LMS/DUD/S32845

Planning Approach to Investigate Variable Uranium Concentrations in Well 0618 Alluvial Groundwater at the Durango, Colorado, Disposal Site

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U.S. DEPARTMENT OF ENERGY | Legacy Management

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Abbreviations

3D	three-dimensional
CDPHE	Colorado Department of Public Health and Environment
DOE	U.S. Department of Energy
DQO	data quality objective
DR	decision rule
EPA	U.S. Environmental Protection Agency
LM	Office of Legacy Management
LMS	Legacy Management Support
NMR	nuclear magnetic resonance
NRC	U.S. Nuclear Regulatory Commission
PFM	passive flux meters
PRB	permeable reactive barrier
^{222}Rn	radon-222
UAR	uranium-234/uranium-238 activity ratio

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Executive Summary

Well 0618 is completed in the alluvial deposit above the compliance aquifer to the northeast of the disposal cell at the Durango, Colorado, Disposal Site. This well has been monitored as a best management practice since 2003 because uranium concentrations measured from this well have been variable and typically elevated above background. Nearby wells 608 and 621 have been included in the monitoring plan as well. In the past, the U.S. Department of Energy, with the support of the U.S. Nuclear Regulatory Commission and the Colorado Department of Public Health and Environment, has previously performed field activities surrounding the transient drainage collection to eliminate potential sources at this area of the disposal site. The purpose of this investigation is to verify the source and identify location(s) of exposure; evaluate risk; and, if needed, implement an appropriate risk-informed mitigation measure. Specific study objectives and data collection activities for this investigation were developed to understand the following:

- The spatial extent and temporal variability of the water table within the alluvium that is impacted by uranium in groundwater
- The source of uranium in groundwater measured at well 0618
- The mass flux of dissolved uranium within alluvial groundwater and factors controlling its variability
- The location of alluvial groundwater discharge and a risk evaluation of potential exposure in the South Creek arroyo

The location(s) where alluvial groundwater is concluded to discharge will serve as the location(s) of exposure where a risk evaluation will be performed to determine if mitigation measures are needed.

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1.0 Introduction

1.1 Objectives and Scope

Since 2003, uranium concentration measurements in well 0618, completed in the alluvial deposit above the compliance aquifer to the northeast of the disposal cell at the Durango, Colorado, Disposal Site (site), have been collected as a best management practice to understand the variability, typically above background, and overall behavior in this well. In the past, the U.S. Department of Energy (DOE) Office of Legacy Management (LM) has performed activities, including removing installations and infrastructure that may have been affecting this well, but highly variable uranium concentrations are persisting. The purpose of this investigation is to verify the source and identify locations of exposure; evaluate risk; and, if needed, implement a risk-informed mitigation measure. This document outlines a comprehensive sequential approach of step-by-step activities that were developed with the support of the U.S. Nuclear Regulatory Commission (NRC) and the Colorado Department of Public Health and Environment (CDPHE). As the investigation progresses, activities identified will proceed, as warranted, to achieve the objective of this investigation. Mitigation measures, if needed, will be determined in cooperation with NRC and CDPHE.

1.2 Background

1.2.1 Transient Drainage System History

During disposal cell construction, seepage appeared on the eastern side slope of the cell. A toe drain and holding pond were installed to manage transient drainage from the tailings. The drain system, consisting of a rock-filled drainage trench over a perforated 6-inch PVC pipe, was constructed on the east side of the cell in 1989. This transient drainage system gathered water and conveyed it to a double-lined holding pond. The seepage water collected in the pond was treated periodically and discharged to the north arroyo in accordance with a CDPHE Industrial Wastewater Treatment Facility discharge permit (Colorado Discharge Permit System Permit No. CO-0041548). In 1995, a permeable reactive barrier (PRB) test facility was installed with a fund from DOE's Office of Science and Technology, and the CDPHE discharge permit was modified to include the PRB facility. The toe drain valve was closed on June 4, 2004; the system was no longer being used for treatment and discharge, and the CDPHE permit was allowed to expire on January 31, 2009. In September 2009, the toe drain valve was opened to allow water to drain to the holding pond. In October 2010, the PRB facility was decommissioned and remediated. In September 2014, the shed which housed the toe drain valves near the base of the disposal cell was removed. During inspection, soil samples collected below the valves indicated selenium and molybdenum concentrations near or slightly above background values, whereas uranium concentrations were greater than background but below the regional risk-based U.S. Environmental Protection Agency (EPA) screening level (DOE 2015a). In September 2017, the transient drainage system, including the holding or evaporation pond, was decommissioned and remediated. All of the contaminated media associated with the PRB facility and holding pond were transported to the Grand Junction, Colorado, Disposal Site (DOE 2019b). Verification sampling following the decommissioning of the transient drainage system and removal of the evaporation pond concluded that areas beneath the former evaporation pond liner found no evidence of contamination in remaining soils (DOE 2018b).

The actions taken with the transient drainage system were in part conducted to assess potential impacts related to uranium concentrations observed in well 0618. A timeline summarizing the associated actions taken with the transient drainage system and assessments in well 0618 since 2003 is shown in Figure 1.

1.2.2 Geology and Hydrogeology

The surficial materials at the disposal site consist of up to 65 feet of unconsolidated Quaternary alluvial and colluvial deposits made up of silty clay and silt soils that are locally interbedded with layers of mixed sandstone and shale bedrock fragments. The thickest areas of the alluvial deposits occur along a subsurface paleochannel feature carved into the underlying bedrock. The alluvium mostly overlies the Cliff House Sandstone, but in the northeast area of Bodo Canyon, the alluvium-filled paleochannel cuts into the underlying Menefee Formation (Figure 2). The Cliff House Sandstone and Menefee Formation make up the uppermost compliance aquifer and consist of interbedded sequences of sandstone, mudstone, siltstone, silty shale, and coal (Kirkham et al. 1999; Kirkham and Navarre 2003; DOE 2019b). Under predisposal cell conditions, saturated conditions existed within the alluvium along the central axis of the paleochannel at depths that seasonally ranged from 20 to 50 feet below ground surface (DOE 1991). Outside of the paleochannel, much of the alluvium was not found to be saturated most of the time. Field estimates of horizontal hydraulic conductivity were typically greater in the alluvium (1.19 to 40 feet per day) than those of the underlying Cliff House Sandstone and Menefee Formation (3.0×10^{-4} to 5.7 feet per day) (DOE 1991). The highest hydraulic conductivity in the alluvium was determined from a 44-hour constant rate pumping test (4 gallons per minute) near well 0618, where the saturated thickness in the alluvium was greatest (DOE 1991). Higher horizontal hydraulic conductivity values in the underlying compliance aquifer were found in weathered and fractured portions of Cliff House Sandstone and coal within the Menefee Formation (DOE 1991). While measurements of vertical hydraulic conductivity were not made (DOE 1991), it is assumed here that the anisotropy (horizontal hydraulic conductivity/vertical hydraulic conductivity) would likely be greater in the compliance aquifer than the alluvium.

The current monitoring network does not allow for a horizontal hydraulic gradient to be quantified in the alluvium. However, groundwater is inferred to flow within the alluvium toward the northeast with a reported horizontal hydraulic gradient of 0.003 foot per foot based on historic water table elevation differences between wells 0604 and 0601 (DOE 1991). Prior to the construction of the disposal cell, groundwater flow within the alluvium was interpreted to be northeast during periods of recharge and would reverse and flow toward the center of the basin during periods when recharge was low (DOE 1991). Downward gradients currently exist near well 0618 to the underlying Cliff House Sandstone (Figure 3) and were also reported in abandoned wells 0601 and 0602 prior to the construction of the disposal cell (DOE 1991).

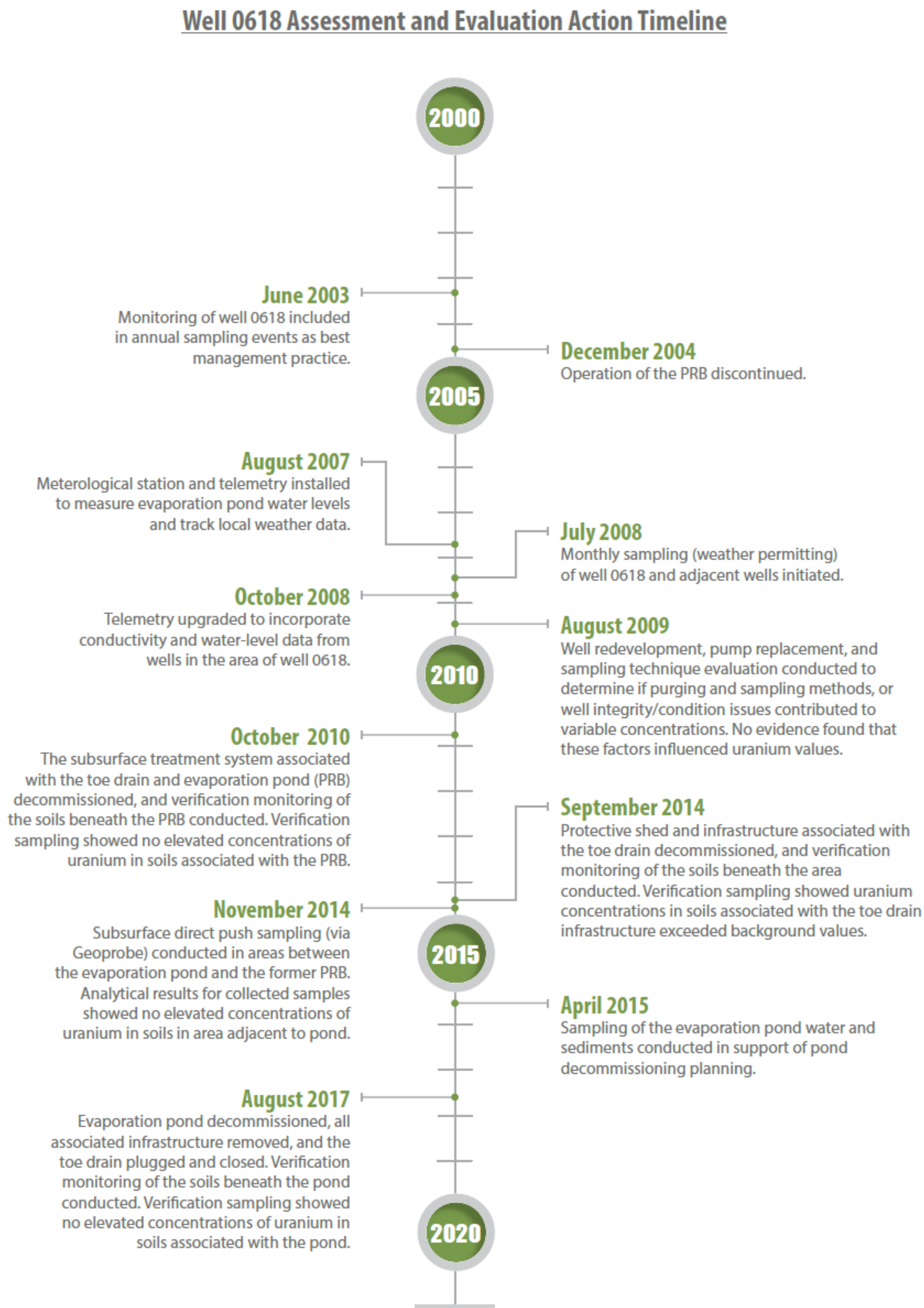

Figure 1. Timeline of Activities and Evaluations Performed to Assess Potential Impacts to Well 0618 Since 2003

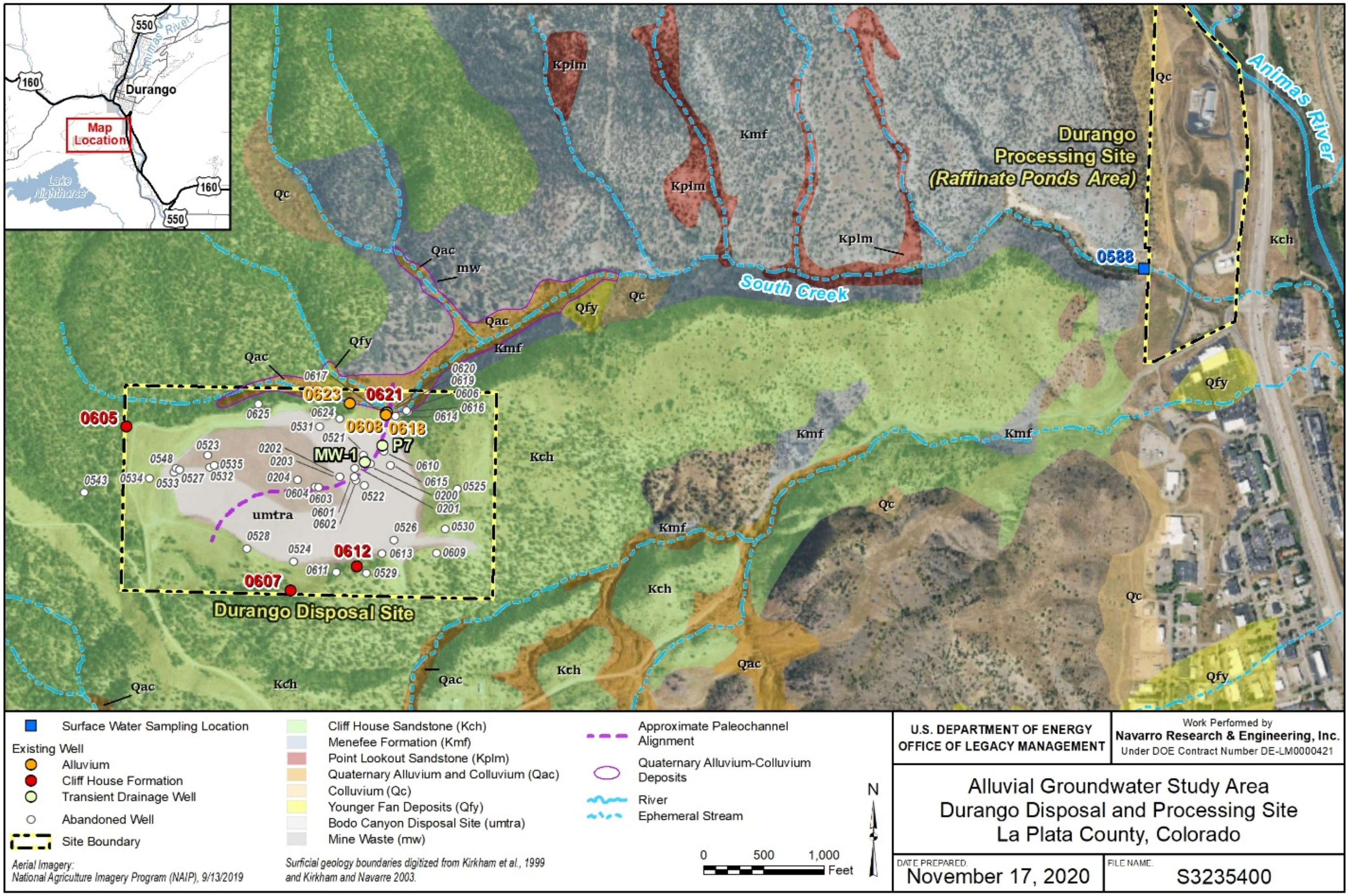

Figure 2. Study Area Map Showing Surficial Geology, Existing Monitoring Wells, Abandoned Wells with Available Boring Logs, and the Approximate Paleochannel Alignment Beneath the Disposal Cell

1.2.3 Conceptual Site Model

The disposal cell's low permeability foundation was designed to control seepage, or transient drainage, of excess moisture from the tailings without adversely impacting groundwater or surface water (DOE 1991). Initial calculations of transient drainage from the disposal cell assumed that tailings seepage would first infiltrate unsaturated alluvium before reaching the underlying water table in the Cliff House Sandstone and subsequently migrate southeast with the hydraulic gradient of compliance aquifer (DOE 1991). With the alluvium remaining saturated near well 0618, any seepage from transient drainage would encounter a shallower water table than anticipated and migrate horizontally (presumably to the northeast) within the alluvium. The most recent monitoring data of pore pressures from transient drainage wells MW-1 and P7 were over 30 feet greater than hydraulic heads measured in alluvial wells 0608 and 0618 (Figure 3), indicating an ample potential driving head for tailings fluids to seep into the alluvium. While a discharge location of alluvial groundwater to the surface has not been identified (DOE 2019b), the general contrasting field hydraulic conductivities between the alluvium and underlying bedrock units suggest that groundwater flow, and the transport of any dissolved uranium within the alluvium, is likely to be predominately horizontal until reaching a point of discharge as surface seepage. The observed variability in the concentration of uranium at well 0618 is closely related to changes in specific conductance and may be related to periodic precipitation events that recharge the alluvium (Figure 4).

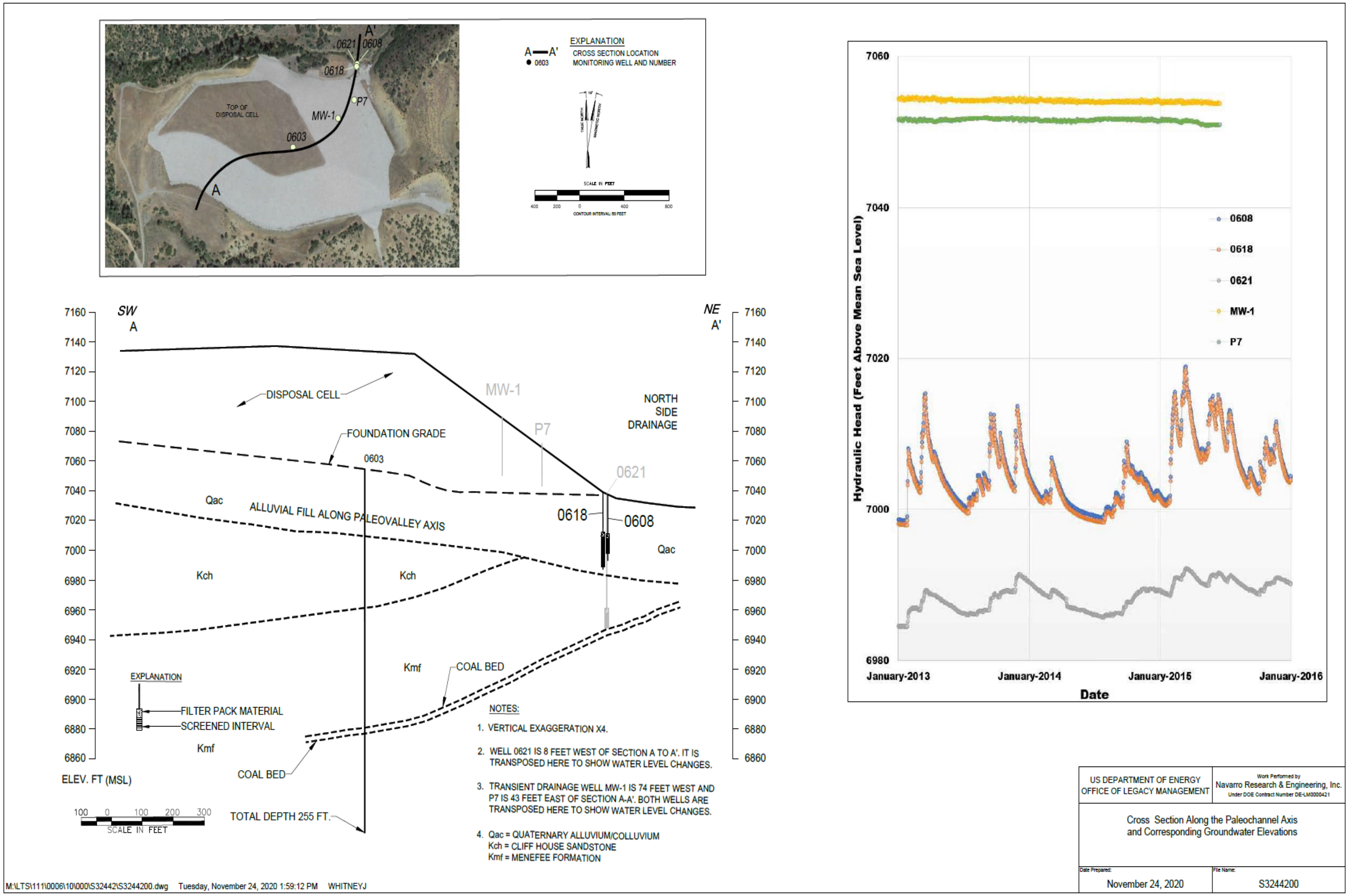

Figure 3. Cross Section Along the Paleochannel Axis and Corresponding Groundwater Elevations

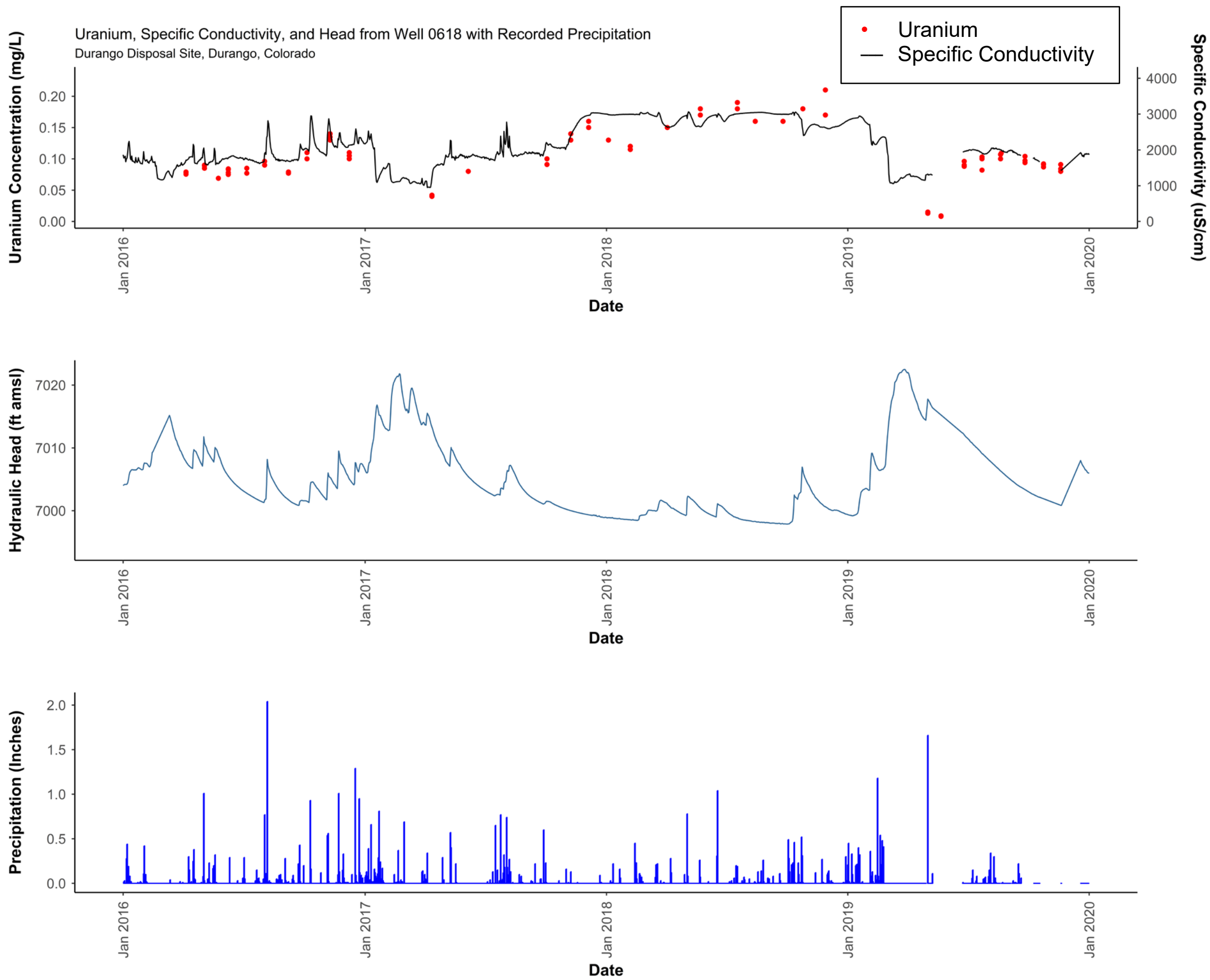

Figure 4. Plot Comparing Changes in Uranium Concentration in Groundwater, Specific Conductivity (Daily), and Hydraulic Head (Daily) from Well 0618 with Recorded Daily Precipitation Between 2016 and 2020

2.0 Data Quality Objectives

Data quality objectives (DQOs) were developed by following EPA guidance (EPA 2006). The DQOs address data gaps that were identified through review of site-specific studies, reports, and routinely collected data, such as groundwater levels at monitoring wells and water quality results from semiannual sampling events. Implementation of the DQO process will follow these seven steps:

[1] State the Problem

- [a] Define the problem that necessitates the study

[2] Identify the Study Objectives

- [a] Develop study objectives and questions.

[3] Identify Information Inputs

[a] Identify the data and information needed to address study questions and objectives.

[4] Define the Study Boundaries

[a] Identify the spatial boundaries and temporal limits of the study.

[5] Develop the Analytic Approach

[a] Identify parameters of interest and develop the logic for inference.

[6] Specify Performance and Acceptance Criteria

[a] Develop performance criteria for new data being collected.

[7] Plan for Obtaining Data

[a] Define the plan that meets performance criteria for obtaining the required data.

The DQO process elements that will guide the investigation are described in the following sections and are summarized in Appendix A.

2.1 State the Problem

Since 2003, uranium concentrations in alluvial groundwater measured in well 0618 at the Durango site have been consistently higher and more variable than other wells onsite, often above the 0.077 milligram per liter approved concentration limit for site point of compliance wells (DOE 2019a; DOE 2019b). The purpose of this plan is to identify data needs and data collection activities required to confirm the source of the uranium and the cause of its elevated and variable concentrations in alluvial groundwater and identify location(s) of exposure; evaluate risk; and, if needed, implement a risk-based mitigation measure.

2.2 Identify the Study Objectives

The following four study objectives (O1–O4) and associated study questions were developed for this work plan:

- O1: Define the spatial extent and temporal variability of the water table within the alluvial paleochannel.
  - What is the three-dimensional (3D) extent and sediment texture of the alluvial channel at the disposal site, including beneath the disposal cell, and in the adjacent South Creek arroyo (north drainage channel)?
  - What is the hydraulic head throughout the alluvium and within the mill tailings, and how does it vary temporally and in response to meteoric input?
- O2: Identify the source of uranium measured in groundwater at well 0618.
  - Is there a hydraulic connection between saturated tailings within the disposal cell and the abandoned-in-place toe drain transient drainage line with alluvial groundwater?
  - Does meteoric water infiltrate the disposal cell cover?

    - How does the bulk geochemistry of water within the disposal cell compare to the bulk geochemistry historically observed in groundwater samples obtained from well 0618?
    - What is the spatial and vertical distribution of uranium concentrations and mill-related uranium in alluvial groundwater?
- O3: Quantify the mass flux of dissolved uranium in alluvial groundwater and identify factors controlling the observed variability in concentration.
    - What is the horizontal hydraulic gradient within the alluvium, and how does it vary temporally?
    - What is the vertical hydraulic gradient within the alluvium and across the alluvium to the underlying compliance aquifer, and how does that vary temporally?
    - Do variations in groundwater elevation, hydraulic gradient, or uranium concentration correlate with recorded precipitation?
    - Can a robust correlation be made of specific conductance and dissolved uranium concentration in groundwater?
    - What is the spatial variability in horizontal and vertical hydraulic conductivity of the alluvium and underlying compliance aquifer?
    - What is the variability in mass flux of dissolved uranium traveling through the alluvium and underlying compliance aquifer near well 0618?
    - How does the mass of uranium dissolved in alluvial groundwater vary over time?
- O4: Identify the location of alluvial groundwater discharge and assess the impact to the South Creek arroyo.
    - Is there evidence of alluvial groundwater discharge within the South Creek arroyo such as seeps or phreatophytes? Outcropping of presumably relatively high hydraulic conductivity members of the Menefee Formation (e.g., coal seams) within the South Creek arroyo may also require monitoring to assess their potential as a location of exposure.
    - What is the spatial and vertical distribution of uranium concentrations and mill-related uranium in alluvial groundwater?
    - What is the distribution of leachable uranium concentrations bound to near surface soils along the South Creek arroyo, and are they a result of permitted discharges (National Pollutant Discharge Elimination System Permit No. CO-0041548), alluvial groundwater discharge, or natural occurrence? What was the total estimated mass of uranium released to the South Creek arroyo during permitted discharges?
    - What is the source of the uranium concentrations measured in the South Creek arroyo at the Raffinate Pond site (location 0588)?

2.3 Identify Information Inputs

The following information inputs were identified to meet each study objective:

- **O1 Information Inputs:** Define the spatial extent and temporal variability of the water table within the alluvial paleochannel.
  - A review and compilation of historical boring logs, fault and lineament study trench logs, and boring logs from newly installed piezometers (see O2) to identify top and bottom contacts of alluvium, descriptions of sediment texture within the alluvium, and top of underlying members of the Cliff House Sandstone and Menefee Formation across the study area. This will also include a review of bedrock topography maps and cross sections created as part of the Remedial Action Plan (DOE 1991). These maps and cross sections will provide valuable information pertaining to interpolated contact elevations and strike and dip measurements of geologic units that make up the compliance aquifer.
  - A review of disposal cell construction as-builts, changes in grade, placement of slimes and tailings, transient drainage system, and details regarding thickness and distribution of the low-permeability liner placed underneath the tailings material.
  - Additional piezometers are needed to define and monitor water table elevations within the alluvium. This will also include monitoring of hydraulic heads from existing and newly installed monitoring wells or piezometers and transient drainage wells. The feasibility of installing piezometers will need to be examined for worker safety, funding, and project risk.
  - Construction of a 3D representation of the site that includes (1) disposal cell, (2) alluvial paleochannel, (3) the underlying compliance aquifer, and (4) temporal variations in hydraulic heads to provide an overall spatial understanding of the study area.
- **O2 Information Inputs:** Identify the source of uranium in groundwater at well 0618.
  - Spatial distribution and vertical profiling of mill-related uranium concentrations collected from discrete groundwater samples in the alluvium with a direct-push rig near the disposal cell and well 0618. Results will be used to optimize the placement of new piezometers and offer a preliminary delineation of mill-related uranium in alluvial groundwater.
  - Installation of nested piezometers, if feasible, to be screened in the alluvium and underlying compliance aquifer in order to monitor concentrations, hydraulic heads, and vertical and horizontal hydraulic gradients near well 0618 and other locations in the immediate vicinity of the disposal cell. The feasibility of installing piezometers will need to be examined for worker safety, funding, and project risk.
  - Geochemical mass balance modeling to simulate the evolution of water chemistry from the disposal cell to well 0618. The result is a set of geochemical reactions (e.g., adsorption, mineral precipitation/dissolution, ion exchange, or dilution) that match the observed chemical concentrations. The reasonableness of these simulations would help distinguish the origins of the uranium detected in well 0618. Confirmation sampling of saturated soils during drilling could offer some verification of the results through detection of a predicted mineral phase absent from background. Geochemical modeling results available to date will be reviewed ahead of any new geochemical modeling task.

- Analysis of transducer temperature and pressure records from transient drainage wells MW-1 and P7 in response to recorded precipitation events.
- An evaluation of this information with other data collected during this work plan will support a decision rule guided task to determine if a conservative tracer test is needed or desired to confirm the disposal cell as the source of uranium in the alluvial aquifer. A conservative tracer study may be conducted by adding tracers at the tailings site and monitoring their arrivals at well 0618, 0621, and others. It should be noted that lack of tracer detection would be inconclusive. This task could offer data to determine if uranium in well 0618 is from the tailings.

- **O3 Information Inputs:** Quantify the mass flux of dissolved uranium in alluvial groundwater and identify factors controlling the observed variability in concentration.
  - Calculation of mass flux of uranium through the saturated alluvium requires representative temporal measurements of uranium concentration in a cross section perpendicular to flow and the flux of groundwater flow through that cross section.
  - Hydraulic conductivity and transmissivity data from historical observations and newly installed piezometers. This will include both horizontal and vertical hydraulic conductivity data, if available. Vertical hydraulic conductivity data of the alluvium can be assessed through an analysis of core material collected during the installation of new piezometers using triaxial or flexible wall permeameter testing. Horizontal hydraulic conductivity can be collected through pneumatic or manual slug testing of well screens and/or through the entire saturated thickness of the well (through solid and screened casing) using borehole nuclear magnetic resonance (NMR) logging.
    - Monitoring hydraulic heads and vertical and horizontal hydraulic gradients from new and existing wells near 0618; locations near the disposal cell; and, if applicable, the identified location of discharge from O2.
    - Temporal measurements of dissolved uranium concentrations in groundwater to establish mass loading. A correlation analysis between dissolved uranium concentration and specific conductance will assess if real-time specific conductance data can be used to provide reliable, real-time uranium flux estimates between sampling events (Figure 5).
    - Temporal monitoring of direct estimates of groundwater and uranium flux within the alluvium and compliance aquifer at multiple locations downgradient of the disposal cell. This can be accomplished using passive flux meters (PFMs) to refine uncertainty in parameters used in the Darcy's Law mass flux estimation (e.g., effective porosity, bulk hydraulic conductivity, temporal integration of hydraulic gradients).
  - Estimates of infiltration based on recorded precipitation events that can recharge the alluvium. This will support our understanding of the variations in groundwater elevation (greater than 20 feet) and uranium concentrations in groundwater at well 0618.
  - Temporal calculations of total dissolved mass of uranium, average uranium concentration, and total volume of groundwater within the alluvium.

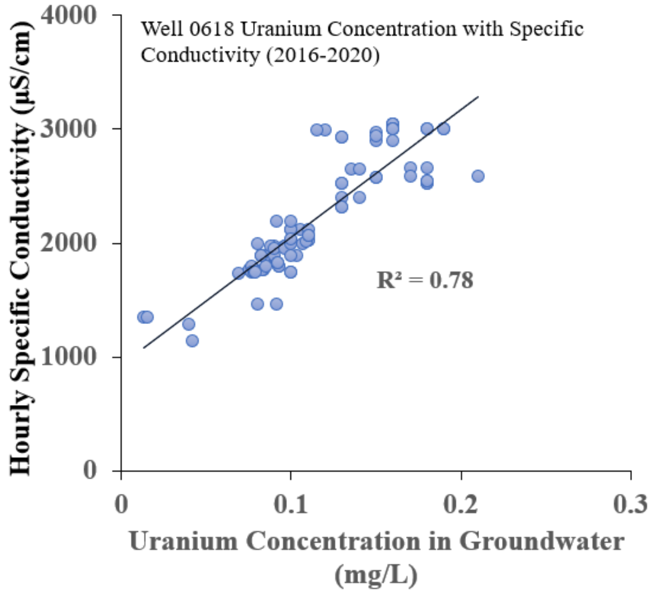

Figure 5. Preliminary Assessment of Correlation Between Dissolved Uranium Concentration in Groundwater with Hourly Specific Conductivity Measurements from Well 0618 Between 2016 and 2020

- **O4 Information Inputs:** Identify the location of alluvial groundwater discharge and assess the impact to the South Creek arroyo.
  - Installation of drive-point piezometers within the South Creek arroyo alluvium at locations indicative of a shallow, consistent water source interpreted through visual observation of seeps or phreatophytes. Another location may include where the relatively permeable coal seam within the Menefee Formation is interpreted to subcrop beneath the alluvium. These piezometers will help interpret if areas of suspected groundwater discharge are geochemically similar to groundwater samples collected from well 0618.
  - Compare the total aqueous geochemistry from groundwater sourced from well 0618, porewater and groundwater samples collected at the suspected location of alluvial groundwater discharge within South Creek arroyo, and location 0588 at the former Raffinate Pond site with a piper diagram.
  - Monitoring of uranium-234/uranium-238 activity ratios (UARs) from piezometers within the alluvium in the South Creek arroyo and location 0588 at the former Raffinate Pond site to assess if measured uranium concentrations there are likely mill-related.
  - Soil samples from the vadose and saturated zones along the South Creek arroyo are needed to derive the estimated location and mass of uranium in the subsurface that may be related to permitted discharges from the transient drainage system or discharges from the alluvial aquifer. Sequential extractions on core and soil samples will determine the leachability of the solid-phase uranium.

2.4 Define the Study Boundaries

The horizontal study boundaries for this study include the Durango disposal site and the South Creek arroyo that extends from the northeast corner of the disposal site to surface water monitoring location 0588, just upstream of the former Raffinate Pond site boundary. The vertical boundary for this study includes the present-day ground surface topography, the alluvial paleochannel, and the uppermost compliance aquifer (Cliff House Sandstone and Menefee Formation).

2.5 Develop the Analytic Approach

This step of the DQO process includes defining the parameters of interest, determining appropriate parameter estimation methods, and developing decision rules. The EPA document titled *Guidance on Systematic Planning Using the Data Quality Objectives Process* (EPA 2006) distinguishes between hypothesis testing and estimation approaches. The DQOs for this work plan primarily utilize estimation approaches rather than formal hypothesis testing. The following parameters of interest were defined for each objective.

O1 Parameters:

- Top and bottom elevations of alluvium and descriptions of sediment texture within the alluvium across the study area.
- Top elevation, bottom elevation, strike, dip, and lithologic descriptions of underlying members of the Cliff House Sandstone and Menefee Formation across the study area.
- Disposal cell construction as-builts, changes in grade, placement of slimes and tailings, transient drainage system and details regarding the elevations, thicknesses, and distribution of components used in the construction of the disposal cell that include:
    - Thicknesses and elevations and textural descriptions of the disposal cell cover components including the rock cover, rooting medium/frost protection layer, biointrusion layer, drain and filter layer, bentonite mat, and radon/infiltration barrier.
    - Thicknesses and elevations of compacted tailings and slimes.
    - Thicknesses and elevations of low-permeability compacted clay liner beneath the tailings material.
    - Elevation and position of transient drainage line and screen intervals of MW-1 and P7.
- Interpolated temporal variations in hydraulic head across the study area.

O2 Parameters:

- Monitoring of hydraulic heads and chemistry of fluids in transient drainage wells MW-1 and P7.
- Historically recorded hydraulic heads, total chemistry of tailings fluids and groundwater samples, and mineralogical composition of the disposal cell liner and alluvial paleochannel.
- Continue monitoring of changes in barometric pressure and precipitation events.
- Known extent of alluvium near the disposal cell.

- Spatial distribution and vertical profiling of uranium concentrations and UARs collected from discrete groundwater samples within the alluvium.
- Monitoring and historical review of major cation, major anion, molybdenum, selenium, and uranium concentrations from existing and newly installed monitoring wells and piezometers across the study area. This will also include periodic monitoring of UARs.
- Monitoring spatial and temporal variations in hydraulic heads across the study area.
- Elevations, specifications, and components used in the construction and decommissioning of the toe drain and associated transient drainage line.
- Observation of solid phases and possible solid phase soil sampling to identify mineral assemblages that support geochemical modeling results.

O3 Parameters:

- Temporal uranium mass flux estimates based on historical transient drainage calculations, Darcy's Law calculations, and direct observation with PFMs.
- Estimates of effective porosity.
- Spatial distribution of temporal mill-related uranium concentrations in alluvial groundwater.
- Temporal calculations of total dissolved mass of uranium, groundwater volume, and average concentration within alluvial groundwater.
- Temporal specific conductance in groundwater data from within the alluvium and lower compliance aquifer.
- Profiling of radon-222 (^{222}Rn), specific conductance, and uranium concentration in the screened interval of well 0618.
- Temporal horizontal hydraulic gradients within the alluvium and vertical hydraulic gradients between the alluvium and underlying compliance aquifer.
- Cross sectional area of saturated alluvium perpendicular to groundwater flow where uranium concentrations and horizontal hydraulic gradients are being monitored.
- Spatial variability in horizontal and vertical hydraulic conductivity and transmissivity within the alluvium and underlying compliance aquifer.
- Temporal precipitation records.
- Drainage areas where precipitation will runoff and infiltrate the alluvium.
- Specific yield of the paleochannel alluvium.

O4 Parameters:

- Mapped location of any identified seeps or established phreatophytes in the South Creek arroyo.
- Spatial distribution of total and leachable uranium concentrations in soil along the South Creek arroyo.
- Temporal UARs from former Raffinate Pond surface water monitoring site 0588.

- Spatial distribution and temporal monitoring of hydraulic heads and total aqueous geochemistry from wells near the disposal cell (including well 0618), wells within the South Creek arroyo, and surface water location 0588.

2.5.1 Decision Rules

The following decision rules (DRs) specifically outline the circumstances for which specific activities will be implemented. At decision points, the project team will convene to assess the data and determine a path forward, including any modifications to this plan. The application of specific investigation technologies and methods mentioned within decision rules below are described in greater detail as specific tasks in Section 3.0.

DR1: Available boring logs to the east of the disposal cell are limited and may not be sufficient to constrain the interpolation and adequately define the paleochannel cross section. Should greater definition of the paleochannel's cross section and degree of saturation be required in this area, then geophysical techniques such as surface NMR, seismic refraction, electrical resistivity tomography, or others will be considered. The geometry of the paleochannel will greatly impact estimates of uranium mass flux in O3.

DR2: The number and location of new piezometers will be recommended following the 3D interpolation of alluvium, a safety assessment of drilling feasibility, and discrete groundwater sampling. At a minimum, sufficient piezometer coverage is needed to monitor hydraulic gradients within the alluvium and underlying compliance aquifer in the vicinity of well 0618.

Decisions made regarding the number and location of manual drive-point piezometers to be installed within the South Creek arroyo will be determined by field reconnaissance to identify features indicative of discharging groundwater such as seeps or established phreatophytes.

DR3: If available hydraulic conductivity data are not of sufficient coverage in the location and depths where the uranium mass flux estimates are being made, then surface or borehole NMR will be considered to provide a representative profile of hydraulic conductivity with depth.

DR4: After collection and analysis of data from other tasks outlined in this plan, a conservative tracer study may be considered to corroborate that uranium measured from well 0618 is sourced from the base of the disposal cell.

2.5.2 Analytical Methods

O1: Spatial interpolation of geologic contacts from boring logs along with spatial and temporal interpolation of groundwater elevations will be the primary means of defining the spatial extent and temporal variability of the water table within the alluvial paleochannel.

O2/O4: Geochemical techniques (e.g., Stiff and Piper diagrams) and geochemical modeling (e.g., PHREEQC) will be used to evaluate and interpret observed geochemical data. Should tracer testing be conducted, established codes would be used for interpreting tracer breakthrough data.

O3: Vendor-provided software will be used for the analysis of PFM data and any acquired geophysical data. Three-point estimation codes will be used to evaluate horizontal hydraulic gradient magnitudes and directions. Hydraulic testing analysis software (e.g., AQTESOLV or approved equivalent) will be used to estimate parameters from slug test results.

2.6 Specify Performance and Acceptance Criteria

Performance and acceptance criteria are used to determine if the DQOs have been met. These criteria establish the acceptable range of error for parameter estimates.

O1/O2/O3/O4: In general, contracted laboratory procedures will guide the acceptance criteria for data developed for both solid-phase and dissolved-phase contaminants. Laboratory quality assurance and quality control manuals develop protocols for acceptance or rejection of results and, in some instances, provide data that contain a qualifier. Where applicable, these qualifiers will be reviewed, and metadata will be evaluated to determine whether specific data points should be deleted from a data set.

O2/O3: Work instructions and procedures will be developed for individual field programs by subject matter experts. Field geology will be observed and logged by a competent geologist in accordance with established field procedures. Slug tests, geophysical data acquisition, and others will be performed through established procedures, work instructions, or industry established methods if subcontracted. Hydrologic data will be compared with data obtained from prior field investigations. The new data will be analyzed by a qualified hydrogeologist who will ensure that new and existing data are incorporated and interpreted according to standard practice. Anomalous data or spurious results will be reviewed, explained, or reduced as appropriate.

2.7 Develop the Data Collection Plan

The desktop and field investigation to support the DQOs consists of multiple tasks as described below. These tasks are listed for each category in anticipated schedule sequence, which is subject to change. As site data are compiled, the study questions, associated data collection activities, and investigation locations may be subject to revision.

- Task 1: Review and Compile Existing Data and Analyses from Historical Reports (applies to objectives O1, O2, and O3)
- Task 2: Integrate Existing Data into a 3D Visualization of the Disposal Site (applies to objective O1)
- Task 3: Identify Feasible and safe Drilling Locations Within the Alluvium for Subsequent Tasks (applies to objectives O1, O2, O3, and O4)
- Task 4: Discrete Groundwater Sampling to Delineate Mill-Related Uranium Plume Near the Disposal Cell (applies to objective O2)
- Task 5: Identify Potential Alluvial Groundwater Discharge Locations Within the South Creek Arroyo (applies to objective O4)
- Task 6: Sample and Instrument Transient Drainage Wells (applies to objective O2)
- Task 7: Review and Conduct Geochemical Modeling (applies to objective O2)

- Task 8: Install, Sample, and Instrument Piezometers at Selected Locations Near 0618 and South Creek Arroyo (applies to objectives O1, O2, O3, and O4)
- Task 9: Collect Solid-Phase Samples and Perform Sequential Extractions and Mineralogical Analyses (applies to objectives O2 and O4)
- Task 10: Evaluate Hydraulic Conductivity of New and Existing Piezometers/Wells (applies to objectives O2, O3, and O4)
- Task 11: Quantify Horizontal and Vertical Hydraulic Gradients (applies to objectives O2 and O3)
- Task 12: Evaluate Recharge to Alluvial Groundwater (applies to objective O3)
- Task 13: Direct Measurement of Dissolved Uranium and Groundwater Flux in Alluvium with Passive Flux Meters (applies to objective O3)
- Task 14: Optional Tracer Testing to Determine if the Tailings are the Source of Uranium in the Alluvial Groundwater (applies to objectives O2 and O4)
- Task 15: Identify Location(s) of Exposure and Evaluate Risk
- Task 16: Reporting

3.0 Data Collection

The data collection effort to address the DQOs will consist of various desktop study and field efforts and methodologies. The individual tasks that have been identified are described in this section.

3.1 Task 1: Review and Compile Existing Data and Analyses from Historical Reports

Existing data and analyses will be compiled and evaluated from numerous archived and historical reports for the site, including the Remedial Action Plan (DOE 1991), Site Completion Report (MK-Ferguson 1995), PRB performance reports (e.g., DOE 2004) and cited literature within. These reports and appended calculation packages contain information inputs discussed in Section 2.3, such as hydraulic and materials properties testing, geologic logs, water levels, aqueous geochemistry, geochemical modeling, aqueous chemistry records from the permitted toe drain outfall, and construction as-builts.

Critical to the completion of this task is to also include a review of sampling records, instrumentation, survey(s), and supplemental databases to confirm the quality of the existing data prior to incorporating into analyses described below. This review will also understand if any of the variability in uranium concentrations measured at the site (well 0618) can be related to changes in sampling procedure or well conditions (DOE 2015b). Wells 0608, 0618, 0621, 0623, MW-1, and P7 will require a camera survey to confirm screen depths, screen condition, and pump placement. Recommendations will be made if instrumentation or sampling equipment and procedures will need to be modified, added, or replaced. A review of the existing survey data is required before proceeding with subsequent tasks. All horizontal and elevation data must be in a consistent datum with a quantifiable error. Boring logs, well construction logs, construction

as-builts, trench logs, and water level data will be evaluated and transformed or resurveyed if necessary.

3.2 Task 2: Integrate Existing Data into a 3D Visualization of the Disposal Site

This task is subject to modification based on DR1.

Compiled and evaluated boring logs, well completion logs, trenches, as-builts, and temporal hydraulic head data from Task 1 will be integrated into a 3D representation of the disposal site using Earth Volumetric Studio. Interpolated 3D surfaces will be created representing the quaternary alluvium/colluvium (including the paleochannel), the Cretaceous units comprising the Cliff House Sandstone and Menefee Formation, present-day ground surface, foundation grade of the disposal cell, clay liner, compacted tailings (if known), radon barrier, and the protective components of the cover system. Other details such as the position of the transient drainage system beneath the cover will also be added to the model.

The position, thickness, and saturated extent of the alluvial paleochannel will be examined through 3D interpolation and extrapolation from known control points. A statistical confidence and uncertainty analysis of the quaternary alluvium/colluvium surface and paleochannel alignment will identify the highest priority locations where further control points are needed to constrain the model, particularly to the northeast of the disposal cell. These locations will be considered for additional borings, discrete groundwater sampling (Task 4), piezometer installation (Task 8), or near surface geophysical data acquisition (DR1).

3.3 Task 3: Identify Feasible and Safe Drilling Locations Within the Alluvium for Subsequent Tasks

It is anticipated that the existing monitoring network will need to be supplemented with additional piezometers and geologic information to satisfy the DQOs. The rugged and heavily wooded terrain around the disposal cell within Bodo Canyon and the South Creek arroyo presents significant access and safety challenges, which may limit the number of feasible drilling locations into the paleochannel. An evaluation of potential drilling locations and methods will be conducted by Legacy Management Support (LMS) Safety and Health personnel, LMS site lead, LMS technical lead, and drilling lead (either LMS contractor or potential subcontractor), with the support of the LM site manager to determine what can safely be accomplished.

3.4 Task 4: Discrete Groundwater Sampling to Delineate Mill-Related Uranium Plume Near the Disposal Cell

This task is subject to modification based on DR2.

Discrete groundwater samples offer the advantage of rapidly collecting groundwater samples at various locations and depths in unconsolidated materials to identify to distribution of constituents of interest without or prior to the installation of wells or piezometers. The purpose of this task is to:

- Assess the extent of dissolved, mill-related uranium in alluvial groundwater in a northwest to southeast transect parallel to the ditch along the cell's eastern extent.

- Identify preferred locations and depths for future piezometer completions.
- Provide screening level information pertaining to the thickness of the quaternary alluvium/colluvium and paleochannel near the disposal cell.

Following the recommendations from Task 3 above, discrete groundwater sampling will occur using a direct-push Geoprobe rig (model 7822DT) to create temporary boreholes by driving steel rods from the surface to refusal. The refusal depth would be interpreted as the minimal thickness of alluvium at that location as it would be assumed the rods have encountered bedrock. A Geoprobe Screen Point 16 discrete groundwater sampling tool will be advanced into the subsurface to the recorded refusal depth and the sampler sheath retracted, exposing the screen to the groundwater. Following purging, a polyethylene tubing and a peristaltic pump will be used to collect samples through the Geoprobe rods and Screen Point 16 groundwater sampling tool. Samples will be preserved, containerized, and shipped in accordance with the *Sampling and Analysis Plan for U.S. Department of Energy Office of Legacy Management Sites* (LMS/PRO/S04351). The samples will be analyzed for major cations, uranium, uranium-234, uranium-238, selenium, strontium, sulfate, manganese, iron, chloride, nitrate, and total organic and inorganic carbon by an accredited laboratory. Alkalinity will be measured in the field. Multiparameter probes will provide pH, temperature, oxidation reduction potential, and specific conductance data. Depending upon the saturated thickness of the alluvium at a given location, up to five discrete groundwater samples may be collected at different depths to provide a vertical profile of dissolved uranium concentration and UARs. After sampling is complete, the probe rods will be pulled from the hole and filled with bentonite chips to ground surface in accordance with the State of Colorado Water Well Construction Rules. Geoprobe operation will be performed under the supervision of an authorized individual.

Results of dissolved uranium concentration and of UARs will be plotted in cross section along with the extent of the quaternary alluvium/colluvium and paleochannel to identify any trends with depth or paleochannel thickness. Results of dissolved uranium concentration and of UARs will also be mapped to delineate the lateral extent of mill related uranium within the alluvium northwest and southeast of the disposal cell.

3.5 Task 5: Identify Potential Alluvial Groundwater Discharge Locations Within the South Creek Arroyo

Field estimates of hydraulic conductivity were generally greater in the alluvium than the underlying compliance aquifer (DOE 1991); therefore, dissolved uranium measured from well 0618 may continue to migrate within the alluvium for as long as it remains saturated. The extent of the alluvial deposit shown on Figure 2 terminates within the South Creek arroyo approximately 2100 feet northeast of well 0618. A field reconnaissance within the South Creek arroyo will be conducted to identify visible evidence that may indicate discharging groundwater. Visible evidence of alluvial groundwater discharging within the South Creek arroyo may include seeps and springs, established phreatophytes, and facultative to obligate wetland plants. Plants that indicate an available, persistent water source include cottonwood, willow, tamarisk, cattails, sedges, rushes, and so on.

The Cretaceous Menefee Formation contains coal seams that were identified as being relatively permeable features of the compliance aquifer beneath the site that could preferentially transmit groundwater (DOE 1991). These coal seams subcrop beneath the alluvium within the South

Creek arroyo (DOE 1991). During the field reconnaissance, evidence of coal outcropping along the canyon slopes and associated changes in vegetation within the arroyo will be documented. Results of this reconnaissance will guide the placement of drive-point piezometers as described in Task 8.

3.6 Task 6: Sample and Instrument Transient Drainage Wells

Historical analytical results from any sampling of MW-1, P7, or the abandoned North Vent Pipe of the transient drainage system do not appear to be available in electronic databases. A review of supplemental databases and site PRB studies (e.g., Morrison et al. 2002a; Morrison et al. 2002b, DOE 2004; and others) will be included in Task 1. Some analytical data are available from tailings fluids between 1988 and 1989 for abandoned wells 0200 through 0204 and will also be examined as part of Task 1. Pending the findings of Task 1, transient drainage wells MW-1 and P7 will likely require sampling to provide:

- A recent detailed geochemical composition of tailings fluids that can be compared to sampling results of alluvial groundwater.
- A comparative dataset to examine if the composition of tailings fluids has changed or have otherwise reached equilibrium since 1989.
- Provide an initial fluid composition for subsequent geochemical modeling described in Task 7.

The specific analytes will be selected following the results of Task 1 and will include the cations and anions necessary to establish redox conditions and achieve a charge balance. Consideration may be given to include $\delta^{34}S_{sulfate}$ and $\delta^{18}O_{oxygen}$ from sulfate in the analysis to evaluate its use as a potential indicator of tailing's fluids in alluvial groundwater.

Fluid pressure from the tailings fluids represents the driving force for transient drainage to occur beneath the disposal cell. In 1999 and 2000, transient drainage wells MW-1 and P7 were outfitted with transducers, respectively, and have recorded temperature and pressure data into 2015 (Figure 3). These transducers remain installed within the wells and were recently retrieved to download available data and assess their calibration. Pending results of the calibration check, new units may need to be purchased and installed. If the purchase of new transducers is required, consideration should be given those that record temperature, pressure, and specific conductivity to allow further comparison with data collected at well 0618.

3.7 Task 7: Review and Conduct Geochemical Modeling

Geochemical modeling at the disposal site was previously conducted to predict final uranium concentrations in the compliance aquifer following transient drainage of the tailings fluids (DOE 1991). Inputs and assumptions documented in calculation packages will be reviewed before conducting additional geochemical modeling. Geochemical modeling is needed to understand the possible evolution of tailings fluids from the disposal cell to groundwater sampled from well 0618. Sampling results from transient drainage wells in Task 6 and an analysis from a population of sampling results from well 0618 will serve as the initial and final compositions in the modeling, respectively. PHREEQC v 3.0 (Parkhurst and Appelo 2013) with an inverse modeling approach will be used to identify the set of geochemical reactions (adsorption, mineral precipitation/dissolution, ion exchange, or dilution) that match the observed

chemical concentrations. Confirmation sampling and analysis of saturated soils during drilling in could offer some verification of the results through detection of a predicted mineral phase absent from background (Tasks 8 and 9). Results from Task 9 may require refinements in the geochemical modeling.

3.8 Task 8: Install, Sample, and Instrument Piezometers at Selected Locations Near 0618 and South Creek Arroyo

This task is subject to modification based on DR1 and DR2.

To meet the DQOs, the existing monitoring network will likely need to be supplemented with additional piezometers near the disposal cell and farther down the South Creek arroyo where any potential alluvial discharge locations are identified in Task 5. Any new piezometers installed will require development and surveying. Pending the outcome of DR2, traditional standpipe piezometers constructed with a slotted PVC screen and solid riser may be replaced with vibrating wire piezometers to temporally monitor temperature and pressure of groundwater to obtain hydraulic gradient information near well 0618.

Piezometer Locations Near Well 0618

Additional piezometers are needed within the paleochannel alignment in order to:

1. Quantitatively monitor horizontal hydraulic gradients within the alluvium and within the underlying compliance aquifer (Task 11 and Task 13).
2. Quantitatively monitor vertical hydraulic gradients between the alluvium and underlying compliance aquifer (Task 11).
3. Define or refine the extent and thickness of the paleochannel (Task 2).
4. Collect soil samples and cores needed to support or supplement the geochemical modeling (Tasks 7 and 9) and provide vertical hydraulic conductivity data (Task 10) unless already identified under Task 1.
5. Provide additional monitoring data to examine the variability and source of dissolved uranium in groundwater (does not apply to vibrating wire piezometers).

The feasibility, number, location(s), and methods of drilling new piezometers in the vicinity of well 0618 will be decided following the findings of Tasks 2, 3, and 4. All piezometers used for monitoring hydraulic gradients will be instrumented with transducers capable of recording pressure, specific conductance, and temperature.

Piezometer Locations Within the South Creek Arroyo

Pending the findings in Task 5, additional piezometers will be needed in the South Creek arroyo to identify the location of alluvial groundwater discharge and assess the overall impact to the South Creek arroyo. Locations for installation will be selected based on an evaluation of the established plant community, visibly identifiable seeps and springs, and location of the Menefee Formation coal subcroping. Installations may also occur at locations upstream and downstream of identified features from Task 5. Given the variable terrain and assumed shallow depth to groundwater, these piezometers will likely be 1 inch in diameter or less, outfitted with a

drive-point, and installed manually with an auger or slide hammer. Given their small diameter, these piezometers may not be equipped with pressure transducers, and consideration will be needed for sampling procedure and permeability testing. Soil samples from the saturated zone will likely be required for mineralogical analyses (Task 9) to support the geochemical modeling (Task 7).

Monitoring

Following the installation of new piezometers, regular monitoring is needed to examine the changes in the total geochemistry as well as spatial and temporal variability of uranium and UARs. Monitoring should occur at the new piezometers and, when feasible, at the Raffinate Ponds surface water location 0588 whenever samples are collected from well 0618. Measured field parameters will include depth to water (at piezometers), alkalinity, oxidation reduction potential, specific conductance, pH, turbidity, and temperature. Samples will be collected and analyzed by a commercial laboratory for uranium, uranium-234, uranium-238, molybdenum, selenium, vanadium, calcium, magnesium, sodium, and potassium, ammonia, chloride, sulfate, and nitrate.

3.9 Task 9: Collect Solid-Phase Samples and Perform Sequential Extractions and Mineralogical Analyses

This task is subject to modification based on DR2.

Solid-phase samples will be collected from the alluvium near the disposal cell and at various locations within the South Creek arroyo during Task 8 to quantify the amount of residual uranium that may be bound to soil above bedrock and identify mineral phases present in the alluvium. These samples will provide information regarding the potential for a secondary source of uranium that is likely sourced from either groundwater discharge or permitted toe drain outfall. Vadose zone and saturated zone samples will be taken at discrete intervals between the ground surface and bedrock or refusal. Samples will be evaluated for percent moisture, major cations, uranium, selenium, strontium, sulfate, manganese, iron, chloride, nitrate, and total organic and inorganic carbon. Additional analytes may be added pending the results of geochemical modeling (Task 7). Aliquots of select samples will be submitted for mineralogical analysis with x-ray diffraction to identify the presence or absence of mineral phases as predicted or required in geochemical inverse modeling (Task 7). Consideration will be made to sieved fraction of soils used in the analyses described in this task.

Sequential extractions are needed on the solid-phase samples to indicate the stability (or leachability) of the solid fraction of uranium mass. The relative contribution of uranium mass in each sample extracted via different solvents suggests how strongly or weakly it is bound to the solid matrix and its potential to be remobilized into groundwater. Uranium mass that is shown to be stable or relatively immobile may be regarded as a lower priority as a potential location of exposure.

Sequential extractions will be performed using the following progression:

1. Deionized water removes any easily dissolved minerals such as evaporites. These are minerals that form as near-surface groundwater evaporates and can include minerals that contain uranium, such as carnotite ($K_2(UO_2)_2(VO_4)_2 \bullet 3H_2O$).

2. Bicarbonate extraction removes loosely adsorbed uranium, such as that adsorbed onto weak hydrous ferric oxide sites.
3. 5% nitric acid extraction removes strongly adsorbed uranium, such as that adsorbed onto strong hydrous ferric oxide sites. Nitric acid may also dissolve minerals in which uranium can coprecipitate, such as calcite.
4. Microwave digestion is more aggressive than the 5% nitric acid leach and dissolves uranium not associated with mineral grains along with additional minerals.
5. Total digestion dissolves all mineral grains and, thus, measures total uranium content. This includes minerals containing uranium such as coffinite ($USiO_4$) or uraninite (UO_2). These minerals may have been naturally present since the alluvium sediments were deposited, or they may have precipitated as mill tailings-derived groundwater carried dissolved uranium through the alluvium.

Results from this task will be put into context regarding the estimated total mass of uranium discharged into the South Creek arroyo from the permitted toe drain outfall (National Pollutant Discharge Elimination System Permit No. CO-0041548).

3.10 Task 10: Evaluate Hydraulic Conductivity of New and Existing Piezometers/Wells

This task is subject to modification based on DR1, DR2, And DR3.

Quantitative hydraulic conductivity data are available from previous investigations for the alluvium and underlying compliance aquifer (DOE 1991). These data will be reviewed and evaluated as part of Task 1. Understanding the variability of hydraulic conductivity within and between the alluvium and compliance aquifer will inform calculations pertaining to the mass flux and mass discharge of uranium (Task 13). The anisotropy of the alluvium and underlying compliance aquifer, when combined with the vertical hydraulic gradient (Task 11), is a key parameter for interpreting the likelihood that uranium could migrate from the alluvium into the compliance aquifer through advection.

Horizontal Hydraulic Conductivity

New and existing wells with sufficiently short screen intervals can be developed (or redeveloped) and subsequently slug tested to obtain hydraulic conductivity data of the formation near the well screen. Slug tests will be done pneumatically or manually depending upon the position of the water table relative to the top of the screen. The water table response will be recorded with a pressure transducer. Slug test response curves will be interpreted using solution method(s) with AQTESOLV analysis software (or approved equivalent).

Slug testing can provide hydraulic conductivity data of the formation at the well screen. NMR geophysical logging offers the advantage that hydraulic conductivity data can be collected along the entire length of PVC well casing. Borehole NMR logging provides information pertaining to vertical variability in hydraulic conductivity within a well and horizontal variability of hydraulic conductivity between wells (Walsh et al. 2013). By doing so, deeper wells screened within the underlying compliance aquifer could also yield hydraulic conductivity data for the alluvium.

Valuable data pertaining to mobile and immobile components of porosity would also be collected during the acquisition.

In areas where monitoring wells do not exist or cannot be installed, NMR logging can be performed using antenna coils placed on the ground surface (Grunewald and Walsh 2013). The diameter of the surface antennas required is controlled by the anticipated depth of investigation. Surface NMR logging at a single location will yield a one-dimensional profile showing variations in hydraulic conductivity and mobile and immobile porosity integrated beneath the area of the antenna.

Vertical Hydraulic Conductivity

Intact core samples collected during Task 8 may be saved and submitted for geotechnical evaluation of vertical hydraulic conductivity using a flexible wall permeameter. For direct comparisons with any borehole or surface NMR datasets, cores may be measured using the Corona lab NMR system, which is designed specifically for core analysis (Keating et al. 2020).

3.11 Task 11: Quantify Horizontal and Vertical Hydraulic Gradients

This task is subject to modification based on DR2.

Understanding the temporal variability of horizontal and vertical hydraulic gradients within and between the alluvium and compliance aquifer will inform calculations pertaining to the mass flux and mass discharge of dissolved uranium (Task 13). As noted in Task 8, hydraulic heads needed for the hydraulic gradient calculations will be monitored with transducers.

Horizontal Hydraulic Gradient

The existing monitoring network is not sufficient to provide a quantitative direction or magnitude of horizontal hydraulic gradient within the alluvium and possibly the underlying compliance aquifer. A total of six piezometers are required to establish a defensible hydraulic gradient in both the alluvium and underlying compliance aquifer. New piezometers used to calculate horizontal hydraulic gradients must be screened at similar elevations where feasible to avoid complications with known vertical hydraulic gradients. Piezometers should be laterally spaced to form a triangle that meets established reliability criteria for the hydraulic gradient calculation (McKenna and Wahi 2006).

Vertical Hydraulic Gradient

Currently, vertical hydraulic gradients between the alluvium and Cliff House Sandstone can only be monitored between wells 0618 and 0621. If new piezometers are required in both the alluvium and the underlying compliance aquifer to establish horizontal hydraulic gradients, they should be installed as a nested pair to allow for the ability to calculate a vertical hydraulic gradient at that location. When combined with hydraulic conductivity data from Task 10, an assessment can be made regarding the potential for advective transport from the alluvium to the underlying compliance aquifer.

3.12 Task 12: Evaluate Recharge to Alluvial Groundwater

Recharge to the alluvium from runoff of the disposal cell cover or higher elevations to the north may offer some control over variability in observed uranium concentrations from well 0618 by mixing water derived from precipitation with uranium dissolved in groundwater. The alluvium in the vicinity of well 0618 remains saturated, and groundwater levels increase by several feet in response to recorded precipitation events to indicate that the alluvium is receiving recharge (Figure 4). Estimates of recharge to the alluvium can be made through a graphical analysis of water table fluctuations in wells 0608 and 0618 combined with an estimate of specific yield (Healy and Cook 2002). If equipped with a transducer, well 0623—a designated upgradient alluvial well—can also be included in the analysis. This analysis assumes that water level increases in piezometers are caused through a proportional flux of recharge across the water table (unconfined conditions) and that variations in the water table are not caused by anthropogenic activities such as pumping or irrigation. The method requires frequent and accurate temporal records of water levels and precipitation and is best applied in shallow water tables that display sharp rises and declines (Healy and Cook 2002). Recharge is estimated as the product of peak water level rise in a piezometer following a discrete precipitation event multiplied by a specific yield estimate of the alluvium. An estimate of specific yield for well 0618 may be available through Task 1, where the pumping test analysis results may be documented. Estimates of specific yield can also be obtained through surface or borehole NMR logging, if conducted (Task 11).

Results from this analysis will be compared to maximum volumetric estimates of recharge to the alluvium upgradient of well 0618 through an analysis of drainage areas and temporal precipitation records from the site meteorological station. Recharge estimates and precipitation totals from this task will be compared to changes in alluvial groundwater geochemistry recorded from wells 0608, 0618, and 0623.

3.13 Task 13: Direct Measurement of Dissolved Uranium and Groundwater Flux in Alluvium with Passive Flux Meters

This task is subject to modification based on DR1, DR2, and DR3.

PFMs are deployed in monitoring well and piezometer screens to provide empirical measurements of groundwater specific discharge (units of L/T) and uranium mass flux (units of M/L^2 T) across the well screen. PFMs are commercially available and consist of nylon mesh tubes containing layers filled with either sorbent or "resident" tracer media (Annable et al. 2005). Groundwater and uranium fluxes are quantified through desorption of the resident tracer and adsorption of uranium, respectively (Stucker et al. 2011). Loss of the resident tracer indicates the cumulative groundwater flux, and accumulation of uranium onto the sorbent (activated carbon or resin) indicates the corresponding mass flux. Typically, PFMs are deployed for 2 weeks, after which the PFMs are retrieved, and the media are analyzed. PFMs should be deployed at each location several times throughout a year to provide flux rates during periods of high and low water table. Depth variations of both groundwater and uranium mass fluxes can be measured from a single PFM by vertically segmenting the exposed sorbent packing and analyzing for resident tracer loss and uranium sorbed (Annable et al. 2005). PFMs will generate meaningful spatial and temporal flux data from any new and established wells and piezometers screened

within the paleochannel and underlying compliance aquifer from both upgradient and downgradient of the disposal cell.

To ensure consistency and reliability of groundwater and uranium mass flux estimates from the PFMs, results will be compared to synchronous estimates of groundwater specific discharge and uranium mass flux derived from Darcy's Law. The Darcy's Law calculation is a product of the analytically measured uranium concentration, the corresponding hydraulic gradient (Task 11), and hydraulic conductivity in the direction of flow (Task 10). Considerations will be necessary to ensure that a time weighted average of uranium concentration and hydraulic gradient are representative of the period that the PFM flux estimates were integrated across. If specific conductivity can be reasonably correlated with uranium concentration (Figure 5), then continuous, real-time estimates of uranium concentration and therefore mass flux are possible. This may require an assessment of synoptic variability in specific conductance, ^{222}Rn, and uranium concentration in profile throughout the screened interval of well 0618 to identify trends present (DOE 2015b; DOE 2018a).

The uranium mass discharge rate is simply the uranium mass flux multiplied by the saturated cross-sectional area perpendicular to flow (Task 1). Temporal estimates of uranium mass discharge through the paleochannel will be compared to uranium mass discharge calculations for anticipated transient drainage as part of the disposal cell design (DOE 1991). Similar mass discharge rates may indicate that transient drainage through the cell is migrating through the saturated alluvium rather than the underlying compliance aquifer. If the observed uranium mass discharge rate is found to be relatively constant over time, then an analysis will be conducted to examine if variations in uranium concentration within the alluvium are related to changes in water level caused by meteoric input.

3.14 Task 14: Optional Tracer Testing to Determine if the Tailings are the Source of Uranium in the Alluvial Groundwater

This task is subject to modification based on DR2 and DR4.

Several tasks described herein will provide data to confirm the source of uranium in groundwater from well 0618 (O2) and identify the location of alluvial groundwater discharge (O4). This task describes an optional natural gradient tracer test that could confirm if the disposal cell is the source for uranium measured in well 0618 and if and where the alluvial groundwater within the paleochannel discharges into the South Creek arroyo.

The natural gradient tracer test may require months to years between tracer injection and detection with the monitoring network. Tracers would be injected into the transient drainage wells MW-1 and P7 screened in the tailings with different tracers used at each injection location. Monitoring wells in the paleochannel alluvium and compliance aquifer would be equipped with instrumentation to detect appearance of the tracer, either using activated carbon packets (for fluorescent dyes) or ion-specific electrodes connected to the site telemetry system. If a tracer breakthrough curve is detected at any well, an analysis of that breakthrough will be conducted using a one-dimensional solution of the advection-dispersion equation to estimate average groundwater velocity and total tracer mass detected. Detection of the injected tracers farther down into the South Creek arroyo would confirm the location of alluvial groundwater discharge. It should be noted that lack of tracer detection would be inconclusive.

3.15 Task 15: Identify Location(s) of Exposure and Evaluate Risk

The tasks outlined within this investigation aim to verify the source and discharge location of dissolved uranium measured from well 0618, understand the variability in uranium concentration and quantify the mass flux of uranium in alluvial groundwater, and assess potential impacts to the South Creek arroyo. The identified location would serve as the location of exposure where human health and environmental risk would need to be evaluated to identify potential receptors. Following a risk evaluation, the need to implement appropriate exposure mitigation measures will be determined. If mitigation measures are needed, a separate workplan would be drafted with CDPHE and NRC to ensure a protective strategy is implemented.

3.16 Task 16: Reporting

Following the completion of the investigation, a draft report summarizing the relevant history and investigation need, approach taken, methods, data and analyses, and conclusions will be developed and submitted to CDPHE and NRC for comment and NRC acceptance. Once the report has been finalized, it will be made available to stakeholders and the general public.

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Appendix A

Summary of Data Quality Objectives

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Table A-1:
Summary of Data Quality Objectives
Durango, Colorado, Disposal Site

Study Objective	Study Questions	Information Inputs	Parameters
O1: Define the spatial extent and temporal variability of the water table within the alluvial paleochannel.	What is the 3D extent and sediment texture of the alluvial channel at the disposal site, including beneath the disposal cell, and in the adjacent South Creek arroyo (north drainage channel)?	A review and compilation of historical boring logs, fault and lineament study trench logs, and boring logs from newly installed piezometers (see O2) to identify top and bottom contacts of alluvium, descriptions of sediment texture within the alluvium, and top of underlying members of the Cliff House Sandstone and Menefee Formation across the study area. This will also include a review of bedrock topography maps and cross sections created as part of the Remedial Action Plan. These maps and cross sections will provide valuable information pertaining to interpolated contact elevations and strike and dip measurements of geologic units that make up the compliance aquifer.	• Top and bottom elevations of alluvium and descriptions of sediment texture within the alluvium across the study area. • Top elevation, bottom elevation, strike, dip, and lithologic descriptions of underlying members of the Cliff House Sandstone and Menefee Formation across the study area. • Disposal cell construction as-builts, changes in grade, placement of slimes and tailings, transient drainage system and details regarding the elevations, thicknesses, and distribution of components used in the construction of the disposal cell that include: a) Thicknesses and elevations and textural descriptions of the disposal cell cover components including the rock cover, rooting medium/frost protection layer, biointrusion layer, drain and filter layer, bentonite mat, and radon/infiltration barrier. b) Thicknesses and elevations of compacted tailings and slimes. c) Thicknesses and elevations of low-permeability compacted clay liner beneath the tailings material d) Elevation and position of transient drainage line and screen intervals of MW-1 and P7. • Interpolated temporal variations in hydraulic head across the study area.
		A review of disposal cell construction as-builts, changes in grade, placement of slimes and tailings, transient drainage system, and details regarding thickness and distribution of the low-permeability liner placed underneath the tailings material.	
	What is the hydraulic head throughout the alluvium and within the mill tailings, and how does it vary temporally and in response to meteoric input?	Additional piezometers are needed to define and monitor water table elevations within the alluvium. This will also include monitoring of hydraulic heads from existing and newly installed monitoring wells or piezometers and transient drainage wells. The feasibility of installing piezometers will need to be examined for worker safety, funding, and project risk.	
		Construction of a 3D representation of the site that includes (1) disposal cell, (2) alluvial paleochannel, (3) the underlying compliance aquifer, and (4) temporal variations in hydraulic heads to provide an overall spatial understanding of the study area.	
O2: Identify the source of uranium measured in groundwater at well 0618.	What is the spatial and vertical distribution of uranium concentrations and mill-related uranium in alluvial groundwater?	Spatial distribution and vertical profiling of mill-related uranium concentrations collected from discrete groundwater samples in the alluvium with a direct-push rig near the disposal cell and well 0618. Results will be used to optimize the placement of new piezometers and offer a preliminary delineation of mill-related uranium in alluvial groundwater.	• Monitoring of hydraulic heads and chemistry of fluids in transient drainage wells MW-1 and P7. • Historically recorded hydraulic heads, total chemistry of tailings fluids and groundwater samples, and mineralogical composition of the disposal cell liner and alluvial paleochannel. • Continue monitoring of changes in barometric pressure and precipitation events. • Known extent of alluvium near the disposal cell. • Spatial distribution and vertical profiling of uranium concentrations and UARs collected from discrete groundwater samples within the alluvium. • Monitoring and historical review of major cation, major anion, molybdenum, selenium, and uranium concentrations from existing and newly installed monitoring wells and piezometers across the study area. This will also include periodic monitoring of UARs. • Monitoring spatial and temporal variations in hydraulic heads across the study area. • Elevations, specifications, and components used in the construction and decommissioning of the toe drain and associated transient drainage line. • Observation of solid phases and possible solid phase soil sampling to identify mineral assemblages that support geochemical modeling results.
	Is there a hydraulic connection between saturated tailings within the disposal cell and the abandoned-in-place toe drain transient drainage line with alluvial groundwater?	Installation of nested piezometers, if feasible, to be screened in the alluvium and underlying compliance aquifer in order to monitor concentrations, hydraulic heads, and vertical and horizontal hydraulic gradients near well 0618 and other locations in the immediate vicinity of the disposal cell. The feasibility of installing piezometers will need to be examined for worker safety, funding, and project risk.	
		An evaluation of this information with other data collected during this work plan will support a decision rule guided task to determine if a conservative tracer test is needed or desired to confirm the disposal cell as the source of uranium in the alluvial aquifer. A conservative tracer study may be conducted by adding tracers at the tailings site and monitoring their arrivals at well 0618, 0621, and others. It should be noted that lack of tracer detection would be inconclusive. This task could offer data to determine if uranium in well 0618 is from the tailings.	
	How does the bulk geochemistry of water within the disposal cell compare to the bulk geochemistry historically observed in groundwater samples obtained from well 0618?	Geochemical mass balance modeling to simulate the evolution of water chemistry from the disposal cell to well 0618. The result is a set of geochemical reactions (e.g., adsorption, mineral precipitation/dissolution, ion exchange, or dilution) that match the observed chemical concentrations. The reasonableness of these simulations would help distinguish the origins of the uranium detected in well 0618. Confirmation sampling of saturated soils during drilling could offer some verification of the results through detection of a predicted mineral phase absent from background. Geochemical modeling results available to date will be reviewed ahead of any new geochemical modeling task.	
	Does meteoric water infiltrate the disposal cell cover?	Analysis of transducer temperature and pressure records from transient drainage wells MW-1 and P7 in response to recorded precipitation events.	

Table A-1:
Summary of Data Quality Objectives
Durango, Colorado, Disposal Site

<table>
<tr><th>Study Objective</th><th>Study Questions</th><th>Information Inputs</th><th>Parameters</th></tr>
<tr><td rowspan="8">O3: Quantify the mass flux of dissolved uranium in alluvial groundwater and identify factors controlling the observed variability in concentration.</td><td>How does the mass of uranium dissolved in alluvial groundwater vary over time?</td><td>Temporal calculations of total dissolved mass of uranium, average uranium concentration, and total volume of groundwater within the alluvium.</td><td rowspan="8">• Temporal uranium mass flux estimates based on historical transient drainage calculations, Darcy's Law calculations, and direct observation with PFMs.

• Estimates of effective porosity.

• Spatial distribution of temporal mill-related uranium concentrations in alluvial groundwater.

• Temporal calculations of total dissolved mass of uranium, groundwater volume, and average concentration within alluvial groundwater.

• Temporal specific conductance in groundwater data from within the alluvium and lower compliance aquifer.

• Profiling of radon-222 (222Rn), specific conductance, and uranium concentration in the screened interval of well 0618.

• Temporal horizontal hydraulic gradients within the alluvium and vertical hydraulic gradients between the alluvium and underlying compliance aquifer.

• Cross sectional area of saturated alluvium perpendicular to groundwater flow where uranium concentrations and horizontal hydraulic gradients are being monitored.

• Spatial variability in horizontal and vertical hydraulic conductivity and transmissivity within the alluvium and underlying compliance aquifer.

• Temporal precipitation records.

• Drainage areas where precipitation will runoff and infiltrate the alluvium.

• Specific yield of the paleochannel alluvium.</td></tr>
<tr><td>What is the spatial variability in horizontal and vertical hydraulic conductivity of the alluvium and underlying compliance aquifer?</td><td rowspan="5">Hydraulic conductivity and transmissivity data from historical observations and newly installed piezometers. This will include both horizontal and vertical hydraulic conductivity data, if available. Vertical hydraulic conductivity data of the alluvium can be assessed through an analysis of core material collected during the installation of new piezometers using triaxial or flexible wall permeameter testing. Horizontal hydraulic conductivity can be collected through pneumatic or manual slug testing of well screens and/or through the entire saturated thickness of the well (through solid and screened casing) using borehole nuclear magnetic resonance (NMR) logging.

• Monitoring hydraulic heads and vertical and horizontal hydraulic gradients from new and existing wells near 0618; locations near the disposal cell; and, if applicable, the identified surface location of discharge/seepage from O2.

• Temporal measurements of dissolved uranium concentrations in groundwater to establish mass loading. A correlation analysis between dissolved uranium concentration and specific conductance will assess if real-time specific conductance data can be used to provide reliable, real-time uranium flux estimates between sampling events.

• Temporal monitoring of direct estimates of groundwater and uranium flux within the alluvium and compliance aquifer at multiple locations downgradient of the disposal cell. This can be accomplished using passive flux meters (PFMs) to refine uncertainty in parameters used in the Darcy's Law mass flux estimation (e.g., effective porosity, bulk hydraulic conductivity, temporal integration of hydraulic gradients).</td></tr>
<tr><td>What is the horizontal hydraulic gradient within the alluvium, and how does it vary temporally?</td></tr>
<tr><td>What is the vertical hydraulic gradient within the alluvium and across the alluvium to the underlying compliance aquifer, and how does that vary temporally?</td></tr>
<tr><td>Can a robust correlation be made of specific conductance and dissolved uranium concentration in groundwater?</td></tr>
<tr><td rowspan="2">What is the variability in mass flux of dissolved uranium traveling through the alluvium and underlying compliance aquifer near well 0618?</td></tr>
<tr><td>Calculation of mass flux of uranium through the saturated alluvium requires representative temporal measurements of uranium concentration in a cross section perpendicular to flow and the flux of groundwater flow through that cross section.</td></tr>
<tr><td>Do variations in groundwater elevation, hydraulic gradient, or uranium concentration correlate with recorded precipitation?</td><td>Estimates of infiltration based on recorded precipitation events that can recharge the alluvium. This will support our understanding of the variations in groundwater elevation (greater than 20 feet) and uranium concentrations in groundwater at well 0618.</td></tr>
<tr><td rowspan="4">O4: Identify the location of alluvial groundwater discharge and assess the impact to the South Creek arroyo.</td><td>Is there evidence of alluvial groundwater discharge within the South Creek arroyo such as seeps or phreatophytes? Outcropping of presumably relatively high hydraulic conductivity members of the Menefee Formation (e.g., coal seams) within the South Creek arroyo may also require monitoring to assess their potential as a location of exposure.</td><td>Installation of drive-point piezometers within the South Creek arroyo alluvium at locations indicative of a shallow, consistent water source interpreted through visual observation of seeps or phreatophytes. Another location may include where the relatively permeable coal seam within the Menefee Formation is interpreted to subcrop beneath the alluvium. These piezometers will help interpret if areas of suspected groundwater seeps/discharge are geochemically similar to groundwater samples collected from well 0618.</td><td rowspan="4">• Mapped location of any identified seeps or established phreatophytes in the South Creek arroyo.

• Spatial distribution of total and leachable uranium concentrations in soil along the South Creek arroyo.

• Temporal UARs from former Raffinate Pond surface water monitoring site 0588.

• Spatial distribution and temporal monitoring of hydraulic heads and total aqueous geochemistry from wells near the disposal cell (including well 0618), wells within the South Creek arroyo, and surface water location 0588.</td></tr>
<tr><td>What is the spatial and vertical distribution of uranium concentrations and mill-related uranium in alluvial groundwater?</td><td>Monitoring of uranium-234/uranium-238 activity ratios (UARs) from piezometers within the alluvium in the South Creek arroyo and location 0588 at the former Raffinate Pond site to assess if measured uranium concentrations there are likely mill-related.</td></tr>
<tr><td>What is the distribution of leachable uranium concentrations bound to near surface soils along the South Creek arroyo, and are they a result of permitted discharges (National Pollutant Discharge Elimination System Permit No. CO-0041548), alluvial groundwater discharge, or natural occurrence? What was the total estimated mass of uranium released to the South Creek arroyo during permitted discharges?</td><td>Soil samples from the vadose and saturated zones along the South Creek arroyo are needed to derive the estimated location and mass of uranium in the subsurface that may be related to permitted discharges from the transient drainage system or discharges from the alluvial aquifer. Sequential extractions on core and soil samples will determine the leachability of the solid-phase uranium.</td></tr>
<tr><td>What is the source of the uranium concentrations measured in the South Creek arroyo at the Raffinate Pond site (location 0588)?</td><td>Compare the total aqueous geochemistry from groundwater sourced from well 0618, porewater and groundwater samples collected at the suspected location of alluvial groundwater discharge within South Creek arroyo, and location 0588 at the former Raffinate Pond site with a piper diagram.</td></tr>
</table>