UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
CENTER FOR ENVIRONMENTAL SOLUTIONS AND EMERGENCY RESPONSE
TECHNICAL SUPPORT COORDINATION DIVISION
919 KERR RESEARCH DRIVE • ADA, OK 74820

November 19, 2024

OFFICE OF
RESEARCH AND DEVELOPMENT

MEMORANDUM

SUBJECT: Technical Review of the Pinyon Plain Mine, Coconino County, Arizona (25-R09-01)

FROM: Randall Ross, Director
Groundwater Technical Support Center

TO: Tony Singh, Assistant Director
U.S. EPA Region 9 WD-GDWB

Per your request for technical support from the Groundwater Technical Support Center (GWTSC), the attached report is provided for the Pinyon Plain Mine. This report was prepared by ERG (Eastern Research Group), a STREAMS IV contractor that provides technical support to the GWTSC. If you have any questions or comments, please do not hesitate to contact me at your convenience (580-436-8611).

This report was prepared based on reviewing recent scientific publications, Arizona state and U.S. government agency reports and publications, Havasupai Tribe hazard mitigation plans, information available from websites, including maps and graphics, as well as technical reports commissioned by the mine operator, Energy Fuels Inc. company.

Scientific, Technical, Engineering and Modeling Support IV (STREAMS IV)

Eastern Research Group (ERG)

Deliverable for ERG-GWTSC-067
Pinyon Plain Mine

Contract #: 68HERC21D0003
Task Order #: 68HERC22F0267

November 19, 2024

Executive Summary

There are two main groundwater aquifers at the Pinyon Plain Mine site: the shallower Coconino aquifer (C-aquifer) and the deeper Redwall/Muav aquifer (R-aquifer). Depths to these aquifers are approximately 941 feet and 2,870 feet below ground surface at the mine site, respectively. These two aquifers are separated by about 2,000 feet of rock layers. Fractures, faults, or dissolution features in limestone (referred to as *karst*) in these layers of rock can allow or restrict groundwater to flow between the aquifers. Studies show that contaminants released at the surface can flow downward through these fractures, faults, or Karst features and potentially enter the groundwater at some locations on the South Rim of the Grand Canyon.

A connection between the C-aquifer and R-aquifer exists in some parts of the South Rim but it is currently unknown if it exists at the Pinyon Plain Mine site. To address this knowledge gap, the principal goal of this analysis was to evaluate whether a connection exists between the two aquifers at the Pinyon Plain Mine site. Another goal was to analyze the potential for groundwater contamination resulting from mining operations and spreading of the contamination away from the Pinyon Plain Mine site. The main finding is that current well data are insufficient to rule out a connection between the two aquifers. Therefore, **the potential for groundwater contamination resulting from operations at the Pinyon Plain Mine site cannot be assessed fully without additional investigations.**

Introduction

The United States Environmental Protection Agency (EPA) is providing expertise and technical advisory services in response to a request from the Havasupai Tribe. This report provides the results of EPA's activities conducting (1) an independent hydrologic analysis of the connectivity between the shallower Coconino aquifer (C-aquifer) and the deeper Redwall/Muav aquifer (R-aquifer) at the Pinyon Plain Mine site, (2) an updated analysis of the potential for groundwater contamination resulting from operations at the Pinyon Plain Mine, and (3) an evaluation of using either existing wells or new wells to monitor the C-aquifer and R-aquifer separately for water quality, groundwater level, and groundwater flow direction.

This report was prepared based on reviewing recent scientific publications, Arizona state and U.S. government agency reports and publications, Havasupai Tribe hazard mitigation plans, information available from websites, including maps and graphics, as well as technical reports commissioned by the mine operator, Energy Fuels Inc. company. A full list of these and other documents is provided in the reference list for this report.

Connection Between the Aquifers

At the Pinyon Plain Mine site, there are two main groundwater aquifers: the shallower Coconino aquifer (C-aquifer) and the deeper Redwall/Muav aquifer (R-aquifer). Depths to these aquifers are, respectively, approximately 941 feet and 2,870 feet below ground surface. These

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

two aquifers are separated by about 2,000 feet of rock layers. The R-aquifer is separated from the C-aquifer by the low permeability Lower Supai layer.

Several studies discussed a potential connection between the two aquifers may occur at specific locations throughout the region (Solder et al., 2020; Solder and Beisner, 2020). The similarity in the ages of the groundwater in these aquifers provides evidence for a connection and for similar recharge locations. Additionally, there are anthropogenic (human-created) substances detected in water samples collected at a few springs along the South-Rim of Grand Canyon (Curry et al., 2023; Beisner et al., 2023; Crossey et al., 2024). However, it is not known if any of these tracers are present in the groundwater at the Pinyon Plain Mine site. If present, these substances could suggest a connection and comparatively rapid exchange between surface water and groundwater in the two aquifers. Further, studies comparing the stable isotopic fingerprint of the C- and R-aquifer at the Pinyon Plain Mine site suggest two distinct water sources (Beisner et al., 2023; Crossey et al., 2024), however alternative interpretations have been offered in the literature. Altogether, ***the direction and amount of groundwater flow, if any, between the C-aquifer and the R-aquifer at the mine site is uncertain.***

Uncertainties about the groundwater flow conditions in both aquifers at the mine site are a result of the lack of data i.e., absence of appropriately located wells that can be sampled and monitored to provide missing information on flow. Additionally, pumps at the bottom of the mine shaft currently control surface water and groundwater seeping into the mine. The pumping from the mine shaft is distorting the natural groundwater flow conditions in the shallower C-aquifer near the mine but should have no effect on the direction and rate of groundwater flow in the deeper regional R-aquifer. ***The current direction (vertical and horizontal) and velocity of groundwater flow to and away from the mine and the direction and velocity after mine closure are currently not well understood***.

Potential for Groundwater Contamination

The primary water quality concerns at the mine site are dissolved uranium and arsenic. Currently, heavy metal contaminated groundwater seeping into the mine is collected in a mine shaft, pumped to the surface, and stored on-site in a lined containment pond. Potential connections between the C-aquifer and the R-aquifer at the Pinyon Plain Mine raise concerns about the potential for groundwater contamination during mining and after mine closure, including potential impacts to the drinking water quality for communities downgradient from the mine. ***If and to what degree mining may have a short-term or long-term effect on water quality at the mine site and downgradient from the site are not well understood*.**

Naturally occurring anoxic (oxygen-free) conditions in the shallower groundwater at the site limit the spread of uranium. However, uranium ores can oxidize within days to months when exposed to surface conditions (Wenrich et al., 1995; Alpine, 2010), indicating the potential for rapid leaching and chemical reaction of the ore minerals (Bern et al., 2017), even in the arid environment of northern Arizona (Alpine, 2010). It is not known how far away from the

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

immediate mine site these anoxic conditions occur. A change of the geochemical subsurface conditions as a result of mining at the site is expected to change the groundwater quality with potentially long-term consequences. These ***long-term geochemical changes and their potential consequences on groundwater quality at the mine site are not well understood***. Further, the ***post-mining clean closure requirements and the long-term contaminant containment strategy for this site are not well tested***. More technical details would be needed before the effectiveness of the mine closure technologies and the long-term monitoring strategy can be fully evaluated.

Groundwater sampling by USGS shows that uranium concentrations around the Pinyon Plain Mine are less than 15 µg/L and that the R-aquifer has higher concentrations than the C-aquifer (Tillman et al., 2021). In contrast, groundwater data collected by the mining company and reported to ADEQ in 2024 as part of the establishment of the mine's groundwater alert levels and aquifer quality limits, include uranium concentrations as high as 43.7 µg/L in one perched monitoring well (see Appendix C of Energy Fuel's Aquifer Protection Permit Minor Amendment Application dated April 8, 2024). Additionally, dissolved uranium concentrations in mine shaft water have risen to 200 µg/L since the shaft was advanced from 450 to 1,400 feet BGS. The current U.S. EPA maximum contaminant level for uranium in drinking water is 30 µg/L. ***It is unclear whether the uranium concentrations in the subsurface water at the mine site and the surrounding area would return to their pre-mining levels and how long that might take.*** A better understanding of the expected fate of dissolved uranium in the post-mining era would be needed for designing appropriate groundwater containment and monitoring strategies, which may have to be in place for years or decades.

Recommendations Summary

To better evaluate the potential current and future risk of groundwater contamination and understand the local groundwater system, this report recommends:

- **Drilling additional wells.** There are currently two wells, monitored periodically by the USGS, on or near the mine site - one completed in the C-aquifer and one in the R-aquifer. There are three additional C-aquifer monitoring wells on the site that were installed by the mining company. These wells do not provide reliable information about the flow of groundwater in the horizontal direction and between aquifers (vertical direction) because they are influenced by pumping seepage water from the mine shaft. It is recommended to drill **at least three new wells in each aquifer (a total of six wells), which would support a better understanding of current and future risks.** Three wells are the minimum number required to establish the groundwater flow direction in any aquifer.
    - New wells should be drilled approximately northeast, west, and south of the mine site and at a distance beyond the influence of the mining operation. The set-back distance from the mine needs to be determined based on additional field work.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

  - A more thorough investigation of whether there are saturated conditions in the Supai is recommended. The well drilled into the R-aquifer at the mine site does not indicate if the Supai is saturated nor do other wells drilled through the Supai in the region. Additional borings in the low permeability layers separating the C- from the R-aquifer, including a slug test that can establish the in-situ conductivity of these units, can provide insights about the potential for vertical flow between the two aquifers.
  - Additional tests and analyses should include:
    - Conducting tests to determine groundwater flow rate and direction.
    - Collecting intact rock and sediment samples during drilling and analyzing samples for parameters such as porosity and hydraulic conductivity.
    - Conducting hydraulic tests in the two aquifers to determine how readily water moves through the rock and sediment and whether water can move from one well to another along faults, fractures, or karst features.
    - Sampling the new wells periodically for dissolved uranium and other compounds, such as arsenic, tritium, and radiocarbon, which provide information about the possible migration direction and velocity of compounds moving away from the site. This sampling has to be a long-term (years to decades) commitment because of the amount of time it may take for contaminants to migrate.
- **Testing and sampling for groundwater contamination.** It is recommended to gather data on potential groundwater contamination by expanding water quality sampling and testing at the site. Existing and new data should build the basis for simulations of geochemical conditions in the subsurface during and after mining and to predict the long-term fate of uranium and other heavy metals. This data may also inform the process for sealing off the mine. Specific recommendation include:
  - Sampling for PFAS in the mine shaft water, current wells, and recommended new wells. One advantage of using human-made compounds such as PFAS as tracers is that their presence would indicate that contaminated surface water is entering the subsurface and how quickly contaminants find their way into the groundwater.
  - Continuing to sample for other contaminants, such as uranium and arsenic. This sampling should take place at existing and future wells near the mine site and may have to continue for year to decades.
  - Conducting a field survey and additional geotechnical testing. This testing should include mapping fractures and testing in-situ permeability of rocks around the wells.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

- Modeling and analyzing data using software such as Modflow or PHREEQC.

Overall, following the recommendations can provide a more detailed and accurate picture of the current and future impact of uranium mining on the groundwater system around the Pinyon Plain Mine. Even though the recommended investigations will improve our understanding of groundwater flow and contaminant transport at the mining site, the area's complex geology and hydrogeology may require additional tests and investments into monitoring infrastructure, particularly wells. Additional investigations may be needed to limit the risk of missing preferential flow paths that could facilitate dissolved contaminants by-passing the monitoring system. Details about these recommendations, including specific testing parameters, are summarized in this report.

Site History

Mineral resources are found in the Grand Canyon and surrounding area. Specifically, the breccia pipes in the Grand Canyon region contain some of the highest-grade uranium ores in the Nation (Alpine, 2010). They are more properly termed "solution-collapse breccia pipes" in this area because they are formed through the collapse of a cave ceiling, are composed of bits of broken rock (also known as breccia), and are shaped like vertical pipes or columns that move upward into overlying formations over time (Alpine, 2010). Up to thousands of these features are located in the Grand Canyon region, and many of these breccia pipes contain high concentrations of sought-after metals such as uranium, copper, silver, lead, zinc, cobalt, and nickel (Alpine, 2010; Wenrich, 1985).

Mining in breccia pipes in the Grand Canyon region began in the 1860s. Prior to 1940, all of the mineral production was for copper, lead, zinc, and silver. The discovery of high-grade uranium deposits in the Orphan Lode (breccia) pipe led to uranium production at this site in 1956. The Orphan mine is located about two miles west of Grand Canyon Village on the South Rim of Grand Canyon National Park (Alpine, 2010).

In 1986, an Environmental Impact Statement (EIS) and Record of Decision for the Pinyon Plain Mine (formerly Canyon Mine) was approved. Construction of the mine's surface facilities commenced immediately afterwards, but the project was put on standby in 1992 with only 50 feet of the shaft completed. In 1997, the mine and its permits were acquired by International Uranium (USA) Corporation (IUC) and its affiliates. IUC changed its name to Denison Mines (USA) Corp. (Denison) in 2007 and to Energy Fuels Inc. (EFR) in 2012 (EFR, 2015).

In 2012, the Department of the Interior directed the USGS to study the potential effects of uranium mining in the Grand Canyon region (U.S. Department of the Interior, 2012). As of August 2023, new mining is not allowed within the Baaj Nwaavjo I'tah Kukveni–Ancestral Footprints National Monument. However, there are a small number of breccia-pipe mines within the national monument that are permitted to continue mining (Biden, 2023), including the Pinyon Plain Mine.

Mining at the Pinyon Plain Mine started in December 2023 and Energy Fuels Inc. plans to operate the mine at an average rate of up to 143 short tons per day of ore for about 28 months (EFR, 2023). No ore processing is carried out on site. All ore is trucked and processed off site. The expected operational life of the facility is 5 to 7 years (EFR, 2024).

Hydrologic analysis of the connectivity between the shallower C-aquifer and deeper R-aquifer at the Pinyon Plain Mine site

The groundwater of the Grand Canyon's South Rim has been studied for many decades (e.g., Bills et al., 2005; Pool et al., 2011), but data are still sparse (Knight and Huntoon, 2022). Based on the limited data available, the analysis of the local groundwater flow at the Pinyon Plain Mine site is built on what we know about the South Rim regional groundwater system.

The regional groundwater system consists of both perched groundwater of limited spatial extent, the Coconino aquifer (C-aquifer), and the considerably deeper regional aquifer or Redwall-Muav aquifer (R-aquifer). The primary regional water-bearing unit is the stratigraphically confined R-aquifer. This aquifer, which lies several hundred feet below the Pinyon Plain Mine breccia pipe orebody, includes Mississippian Redwall and Cambrian Muav limestones, two formations which behave as a single hydrostratigraphic unit. At the mine site, this unit is about 738 feet thick with an estimated saturated thickness of approximately 110 feet (ADEQ, 2022b). The hydrologic system in the R-aquifer is – and has been since the late Mississippian – karstic (limestone). Leaching and dissolution of the limestone by flowing groundwater, known as karstification, in the R-aquifer has produced dissolution-enhanced conduit flow pathways to various degrees and has been critical in the development of breccia pipes (Hill and Polyak, 2020). R-aquifer groundwater likely flows north toward the Grand Canyon from a divide near the town of Tusayan (Tusayan divide). South of the divide, the flow is in southerly and western direction (Curry et al., 2020; Knight and Huntoon, 2022). The Pinyon Plain Mine is just over 6 miles south of the town of Tusayan (Figure 1). It is unclear whether the area of the mine is north or south of the groundwater divide. The Havasupai Reservation is about 20 miles northwest of the mine and Havasu Springs is located inside the reservation, about 40 miles northwest of the mine.

Measurements of the R-aquifer water levels at the mining site indicate more than 300 feet of artesian head pressure (ADEQ, 2022a). Artesian pressure is the pressure that forces groundwater upward toward the surface without the need for pumping. It occurs when an aquifer is confined between impermeable rocks or clay, creating positive pressure. This means that water in a well drilled into the R-aquifer would rise about 300 feet above the level at which the well first encounters water in the aquifer. Because the R-aquifer is several hundred feet below the ore body and is more than 700 feet thick, this artesian pressure is not sufficient to force groundwater vertically upward and out of the R-aquifer strata or may preclude water from entering the aquifer from above, at least at this location.

On the Coconino Plateau, the C-aquifer system includes the hydraulically connected Kaibab Formation, the Coconino Sandstone, the Schnebly Hill Formation, and the Upper and Middle Supai Formations (Figure 2) (Bills et al., 2007; ADWR, 2015). The Toroweap Formation is not part of the aquifer system (Bills et al., 2007). The C-aquifer is a relatively shallow and unconfined aquifer, consisting of hydraulically connected sandstones and limestones (i.e., the C-aquifer's main water-bearing units are the Kaibab Limestone, Coconino Sandstone, and upper sequences of the Supai Formation (Bills et al., 2007)).

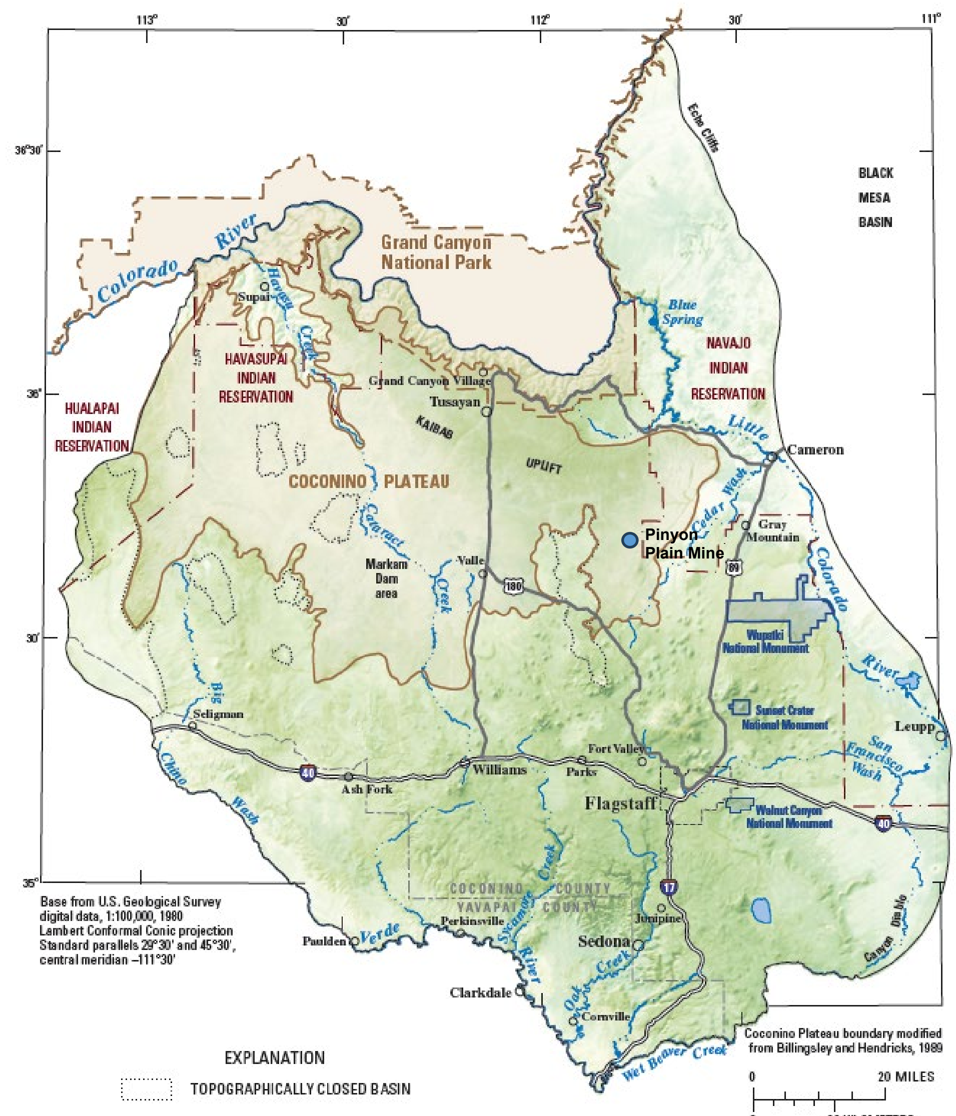


Figure 1: Location and geographic features of the Coconino Plateau, Coconino and Yavapai Counties, Arizona. The Pinyon Plain Mine (blue circle) is about 6 miles south of the town of Tusayan. The springs on the Havasupai Reservation are about 40 miles northwest of the mine site, near Supai village (Modified after Bills et al., 2007).

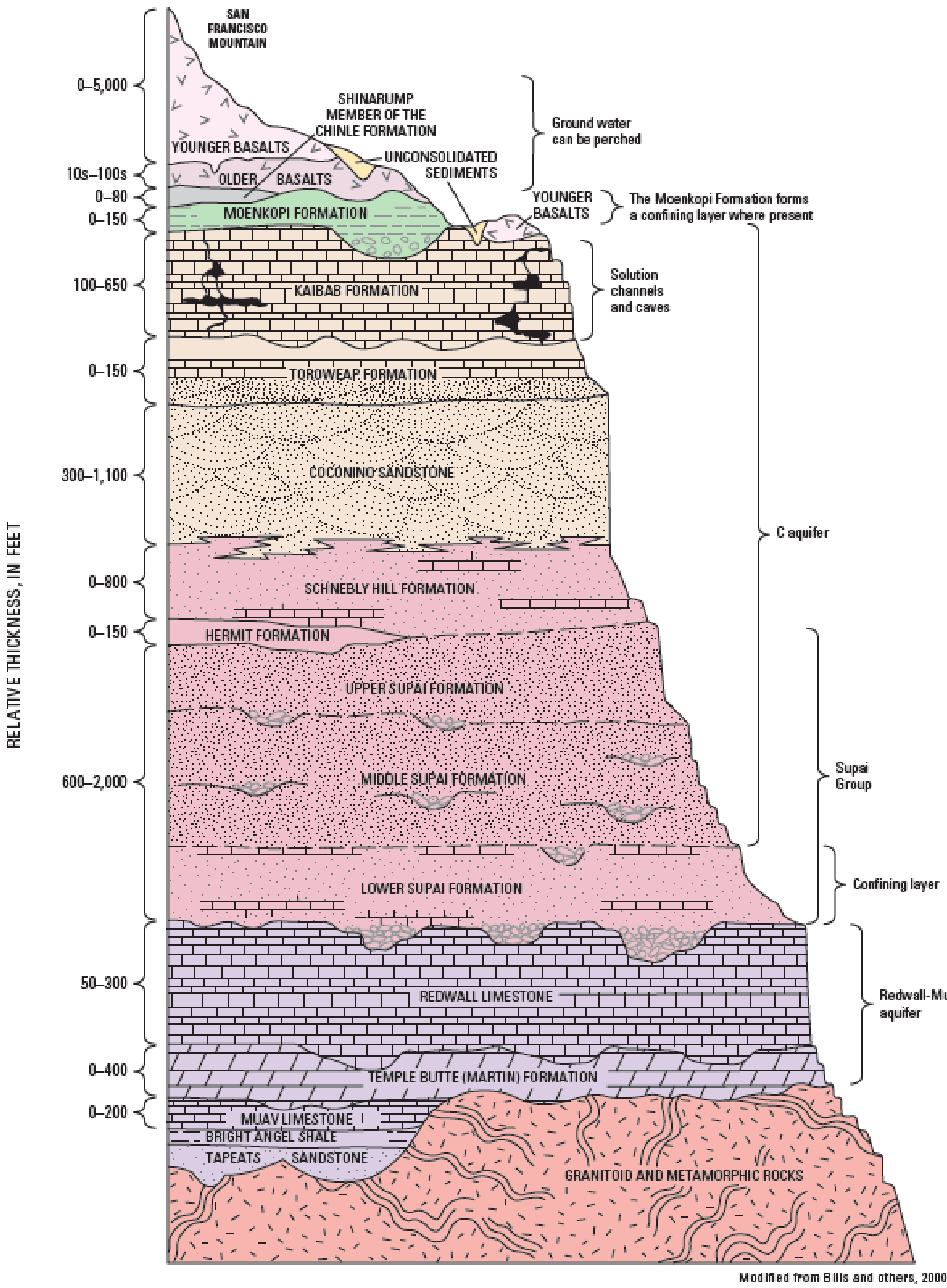


Figure 2: Generalized stratigraphic section of rock units on the Coconino Plateau, Coconino County, Arizona. The approximate vertical extent of the Coconino (C-aquifer) and Redwall-Muav (R-aquifer) aquifers on the plateau are also shown but vary from location to location (Source: Bills et al., 2007).

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

At the mine site, the Coconino Formation is approximately 575 feet thick with a saturated thickness of about 184 feet (EFR, 2024). Perched groundwater occurs mostly within the Coconino Sandstone at the mine site. The rocks composing the C-aquifer generally are well-drained by canyons or extensional fault zones, and the saturated zones are spatially discontinuous and unconfined (Knight and Huntoon, 2022). While fully saturated in the far eastern and southeastern portions of the Coconino Plateau, the C-aquifer mainly occurs as relatively small and discontinuous perched water-bearing zones across most of the area (Solder et al., 2020). Perched groundwater can be in direct contact with mineralized breccia pipes where they intersect the Coconino aquifer (Alpine, 2010).

There is uncertainty about the groundwater flow direction and velocity of both aquifer systems at the Pinyon Plain Mine site. A rudimentary potentiometric surface map for the R-aquifer was created from a small number of water level measurements (Bills et al., 2007). It shows groundwater flow toward large springs in the Little Colorado River (Blue Spring) and Cataract Canyon (Havasu Spring). Knight and Huntoon (2022) inferred south and west directed flow in the R-aquifer in the Pinyon Plain Mine area. EFR (2022) estimated an east directed flow in the C-aquifer at the mine site but also considers a south-west flow direction as plausible.

The perched C-aquifer and regional R-aquifer systems are generally separated by 2,000 feet or more of unsaturated strata. However, steeply dipping faults and fault zones complicate groundwater circulation patterns by serving as barriers to lateral flow perpendicular to them (USGS, 2002). In contrast, fracture and dissolution permeability within or parallel to the planes of the faults commonly provide high-capacity vertical and horizontal flow paths. This allows for downward circulation of groundwater from the perched groundwater zones to the deep regional aquifer and enables very rapid flow of groundwater laterally from beneath distant recharge areas to karst springs deep in the canyons (Knight and Huntoon, 2022). The hydrotectonic concepts for the Grand Canyon area introduced by Crossey et al. (2024) considers distinct structural sub-basins, fast fault conduits, confined aquifers, karst aquifers, upwelling geothermal fluids, and induced seismicity as factors influencing the regional groundwater system.

Regional fractures and faults are omnipresent in the Grand Canyon area (Huntoon, 1977). These geologic structures can be barriers to groundwater flow or can be highly permeable, in which case faults and fractures can serve as high-capacity conduits that allow groundwater circulation pathways from the C- to underlying R-aquifer (Knight and Huntoon, 2022). Beisner et al. (2023) used anthropogenic chemical substances as tracers for investigating the fate of treated wastewater effluent discharged within the Grand Canyon National Park. Multiple anthropogenic substances (pharmaceuticals and personal care products (PPCPs), per- and polyfluoroalkyl substances (PFAS)) were found in Bright Angel Wash and Monument Spring. The anthropogenic tracers used in their study provided insight into which geologic structures are local conduits versus barriers to flow. Crossey et al. (2024) hold that natural and anthropogenic substances present in recharge from the surface can travel two km vertically and tens of

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

kilometers laterally in days to months via fracture conduits to mix with older karst baseflow. While a USGS geophysical evaluation and mapping at 500 m^2 resolution suggests that no significant geologic structures adjacent to the Pinyon Plain Mine breccia pipe are expressed at the surface (Gettings and Bultman, 2005), the mine is surrounded by a ring fracture zone that extends up to 300 feet beyond the breccia pipe (EFR, 2023).

Groundwater flow between the two aquifers occurs locally through several hundreds of feet of Hermit Formation and Supai Group, which act as leaky aquitards (Solder et al., 2020). The vertical permeabilities in extensional fault zones can be very high (Caine et al., 1996) and equal to that in well-developed karst (well-dissolved limestone), as interpreted by Knight and Huntoon (2022). Laboratory test on cores from the exploration drill holes at the mine site show that hydraulic conductivities of intervening geologic units between the C- and R-aquifers are low, ranging from a maximum of 6.18 $\times10^{-7}$ cm/sec in the Upper Supai, to consistently below 1 $\times10^{-8}$ cm/sec in Lower Supai and Redwall (ADEQ, 2022b). However, fractures and dissolution pathways, if present, can increase the hydraulic conductivity to much higher in-situ values.

The solution-collapse breccia pipes in the Grand Canyon region are unique in the world. These deposits are vertical or near vertical, circular to elliptical bodies of broken rock comprised of slabs, rotated angular blocks, and fragments of surrounding and stratigraphically higher formations. Host rocks include breccias of limestone, sandstone, siltstone, and shale in a finer grained sand matrix cemented by carbonate minerals with high acid-buffering capacity (Wenrich et al., 1997). The inclusion of breccia made of stratigraphically higher formations suggests that the pipe at the Pinyon Plain Mine formed by solution collapse of underlying calcareous rocks, such as the Redwall Limestone (EFR, 2023). Breccia in solution collapse pipes is relatively permeable where not silicified (Wenrich et al., 1985; Wenrich et al., 1997). This geology strongly influences the local hydrogeology and groundwater flow. That is, the mine is surrounded by a ring fracture zone (EFR, 2023). Some ring fractures have been mineralized over time, which reduces their permeability, while other ring fractures can be permeable and therefore locally focus groundwater flow. ADEQ (2022b) sees strong evidence which indicates that there are no macro features (ring fractures, faults, karst features, or other conduit-flow features) that act as discreet flow paths from the C-aquifer to the R-aquifer to affect water quality in the underlying R-aquifer.

The Pinyon Plain Mine is part of the Havasu Canyon Watershed (USDA, 2010). The watershed covers approximately 1,877,120 acres (2,933 square miles) and the Havasupai Reservation, and a portion of the Hualapai Reservation is located within the watershed (Figure 3). Major land uses in the watershed include range and forest. Recreational uses are also important activities both on federal and tribal lands. Major towns and cities include the City of Williams and Supai Village. Supai is downgradient from Havasu Creek Springs and located approximately 40 miles NW from the Pinyon Plain Mine. The USGS operates the Havasu Creek Spring gage (installed 1995; ID 09404110), which is located 1.5 miles above Supai, and monitors streamflow every 15 minutes. Fern Spring is also near Supai and there is at least one well in the area (Supai Well

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

No.3; [USGS Map,](#) 2024). Supai Well No.3 draws water from a local Holocene alluvial aquifer, whereas Fern Springs and Havasu Creek Springs discharge water from the R-aquifer. For these locations, uranium and arsenic water quality data are available at USGS Map (2024). Other water quality parameters for these sites can be obtained from the USGS National Water Information System (NWIS).

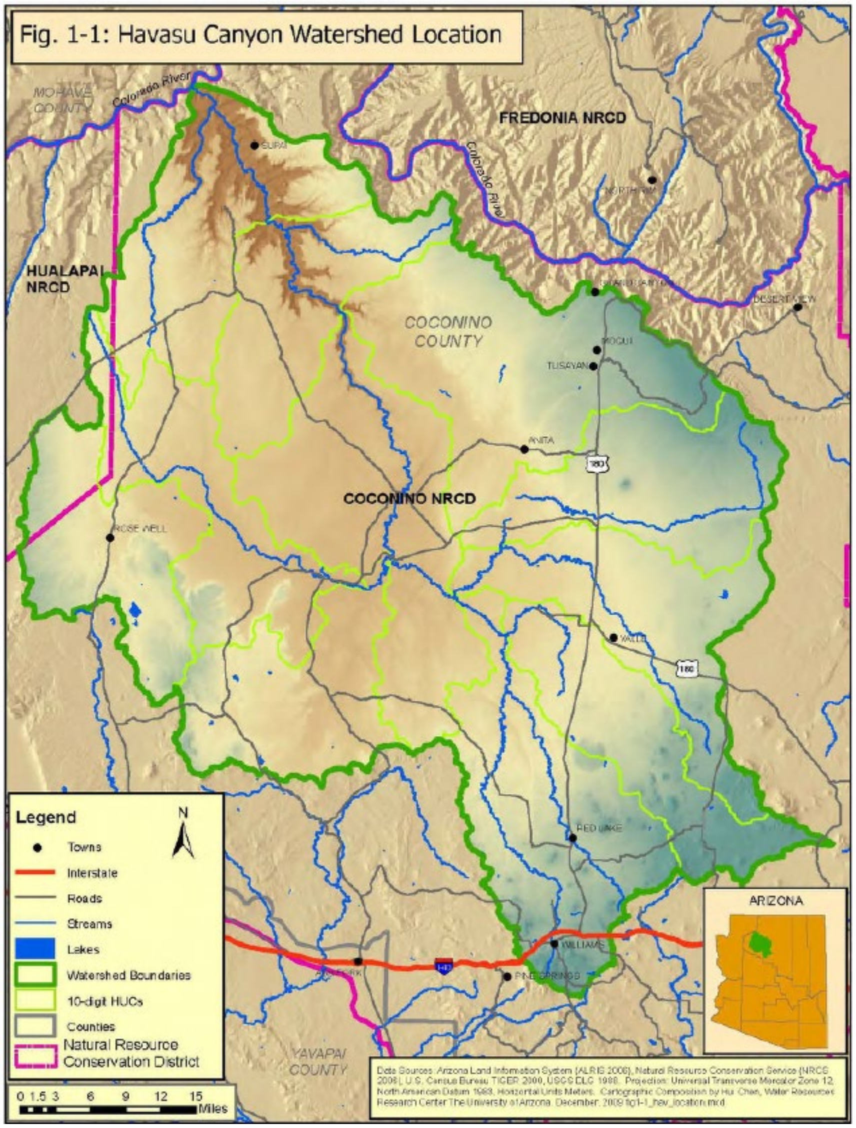


Figure 3: The Havasu Canyon watershed. The Pinyon Plain Mine is located about 6 miles south of the town of Tusayan (Source: USDA, 2010).

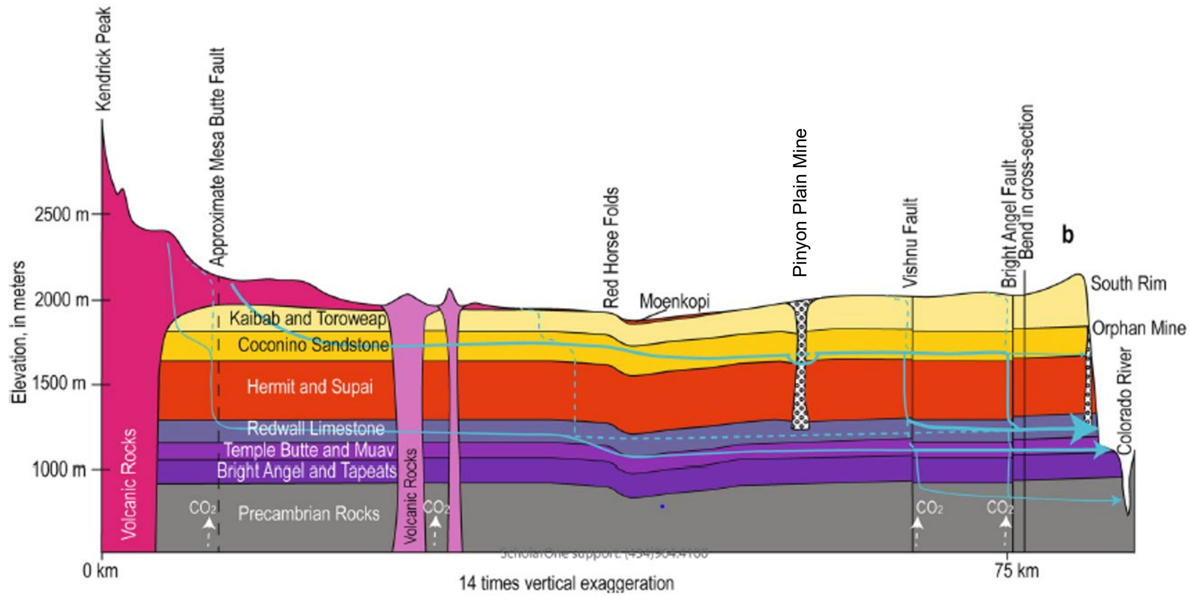


Figure 4: Conceptual groundwater flow diagram for the South Rim of the Grand Canyon. The corresponding profile line connects the San Francisco Peaks to the South with the Grand Canyon village to the north (Modified after Beisner et al., 2020). Solution-collapse breccia pipes are distinguished by concentric-inward-dipping beds that generally surround a basin, amphitheater-style erosion, concentric drainage, soil and vegetation patterns, breccia, and altered and mineralized rock (Wenrich and Sutphin, 1988). Ring fractures surrounding the pipes tend to erode readily, which causes development of concentric drainage around breccia pipes.

The Crossey et al. (2006) conceptual groundwater flow model is based on the mixing of deeper and older 'hypogenic' (= lower world) with shallower and younger 'epigenic' (=upper world) waters along fractures and faults. Figure 4 illustrates the conceptual groundwater flow as proposed by Beisner et al. (2020) and similarly by Solder et al. (2020). The corresponding profile line connects the San Francisco Peaks to the south with the South rim and Grand Canyon Village to the north.

These two conceptual groundwater flow models are not mutually exclusive and, based on tracer data, it is very likely that deep and shallow groundwater flow paths co-exist. The regional flow is characterized by old groundwater (10^2 to 10^4 years), and the shallower, more local flow by younger groundwater (10 to 10^2 years) (Solder et al., 2020). Based on stable isotope data (δ^2H and $\delta^{18}O$), recharge to South Rim groundwater likely occurs at multiple locations and across the entirety of the year. Weak seasonal variations in stable isotope data were observed in groundwater in the Pinyon Plain Mine perched groundwater observation well, which could be interpreted as evidence for the C-aquifer to be primarily recharged by summer precipitation or being possibly disconnected from the regional groundwater system altogether (Solder and Beisner; 2020). As noted by Solder et al. (2020), the mean average age at the Pinyon Plain Mine observation well screened in the C-aquifer is similar to the ages in nearby R-aquifer wells (10,644 years versus 12,040 years, respectively). This finding suggests a hydrologic connection

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

in the Pinyon Plain Mine area or that the two aquifer systems have similar recharge sources and groundwater velocities.

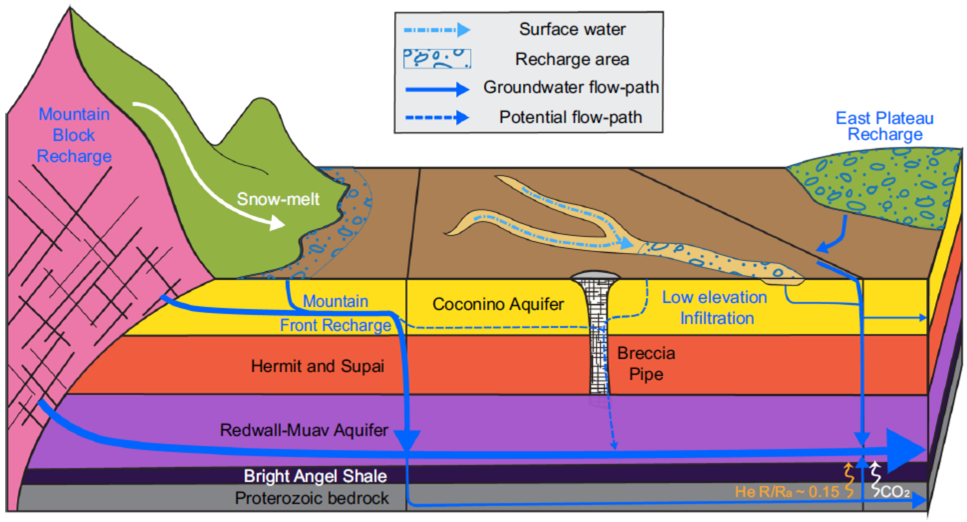


Figure 5: Conceptual groundwater flow diagram for the South Rim, Grand Canyon, USA. Groundwater recharge sources labeled with blue text. Relative flow amounts indicated by size of flow-path arrows. Dissolved gases sourced from bedrock and transported along faults indicated by curvy arrows at bottom right (Figure 7 from Solder et al., 2020).

Solder et al. (2020) states that previous models postulated a distinct physical separation of the C- and R-aquifer groundwater flow systems recharged solely from snowmelt off the San Francisco Peak but found that interpretation inconsistent with the tracer data of their study. According to their analysis, several preferential groundwater flow pathways exist on the South Rim (Figure 5), including groundwater inflows from mountain front recharge, surface water (precipitation runoff) infiltration, and deep, regional flow paths. For reference, the South Rim area has a very limited modeled potential recharge of 0–1 in/year (Knight and Huntoon 2022).

Regional numerical modeling (MODFLOW) was completed by the USGS (Pool et al., 2011). This model was developed mostly for simulating groundwater in the Little Chino, Big Chino, and Verde Valleys, and not for the area north of Flagstaff. This model was considered in the ADEQ evaluation of the Individual Aquifer Protection Permit (APP) application (ADEQ 2022b). The model predicts a southwesterly flow direction in the mine area. The authors caution that their model lacks documentation of the response of the groundwater system to changes in withdrawals and recharge in many areas. Also, the model's aquifer storage properties are poorly defined throughout most of the study area, and the hydrologic importance of geologic structures, such as faults and fractures, was not simulated (Pool et al., 2011).

The CARAMP0F 1 flow model (based on the USGS NARGFM1F 2) was also considered by ADEQ in the evaluation of the application and Individual APP Permit (ADEQ, 2022b). The CARAMP model predicted groundwater heads out to 100 years under different development and climate projection scenarios (CPWAC, 2021). Scenario 1 captured the baseline conditions (Figure 6). The model suggests that under baseline conditions, pumping near Tusayan village could draw groundwater from the direction of the Pinyon Plain Mine area. Common to all groundwater flow models is that their scale and resolution is too coarse and therefore of little value for the interpretation of the local hydrogeology at the Pinyon Plain Mine site.

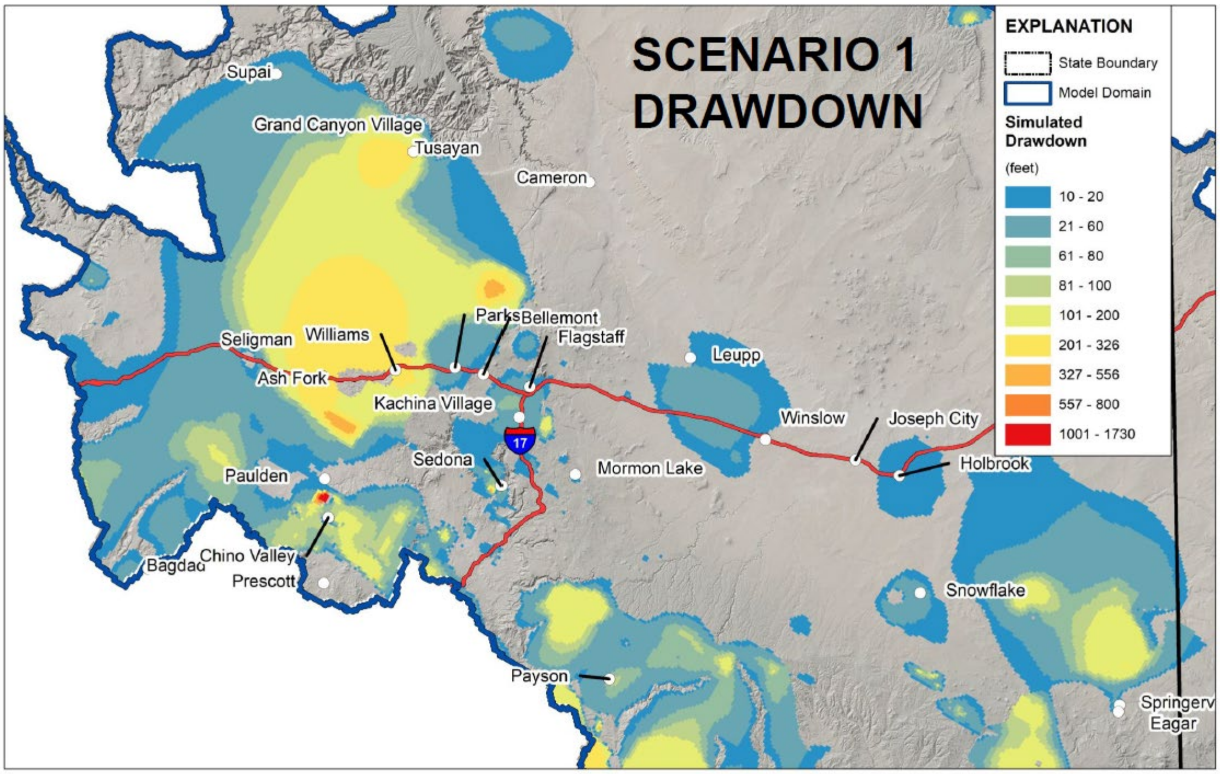


Figure 6: Regional numerical modeling covered by the CARAMP0F 1 flow model (based on the USGS NARGFM1F 2). One project goal was to assess the impacts on surface water flows in rivers, springs, and riparian areas after 100 years of simulated pumping. Scenario 1 captured the baseline conditions (Source: CPWAC 2021; ADEQ 2022b)

The regional groundwater flow direction in the R- aquifer is to the southwest, based on regional studies. In the C-aquifer, based on findings from the Initial Hydrogeologic (Monitoring) Report by Hydro Geo Chem, Inc. dated June 24, 2022 (EFR, 2024), it appears that determining the groundwater flow directions on the immediate mine site may not be possible at present until reequilibration of the groundwater system has occurred post-closure (EFR, 2024). Further, cones of depression computed from water level and pumping test data clearly show that all perched (Coconino) groundwater within the vicinity of the mine site is currently flowing toward the shaft; this condition is expected to continue until mining ceases and the shaft is abandoned and sealed as described in EFR (2020).

The interpretation of South Rim groundwater origin, age and flow paths is further complicated by water imports from the North Rim. For over 60 years, the *Transcanyon Pipeline* transports

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

Roaring Springs water from the North Rim to the South Rim. The pipeline has a capacity of up to 42 L/s. Based on a simple stable isotopic mixing model, Curry et al. (2023) found that the groundwater at the Pinyon Plain Mine may contain tens of percent of North Rim water. Curry et al. (2023) suggests that the hydrochemical variability of South Rim springs and groundwater is primarily due to anthropogenic groundwater mixing and secondarily due to variations in local recharge, as proposed by others. Further, these researchers take the presence of geochemical tracers (major ions, stable isotopes) and trace amounts of anthropogenic substances as evidence that uranium mining, local groundwater pumping, management of the *Transcanyon Pipeline,* and water reclamation infrastructure are all part of an interconnected South Rim groundwater system. However, no anthropogenic tracer samples were collected from the groundwater at Pinyon Plain mine. Therefore, it is unknown whether the groundwater at the mine site is influenced by the *Transcanyon Pipeline* and water reclamation infrastructure at Grand Canyon Village.

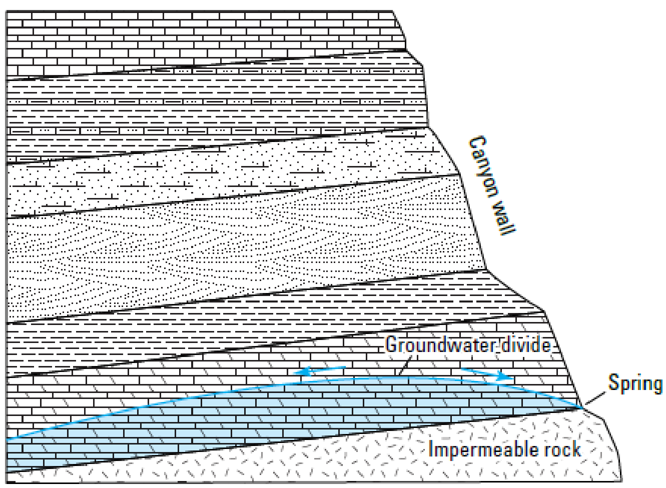


Figure 7: Most South Rim springs discharge a fraction of groundwater from aquifers where the strata dips away from the canyon wall. Note that a groundwater divide demarcates the flow regimes towards and away from the canyon. Larger discharges can be expected when the strata dips towards the canyon wall. (Source: Knight and Huntoon, 2022).

Springs are an important element of the area's hydrological system and cultural fabric (Havasupai Tribal Council, 2022). Most springs discharge water from the R-aquifer, including Havasu Creek Springs. A few, typically smaller springs of the South Rim are examples of water discharges from perched C-aquifers, as in the case of Dripping Springs at the Coconino Sandstone–Hermit Shale contact (Hill and Polyak, 2010). These springs are conceptualized by Knight and Huntoon (2022) as discharging a comparably small fraction of groundwater from an aquifer where the strata dips away from the canyon wall, as is the case for most parts of the South Rim. Much of the remaining groundwater then follows approximately SW sloping sedimentary deposits that make up the C-aquifer. The Tusayan groundwater divide set back from the South Rim of the Grand Canyon separates the flow of groundwater to the principal

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

point of discharge for the groundwater system at Havasu Creek Springs from the minor amount of flow that occurs in the springs below the South Rim (Knight and Huntoon, 2022). The divide's existence could be explained by Figure 7.

Overall, several studies using different lines of evidence strongly suggest that connectivity between the shallower C-aquifer and deeper R-aquifer is likely in some parts of the region. It is also plausible that the two groundwater systems are both being recharged from the same location. For example, it is plausible that in both aquifers, old groundwater that is isotopically depleted (like at the Pinyon Plain Mine wells) could be recharged from snowmelt at the San Francisco peaks area near Flagstaff and flow slowly towards the mine location (Figures 4 and 5). However, the extent and timeframe over which these aquifers communicate, including at the Pinyon Plain Mine site, is not well understood and needs to be better constrained with data from additional wells.

Synthesis of Hydrologic Analysis

EPA conducted an independent hydrologic analysis of the published evidence for connectivity between the shallower C-aquifer and deeper R-aquifer at the Pinyon Plain Mine site. Important, and sometimes contradictory, findings from analyzing published information about the connectivity between the shallower C-aquifer and deeper R-aquifer in Pinyon Plain Mine area are synthesized here:

- The regional groundwater flow on the South Rim is controlled by five main features, namely (1) karst systems developed on joint fractures and faults, (2) large regional faults, (3) lithology and regional dip of the rock matrix, (4) incision of the Colorado River and its tributaries through rock units of the aquifer, and (5) the relatively impermeable Bright Angel Shale (Solder et al., 2020).
- Important hydrologic dynamics include locations and rates of potential groundwater recharge, vertical pathways from the surface and the overlying C-aquifer to the R-aquifer, and the locations, magnitude, geochemical signature, and hydrostratigraphic setting of groundwater discharge from springs (Knight and Huntoon, 2022).
- Existing numerical groundwater models of the region (e.g., Pool et al., 2011; CPWAC, 2021) are at a scale and resolution that is too coarse and therefore of little value for the interpretation of the local hydrogeology at the Pinyon Plain Mine site.
- At the mine site, there are no springs, sinkholes, closed depressions, buried alluvial channels, or other (epi)karst features, as evidenced by exploratory boreholes, aerial photography, logging of the shaft, and topography (ADEQ, 2022b; EFR, 2024).
- A ring fracture zone, together with downward dipping strata, directs surface water flow toward the breccia pipe at the Pinyon Plain Mine site (EFR, 2023), but the vadose zone (about 900 feet) above the C-aquifer is considered sufficiently thick for protecting groundwater from surface infiltration (ADEQ, 2022b).

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

- While the flow direction in the perched C- aquifer and the regional R-aquifer cannot be determined with the existing set of wells at the mine site, it is presumed south to southwest (ADEQ, 2022b) or possibly east in the C-aquifer (EFR, 2024).
- Breccia in solution-collapse pipes is relatively permeable where not silicified (Wenrich et al., 1985; Wenrich et al., 1997). The current degree of silicification and, by extension, permeability of the Pinyon Plain Mine breccia pipe is not well described, although EFR (2023) considers it impermeable, or at most as having very low permeability, according to ADEQ (2022b).
- The overall similarity in the range of stable isotopic values between the C- and R-aquifers on the South Rim either suggests a direct connection between the perched C-aquifer and R-aquifer in the mining area is likely (Curry et al., 2023; Crossey et al., 2024) or it could simply be coincidental (ADEQ, 2022b), or it could suggest a common recharge location/altitude/time (Solder et al., 2020).
- The average age of the groundwater at the Pinyon Plain Mine observation well screened in the C-aquifer appears to be similar to that of groundwater in nearby R-aquifer wells (10,644 years versus 12,040 years, respectively; Solder et al., 2020). ADEQ (2022b) argues that the data on mean age are not sufficient to conclude there is an interconnection without other evidence.
- The groundwater in the Pinyon Plain Mine area may contain a fraction of water piped in from the North Rim, based on extrapolation of stable isotope data. Curry et al. (2023) considers the data as evidence that uranium mining, local groundwater pumping, and management of the *Transcanyon Pipeline* and water reclamation infrastructure are all part of an interconnected South Rim groundwater system.
- Geochemical fingerprints of the springs and groundwater in the region do not indicate flow or direct hydraulic connection between the C-aquifer, R-aquifer, and springs in the Grand Canyon, or the time scale of the connection (ADEQ, 2022b). Curry et al. (2023) holds that given the potential for fault-influenced flow combined with karst complexities, any change in the head in groundwater wells near the divide and especially along faults will likely affect South Rim springs. Models of future groundwater extraction scenarios appear to support this assessment (CPWAC, 2021), but these models' spatial resolution is too coarse to provide details about the mine site.
- The role and location of the Tusayan divide immediately north of the mine remains largely unknown.
- Because of the ongoing dewatering of the mine shaft, the natural groundwater gradient in the C-aquifer has been altered at the mine site (ADEQ, 2022b; ERT, 2023). Therefore, the existing C-aquifer wells on the site are not expected to provide insights into the natural groundwater flow direction until after mine closure.
- While connectivity at the mine site is important, it is also critical to understand if the two groundwater systems could be connected at any point downgradient from the site. That is,

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

if the perched groundwater were to become contaminated at the mine site and moved away from the mine, would it at some point move down to the regional aquifer?

Recommendations

Scarcity of wells and poor public documentation of water levels and historical data is such that additional data about geochemical and water level variation of key wells at the Pinyon Plain Mine and nearby settlements, such as Tusayan and Grand Canyon Village, are needed (Curry et al., 2023). There appear to be three regional aquifer wells in the town of Tusayan, about 6 miles away. Another well is Patch Karr Well, approximately thirty kilometers from the mine (ADEQ, 2022b). At the mine site, the present two monitoring wells, one in the C-aquifer and one in the R-aquifer, are inadequate to resolve direction and rate of groundwater flow or quantify contaminant transport. The additional three perched wells on the mine site are influenced by the mine shaft dewatering operation and therefore do not provide reliable insights into natural groundwater flow conditions.

Recommendation: In any aquifer, at least three wells are required to resolve the direction of groundwater flow, including determining the rate of groundwater flow or quantifying contaminant transport. The existing C-aquifer wells at the mine site are influenced by the mining activities, therefore, it must be assumed that the natural groundwater flow direction near the mine is altered because of pumping from the mine shaft. The existing single R-aquifer regional well by itself is insufficient for determining direction and velocity of groundwater flow in the deeper aquifer at the site. Also, the well hydraulics may be affected by the well's close vicinity to the mine site. Thus**, it is recommended to install three new wells each in both the C- and R-aquifers (six wells total).**

The R-aquifer wells should be screened in the Redwall Limestone in potentially water-bearing rock layers, if present, and in the deeper Muav formation. Different water-bearing layers should be physically separated by seals above and below these layers, for testing and sampling. The set-back distance of these new wells must be large enough to avoid disturbances of the natural water levels due to mining activities and need to be beyond the reach of ring fractures centered on the breccia pipe. It is recommended to determine the actual set-back distance based on additional field work and ring fracture mapping.

Geophysical tests inside the newly installed wells are recommended. Specific tests are: (1) Gamma and Neutron logging for lithology, mineralogy, and total porosity; (2) Nuclear magnetic resonance logging for total, free, and bound porosity as well as hydraulic conductivity; (3) Single-point resistance for lithology and fractures; and (4) Acoustic-televiewer and caliper logs to record location, images, strike and dip of fractures (if present), and lithological contacts. These tools should be applied to all formations encountered during drilling. Ideally, one of the three new wells should be installed upgradient (presumably northeast of the mine), one to the west, and one to the south. This constellation should increase the chance of catching potential groundwater contaminants as they are transported away from the mine site. Further, it is recommended to install at least three piezometer wells in the Supai formation, particularly in the Esplanade Sandstone, after the recommended three new R-aquifer have been installed. That is, rock layers should be targeted that may be saturated based on data collected during the drilling of the recommended three new R-aquifer wells. These piezometer wells would provide insights about vertical flow between the upper and lower aquifers. Another recommendation is to conduct in-hole tracer dilution tests to estimate the groundwater flow rate at the screened interval of each existing and recommended wells.

Given the uncertainties related to the hydrogeologic conditions at the Pinyon Plain Mine site, the potential for groundwater contamination resulting from operations at the Pinyon Plain Mine site cannot be assessed adequately without additional investigations.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

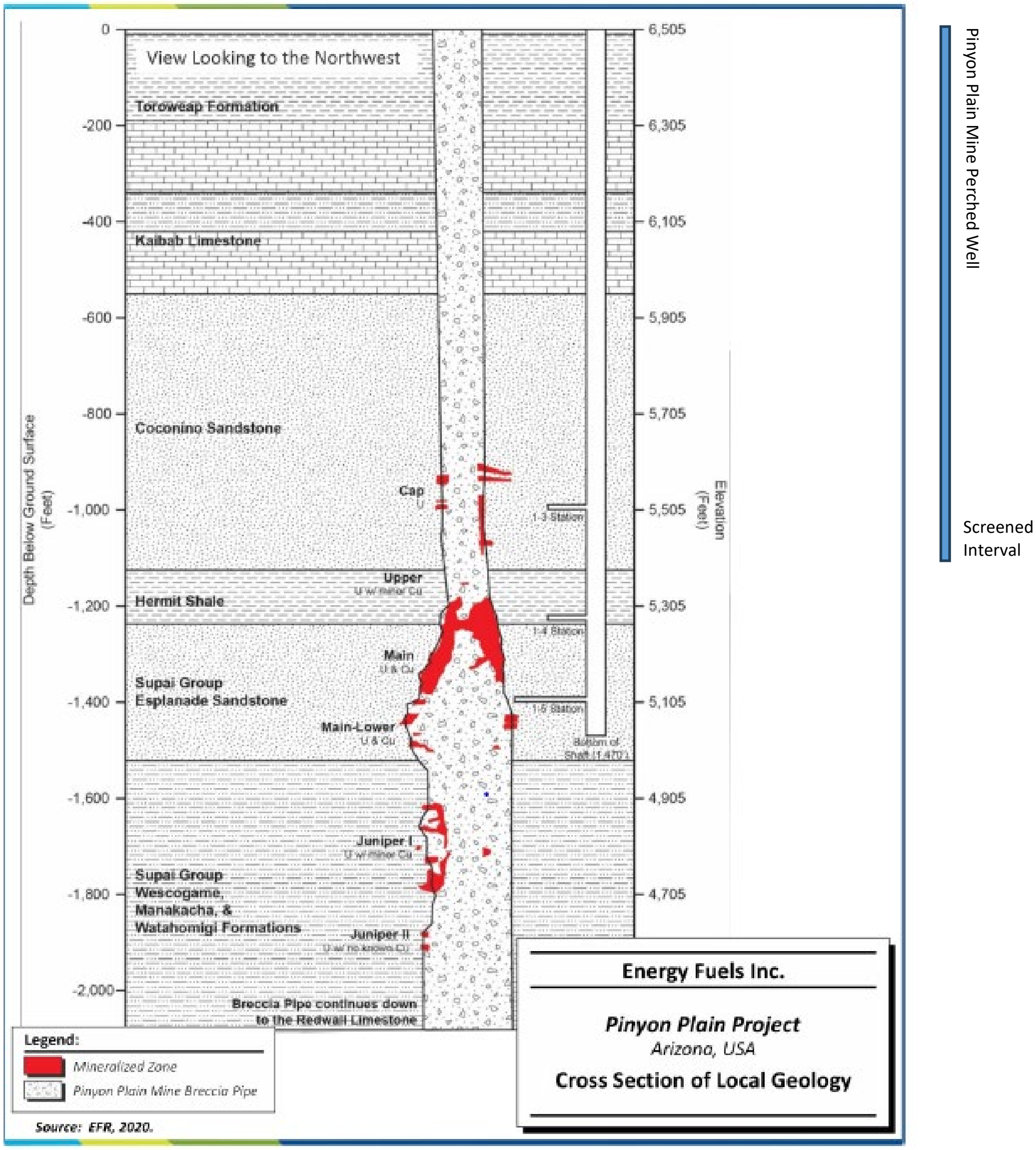


Figure 8: Cross section of local geology at the Pinyon Plain Mine, Arizona, USA. Blue vertical bar: Pinyon Plain Mine Perched Well (USGS 355254112054901), screened at 1,115 to 1,135 feet below ground surface in the lower Coconino formation. Mineralization extends vertically both inside and outside the pipe over approximately 1,450 to 1,700 vertical feet, but potentially economic grade mineralization has been found mainly in the collapsed portions of the Coconino, Hermit, and Esplanade horizons and at the margins of the pipe in ring fracture zones. Sulfide zones are found scattered throughout the pipe but are especially concentrated in a sulfide cap near the Toroweap-Coconino contact, where the cap averages 20 feet in thickness and consists of pyrite and bravoite, an iron-nickel sulfide. The mineralization assemblage consists of uranium-pyrite-hematite with massive copper sulfide mineralization common in and near the uranium zone. The strongest mineralization appears to occur in the lower Hermit-upper Esplanade horizons in an annular fracture zone. Arsenic is present where tennantite mineralization occurs. Additionally, lower quantities of silver, zinc, lead, molybdenum, copper, nickel, and vanadium are present and scattered throughout the pipe (Modified after: EFR, 2023).

Analysis of the potential for groundwater contamination resulting from operations at the Pinyon Plain Mine

As summarized by Curry et al. (2020), the geochemical composition of South Rim groundwater can be explained by: (1) a multi-permeability R-aquifer (karst); (2) mixing of "upper world" and lower world waters; (3) spring composition determined by percentage of winter versus summer recharge in different springs; (4) variable C-aquifer contributions as meteoric waters descend to the regional R- karst aquifer; and (5) very fast-traveled groundwater along fault and karst conduits interacting with baseflow pathways. In general, fractures and faults control the chemical mixing between the regional and local groundwater sources, the transport of deeply sourced and local recharge fluids, groundwater age, and thus the relative vulnerability of groundwater to depletion and contamination. Local conditions and preferential flowpath, however, ultimately determine the potential for groundwater contamination from mining activities.

Breccia pipe orebodies in northern Arizona are enriched in uranium, but also contain arsenic, copper, and other metals (Wenrich, 1985). In general, the ore minerals are located within the breccia pipe column and in the ring fracture zone that surrounds it (Alpine, 2010). Sulfide minerals associated with orebodies have the potential to produce acidic waters. Fortunately, limestone and calcareous sandstone rocks surrounding the ore have the ability to buffer much of the acidity with which they come in contact (Wenrich et al., 1995).

Uranium mineralization in the Pinyon Plain Mine is concentrated in three stratigraphic levels or zones (Upper/Cap, Main, and Juniper) with a vertical extension from a depth of 650 feet to more than 2,100 feet, resulting in at least 1,450 feet of mineralization (Figure 8) (EFR, 2023). Although uranium is the contaminant of primary concern, most, if not all the other metals potentially present in the Pinyon Plain Mine ore can be potentially harmful to humans and biota. Arizona's breccia pipe mineral deposits are generally porous and weather when exposed to oxidized, carbonate-rich water and/or acidic water (Alpine et al., 2010; Bern et al., 2022). Based on experience with newly mined deposits in the region, the uranium ores can oxidize within six months when exposed to surface conditions (Wenrich et al., 1995) or even faster under laboratory conditions (Bern et al., 2022), indicating a potential for rapid leaching and chemical reaction of these materials, even in the arid environment of northern Arizona (Alpine et al., 2010).

Several recent studies have examined if metals associated with breccia-pipe uranium deposits are detectable in surface- and groundwater, soils, and biota, and if there is evidence for contaminant transport in vertical and lateral direction away from the mine site. The following summarizes the major findings of these studies.

Groundwater: The perched and regional groundwater wells are currently sampled by USGS once per year to establish groundwater conditions in the shallow and deep groundwater systems of the C-and R-aquifer, respectively. Water is collected from the wells and analyzed for

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

major ions, trace elements (including uranium, arsenic, copper, lead, and others), and select stable and radiogenic isotopes. Water-quality results from both the perched and regional groundwater wells are publicly available through the USGS National Water Information System (USGS, 2024d).

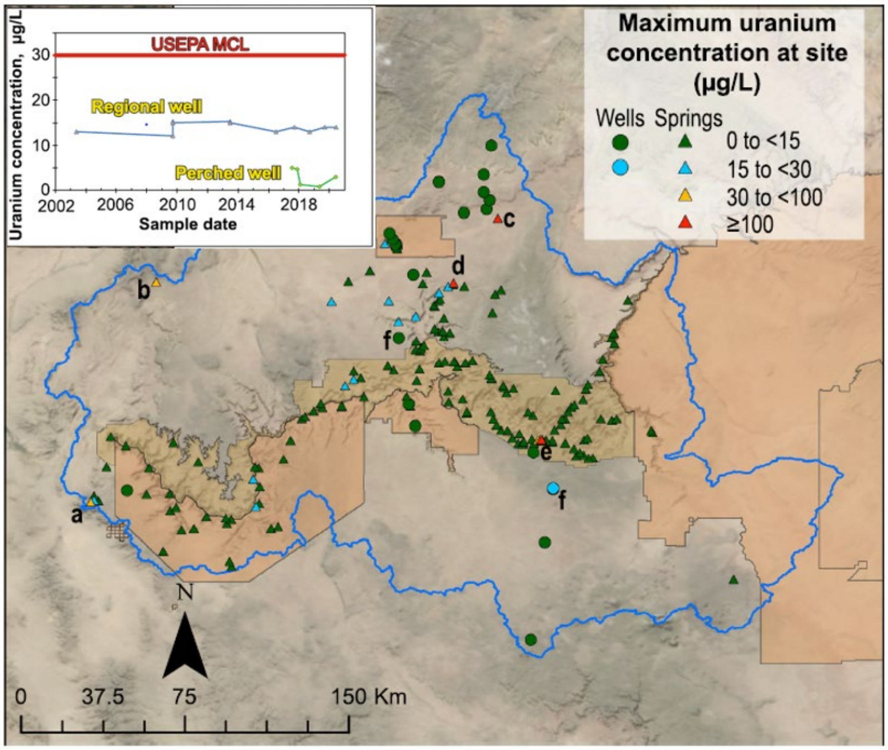
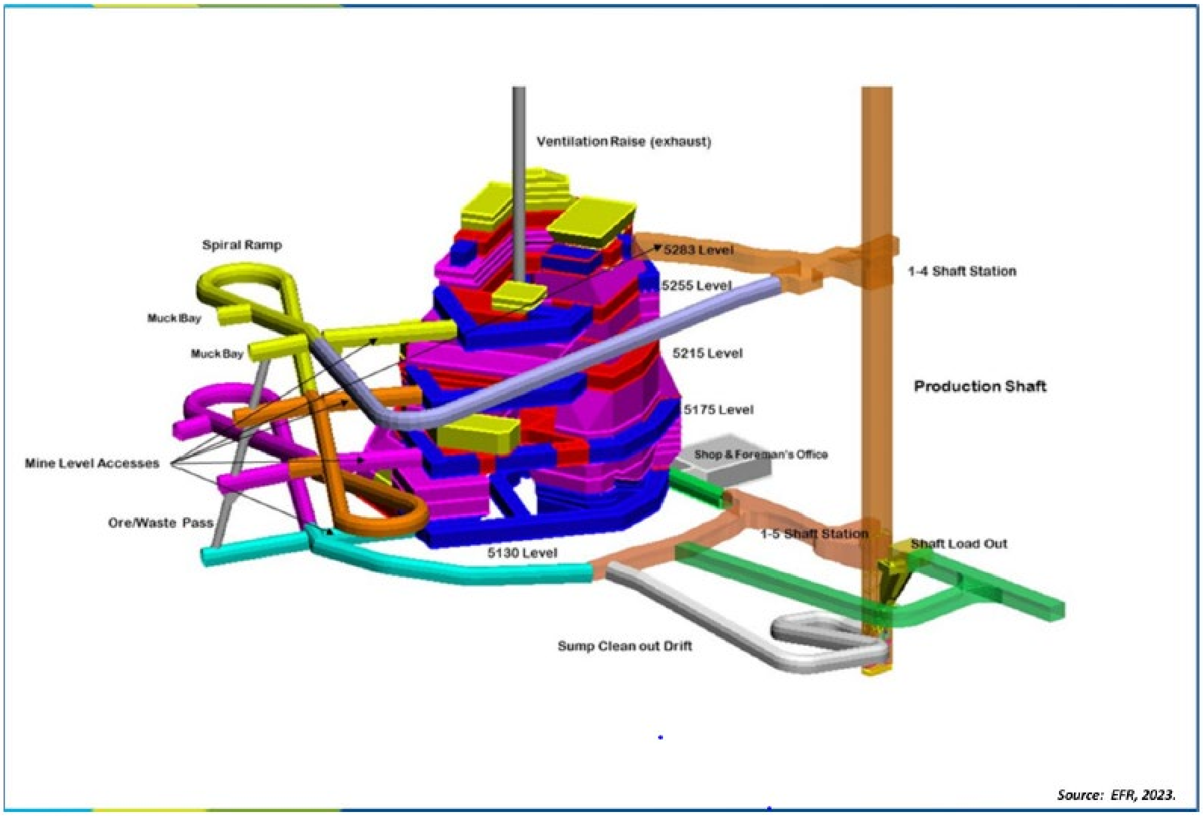


Figure 9: Map of maximum uranium concentration at 206 groundwater sites in the Grand Canyon region. Letters indicate sites that are discussed in the study by Tillman et al. (2021). f = Pinyon Plain Mine. Insert: Observed uranium concentrations in water samples from both wells (Modified after: Tillman et al., 2021).

Tillman et al. (2021) collected 206 groundwater samples in the Grand Canyon area, including from the two wells monitored by the USGS at the Pinyon Plain Mine site and select springs (Figure 9). At 195 sites, they documented maximum uranium concentrations less than U.S. EPA maximum contaminant level (MCL) of 30 µg/L for drinking water. At 177 sites (86%), uranium concentrations were less than15 µg/L, the Canadian benchmark for protection of aquatic life in freshwater. Eight sites had above-MCL uranium concentrations, and some were in close proximity to former Pigeon and Orphan mine sites. At the Pinyon Plain Mine site, uranium concentrations in groundwater were at or below 15 µg/L (see insert Figure 9). It is noted that the uranium concentrations in groundwater from the deeper R-aquifer well were higher than in the perched C-aquifer well, but still only half the MCL.

The USGS reports water quality data for the R- and C-aquifer wells at the Pinyon Plain Mine site through September 2023 (USGS Map, 2024). For the R-aquifer well, the uranium concentrations ranged from 12.1 to 15.3 µg/L and arsenic from 0.16 to 0.5 µg/L. For the C-aquifer well, the uranium concentrations ranged from 0.32 to 5.0 µg/L and arsenic from 0.51 to 4.6 µg/L. The same dataset was evaluated by Tillman et al. (2021).

Pumping of seepage water from the Pinyon Plain Mine shaft forces the local perched groundwater to flow radially towards the mine site (ADEQ, 2022; EFR, 2023). Because of the ongoing dewatering of the mine shaft, the natural groundwater gradient has been altered. Therefore, the current wells in the C-aquifer are not expected to provide insights into the natural groundwater flow direction within the perched C-aquifer at the site (EFR, 2024).



Notes: View looking northwest.

Figure 10: Pinyon Plain Mine overall mine design and naming convention. The mine shaft has reached 1,470 feet down from the surface. Access to the orebody will be through a 10-foot by 10-foot spiral ramp located on the south side of the breccia pipe. From five mining levels, a circular drift will be developed around the inside perimeter of the breccia pipe, alternating though ore and waste. An eight-foot diameter exhaust ventilation raise is designed in the center of the breccia pipe (Source: EFR, 2023).

Perched groundwater enters the mine shaft when aquifer units are encountered during shaft construction and mining the ore body, with the amount and duration of groundwater varying by depth. Between 2013 and 2019, the rate of groundwater flow into the shaft increased from an estimated 2.5 gallons per minute (gpm) to 20.4 gpm. In 2021, about 8.2 million gallons of water were pumped out of the mine shaft (15.6 gpm) (Reimondo, 2022; EFR, 2023b). Groundwater entering the shaft is increasingly polluted with dissolved uranium and arsenic

(Figure 11). As long as water entering the mine shaft is not permitted to accumulate, the mine site is adequately graded to eliminate offsite runoff, and the containment pond liner remains impermeable, metals contamination of groundwater appears unlikely during normal active mining operations (Tillman et al., 2023).

Tillman et al. (2021) reports anoxic conditions in perched groundwater (C-aquifer) at the Pinyon Plain Mine site (dissolved oxygen ≤ 0.1 mg/L during all sampling events). Under anoxic conditions, the mobility of dissolved uranium, like that of many metals, is limited in the shallow groundwater. But when exposed to atmospheric conditions, breccia pipe type uranium ores can rapidly oxidize, suggesting a potential for rapid leaching (Wenrich et al., 1995; Bern et al., 2022).

Bern et al. (2022) conducted laboratory tests that used fluids with the same geochemistry as groundwater in contact with breccia ore. The experiments simulated shallow groundwater in a carbonate aquifer followed by contact with breccia ore, followed by downgradient flow under anoxic and aged, oxic conditions. Uranium, arsenic, cobalt, nickel, and zinc concentrations increased significantly in waters that were in contact with breccia. In one set of experiments, uranium increased from 0.5 µg/L to 201,000 µg/L. Further, processes that occurred downgradient resulted in slightly reduced concentrations of dissolved uranium, cobalt, and nickel whereas zinc was partially attenuated. Uranium remained well above 100,000 µg/L in uranium rich ore samples and above 100 µg/L (on average) in sulfide rich material. The authors conclude that patterns such as these indicate which trace elements originating in breccia ore have the greatest likelihood of being found at a well, spring, or other downgradient location.

At the Pinyon Plain Mine, the mine shaft was advanced to 300 feet by 2013 and to 450 feet in 2015. By 2016, the mine shaft reached a depth of 1,400 feet and 1,450 feet by 2017. The current depth of 1,470 feet was reached in 2018 (Reimondo, 2020; EFR, 2023b). The mine shaft, the proposed vent shaft, and the spiral ramp located on the south side of the breccia pipe (Figure 10) brings the host rock and the ore body in contact with atmospheric air. Since 2015, dissolved uranium concentrations in the water collected inside the mine shaft increased to about 200 µg/L. Over the same period, arsenic was detected in the shaft water and its concentration increased to about 160 µg/L on average. Both metal concentrations exceed the U.S. EPA MCL in drinking water by several times (Figure 11) (Reimondo, 2022). As noted by ADEQ (2022b), the breccia ore body had not been intersected by the mineshaft at that time. Hence, most of the uranium and arsenic present in the mine shaft sump appears to be leaching from the perched aquifer, although a fraction might be originated from ore rich sediments accumulating in the water filled bottom of the mine shaft. Based on groundwater quality data summarized in Reimondo (2022) and reported by EFR (2023b), ADEQ's earlier statement that uranium concentrations were variable but did not show an increasing trend after the mine shaft reached its current depth in 2018 (ADEQ, 2022b), must be revised. Further, ADEQ's (2022b) argument that the shaft does not intersect the breccia pipe and as such, does not represent geochemistry during future mining operations, is valid but also implies that metal concentrations in the mine shaft water will likely be even higher when the ore body is exposed to oxic conditions during mining activities. It is currently not well understood if heavy metal enriched waters can migrate away from the site (and if so, how fast), either during active mining or in the time following the mine closure.

As described above, the South Rim groundwater origin, age, and flow paths may be, to some degree, influenced locally by water imports from the North Rim. Curry et al. (2023) analyzed a suite of tracers and stated that the groundwater at the Pinyon Plain Mine may contain tens of percent of North Rim water, based on stable isotopic data. The authors interpreted the data as evidence for an interconnected South Rim groundwater system influenced by uranium mining, local groundwater pumping, management of the *Transcanyon Pipeline,* and water reclamation infrastructure.

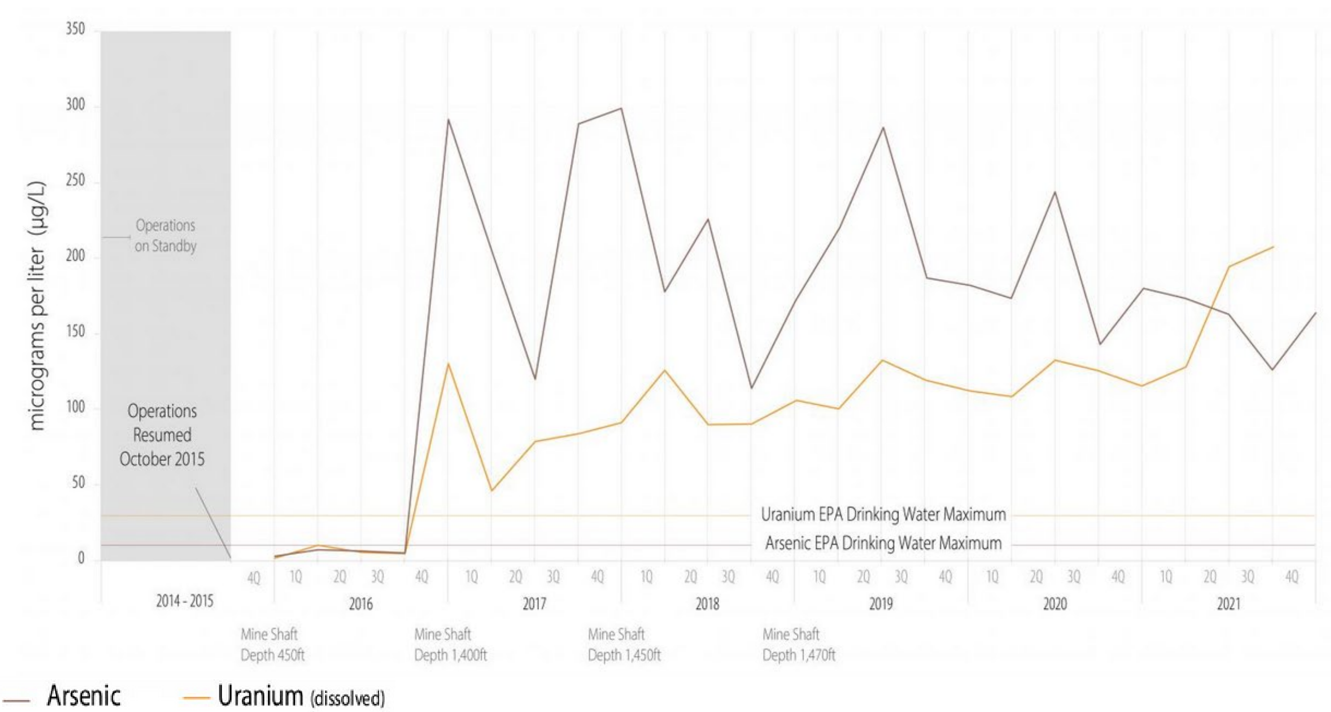


Figure 11: Pinyon Plain Mine composition of water pumped from the mine shaft. U.S. EPA MCL for uranium in drinking water is 30 µg/L and 10 µg/L for arsenic. Data Source: Canyon Mine non-storm water impoundment 3.04 General aquifer protection permit No. P-100333 Annual Report for 2016 through 2021; Graph from: Reimondo (2022).

Surface water: Tillman et al. (2020) monitored major surface waters in the Grand Canyon area for select elements associated with breccia-pipe uranium deposits, including uranium, arsenic, cadmium, and lead. Aqueous concentrations of these metals in the mainstem Colorado River monitoring sites varied little during the study period and were all well below human health and aquatic life benchmark criteria (30, 10, 5, and 15 µg/L maximum contaminant levels and 15, 150, 0.8, and 3.1 µg/L aquatic life criteria, respectively). However, nearly two thirds of Havasu

Creek water samples were found to have arsenic concentrations that exceeded its maximum contaminant level.

Springs: Beisner et al. (2020) documented the geochemical evolution of groundwater discharging from the Redwall-Muav (R) aquifer south of the Grand Canyon. Out of 28 groundwater sample sites, 25 were springs, including Havasu Creek Springs, which is about three miles upstream of Supai and discharges a steady flow of approximately 70 cubic feet per second. The springs issue from the Redwall Limestone and are the main groundwater discharges from the "Coconino Trough" structural feature (USDA, 2010). Beisner et al. (2020) collected samples from 2016 to 2018 and combined their data with data from previous studies of South-Rim groundwater chemistry. Elemental concentration in groundwater samples for arsenic and uranium at Havasu Creek Springs ranged from 10 to 14 µg/L and 2.0 to 4.9 µg/L, compared to <1 µg/L and 10 to 19 µg/L at the Pinyon Plain Mines site. While the uranium concentrations reported by Beisner et al. in 2020 at Havasu Creek Springs were below the U.S. EPA drinking water standard for uranium (30 µg/L), the standard for arsenic (10 µg/L) was exceeded. The USGS reports limited water quality data for Havasu Creek Springs, Fern Springs, and Supai Well No. 3 (USGS Map, 2024). In the case of uranium and arsenic, data sets are available for these three sampling locations for the period of 1994 to 2016. At Havasu Creek Springs, the uranium concentrations ranged from 3.6 to 4.0 µg/L and arsenic from 14 to 17 µg/L. The same dataset was evaluated by Beisner et al. (2020). Concentrations at Fern Spring were 3.1 to 4.0 µg/L for uranium and 7.1 to 8.0 µg/L for arsenic and 3.0 to 3.7 µg/L and 5.2 to 12 µg/L at Supai Well No. 3, respectively.

For comparison, the Horn Creek Spring issues from the Redwall–Muav aquifer at the Grand Canyon wall just downslope from the former Orphan Mine, which is one of the oldest uranium breccia mines on the South Rim and located about two miles northwest of Grand Canyon Village. The first documented sampling of this site for uranium was in 2002 with reported uranium concentrations as high as 400 µg/L (Tillman et al., 2021). Concentrations have varied considerably since the USGS began monitoring the site in 2018, with concentrations as low as 151 µg/L in January 2020, just 6 months before a high of 293 µg/L (Tillman et al., 2021). In general, groundwater emerging from the bedrock in the headwaters of Horn Creek has the highest uranium concentrations in the region (Beisner et al., 2023). At Pigeon Spring, near the former Pigeon Mine site and just north of the Grand Canyon, uranium concentrations vary between approximately 60 to 100 ug/L (See Fig. 5 in Tillman et al., 2021). However, according to evidence documented in a study by the USGS, uranium levels in the Pigeon Spring are likely due to a natural source of uranium and not related to the nearby former Pigeon Mine (Beisner et al., 2017; USGS, 2017).

Soil: Metals have been detected in the surface soils. Arsenic, molybdenum, uranium, and vanadium were found in triplicate samples collected from surface soils at the mine site (Naftz and Walton-Day, 2016). With regard to arsenic, Tillman et al. (2023) found that its transport from land surface downward to groundwater near mine sites in the Grand Canyon region is unlikely during near-future time periods, owing to groundwater depth (>900 feet to the C-aquifer near Pinyon Plain Mine) and lack of evidence of recent groundwater recharge (Pinyon Plain Mine wells have radiocarbon ages that indicate the mean age of the water is greater than 10,000 years old, referencing Solder et al. (2020)). Gamma activities were slightly elevated in soils within the mining site (up to 28 μR/h), while off-site gamma activities in soil and stream-sediment samples were lower (6 to 12 μR/h) (Naftz and Walton-Day, 2016).

Biota: Hinck et al. (2017) characterized the pre-mining concentrations of ten metals and radiation levels, as well as the histopathology in vegetation, invertebrates, amphibians, birds, and mammals at the Pinyon Plain Mine. Bioaccumulation of arsenic, lead, selenium, titanium, and uranium was evident in Western spadefoot (*Spea multiplicata*) tadpoles from the mine containment pond. Metals in mine pond sediments and water may pose a risk of direct toxicity to native amphibians but may also transfer metals from the mine pond to terrestrial wildlife, as anticipated in the USGS Grand Canyon Science Plan (2014).

Overall, both geochemical and other factors have a large effect on downgradient concentrations of elements found in breccia ore. Geochemical factors include the make-up of the rocks surrounding the breccia ore body, the breccia ore mineralogy, and presence or absence of oxygen and other dissolved gases in the groundwater. Other factors include site heterogeneity, the amount of water that contacts the breccia ore, and mixing with waters that are not contaminated with constituents from breccia ores (Bern et al., 2022).

The type of breccia pipes mined in the Grand Canyon area is narrow and of low ore tonnage yield, compared to open pit mines or other mining operations. This narrow horizontal footprint implies that mine operations should be limited to shorter lateral tunnels away from the mineralized zone (Bern et al., 2022). A lower potential for environmental problems associated with the mobilization of trace elements relative to other deposit types is indicated by the comparatively small scale of breccia ore deposits, buffering capacity of adjacent carbonate rock, few changes to natural flow paths, and potential dilution by unaffected groundwaters (Bern et al., 2022).

Synthesis of Analysis of Potential for Groundwater Contamination

An analysis was conducted of the potential for groundwater contamination resulting from operations at the Pinyon Plain Mine. The main conclusions are:

- The extent to which current and past uranium mining activities may have affected groundwater uranium concentrations on the Coconino Plateau remains poorly known (Tillman et al., 2021).
- Local geologic and hydrogeological conditions, including anthropogenic influences, govern the geochemistry of groundwater at the Pinyon Plain Mine site.
- Sulfide minerals associated with the Pinyon Plain Mine orebody have the potential to produce acidic waters but breccias that host the orebodies, and the surrounding host rock have a high capacity to buffer acid waters. However, laboratory experiments

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

suggest that potentially much higher than permissible uranium concentrations can occur downgradient from a breccia ore body (Bern et al., 2022).

- The potential for rapid leaching and chemical reaction of the breccia pipe ore deposits, once in contact with the atmosphere, has not been studied in sufficient detail at Pinyon Plain Mine site.
- At the Pinyon Plain Mine site, uranium concentrations in groundwater collected from the C- and R-aquifer monitoring wells were at or below 15 µg/L. Compared to each other, the uranium concentrations in groundwater from the deeper R-aquifer well were higher than in the perched C-aquifer well (Tillman et al., 2021) but still within the EPA water quality limits.
- Anoxic conditions prevail in the perched groundwater at the Pinyon Plain Mine site (Tillman et al., 2021). Under these conditions, the mobility of dissolved uranium is limited. Introduction of atmospheric oxygen during mining is likely to increase uranium mobility. Dissolved uranium concentrations in the seepage water collected in mine shafts have been on the rise since sampling of the mine shaft water started in 2016. Similarly, arsenic concentrations have increased well above the permissible drinking water limits.
- ADEQ's (2022b) argument that the shaft does not intersect the breccia pipe and as such, does not represent geochemistry during future mining operations, is valid but also implies that heavy metal concentrations in the mine water will likely be even higher once the ore body is exposed to oxic, atmospheric conditions.
- Perched groundwater entered the mine shaft at a rate of 15.6 gpm in 2022, which is higher than the expected rate of 2.5 gpm (Reimondo, 2022; ADEQ, 2022b).
- Surface water concentrations of uranium, arsenic, cadmium, and lead in the Grand Canyon area were well below human health and aquatic life benchmark criteria, except for arsenic at the Havasu Creek location (Tillman et al., 2020).
- Gamma activities in soil and stream-sediment samples were low outside the mining site but slightly elevated inside (Naftz and Walton-Day, 2016).
- Uranium and arsenic contamination of the groundwater appears unlikely during normal active mining operations as long as water entering the mine shaft is not permitted to accumulate, the mine site is adequately graded to eliminate offsite runoff, and the containment pond liner remains impermeable (Tillman et al., 2023).

Recommendations

The previous work by Curry et al. (2023) and Beisner et al. (2023) suggests that anthropogenic substances in combination with isotopic tracers can provide insights into the potential for groundwater contamination resulting from operations at the surface or from lateral inflow of groundwater to and away from the mine. Because of the relatively isolated location of the Pinyon Plain Mine site, generally lower concentrations of most anthropogenic substances, like the ones detected in the aforementioned studies near the Grand Canyon Village, must be

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

expected. For instance, per- and polyfluoroalkyl substances (PFAS; aka “forever chemicals”) were found in low concentrations in groundwater from the bedrock at Horn Creek. Horn Creek is located near the Orphan Mine mineralized breccia pipe deposit on the South Rim of the Grand Canyon. The detected PFAS may be related to mining process materials or other anthropogenic activities in that area (Beisner et al., 2023). PFAS might be present at the Pinyon Plain Mine site. We recommend sampling and analyzing for PFAS, including 40 PFAS compounds regularly analyzed using EPA Method 1633 in the mine shaft water and surrounding wells as indicators of surface water infiltration, potential pollution sources associated with full-scale mine operations, or mixing with groundwater from other locations. PFAS should be also analyzed in surface runoff collected within the confines of the mine site. This data set would indicate which, if any, PFAS are generated right on the site. Also, the make-up of the PFAS collected at the mine site, including in the mine shaft, if present at all, should be compared to the PFAS fingerprint of water samples collected near the Grand Canyon Village. Similarities or differences in the PFAS make up, including ratios of certain PFASs could possibly indicate if a hydraulic connection exists between the sites and/or aquifers, and the surface. PFAS data should complement the ongoing, periodic assessment of other water quality parameters, such as uranium and arsenic, at POC monitoring wells already installed and new wells recommended for installation near the mine site.

Further, because there is lingering uncertainty about the presence of ring fractures or other geologic features at the mine site, we recommend conducting a field survey with a specific focus on mapping ring fractures if present. Related breccia pipe deposits may serve as a conduit for infiltrating surface water or groundwater leaking from higher stratigraphic formations. The pipes also could be impermeable. To address this knowledge gap, testing the in-situ permeability of the breccia pipe rocks is recommended. While laboratory tests have been performed, more informative in-situ permeability tests have not been performed in the past or results of such tests have not been reported. The potential for iron mobilization during leaching as a function of time needs to be documented and evaluated against the ADEQ (2022b) statement that the “abundance of iron oxide rich sediments throughout the stratigraphic column which have the ability to sorb dissolved metals that may be present in the water.” It is recommended that existing geochemical data and new data as they become available are modeled and analyzed in an appropriate software environment, such as PHREEQC. Such an analysis could also aid in the design and execution of post-mining closure activities.

Given the uncertainties related to the geochemical conditions at the Pinyon Plain Mine site, the potential for groundwater contamination resulting from operations at the Pinyon Plain Mine site cannot be assessed fully without additional investigations.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

Analysis for establishing either existing wells or a new well located between the Havasupai Reservation and the Pinyon Plain Mine site, completed separately in the C-aquifer and the R-aquifer, to be monitored for water quality and groundwater level

The USGS samples two wells at the Pinyon Plain Mine site annually. The *Pinyon Plain Mine Perched Well* (USGS 355254112054901) was drilled in 2017 and is 1,150 feet deep. It is completed in the Coconino Sandstone (C-aquifer) (USGS, 2024b). The *Pinyon Plain Mine Regional Well* (355308112054101) is 3,086 feet deep and completed in the Muav Limestone (lower R-aquifer) (USGS, 2024c; EFR, 2024). It was drilled in 1986. The regional well is sampled periodically by USGS with cooperation from the mine operator, Energy Fuels (Tillman et al., 2021). The two wells are approximately 750 feet apart along an NNW to SSE axis (Figure 12A).

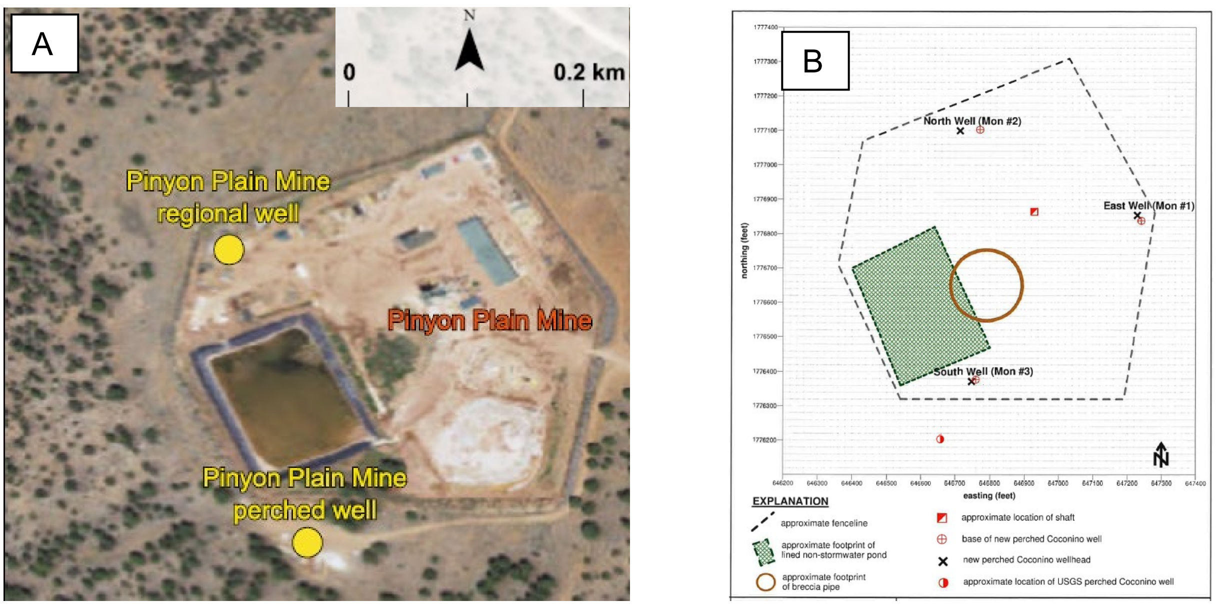


Figure 12: (A) Location of the Energy Fuels Inc. Pinyon Plain Mine regional well and USGS Pinyon Pine Mine perched well. The regional well is completed in the R-aquifer and is referred to as point of compliance (POC) well POC#4 in Table 2. The Pinyon Pine Mine perched well is completed in the C-aquifer (Modified after Tillman et al., 2021). (B) Location of on-site monitoring wells POC# 1 through 3 (Source: EFR, 2024).

In September and October 2020, three additional wells were installed at the mine within the perched C-aquifer (EFR, 2024). These three point of compliance (POC) monitoring wells are referred to as POC #1 -East Well, POC #2 -North Well, and POC #3 -South Well (Table 1; Figure 12 B). The fourth POC well (POC #4) is the *Pinyon Plain Mine Regional Well* (USGS 355308112054101; Figure 12 A), which is a multi-purpose well used for both water supply and water quality monitoring. It is located on the north portion of the mine site, and approximately 450 feet away from the mine shaft. It is assumed that this well is located upgradient from the mine (EFR, 2023). The well has approximately 209 feet of perforated casing installed in the R-aquifer in the depth interval from 2,584 to 2,960 feet (EFR, 2020).

POC #	POC Location	ADWR Registration Number	Latitude (North)	Longitude (West)	Aquifer	Screen Interval (ft bls)
POC #1	East Well (Hole ID: CYN-MON-01)	55-924769	35° 53' 00.0801"	-112° 05' 41.3282"	Coconino	920-1,148
POC #2	North Well (Hole ID: CYN-MON-02)	55-924770	35° 53' 02.5022"	-112° 05' 47.5984"	Coconino	920-1,130
POC #3	South Well (Hole ID: CYN-MON-03)	55-924771	35° 52' 55.2988"	-112° 05' 47.1674"	Coconino	920-1,145
POC #4	Located North of the Non-Stormwater Impoundment	55-515772	35° 53' 00"	-112° 05' 48"	Redwall-Muav	2,584-2,960

Table 1: Point of compliance (POC) monitoring wells installed at the Pinyon Plain Mine site. The POC well (POC #4) in the R-aquifer is the existing on-site monitoring well *Pinyon Plain Mine Regional Well* (Source: EFR, 2023).

The depth to water in the perched C-aquifer in November 2020 was 985.2 feet for the East well (POC#1); 986.1 feet for the North well (POC#2); and 955.6 feet for the South well (POC#3). The water level data indicates that groundwater within the vicinity of the mine site is currently flowing toward the mine shaft. This is because the water level in the mine shaft is maintained well below the natural (pre-mining) water level in the C-aquifer. Hence, the shaft behaves as a continuously over-pumped well ("drain") within the C-aquifer since the mine shaft penetrated the aquifer in late 2016 (EFR, 2022). The estimated hydraulic gradient (i.e., the expected direction of groundwater flow in the C-aquifer) is generally eastward and estimated to range from 0.026 feet per foot (ft/ft) to 0.028 ft/ft. Estimates of hydraulic conductivity in the three recently installed POC wells range from approximately 0.02 feet per day (ft/day) to 0.14 ft/day. Results for storage coefficient and specific yield are typical for an unconfined aquifer, except at the North well (POC#2) where estimates of both parameters are relatively low and more characteristic of a confined or semi-confined aquifer (EFR, 2022). The average rate of perched groundwater migration within the C-aquifer prior to shaft installation is approximately 3.6 feet per year [ft/yr], assuming a hydraulic gradient of 0.028 ft/ft. Although the pre-shaft hydraulic gradient was estimated for the perched Coconino, there are large uncertainties in the estimates, as such evaluation depends in large part on development of a near-symmetrical cone of depression around the shaft (EFR, 2022).

Based on findings from the Initial Hydrogeologic (Monitoring) Report by Hydro Geo Chem, Inc dated June 24, 2022, it appears likely that pre-determining which of the three C-aquifer wells will serve as a downgradient Point of Compliance well may not be possible at present; and that evaluating the actual pre-shaft hydraulic gradients in the C-aquifer may not be possible until reequilibration of the groundwater system has occurred post-closure (ERF, 2024). Also, it is noted that the POC#1 to POC#3 wells do not provide information that could confirm the presumed low conductivity of the Hermit formation and the Lower Supai Formation; the latter being considered a confining layer (Bills et al., 2007).

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

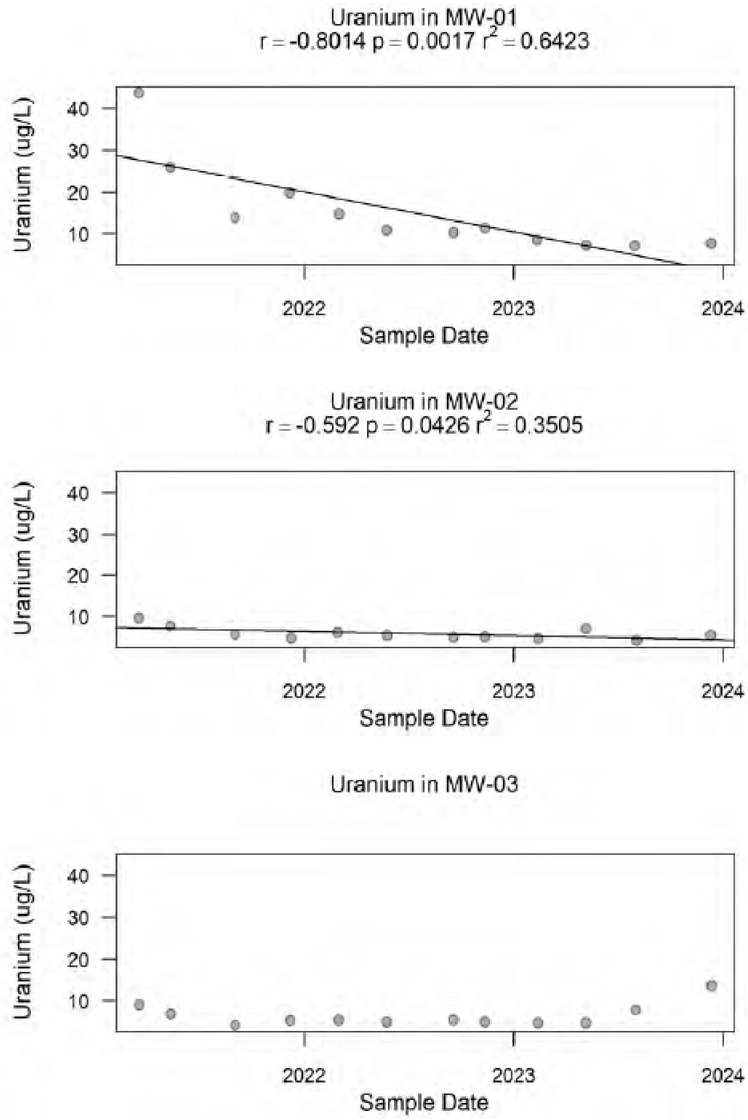


Figure 13: Time series plots and trend analysis for uranium in groundwater from POC #1, POC #2, and POC #3 at the Pinyon Plain Mine. Statistically significant decreasing trends in uranium groundwater concentrations were reported in POC# 1 and 2. (Source: EFR 2024).

POC#1 to #3 have been monitored to establish ambient water quality for 12 successive quarters (Q 1 2021 through Q4 2023). The data sets were statistically analyzed to determine alert level (AL) and aquifer quality limits (AQL) for each POC well and each constituent listed in the Arizona Aquifer Water Quality Standards (AWQS). The POC#1 to #3 uranium time series data, including trendlines as reported in ERF (2024) are shown in Figure 13 (therein referred to as wells MW-1 to MW-3). A graphical summary of the POC#4 (R-aquifer well) data was not reported. Statistically significant decreasing trends in uranium groundwater concentrations were reported for POC# 1 and #2. However, the concentrations of uranium in these wells are likely depressed because it is likely that fresh, uncontaminated groundwater is pulled-in from outside the mine due to the ongoing dewatering of the mine shaft and the resulting creation of a cone of depression which is pulling in groundwater from afar.

Curry et al. (2020) points to the scarcity of wells and poor public documentation of water level and historical data and identifies a need for additional data about geochemical and water level variation of key wells, including at the Pinyon Plain Mine site. The need for additional observation wells completed separately in the C-aquifer and the R-aquifer is further underlined by the discrepancy between the originally estimated rate of groundwater flow into the mine shaft (2.5 gpm) and the current rate of 15.6 gpm (Reimondo, 2022). EFR (2023) expects that despite the low permeability of the Coconino sandstone at the site, mining activities that penetrate saturated portions of the Coconino sandstone experience water seepage at rates similar to those currently measured at the shaft. EFR (2023) links the seepage rate to the relatively large, saturated thickness (approximately 200 feet) of the Coconino sandstone and its hydraulic conductivity. Further, EFR (2023) expects that the Upper Supai has a hydraulic conductivity (and transmissivity, which is the product of hydraulic conductivity and the thickness of the saturated formation) that is substantially lower than that of the Coconino sandstone. Therefore, mine workings that penetrate the Upper Supai are expected to produce very little water, as supported by the current low seepage entering the mine shaft from the Upper Supai. Potential seepage from perched water zones in other formations penetrated by the shaft (such as the Kaibab and Toroweap) is considered relatively small. Lastly, mine workings that penetrate the breccia pipe are expected to produce little to no water due to the anticipated nearly impermeable nature of the breccia material.

The amount of water that actually seeps into the mine workings is draining to and pumped from a lined sump at the base of the mine shaft. Effectively, the shaft acts as a well that is continuously overpumped to the extent that a seepage face is created, as explained above. As long as the shaft is in use and water is being pumped from the lined sump at the bottom of the shaft, groundwater flow will be directed inward from the C-aquifer into the shaft (EFR, 2023). Conceptually, the EFR (2023) assessment of the mineshaft serving as de-facto well, controlling the seepage from the overlying formations, is realistic, but there is considerable uncertainty about the hydraulic characteristics of those formations contributing the leakage. Specifically, the hydraulic conductivity will vary from subsection to subsection within the formations. This heterogeneity within the formations is reflected in the existence of perched aquifer systems in the C-aquifer at the site. Therefore, there is a potential that during mining activities, such as drilling the vent shaft and tunnels that appear to be located outside the breccia ore body (see Fig. 10: Mine design), layers with higher hydraulic conductivity and possibly higher water saturation will be encountered, which could lead to locally much higher seepage rates than currently anticipated. This is of concern for several reasons. First, the extra capacity of the mine shaft pump(s) has to be sufficient to capture an unexpected increase in seepage. Second, the surface containment pond (including auxiliary on-site storage tanks) must be of sufficient size to capture any additional seepage, including possibly accommodating runoff from the mine

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

surface during particularly wet times of the year. Failure of either system would likely lead to (partial) flooding of the mine and, potentially, the escape of heavy metal contaminated water downgradient.

Finally, modern breccia-pipe uranium mines are required to seal water bearing geologic units prior to mine closure, but the effectiveness of shaft-sealing practices has not been evaluated through observational data (Tillman et al., 2023). Even when sealed from water entering the mine workings from the surface, groundwater seepage into the mine is likely to continue for long periods of time, ultimately leading to flooding once pumping from the mine shaft eventually ends. At that point, acid drainage and toxic metals (such as arsenic, lead, and zinc) could be a problem in the immediate vicinity of mineralized deposits that are likely to remain in some parts of the mine. Therefore, the potential effects of continued seepage after the end of the mining activities must be considered in designing the mining closure practices.

In general, limestone and calcareous sandstone host rocks efficiently buffer acidic runoff water, and buffer downward percolating water prior to, or during, their transport in aquifer systems. However, as the presence of anthropogenic substances in Monument Spring groundwater on the South Rim demonstrates (Beisner et al., 2023), highly permeable conduits exist locally, which could facilitate the potentially fast and long-distance transport of dissolved groundwater contaminants away from the mine site. Installing observation wells near the Pinyon Plain Mine site (see recommendations above) in addition to new wells located between the Havasupai Reservation and the mine are recommended. These wells must be completed separately in the C-aquifer and the R-aquifer and monitored for water quality and groundwater level for potentially long periods of time (years to decades).

Synthesis of Evaluation of Sufficiency of Existing Wells

An evaluation was conducted to determine whether monitoring existing wells is sufficient or, if new wells are needed to monitor the C-aquifer and R-aquifer separately for water quality, groundwater level, and groundwater flow direction, including an analysis where new wells should be located relative to the Pinyon Plain Mine site and the Havasupai Reservation. The main findings are:

- Pumping from the mine shaft for controlling the inflow of seepage water disturbs the natural groundwater flow hydraulics at the site. Therefore, the existing network of wells at or near the Pinyon Plain Mine site is insufficient to establish a reliable groundwater flow direction and flow velocity in either the C- or R-aquifer.
- The existing wells only give limited insights into vertical flow between upper and lower aquifers and the hydraulic characteristics of the (leaky) aquitards at the mine site and in the area surrounding it are not well established.
- Evaluating the actual pre-shaft hydraulic gradients and groundwater flow velocity in the C—aquifer at the mine site may not be possible until reequilibration of the groundwater system has occurred post-closure.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

- Additional monitoring wells could permit sampling for water quality parameters, specifically dissolved uranium, arsenic, and PFAS. As such, these wells, together with monitoring the mine shaft water quality, can potentially serve as early warning systems for water resources located farther away from the mine site.

Recommendations

The knowledge gaps regarding the hydraulic characteristics of the two main aquifers and potentially leaky aquitards at the mine site, including uncertainty about the groundwater flow direction and flow velocity, can be reduced by drilling additional wells. **We recommend drilling at least three additional wells in each of the C- and R-aquifers (6 wells total) at a set-back distance that is sufficiently far to overcome the hydraulic disturbances caused by mining operations.** Cores should be collected during drilling and analyzed for hydrogeologic characteristics of the rock material, including porosity and hydraulic conductivity. Geophysical in-situ measurements should accompany the well drilling to locate and describe major fault and karst structures if present. Also, the geophysical measurements may identify one or more perched aquifers in the C-aquifer. Perched aquifer intervals that yield water could be isolated with well-packers and tested individually. Importantly, aquifer (hydraulic) tests should be conducted in both aquifers to determine further aquifer characteristics. Some characteristics that would be useful to measure include the radius of the cone of depression due to pumping, hydraulic conductivity, and the location of fractures that might serve as conduits between wells.

We also recommend drilling wells in the low permeability layers separating the shallow from the deep aquifer. Drilling those wells (assume two wells) close to the mine property would provide an opportunity to conduct additional tests, such as slug tests, to determine the actual in-situ conductivity of these units.

The new wells, including the already existing wells and possibly the mine shaft, need to be periodically sampled for dissolved uranium and other compounds that could provide information about the possible migration direction and velocity of compounds that may be emanating from the site. The sampling must be a long-term commitment (possibly years to decades) because of the comparatively long time it may take for pollutants to migrate downgradient.

Even though the recommended investigations will improve our understanding of the groundwater flow and contaminant transport at the mining site, the area's complex geology and hydrogeology may require additional tests and investments into monitoring infrastructure, particularly wells. Additional investigations may be needed to limit the risk of missing preferential flow paths that could facilitate dissolved contaminants to bypass the monitoring system.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851

Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA

Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

ERG
www.erg.com

Literature Cited

Alpine, A.E., ed., 2010, Hydrological, geological, and biological site characterization of breccia pipe Uranium deposits in northern Arizona: U.S. Geological Survey Scientific Investigations Report 2010–5025, 354 p., 1 pl., scale 1:375,000. Accessed June 2, 2024, at https://doi.org/10.3133/sir20105025.

Arizona Department of Environmental Quality (ADEQ) 2022a. Pinyon Plain Mine Aquifer Protection Program Permit No. P-100333 – Executive Summary. Link

Arizona Department of Environmental Quality (ADEQ) 2022b. Summary and response to public comments. Energy Fuel Resources – Pinyon Plain Mine. Arizona Department of Environmental Quality Permit #100333, LFT #84446. April 28, 2022. Accessed 11 June 2024 at https://static.azdeq.gov/wqd/pinyonplain/2022_indpermit_rs.pd

ADEQ, 2024. Pinyon Plain Mine Frequently Asked Questions (FAQs): Will the mine contaminate groundwater? Arizona Department of Environmental Quality. Accessed 09 June 2024 at: https://www.azdeq.gov/PinyonPlainMine/FAQ

ADWR 2015. Coconino Plateau Water Resources Map., 2015. Arizona Department of Water Resources. April 2015. Accessed 01 Nov. 2024 at: https://www.azwater.gov/sites/default/files/2022-11/CPWP_GroundwaterX.pdf

Beisner, K.R., Paretti, N.V., Tillman, F.D. *et al.* Geochemistry and hydrology of perched groundwater springs: assessing elevated uranium concentrations at Pigeon Spring relative to nearby Pigeon Mine, Arizona (USA). *Hydrogeol J* 25, 539–556 (2017). https://doi.org/10.1007/s10040-016-1494-8

Beisner K.B., Solder J.E., Tillman F.D., Anderson J.R., Antweiler R.C., 2020. Geochemical characterization of groundwater evolution south of Grand Canyon, Arizona (USA). Hydrogeology Journal (2020) 28:1615–1633. https://doi.org/10.1007/s10040-020-02192-0

Beisner K.R., Paretti N.V., Jasmann J.R., Barber L.B., 2023. Utilizing anthropogenic compounds and geochemical tracers to identify preferential structurally controlled groundwater pathways influencing springs in Grand Canyon National Park, Arizona, USA. J. Hydrology: Regional Studies, Volume 48, 101461. https://doi.org/10.1016/j.ejrh.2023.101461.

Bern, C.R., Campbell, K.M., Walton-Day, K. *et al.,* 2022. Laboratory Simulation of Groundwater Along Uranium-Mining-Affected Flow Paths Near the Grand Canyon, Arizona, USA. *Mine Water Environ* 41, 370–386 (2022). https://doi.org/10.1007/s10230-022-00872-9

Biden, J.R., 2023, Establishment of the Baaj Nwaavjo I'tah Kukveni–Ancestral footprints of the Grand Canyon National Monument: Federal Register, v. 88, no. 156, p. 55331–55344, accessed January 3, 2024, at https://www.govinfo.gov/content/pkg/FR-2023-08-15/pdf/2023-17628.pdf.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

Bills D.J., Flynn M.E., Monroe S.A., 2005. Hydrogeology of the Coconino Plateau and adjacent areas, Coconino and Yavapai Counties, Arizona. Scientific Investigations Report 2005-5222. https://doi.org/10.3133/sir20055222

Bills, D.J., Flynn, M.E., and Monroe, S.A., 2007, Hydrogeology of the Coconino Plateau and adjacent areas, Coconino and Yavapai Counties, Arizona (ver. 1.1, March 2016): U.S. Geological Survey Scientific Investigations Report 2005–5222, 101 p., 4 plates, http://dx.doi.org/10.3133/sir20055222 .

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, 24:11, 1025–1028. https://doi.org/10.1130/0091-7613(1996)024%3C1025:FZAAPS%3E2.3.CO

CPWAC, 2021. Coconino and Redwall-Muav aquifer modeling project. Coconinio Plateau Water Advisory Council. Educational workshop May 28, 2021. Accessed 11 June 2024 at: https://cpwac.org/presentations/

Crossey, L.J., Fischer, T.P., Patchett, P.J., Karlstrom, D.E., Hilton, D.R., Huntoon, P., Newell, D., Reynolds, A., 2006. Dissected hydrologic system at Grand Canyon: interaction between deeply derived fluids and plateau aquifer waters in modern springs and travertine. Geology 34 (1), 25–28.

Crossey, L.J. & Karlstrom, K.E. & Curry, B. & McGibbon, C. & Reed, C. & Wilgus, Justin & Whyte, C.J. & Darrah, T. (2024). Hydrotectonics of Grand Canyon Groundwater. Annual Review of Earth and Planetary Sciences. 52. https://doi.org/10.1146/annurev-earth-080723-083513

Curry, B.H., Crossey, L.J. & Karlstrom, K.E. The Grand Canyon National Park (USA) water corridor: water supply, water quality, and recharge along the Bright Angel Fault. Hydrogeol J 31, 1773–1794 (2023). https://doi.org/10.1007/s10040-023-02633-6.

Energy Fuels Resources (EFR) 2015. Application for Construction Approval of the Canyon Underground Uranium Mine, Coconino County, Arizona. July 2, 2015.

Energy Fuels Resources (EFR) 2020. Pinyon Plain Mine Hydrogeologic Report, Kaibab National Forest, Coconino County, Arizona. Prepared by Hydro Geo Chem Inc, November 11, 2020.

Energy Fuels Resources (EFR) 2022. Initial Hydrogeologic (Monitoring) Report Pinyon Plain Mine, Coconino County, Arizona. Prepared by Hydro Geo Chem Inc., June 24, 2022.

Energy Fuels Resources (EFR) 2023. Technical Report on the Pre-Feasibility Study on the Pinyon Plain Project, Coconino County, Arizona, USA. Report prepared by SLR International Corporation for Energy Fuels Inc. February 23, 2023.

Energy Fuels Resources (EFR) 2023b. Pinyon Plain Mine, Individual Aquifer Protection Permit No. P-100333, Annual Report for 2023. Accessed November 14, 2024, at https://static.azdeq.gov/wqd/pinyonplain/wq_annual_rpt.pdf

Energy Fuels Resources (EFR) 2024. Aquifer Protection Permit No. P-100333, LTF 95297, Pinyon Plain Mine-Minor Amendment Application. April 8, 2024. Accessed Oct. 31, 2024, at: https://static.azdeq.gov/wqd/pinyonplain/2024_app.pdf

Gettings, Mark E. and Bultman, Mark W., 2005. Candidate-Penetrative-Fracture Mapping of the Grand Canyon Area, Arizona, from Spatial Correlation of Deep Geophysical Features and Surficial Lineaments, U.S. Geological Survey Data Series 121, 26 p., poster, presentation, and 8 Plates. https://pubs.usgs.gov/ds/121/

Havasupai Tribal Council, 2022: Plan to reduce harm from hazards to Havasu Baaja. Havasupai tribe hazard mitigation plan. November 2022.

Hill, C.A., Polyak, V.J., 2010. Karst hydrology of Grand Canyon, Arizona, USA. J. Hydrol. 390, 169–181. https://doi.org/10.1016/j.jhydrol.2010.06.040

Hill C.A., Polyak V.J., 2020. A karst hydrology model for the geomorphic evolution of Grand Canyon, Arizona, USA, Earth-Science Reviews, Volume 208. https://doi.org/10.1016/j.earscirev.2020.103279

Hinck, J.E., Cleveland, D., Brumbaugh, W.G., Linder, G., and Lankton, J., 2017, Pre-mining trace element and radiation exposure to biota from a breccia pipe uranium mine in the Grand Canyon (Arizona, USA) watershed: Environmental Monitoring and Assessment, February 2017

Huntoon, P. 1977. Holocene faulting in the western Grand Canyon, Arizona. Geol. Soc. Amer. Bull., 88:1619-1622. No. 71108.

Knight JE, Huntoon PW, 2022: Conceptual models of groundwater flow in the Grand Canyon Region, Arizona. US Geol. Surv. Sci. Invest. Rep. 2022-5037. https://doi.org/10.3133/sir20225037

Naftz, D., Walton-Day, K., 2016. Establishing a pre-mining geochemical baseline at a uranium mine near Grand Canyon National Park, USA: Geoderma Regional, 7:1, 76-92.

Pool, D.R., Blasch, K.W., Callegary, J.B., Leake, S.A., and Graser, L.F., 2011. Regional groundwater-flow model of the Redwall-Muav, Coconino, and alluvial basin aquifer systems of northern and central Arizona: U.S. Geological Survey Scientific Investigations Report 2010-5180, v. 1.1, 101 p.

Reimondo A., 2020. Canyon Mine: why no uranium mine is "safe" for the Grand Canyon. Rep., Grand Canyon Trust, Flagstaff, AZ. https://www.grandcanyontrust.org/Canyon-Mine-Report

Reimondo A, 2022. Update: flooding at uranium mine near Grand Canyon. https://www.grandcanyontrust.org/blog/update-floodingUranium-mine-near-grand-canyon . Accessed 06/11/2024.

Solder et al., 2020: Rethinking groundwater flow on the South Rim of the Grand Canyon, USA: characterizing recharge sources and flow paths with environmental tracers. Hydrogeology J., 28:1593–1613. https://doi.org/10.1007/s10040-020-02193-z

Solder and Beisner (2020) Critical evaluation of stable isotope mixing end-members for estimating groundwater recharge sources: case study from the South Rim of the Grand Canyon, Arizona, USA. Hydrogeol J. https://doi.org/10.1007/s10040-020-02194-y

Tillman, F.D, Anderson, J.R., Unema, J.A., and Chapin, T.P., 2020, Assessing uranium and select trace elements associated with breccia pipe uranium deposits in the Colorado River and main tributaries in Grand Canyon, USA: PLOS One, 15:11, e0241502. https://doi.org/10.1371/journal.pone.0241502

Tillman FD, Beisner KR, Anderson JR, Unema JA, 2021. An assessment of uranium in groundwater in the Grand Canyon region. Sci Rep 11, 22157: 1–15 https://doi.org/10.1038/s41598-021-01621-8

Tillman FD, Beisner KR, Jones CJR, 2023. Arsenic in groundwater in the Grand Canyon region and an evaluation of potential pathways for arsenic contamination of groundwater from breccia pipe uranium mining. PLOS Water 2(6): e0000109. https://doi.org/10.1371/journal.pwat.0000109

U.S. Department of the Interior (USDOI), 2012, Record of decision—Northern Arizona withdrawal; Mohave and Coconino Counties, Arizona: U.S. Department of the Interior, 24 p., accessed December 19, 2023, at https://webapps.usgs.gov/Uraniummine/documents/DOI%20%282012%29%20ROD%20Northern%20Arizona%20Withdrawal.pdf

U.S. Department of Agriculture (USDA), 2010. Havasu Canyon Watershed Rapid Watershed Assessment Report. USDA Natural Resources Conservation Service and University of Arizona, Water Resources Research Center. 2010-06-01: S1P2, S2P1. Accessed November 26, 2024 at https://web.archive.org/web/20170520115722/https:/www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_064903.pdf

U.S. Geological Survey (USGS), 2002. Investigation of the Geology and Hydrology of the Coconino Plateau of Northern Arizona: A Project of the Arizona Rural Watershed Initiative. USGS Fact Sheet 113-02. Prepared in cooperation with the Arizona Department of Water Resources. https://pubs.usgs.gov/fs/0113-02/report.pdf

U.S. Geological Survey (USGS), 2017. The former Pigeon Mine in northern Arizona. State News Release January 24, 2017, Link

U.S. Geological Survey (USGS), 2024a. Balancing Natural Resource Use and Extraction of Uranium and Other Elements in the Grand Canyon Region. Fact Sheet 2024-2003. https://doi.org/10.3133/fs20243003

U.S. Geological Survey (USGS), 2024b: Pinyon Plain Mine Perched Well (355254112054901). Link

U.S. Geological Survey (USGS), 2024c: Pinyon Plain Mine Regional Well (355308112054101). Link

U.S. Geological Survey (USGS), 2024d: Characterize Groundwater Chemistry Before Mining at Pinyon Plain (formerly Canyon) Mine. Link

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA

U.S. Geological Survey (USGS) Map, 2024. Uranium and Arsenic in Groundwater in the Grand Canyon Region. Link.

Wenrich, K.J., 1985, Mineralization of breccia pipes in northern Arizona: Economic Geology, v. 80, p. 1722–1735.

Wenrich K.J., Sutphin H.B., 1988. Recognition of breccia pipes in northern Arizona, in Fieldnotes: Tucson, Arizona Ariz. Bur. Geol. Miner. Technol., 18 (1) (1988), pp. 1-5 Link

Wenrich K.J., Billingsley G.H., Huntoon P.W., 1997. Breccia-pipe and geologic map of the northeastern part of the Hualapai Indian Reservation and vicinity, Arizona. U.S. Geol. Surv. Map I-2440, 1:48,000.

110 Hartwell Avenue, Lexington, MA 02421-3136 • Phone: 781.674.7200 • Fax: 781.674.2851
Arlington, VA • Atlanta, GA • Austin, TX • Boston, MA • Chantilly, VA • Charlottesville, VA • Golden, CO • Herndon, VA
Lexington, MA • Nashua, NH • Prairie Village, KS • Research Triangle Park, NC • Sacramento, CA • San Diego, CA