A community-based health risk assessment following the Gold King Mine Spill: Results from the Gold King Mine Spill Diné Exposure Project

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Abstract

The Gold King Mine Spill (GKMS) disaster resulted in three million gallons of acid mine drainage-containing arsenic and lead being released into a tributary of the San Juan River. The San Juan River flows through the Navajo Nation and the Diné (Navajo) rely on this river for a variety of purposes lending to unique exposure pathways. We administered questionnaires in three Navajo communities in collaboration with the Navajo Nation Community Health Representatives to obtain frequency and duration data on 43 activities (e.g., praying with river water, fishing from the river). These activities were utilized to conduct a community-based probabilistic risk assessment from exposure to arsenic (As) and lead at three different time points (i.e., pre-GKMS, peak-GKMS, and post-GKMS) for four different

exposure scenarios: 1) recreational, 2) cultural, 3) dietary, and 4) aggregate. The aggregate scenario combines exposure from engaging in recreational, cultural, and dietary related activities. Utilizing the Lifeline Community-Based Assessment Software ™ distributions were incorporated for different exposure factors (e.g., hand-to-mouth contacts, transfer efficiency) along with Diné-specific activities (e.g., using the sediment as sunscreen) to estimate dose. The estimated lead and arsenic (As) hazard quotients (HQs) for the recreational, cultural, and dietary scenario for all time points were less than one, indicating no excess non-cancer risks. Only the dietary scenario resulted in an excess cancer risk, with less than 1% of the simulated estimates exceeding the 1×10^{-04} cancer risk guideline from exposure to arsenic through the dietary scenario (e.g., consuming fish from the San Juan River) at all time points. This risk assessment is the first to incorporate the unique exposure pathways of the Diné people following the GKMS and highlights the need to incorporate community-specific pathways during the risk analysis process.

Introduction

On August 5th, 2015, a plug was accidently disturbed at the Gold King Mine located in Silverton, Colorado resulting in the release of 3 million gallons of acid mine drainage-containing arsenic (As) and lead into Cement Creek a tributary of the Animas and San Juan Rivers (Teufel-Shone et al., 2021; Van Horne et al., 2021). The 275-mile San Juan River flows through the Navajo Nation located in the four corners area (Utah, Colorado, Arizona, and New Mexico) of the United States. The Diné (Navajo) are reliant on the San Juan River for a variety of purposes, resulting in unique exposure pathways that have not been formally documented or incorporated in a risk assessment. While the health effects of lead and arsenic are widely known, there is a lack of empirical data on long-term health effects and exposure levels in communities following catastrophic mine spills. Previous studies have investigated the environmental effects of mine spills (Cooke et al., 2016; Romero-Freire et al., 2016; Solà et al., 2004), but only one study has investigated the resulting exposures in humans (Gil et al., 2006). Urinary arsenic levels were found to be higher in the population affected by the spill compared to those not affected (1.73 vs 1.29 μg/g creatinine) (Gil et al., 2006).

The Gold King Mine Spill (GKMS) disaster caused widespread concerns about health risks associated with exposure to the contaminants in the San Juan River (Teufel-Shone et al., 2021; Van Horne et al., 2021). Concerns were driven by many factors including declaration of lawsuits, media coverage, scientific and cultural uncertainty, and potential impacts to agriculture, human health, animal and environmental welfare (Homeland Security Digital Library, Naval Postgraduate School, 2017; Montoya, 2017). These worries were amplified when the Navajo Nation was not informed that the GKMS had occurred until two days after the initial event. The lack of information, unsatisfactory dynamics, and

timeliness contributed to the distrust in the risk assessment process conducted by governmental organizations.

One of the challenges in conducting risk assessments studies among Indigenous communities is the lack of knowledge regarding their exposure pathways and activity patterns (Rohlman et al., 2019; Burger & Gochfeld, 2011; Burger, Gochfeld et al., 2012; Burger et al., 2010). Theoretical frameworks for conducting risk assessment with Indigenous communities have been published (Arquette et al., 2002; Harper et al, 2012). These frameworks for evaluating risks in Indigenous communities recognize the inextricably linked socio-cultural, spiritual, ecological and community dependency factors (Arquette et al., 2002; Harper & Harris, 2000; Harper et al., 2007). Burger (2011) summarized general exposure pathways that are relevant to Indigenous communities for more accurate risk assessments: consumptive (e.g., dietary ingestion), non-consumptive (e.g., walking hiking, biking, watching birds, use of habitat without removing resources), and eco-cultural exposures (e.g., medicinal, religious or cultural practices unique to the community) (Harris & Harper, 2000). While these theoretical frameworks are available, there continues to be a lack research focusing on quantitative risk assessments with Indigenous communities. Risk assessments rarely incorporate culturally-distinct activities (e.g., putting *chíí* (red earth) on face for prayers) (Van Horne et al., 2021), which may predispose some individuals such as the Diné to higher exposures (Harper & Harris, 2000). Risk assessments that do not incorporate community specific activities are ineffective for gauging exposure in Native communities as they fail to account for the cultural factors including consumption of local livestock and their reliance on the environment. The risk assessment presented in this paper demonstrates that conducting a risk assessment using only a recreational scenario without considering dietary and culturally specific pathways can result in underestimating the exposures of a community.

92 Community-specific pathways of exposure are crucial in understanding cumulative and aggregate risk
93 for Indigenous communities (Mccoy, 2010). The recreational risk assessment conducted by government
94 agencies after the GKMS concluded that there would be no excess risk from coming into contact with the
95 San Juan River water or sediment (U.S. EPA, 2015). This initial risk assessment was based on a
96 hiking/camping recreational scenario (U.S. EPA, 2015). However, as the government agency did not
97 account for Diné-specific exposure pathways or consider cultural or spiritual activities, the full extent of
98 the GKMS effects on the community were unknown (Figure 1).
99
100 The objective of this study was to evaluate the non-cancer health risk from exposure to arsenic
101 and lead and cancer risk (arsenic only) to the Diné communities who rely on the San Juan River, which
102 was impacted by acid mine drainage from the GKMS disaster. We simulated a dose by incorporating 43
103 activities that the Diné engage in with the San Juan River into a probabilistic exposure assessment. We
104 considered the following four different scenarios: 1) a recreational scenario that includes three
105 recreational activities; 2) a cultural scenario that includes 30 activities related to livelihood, cultural and
106 spiritual and arts and crafts activities; 3) a dietary scenario that includes ten dietary items that could have
107 been impacted by the GKMS; and 4) an aggregate scenario that incorporates all three scenarios (Table S1-
108 S3). For each of these scenarios we consider three time periods (1) pre-GKMS 1990-2008 2) peak-GKMS
109 August 8th, 2015, to August 18th, 2015, and 3) post-GKMS November 10th, 2015, to July 31st, 2016.
110

Materials and Methods

Study background

The Gold King Mine Spill Diné Exposure Project was formed to investigate the impacts of the 2015 Gold King Mine Spill disaster on the Diné people (Teufel-Shone et al., 2021; Van Horne et al., 2021). The project brought together a community-based multi-collaborative and interdisciplinary team of Diné centered researchers and community leaders. Key partners included the Navajo Nation Department of Health Community Health Representatives, Diné College, T'o Bee Nihi Dziil (with water, we are strong; a grassroots community group), Shiprock Chapter, and the Navajo Nation Environmental Protection Agency. In addition to Diné scientists on our team, the project was also guided by Diné cultural experts and Diné experts from Diné faith-based organizations.

Approval for the project was obtained from the University of Arizona Office for Human Research Protections and from the Navajo Nation Human Research Review Board (NNHRRB) (NNHRRB, n.d). Numerous government and community resolutions were obtained from the Northern Navajo Agency Council (Northern Agency Council, n.d), Shiprock Chapter (Shiprock Chapter, n.d), the San Juan River Farm Board (San Juan River Farm Board, n.d), Navajo Nation Grazing Committee District #12 and Navajo Nation Grazing Committee #13 (Grazing Management Office, n.d). In addition to the institutional review board approvals, and the resolutions obtained, this project also received numerous letters in support of the project. Letters were received from the President and Vice-President of the Navajo Nation Russell Begaye and Jonathan Nez; Directors of the Navajo Nation EPA (Navajo Nation EPA, n.d), Natural Resources (Division of Natural resources, n.d); Program director of Navajo Community Health Representatives Program (Community Health Representatives Program, n.d); Diné College Division of Science and Physical Education (Diné College, n.d); Community Outreach and Patient Empowerment (Community Outreach and Patient Empowerment, n.d); Little Colorado River Watershed Association (Little Colorado River Watershed Chapters Association, n.d); and Black Mesa Water Coalition (Black Mesa Water Coalition, n.d).

The study location and population have been described previously in detail (Van Horne et al., 2021). Briefly, this study was conducted on the Navajo Nation in the chapters of Shiprock, Upper Fruitland and Aneth (Figure 2). Navajo Nation Community Health Representatives (NN CHR) recruited participants residing within one-mile of the San Juan River in Upper Fruitland, Shiprock, and Aneth from August 8th-12th, 2016. Within the same week, a questionnaire regarding activity and dietary patterns with the San Juan River before and after the GKMS was administered to 63 Diné adults.

Participant characteristics

148 The study population for this community-based probabilistic risk assessment consisted of a total
149 of 63 Diné adults (18-84 years), from three different chapters on the Navajo Nation. Participants had to
150 reside in Upper Fruitland, Shiprock or Aneth and be within one mile of the San Juan River. The average
151 age of participants was 51, and 42 of the adults identified as female. A total of 25 adults resided in the
152 Aneth Chapter, 18 in Shiprock, and 20 in Upper Fruitland.
153
154 **Contaminants of concern**
155
156 Arsenic and lead were determined to be the contaminants of greatest concern. This is based upon
157 the concentrations in water samples obtained by U.S. EPA (U.S. EPA 2017) on the day of the GKMS in
158 comparison to the National Recommended Water Quality Criteria (WQC) for protection of aquatic and
159 human life under the Clean Water Act (Federal Water Pollution Control Act, 2002) (Table 1).
160
161 **Determination of time periods**
162
163 The United States Geological Survey (USGS) Gold King Mine database contains information on
164 pre-GKMS sediment and water samples collected by various agencies along the Animas and San Juan
165 River going back to 1968 (no longer accessible but data was downloaded). However, for the pre-GKMS
166 period only historical environmental samples (1990-2008) that were analyzed with the same analytical
167 method were included in the analysis. The peak-GKMS period was considered to be between August 8th
168 and August 18th, 2015 (U.S. EPA, 2017). The peak-GKMS arsenic and lead measurements were obtained
169 from water and sediment samples collected from the San Juan River by federal (U.S. EPA region 6, 8, and
170 9, and the USGS), state (Colorado Department of Public health and Environment, New Mexico
171 Environment Department, Utah Department of Environmental Quality), tribal (Southern Ute Indian

Tribe, Ute Mountain Ute Tribe, Navajo Nation EPA), municipal (City of Farmington) , and non-governmental organizations (Mountain Studies Institute, Rivers of Colorado Water Watch Network (U.S. EPA, 2017). The post-GKMS period consist of samples taken by the GKMS Diné Exposure Project (current study) within a one-year period after the GKMS (Figure 3) (Supplementary Tables S1-S2).

Analytical Environmental Sample Analysis

Pre-GKMS water samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS). Pre-GKMS arsenic in sediment samples were analyzed by graphite furnace atomic absorption (GFAAS). Pre-GKMS lead in sediment samples were analyzed via inductively coupled plasma-mass spectrometry (ICP-MS). The limit of detection and analytical lab are not reported by the dataset acquired from the USGS database (USGS, 2015).

Peak-GKMS water samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) according to U.S. EPA Method 200.8. The limit of detection varied by contaminant and were as follows: arsenic in water (0.37 μg/L), and lead in water (0.06 μg/L). Peak-GKMS water samples were analyzed at Test America (Phoenix, AZ). Peak-GKMS sediment samples were analyzed at Test America (Phoenix, AZ). All sediment samples were processed, and acid digested in accordance with U.S. EPA Method 3051. Arsenic and lead in sediment samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS Hopkinton, MA, USA) according to U.S. EPA Method 6020A. The limit of detection (LODs) varied by contaminant and were as follows: arsenic in sediment (0.09 mg/kg), and lead in sediment (0.06 mg/kg).

Post-GKMS water samples were analyzed at the Arizona Laboratory of Emerging Contaminants (ALEC). Arsenic and lead in water samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS, Elan DRC-II) with a High-Performance Liquid Chromatography system according to U.S. EPA Method 200.8 (Perkin Elmer Series 200 HPLC system, Hopkinton, MA, USA). The limits of detection (LODs) varied by batch (1-4) and were as follows: arsenic (0.0093, 0.01, 0.009, and 0.006 μg/L), and lead (0.001, 0.003, 0.0004 and 0.004 μg/L). Post-GKMS sediment samples were analyzed at Dr. Jani Ingram's Laboratory at Northern Arizona University, the limit of detections were 8.5×10^{-5} mg/kg (As) and 2.6×10^{-5} mg/kg (Pb). All sediment samples were processed, and acid digested in accordance with U.S. EPA Method 3051. Arsenic and lead in sediment samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS (Thermo Fisher X Series 2, Hopkinton, MA, USA) according to U.S. EPA Method 6020A. A summary of chemical analysis by sample type and time period are presented in Table 2.

Activity Pattern Data

Activity pattern data were obtained via a questionnaire administered to participants by the Navajo Nation Community Health Representatives. There were 43 activities included in the questionnaire (Supplementary Table S3). For each activity information on frequency, duration, and season was obtained (Table S16) (Van Horne et al., 2021).

Dose estimates

Dose estimates for participants affected by the GKMS were simulated using the Community Based Assessment Software (CBAS). CBAS is an exposure and probabilistic risk assessment software that

was developed in collaboration with the U.S. EPA for work with Indigenous communities (Chaisson et al., 2012; Chaisson et al., 2010). This software uses a Monte-Carlo framework to incorporate the variability of different exposure factors (e.g., activity duration, activity frequency, hand-to-mouth contacts) (Supplementary Table S4-S9) to estimate a distribution of dose. The parameters required for this risk assessment were: hand-to-mouth contacts, hand to-object contacts, hand-to-object contact duration, the fraction of the hand inserted into the mouth during a hand-to-mouth contact, the fraction of the hand that comes in contact with the object, transfer efficiency, the probability that an activity will occur, the duration and frequency of that activity, and the residue of the contaminant on the object that comes into contact with the hands (Table 3). As denoted in Figure 1 each activity can be conceptualized as a pathway, and for each activity (Table S3) the appropriate parameters (Tables S4-S10) were determined. The simulated dose represents the oral routes (non-dietary and ingestions mechanism) and was calculated based on equations 1 and 2 and is depicted in the conceptual model (Figure 4).

Equation 1. Estimation of dose from oral (dietary ingestion) route

$$\text{ADD} = \frac{C_{medium} * IngR * EF * ED}{BW * AT}$$

where:

C_{medium} = Concentration of contaminant in medium (e.g., mg/L, mg/g)

IngR = Ingestion Rate (e.g., L/day, g/day)

EF = Exposure Frequency (days/year)

ED = Exposure Duration (years)

BW = Body Weight (kg)

AT = Averaging Time (days)

Equation 2. Estimation of dose from oral (non-dietary ingestion) route

$$\text{ADD} = \frac{C_{surface\ residue} * CR * TE * EV * ET * EF * ED}{BW * AT}$$

where:

$C_{surface\ residue}$ = Concentration of contaminant on the surface of the hands or objects that are mouthed (e.g., mg/cm^2)

CR = Contact rate with contaminated surface (e.g.,cm^2/event)

TE= Transfer efficiency (unitless)

EV= Event Frequency (events/hour)

ET = Exposure time (hours/day)

EF = Exposure Frequency (days/year)

ED = Exposure Duration (years)

BW = Body Weight (kg)

AT = Averaging Time (days)

Recreational, cultural, dietary, and aggregate scenarios

The recreational scenario aimed to model recreational activities (e.g., playing, swimming) that the Diné reported doing along the San Juan River (Van Horne et al., 2021). The cultural scenario aimed to model the exposure occurring while engaging in livelihood, cultural/spiritual and arts/crafts activities. This is an important and consideration as cultural and spiritual activities are not typically evaluated in western methods (Lerma, 2017a; Markstrom & Charley, 2003). The dietary scenario aimed to model dietary related activities (e.g., consuming fish from the San Juan River). The aggregate scenario combines exposure from engaging in recreational, cultural, and dietary related activities. A summary of activities considered for each scenario are listed in Supplementary Table S3.

Conversion of activity frequency, probability, and duration

For each activity the frequency and duration were converted from a categorical to a continuous variable. The frequency of each activity for each participant was converted to events per week and duration was converted to minutes per day. This method has been used for dietary activities in previous studies and is adapted here for recreational and cultural activities (Wilson et al., 2014). The probability that an activity will occur on any given day that season (winter, spring, summer or fall) is based on the seasonal information obtained from the questionnaire. The probability of occurrence was calculated based on the number of people conducting that activity in that season. Parameters used for the model are listed in Supplementary Table S4-S9.

Activity distributions

CBAS allows for exposure factors to be entered as point values or distributions (i.e., lognormal, normal, triangular, pareto, or uniform). To determine which distributions fit activity patterns the following steps were carried out for each activity that was conducted by at least five individuals. First, individual distribution parameters for candidate distributions (i.e., lognormal, normal, triangular, pareto, or uniform) were estimated for frequency and duration data. For the second step, three different goodness-of-fit test (GOF) (i.e., Kolmogorov-Smirnov, Cramer-Von Mises, and Anderson-Darling) were used to estimate if the parameters estimated based on the empirical data were from the theoretical distribution (i.e., lognormal, normal, triangular, pareto, or uniform) (Engmann & Cousineau, 2011; Littell et al., 1979; Razali, 2011; Wozniak, 1994; Yazici & Yolacan, 2007). A p-value < 0.05 indicated that the data did not fit the theoretical distribution. Finally, if more than one distribution fit the data a visual inspection of the histogram and the cumulative distribution frequency plot were conducted to compare the

empirical data to the theorical distribution for all the remaining theoretical distributions that had a p-value > 0.05 on the GOF test (Law and Kelton, 2000). For all activities, a triangular distribution was not ruled out using the GOF tests. Additionally, most of the participants reported engaging in activities three to five times a week and thus a triangular distribution was deemed the most appropriate for frequency and duration data. A summary of the final distribution assigned to each activity based on these steps are presented in Supplementary Table S4-S9.

Hand-to-mouth and hand-to-object distributions

This study relied on previously published data for the following parameters: frequency of hand-to-object contacts, frequency of hand-to-mouth contacts, and duration of hand-to-object contacts (AuYeung et al., 2006; Beamer et al., 2008, 2012, 2015; Xue et al., 2007). Adult-specific data on these parameters is scarce and as there was no difference in frequency of mouthing activities after age seven it was assumed that rate of hand-to-object contacts, rate of hand-to-mouth contacts, and duration of hand-to-object contacts was applicable to adults (Beamer et al., 2012). A summary of the frequency of hand-to-object contacts, the frequency of hand-to-mouth contacts, the duration of hand-to-object contacts and the theoretical distribution assigned to each is presented in Supplementary Table S4-S9.

Fractional surface areas

To estimate loadings of contaminants onto the hands during hand-to-object contacts, the fraction of total hand surface inserted into the mouth and touching objects is necessary. AuYeung et al. (2008) used the hand contact data (AuYeung et al., 2006; Beamer et al., 2008, 2012, 2015; Xue et al., 2007) in addition to estimates of surface area for each contact to estimate fractional surface areas (FSA) by object category (AuYeung et al., 2008). For the current assessment, an object and corresponding FSA from AuYeung et al. (2008) was assigned. For example, basket weaving was assigned to the object category "wood" which has an FSA of 0.18 for both hands. A summary of the FSAs and object category assigned to each activity are presented in Supplementary Table S4-S9.

Transfer efficiency

Transfer efficiency is the fraction of contaminant that is transferred from a surface to the skin during a contact event (hand-to-object contact) (Cohen Hubal et al., 2005). There are no metal-specific studies that evaluate transfer efficiency. Beyer et al., 2014 derived an average transfer efficiency of 0.07 by summarizing previous transfer efficiency studies and adapted it for use in their metal transfer study. As this study focuses on exposure to arsenic and lead, we utilized their derived transfer efficiency of 0.07 (Beyer et al., 2014).

Environmental residue conversions

This study only analyzed arsenic and lead in soil and water and not in any surfaces of objects near the San Juan River. To estimate the liquid and dry residue of arsenic and lead on a solid surface, equations 3 and 4 were used, respectively. Equation 3 represents the concentration of the contaminant (arsenic or lead) in the river water. The volume of liquid per area was derived by assuming a thickness of 0.015 cm over a 100 cm^2 area and the density of water of 1 $\frac{g}{cm^3}$ (McKone and Howd, 1992).

Equation 3. Estimation of liquid residue on solid surface

$$Lrss = C_l \cdot V$$

where:

Lrss = Liquid residue on solid surface $\frac{\mu g}{cm^2}$

C_l = Concentration of substance in liquid $\frac{\mu g}{L}$

V = Volume of liquid per area $\frac{L}{cm^2}$

Equation 4 represents the concentration of the contaminant (arsenic or lead in the river sediment. The mass of solid per area was derived by assuming a thickness of 0.5 cm over a 100 cm^2 area and the density of sediment of 2.65 $\frac{g}{cm^3}$ (McKone and Howd, 1992).

Equation 4. Estimation of dry residue on solid surface

$$Drss = C_s \cdot M$$

where:

Drss = Dry residue on solid surface $\frac{\mu g}{cm^2}$

C_s= Concentration of substance in solid $\frac{\mu g}{g}$

M = Mass of solid per area $\frac{g}{cm^2}$

Dietary-related activity information

Dietary-related activities are summarized in Supplementary Table S10. We did not ask participants what specific food item they cooked underground, cooked with wooden sticks, or cooked in earthen stoves. We consulted with our Diné community partners to obtain information regarding which specific food items would be cooked using these traditional practices. Corn and sheep are food items that can be cooked underground, blue corn mush is a food item that is stirred with wooden sticks, and bread are bread cooked in underground ovens made of earthen stoves. We replaced "cooked underground", "cooked with wooden sticks", or "cooked in earthen stoves" with these suggested food items.

The probability of consuming each dietary item is derived from the questionnaire described in Section 2.6. The number of participants reporting consuming an individual item was multiplied by the frequency category and then divided by the total number of participants (Subar et al., 2006). The probability of consumption for each dietary related item is summarized in Supplementary Table S10.

Portion size for dietary items was not asked during administration of the activity questionnaire. We utilized previous food studies conducted on the Navajo Nation to assign a portion size (Wolfe et al., 1985; Sharma et al., 2010; Samuel-Nakamura, et al., 2017). The portion size for fish intake is based on the United States Department of Agriculture 2015-2020 dietary guidelines (USDA, 2015). The portion size for each dietary related item is summarized in Supplementary Table S10.

We relied on previously published studies to estimate the concentration of arsenic and lead in dietary items. We focused on studies that had been conducted on the Navajo Nation or studies that had been conducted as part of other mine spills (Cabrera et al., 2008; Samuel-Nakamura, 2013; Samuel-Nakamura, et al., 2017; Solà et al., 2004). The concentration obtained from previously published studies served as the pre-and post-GKMS concentration inputs. Although there have been diet studies conducted on Navajo Nation (Ballew et al., 1997; Samuel-Nakamura, et al., 2017; Wolfe et al., 1985), to our knowledge, none have collected food items listed on our survey and analyzed them for arsenic or lead during or immediately following the GKMS. Only corn was collected and analyzed (two years after the GKMS) for arsenic and lead as part of this current study. Due to the lack of data, as a conservative assumption we assumed that the concentration of arsenic and lead would increase in the food by the same proportion that they did in the San Juan River water, which was 10% for arsenic and 25% for lead, respectively (Aladesanmi et al., 2019). A summary of the arsenic and lead concentrations for dietary items is listed in Supplementary Tables S11-S14.

Arsenic risk assessment

We used the CBAS to estimate the cumulative dose from exposure to arsenic and lead. We simulated the dose for 500 people at each age (total of 68 ages: range 18-85) by randomly selecting their exposure factors and environmental concentrations. Each of the simulated dose for the 500 people is iterated 16 times resulting in a total of 544,000 simulations (68 ages x500x16) (Figure 3).For non-cancer health risk, hazard quotients (HQ) were computed by dividing the average daily dose (ADD) by the reference dose (RfD) (equation 5). The reference dose for arsenic is 3.0×10^{-04} mg/kg-day. A HQ less than one was deemed an acceptable risk level (U.S. EPA, 1989, 2005, 2014).

Equation 5. Non-cancer health risk calculation for arsenic

$$HQ = \frac{ADD}{RfD}$$

where:

HQ = Hazard quotient (unitless)

ADD = Average daily dose (mg/kg-day)

RfD = Oral reference dose (mg/kg-day)

For cancer health risk (CR), the simulated dose was multiplied by the cancer slope factor (CSF) of 1.5 $(mg/kg\text{-}day)^{-1}$ (equation 6). The acceptable cancer risk guideline can range from 1×10^{-06} to 1×10^{-04} as the acceptable threshold (U.S. EPA, 1989).

Equation 6. Cancer health risk calculation for arsenic

$$CR = ADD \cdot CSF$$

where:

CR = Cancer risk (unitless)

ADD =Average daily dose (mg/kg-day)

CSF = Cancer slope factor $(mg/kg\text{-}day)^{-1}$

Lead risk assessment

Although there is no a reference dose (RfD) for lead, the Joint FAO/WHO Expert Committee on Food Additives (JECFA) have designated a provisional tolerable weekly intake (PTWI) for lead of 50 μg/kg-week (or 0.007 mg/kg-day) for adults (World Health Organization, 2011). This PTWI value was used to conduct the lead risk assessment in the similar way that the RfD for arsenic was used to calculate hazard quotients. The simulated lead dose estimates mg/kg-day were divided by the PTWI (equation 7). A HQ less than one was deemed an acceptable risk level.

Equation 7. Non-cancer health risk calculation lead

$$HQ = \frac{ADD}{PTWI}$$

where:

HQ = Hazard quotient (unitless)

ADD = Average daily dose (mg/kg-day)

PTWI = Provisional tolerable weekly intake (mg/kg-day)

Sensitivity analysis

A sensitivity analysis was conducted to determine how parameter inputs influence the outcome. We followed a two-step sensitivity analysis process. First, we changed one input parameter at a time, while holding all others constant. Second, we computed a sensitivity ratio by dividing the percent change in the input parameter by the percent change in the outcome (equation 8.) (U.S. EPA, 2006a). The lower and upper empirical values were chosen for the sensitivity analysis to understand the range in variability. The larger the absolute value of the sensitivity ratio, the more influential the parameter.

441

442 Equation 8. Sensitivity ratio

443 $\mathrm{SR}_i = \frac{\Delta \mathrm{Dose}}{\Delta \mathrm{PR}_i}$

444 where:

445 SR_i = Sensitivity ratio for parameter i

446 ΔDose= Percent change in the dose

447 $\Delta \mathrm{PR}_i$ = Percent change in parameter i

448

449 **Results**

450

451 **Estimated average daily dose of arsenic**

452

453 The simulated community dose estimates (n= 544,000) are depicted in Figure 5. Overall, non-
454 cancer health risk (HQs) from exposure to arsenic were all below one. Regardless of scenario, dose
455 estimates were highest during the peak- of the GKMS followed by pre- and post-GKMS periods.
456 Regardless of time period, the dietary exposure scenario contributed the most to the dose estimates for
457 arsenic, with the dose being eight to nine orders of magnitude greater compared to the dose from the
458 recreational scenario, and four to five orders of magnitude greater compared to the dose from the cultural
459 scenario (Table 4). The mean aggregate arsenic dose for all scenarios during the pre-GKMS period was
460 4.42×10^{-06} mg/kg-day. The peak-GKMS mean dose was 5.03×10^{-06} mg/kg-day, and the post-GKMS was
461 4.38×10^{-06} mg/kg-day. The mean arsenic dose for the recreational scenario during the pre-GKMS period
462 was 1.30×10^{-13} mg/kg-day. The peak-GKMS mean dose was 1.71×10^{-13} mg/kg-day, and the post-GKMS
463 was 2.02×10^{-14} mg/kg-day. The mean arsenic dose for the cultural scenario (e.g., cultural, and spiritual,
464 arts and crafts, and livelihood) during the pre-GKMS period was 6.14×10^{-09} mg/kg-day. The peak-GKMS

mean dose was 9.43 x 10^{-09} mg/kg-day, and the post-GKMS was 8.07 x 10^{-09} mg/kg-day. Compared to the dose from recreational activities, the dose from the cultural scenario was four to five orders of magnitude greater. For the dietary scenario, the mean arsenic dose during the pre-GKMS period was 4.41 x 10^{-06} mg/kg-day. The peak-GKMS mean dose was 5.03 x 10^{-06} mg/kg-day, and the post-GKMS mean was 4.37 x 10^{-06} mg/kg-day. Compared to the dose from recreational activities, the dose from the dietary exposure scenario was eight to nine orders of magnitude greater.

Arsenic hazard quotient (non-cancer health risk)

The computed HQs by time period and scenario are presented in Table 5. The simulated dose estimates for the recreational scenario, cultural scenario (e.g., cultural, and spiritual, arts and crafts, and livelihood activities), dietary, and aggregate scenario were all below the arsenic reference dose (RfD) of 3.00 x 10^{-04} mg/kg-day, which resulted in a HQ less than one.

Cancer risk assessment

The computed cancer risk from exposure to arsenic by time period and scenario are presented in Table 6. The cancer risk estimates for the recreational, cultural scenario (e.g., cultural, and spiritual, arts and crafts, and livelihood activities) were all below the cancer risk guideline of 1 x 10^{-04} mg/kg-day. When accounting for the dietary scenario, < 1% of the scenarios exceeded the cancer risk guideline during the pre-GKMS (range: 0.00 to 1.24 x 10^{-04}), peak-GKMS (range: 0.00 to 1.25 x 10^{-04}) and post-GKMS periods (range: 0.00 to 1.02 x 10^{-04}).

Estimated average daily dose of lead

The simulated community dose estimates (n= 544,000) are depicted in Figure 6 and Table 7. Overall non-cancer health risk from exposure to lead were low (Table 8). Regardless of scenario, exposure was highest during the peak- of the GKMS followed by pre- and post-GKMS periods. Regardless of time period, the exposure was highest for the dietary scenario, followed by the cultural and recreational scenarios. The mean lead dose for the recreational scenario during the pre-GKMS period was 8.92×10^{-13} mg/kg-day. The peak-GKMS mean dose was 1.56×10^{-12} mg/kg-day, and the post-GKMS was 5.21×10^{-14} mg/kg-day. The mean lead dose for the cultural scenario (e.g., cultural and spiritual, arts and crafts, and livelihood) during the pre-GKMS period was 6.24×10^{-08} mg/kg-day. The peak-GKMS mean dose was 6.52×10^{-08} mg/kg-day, and the post-GKMS was 6.32×10^{-08} mg/kg-day. Compared to the dose from recreational activities, the dose from the cultural scenario was five to six orders of magnitude greater. For the dietary scenario, the mean lead dose during the pre-GKMS period was 6.83×10^{-06} mg/kg-day. The peak-GKMS mean dose was 1.19×10^{-05} mg/kg-day, and the post-GKMS mean was 6.82×10^{-06} mg/kg-day. Dietary exposure contributed the most to the dose estimates for lead (Table 7), with the dose being eight to nine orders of magnitude greater compared to the dose from recreational scenario, and two to three orders of magnitude greater compared to the dose from the cultural scenario.

Lead hazard quotient (non-cancer health risk)

The computed HQs by time period and scenario are presented in Table 8. The simulated dose estimates for the recreational, cultural, and dietary scenarios were all below the lead provisional tolerable weekly intake (PTWI) of 7.14×10^{-03} mg/kg-day, which resulted in a HQ below one.

Sensitivity analysis

513

514 The computed sensitivity ratios by parameter are presented in Table S15. The most influential
515 parameter based on the sensitivity ratio was the frequency of hand-to-mouth contacts, followed by the
516 fraction of the hand that is inserted into the mouth, and the fraction of the hand that comes into contact
517 with an object (e.g., floor, grass, water). The sensitivity ratio is based on the percent change in the dose
518 compared to the percent change in the parameter input. This indicates that the dose is influenced more by
519 changes in these three exposure factors (e.g., hand-to-mouth contacts) compared to other parameters
520 (e.g., activity probability, activity duration). One of the least influential parameters was the hand-to-object
521 contact duration, indicating that the number of times the hand comes into contact with the mouth is more
522 influential than how long the hand is in contact with the contaminated object.

523

524 **Discussion**

525

526 The objective of this study was to evaluate the non-cancer health risk from exposure to arsenic
527 and lead and cancer risk (arsenic only) to the Diné communities who rely on the San Juan River and were
528 impacted by the GKMS disaster. We considered the following four different scenarios: 1) a recreational
529 scenario; 2) a cultural scenario that included activities related to livelihood, cultural and spiritual and arts
530 and crafts activities; 3) a dietary scenario; and 4) an aggregate scenario that incorporated all three
531 scenarios. The addition of more activities in each scenario resulted in estimates that increase by orders of
532 magnitude. Overall, the simulated dose estimates from exposure to arsenic and lead by engaging in the
533 43 different activities were relatively low. The scenario that contributes the most to the overall simulated
534 dose estimates was the dietary scenario, followed by the cultural and recreational scenarios. In
535 comparison to the ingestion of dietary items, engaging in recreational and cultural activities alone does
536 not contribute significantly to the overall lead or arsenic dose. The calculated HQs from exposure to

arsenic and lead by engaging in recreational and cultural activities and consumption of food were all below one, which suggest that there is no excess "risk of concern". This risk assessment indicates that less than 1% are at an excess cancer risk. While the estimated HQs for the exposure pathways impacted by the GKMS were less than one, there are two to nine orders of magnitude difference in dose estimates between the recreational, cultural, and dietary pathways. It is crucial to account for these pathways in the risk assessment, as there remains long-term uncertainty surrounding the potential accumulation of contaminants in the San Juan River. The Diné have a strong reliance on the San Juan River and use it for a variety of purposes (Teufel-Shone et al., 2021; Van Horne et al., 2021). Incorporating the cultural and dietary pathways respects the Diné's spatio-temporal relationship with the San Juan River and provides the community with autonomy to make their decisions (Cavazos Cohn et al., 2019).

After the GKMS, questions arose from members of the community and scientific entities regarding how representative and ultimately appropriate the health risk assessment process used by the governmental agencies. A primary concern was on the exposure scenario used by the U.S. EPA, which members of the Navajo Nation felt did not account for their reliance of the San Juan River. One of the assumptions the U.S. EPA made was that an adult hiker, would be drinking two liters of water a day and ingesting 100 mg of soil a day for 64 days (U.S. EPA, 2015b). Based on these exposure parameters the U.S. EPA determined they would use a screening value for arsenic in water of 50 µg/L and arsenic in sediment of 4,200 mg/kg. For lead, the water screening value was 200 µg/L and in sediment it was 20,000 mg/kg. One of the most puzzling aspects of their approach is that they did not disclose what RfD or adult body weight were utilized to calculate the screening values. As such it is difficult to compare our estimates with theirs. Nonetheless based on the available information and monitoring conducted by U.S EPA, we estimated the arsenic dose for a hiker to be between 2.5×10^{-05} to 1.05×10^{-04} mg/kg-day and the lead dose estimates to be between 1.00×10^{-04} to 5.01×10^{-04} mg/kg-day (U.S. EPA, 2015). Based on these estimates

both the governmental and our dose estimates would conclude that there would be "no adverse" effects. While our conclusions are similar, in our approach we determined that there are orders of magnitude difference between the recreational, cultural, and dietary scenarios. As long-term environmental conditions on the San Juan River are unknown it is important to consider community-specific pathways in the risk assessment process. The difference in approaches and assumptions reaffirms the need to conduct risk assessments that are representative of the community instead of relying on scenarios that do not take into account the environmental and community reality (Arquette et al., 2002). Moving forward, it is evident that communities themselves, rather than entities that do no not understand the community-specific lifestyles, should play key roles in designing and participating in risk assessments.

The cancer risk estimates are similar to studies conducted in mining impacted areas (Peplow & Edmonds, 2004). One study estimated the cancer risk from exposure to arsenic via ingestion of groundwater for people living near abandoned mines in Twisp, Washington, and these cancer risk ranged from 0.00 to 5.7×10^{-03} (Peplow & Edmonds, 2004). Similarly the cancer risk ranged from 2.7×10^{-09} to 1.5×10^{-02} for people consuming home garden vegetables and water containing arsenic in a mining area in Arizona (Ramirez-Andreotta et al., 2013). Across the United States the cancer risk from exposure to arsenic via drinking water has been estimated to be between 1.1×10^{-05} to 1.52×10^{-04} (Kumar et al., 2010). Furthermore, a current issue is the determination of an acceptable cancer risk guideline, which can range from 1×10^{-6} to 1×10^{-4} as the acceptable threshold (U.S. EPA, 1989). These guidelines should be specific to the community and be based on what the community deems is an acceptable guideline to reduce excess risk. Even though the estimated risks are low it is important to highlight that a comprehensive risk assessment is still valuable as demonstrated by the wide range of dose estimates (four to nine orders of magnitude for arsenic, and two to nine orders of magnitude for lead) between the recreational, cultural, and dietary scenarios in this risk assessment.

585

586 Unlike the environmental samples, the dietary items included in in this risk assessment (with the
587 exception of corn) were not tested for arsenic or lead. The lack of arsenic and lead measurements in food
588 consumed by the Diné is a limitation in our study. Future studies should test various foods among
589 Navajo communities to reduce uncertainty regarding the dietary pathway as the main contributor to the
590 aggregate arsenic and lead dose estimates. Our study relied on mutton data from previous work on
591 Navajo Nation from 2012-2013, where corn, soil, water used for irrigation and mutton were analyzed for
592 various contaminants including arsenic and lead (Samuel-Nakamura, 2013). While the arsenic and lead
593 concentrations for soil and water used for irrigation are comparable, the concentration of arsenic and lead
594 in corn varied widely. In our study the average concentration of arsenic in corn was 0.0005 ± 0.0003 ppm,
595 which was lower compared to 0.65 ± 0.3 ppm as reported by Samuel-Nakamura (2013). For lead, the
596 average concentration in corn was 0.002 ± 0.003 ppm, compared to 0.21 ± 0.03 ppm. We used the dry-ash
597 process which can result in volatilization of elements such as arsenic and lead and may result in reduced
598 concentrations in the samples, and thus underestimate the risk through the dietary scenario (Munoz et al.,
599 2013). As we did not collect or test mutton for arsenic and lead, we had to rely on the data available by
600 Samuel-Nakamura (2013) which may not currently capture the concentration of arsenic and lead in the
601 mutton consumed in our study.

602

603 There are limitations in our risk assessment, methods, and assumptions in our process. A
604 prominent issue with determining risk is the lack of Diné-specific activity factors, specifically, behaviors
605 during each of the activities (e.g., hand-to-mouth, and hand-to-object activity patterns). Risk analyses
606 often rely on the U.S. EPA's Exposure Factors Handbook. The studies included in the U.S. Exposure
607 Factors Handbook are compiled from various studies across the U.S, with varying demographics,
608 geography, and collection methods. As such, the Handbook may not be representative of Indigenous or

609 other communities but could still be used as a resource when no other data exists. We recommend that
610 future studies work with Diné communities to gather quantitative information on Diné exposure factors,
611 which are necessary to accurately assess exposure and health risks. A major limitation is that we did not
612 test the food items (with the exception of corn) included in this risk assessment for arsenic and lead. As
613 the dietary pathway was the main contributor aggregate arsenic and lead dose estimates, we may not be
614 accurately capturing the dietary arsenic and lead dose estimates for the Diné. Information is also needed
615 on the concentration of arsenic and lead in meat products. Especially mutton and wild game as a
616 previous study reported that Navajos consume twice as much meat than is recommended compared to
617 the U.S. general population (Sharma et al., 2010). Future studies should investigate the association
618 between increasing contaminants in water and concentration of contaminants in various food items. For
619 this study, we assumed that the concentration of arsenic in dietary items would increase by 10% and lead
620 would increase by 25% during peak-GKMS levels. This is based on a conservative approach, as there was
621 an increase of arsenic and lead concentrations in the San Juan River during the peak of the GKMS. Even
622 with this conservative approach the HQs were all below one, and less than 1% of the simulated persons
623 exposed were above the 1×10^{-04} cancer risk threshold. Additionally, we only conducted a risk assessment
624 for arsenic and lead, and thus there remains uncertainty surrounding the risk from exposure to other
625 contaminants present in the San Juan River.
626
627 A critical challenge was considering and being respectfully of the *Diné* concept of and
628 relationship to their environment (Lerma, 2017a; Navajo Nation Council, 2002; Yazzie, 2003). To the Diné,
629 water is life and since time immemorial, Tó (water) has been part of the Diné Lifeway (Lerma, 2017a;
630 Navajo Nation Council, 2002; Yazzie, 2003). The disturbance of the San Juan River was a direct attack on
631 the Diné Lifeway, which recognizes that the Four Sacred Elements Tó (water), Kǫ' (fire/light), Nitłchí (air),
632 and Tadidiin (pollen/earth) are strongly linked to ancient Diné principles and values which must guide

community engagement, risk assessment, and risk communication (Lerma, 2017a; Markstrom & Charley, 2003; Waugh et al., 2011). To effectively apply Diné principles and values, western researchers and educators must understand that a traditional belief among the Diné is that illness and imperfection of the environment are directly related to an imbalance in their lives. In the case of the GKMS when the contaminants infiltrated the San Juan River it led to a disruption of the balance between Mother Earth and Father Sky (Cavazos Cohn et al., 2019; Griffin-Pierce, 1992; Markstrom & Charley, 2003; Van Horne et al., 2021). There are essential differences between *Diné* and western approaches and application of the sciences and knowledge. Knowing is not the same as knowledge, which is passed down within and to communities through a relationship (Gonzales, 2020). It is critical to understand that these differences also apply to the process of research, assessment methods and analysis. Rather than segmenting and categorizing subjects as in western thought, *Diné* philosophy looks through the lens from a holistic approach (Kahn-John (Diné) & Koithan, 2015). The most important distinction in learning to apply this is the notion of the sacred and the secular. Western tradition separates the two while the *Diné* tradition embodies the two approaches. Modern western analysis leaves out so much from the Diné view – it leaves out the sacredness, the livingness, the soul of the earth. Measurement does not play the foundational role; it is only one of many factors to be considered. With *Diné* Scientists, the project was able to have a better understanding and able to engage in effective risk communication with the *Diné* communities and conduct their analysis of risk. While, guides for conducting a more representative risk assessment are available (Harper et al., 2012), in practice risk assessments among Indigenous communities continue to improperly account for Indigenous lifestyles. As extractive processes such as mining continue to impact Indigenous communities (Lewis et al., 2017), we provide recommendations to ensure that exposure and risk analysis are both robust and uphold Indigenous sovereignty. These recommendations include utilization of timely messaging to ensure trust, utilization of community participatory frameworks, and integration of concepts of Indigenous health (Table 9).

Conclusion

This study provides estimates of risk that are inclusive of various Diné exposure pathways that were potentially affected by the Gold King Mine Spill. The estimated HQs from exposure to arsenic and lead for the recreational, cultural, and dietary scenarios for all time periods were less than one, which indicates "no excess risk of concern". In our study there were two to nine orders of magnitude difference in dose estimates between the recreational, cultural, and dietary pathways. This is critical to consider, especially when there remains uncertainty surrounding the long-term accumulation of contaminants in the San Juan River. Due to the lack of information surrounding risks in using the San Juan River, many residents decided to reduce their engagement with the river (Van Horne et al., 2021). The results presented here indicate that the community could have continued engaging in their cultural activities without added risk. Improving the risk assessment process to account for Diné-specific activities will provide an improved risk communication message for this community. This will provide adequate information to aid them in making better-informed choices during and immediately after a spill occurs.

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Data availability In accordance with Indigenous Sovereignty and agreements with the Navajo Nation Human Research Review Board any data connected with biological samples from members can only be shared with appropriate Indigenous policies and permissions. Researchers who are interested in accessing these data can submit a request directly to the Navajo Nation Human Research Review Board.

Declarations

Conflict of interest The authors declare that they have no conflict of interest that are relevant to the content of this article.

Figures

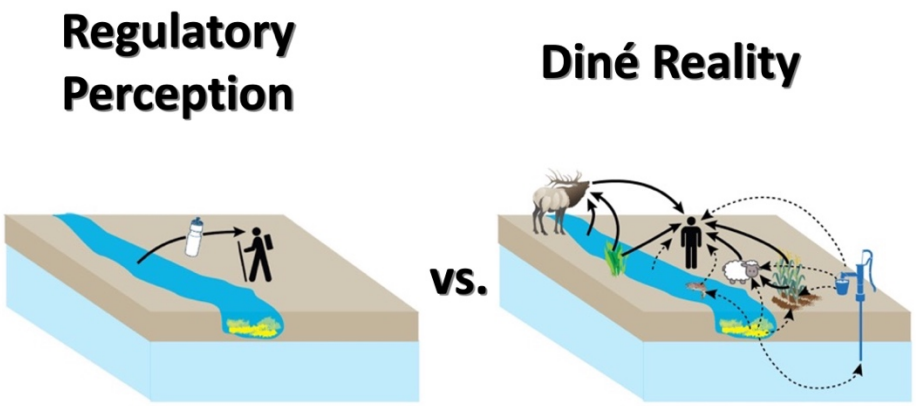


Figure 1. Regulatory perspective vs. Diné reality

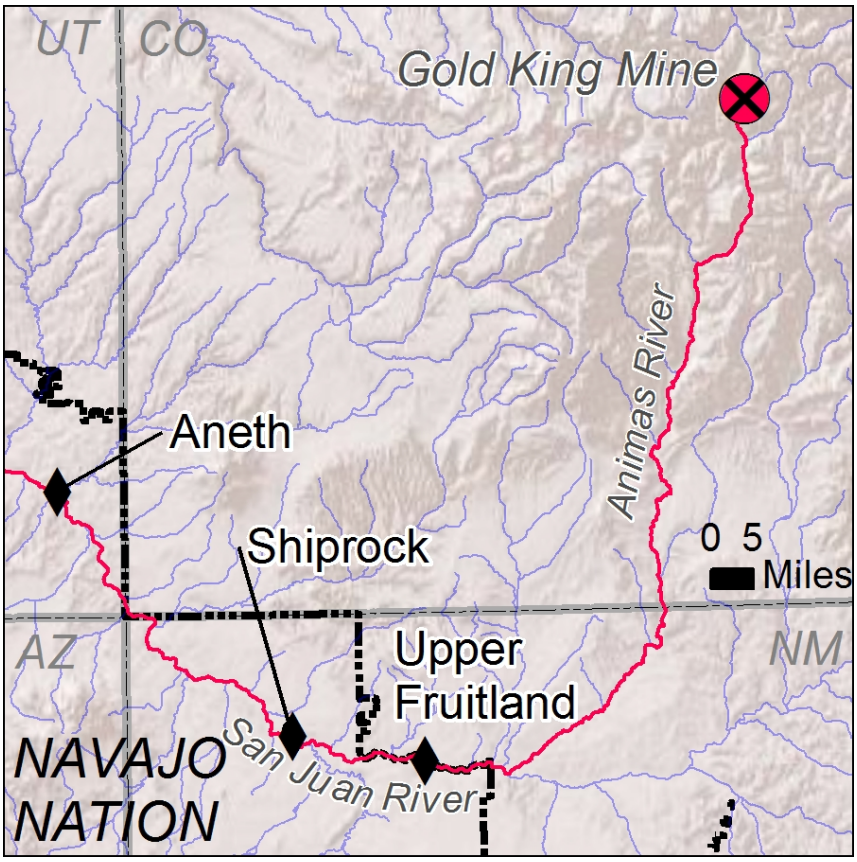
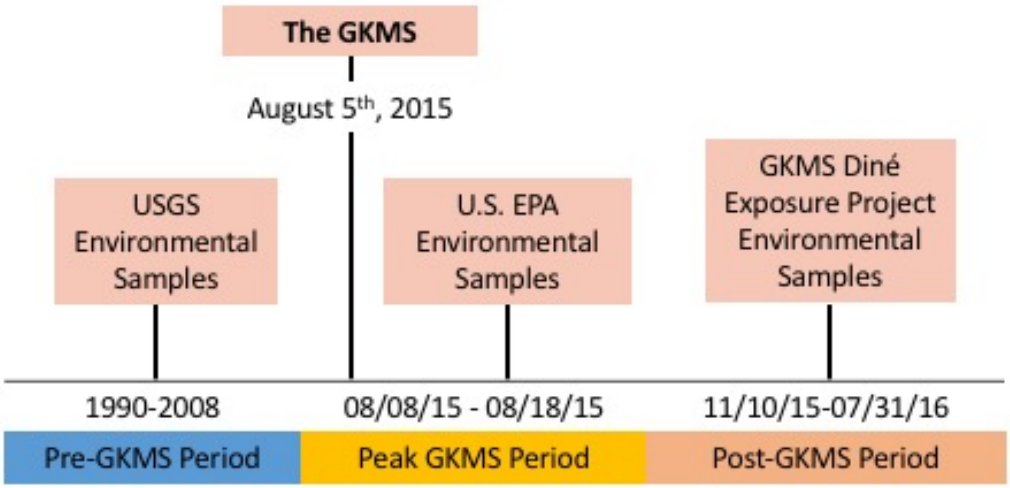


Figure 2. Gold King Mine in Silverton CO in relation to Navajo Nation

710



711
712 Figure 3. Time periods considered in this risk assessment
713

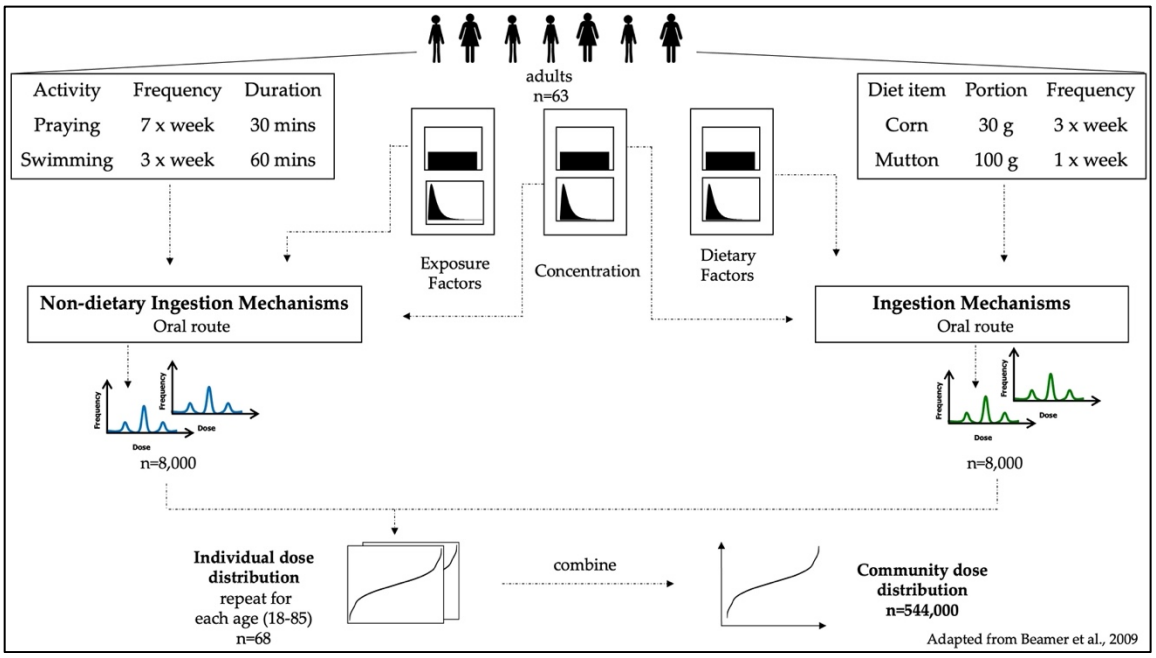


Figure 4. Conceptual model flow for Lifeline Community Based Assessment Software (CBAS) and data integration

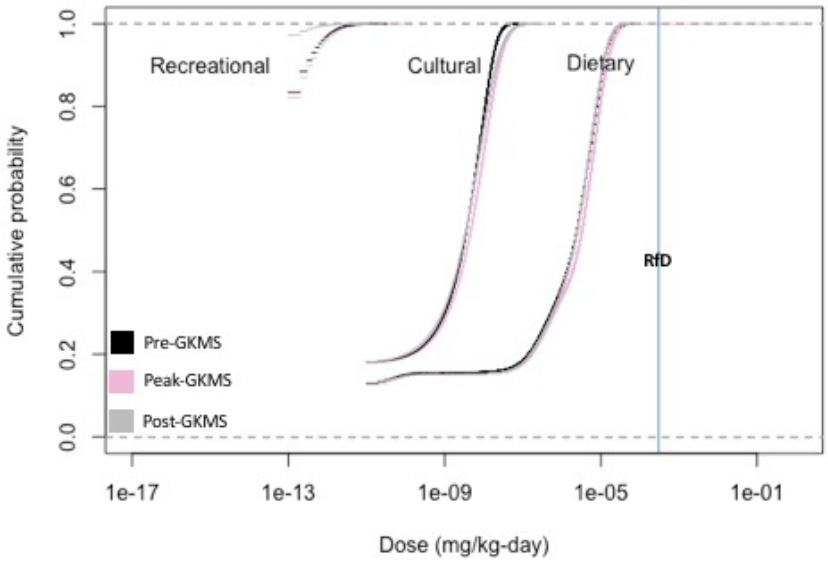


Figure 5. Community dose distributions of arsenic dose by scenario and time period simulations (n=544,000)

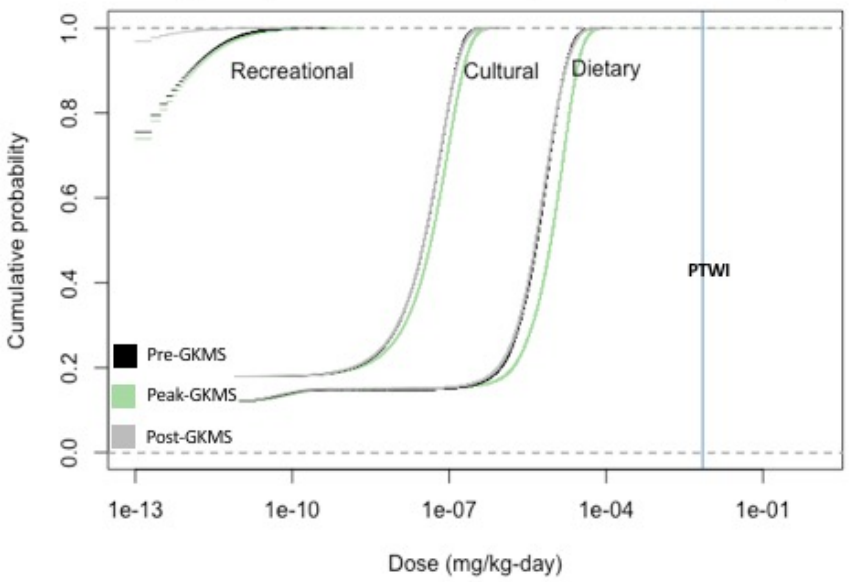


Figure 6. Community dose distributions of lead dose by scenario and time period simulations (n=544,000)

733 Tables

734

735 Table 1. Metal concentration (μg/L) from U.S. EPA at Cement Creek (August 5, 2015), Water Quality
736 Criteria (WQC) (μg/L) and ratios.

Metal	Concentration	WQC	Ratio
Fe	9,930,000	1,000**	9,930
Pb	179,000	2.5**	71,600
Zn	44,000	7,400	6
Cu	36,700	1,300	28
As	8,230	0.018	457,222
Cd	165	0.25**	660

737 **for aquatic life only, no human health
738
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740

741 Table 2. Environmental data sources and chemical analysis by sample type and time period

Time period	Data Source	Processing method	Analytical method	Analytical instrument	LOD
Water μg/L					
Pre-GKMS	USGS 2015	Not applicable	Not reported	ICP-MS	Not reported
Peak-GKMS	U.S. EPA 2015	Not applicable	EPA 200.8	ICP-MS	0.37 (As) 0.06 (Pb)
Post-GKMS	Current study	Not applicable	EPA 200.8	ICP-MS	a
Sediment mg/kg					
Pre-GKMS	USGS 2015	Not reported	Not reported	GFAAS (As) ICP-MS	Not reported
Peak-GKMS	U.S. EPA 2015	EPA 3051	EPA 6020A	ICP-MS	0.09 (As) 0.06 (Pb)
Post-GKMS	Current study	EPA 3051	EPA 6020A	ICP-MS	8.5×10^{-5} (As) 2.6×10^{-5} (Pb)

742 [a] = varied by batch, and contaminant for arsenic; batch 1 = 0.0093 μg/L, batch 2 = 0.01 μg/L, batch 3 = 0.009 μg/L, batch
743 4 = 0.006 μg/L ; for lead; batch 1 = 0.001 μg/L, batch 2 = 0.003 μg/L, batch 3 = 0.0004 μg/L, batch 4 = 0.004 μg/L
744
745

746 Table 3. Parameters and abbreviations for CBAS

Parameter	Units	Abbreviation	Citation
Hand-to-mouth contacts	events per hour	H_m	(Beamer et al., 2008; Beamer et al., 2012)
Hand-to-object contacts "how many times hands touches material/object"	events per hour	HO_{freq}	(Beamer et al., 2008; Beamer et al., 2012)
Hand-to-object contact duration	minutes	HO_{dur}	(Beamer et al., 2008; Beamer et al., 2012)
Fraction of hand inserted during the hand-to-mouth event full front	unitless	FSA_{mff}	(AuYeung et al., 2008)
Fraction of hand inserted during the hand-to-mouth event partial front	unitless	FSA_{mpf}	(AuYeung et al., 2008)
Fraction of hand inserted during the hand-to-mouth event partial front	unitless	FSA_{mpf}	(AuYeung et al., 2008)
Hands contact fraction with object (material)	unitless	HO_f	(AuYeung et al., 2008)
Transfer efficiency	unitless	T_{eff}	(Beyer et al., 2013)
Proportion of substance that is material of interest	unitless	P_{mi}	Lifeline
Object (material) surface factor	unitless	O_{sf}	Lifeline
Activity probability	unitless	A_p	Present study
Activity duration	minutes	A_{dur}	Present study
Activity frequency	events per hour	A_{freq}	Present study
Object (material) type	unitless	O_t	Present study
Residue of contaminant on solid surface	$\mu g/cm^2$	R_{ss}	Present study

747

748 Table 4. Community dose distributions of arsenic dose (mg/kg-day) by scenario and time period
749 (n=544,000)

Time period	Mean	SD	Min	25%	50%	75%	Max
Pre-GKMS							
Recreational	1.30×10^{-13}	5.13×10^{-13}	0.00	0.00	0.00	1.00×10^{-13}	2.84×10^{-11}
Cultural	6.14×10^{-09}	7.34×10^{-09}	0.00	5.30×10^{-10}	3.60×10^{-09}	9.17×10^{-09}	9.85×10^{-08}
Dietary	4.41×10^{-06}	5.65×10^{-06}	0.00	2.93×10^{-07}	2.46×10^{-06}	6.43×10^{-06}	8.34×10^{-05}
Aggregate	4.42×10^{-06}	5.65×10^{-06}	0.00	3.00×10^{-07}	2.46×10^{-06}	6.44×10^{-06}	8.35×10^{-05}
Peak-GKMS							
Recreational	1.71×10^{-13}	8.28×10^{-13}	0.00	0.00	0.00	1.00×10^{-13}	1.04×10^{-10}
Cultural	9.43×10^{-09}	1.33×10^{-08}	0.00	6.30×10^{-10}	4.69×10^{-09}	1.28×10^{-08}	2.62×10^{-07}
Dietary	5.03×10^{-06}	6.39×10^{-06}	0.00	3.10×10^{-07}	2.96×10^{-06}	7.22×10^{-06}	8.28×10^{-05}
Aggregate	5.03×10^{-06}	6.39×10^{-06}	0.00	3.20×10^{-07}	2.97×10^{-06}	7.23×10^{-06}	8.28×10^{-05}
Post-GKMS							
Recreational	2.02×10^{-14}	1.83×10^{-13}	0.00	0.00	0.00	0.00	1.53×10^{-11}
Cultural	8.07×10^{-09}	1.30×10^{-08}	0.00	4.30×10^{-10}	3.52×10^{-09}	1.02×10^{-08}	3.40×10^{-07}
Dietary	4.37×10^{-06}	5.49×10^{-06}	0.00	3.26×10^{-07}	2.50×10^{-06}	6.31×10^{-06}	6.78×10^{-05}
Aggregate	4.38×10^{-06}	5.49×10^{-06}	0.00	3.35×10^{-07}	2.51×10^{-06}	6.33×10^{-06}	6.78×10^{-05}

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755 Table 5. Community distributions of arsenic non-cancer risks (HQs) by time period and scenario
756 (n=544,000)

Time period	Mean	Min	25%	50%	75%	Max	% > RfD
Pre-GKMS							
Recreational	4.34×10^{-08}	0.00	0.00	0.00	3.33×10^{-08}	9.47×10^{-06}	0
Cultural	2.05×10^{-05}	0.00	1.77×10^{-06}	1.20×10^{-05}	3.06×10^{-05}	3.28×10^{-04}	0
Dietary	1.47×10^{-02}	0.00	9.78×10^{-04}	8.19×10^{-03}	2.14×10^{-02}	2.76×10^{-01}	0
Aggregate	1.47×10^{-02}	0.00	9.98×10^{-04}	8.21×10^{-03}	2.15×10^{-02}	2.76×10^{-01}	0
Peak-GKMS							
Recreational	5.69×10^{-10}	0.00	0.00	0.00	3.33×10^{-10}	3.47×10^{-07}	0
Cultural	3.14×10^{-05}	0.00	$2.10x\ 10^{-06}$	1.56×10^{-05}	4.28×10^{-05}	8.74×10^{-04}	0
Dietary	1.68×10^{-02}	0.00	1.03×10^{-03}	9.85×10^{-03}	2.41×10^{-02}	2.78×10^{-01}	0
Aggregate	1.68×10^{-02}	0.00	1.07×10^{-03}	9.89×10^{-03}	2.41×10^{-02}	2.78×10^{-01}	0
Post-GKMS							
Recreational	6.72×10^{-11}	0.00	0.00	0.00	0.00	5.10×10^{-08}	0
Cultural	2.69×10^{-05}	0.00	1.43×10^{-06}	1.17×10^{-05}	3.41×10^{-05}	1.13×10^{-03}	0
Dietary	1.46×10^{-02}	0.00	1.09×10^{-03}	8.34×10^{-03}	2.10×10^{-02}	2.26×10^{-01}	0
Aggregate	1.46×10^{-02}	0.00	1.12×10^{-03}	8.36×10^{-03}	2.11×10^{-02}	2.26×10^{-01}	0

757 HQ > 1 suggests a "risk of concern", RfD for arsenic is 3.0×10^{-04} mg/kg-day.
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759

760

761 Table 6. Community distributions of arsenic cancer risks by time period and scenario (n=544,000)

Time period	Mean	Min	25%	50%	75%	Max	% > CRG
Pre-GKMS							
Recreational	1.95×10^{-13}	0.00	0.00	0.00	1.50×10^{-13}	4.26×10^{-11}	0
Cultural	9.22×10^{-09}	0.00	7.95×10^{-10}	5.40×10^{-09}	1.38×10^{-08}	1.48×10^{-07}	0
Dietary	6.62×10^{-06}	0.00	4.40×10^{-07}	3.69×10^{-06}	9.65×10^{-06}	1.24×10^{-04}	0
Aggregate	6.63×10^{-06}	0.00	4.49×10^{-07}	3.69×10^{-06}	9.66×10^{-06}	1.24×10^{-04}	1
Peak-GKMS							
Recreational	2.56×10^{-13}	0.00	0.00	0.00	1.50×10^{-13}	1.56×10^{-10}	0
Cultural	1.41×10^{-08}	0.00	9.45×10^{-10}	7.04×10^{-09}	1.92×10^{-08}	3.93×10^{-07}	0
Dietary	7.54×10^{-06}	0.00	4.65×10^{-07}	4.43×10^{-06}	1.08×10^{-05}	1.25×10^{-04}	0
Aggregate	7.55×10^{-06}	0.00	4.80×10^{-07}	4.45×10^{-06}	1.08×10^{-05}	1.25×10^{-04}	1
Post-GKMS							
Recreational	3.02×10^{-14}	0.00	0.00	0.00	0.00	2.30×10^{-11}	0
Cultural	1.21×10^{-08}	0.00	6.45×10^{-10}	5.28×10^{-09}	1.53×10^{-08}	5.10×10^{-07}	0
Dietary	6.55×10^{-06}	0.00	4.88×10^{-7}	3.75×10^{-06}	9.47×10^{-06}	1.02×10^{-04}	0
Aggregate	6.56×10^{-06}	0.00	5.03×10^{-7}	3.76×10^{-06}	9.49×10^{-06}	1.02×10^{-04}	1

762 [1]CRG = Cancer risk guideline for arsenic = 1×10^{-04} mg/kg-day
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769 Table 7. Community dose distributions of lead dose (mg/kg-day) by scenario and time period
770 (n=544,000)

Time period	Mean	SD	Min	25%	50%	75%	Max
Pre-GKMS							
Recreational	8.92×10^{-13}	6.11×10^{-13}	0.00	0.00	0.00	1.00×10^{-13}	3.90×10^{-10}
Cultural	6.24×10^{-08}	7.04×10^{-08}	0.00	6.82×10^{-09}	4.00×10^{-08}	9.40×10^{-08}	9.13×10^{-07}
Dietary	6.83×10^{-06}	7.38×10^{-06}	0.00	1.57×10^{-06}	4.72×10^{-06}	9.68×10^{-06}	9.25×10^{-05}
Aggregate	6.91×10^{-06}	7.389×10^{-06}	0.00	1.64×10^{-06}	4.79×10^{-06}	9.75×10^{-06}	9.26×10^{-05}
Peak-GKMS							
Recreational	1.56×10^{-12}	1.91×10^{-11}	0.00	0.00	0.00	2.00×10^{-13}	2.03×10^{-09}
Cultural	6.52×10^{-08}	7.58×10^{-08}	0.00	6.74×10^{-09}	4.09×10^{-08}	9.66×10^{-08}	8.52×10^{-07}
Dietary	1.19×10^{-05}	1.18×10^{-05}	0.00	2.78×10^{-06}	8.87×10^{-06}	1.75×10^{-05}	1.22×10^{-04}
Aggregate	1.19×10^{-05}	1.18×10^{-05}	0.00	2.85×10^{-06}	8.94×10^{-06}	1.76×10^{-05}	1.22×10^{-04}
Post-GKMS							
Recreational	5.21×10^{-14}	1.04×10^{-12}	0.00	0.00	0.00	0.00	2.60×10^{-10}
Cultural	6.32×10^{-08}	7.37×10^{-08}	0.00	6.56×10^{-09}	3.99×10^{-08}	9.37×10^{-08}	1.06×10^{-06}
Dietary	6.82×10^{-06}	7.62×10^{-06}	0.00	1.48×10^{-06}	4.56×10^{-06}	9.53×10^{-06}	9.16×10^{-05}
Aggregate	6.88×10^{-06}	7.63×10^{-06}	0.00	1.55×10^{-06}	4.63×10^{-06}	9.60×10^{-06}	9.17×10^{-05}

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Table 8. Community distributions of lead (Pb) non-cancer risks (HQs) by time period and scenario (n=544,000)

Time period	Mean	Min	25%	50%	75%	Max	% > PTWI
Pre-GKMS							
Recreational	1.25×10^{-10}	0.00	0.00	0.00	1.40×10^{-11}	5.47×10^{-08}	0
Cultural	8.74×10^{-06}	0.00	9.55×10^{-07}	5.61×10^{-06}	1.32×10^{-05}	1.28×10^{-04}	0
Dietary	9.57×10^{-04}	0.00	2.20×10^{-04}	6.61×10^{-04}	1.36×10^{-03}	1.30×10^{-02}	0
Aggregate	9.66×10^{-04}	0.00	2.29×10^{-04}	6.70×10^{-04}	1.37×10^{-03}	1.30×10^{-02}	0
Peak-GKMS							
Recreational	2.19×10^{-10}	0.00	0.00	0.00	2.80×10^{-11}	2.84×10^{-07}	0
Cultural	9.13×10^{-06}	0.00	9.44×10^{-07}	5.72×10^{-06}	1.35×10^{-05}	1.19×10^{-04}	0
Dietary	1.66×10^{-03}	0.00	3.90×10^{-04}	1.24×10^{-03}	2.45×10^{-03}	1.71×10^{-02}	0
Aggregate	1.67×10^{-03}	0.00	4.00×10^{-04}	1.25×10^{-03}	2.46×10^{-03}	1.71×10^{-02}	0
Post-GKMS							
Recreational	7.30×10^{-12}	0.00	0.00	0.00	0.00	3.64×10^{-08}	0
Cultural	8.86×10^{-06}	0.00	1.19×10^{-07}	5.59×10^{-06}	1.31×10^{-05}	1.48×10^{-04}	0
Dietary	9.55×10^{-04}	0.00	2.07×10^{-04}	6.38×10^{-04}	1.34×10^{-03}	1.28×10^{-02}	0
Aggregate	9.64×10^{-04}	0.00	2.17×10^{-04}	6.48×10^{-04}	1.35×10^{-03}	1.28×10^{-02}	0

HQ > 1 suggests a "risk of concern", PTWI = 7.0×10^{-03} mg/kg-day

793 Table 9. Lessons learned and suggestion that can aid in future exposure and risk assessments with
794 Indigenous communities.

Lesson	Suggestion	Example
1. Timely and accurate messaging of situation to community affected is critical for trust.	Mobilize emergency management systems and have a trustworthy spokesperson deliver the message. Ensure the messages are available through various channels (e.g., newspaper, official social media accounts, websites) and in languages used by the community.	As information on the spill was not provided to the Navajo Nation, members of our team provided the first fact sheet to inform Diné people of the situation.
2. Utilize community participatory research frameworks throughout the research process.	Investigators should include community partners familiar with the needs of the community as investigators and not just consultants in the conceptualization, design, and implementation of studies.	The project involved collaboration with many Diné people. They were included in leadership roles, co-investigator, trainees, advisors. Most importantly we approached the project with shared decision-making power.
3. Recognize that research with Indigenous communities might require formal agreements, permission from various groups, and buy in from many entities.	Form a partnership with people who are familiar with the research approval process in the Indigenous communities you wish to work with.	The project received approval from the Navajo Nation Human Research Review Board and obtained over 10 resolutions from various governing localities on Navajo Nation.
4. Ensure the exposure and risk assessment scenarios are relevant to communities.	Integrate pathways and activities that are culturally relevant by discussing with partners who are embedded in the community, and/or conduct focus groups	The project relied heavily on elders to document the activities and scenarios relevant to the community. These were then further investigated using qualitative (focus groups) and quantitate methods (surveys, risk assessment).
5. Integrate concepts of Indigenous health in addition to risk assessment end points (e.g., Hazard Quotient).	In addition to cumulative and aggregate risk assessment models assess impacts by integrating a broader definition of health and not just absence of disease.	We integrated the Diné Lifeway concept, which recognizes that the Four Sacred Elements Tó (water), Kǫ' (fire/light), Nitchí (air), and Tadidiin (pollen/earth) are strongly linked to Diné values. This guided community engagement, risk assessment, and risk communication.
6. Identify and utilize effective communication materials and channels.	Results dissemination and risk communication is an important part of the research process.	The project provided information and materials at in-person community events, home visits to participants, and creation of YouTube videos in the Diné language
7. Document methodology to ensure a rigorous exposure and risk assessment can be done for other contaminants and scenarios.	Make information on sampling data, activity pattern data, dietary data, and all inputs utilized available for use by Indigenous entities.	All data and outputs were transferred to Navajo Nation HRRB in accordance with their stated agreements. A codebook, presentation, full report, and all materials were documented for accessibility, replication, or future research in this area.

8. Provide resources for future events.	Make a plan to provide a guidebook, transfer sampling tools, or build capacity to mobilize response.	The project engaged Diné college students and Navajo Nation Community Health Representatives in a weeklong training where they learned how to use low-cost materials to conduct their own environmental sampling.

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