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Dissolved Uranium and Arsenic in Unregulated Groundwater Sources – Western Navajo Nation

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Abstract

Concentrations of dissolved uranium (U) and arsenic (As) above drinking water standards in unregulated water sources pose various human health risks. Although high natural background concentrations may occur in some environments (Runnells et al. 1992), anthropogenic contamination concerns are especially troublesome on the Navajo Nation (NN), where past U mining activity may have contaminated water supplies. This research investigated U and As groundwater contamination issues in unregulated wells in the western portion of the NN. Objectives of this research were to provide insights to human health risks by assessing the spatial extent and seasonal variability of U and As concentrations while effectively communicating the potential contamination risks to the local Navajo people. Eighty-two unregulated wells were sampled in 2018; nine of these sources exceeded the maximum contaminant level (MCL) for drinking water standards for U (30 μg/L), and 14 exceeded the MCL for drinking water standards for As (10 μg/L). U and As levels were highest in the southwest portion of the study area and seasonal variability was observed in a subset of wells, especially shallower hand dug wells and hand pumps. The results were compiled into a report that was presented to NN chapters included in the study as well as the Navajo Department of Water Resources and the NN Environmental Protection Agency. Implications for regional water quality patterns can help to direct policy recommendations for well monitoring, water use, and remediation targets.

Keywords

water quality; tribal; health; well monitoring

The Navajo Nation (NN) has over 300,000 tribal members, and approximately half of the population reside on the Reservation, which spreads over parts of Arizona, New Mexico, and Utah (Figure 1) (Navajo Division of Health 2013). Additionally, the NN has some of the world's largest uranium (U) deposits on their lands (DeLemos et al. 2007). U mining occurred on the NN from the early 1900s until 1986 (Fettus and McKinzie 2012).

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Navajo communities with past mining legacies have been exposed to increased levels of contaminants from mining operations (Eichstaedt 1994). There are over 500 abandoned U mine (AUM) sites and over 1,200 mine features spread throughout the NN. Mine features include pits, waste piles, and trenches. Contamination of groundwater from U mining can occur due to erosion of tailing piles and from open pit mining below the water table that produce mine waste water (US EPA 2007). Through increased exposure to water and oxygen, mining activities increase the mobilization of elements such as U and arsenic (As); therefore, the risk of contamination of natural water sources is greater in mining areas (Hoover et al. 2017; Credo et al. 2019). Arsenic is a natural occurring contaminant that is elevated in groundwater in the southwestern United States due in part to desorption reactions with metal oxides, dissolution reactions, a concentration effect due to high evaporation rates in arid zones, and mining activity (Smedley and Kinniburgh 2002). Higher As and U concentrations may occur together because both are more soluble in their oxidized form and can be co-precipitated in the same minerals. Thus, they are often found together in anomalously high concentrations associated with U mining (Smedley and Kinniburgh 2002; Mkandawire and Dudel 2005; Hoover et al. 2017). In addition, regions surrounding mines will have higher background concentrations, because rocks may occur with concentrations of U too low to be considered profitable to mine or because there are deposits that have yet to be discovered and mined. Given the dangers associated with U and As exposure, it is important to determine what communities may be at risk.

Areas with natural mineral deposits can have high levels of dissolved metals due to acid rock drainage (ARD). ARD, caused by the weathering and oxidation associated with all sulfide minerals, is a natural process which mobilizes metals and must be considered when creating remediation goals (Kwong et al. 2009). A subset of ARD is acid mine drainage (AMD) which occurs when mining activities increase the acidity of waters by exposing pyrite and other sulfide minerals to oxygen and water sources, thereby increasing the level of dissolved metals in the water. Also, mining operations can increase the amount of water being discharged after contact with sulfide minerals, resulting in even greater mobilization of metals (Nordstrom 2015).

The quality of water from private wells, which is not regulated by a government agency, creates concerns for public health. Twenty-three % of private wells in the United States exceeded a human-health benchmark for one or more contaminants (DeSimone et al. 2009). Unregulated wells typically have more contamination issues than regulated wells because they may not be as deep, may be located in different aquifer or geologic zones, and may be less soundly constructed than municipal wells (Johnson and Belitz 2017). Also, unregulated wells are not regularly tested for contaminants and often lack water treatment systems (Malecki et al. 2017).

However, unregulated wells provide important water sources for sparsely populated areas where regulated water sources, such as municipal water systems, are unavailable. This fact is especially evident on the NN where approximately 30% of homes lack access to municipal water supplies and rely on hauling water to meet their needs (US EPA 2018). Because many Navajo people live in low-density areas, the cost to benefit ratio of developing water infrastructure is unfeasible (US DOI 2015). Historically, livestock has played an important role in the Navajo culture and economy. Raising livestock requires relatively large amounts of land, thereby preventing some Navajo from living in areas where public water supplies are available. Instead, they live in sparsely populated areas where the closest water supply is from unregulated, shallow, windmill-powered wells originally installed for livestock use. There are approximately 900 windmill wells throughout the NN (NNDWR 2011). Data on the water quality of these unregulated sources are limited, especially for the western portion of the NN. In the middle and eastern portions of the NN extensive work has been done to collect water quality data and compile past data collected as shown by the 2017 Hoover et al. research.

The NN is within the Colorado Plateau region where the climate is largely controlled by orographic effects and elevation. Areas below 1370 m (4,500 ft) are semiarid. The average precipitation is 20 to 30 cm per year. However, some lowland areas may receive less than eight cm of precipitation per year. A majority of the NN is in a rain shadow where most of the precipitation comes from the south and is blocked by the southern rim of the Colorado Plateau. Up to 65% of the yearly precipitation occurs during the late summer months (July and August) and can result in flash flooding. All runoff goes to the Colorado River, either directly or via one of the tributaries (the San Juan and the Little Colorado Rivers) (Cooley et al. 1969).

In the western portion of the NN, rocks from the Cretaceous Dakota Formation and below are present. However, regional erosion patterns have resulted in progressively older rocks being exposed at the surface in the southwest portion of the NN (Peirce et al. 1970). Recharge of the aquifers occurs in upland areas, which divides the land into five separate hydrologic basins: Black Mesa, San Juan, Blanding, Henry, and Kaiparowits. Water that is recharged in the upland areas moves downward towards the major rivers and tributaries (Cooley et al. 1969).

The main sources of groundwater for the NN come from the Navajo (N) aquifer, the Coconino (C) aquifer, and shallow alluvium aquifers (Cooley et al. 1969). The N aquifer is an important groundwater source in areas north of the Little Colorado River and water quality is considered relatively good except in areas where past U mining and milling occurred (ADWR 2009). Formations of the N aquifer include the Jurassic Navajo Sandstone, Kayenta Formation, and Lukachukai Member of the Wingate Sandstone. These formations are hydraulically connected and act as a single aquifer (Eychaner 1983). The N aquifer receives recharge in areas near Shonto where Navajo Sandstone is exposed at the surface. In other parts of Black Mesa the N aquifer has overlying confining layers which limit recharge (Lopes and Hoffmann 1997). Groundwater that is recharged near Shonto flows radially in the southwest direction to Tuba City, as well as to the south and east (Eychaner 1983).

The C aquifer is an important groundwater source south of the Little Colorado River. North of the river the C aquifer is too deep to access and the high level of salinity (total dissolved solids) makes it undesirable to use for a drinking water source (ADWR 2009). The C aquifer includes the Pennsylvanian and Permian Upper and Middle Supai Formations, the Permian Coconino Sandstone, and the Permian Kaibab and Schnebly Hill Formations (Bills et al. 2016).

Human health risks from living close to AUM sites have been documented and include kidney diseases, hypertension, and other chronic diseases (Hund et al. 2015). However, information on the health impacts from past mining is lacking for tribal communities. The small population sizes, absent or ineffective policies, and a lack of infrastructure in tribal communities have created problems in understanding the full health impact of past mining activities (Lewis et al. 2017). While research is limited, important studies have been conducted. For example, the Navajo Birth Cohort Study is a long-term, collaborative research project that examined how U exposure affected pregnant Navajo women and their infants. Exposure risks were assessed via biomonitoring, home assessments, and surveys. This study was important to inform individuals with higher risks of the dangers they faced, as well as to develop future policies to mitigate the health risks (Hunter et al. 2015).

The Safe Drinking Water Act sets the maximum contaminant level (MCL) for U at 30 μg/L (US EPA 2000). Human health effects of chronic U exposure include kidney disease and various cancers (ATSDR 2013). The level of uptake and toxicity of different U compounds is still not well understood and requires further research (Bjørklund et al. 2017). Long-term As exposure can lead to skin problems, cardiovascular disease, and lung, bladder, liver, kidney, and skin cancers due to its toxic and carcinogenic properties (ATSDR 2007). The MCL for As in the United States is 10 μg/L (US EPA 2001). Concerns about As contamination issues have been documented world-wide in countries such as China, Pakistan, Bangladesh, India, Vietnam, Mexico, Poland, Argentina, and the United States (Smedley and Kinniburgh 2002; Ng et al. 2003; Nelson et al. 2005; Naseem et al. 2012; He and Charlet 2013; Shakoor et al. 2015; Verma et al. 2015; Chabukdhara et al. 2017). Up to 100 million people globally may face health risks caused by As contamination (Ng et al. 2003).

The NN has established water quality standards for surface water and drinking water sources. These standards are enforced at monitored wells to ensure that negative health effects do not occur. The NN Water Quality Program (NNWQP) is operated under the NN Environmental Protection Agency (NN EPA) and is responsible to ensure the water quality standards are enforced. The NNWQP states that the domestic water supply must not exceed 30 μg/L for U and 10 μg/L for As. In addition, As must not exceed 200 μg/L for livestock water. There is no listed maximum for U in livestock water (NN EPA 2007).

A pathway of exposure to contaminants can exist in drinking water from unregulated sources. As mentioned previously, the lack of access to regulated water in their homes causes about 30% of Navajo households to depend on hauling water to meet their needs (US EPA 2018). This practice of hauling water has greatly increased the cost of water for the Navajo people. The typical cost for water users in urban areas is $600 per acre-foot of water. Navajo people who depend on hauling water pay about 71 times this amount ($43,000 per acre-foot of water). For reference, one acre-foot of water is about 330,000 gallons and the per capita use of non-tribal communities near the NN is 190 gallons per day. The per capita use for the NN is 10 to 100 gallons per day and largely depends on the availability of water resources (NNDWR 2011). Considering the cost of hauling water, it is important to recognize that unregulated water sources may provide the closest and most convenient water supply. Therefore, determining the safety of using unregulated water sources for drinking water will remain an important objective for research on the NN.

Understanding the spatial variability of groundwater contamination issues is critical for future resource management. Further, improving the capacity of tribal nations to mitigate health risks and to manage their natural resources in culturally appropriate ways is critical for sustainable future resource management (Lewis et al. 2017). Objectives of this research are to provide insights on human health risks by assessing the spatial variability of U and As concentrations in unregulated groundwater on the western portion of the NN and to communicate contamination risks to the local Navajo people.

Methods

Study Area

The NN is comprised of five agencies each made up of tribal chapters, similar to states made up of counties. The study area focused on twelve chapters in the Western Agency of the NN (Figure 2). Seven of the chapters are located within the western AUM region and the remaining chapters were included in the study based on community requests to test water in those chapters. U mining occurred in the western AUM region from 1951 to 1963, and the U.S. Environmental Protection Agency (US EPA) has identified 126 AUM structures in the area correlating to that time (US EPA 2007).

The study boundaries include the following chapters of the Western Agency in the NN: Bodaway-Gap, Cameron, Coalmine Canyon, Coppermine, Inscription House, Kaibeto, LeChee, Leupp, Navajo Mountain, Shonto, Tonalea, and Tuba City. There are 82 unregulated wells or water sources identified and tested within these chapters. Water samples from wells in this area have been collected and analyzed for U and As since 2003 by the Ingram Lab at Northern Arizona University.

The study area is sparsely populated, with Tuba City having the largest population size of the chapters. The population sizes for the chapters ranged from 542 to 9,265 as shown in Table 1 (U.S. Census Bureau 2010). The population density for the NN is much lower than the United States overall, with only 6.33 persons per square mile as compared to the U.S. average of 345 persons per square mile (Navajo Division of Health 2013).

Chapter Resolutions for Environmental Testing

To ensure that a consensus existed for this research to be conducted, it was important to engage communities at different levels (chapter and agency). Chapter Resolutions were requested and approved to gain permission to carry out this study in the Navajo Mountain and Tuba City Chapters. Additionally, pre-existing chapter Resolutions from the Leupp and Cameron Chapters provided approval for the Ingram Lab Group’s previous water sampling. A general Resolution from the Western Agency was requested and approved at the NN Western Agency Meeting in June of 2018.

Field and Laboratory Methods

Fieldwork methods included locating unregulated wells using GPS; measuring field parameters including, pH, specific conductance, temperature, and oxidation-reduction potential (ORP); and collecting water samples. Water samples were collected in 2018 at different times of the year to evaluate seasonal variability. Water samples were filtered with 0.45 μm membrane filters (Whatman 0.45μm PVDF). Samples for cation and metal analysis were acidified in the field with ultra-pure nitric acid (VWR Aristar Ultra nitric acid) to store metals and metalloids in a soluble state. The subset of samples that had carbon and nitrogen analyses performed were filtered in the field with glass microfiber filters (Whatman Glass Microfiber Filters GF/C Diameter 47mm) into glass vials and care was taken to ensure no head space was left, since the interaction with oxygen could alter the results. Specific conductance, pH, ORP, and temperature were recorded in the field with a portable Thermo Scientific Orion 4-Star Plus meter. Calibration of the meter occurred directly before every sampling event for conductivity, pH, and ORP, and the calibration was routinely checked while in the field. For specific conductance and pH, a three-point calibration was performed with pH and conductivity standards. For the ORP, a one-point calibration was performed with Zobell's solution, which is a potassium ferric-ferro cyanide solution with a known ORP (Eh) value. Field notes and photos were taken at every site. One field blank was collected at a random site for each sampling trip.

Water samples were analyzed for dissolved U and As using US EPA water analysis methods (6020B and 200.8) via inductively coupled plasma-mass spectrometry (ICP-MS), Thermo Fisher Scientific X-Series 2 ICP-MS. Usage of internal standardization was to correct for instrument drift and matrix effects during the data collection. For the water analysis, multi-element calibration standards were prepared containing 0, 0.1, 0.5, 1.0, 2.0, and 5.0 μg/L of the analytes, with an internal standard of 1.0 μg/L of iridium-193. The analysis was confirmed by analyzing the Standard Reference Material 1640a, which has certified concentrations of U and As. To ensure the quality of the data, other quality assurance/quality control (QA/QC) measures were followed, including analyzing blanks, analyzing calibration check standards, and the use of an internal standard (iridium-193).

Calibration standards were used to produce calibration curves for each analyte. The instrument signal for the analyte of interest and the internal standard were given in the form of counts per second (CPS). The CPS of the analyte of interest was divided by the CPS of the internal analyte. This produced a ratio that accounts for the signal of the external standard to the internal standard produced during instrument drift. The known concentration on the x-axis of the external standards was plotted on a scatter plot versus the ratio on the y-axis. After the least squares best fit line (as determined by the Excel software) was applied to the scatter plot, the resulting linear equations could be used to calculate the concentration in μg/L for each sample. The squares of the correlation coefficient values, R^2, were assessed with each calibration. R^2 values of 0.999 or better were deemed sufficient to utilize the calibration.

For each analysis, the instrument was switched from vacuum to operation mode. Once operating, the instrument was warmed-up by pumping water for 15 minutes, followed by 30 minutes in 2% nitric acid. This warm-up time allowed for the determination of contamination in the nitric acid prior to analysis. It additionally provided time for the instrument parameters to be optimized, maximizing analyte signal and increasing stability of readings at the detector. To maintain stability of reading, approximately 100 sweeps of three replicates were processed at the detector per sample.

Once the tuning was complete, the calibration standards were analyzed, first including a reagent blank, followed by the National Institute for Standards and Technology (NIST) Standard Reference Material (SRM) 1640a for trace elements in natural water, and then the diluted unknown samples. The SRM 1640a was used to check the validity of the calibration curves and the reproducibility in sample preparation prior to analysis. After every 15–20 unknown samples a check standard was analyzed to check instrument signal.

Results

The U and As data collected in 2018 were combined with past data collected by the Ingram Lab Group to examine the spatial variability. The data were entered in ArcMap Version 10.5 to create U and As concentration maps (Figures 3 and 4). These maps help to visualize the spatial variability of U and As. Additionally, the maximum, minimum, median, and mean for U and As determined for each of the 82 water samples are provided in Table 2. The highest levels of U and As were found in the southwestern portion of the Coalmine Canyon Chapter. Nine unregulated water sources exceeded the U MCL of 30 μg/L and fourteen exceeded the As MCL of 10 μg/L. Figure 5 shows the exceedances for the similar wells tested with water samples collected over dates from April to December 2018. The plot provides the MCL for U and As, along with the levels of U and As determined in the water sources. For example, the U levels between 124 and 128 μg/L at the top of the figure are the same well tested three times.

The highest levels of U were found in the southwestern portion of the study area (Figure 3). This area correlates with the location of a majority of the AUM sites in the study area. Mining activity may be responsible for these elevated levels; however, since pre-mining baseline levels are unknown it is impossible to determine the source. Since mining occurred in areas with high U levels these results may be due to natural sources. More spatial variability occurred for As (Figure 4) compared to U. The highest levels of As occurred in the southwestern portion of the study area, similar to U, but As levels also varied in water sources in and around the Tuba City Chapter.

The field data revealed that the water was basic and had a wide range in conductivity values (Table 2). The pH values ranged between 7.22 and 9.78. The secondary MCL (SMCL) for pH is below 6.5 and above 8.5 (US EPA 2015). Twenty-nine water sources had pH levels above 8.5. Specific conductance is a measure of how many ions are present in water and can be used to estimate the amount of total dissolved solids (TDS) (Geddes et al. 2014). The SMCL for TDS is 500 parts per million (ppm) (US EPA 2015). To estimate the amount of TDS in water the conductivity value must be multiplied by a factor between 0.55 and 0.90, which is empirically determined and beyond the scope of this study (Geddes et al. 2014). Conductivity values ranged between 78 μS/cm and 11,980 μS/cm. Using the conservative conversion factor of 0.55, any conductivity values above 910 μS/cm would exceed the SMCL of 500 ppm for TDS, which could result in deposits, staining, or salty tasting water (US EPA 2015). There were 23 water sources with conductivity values above 910 μS/cm. The highest conductivity values were found in the Leupp Chapter and the southwestern portion of the Coalmine Canyon Chapter.

The Navajo Department of Water Resources provided a well database which had aquifer information and well depth for many of the water sources in this study. The aquifer information was used to create a map (Figure 6) to visualize the trends. A majority of the wells pump water from the N aquifer. One well in the Navajo Mountain Chapter was completed in the Wingate Sandstone which is beneath the Navajo Sandstone but is hydraulically connected; therefore, it is considered part of the N aquifer (Figure 1). In the southern portion of the study area, specifically the Leupp Chapter, most wells pump water from the C aquifer. There was also a subset of wells in the southwestern portion of the study area that access water from the Chinle Formation, the Shinarump Member of the Chinle Formation, and the Moenkopi Formation which lies on top of the Coconino Sandstone layer. These layers are generally thought of as confining units and likely only produce very small amounts of water. A portion of the water sources did not have any corresponding aquifer information in the well database.

Some overall trends of the groundwater quality from the N and C aquifers became evident while doing this research. The N aquifer had lower conductivity levels and lower concentrations of ions compared to the C aquifer. The highest concentrations of U and As were found in wells with unknown aquifer information; however, nearby wells were located within the Moenkopi and Chinle Formations (Figure 6). While the highest levels of U and As were found in wells in the same region where past mining occurred, it is difficult to attribute these concentrations to mining activities alone. For example, one well had high levels of U and As but was not near an AUM. The closest mining operation was several miles to the north, but it was in a canyon, therefore, it is down-gradient of the well. Additionally, several wells had relatively low levels of U and As and were very close to AUMs. The complete dataset and a more in-depth analysis of all the data collected can be found in Jones 2019.

Discussion

Importance of Communicating Results

Engaging community members while designing the research plan, as well as disseminating the results back to the community members, were integral to the design and communication of this project. The community members provide information on the location and use of the wells; this information guides both the field collection and dissemination to the community. Various health risks of the contaminants were discussed, and requests from the community for testing of specific wells improved the study. The final report given back to the local people included maps of the well locations and concentrations of dissolved U and As. The report interpreted the results for each chapter in layman’s terms. A summary of the report was provided in the Navajo language as well, and dissemination was effective due to the invaluable help of chapter officials. Understanding the steps and procedures that are needed to do research on the NN was extremely important. The Resolutions that were approved helped to engender trust that this research was respectful of Navajo customs.

Unregulated water sources can cause human health issues and communicating the risks that Navajos face in drinking from these sources remains a top priority. However, language and cultural barriers may inhibit effective communication. Researchers have

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worked to incorporate the Navajo peoples' perspectives to provide culturally significant communication methods (DeLemos et al. 2009). Maps can provide clear and effective ways to communicate the environmental and human health risks. Gaining feedback from Navajo community members concerning the efficacy of these maps will engender more culturally appropriate forms of communication.

A report was created with the 2018 data and copies were given to all the chapters in the study area as well as to the Navajo Department of Water Resources, the NN EPA, and the Navajo Tribal Utility Authority. Additionally, the researchers provided in-person presentations of the results to many of the chapters in the study during their monthly community meetings as well as at the Western Agency quarterly meeting. At these meetings, copies of the report were distributed to the meeting attendees, and community members had the opportunity to ask questions and talk to the researchers individually. This report was created to add to the knowledge about water quality issues for the western NN. While the report does not consider all water quality issues or possible pollutants, it can be used to direct future studies to determine where safe drinking water sources exist.

Implications for Regional Water Quality Patterns

The main source of water for the western portion of the NN comes from the N aquifer; however, increased withdrawals from the C aquifer have been proposed to supply the Navajo people with an alternative water resource (Leake et al. 2005). Seepage of contaminated mine groundwater to surface water introduces a pathway of exposure. The movement of shallow groundwater sources is influenced by precipitation and topography while deeper groundwater is more influenced by fracturing and fault zones in geologic units (Bartolo et al. 2017).

Pre-mining baseline studies to establish if natural geological sources of U and As are responsible for water contamination issues are not available for the study area. For other areas where baseline studies exist, the focus is on stream sediments and soils. The change in geochemical factors in water over time is not usually considered. However, temporal sampling is important to evaluate how geochemical factors of water can vary with seasonally. For example, biological activity and sorption rates vary due to temperature and precipitation intensities and amounts affect water flowpaths and reaction times (Levitan et al. 2014).

Determining background levels of metal concentrations is important in mining regions since remediation of these sites to levels below pre-mining levels is difficult or impossible. Natural background concentrations may be above what is considered safe for drinking water; therefore, remediation of groundwater to levels considered safe to drink may be unfeasible. When baseline studies do not exist, one method to determine background levels is to compare levels of mined areas to close by areas which were not mined (Runnells et al. 1992).

Limitations

Other wells likely exist in the study area that were not tested, since the locations of those wells were unknown. Further, it was not known which wells were commonly used by people for their drinking water; therefore, human-use surveys would be helpful for future research. Past students' work was limited to certain wells; therefore, large gaps in the data existed. This study included a larger number of wells, but temporal change could not be studied since no long-term data exist for many wells.

Large fluxes in concentrations may be due to evaporation, precipitation, and groundwater pumping rates (concentration and dilution factors). Most of the unregulated water sources tested were windmills, which pump water into storage tanks when the wind is blowing. The storage tanks can be open on top or covered. The uncovered storage tanks allow for a greater amount of evaporation which would increase the levels of U and As found (due to concentration). Additionally, the shallow dug wells can have a large amount of evaporation occurring. The effect of evaporation and the concentration of contaminants would be greater during the hot, dry summer months. Dilution of contaminants can occur from heavy rains during the late summer months or from increased pumping of the groundwater when there is sufficient wind to power the turbine.

Water sampling methods followed how local Navajo people collected their water. Because the water was coming from holding tanks, the well could not be purged for the recommended time to ensure that the water was coming from the aquifer. The water also had time to interact with air while in the holding tank; therefore, properties of the groundwater may have changed during the time it spent on the surface. Additionally, the well construction was unknown, and there could have been leakage from an overlying aquifer, or deposition from blowing dust, which would alter concentrations. These study limitations make it hard to say if the results are truly representative of the aquifer water quality.

Conclusion

This research combined physical science with community engagement, which is critical to achieve solutions to environmental challenges. Field and chemistry work were essential to provide the data. However, social interactions, such as community presentations and discussions, were critical to make the data relevant. The relationship between researchers and community members is also important to consider. This research focused on improving relations between the two groups and creating an open dialogue that allows for solutions to problems. The results from this research can be useful to provide data for comparison to future water quality testing, for determining particularly problematic mining areas, and to determine the existence of possible natural sources of dissolved U and As. However, wells with open holding tanks provided an uncertainty in the results.

Collaboration with stakeholders was essential for this research. The Resolution process to gain permission to sample the water sources helped to make connections with stakeholders which proved to be useful for other parts of this project. Connections with community members helped to locate additional wells that the local people wanted tested. The dissemination of the results was assisted by collaborating with community officials. Therefore, it was only through collaborations with multiple stakeholders that this research was possible.

The final recommendations that were made to the Navajo people included adding signage to wells that exceeded the MCLs of U and As to warn people of the risks. It was also recommended that wells that were very low in U and As be considered for addition to the regulated water system. Closing the wells was not recommended since these water sources are also used for livestock water and were still considered safe for that purpose. Maps representing water sources with toxic U and As concentrations, along with alternative cleaner water sources, may provide effective forms of communicating risks. Water is limited for the Navajo people and the protection of water quality must remain a priority into the future. By working in collaboration with the Navajo communities and their leaders, the results from this study can be utilized by the NN to develop strategies for water utilization on their lands.

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References

Agency for Toxic Substances and Disease Registry (ATSDR). 2007. Toxicological Profile for Arsenic. Available at: https://www.atsdr.cdc.gov/toxprofiles/tp2.pdf. Accessed February 24, 2020.

Agency for Toxic Substances and Disease Registry (ATSDR). 2013. Toxicological Profile for Uranium. Available at: https://www.atsdr.cdc.gov/toxprofiles/tp150.pdf. Accessed February 24, 2020.

Arizona Department of Water Resources (ADWR). 2009. Arizona Water Atlas - Volume 2. Eastern Plateau Planning Area. Available at: https://azmemory.azlibrary.gov/digital/collection/statepubs/id/11253/. Accessed February 24, 2020.

Bartolo RE, Harford AJ, Bollhöfer A, van Dam RA, Parker S, Breed K, Erskine W, Humphrey CL, and Jones D. 2017. Causal models for a risk-based assessment of stressor pathways for an operational uranium mine. Human and Ecological Risk Assessment: An International Journal 23(4): 685–704.

Bills DJ, Flynn ME, and Monroe SA. 2016. Hydrogeology of the Coconino Plateau and Adjacent Areas, Coconino and Yavapai Counties, Arizona. U.S. Geological Survey Scientific Investigations Report 2005–5222. Available at: https://pubs.usgs.gov/sir/2005/5222/sir2005-5222_text.pdf. Accessed February 25, 2020.

Bjørklund G, Christophersen OA, Chirumbolo S, Selinus O, and Aaseth J. 2017. Recent aspects of uranium toxicology in medical geology. Environmental Research 156: 526–533. [PubMed: 28431380]

Chabukdhara M, Gupta SK, Kotecha Y, and Nema AK. 2017. Groundwater quality in Ghaziabad District, Uttar Pradesh, India: Multivariate and health risk assessment. Chemosphere 179: 167–178. [PubMed: 28365502]

Cooley ME, Harshbarger JP, and Hardt WF. 1969. Regional Hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah. U.S. Geological Survey Professional Paper 521-A. Available at: https://pubs.usgs.gov/pp/0521a/report.pdf. Accessed February 25, 2020.

Credo J, Torkelson J, Rock T, and Ingram JC. 2019. Quantification of elemental contaminants in unregulated water across western Navajo Nation. International Journal of Environmental Research and Public Health 16: 2727–2741.

DeLemos JL, Brugge D, Cajero M, Downs M, Durant JL, George CM, Henio-Adeky S, et al. 2009. Development of risk maps to minimize uranium exposures in the Navajo Churchrock mining district. Environmental Health 8(1): 29. [PubMed: 19589163]

DeLemos JL, Rock T, Brugge D, Slagowski N, Manning T, and Lewis J. 2007. Lessons from the Navajo: Assistance with environmental data collection ensures cultural humility and data relevance. Progress in Community Health Partnerships: Research, Education, and Action 1(4): 321–326.

DeSimone LA, Hamilton PA, and Gilliom RJ. 2009. The Quality of Our Nation's Waters—Quality of Water from Domestic Wells in Principal Aquifers of the United States, 1991–2004—Overview of Major Findings. U.S. Geological Survey Circular 1332. Available at: https://pubs.usgs.gov/circ/circ1332/includes/circ1332.pdf. Accessed February 25, 2020.

Eichstaedt PH 1994. If You Poison Us: Uranium and Native Americans. Red Crane Books, Santa Fe, NM, pp. 33–45.

Eychaner JH 1983. Geohydrology and Effects of Water Use in the Black Mesa Area, Navajo and Hopi Indian Reservations, Arizona. U.S. Geological Survey Water-Supply Paper 2201. Available at: https://pubs.usgs.gov/wsp/2201/report.pdf. Accessed February 25, 2020.

Fettus G and McKinzie M. 2012. Nuclear Fuel's Dirty Beginnings: Environmental Damage and Public Health Risks from Uranium Mining in the American West. Available at: https://www.nrdc.org/resources/nuclear-fuels-dirty-beginnings-environmental-damage-and-public-health-risks-uranium-mining. Accessed February 25, 2020.

Geddes L, Kunihiro K, and Turner E. 2014. Conductivity. In: Simplified Procedures for Water Examination, 6th Ed. American Water Works Assocociation, pp. 123–126.

He J and Charlet L. 2013. A review of arsenic presence in China drinking water. Journal of Hydrology 492: 79–88.

Hoover J, Gonzales M, Shuey C, Barney Y, and Lewis J. 2017. Elevated arsenic and uranium concentrations in unregulated water sources on the Navajo Nation, USA. Exposure and Health 9(2): 113–124. [PubMed: 28553666]

Hund L, Bedrick EJ, Miller C, Huerta G, Nez T, Ramone S, Shuey C, Cajero M, and Lewis J. 2015. A Bayesian Framework for estimating disease risk due to exposure to uranium mine and mill waste on the Navajo Nation. Journal of the Royal Statistical Society. Series A: Statistics in Society 178(4): 1069–1091.

Hunter CM, Lewis J, Peter D, Begay MG, and Ragin A. 2015. The Navajo birth cohort study. Journal of Environmental Health 78(2): 42–46. [PubMed: 26502566]

Johnson TD and Belitz K. 2017. Domestic well locations and populations served in the contiguous U.S.: 1990. Science of The Total Environment 607–608: 658–668.

Jones LM 2019. Temporal and Spatial Variability of Dissolved Uranium and Arsenic in Unregulated Groundwater Sources - Western Navajo Nation. Thesis, Northern Arizona University, Flagstaff, Arizona.

Kwong YT, Whitley G, and Roach P. 2009. Natural acid rock drainage associated with black shale in the Yukon Territory, Canada. *Applied Geochemistry* 24(2): 221–231.

Leake SA, Hoffmann JP, and Dickinson JE. 2005. Numerical Ground-Water Change Model of the C Aquifer and Effects of Ground-Water Withdrawals on Stream Depletion in Selected Reaches of Clear Creek, Chevelon Creek, and the Little Colorado River, Northeastern Arizona. U.S. Geological Survey Scientific Investigations Report 2005–5277. Available at: https://www.usbr.gov/lc/phoenix/reports/ncawss/allfiles/02_USGSCAquiferModel2005.pdf. Accessed February 25, 2020.

Levitan DM, Schreiber ME, Seal RR, Bodnar RJ, and Aylor JG. 2014. Developing protocols for geochemical baseline studies: An example from the Coles Hill uranium deposit, Virginia, USA. Applied Geochemistry 43: 88–100.

Lewis J, Hoover J, and MacKenzie D. 2017. Mining and environmental health disparities in Native American communities. Current Environmental Health Reports 4(2):130–141. [PubMed: 28447316]

Lopes TJ and Hoffmann JP. 1997. Geochemical Analyses of Ground-Water Ages, Recharge Rates, and Hydraulic Conductivity of the N Aquifer, Black Mesa Area, Arizona. U.S. Geological Survey Water-Resources Investigations Report 96–4190. Available at: https://pubs.usgs.gov/wri/1996/4190/report.pdf. Accessed February 25, 2020.

Malecki KMC, Schultz AA, Severtson DJ, Anderson HA, and VanDerslice JA. 2017. Private-well stewardship among a general population based sample of private well-owners. Science of the Total Environment 601–602: 1533–1543.

Mkandawire M and Dudel EG. 2005. Accumulation of arsenic in Lemna Gibba L. (Duckweed) in tailing waters of two abandoned uranium mining sites in Saxony, Germany. Science of The Total Environment 336(1–3): 81–89.

Naseem S, Afridi HI, Kazi TG, Arain SS, Ullah N, and Brahman KD. 2012. Evaluation of high levels of fluoride, arsenic species and other physicochemical parameters in underground water of two sub districts of Tharparkar, Pakistan: A multivariate study. Water Research 47(3): 1005–1020. [PubMed: 23260172]

Navajo Division of Health. 2013. Navajo Population Profile 2010 US Census. Window Rock Available at: http://www.nec.navajo-nsn.gov/Portals/0/Reports/NN2010PopulationProfile.pdf. Accessed February 25, 2020.

Navajo Nation Department of Water Resources (NNDWR). 2011. Water Resource Development for the Navajo Nation. Shiprock, Navajo Nation. Available at: http://www.frontiernet.net/ñndwr_wmb/PDF/Reports/DWRReports/DWR2011%20Water%20Resource%20Development%20Strategy%20for%20the%20Navajo%20Nation.pdf. Accessed February 25, 2020.

Navajo Nation Environmental Protection Agency (NN EPA). 2007. Navajo Nation Water Quality Standards 2007. Window Rock. Available at: https://www.epa.gov/sites/production/files/2014-12/documents/navajo-tribe.pdf. Accessed February 25, 2020.

Nelson BJ, Varekamp JC, Shope CL, Baffico G, Gammons CH, Pedrozo F, and Wood SA. 2005. Hydrogeochemistry and rare earth element behavior in a volcanically acidified watershed in Patagonia, Argentina. Chemical Geology 222(3–4): 249–267.

Ng JC, Wang J, and Shraim A. 2003. A global health problem caused by arsenic from natural sources. Chemosphere 52(9): 353–359.

Nordstrom K 2015. Baseline and premining geochemical characterization of mined sites. Applied Geochemistry 57: 17–34.

Peirce HW, Keith SB, and Wilt JC. 1970. Arizona Geological Survey Bulletin 182 - Coal, Oil, Natural Gas, Helium, and Uranium in Arizona - Plate 9. Available at: http://repository.azgs.az.gov/uri_gin/azgs/dlio/1270. Accessed February 25, 2020.

Runnells DD, Shepherd TA, and Angino EE. 1992. Metals in water - Determining natural background concentrations in mineralized areas. Environmental Science & Technology 26(12): 2316–2323.

Shakoor M, Niazi N, Bibi I, Rahman M, Naidu R, Dong Z, Shahid M, and Arshad M. 2015. Unraveling health risk and speciation of arsenic from groundwater in rural areas of Punjab, Pakistan. International Journal of Environmental Research and Public Health 12(10): 12371–12390. [PubMed: 26445051]

Smedley PL and Kinniburgh DG. 2002. A review of the source, behaviour and distribution of arsenic in natural waters. Applied Geochemistry 17(5): 517–568.

U.S. Census Bureau. 2010. American Indian and Alaska Native Summary File. DP-1 - Profile of General Population and Housing Characteristics: 2010. Available at: https://factfinder.census.gov/rest/dnldController/deliver?_ts=600687698222. Accessed February 25, 2020.

U.S. Department of the Interior (US DOI). 2015. Southwestern Navajo Rural Water Supply Program Appraisal Study Navajo Nation, Arizona Little Colorado River Basin. Available at: http://www.frontiernet.net/ñndwr_wmb/PDF/SWNavajoFinalReport_2015.pdf. Accessed June 26, 2019.

U.S. Environmental Protection Agency (US EPA). 2000. National Primary Drinking Water Regulations; Radionuclides; Final Rule. Federal Register. Washigton, D.C. Available at: https://www.govinfo.gov/content/pkg/FR-2000-12-07/pdf/00-30421.pdf. Accessed June 26, 2019.

U.S. Environmental Protection Agency (US EPA). 2001. National Primary Drinking Water Regulations; Arsenic and Clarifications to Compliance and New Source Contaminants Monitoring; Final Rule. Federal Register. Washigton, D.C. Available at: https://www.govinfo.gov/content/pkg/FR-2001-01-22/pdf/01-1668.pdf. Accessed February 25, 2020.

U.S. Environmental Protection Agency (US EPA). 2007. Abandoned Uranium Mines Project: Arizona, New Mexico, Utah, 1994–2000. San Francisco. Available at: https://www.epa.gov/sites/production/files/2017-01/documents/navajo_nation_aum_screening_assess_report_atlas_geospatial_data-2007-08.pdf. Accessed February 25, 2020.

U.S. Environmental Protection Agency (US EPA). 2015. Secondary Drinking Water Standards: Guidance for Nuisance Chemicals. Available at: www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals. Accessed February 25, 2020.

U.S. Environmental Protection Agency (US EPA). 2018. Navajo Nation: Cleaning Up Abandoned Uranium Mines. Providing Safe Drinking Water in Areas with Abandoned Uranium Mines. Available at: https://www.epa.gov/navajo-nation-uranium-cleanup/providing-safe-drinking-water-areas-abandoned-uranium-mines. Accessed February 25, 2020.

Verma S, Mukherjee A, Choudhury R, and Mahanta C. 2015. Brahmaputra River basin groundwater: Solute distribution, chemical evolution and arsenic occurrences in different geomorphic settings. Journal of Hydrology: Regional Studies 4: 131–153.

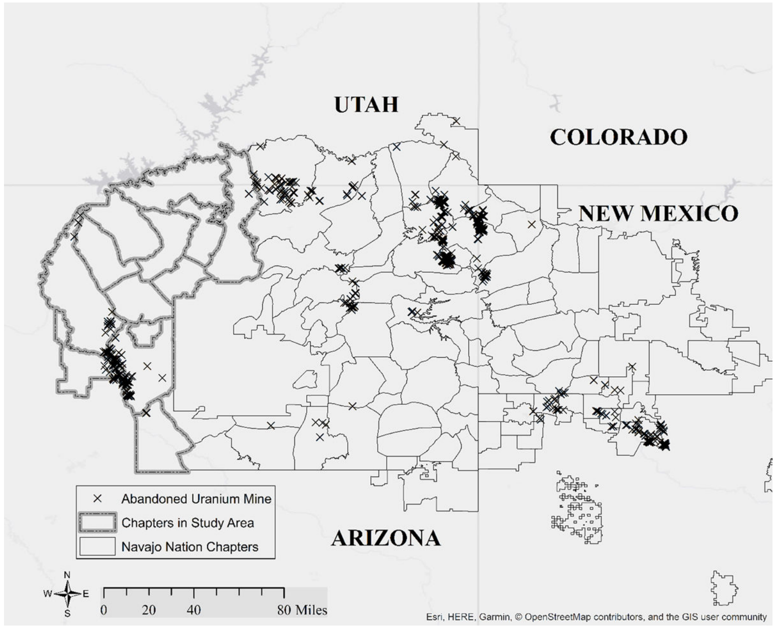

Figure 1.
Entire Navajo Nation with chapters, agencies, and abandoned uranium mines.

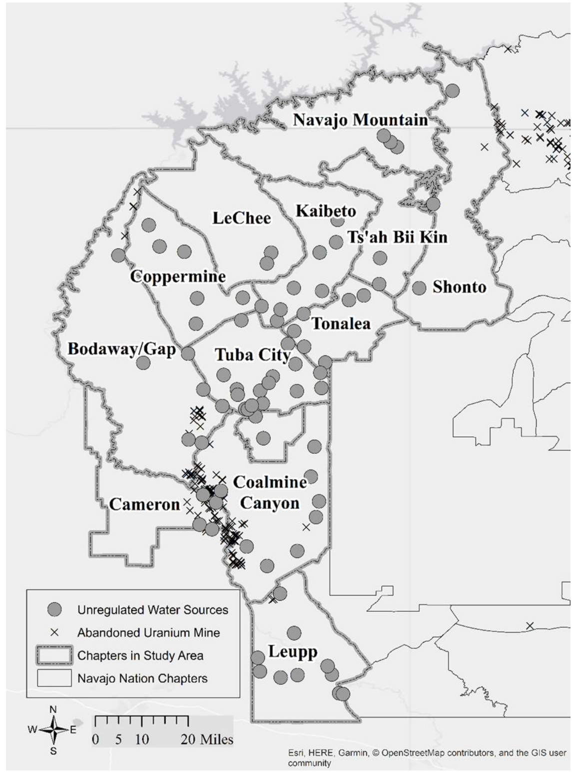

Figure 2.

Western Navajo Nation, unregulated water sources, and abandoned uranium mines.

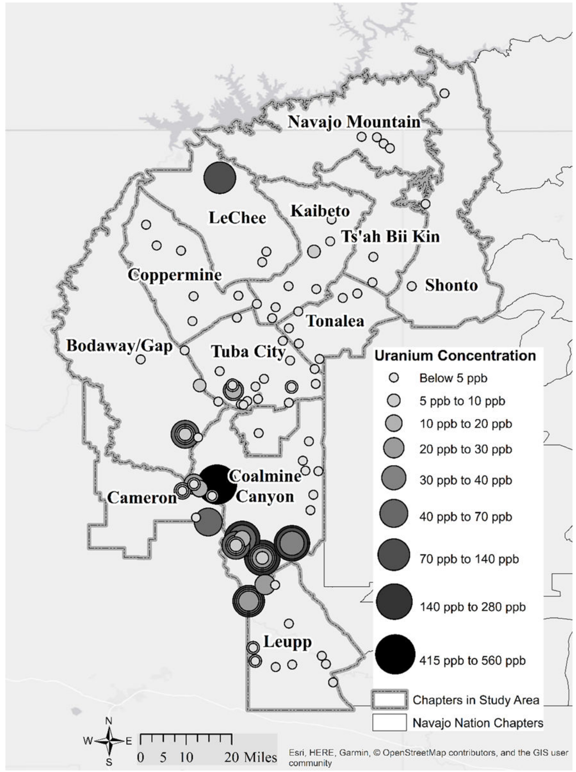

Figure 3.
Uranium concentration in parts per billion for the western portion of Navajo Nation.

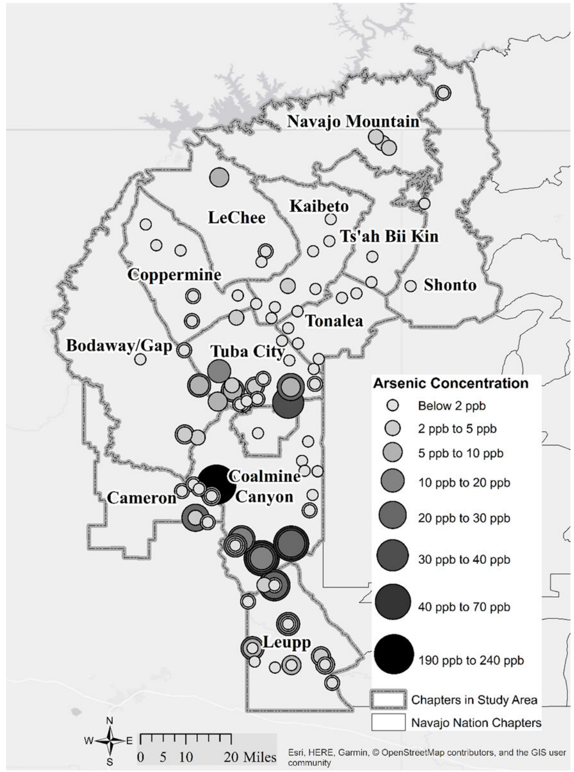

Figure 4.

Arsenic concentration in parts per billion for the western portion of Navajo Nation.

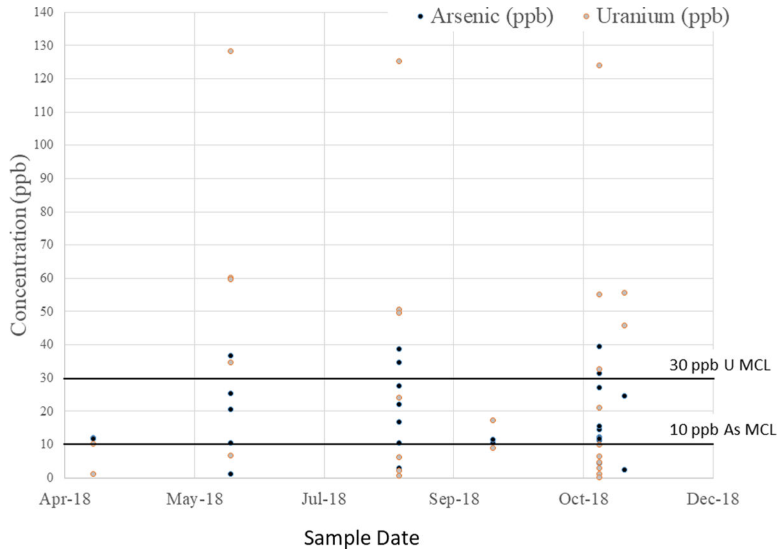

Figure 5.

Arsenic and uranium levels determined from April to December 2018 compared to the maximum contaminant level (MCL) values shown as horizontal lines (As MCL = 10 μg/L; U MCL = 30 μg/L).

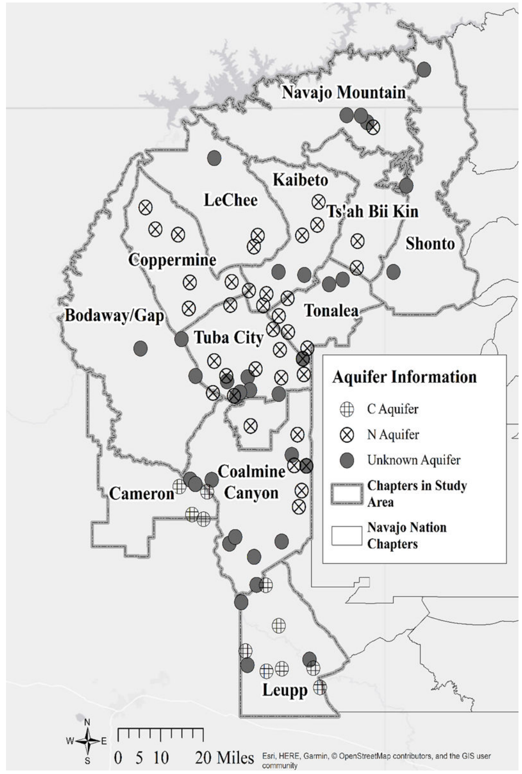

Figure 6.

Aquifer information provided by the Navajo Department of Water Resource’s Well Database for unregulated wells tested in 2018 by the Ingram Lab Group.

Table 1.

Summary of populations of the chapters in the western portion of the Navajo Nation (U.S. Census Bureau 2010).

Chapter	Population
Bodaway-Gap	1,704
Cameron	1,122
Coalmine Canyon	691
Coppermine	590
Inscription House	1,252
Kaibeto	1,963
LeChee	1,660
Leupp	1,611
Navajo Mountain	542
Shonto	2,124
Tonalea	2,595
Tuba City	9,265

Table 2.

Summary of field data collected in 2018 for groundwater in the western portion of the Navajo Nation and the overall U and As results for the 82 samples.

	Minimum	Maximum	Median	Mean
Temperature (°C)	7.1	31.3	21.2	18.9
pH	7.22	9.78	8.27	8.25
Conductivity (µS/cm)	77.6	11,980	415	540.7
Oxidation-reduction potential (volts)	0.17	0.63	0.45	0.44
U (µg/L)	BDL	560.2	2.46	2.3
As (µg/L)	BDL	234.4	2.08	2.76

BDL = Below Detection Limit (U=0.001 µg/L; As=0.030 µg/L).