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Determining environmental impacts from historical uranium mining operations using multiple lines of evidence and communicating the process and conclusions to the community

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Abstract

Determining environmental impacts from historical uranium mining operations at abandoned uranium mines creates unique challenges. The radionuclides and metals associated with uranium ore are naturally occurring in heterogeneous concentrations, such that it is difficult to distinguish between concentrations of radionuclides and metals that are naturally occurring and those that may have been technologically enhanced through mining activities. The term 'Technologically Enhanced Naturally Occurring Radioactive Material' (TENORM) is used to distinguish concentrations that resulted from historical mining from naturally occurring radioactive material (NORM) that are not related to mining operations. Multiple lines of evidence (MLE) are used to determine the nature and extent of contamination, understand potential fate and transport pathways, and develop a conceptual site model of the extent of mining-impacted material, including TENORM, on mine sites.

The MLEs include reviewing historical mining and reclamation activities; conducting interviews with residents and consulting with reclamation staff; reviewing historical and current aerial photographs; analysing geologic stratigraphy, hydrogeology, geomorphology and hydrology; analysing disturbance mapping (as it relates to vegetation changes associated with possible mining or reclamation activities); identifying prominent wind direction; and characterising site data (including visual observations, radiation surveys and surface and subsurface soil sampling). Through the use of MLEs, site media are classified as NORM or TENORM. Areas determined to be TENORM undergo a risk assessment to determine cleanup areas and volumes.

Communicating areas of TENORM can be challenging to present to the community. The key to overcoming those challenges is educating the community on how conclusions are drawn and what will be addressed by action or left in place.

Keywords: *closure, TENORM, NORM, radioactive, community outreach, technologically enhanced radioactive material, naturally occurring radioactive material, uranium*

1 Introduction

Uranium mining was conducted on the Navajo Nation, located in the four-corners region of the United States, including northwestern New Mexico, northeastern Arizona and southeastern Utah, with peak mining occurring between the 1940s and 1960s (United States Environmental Protection Agency 2007). Determining environmental impacts from historical uranium mining operations at abandoned uranium mines (AUMs) creates unique challenges. The geologic formations historically mined for uranium contain naturally elevated and variable concentrations of radionuclides and metals, such as radium-226 (Ra-226), arsenic, thorium, uranium, and vanadium, which are difficult to distinguish from the natural surroundings. The term 'Technologically Enhanced Naturally Occurring Radioactive Material' (TENORM) is used to distinguish materials that have been concentrated or exposed because of historical mining-related activities from naturally occurring radioactive material (NORM) that is not affected by mining operations.

Uranium ore was mined from deposits located at or near the surface because of the presence of outcrops containing ore-bearing rock at the mine sites (Chenoweth 1985). The presence of the naturally exposed ore-bearing rock at the mine sites can result in similar soil sampling results and radiation data being measured in both NORM and TENORM areas when conducting environmental investigations. The ore was trucked to mills for processing, and waste rock consisting of overburden and low-grade ore was typically left near mine openings or pushed over steep cliffs during mining activities (Chenoweth 1988). Site characterisation data collected at the mine site and a multiple-lines-of-evidence (MLE) approach are used to determine the nature and extent of contamination, understand potential fate and transport pathways, develop a conceptual site model and determine the area of mining-impacted material, including TENORM, resulting from historical mining activities. After the area of TENORM present at the mine site is determined, a risk assessment is performed to refine the TENORM area and determine the volume of soil that requires cleanup. This process has been used at multiple mines sites; it is approved by regulatory agencies and has been presented to the communities within the Navajo Nation.

2 Multiple-lines-of-evidence approach

The MLE approach evaluates materials impacted by mining-related activities, including NORM and TENORM designation. The MLE approach is particularly important when assessing radiation survey results and analytical soil data that are elevated but are indicative of natural conditions and not caused by mining-related activities. Examples of the MLEs that are employed and how they are used are as follows:

- Available historical data, including aerial photographs, historical records, Atomic Energy Commission (AEC) records, Navajo Abandoned Mine Lands reclamation records, interviews with community members and site visits.
  - Review available historical aerial photos and light detection and ranging data, including years before, during and after mining. Features, such as roads, disturbances and drainages, are identified and used to understand the mine site's conceptual site model (CSM).
  - Academic reports, AEC records, lease and production information and other documents relevant to the site are used to understand years of operation and the amount of uranium ore that was produced from the mine site.
  - Historical reclamation records from Navajo Abandoned Mine Lands and the U.S. Environmental Protection Agency contain information related to the location and reclamation of historical mining features, such as portals, rim strips and waste rock piles. This information is used to determine where potential mining-related activities may have occurred on the mine site.
  - Ethnography and cultural resource surveys are used to get first-hand accounts of mining history in the area and identify culturally sensitive items too so they may be protected and/or avoided.
- Geology and geomorphology, including hydrology/transport pathways, topography, local geology and aerial photography.
  - U.S. Geological Survey geologic maps, in conjunction with geologic contact mapping conducted in the field, assists in determining background reference areas and identifying where ore-bearing rock may be exposed at the mine site.

- Feature documentation and disturbance mapping, including historical documentation and visual observations of exploration, mining and reclamation.
  - Field personnel document and describe mine features (for example, portals and waste rock piles), streams, structures and inaccessible areas. This information is used to ground truth historical information and put together the mine site's CSM. Drainages that may transport contaminants away from the mine site were also documented.
  - Qualified biologists and field personnel map areas of disturbed vegetation and visual observation of evidence of mining, such as exploration, mining and reclamation. These disturbances are generally located where vegetative covers have been placed on historical reclamation features. This information is used to identify which portions of the mine site have and have not been disturbed by mining-related activities.
- Site characterisation data, including radiation survey data and soil, sediment and water samples.
  - Radiation surveys across the mine site surfaces (including haul roads and drainages) and soil sampling are conducted to characterise the nature and extent of impacts to the soil and sediment at the mine site. Potential sources of contamination at the mine site include areas around the mine openings, waste rock piles, ore spilled from haul trucks on access and haul roads and areas where explosives were used and equipment maintenance and fuelling occurred.
  - Analytical data from radiation surveys and soil samples collected at the mine site (including haul roads and drainages) are compared with the data collected in background areas, which are representative of the physical conditions at the mine site that have not been impacted by historical mining-related activities.

Each of these MLEs is included and evaluated in the CSM for the mine sites. The CSM is intended to be a dynamic framework that facilitates future decision-making processes.

3 Example of MLE approach in determining TENORM

The following is an example of how site data and MLEs are used to determine areas of NORM and TENORM at the mine site. Mining-related features, such as portals, rim strips and waste rock piles, are identified through historical records review prior to the field investigation (Figure 1). The locations of historical mining-related features are used to focus the field investigation and inform sampling locations.

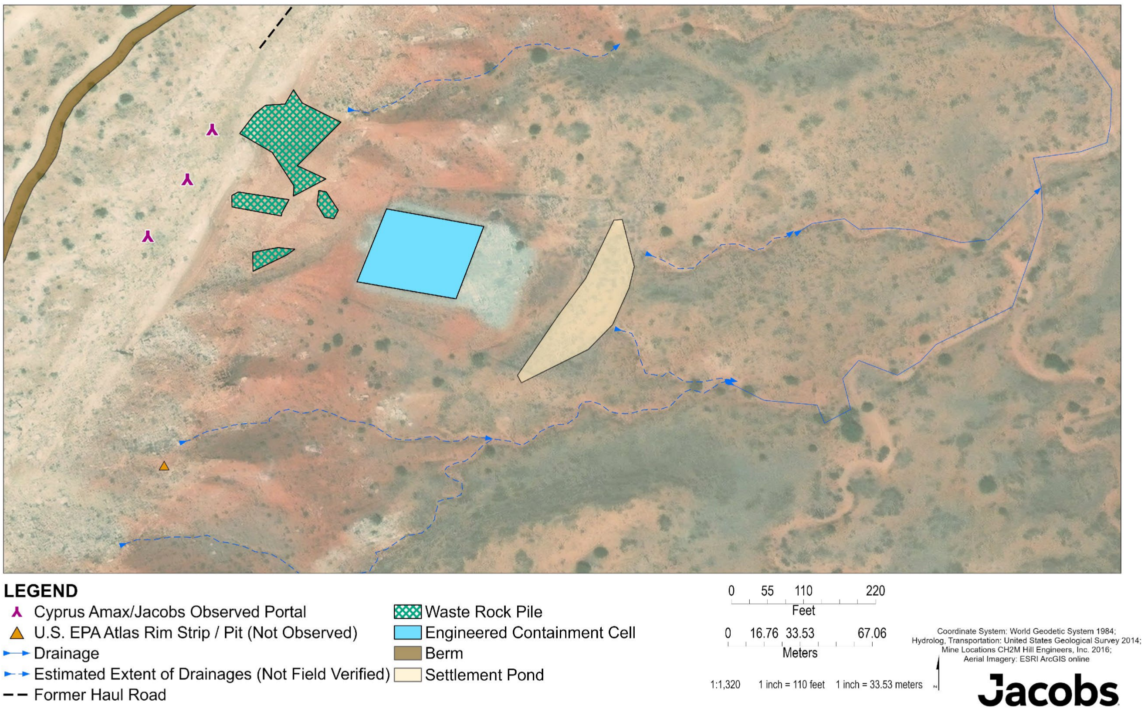


Figure 1 Mine site features

Radiation surveys are performed across accessible portions of the mine site, former haul roads and drainages. Surface and subsurface soil sampling and laboratory analysis for radionuclides, including Ra-226, and metals are performed across the mine site to achieve lateral and vertical delineation (Figure 2).

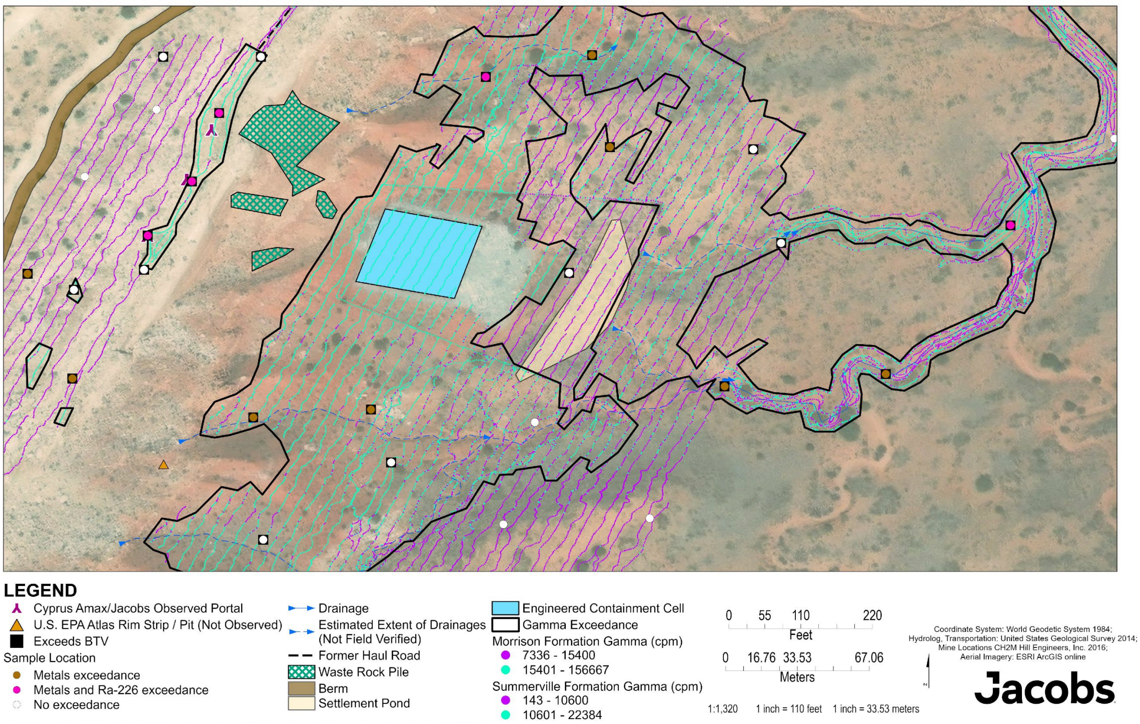


Figure 2 Investigation results

Radiation survey data and analytical soil data that are inconsistent with their respective background area are identified for further investigation to determine whether they are caused by natural variability in the native soil or are a result of mining-related activities at the site using the MLE approach. Exceedances determined to be caused by mining-related features are considered TENORM; exceedances determined to be due to natural variability of radionuclides and metals are considered NORM.

The lines of evidence that were used to determine the area of TENORM for this example include the following:

- Historical records indicate that mining features, such as portals and waste rock piles, were present, and the mining features were observed and documented during the field investigation.
- The mine was active from 1942 to 1944 and from 1948 to 1952 and produced approximately 800 tons (726 tonnes) of ore containing 3,000 pounds (1,360 kilograms) of uranium and 28,000 pounds (12,700 kilograms) of vanadium.
- Reclamation work was conducted and included backfilling three adits (portals) with mine waste rock, burying mine waste rock, closing three portals, excavating five waste rock piles and scarifying access roads. A berm, an outlet gabion, a settlement pond and an engineered cell with filter fabrics to minimise soil migration were constructed.
- Visible waste rock was observed during soil sample collection.
- Gamma count rates and analytical soil data that are inconsistent with background for Ra-226 and metals were measured around the portals and waste rock piles.
- Data inconsistent with background are located within a drainage downgradient from documented mining features.

The lines of evidence that were used to determine whether a location should be considered NORM include the following:

- Historical records did not document mining-related features or reclamation activities occurring in portions of the mine site.
- Historical aerial photographs do not reveal any disturbances in an area during times when mining was documented to have occurred.
- Exposed bedrock from an ore-bearing rock is prevalent in the area, which can contribute to elevated Ra-226 and metals concentrations.
- Concentration of Ra-226 and metals results above background level are observed in portions of the mine site that are topographically above where historical mining is documented to have occurred.
- No disturbances of vegetation or the ground surface are observed that would indicate historical mining or reclamation occurred.

Using the MLE approach, the TENORM areas at the mine site were determined as shown in Figure 3.

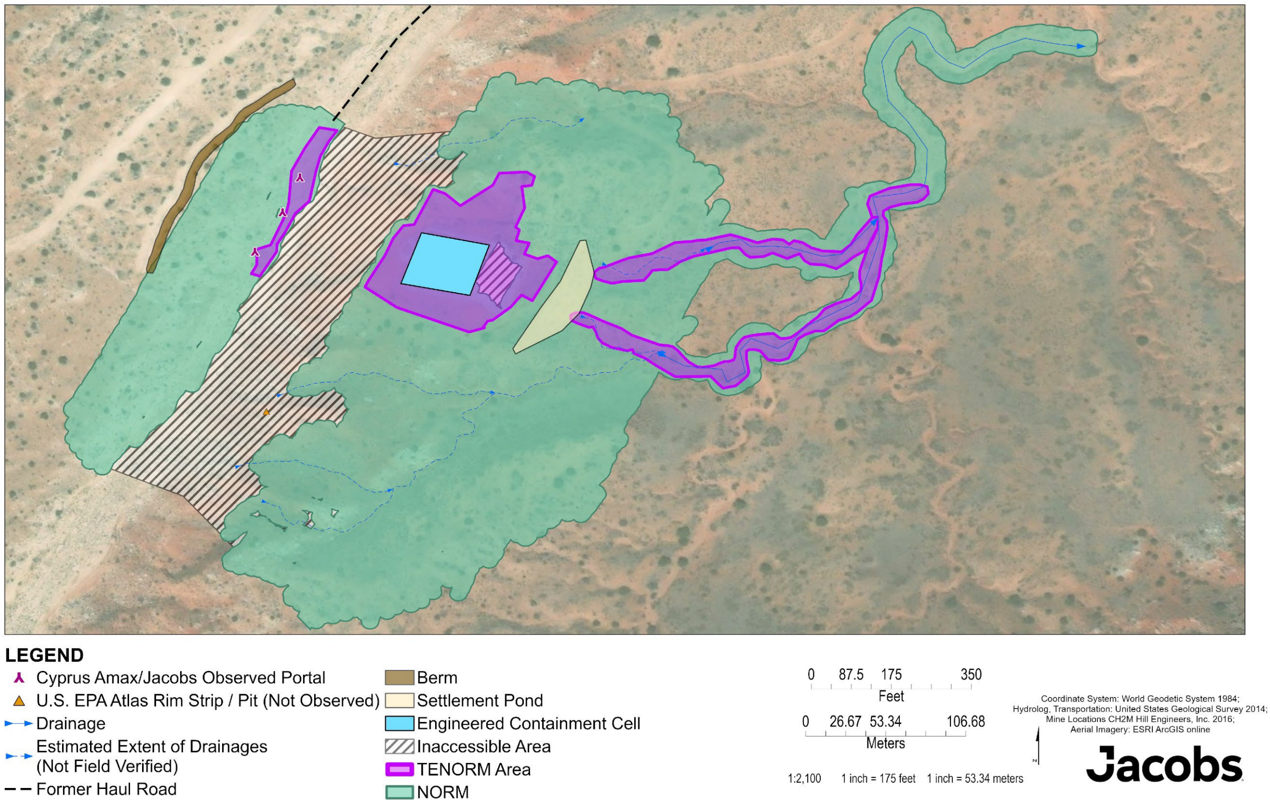


Figure 3 TENORM area

4 Risk assessment

After the TENORM boundary is determined, a risk assessment is performed using the data within the TENORM boundary to evaluate current and future human health and ecological risk. The risk assessment identifies human health contaminants of concern and contaminants of ecological concern. In addition, the risk assessment results are used to determine cleanup goals and the extent of a response action. The results of the risk assessment are used in conjunction with background concentrations and Los Alamos National Laboratory (LANL) Preliminary Remediation Goals (PRGs) to determine final cleanup goals for a given location. The cleanup goal depends on geology and future land use and varies based on the location.

The objective of the human health risk assessment is to evaluate whether the detected contaminants pose an unacceptable cancer risk or noncancer hazards. For this example, a target risk of 1 in 10 thousand (1×10^{-4}) and a target hazard quotient of 1 for current or potential future human receptors are used. The CSM for sources, transport pathways, exposure routes and receptors in the human health risk assessment is shown in Figure 4.

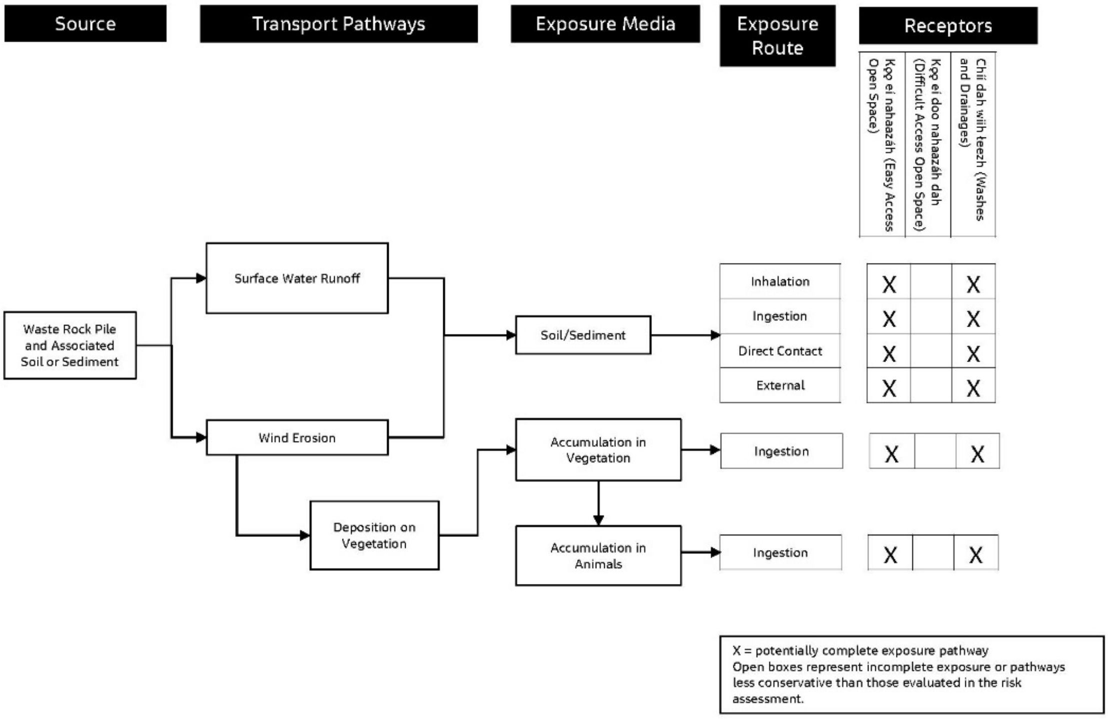


Figure 4 Human health conceptual site model

The purpose of the ecological risk assessment is to evaluate whether ecological receptors, including plants, invertebrates, birds and mammals, might be adversely affected by exposure to site-related contaminants. The CSM for ecological receptors is shown in Figure 5.

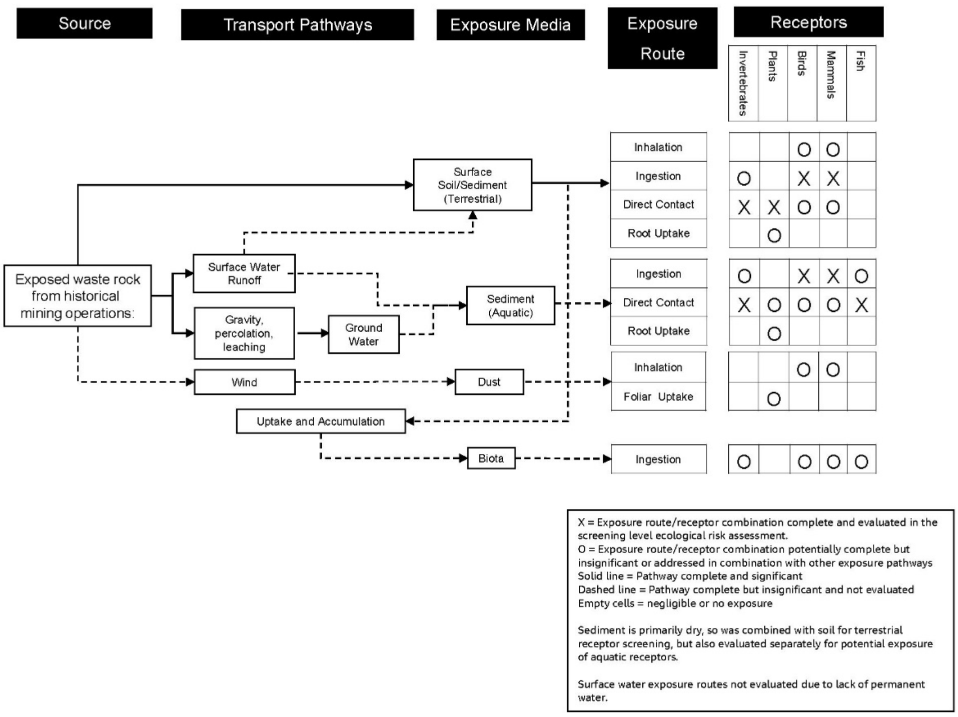


Figure 5 Ecological health conceptual site model

The cleanup extents for the mine site are determined by comparing the analytical data within the boundaries of the TENORM areas (Figure 3) with the cleanup goals determined by the risk assessment. The cleanup goals used for the example mine site are presented in Table 1 and represent the lower of the human health and ecological risk-based screening levels or the LANL PRG if the risk-based screening level was greater than the background concentration.

Table 1 Example cleanup goals for the mine site

Location	Radium-226 (pCi/g)	Arsenic (mg/kg)	Uranium (mg/kg)	Vanadium (mg/kg)
Soil	5.9	6.4	15	80
Soil in drainage	1.5	5.1	--	80

Notes:

-- = No value for uranium in this example.
mg/kg = milligrams per kilogram
pCi/g = picocuries per gram

Values for soil are examples for the Morrison Formation geology and an easy-access, open-space future land use. Values for soil in drainages are examples for the Summerville Formation geology.

An example of the extent of the mine site requiring cleanup is presented in Figure 6.

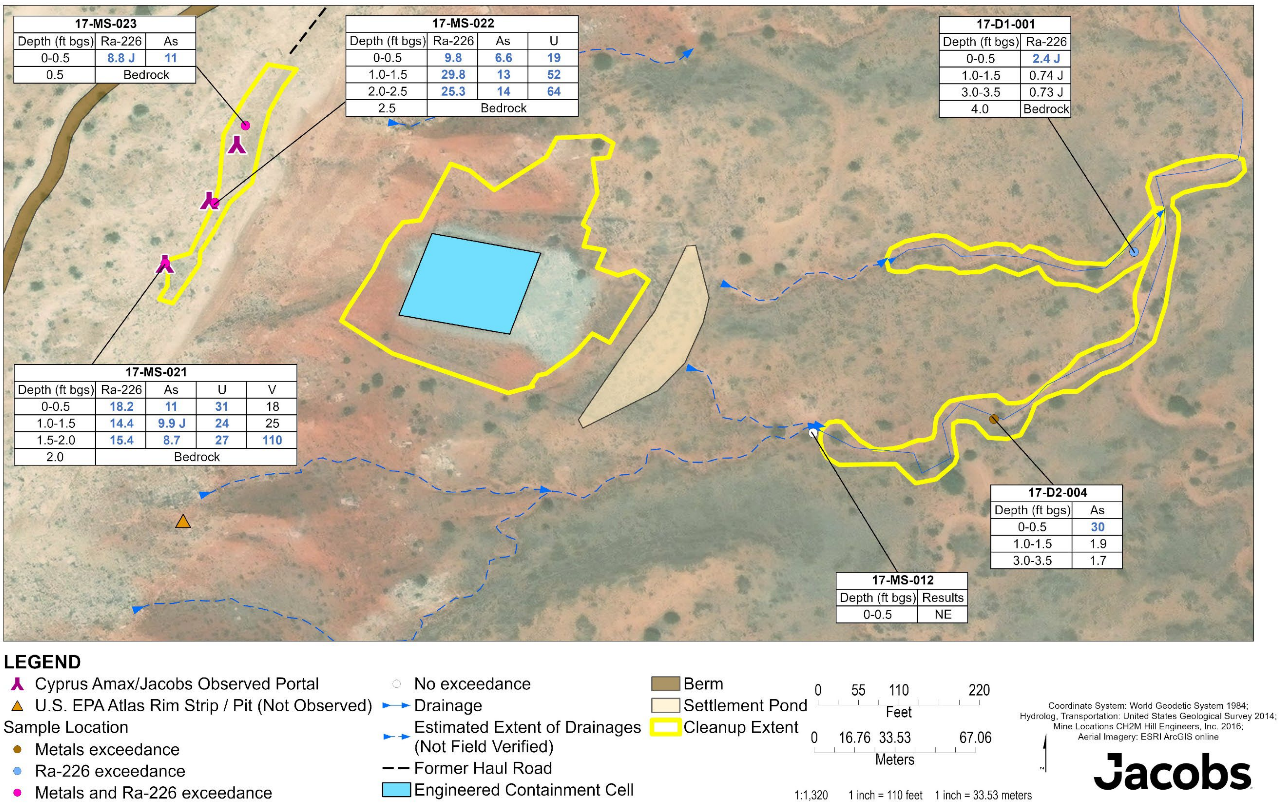
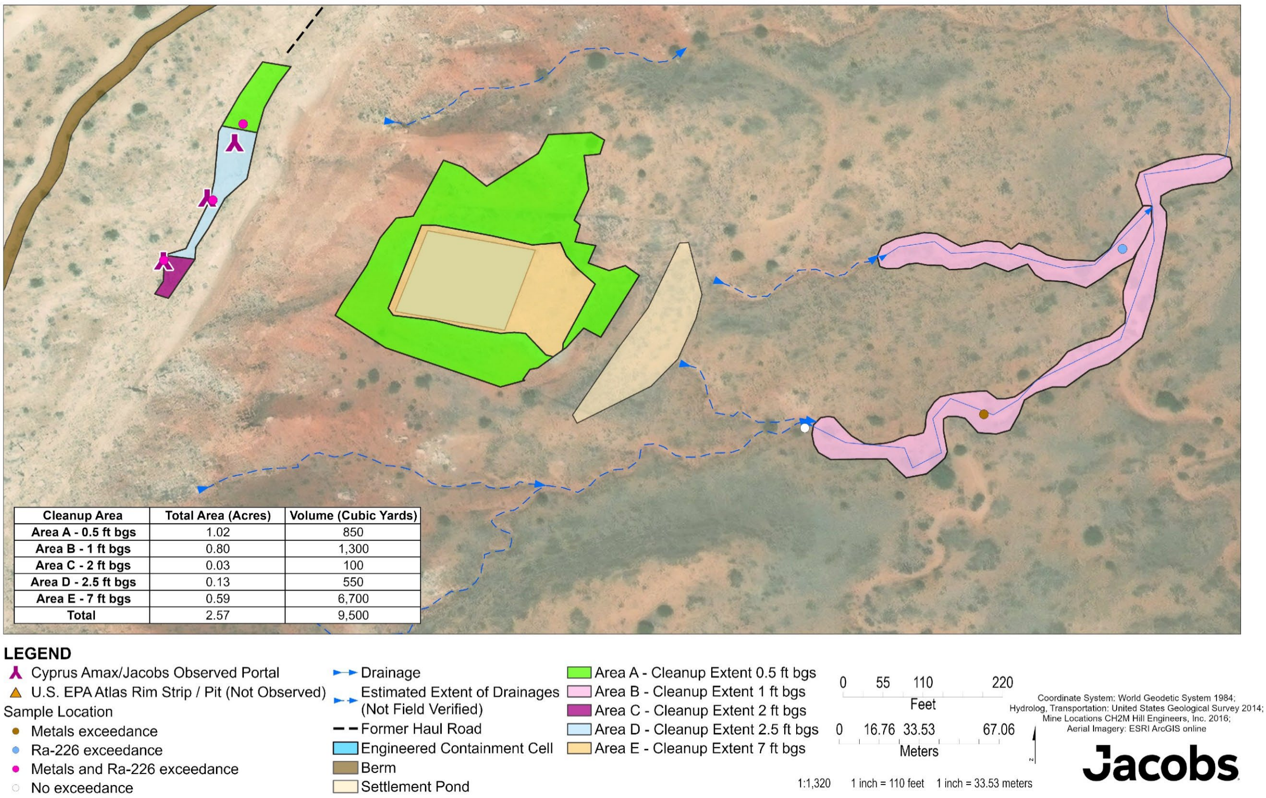


Figure 6 Cleanup extent

5 Cleanup volumes

A polygon is placed around sample locations (Figure 6) that exceed the cleanup goals identified in Table 1. The cleanup volume is calculated by using geographic information system tools and analytical data to estimate the volume of soil within the TENORM area that exceeds the cleanup goals for the site. Cleanup volumes are shown in Figure 7.



Cleanup Area	Total Area (Acres)	Volume (Cubic Yards)
Area A - 0.5 ft bgs	1.02	850
Area B - 1 ft bgs	0.80	1,300
Area C - 2 ft bgs	0.03	100
Area D - 2.5 ft bgs	0.13	550
Area E - 7 ft bgs	0.59	6,700
Total	2.57	9,500

Figure 7 Cleanup volumes

6 Community communication

Effectively communicating the MLE and risk assessment process can be challenging to describe to community members of the Navajo Nation because of the complex scientific terminology and concepts and different ways of thinking, discussing and understanding. But those challenges can be addressed by educating the community on the risk assessment process and explaining how conclusions are made in an approachable and understandable way, starting by engaging with the community according to their preferred method of receiving information and their decision-making process. One way is to use a circular model for decision making following the Navajo traditional characteristics of each of the Four Directions, flowing from east to west, shown in Figure 8.

The nested, circular model of problem solving includes the four nested stages of thinking (*nitsáhákees*), planning (*nahat'á*), implementation (*Iiná*) and eventual results (*sihasin*) shown in Figure 8. The traditional characteristics of each of the Four Directions are as follows: *nitáhákees*, for intuition, discovery and thinking of the East; *nahat'á*, or planning, to carefully examine and involve all interests and knowledge holders in the process of the South; *Iiná* to implement thought and consensual plans actively and for good results of the West; and *sihasin*, or reflection and reconsideration, to assess the result of thinking, talking, planning and doing of the North (Navajo Nation 2018).

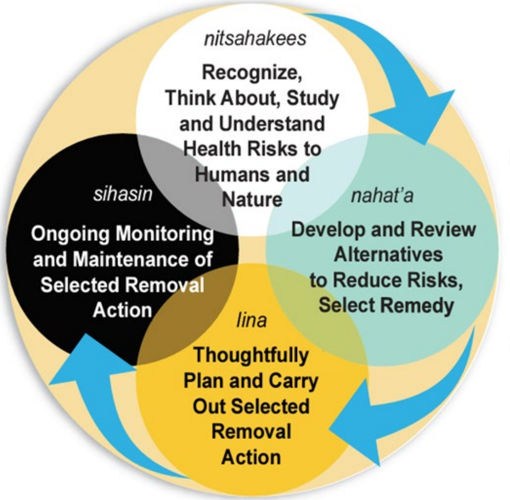


Figure 8 Circular model of decision making

Research, site characterisation, MLE process, risk assessment and TENORM volume calculations occur in the thinking (*nitsáhákees*) stage. This stage gathers information about the site, including historical mining activities, previous reclamation work and the current state of the area; and evaluates this information through a MLE approach to make thoughtful decisions; answers the questions that arise with careful examination and consideration of interests of people and knowledge holders and makes choices that will bring the desired results.

7 Conclusion

Determining environmental impacts from historical uranium mining operations at AUMs creates unique challenges. Radionuclides and metals are naturally present in heterogeneous concentrations, which makes it difficult to distinguish natural conditions from impacts caused by historical mining operations. The MLE approach is used to determine the nature and extent of contamination, understand potential fate and transport pathways, develop a CSM and determine the area of mining-impacted material, including TENORM, resulting from historical mining activities.

By performing a risk assessment on TENORM areas, human health and ecological contaminants of concern are identified, and an evaluation is performed to determine whether detected contaminants pose unacceptable risk. The risk assessment results are used to determine cleanup goals at the mine site, and the extent of the response action (area and volume) is determined by comparing the data with the cleanup goals.

Effective community communication is achieved by involving the community early in the process and by building trust through educating the community on how conclusions are drawn and what will be addressed by the response action (TENORM) or left in place (NORM). A community's preferred method of receiving information and their decision-making process should be considered to be effective in communicating these technical topics.

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