in class (world-class) management, modeling and utilization of subsurface data using EVS and the supplemental tools that they have developed in-house to support DOE-LM. For example, developing workflows within EVS to estimate plume statistics to assess natural attenuation, well concentration trends, plume characteristics, and to interface the results with geographical information systems such as ARC GIS.

Summary Assessment

Recommendation was fulfilled; A few recommendations (minor) are included in the information below.

DOE-LM and LMS implemented state of practice 3D data management and visualization capabilities using EVS. DOE's structure, a nationwide strategic contractor with centralization of technical support and applied studies is an effective approach. The world class data visualization and data modeling capabilities demonstrated for Shiprock are one example of the value of this structure. The Shiprock retrospective

review team recommends that DOE-LM assure continued support and resources for the team of scientists and engineers that are providing this important function. Specifically for the data visualization, the review team recommends a continued focus on how EVS fits within the DOE data management ecosystem and to specifically implement strategies and policies to assure viable interchange and interoperability of information with other databases, numerical models, geographical information systems, emerging AI systems, and outside data users/needs (e.g., Tribal Nations, regulators or stakeholders).

Site Characterization Approaches

4. Revise key reports, such as the Terrace Mill / Non-Mill Report.

Summary of Original Recommendation and Objectives

This recommendation was a general recommendation that encouraged the Shiprock team to revise key reports such as the mill and non-mill characterization report. At Shiprock such reports are foundational to the site conceptual model. For example, the ability to distinguish mill related contamination from natural conditions (e.g., uranium in the groundwater resulting from mill operations versus naturally occurring uranium present in the subsurface) is crucial to developing the most effective strategies for protecting the stakeholders and community.

Summary Review of Shiprock Activities and Progress

The Shiprock team revised and finalized the Mill / Non-Mill Characterization Report (LMS/SHP/S14504, 2022 - *Investigation of Non-Mill-Related Water Inputs to the Terrace Alluvium at the Shiprock, New Mexico, Disposal Site*). The report supports the use of supplemental standards for the west terrace because the groundwater in the Mancos is naturally of poor quality (i.e., "limited use") due to the presence of salts and related constituents. Currently, the east terrace compliance strategy is active pump and treat to limit surface expression of seeps into Many Devils Wash and Bob Lee Wash and reduce the flow of groundwater from the terrace to the floodplain. Contributions of non-mill-related anthropogenic water sources may be hindering the dewatering effort, resulting in reduced remedy effectiveness. The objective of the Mill / Non-Mill investigation was to understand the sources of groundwater that presently exist in the shallow terrace groundwater system using uranium concentrations and isotope activity ratios, sulfate concentrations and sulfur/oxygen isotope ratios, tritium concentrations, hydrogen and oxygen isotope ratios, and total chlorine concentrations and isotope ratios. The results and interpretation of these data provide a basis for evaluating five potential sources of groundwater recharge. These sources are (1) water related to the operation of the uranium mill, (2) domestic water use on the terrace, (3) irrigation water, (4) groundwater present on the terrace before mill operation, and (5) the infiltration of meteoric water. The various measurements were made at sampling locations representing various areas of the site – see Figure 9.

The uranium and sulfate data identified a zone of mill-affected groundwater. The remaining data provided information that identified and clarified the potential role(s) of mill and non-mill terrace groundwater contributors/sources, notably: confirmed sources included water related to the operation of the uranium mill and water associated with domestic water use on the terrace, likely sources included irrigation water, unlikely sources included groundwater present on the terrace prior to mill operation, and minimal sources included infiltration of meteoric water and groundwater from flowing well 0648.

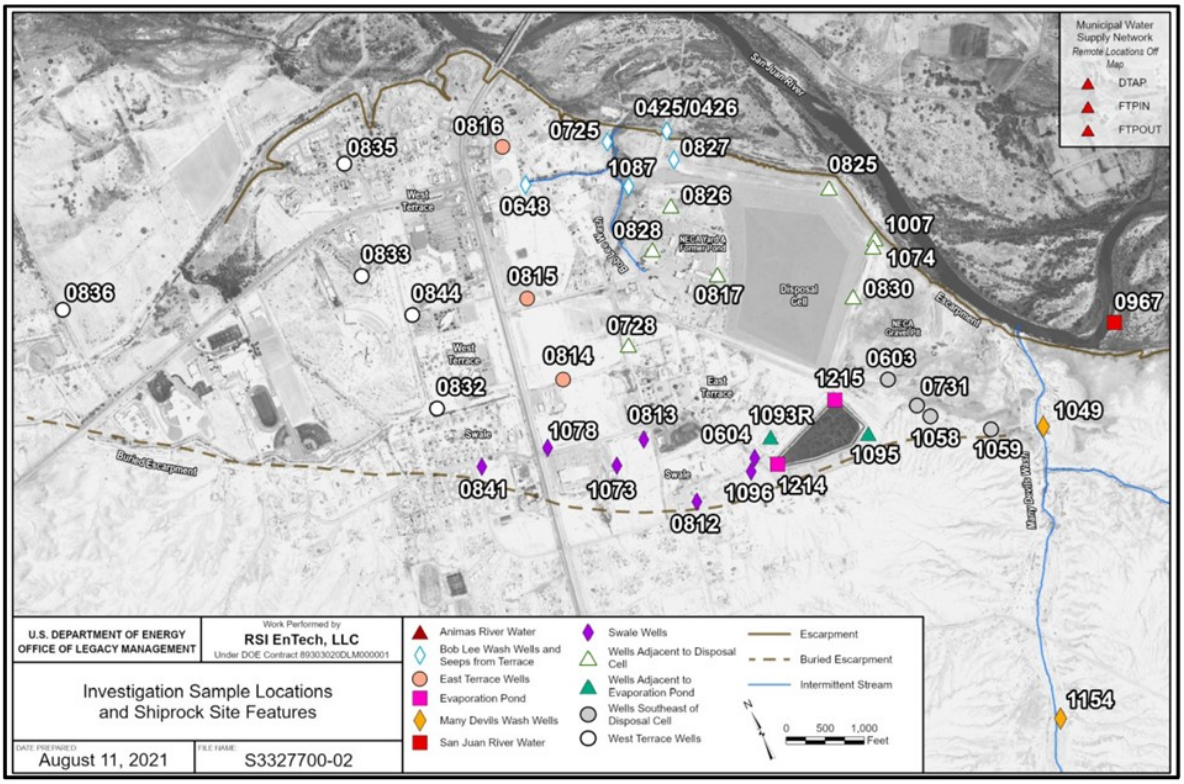

Figure 9. Mill / Non-Mill Investigation Sample Locations and Shiprock Site Features.

Since the isotope data alone cannot further quantify the amounts of water from the various sources, the Mill / Non-Mill Report recommended using other lines of inquiry moving forward, such as hydrogeologic methods to directly measure precipitation recharge and irrigation losses compared to past and current water losses from the tailings, as well as a better determination of domestic water losses from pipelines. A conclusion of this report is that any groundwater flowing into the area of the terrace containing mill-derived solid-phase uranium and sulfate will become contaminated regardless of origin. Dissolution of primary and secondary mill-derived solid-phase uranium and sulfate will support long-term durable source mass fluxes will continue for an extended period until the solid phase is exhausted.

Summary Assessment

Recommendation was fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team has done an exemplary job in updating and finalizing key reports, notably the Mill / Non-Mill Investigation Report. This report used state of the art and state of practice methods (such as uranium, sulfate, oxygen, hydrogen and chlorine isotopes and isotope ratios as well as trace tritium measurements and other concentration metrics). The interpretations were consistent with the relevant scientific literature. As a follow-up, the review team concurs with the Shiprock team finding that follow-up studies to provide more quantitative estimates of the various contributions of terrace water sources are needed. Some of these activities are straightforward and could be performed by setting up a focused

cooperation with the Navajo water authority or by a research effort using student interns or university collaborators. For example, more information on irrigation and evapotranspiration could be pursued with academic partners based on field measurements, remote sensing and historical aerial photography.

Site Characterization Approaches

5. Implement additional drilling, borehole logging and core analysis and data collection activities

Summary of Original Recommendation and Objectives

This recommendation provides key foundational information to close data gaps, advance the site conceptual model and support GCAP development. The recommended strategy for the drilling including representative drilling and sampling in all key domains identified in the Shiprock site conceptual model as well as to install boreholes that represent a flow line from the terrace to the floodplain and San Juan River.

This recommendation addressed the need to collect additional solid phase and fluid samples through the installation of new monitoring wells and borings including locations on both the terrace and floodplain. Samples collected were recommended for solid phase analysis, including sequential extractions to better constrain secondary sources of contaminant release. Where possible, it was recommended that such to-be-installed monitoring wells and borings be used to obtain complementary information regarding formation properties using borehole geophysical approaches, with both data types used to better delineate the spatial distribution of the contaminant plume and subsurface features and/or properties that contribute to contaminant flux.

Recommendations for this work fell into two primary categories.

- Installing wells and collecting solid materials for chemical and contaminant characterization and sequential extraction to support geochemical modeling and interpretation of residual sources and flow paths. Drilling to focus on collecting linked data in terrace and floodplain, and on areas of transmissive Mancos shale to help understand plume structure and provide key information for concentration modeling and on former, now-buried arroyos.
- Work up data from analysis of coring solid materials and sequential extraction to help understand secondary sources.

Summary Review of Shiprock Activities and Progress

The Shiprock team planned two phases of drilling and sampling in response to these recommendations – Phase 1 focused on the terrace and floodplain and Phase 2 will focus on the terrace, arroyos and disposal cell.

Phase 1 GCAP drilling terrace wells were installed along with wells and borings in floodplain. The drilling focused on collecting solid materials for characterization and sequential extraction. The locations were selected to provide linked data in terrace and downgradient floodplain, and on areas of transmissive Mancos Shale (to help understand plume structure and provide key information for concentration modeling) and on heterogeneity and preferential flow and the former arroyos.

Phase 2 GCAP drilling. Next phase of drilling will build on Phase 1 and on additional geophysics studies and magnetometer survey. This phase will include additional terrace locations, arroyos, and disposal cell.

The COVID pandemic and work restrictions along with the prioritization of the evaporation pond replacement delayed the implementation of this work. At the time of the review, Phase 1 drilling and data evaluation were complete and planning for Phase 2 drilling was complete.

The following provides a synopsis of example results from the boring and analysis effort.

A total of 31 wells were installed in 2022 along with 10 borings, with solid phase samples collected for geochemical and mineralogical analysis from 41 locations. Elevated concentrations of solid phase uranium on the terrace alluvium were found to be associated with discrete lenses of high iron, organic matter, and clay content. Elevated concentrations of solid-phase uranium within the alluvium and fill (> 7 mg/L) were found near the evaporation pond, in the footprint of a former raffinate pond near the disposal cell, and within two of the former arroyos. Generally, elevated concentrations of solid-phase uranium were isolated to the transmissive portion of the Mancos shale. Such data were corroborated through the deployment of passive flux meters (PFMs) deployed in a subset of monitoring wells installed in 2022 (see relevant section on PFM pilot study and recommendation assessment). Thirteen of the newly installed monitoring wells (1148, 1151, 1153, 1161, 9025-9032, 9034) were used to obtain borehole geophysical logging data including fluid electrical conductivity and temperature, spectral gamma ray spectroscopy for solid-phase K, U, and Th concentrations, formation conductivity, and NMR imaging for hydrogeologic properties including water content and saturated hydraulic conductivity [N.B. NMR logging was not possible in wells 1148, 9025, 9028, and 9029 owing to deviated wellbores]. Of note, well numbers 600, 9028, and 9034 are located on the terrace north of the disposal cell and along the escarpment, while well 1153 is located on the floodplain directly beneath one of the now buried/infilled arroyos (Figure 10).

The information from the Phase 1 drilling and geophysical studies are a useful resource in planning for Phase 2 drilling and sampling activities. For example, deviations in geophysical parameters such as electrical resistivity, may be used identify “potential areas of concern”. Figure 11 is an example showing areas that might be considered to additional direct sampling and installation of monitoring wells associated during Phase 2 drilling to aid in better delineation of the contaminant plume and its relationship to the disposal cell and evaporation pond. Furthermore, geophysical data provided confirmation of inferred and historically extrapolated locations of so-called “buried arroyos” that exist along the ‘escarpment’ interface that separates the upper terrace, which hosts the disposal cell and pond, and the lower floodplain. Such arroyo features are believed to represent locations of preferential transport of contaminated groundwater and geophysical data, both surface and borehole, strongly supports this conjecture.

These geophysically-identified regions along the escarpment extend Phase 1 drilling locations and represent further areas to interrogate via Phase 2 drilling activities. Based upon strong correlations observed between surface and borehole geophysical data and the direct sampling and measurement locations (e.g., wells installed for the emplacement of passive flux meters; spectral gamma logging data and direct quantification of solid phase uranium concentrations) as part of the Phase 1 work, it is not anticipated that follow-on geophysical data collections will be required post-drilling under Phase 2 activities.

Finally, supplementary geophysical datasets (esp. flux gate magnetometer) were recommended as part of the high-risk site assessment as necessary for validating locations atop the disposal cell that avoid subsurface areas where metal debris may be localized; such data will be a critical component of defining locations for Phase 2 drilling regardless of whether it is performed in association with planned drilling and sampling needed to better define the lateral extent of the contaminant plume.

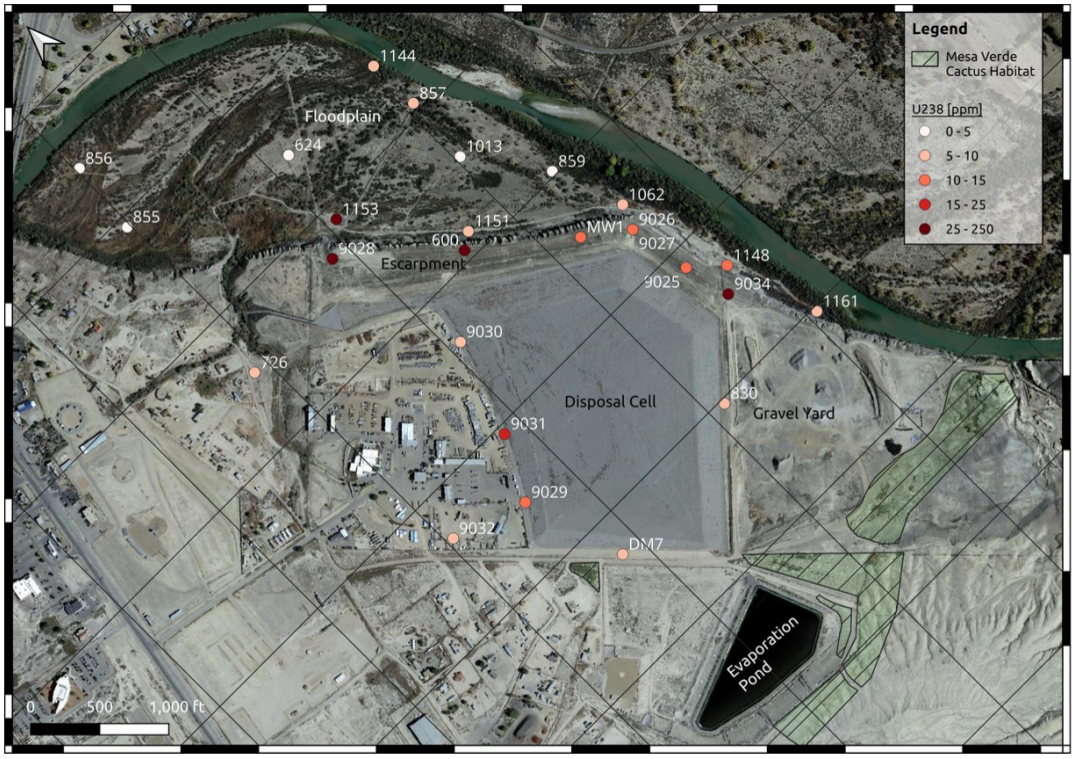

Figure 10. Map Illustrating the Maximum Recorded Formation Uranium Concentration at each of the Monitoring Wells Logged using the Spectral Gamma Ray Spectroscopy Tool.

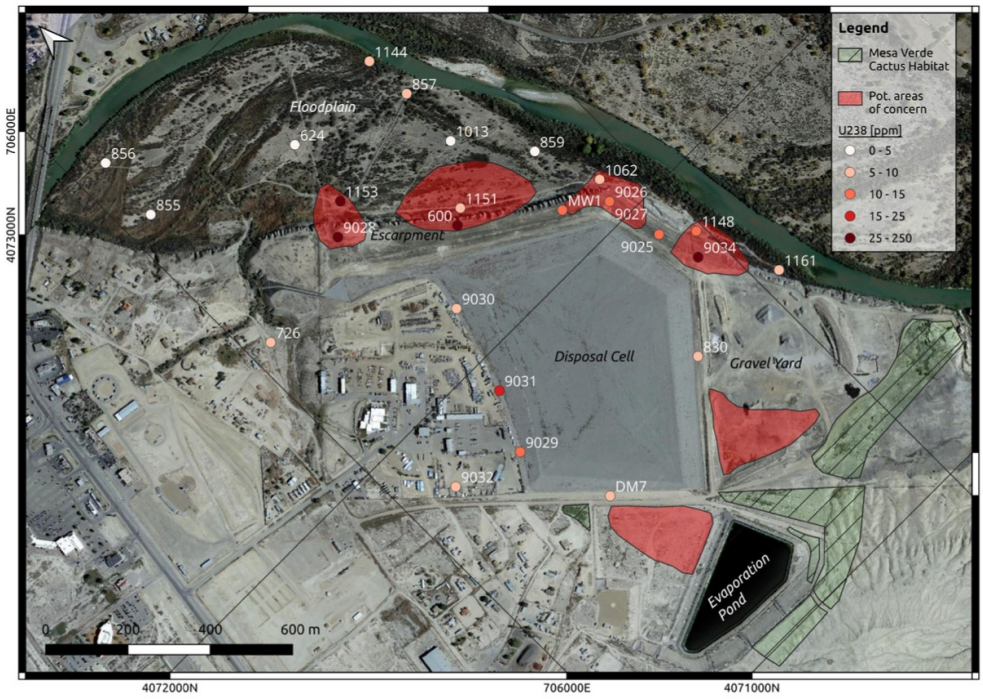

Figure 11. Regions (Red) Identified as "Potential Areas Of Concern" Based on Deviations from Regional Geophysical Signatures (e.g. Electrical Resistivity) at the Shiprock Site that are being used to Identify Areas for Phase 2 GCAP Drilling and Sampling, with a Planned Focus on the Area Bracketed by Well 9024 and the Evaporation Pond.

Summary Assessment

Recommendation was partially fulfilled; additional recommendations (minor) are outlined below.

Phase 1 GCAP drilling and sampling completed in 2022. Geophysical logging and data intercomparisons with solid phase analysis in 13 of the monitoring wells installed as part of this activity completed in 2023. Data analysis has been completed, with results and associated report still being finalized prior to public release. The Shiprock team completed Phase 1 drilling during a difficult period that included pandemic and DOE-LM directives (and Tribal & stakeholder guidance) to focus resources on the evaporation pond activities.

Phase 2 is in progress and is included in baseline planning activities at the Shiprock site, with future drilling potentially occurring as distinct activities – potentially decoupling drilling through the disposal cell cover from additional drilling in the Terrace and floodplain. In performing Phase 2, the Shiprock team should consider any lessons learned from Phase 1 (what methods worked well?) and modify or streamline activities as appropriate based on that knowledge.

Site Characterization Approaches

6. Complete pilot study of passive flux meters (with media that provide data on key COCs).

Summary of Original Recommendation and Objectives

This recommendation was intended to provide a direct or semidirect measure of flux – since a fluxed based conceptual model was a core recommendation from the NNLEMS collaboration. Specifically, the collaboration recommended installation of passive flux meters in new and/or existing wells within and around the disposal cell and on the floodplain to integrate hydraulic conductivity, hydraulic gradient, effective porosity, and mass transfer and provide direct flux quantification for both groundwater and COCs.

Summary Review of Shiprock Activities and Progress

The Shiprock team developed a clear and technically based plan for deploying passive flux meters with an emphasis on using linked or paired locations on the terrace and in the floodplain to provide clearer and more useful information. The fieldwork for the passive fluxmeter deployment was completed as well as initial interpretation. The results were generally consistent with standard flux calculations and did support some refinement in the conceptualization of heterogeneity, preferential flow and the effects of key features such as former arroyos.

Summary Assessment

Recommendation was generally fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team performed an appropriate implementation of passive fluxmeters. The Shiprock team should consider incorporating the knowledge in the EVS and numerical model. Based on the field logistics and results, the Shiprock team should decide as to the need or value of additional borehole based passive flux measurement, and to assess alternatives based on other measurements and projections -- such concentration and modeled flow. If additional borehole based passive fluxmeter measurements are made, the team should consider collecting supplemental information in preferential flow paths.

Site Characterization Approaches

7. Improve estimates of water flux to San Juan River using thermal survey

Summary of Original Recommendation and Objectives

This recommendation was intended to provide information about the interchange of water between the floodplain and the San Juan River. The recommendation focused on use of porewater sampling or thermal methods to identify and quantify the spatial and temporal pattern of water discharge/recharge. This work would support better calibration of numerical models and provide a more complete understanding of flushing zones under the floodplain. The specific recommendation included the following text:

"[consider] use of Heary pushpoint sampler (MHE Products) or similar to conduct pore water sampling at the floodplain-San Juan River interface coupled with thermal flux meters to measure seasonal and spatial variations in groundwater flux towards the point of exposure"

Summary Review of Shiprock Activities and Progress

The Shiprock team implemented an alternative thermal survey based on an infrared camera. In the field, the team encountered difficulties in maintaining a consistent calibration, and the remote sensing of temperature in a variable water column complicated the interpretation. Thus, these initial survey data are considered semiquantitative.

Summary Assessment

Recommendation was partially fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team performed a reasonable implementation of a thermal survey with equivocal results. This is a relatively important data gap since it directly links to the nature and pattern of flushing beneath the floodplain. Thus, additional – more sensitive and quantitative -- studies should be considered. As a relevant example, researchers from PNNL (led by Fred Day-Lewis) recently completed a similar study in the Colorado River adjacent to the former DOE mill & disposal site in Moab, Utah. This study used pore water samples, boat towed geophysics and various thermal sensors to obtain information on the spatial and temporal fluxes of water and contaminants into the Colorado River. Lessons learned from that study may be a useful resource for the Shiprock team in planning any future studies in the San Juan River.

Site Characterization Approaches

8. Develop updated background concentrations with consensus from Navajo agencies for the terrace and floodplain and for areas influenced by artesian flowing well water, Arroyos, etc.

Summary of Original Recommendations and Objectives

Groundwater standards must be protective of human health and the environment, and they must be achievable. Shiprock has mill-related groundwater contamination at concentrations that are significantly elevated from background concentrations; however, high background concentrations observed in the floodplain background wells upstream of the site, and in the Many Devils Wash area wells, indicate that the cleanup standards in the 2002 GCAP may not be achievable.

Background concentrations will be statistically analyzed and communicated with stakeholders and regulators. Consensus will be developed regarding both appropriate background concentrations for the floodplain and the establishment of background concentrations for the terrace.

The actions recommended include the following:

- Statistical analysis of background concentrations from floodplain background wells, non-mill-related groundwater surrounding the Shiprock site, Many Devils Wash, and existing analog sites in the area.
- Development of communication tools through statistics and visuals, including Principal Component Analysis, to use as discussion aids.
- LM and LMS contractor personnel travel to Navajo Nation to meet with the Navajo Abandoned Mine Lands Reclamation)/Uranium Mill Tailings Remedial Action Department and Navajo NEPA to discuss data.
- Determination, upon review of the data whether the necessary information exists to develop standards for the terrace and confirm standards for the floodplain. If additional data are needed, a plan will be developed to obtain additional data, for example from an analog site.
- Background concentrations, once developed, will be included in the plans for the revised GCAP and will be presented to NRC for concurrence.

Because background concentrations at the site are elevated (particularly for ground waters within the Marcos shale beneath the tailings materials), an accurate understanding of naturally occurring groundwater contamination is essential to form achievable groundwater standards. If groundwater standards are set below concentrations that can be reasonably expected in naturally occurring groundwater, there is a significant risk that groundwater compliance would never be achieved. Additionally, Navajo Nation has raised concerns about the application of supplemental standards and alternate concentration limits at the site.

The NLN process confirmed that Navajo Nation agencies were open to discussing the reevaluation of background concentrations to clarify groundwater cleanup standards. Consensus between DOE-LM and Navajo Nation regarding statistically based background concentrations for the terrace and floodplain areas will reduce regulatory risk because it will promote achievable, risk-based groundwater standards for the revised GCAP. The development of communication tools using statistics will reduce stakeholder risks associated with changing groundwater cleanup standards, especially if statistical analysis advocates to elevate them.

Summary Review of Shiprock Activities and Progress

To establish the contributions derived from the Mancos Shale, 51 locations were sampled locally and regionally in Colorado, New Mexico, and Utah. Many of the groundwater samples were saline with nitrate, selenium, and uranium concentrations commonly exceeding 250,000, 1000, and 200 µg/L, respectively. Higher concentrations were limited to groundwater associated with shale beds, but were not correlated with geographic area, stratigraphic position, or source of water. The elevated concentrations suggest that naturally occurring contamination should be considered when evaluating groundwater cleanup levels. Note that the information generated by the Shiprock team confirmed that background concentrations are highly variable in space and time, influenced on a landscape scale by the relative contributions of water from the Mancos Shale and water contributed by the San Juan River, infiltration and flooding from rainfall and snowmelt, and localized sources of water such as leaking water utilities and flowing wells. On a local scale these contributions can vary seasonally, for example as river water flowing beneath portions of the floodplain area shift in response to river stage and climate factors. Because of these complexities, the Shiprock team did not need to precisely follow the specificity of the original NNLEMS recommendations, rather to collect information that would aid in assessing background concentrations in a technically defensible manner.

The Shiprock evaluation entailed the following steps: (1) identifying representative background wells; (2) deriving background concentrations for each of the secondary COCs; and (3) comparing the applied background levels to the current spatial distribution of each secondary COC and corresponding temporal concentrations in site monitoring wells. Candidate background wells were selected for three hydrologically and geochemically distinct areas of the site: the terrace; the northern floodplain, with groundwater sourced from terrace artesian well 0648 (screened within the underlying Morrison Formation); and the southern floodplain, receiving hyporheic flow from the San Juan River. For each of these three areas, candidate background wells were initially identified based on uranium-234/uranium-238 isotope activity ratios greater than 1.20, suggesting a non-mill origin of the uranium in groundwater. This initial subset was then culled to exclude any wells with statistically significant temporal trends in COC concentrations. Using these criteria, wells 0832 (west swale area) and 1049 (Many Devils Wash) were selected as being most representative of background conditions on the terrace.

For purposes of evaluating background conditions, the floodplain was divided into two regions because of differing geochemical influences and water sources. Most of the recharge onto the northern portion of the floodplain is sourced from terrace artesian well 0648 at the head of Bob Lee Wash, while recharge in the remainder (southern portion) of the floodplain is primarily sourced from the San Juan River in the form of hyporheic flow. Considering these different water sources, terrace well 0648 was applied as

background for the northern floodplain, and westernmost near-river floodplain wells 0782R and 0783R were applied to the southern portion of the floodplain in the hyporheic zone. Wells 0797 and 0850, on another floodplain about 1 mile upstream of the site, have been designated as background wells in the GCAP and LM's previous site reports and investigations. For this study, their use as comparative background wells was not supported because (1) the geochemistry at these locations is not influenced from the Morrison Formation and (2) direct influence from the San Juan River has not been established from analysis of geochemistry or groundwater flow.

For each secondary COC and site region, background concentrations were derived using the following steps: (1) exploratory data analysis, (2) screening for and identification of outlier concentrations, and (3) derivation of background concentration based on an upper bound measurement from the wells selected as representative of site conditions not affected by site-related activities. In most cases, this value was equivalent to the maximum or nonoutlier maximum (NOLM) concentration in the background data set. More elaborate statistical approaches were initially considered—for example, derivation of upper prediction or tolerance limits with assigned confidence coefficients (e.g., 95%)—but, in all cases, these tolerance limits were equivalent to the maximum result. Therefore, for simplicity and reproducibility, the aforementioned maximum or NOLM values were applied. The comparative background concentrations applied to the three site regions—terrace, northern floodplain, and southern floodplain—are summarized as follows:

- Ammonia—0.3 milligram per liter (mg/L), 0.54 mg/L, and 0.17 mg/L
- Manganese—0.18 mg/L, 0.094 mg/L, and 3.2 mg/L
- Selenium—2 mg/L, 0.002 mg/L, and 0.002 mg/L
- Strontium—12 mg/L, 12.1 mg/L, and 2.7 mg/L

These background concentrations are considered preliminary for comparative purposes and are not intended as compliance goals.

Results

For all analytes except strontium, this analysis indicates that, at least for a portion of site wells, a COC designation is still warranted. Conclusions specific to each COC are summarized below:

- Given highly elevated concentrations in the disposal cell and evaporation pond region and on the floodplain near Trench 2, ammonia still warrants designation as a COC. Some wells in the swale region of the terrace with elevated ammonia were previously interpreted as non-mill affected based on uranium isotope signatures.
- Manganese still warrants designation as a COC given highly elevated levels in several wells near the evaporation pond, most notably in well 0603, a well also characterized by high ammonia. Manganese is also elevated in a subset of northern floodplain wells, albeit at levels much lower than those found on the terrace. Although these findings warrant manganese's continued designation as a COC, it is not clear that this analyte is useful as an indicator of milling-related impacts nor that it is helpful in assessing remediation progress.
- Selenium concentrations in all terrace wells were within the observed background range of 1–5 mg/L. These results are consistent with those found for Many Devils Wash, demonstrated to have a naturally occurring (Mancos Shale-derived) origin. On the floodplain, selenium concentrations are elevated in only a small proportion of wells at the base of the escarpment near Trench 1.

Although selenium concentrations are below background or risk-based levels in most site wells, given the limitations of the background data set and uncertainties regarding the source of elevated selenium on the floodplain, continued monitoring as a COC (at least provisionally) is recommended.

- Continued designation as a COC is not warranted for strontium. Although concentrations in a small proportion of site wells exceed background and the U.S. Environmental Protection Agency's risk-based value (both 12 mg/L), strontium has never been identified as a milling-related constituent, nor has a clear spatial pattern indicative of a contaminant plume ever been observed.

Status:

The primary recommendations stemming from this study to date are as follows:

- Information regarding the mill-era groundwater flow field and chemical composition of fluids within the tailings impoundments and raffinate ponds would further understanding of the current distribution of ammonia and selenium (along with other COCs) and potential loading onto the floodplain.
- Possible explanations for the unusual chemical signatures in terrace well 0603, near the evaporation pond, warrant further evaluation.
- Significant increases in concentrations of all seven COCs in near-river floodplain well 1136 warrant continued monitoring and evaluation. The persistence of COCs in this and other localized regions of the floodplain suggests that interactions with aquifer solids should be investigated as potential secondary sources.

Reference Documents: Reevaluation of Ammonia, Manganese, Selenium, and Strontium as Contaminants of Concern (COCs) for the Shiprock, NM, Disposal Site, April 2022

Summary Assessment

Significant progress has been made to date. The study continue will as part of a work plan to ascertain background more precisely on the terrace for the primary COCs. The site plans to engage the tribal agencies at the conclusion of this effort – more inclusive (earlier proactive) communication with the Tribal technical subject matter experts may assist in maximizing the acceptance and usability of the background information.

Remedy Progress, GCAP Support, and Compliance Strategy

This set of LOIs focused on both ex-situ and in-situ treatment options with a specific emphasis on addressing the high priorities identified by the Navajo Nation – notably developing a path forward to reduce the footprint and potential impacts of the existing evaporation pond associated with the interim pump and treat system.

Remedy Progress, GCAP Support, and Compliance Strategy LOIs

1. Evaluate major efforts at Shiprock that focused on mitigating challenges associated with aging evaporation ponds (ex-situ technologies)
2. Perform bench-scale tests for remedial technologies prioritized by the NLN collaboration and detailed literature review (in-situ technologies)

Narratives for Remedy Progress, GCAP Support, and Compliance Strategy LOIs follow.

Remediation

1. Evaluate major efforts at Shiprock that focused on mitigating challenges associated with aging evaporation ponds (ex-situ technologies)

Summary of Original Recommendation and Objectives

This recommendation addressed the current and future regulatory, stakeholder and human health risks associated with the flux of contaminants in the groundwater underlying the Shiprock Disposal Site. The recommendation addressed both ex-situ technologies (i.e., associated with pump and treat) and in-situ technologies and strategies. The activities and progress of these two categories are evaluated separately – this section focuses on ex-situ technologies.

At the time of the initial NNLEMS collaboration, water from the pump and treat system was dispositioned using evaporation in a large evaporation pond. The pond liner was approaching its design lifetime and there were concerns that liner failure would lead to leaks and releases. Potential leaking or failure of the aging pond liner was a recognized and high-profile risk driver for regulators, stakeholders DOE, and the Navajo Nation.

To address these risks, the NNLEMS collaboration recommended a range of laboratory tests to assess the state of the existing pond liner (e.g., sampling and analysis of the amount of remaining UV protecting compounds in the existing liner) and (if sun exposed liner is nearing end of life) consideration of applying and overlay liner of fresh material in the upper portion of the pond that is exposed to sunlight. Further, the NNLEMS collaboration supported the DOE-LM engineering evaluation of alternatives to simple evaporation. The NNLEMS list of ex-situ technologies included:

- Water Treatment
    - Membrane technologies (ultrafiltration, nanofiltration, reverse osmosis)
    - Ion exchange.
    - Distillation.
    - Electrocoagulation or chemical coagulation as a pretreatment.
    - Biological treatment media or bioreactor.
    - Media filtration.
    - Chemical sulfate removal.
- Water Management and Disposition
    - Evaporation (similar to ongoing remedial action).
    - Reinjection of treated water with or without oxidant addition (i.e., bicarbonate)
    - Phytoremediation, as a component of the compliance strategy.
    - Evapotranspiration (ET) disposal cell cover, as a component of the compliance strategy.

Summary Review of Shiprock Activities and Progress

Developing a path forward and working with the Navajo Nation, regulators and stakeholders to address the need for ongoing and future ex-situ water treatment and disposition has been one of the top priorities for DOE over the past 5 years. Highlights of the activities are summarized below.

DOE's LM contractor performed and engineering alternatives analysis to identify the appropriate options for treating and dispositioning groundwater generated by future pump and treat operations. Navajo technical staff and leaders and regulators were regularly briefed on the evaluation progress and on the options.

The condition of the existing pond liner was assessed. The laboratory data confirmed that the liner was nearing end of life. Logistics and costs associated with disposal of the accumulated evaporative solids and liner replacement were included in the engineering evaluation.

When complete, the engineering evaluation focused on a combination strategy that includes active treatment, offsite disposal of secondary wastes, and onsite evaporation of a "low volume" concentrate discharge using a small-lined evaporation pond. The objective of treatment is to restore most of the water (e.g., 70 to 90%) for beneficial release to the environment. The objectives of the remaining actions are to cost effectively isolate and/or control risks from the contaminants removed from the contaminated groundwater and to responsibly disposition any additional secondary wastes generated during water treatment. The preferred technology combination includes sequential electrocoagulation (EC) and reverse osmosis (RO) for water treatment an evaporation (Evap) in a small footprint lined pond for distribution of the concentrated waste brine. The public supported the results of the engineering evaluation. Implementation of the RO/EC/Evap strategy is underway.

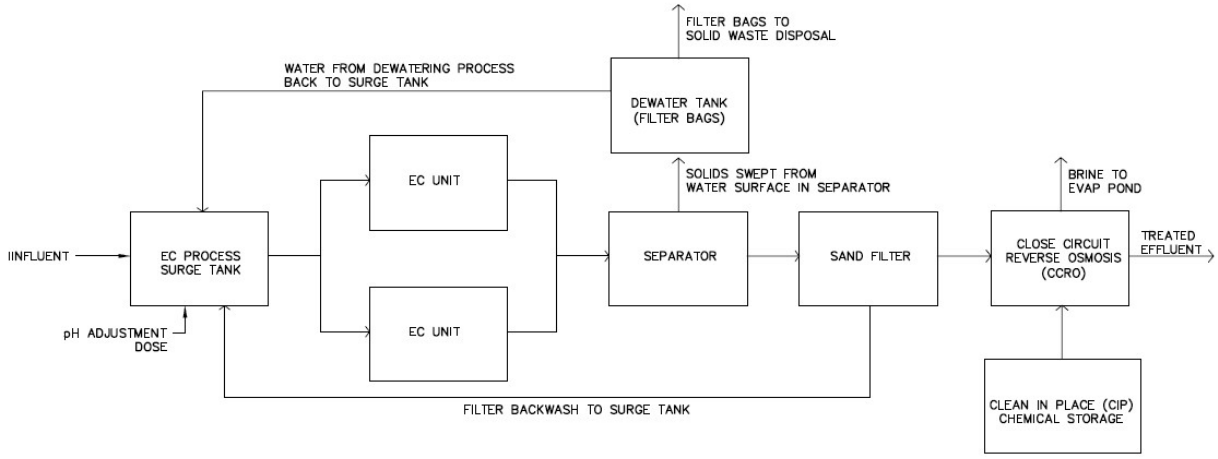

Figure 12. Schematic Diagram of Ex-situ Treatment System being Implemented by the Shiprock Team.

The Shiprock team has developed a final ex-situ groundwater treatment system design and implementation plan (Figure 12)(report No. LMS/SHP/44869). This report addresses and documents system requirements, operations and maintenance (O&M), water treatment performance objectives and metrics, secondary waste generation and disposition, and potential risks associated with implementation and operation. In particular, the design and implementation plan generally recognize the potential challenges associated with operating EC and RO systems on waters with high dissolved solids (sulfates and other salts) and the associated potential impacts on system maintenance and secondary waste

generation. The Shiprock team considered analogous commercial and technology performance experience related to treating fracking and similar geologic wastewater. The core treatment technologies EC and RO have been used for such treatment. The selected filter bag technology for separation of solids generated by the EC system is straightforward and appropriate. The Shiprock team commendably identified a complete offsite disposal pathway for generated secondary waste solids (a topic that is sometimes overlooked in the early design stages) and reasonably accounted for disposition of the brine/concentrate in a small footprint pond that, compared to the current large evaporation pond, is more acceptable to the nearby community. The Shiprock team also included reasonable estimates for future labor and operations and maintenance (O&M) resources in the evaluation and planning.

Nonetheless, treatment of Shiprock groundwater will be challenging. Some of the key performance risks are geochemical in origin, including formation of excess precipitates in the EC and RO systems or in system piping/valves – the groundwater is already near solubility for some solids and precipitation may pose a problem as the groundwater is successively concentrated in the sequential process. This issue impacted the effectiveness, efficiency and success of the membrane-based groundwater treatment system at the DOE Tuba City, AZ mill/disposal site (see SRNL-STI-2013-00619). During operation, the EC system will generate auxiliary aluminum oxide solids and controlling the quantity of these additional solids may be challenging during long-term continuous operation. Finally, compared to other water treatment unit operations, EC systems are less common and therefore there is more uncertainty in the details of design and operations and more uncertainty in expected performance. To address these various challenges, system design should emphasize easy access for O&M and cleaning as well as operational flexibility to respond to the observed performance during a startup and shake out period. When selecting contractors for final design and implementation, it would be prudent for DOE to identify and select companies with a proven track record of successfully treating analogous or similar water such as produced water from fracking or similar geologic operations at a similar scale.

Summary Assessment

Recommendation was fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team has done an exemplary job in advancing the ex-situ treatment planning and mitigating the associated risks. Communication with regulators, stakeholders and the technical and leadership representatives from the Navajo Nation were key to this progress. The potential concerns identified above should be considered in developing the startup strategy for the system and in refining system operations over the first year or so of operation.

Remediation

2. Perform bench-scale tests for remedial technologies prioritized by the NLN collaboration and detailed literature review (in-situ technologies)

Summary of Original Recommendation and Objectives

Accurate predictions of remedial technology performance will benefit from bench scale testing ahead of field implementation for most alternatives to pump-and-evaporate. It is recommended that fresh solid phase sample from the site characterization activities be used for these bench scale tests and that the tests be conducted within a reasonable timeframe after sample collection to obtain the most accurate results.

With respect to in-situ amendments the following recommendations to sequester or treat contaminants included:

- Phosphate amendments (with or without citrate).
- Silicate amendments.
- Permeable reactive barriers utilizing filter media or similar amendments.
- Slurry wall or other containment configurations.

Should bench scale testing require fresh core sample, the following actions are included:

- Store solid phase core for future bench scale testing in refrigerated conditions.
- Evaluation of peer-review literature for microbiological studies of relevance to bio-stimulated remediation (e.g. phosphate amendments) of primary contaminants of concern, including uranium, nitrate, and sulfate.
- Perform bench scale testing on select technologies, if they are recommended after the site conceptual model update, soon after fresh core samples are collected.

This recommendation addressed the current and future regulatory, stakeholder and human health risks associated with the flux of contaminants in the groundwater underlying the Shiprock Disposal Site. The activities and progress on the literature review and the in-situ technologies are described below.

Summary Review of Shiprock Activities and Progress

The literature review completed by Geosyntec observes that the three primary target remediation areas of the Shiprock site are the mill terrace area, the non-mill-terrace area, and the floodplain area. Based on currently available data, the recommended conceptual remedial approach includes:

- Immobilizing known COC sources in the mill and non-mill terrace area,
- Decreasing migration of water/contaminants from the terrace to the floodplain via the escarpment,

- Dewatering the terrace bedrock via groundwater extraction, treating the extracted water, and returning treated water to the floodplain to enhance flushing, and
- Expediting the time needed to flush remaining COCs from the floodplain soil and groundwater.

Further, Geosyntec examined a total of eight applicable remedial technologies, plus three ex-situ treatment trains. These were evaluated against the technology evaluation criteria, and the most applicable technologies are ranked (below) for each target area. A separate ranking was provided for the ex-situ treatment trains. A detailed discussion of site-specific considerations of each remedial technology and associated data needs is provided in the body of the report.

Mill terrace area. The most applicable technologies are:

- Ranking first (most favorable), a combination of:
  - Improvements to the disposal cell cover.
  - Installation of passive hydraulic barriers such as slurry walls at the upgradient perimeter of the disposal cell.
  - Phytoremediation with immobilization.
- Ranking second:
  - Active barriers with ex-situ treatment.
  - In-situ stabilization.
- Ranking third:
  - Permeable reactive barriers (PRBs).

Non-mill terrace area. The most applicable technologies are:

- Ranking first: phytoremediation with immobilization.
- Ranking second: active barriers with ex-situ treatment; and
- Ranking third: PRBs.

Floodplain. The most applicable technologies are:

- Ranking first: soil flushing/in-situ leaching.
- Ranking second: excavation of floodplain source area soil with off-site disposal; and
- Ranking third: active barriers with ex-situ treatment.

Three several potential ex-situ treatment trains appropriate for consideration were discussed further and e-situ section of this report attachments.

Three applicable ex situ treatment trains were selected for consideration and were ranked (these are discussed further in the ex-situ section of this report).

The high-risk site retrospective team supports the progress toward developing a combined remedy for Shiprock – a defense in depth strategy that includes both active and passive elements and that combines ex-situ and in situ actions. Specifically, the panel supports targeted and selective application of in situ sequestration to help control source-mass releases and cross-boundary fluxes in the preferential flow paths from the terrace to the floodplain. The work at Shiprock has been informed by past successful laboratory and field studies/applications of sequestration using injectable in situ hydroxyapatite reagents

and polyphosphate reagents (e.g., studies done at Hanford, WA, at the Homestake Grants, NM site, at the Old Rifle, CO site; and the Moab Site. Several specific findings related to in situ sequestration – "Evaluation of Hydroxyapatite to Sequester Uranium from Groundwater and Sediment in the Floodplain of the Shiprock, New Mexico, Disposal Site" -- were developed by the panel.

The use of in situ sequestration (hydroxyapatite or polyphosphate) is unlikely to be effective as a primary or sole remediation technology due to the large contaminant mass, the remediation timeframe and the nature and complexity of subsurface geochemistry and potentially variable spatial remedial objectives (e.g., terrace groundwater versus floodplain groundwater). If in situ sequestration was used as primary of sole treatment, the contaminant mass, large plume size and persistent source mass flux would likely: increase treatment duration and necessitate injection of large amounts of reagents at locations where the treatment itself has the potential to cause collateral impacts (such as release of phosphate or ammonium into the river). When applied at a large scale, there is also potential for solubilization of arsenic and collateral increases in groundwater concentrations. Nonetheless, the panel supports continued development of in situ sequestration concepts for the Shiprock site – but applied in a more targeted and surgical manner to achieve specific and identifiable remedial performance objectives. These include suppression of source mass flux and/or reduction of cross boundary flux from the terrace to the floodplain in identified preferential flow path locations.

Summary Assessment

Recommendation is in progress; additional observations and recommendations (minor) are outlined below.

The literature review has been completed by Geosyntec as recommended.

The Shiprock team has done a commendable job in advancing the in-situ treatment planning and execution. The conclusions associated with the hydroxyapatite (calcium citrate-Na-phosphate amendment) above are not unreasonable. However, the benefit of this amendment is for hot-spot treatment and the temporary attenuation (months to years) of uranium and COC fluxes while pump-and-treat and or other approaches would typically be used concurrently at a site with a high residual source mass.

Going forward, the GCAP Program has plans to conduct a remedial alternatives evaluation at Shiprock that would at this time include in situ options. Replanning and further evaluation of in situ is on hold as current site efforts and resources are focused on pond removal and water treatment unit installation.

Importantly, a comprehensive defense in depth approach to a GCAP, including ex situ (pump and treat) and targeted in situ technologies may be appropriate for consideration. For example, if heterogeneities and zones of higher flux from the terrace to the floodplain areas are clearly identified and delineated, these might represent areas of opportunity to deploy in situ technologies and support a composite strategy that is efficient and effective, and which minimizes the releases of contaminants to the surrounding environment and the associated risks.

Tribal, Stakeholder, Regulatory, and STEM Activities

The final set of LOIs relate to the tribal, stakeholder, regulatory, and STEM activities that were recommended in the 2020 document. These are addressed in a single narrative since the issues and needs are generally not technical in nature.

Tribal, Stakeholder, Regulatory, and STEM Activities LOIs

All Navajo Nation and Stakeholder Regulator and STEM Related LOIs

Narrative for the Tribal, Stakeholder, Regulatory, and STEM Activities LOI follows.

All Navajo Nation and Stakeholder Regulator and STEM Related LOIs

Summary of Original Recommendations and Objectives

Stakeholder community and technical interactions were emphasized in the LM-NNLEMS collaboration recommendations and actions. There were numerous specific recommendations that covered a wide range of topics including continuing/maintaining communications, supporting STEM activities, providing or limiting public access to areas as appropriate to minimize risks, and coordinating with tribal subject matter experts to the assure quality and acceptability of GCAP related decisions.

Specific stakeholder related recommendations (LOIs) included:

- Affirm and Prioritize Coordination Efforts Between DOE-LM and Navajo Nation Entities (including maintaining regular communication and actively engaging with Navajo Nation Leaders and technical representatives.
- Work with the Navajo Nation to finalize Institutional Controls at the Shiprock Site (including 1) finalizing the water use restriction with the Navajo Nation Water Control Authority (NNWCA), 2) determining if grazing restrictions are still needed at the Shiprock site, and 3) assigning appropriate land status for areas such as the floodplain that contain remediation infrastructure or mill-related contamination but are offsite).
- Mentor Young Community Members Through STEM Workshops at the Site and Internships for Students from Diné College Shiprock Campus and Navajo Technical University's New Environmental Engineering Program
- Develop Beneficial Reuse Opportunities for the Floodplain, with Conceptual Plans for a Recreational Trail and Informational Kiosk
- Create Interactive Decision Points at Crucial Junctures During the GCAP Process, Directly Engaging NLN, Navajo Nation, and NRC for Input
- Update the Site Water Balance with Data from the Navajo Tribal Utility Authority (NTUA), the Navajo Engineering Construction Authority (NECA), and the Shiprock Chapter Regarding evaluation of Infiltration Sources and Potential Opportunities to Control Them

Summary Review of Shiprock Activities and Progress

In response to is stewardship responsibilities, DOE-LM has developed, demonstrated, refined and implemented best practice approaches to public engagement –LM is the premier organization within DOE in effectively and positively working with stakeholders. Key documentation of the stakeholder engagement activities at Shiprock over the past five years is provided in LMS/SHIPROCK/S18769 (Community Involvement Plan Shiprock, New Mexico, Disposal Site , May 2024). At Shiprock, DOE-LM has applied their relevant culture and experience to maintain and beneficially expand stakeholder engagements, including providing opportunities for involvement, supporting public awareness, informing the public about current and planned site-related activities, educating the public about site activities, providing access to site information, reports, and other documents, participating in Navajo Nation fairs,

STEM events, and community events, continuing coordination with the Shiprock Chapter House to maintain the information kiosk that shares Shiprock disposal cell history and promotes long-term information sharing. Some of the methods used for communication include participating in regular meetings with stakeholders, sharing information through in-person outreach activities, and eliciting feedback and suggestions.

LM provides general informational materials at outreach events, including (all of these are also on LM's website): Site fact sheet for Shiprock (and nearby DOE-LM sites such as Mexican Hat, Utah, Disposal Site, Monument Valley, Arizona, Processing Site, and Tuba City, Arizona, Disposal Site); Working with the Navajo Nation and Hopi Tribe fact sheet; Window Rock, Arizona, Navajo Nation Community Outreach Network Office fact sheet and map; Women of the Manhattan Project coloring book; DOE-LM overview brochure; DOE-LM Strategic Plan brochure; DOE-LM video about work done on the Navajo Nation; Uranium and Radiation on the Navajo Nation resource list; DOE-LM children's brochure; and the Community Outreach Network information sheet. Many Shiprock site projects require and generate project specific information sheets that detail the work being done. DOE-LM distributes and shares all information sheets with the Chapter House, local businesses, and residences near the site. Further, DOE-LM team at Shiprock has provided active STEM support to local schools and has collaborated with local university professors and with students (undergraduate students, graduate students and interns) during this period.

Figure 13 and Figure 14 depict examples of ongoing interactions. Figure 13 shows a site visit with Shiprock Chapter House leadership and technical representatives. Figure 14 is a graphical representation of the types of interactions and how they are scheduled to ensure effective communication.

Figure 13. DOE-LM site tour with Shiprock Chapter House leadership and the Navajo Abandoned Mine Lands Department staff

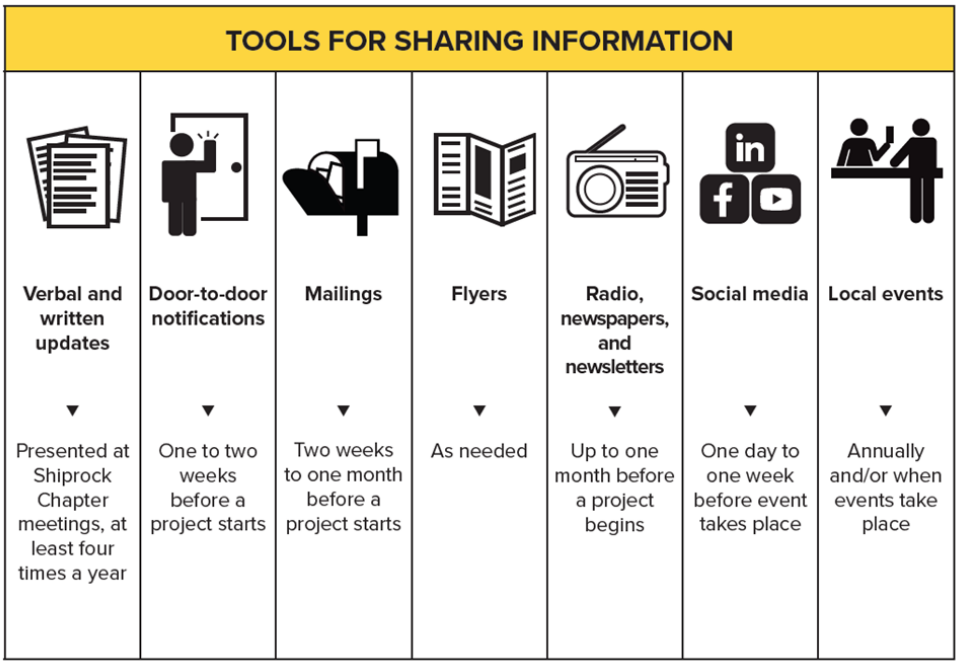

Figure 14. DOE-LM tools and timeframes for sharing information with stakeholders

One of the technical recommendations has not been implemented – specifically to coordinate with the Tribal water authority to gather information on the potential for terrace impacts resulting from the water contributed to the subsurface from leaking water lines. This activity was delayed allowing the Shiprock team and resources to focus on developing and implementing solutions to address the aging evaporation pond. The possibility that anthropogenic water may be impacting groundwater on the terrace in this semiarid setting is an unresolved data gap. Thus, we recommend that the Shiprock team pursue this straightforward collaboration in the near- to mid- term. A primary objective of the effort would be to update and quantify the potential contribution of leaking water to site water balance in collaboration with the NTUA, NECA and the Shiprock Chapter. If the contributions from leaking water are identified as significant, then the collaboration could then evaluate engineering alternatives to mitigate or beneficially control leakage.

A recommendation related to providing public access to the floodplain area (with supporting infrastructure) were not implemented during this period. These concepts along with details of ICs and other topics represent longer term actions that need to be considered and formalized in the GCAP process so there is no urgency to implement these in the near- to mid-term timeframe.

Summary Assessment

Recommendations were fulfilled; additional recommendations (minor) are outlined below.

The Shiprock team has done an exemplary job in working with the Navajo Nation, stakeholders, community, schools, and others. The DOE-LM outreach and stakeholder program has been developed and steadily improved over several decades and currently is an exemplar of “best practices” that provides a model that can be valuable to the rest of DOE and other Federal Agencies. The DOE-LM skillset and organizational culture was clearly demonstrated over the past five years at the Shiprock site. There was a delay in the collaboration with the Navajo to evaluate potential anthropogenic water sources to the Terrace groundwater system -- this delay was associated with the need to allocate more resources and staff focus on replacement of the aging evaporation pond. The recommended updated water balance that includes defensible water leaks and other anthropogenic sources of water (and identification of possible low-cost fixes if significant) remains important and would be appropriate to pursue in the near- to mid-term.

Appendix B: Shiprock Workshop Agenda and Participants

Agenda:

Agenda for Shiprock Workshop

January 14, 2025

10AM to 1PM MT

Start Time	Duration	Topic	Speakers/Participants
10:00 AM	5 minutes	Introductions (name, affiliation, expertise)	All
10:05 AM	10 minutes	Project background and objectives	Lab Team: Chris Johnson (PNNL) Brian Looney (SRNL) Mark Rigali (SNL) Ken Williams (LBL)
10:15 AM	5 minutes	Initial questions from participants	All
10:20 AM	50 minutes	Site Characterization, Modeling, and Other Actions to Address GCAP Data Gaps	Lab Team, Shiprock Team, LM HQ
11:10 AM	5 minutes	**Break**	
11:15 AM	40 minutes	Remedy Progress, GCAP Support, and Compliance Strategy	Lab Team, NRC, LM HQ, Shiprock Team
11:55 AM	40 minutes	Tribal, Stakeholder, Regulatory, and STEM Activities	Lab Team, NRC, Navajo Nations, LM HQ, Shiprock Team
12:35 PM	15 minutes	Final Summary Discussion for Long-Term Compliance	All
12:50 PM	10 minutes	Final questions, thoughts, comments	All

Figure 15. Agenda for the January 2025 Shiprock Workshop

Participants:

DOE-LM: Darina Castillo, Jalena Dayvault, Anthony Farinacci, Bill Frazier, Chris Jarchow, Tania Smith Taylor, Joni Tallbull,

National Laboratory Network: Carol Eddy-Dilek (SRNL), Chris Johnson (PNNL), Brian Looney (SRNL), Mark Rigali (SNL), Ken Williams (LBNL)

NRC: Bill Von Till

Shiprock Site/RSI: Elizabeth DuQuette, Susan Kamp, Jon Luellen, Brian Peake, Doc Richardson, Pete Schillig

Navajo AML: Ernest Grayeyes

Meeting Moderator: Emily Fabricatore (SRNL)