

## Water quality, availability, and acute gastroenteritis on the Navajo Nation – A pilot case-control study

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### ABSTRACT

The Navajo Nation includes approximately 250,000 American Indians living in a remote high desert environment with limited access to public water systems. We conducted a pilot case-control study to assess associations between acute gastroenteritis (AGE) and water availability, use patterns, and quality. Case patients with AGE and non-AGE controls who presented for care to two Indian Health Service hospitals were recruited. Data on demographics and water use practices were collected using a standard questionnaire. Household drinking water was tested for presence of pathogens, coliforms, and residual chlorine. Sixty-one subjects (32 cases and 29 controls) participated in the study. Cases and controls were not significantly different with respect to water sources, quality, or patterns of use. Twenty-one percent ( $n = 12$ ) of study participants resided in dwellings not connected to a community water system. Eleven percent ( $n = 7$ ) of subjects reported drinking hauled water from unregulated sources. Coliform bacteria were present in 44% ( $n = 27$ ) of household water samples, and 68% ( $n = 40$ ) of samples contained residual chlorine concentrations of  $<0.2$  mg/L. This study highlights issues with water availability, quality, and use patterns within the Navajo Nation, including sub-optimal access to community water systems, and use of water hauled from unregulated sources.

**Key words** | acute gastroenteritis, coliforms, hauled water, Navajo Nation

### BACKGROUND

Acute gastroenteritis (AGE), characterized by sudden onset of diarrhea, vomiting, nausea, and abdominal pain, is a major cause of morbidity in the United States. Approximately 179 million cases of AGE are estimated to occur

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annually in the United States, resulting in 600,000 hospitalizations and an estimated 5,000 deaths (Jones *et al.* 2007; Scallan *et al.* 2011). American Indian and Alaskan Native (AI/AN) children historically have had disproportionately high rates of AGE when compared to the general US population (Santosham *et al.* 1995; Singleton *et al.* 2007). Furthermore, rates of AGE in AI/AN children living in the southwestern US are some of the highest when

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compared to rates of AGE among AI/AN children in other areas of the United States (Holman *et al.* 1999; Singleton *et al.* 2007).

The Navajo Nation is the largest reservation in the United States, encompassing nearly 24,000 square miles of remote high desert and includes approximately 250,000 persons. The median household income is 53% of the national average (\$27,389 vs. \$51,914), and one-third of all households on the Navajo Nation have incomes of less than \$15,000 per year (Arizona Policy Research Institute 2013). Additionally, 38% of households on the Navajo Nation are below the poverty line, compared to 15% of households in the United States (Arizona Policy Research Institute 2013). Poverty, geographic isolation, lifestyle constraints, and healthcare utilization challenges are likely contributors to health disparities and the increased disease rates borne by the Navajo people. In particular, access to safe drinking water for persons residing within the Navajo Nation can be limited. It is estimated that 21–32% of reservation households are not connected to public water systems compared to 0.5% of households nationally and 9% for American Indian tribes overall (First Things First Navajo Nation Regional Partnership Council 2010; Indian Health Service Sanitation Facilities Construction Program 2010; Centers for Medicare and Medicaid Services 2014). The Navajo Tribal Utility Authority (NTUA) and Navajo Nation Department of Water Resources (NDWR) provide watering points that include public water taps at trading posts, Chapter houses, schools, and border towns, in order that regulated water may be hauled for human consumption. However, while staff from over 50 of the 110 Navajo Chapters indicated in a NDWR telephone survey that watering points are the primary or secondary sources, respondents in over 20 Chapters noted that unregulated, untreated livestock wells were the primary or secondary source of drinking water for the people in their Chapter (Navajo Nation Department of Water Resources 2011). These water sources have been found to be contaminated by fecal coliforms and can contain arsenic and uranium levels that often exceed EPA drinking water standards (Murphy *et al.* 2011).

In Alaska, an ecologic study reported an association between lack of in-home water service and rates of infectious disease hospitalization among rural Alaska Natives (Hennessey *et al.* 2008). A dose–response relationship was

described whereby communities with the lowest in-home water service availability experienced the highest hospitalization rates. These hospitalization rates decreased with improved access to in-home water. In the Alaska study population, 27% of homes overall did not have access to in-home water, a rate similar to that seen on the Navajo Nation.

Despite high rates of diarrheal disease and challenges to the access of safe potable water on the Navajo Nation, there is a dearth of published information regarding water quality, availability, use patterns and associated health outcomes among Navajo people. The objective of this pilot study was to describe water use, availability, and quality among those who presented for care for AGE at two Indian Health Service hospitals on the Navajo Reservation as well as Navajo who presented for care and did not have AGE. We also aimed to evaluate the feasibility of conducting a case-control study of the association of water and AGE. The information from this study can begin to fill gaps in understanding the importance and potential health benefits of improved access to safe, regulated water for inhabitants of this region and help direct future research on this topic.

## METHODS

### Study subjects

American Indian patients of any age residing within the boundaries of the Fort Defiance and Chinle Service Units of the Navajo Nation who presented for care to the Fort Defiance or Chinle Hospitals with clinician-diagnosed AGE were recruited for enrollment as case patients from May 2010 to June 2011. These hospitals provide service to approximately 40% of the population residing on the Navajo Reservation (Navajo Epidemiology Center 2013). In order to have a study population that spanned the entire age spectrum, investigators attempted to enroll equal numbers of participants in the following age strata – less than 5 years; 6 to less than 18; 18 to less than 65; and 65 and older. Controls admitted with conditions other than AGE were matched to case patients on date of service, age strata, and Service Unit of residence. Study subjects were evenly enrolled over the wet (July through December) and

the dry (January through June) seasons. Case patients and controls were excluded if they had any other known non-infectious acute or chronic disease that may include symptoms of AGE (e.g., abdominal or colorectal cancer, gastric reflux or gastrointestinal ulcers, HIV/AIDS, inflammatory bowel disease, food allergies, pregnancy, and anxiety disorder). Written informed consent was obtained from all participants 18 years or older. Written parental permission was obtained for individuals under 18 years of age at recruitment; subjects 7 to 17 years of age provided written assent. For participants who were illiterate or non-English speaking, informed consent was obtained after verbal review with the aid of a translator. For these participants, an additional witness signature was obtained on the consent form. The study protocol was reviewed and approved by Institutional Review Boards (IRBs) at the Centers for Disease Control and Prevention (CDC), Johns Hopkins University, and the Navajo Nation prior to implementation.

Study subjects were surveyed by study personnel using a standardized questionnaire. This survey included questions regarding demographic information, clinical information including characteristics and duration of symptoms (for case patients), and household water use practices including water source, volume collected and stored, transport methods and handling practices, and personal and household hygiene practices. If another household member (e.g., parent) was more knowledgeable about these household water use practices, that individual could provide responses on behalf of the study participant. Individuals who participated in the study were reimbursed up to \$10 for their time.

### Clinical specimen collection and laboratory testing methods

At least 10 g of stool was collected from study subjects. Specimens were collected in sterile containers and refrigerated at 4 to 8 °C and overnight shipped on ice on a weekly basis to CDC laboratories. An aliquot (at least 3 g) of the stool was stored in 10% formalin for routine examination of ova and parasites. Once received at CDC, stool specimens were tested for bacterial, parasitic, and viral pathogens. Viral nucleic acid was extracted using MagMax 96 viral RNA extraction kit (ThermoFisher, Waltham, MA, USA) on an automated KingFisher instrument (ThermoFisher).

Specimens were tested for pathogenic viruses (norovirus, astrovirus, and sapovirus) by using the AgPath-ID One-Step RT-PCR Kit (ThermoFisher) on the 7500 Realtime PCR platform (ThermoFisher) (Belliot *et al.* 1997; Okada *et al.* 2006; Vega *et al.* 2011). Microscopy of wet-mount of formalin-ethyl acetate concentrates of specimens were used for the examination of helminth eggs. For the examination of pathogenic protozoa (*Cryptosporidium*, *Giardia*, and *Enterocytozoon*), DNA was extracted from unpreserved specimens and small subunit rRNA, triosephosphate isomerase, internal transcribed spacer gene-based PCR analyses of the extracted DNA were used as the detection tools, respectively (Ye *et al.* 2014). All stool specimens were cultured by standard methods for detection of *Shigella*, *Salmonella*, *Vibrio*, *Campylobacter* species, *Escherichia coli*, and *Yersinia enterocolitica* (Fitzgerald & Nachampkin 2007; Nataro *et al.* 2007). Sweeps of the bacterial growth on MacConkey agar plates were collected and tested by PCR to detect the following diarrheagenic *E. coli* (DEC) virulence factors: Shiga toxins 1 and 2 (*stx1* and *stx2*), intimin (*eae*), enterohemolysin (*E-hly*), and heat-labile and heat-stable enterotoxins *elta*, *stla*, and *st1b* (Schultz *et al.* 1994; Schmidt *et al.* 1995; Paton & Paton 1998).

### Water sample collection and laboratory testing methods

Study staff visited the home of each case patient and control to sample the primary residence drinking water within 1 week of study enrollment. Three drinking water samples were collected during the home visits: a 10 mL sample for residual chlorine testing; a 250 mL grab sample for total coliform and *E. coli* testing; and approximately 100 liters of water were sampled by dead-end ultrafiltration (UF). Residual chlorine was assessed during the home visit using the Hach Chlorine Colorimeter II Kit (Lampoc, CA, USA), in which at least 10 mL of drinking water was placed into a glass vial, followed by dissolution of free chlorine reagent into the vial and analysis of the sample via the colorimeter. The grab sample of water was collected following residual chlorine testing and stored in a chilled cooler after collection and during transit to the laboratory for testing. Coliform and *E. coli* testing were conducted at a laboratory on the Navajo Reservation using membrane filtration and culture on MI Agar per procedures in EPA Method 1604

(United States Environmental Protection Agency 2002). Analysts were proficiency-tested in the membrane filtration method prior to the start of the study. Approximately 100 liters of drinking water was filtered through a REXEED 25SX dialysis filter (i.e., ultrafilter) (Asahi Kasei Medical Company, Tokyo, Japan) using a standard protocol. The UF procedure has been demonstrated to be effective for recovering a wide range of waterborne bacterial, viral, and protozoan pathogens (Smith & Hill 2009; Mull & Hill 2012; Hill 2016). The filtered effluent was collected hygienically into portable containers and returned to the household, if desired. Ultrafilters were sealed in a leak-proof bag following UF and stored in a chilled cooler until shipment to CDC for processing and analysis. Ultrafilters were backwashed with a Tween 80-based solution to generate a ~500-mL sample for secondary concentration, nucleic acid extraction, and molecular analysis (Smith & Hill 2009). All stool specimen and water sample results were shared with the study subjects once testing was completed. Additionally, positive stool results were reported to the subject's IHS health care provider and positive water sample results were reported to the IHS, the Navajo Nation Environmental Protection Agency (NNEPA), and the NTUA, if the positive sample was from a municipal water source.

Statistical differences between cases and controls were assessed by calculating odds ratios and 95% confidence intervals. Statistical differences between categorical characteristics were assessed using Chi-square or Fisher's exact test; differences between discrete variables were assessed

using the Wilcoxon rank sum test. Significant differences were assessed at the  $p = 0.05$  level.

## RESULTS

A total of 72 individuals were contacted to participate in the study. Seven (10%) refused to participate; additionally, investigators were unable to collect stool specimens and/or water samples from four (6%) individuals. Thus, data were analyzed from 61 individuals; 32 (52%) were case patients and 29 (48%) were controls.

Mean age of study participants was 39 years (range: 10 months–87 years; Table 1); 36 (59%) participants were female. Forty-two (69%) participants reported living in a framed house; households included a median of five individuals who regularly slept in primary residences (range: 1–11 people). Case patients were similar to controls with respect to age, sex, residence type, and household size.

### Case-control analysis

Case patients and controls were not significantly different with respect to their primary residences' connections to community water systems, opinions of community water systems, history of drinking hauled water (i.e., water brought to one's primary residence from an outside source), hauled water sources, opinions of hauled water, or problems with aesthetic water quality (Table 2). Therefore, the descriptive

**Table 1** | Characteristics of study participants, Fort Defiance and Chinle service units of the Navajo Nation, May 2010–June 2011

Variable name	Total ( <i>n</i> = 61)	Acute gastroenteritis cases ( <i>n</i> = 32)	Controls ( <i>n</i> = 29)	<i>p</i> -value
Age in years, mean (range)	38.5 (0–87)	39.5 (0–87)	37.4 (2–82)	0.741
Sex, no. (%)				
Male	25 (41)	15 (47)	10 (35)	0.328
Female	36 (59)	17 (53)	19 (66)	
Type of house, no. (%)				
Framed house	42 (69)	21 (66)	21 (72)	0.568
Other type of building (e.g., mobile home, apartment, hogan, shade house)	19 (31)	11 (34)	8 (28)	
Number of people regularly sleeping in primary residence, median (range)	5.0 (1–11)	4.0 (1–11)	6.0 (1–10)	0.074
Mean age of people regularly sleeping in primary residence (range)	34.7 (0–100)	36.4 (0–94)	32.9 (0–100)	0.277

**Table 2** | Water use and availability among study participants enrolled at Fort Defiance and Chinle service units of the Navajo Nation, May 2010–June 2011

Variable	Total ( <i>n</i> = 61)	Acute gastroenteritis cases ( <i>n</i> = 32)	Controls ( <i>n</i> = 29)	Odds ratio (95% CI)	<i>p</i> -value
Primary residence connected to community water system (%)	48 (79)	25 (78)	23 (79)	1.07 (0.31, 3.67)	0.910
Drank hauled water in last 4 weeks (%)	19 (31)	10 (31)	9 (31)	1.58 (0.34, 7.22)	0.708
Sources of hauled water <sup>a</sup> (%)					
Regulated <sup>b</sup>	12 (63)	6 (60)	6 (67)	0.750 (0.11, 4.90)	1.000
Unregulated <sup>c</sup>	7 (37)	3 (30)	4 (44)	0.54 (0.08, 3.53)	0.650
Water treatment not known <sup>d</sup>	3 (16)	1 (11)	2 (22)	2.00 (0.15, 26.73)	1.000
Mean number of miles traveled to haul water (range)	15.3 (1–120)	22.8 (1–120)	7.8 (1–20)	N/A	0.543
Mean number of times per week water is hauled (range)	1.8 (0.3–4)	1.9 (0.5–4)	1.8 (0.25–4)	N/A	0.878
Type of container used to haul water <sup>a</sup>					
Closed container	16 (89)	9 (90)	7 (88)	1.29 (0.07, 24.38)	1.000
Open container	4 (22)	2 (20)	2 (25)	0.75 (0.08, 6.96)	1.000
Not answered	1 (5)	0 (0)	1 (11)	Undefined	1.000
Why hauled water is used (%)					
No access to public water	7 (37)	4 (40)	3 (33)	1.33 (0.20, 8.71)	0.585
Hauled water is better for health	2 (11)	2 (20)	0 (0)	Undefined	
Distrust public water supply	2 (11)	1 (10)	1 (11)	0.89 (0.05, 16.66)	
Dislike taste of public/private well water	2 (11)	0 (0)	2 (22)	Undefined	
Cost	0 (0)	0 (0)	0 (0)	N/A	
Unsure/Other/Not answered	6 (32)	3 (30)	3 (33)	0.86 (0.12, 5.94)	
Separate container used to store drinking water <sup>e</sup>	13 (68)	7 (70)	6 (67)	0.86 (0.12–5.94)	1.000
Drinking water container cleaned <sup>e</sup>					
Yes	15 (79)	8 (80)	7 (78)		
No/not answered	4 (21)	2 (20)	2 (22)	1.14 (0.13, 10.39)	1.000
Drinking water is sanitized <sup>e</sup>	3 (16)	2 (20)	1 (11)	0.50 (0.04, 6.86)	1.000

<sup>a</sup>Study participants were allowed to provide multiple answers.

<sup>b</sup>Includes bottled water from grocery stores or trading posts; water from Chapter houses or watering points; Navajo Housing Authority apartment building.

<sup>c</sup>Includes water from windmill-driven or private wells.

<sup>d</sup>Includes relatives' residences.

<sup>e</sup>Of those who reported drinking hauled water in the past 4 weeks.

characteristics for all study participants are reported for these variables.

### Water use and availability

Seventy-nine percent (*n* = 48) of study participants lived in primary residences that were connected to community water systems (Table 2). Overall, 31% (*n* = 19) of participants reported drinking hauled water in the last 4 weeks. Of these, 47% (*n* = 9) reported living in a residence with a connection to a community water system. Common sources of hauled

water included water that was regulated, such as bottled water from grocery stores or trading posts (*n* = 6), Chapter houses or watering points (*n* = 5), and a Navajo Housing Authority apartment building. In addition, sources of hauled water included water that presumably had not been treated or regulated, such as windmill-driven or private wells (typically untreated and shallow water sources) (*n* = 7). Respondents who drank hauled water also reported obtaining water from sources for which treatment or regulation was unknown, such as a relative's residences (*n* = 3). Participants who reported drinking hauled water were, on average, older

than participants who did not drink hauled water (mean age = 39.1 vs. 22.3 years), but this difference was not significant ( $p$ -value = 0.097). Water was most commonly hauled in closed containers (89%;  $n = 16$ ), but 4 of the 19 (22%) individuals who reporting drinking hauled water also reported hauling drinking water in open containers. Three (16%) of the 19 respondents who reported drinking hauled water reported sanitizing their drinking water.

When asked why participants drank hauled water, respondents reported having no access to public or private well water; believed that hauled water is better for one's health; reported that they distrusted the public water supply; or reported disliking the taste of public or private well water.

### Opinions and perceptions of water quality

Forty-one percent ( $n = 25$ ) of study participants reported having a 'bad' opinion of their community water system

(Table 3). Thirty-six percent ( $n = 22$ ) also reported having a positive opinion of hauled water. Thirteen (59%) of the 22 respondents who had positive opinions of hauled water also had a positive opinion of their community water system. Participants with positive opinions of hauled water were on average older than those with negative opinions of hauled water (mean age = 41.2 vs. 27.4 years), but this difference was not significant ( $p$ -value = 0.086). While 10 (53%) of the 19 respondents who reported drinking hauled water also reported having a negative opinion of their community water system, a negative opinion of community water systems was not significantly associated with actually drinking hauled water ( $p$ -value = 0.126; OR = 4.44, 95% CI = 0.74, 26.68).

Thirty-nine percent ( $n = 24$ ) of the 61 study participants reported having problems with the aesthetic quality of their drinking water (Table 3). Of the respondents who reported aesthetic water quality problems, 71% ( $n = 17$ ) reported having problems with the color of their drinking water;

**Table 3** | Opinions and perceptions of water quality among study participants enrolled at Fort Defiance and Chinle service units of the Navajo Nation, May 2010–June 2011

Variable	Total ( $n = 61$ )	Acute gastroenteritis cases ( $n = 32$ )	Controls ( $n = 29$ )	Odds ratio (95% CI)	$p$ -value
Opinion of community water system (%)					
Good	23 (38)	12 (38)	11 (38)	Ref.	0.977
Bad	25 (41)	14 (44)	11 (38)	1.17 (0.37, 3.64)	
No opinion	6 (10)	3 (9)	3 (10)	0.92 (0.15, 5.53)	
Don't know/Not answered	7 (12)	3 (9)	4 (14)	0.69 (0.13, 3.79)	
Opinion of hauled water (%)					
Good	22 (36)	12 (37)	10 (35)	Ref.	0.358
Bad	16 (26)	8 (25)	8 (28)	0.83 (0.23, 3.03)	
No opinion	4 (7)	4 (13)	0 (0)	Undefined	
Don't know/No answer	19 (31)	8 (25)	11 (38)	0.61 (0.18, 2.09)	
Problems with drinking water quality (%)	24 (39)	11 (34)	13 (45)	0.62 (0.22, 1.80)	0.381
Types of water quality problems <sup>a</sup> (%)					
Color	17 (71)	9 (82)	8 (62)	2.81 (0.42, 18.74)	0.386
Bad taste	14 (58)	7 (64)	7 (54)	1.50 (0.29, 7.75)	0.697
Smell	11 (46)	6 (55)	5 (39)	1.92 (0.38, 9.80)	0.682
Other	2 (8)	1 (9)	1 (8)	1.20 (0.07, 21.72)	1.000
Illness	1 (4)	1 (9)	0 (0)	Undefined	0.458
Concerned about water quality (%)	33 (54)	24 (75)	9 (31)	6.33 (2.05, 19.54)	0.009
Willing to pay for quality water (%)	54 (89)	30 (94)	24 (83)	2.50 (0.42, 14.83)	0.404

<sup>a</sup>Study participants were allowed to provide multiple answers.

58% ( $n = 14$ ) reported that their drinking water had a bad taste; and 46% ( $n = 11$ ) reported that their drinking water smelled. Forty-seven percent ( $n = 21$ ) of respondents who were connected to a community water system reported having problems with the aesthetic quality of their drinking water, but they were not more likely to have aesthetic drinking water quality problems when compared to respondents not connected to community water systems ( $p = 0.208$ ; OR = 2.63, 95% CI = 0.63, 10.99). Respondents with specific aesthetic water quality problems such as taste, color, or smell were also not associated with being connected to community water systems. Seven of the 19 (37%) respondents who reported drinking hauled water reported having problems with the aesthetic quality of their drinking water, and they were not more likely to have aesthetic drinking water quality problems when compared to respondents who did not drink hauled water ( $p = 1.000$ ; OR = 0.88, 95% CI = 0.29, 2.75). Of the 9 respondents who were connected to a community water system and drank hauled water, 44% ( $n = 4$ ) reported problems with aesthetic drinking water quality.

Fifty-four percent ( $n = 33$ ) of all respondents reported being generally concerned about water quality (Table 3), and cases were more likely to report a concern about water quality when compared to controls ( $p = 0.009$ ; OR = 6.33, 95% CI = 2.05, 19.54). Among cases, being

connected to a community water system or drinking hauled water were not associated with general concerns about water quality. Eighty-nine percent ( $n = 54$ ) of all respondents reported being willing to pay for higher quality water; being connected to a community water system or drinking hauled water was not associated with willingness to pay for higher quality water.

### Laboratory testing

Water samples collected at households were drawn from taps ( $n = 46$ , 75%), a bucket, an outdoor garden hose, a barrel, and bottled water. Eight (13%) households provided water samples from wells. Of the 13 residences reportedly not connected to community water systems, water samples were collected from 6 (46%) wells, 4 (31%) taps, a tank, a bucket, and an unnamed source. Forty-six percent ( $n = 27$ ) of water samples tested positive for coliform bacteria (Table 4). Forty percent ( $n = 18$ ) of tap water sources were coliform-positive, while 75% ( $n = 6$ ) of well water sources tested positive for coliforms. Nine percent ( $n = 5$ ) of samples tested positive for *E. coli*, and 3% ( $n = 2$ ) tested positive for *Cryptosporidium* spp. Fifty percent ( $n = 4$ ) of well water samples were positive for *E. coli*; one tap water source was contaminated with *E. coli*, and both *Cryptosporidium*-positive water sources were derived from tap water. All

**Table 4** | Drinking water and stool specimen testing results for study participants enrolled at Fort Defiance and Chinle service units of the Navajo Nation, May 2010–June 2011

Water or stool specimen test result	Total ( $n = 61$ )	Acute gastroenteritis cases ( $n = 32$ )	Control ( $n = 29$ )	Odds ratio (95% CI)	$p$ -value
Water samples: (%)					
Total coliform-positive	27 (46)	12 (38)	15 (56)	0.48 (0.17, 1.37)	0.197
<i>E. coli</i> -positive	5 (9)	2 (6)	3 (11)	0.53 (0.08, 3.45)	0.652
<i>Cryptosporidium</i> spp.-positive	2 (3)	1 (3)	1 (4)	0.90 (0.05, 15.13)	1.000
Residual chlorine <0.2 mg/L	40 (68)	22 (69)	18 (67)	1.10 (0.37, 3.29)	1.000
Stool specimens: (%)					
Diarrheagenic <i>E. coli</i> -positive	8 (14)	4 (13)	4 (15)	0.88 (0.20, 3.95)	1.000
Norovirus-positive	5 (8)	5 (16)	0 (0)	Undefined	0.054
<i>Cryptosporidium</i> spp.-positive	3 (5)	2 (7)	1 (4)	1.93 (0.17, 22.51)	1.000
Sapovirus-positive	2 (3)	1 (3)	1 (4)	1.11 (0.07, 18.55)	1.000
<i>Salmonella</i> spp.-positive	2 (3)	2 (6)	0 (0)	Undefined	0.492
Astrovirus-positive	0 (0)	0 (0)	0 (0)	N/A	N/A

household water samples were negative for norovirus, rotavirus, *Giardia* spp., *Campylobacter* spp., and *Shigella sonnei*. Sixty-eight percent ( $n = 40$ ) of water samples contained residual chlorine levels below 0.2 mg/L, a minimum level that has been suggested as evidence of effective chlorination and for control of most pathogens (US EPA 2002). Water sample coliform, pathogen, and residual chlorine test results were similar among case patients and controls. Sixty-three percent ( $n = 29$ ) of tap water sources contained low residual chlorine levels, and all water sources collected from bottled water, a bucket, garden hose, or tank contained low residual chlorine levels. Furthermore, 7 of 8 (88%) well water sources contained low residual chlorine levels. Study participants with water sources contaminated with fecal coliforms were not more likely to report general or aesthetic (i.e., color, taste, smell) issues with water quality. Eleven of 18 (61%) study participants who reported drinking hauled water in the past 4 weeks had drinking water that was contaminated with coliforms. Of the 11 water sources obtained from participants who drank hauled water and had coliforms present in their drinking water, 6 (55%) were well water sources; 3 (27%) were from tap water sources; a bucket water source; and a garden hose. Study participants with water samples that had low (<0.2 mg/L) residual chlorine levels were more likely to report having concerns with water quality ( $p = 0.031$ ; OR = 3.43, 95% CI = 1.09, 10.78), but aesthetic water quality issues were not associated with low residual chlorine levels in water samples.

Fourteen percent ( $n = 8$ ) of study participants were infected with diarrheagenic *E. coli* as determined through stool specimen testing (Table 4). Diarrheagenic *E. coli*-infected individuals were equally split between case patients and controls, and presence of *E. coli* in drinking water was not associated with diarrheagenic *E. coli* infection. Eight percent ( $n = 5$ ) of study participants were infected with norovirus; all norovirus-infected participants were case patients. Five percent ( $n = 3$ ) of study participants were infected with *Cryptosporidium* spp. (2 case patients and 1 control); the presence of *Cryptosporidium* in drinking water was not associated with *Cryptosporidium* infection. Three percent ( $n = 2$ ) of participants were each infected with sapovirus (1 case patient and 1 control) and *Salmonella* species (2 cases).

## DISCUSSION AND CONCLUSION

This pilot study describes the availability of community water systems, the use of hauled water for drinking, and issues related to water quality among healthcare-seeking persons in the central Navajo Nation. While significant associations between these water-related factors and AGE were not demonstrated, several issues were identified that may warrant further investigation. Nearly 80% of study participants reported living in a household that was connected to a community water system, yet almost one-third of respondents chose to drink hauled water. While hauled water was sometimes obtained from regulated or treated sources (e.g., bottled water from a grocery store), some respondents potentially increased their risk of exposure to pathogens that cause AGE by drinking hauled water from unsafe sources such as unregulated windmill well water. Drinking water samples from participants' homes were commonly positive for coliform bacteria and pathogens that cause AGE and often had inadequate levels of residual chlorine.

Overall, nearly half of the study participants' drinking water samples tested positive for coliform bacteria. Furthermore, over 60% of participants who drank hauled water had drinking water contaminated with coliforms, and many of these were well water sources. This high proportion of drinking water samples with coliforms present is similar to a recent report where 39% of municipal and well drinking water samples from the Crow Reservation in Montana, USA were contaminated (Richards *et al.* 2015). Similarly, over 50% of end-line water samples recently collected from drinking water systems in rural Alabama were coliform-positive (Wedgworth *et al.* 2015). Drinking water supplies are more likely to be contaminated with coliforms in rural areas globally, including from both improved and unimproved water sources (Bain *et al.* 2014).

A 2010 needs assessment reported 21% of Navajo households did not have complete plumbing facilities (First Things First Navajo Nation Regional Partnership Council 2010). Similarly, 21% of participants in this study reported no residential connections to community water systems. Nearly one-third of study participants reported drinking hauled water in the last 4 weeks, and nearly half

of these individuals reported living in a residence that was connected to a community water system. Study participants were willing to travel up to 100 miles and travel multiple times per week to obtain hauled water. These participants gave varied reasons for drinking hauled water while living in residences with connections to community water systems, including ceremonial uses, lack of trust in public water supplies, and disliking the taste of public water. While some of the hauled water sources that were reported may be considered safe (e.g., water from a grocery store or trading post), water sources such as windmill wells are designed for livestock use only and are not designated as safe for human consumption.

Our results show mixed opinions regarding community water systems and hauled water. Participants with positive opinions of hauled water were, on average, older than those with negative opinions of hauled water; however, this difference was not significant, and perhaps due to the small number of study participants. Our study also showed that almost half of the study participants indicated that they had one or more aesthetic water quality problems, such as water being off-color, or having a bad taste or smell. There are few published studies that examine perceptions of aesthetic water quality in the United States. One recent study examining perceptions of aesthetic water quality among users of community water systems in rural Alabama reported that 20% of participants expressed problems with water taste, color, and/or odor (Wedgworth *et al.* 2014). Poor perceptions of aesthetic water quality can lead to the use of alternative water sources and is known to be a major determinant of bottled water use outside of the United States (Doria 2006).

Over two-thirds of household water samples from study participants had residual chlorine levels that were less than 0.2 mg/L, and that 63% of tap water sources had residual chlorine levels below this amount. The residual chlorine in drinking water indicates how much remains of the chlorine initially added to inactivate pathogens that may cause AGE. Low levels of residual chlorine can indicate a contamination event or problems with the water system (e.g., inadequate disinfection). Study personnel contacted NTUA staff following the observation that many tap water samples had low residual chlorine levels. The NTUA staff attributed the low chlorine residual levels to increasing household distances

from the large water storage tanks used near Chinle, where water is subsequently gravity-fed into the town. The NTUA staff indicated that residual chlorine levels in smaller holding tanks used immediately prior to point-of-use distribution in Chinle would be checked and chlorine levels adjusted as necessary.

Several different pathogens that cause AGE were found among participants in our study. One-third of all study participants were infected with a pathogen that causes AGE, and 21% of controls who did not report symptoms of AGE were also infected with bacterial or viral pathogens. Bacterial pathogens (diarrheogenic *E. coli*, *Salmonella* spp.) were most commonly identified, with 16% of study participants (and 15% of controls) found to be infected. Viral pathogens were found among 11% of study participants, which is consistent with earlier studies. The presence of bacterial or viral pathogen infection among control participants indicates either asymptomatic infection or prolonged post-symptomatic shedding. Asymptomatic infections of diarrheogenic *E. coli* (Ludwig *et al.* 2002), norovirus (Patel *et al.* 2008), sapoviruses (Oka *et al.* 2015), and *Cryptosporidium* (Checkley *et al.* 2015) have been described previously.

This study has several limitations. Most importantly, as an exploratory pilot study, the number of study participants was relatively small and thus the study lacked the power to detect statistically significant associations between AGE and water use, availability, and quality. This pilot study identified the prevalence of factors potentially associated with AGE, and the estimated prevalence of these factors can be used to provide appropriate sample size estimates for additional, larger studies. However, the prevalence of some factors (e.g., drinking hauled water from unregulated water sources) was very similar among cases and controls, indicating that a very large sample size would be needed to detect statistically significant associations with these factors. Also, the representativeness of our study population to the larger Navajo Nation may be limited as we only included patients seeking health care at two of the seven Service Units. In addition, cases were limited to people who sought medical care for AGE, and people with presumably less severe cases of AGE who did not present for medical care would not be represented among our study population. Additionally, the drinking water samples that were collected and tested were largely taken from tap water sources; however,

household tap water sources may not have been used for drinking in all instances. Additionally, a single negative test result from a drinking water sample collected at a single point in time does not necessarily indicate drinking water quality in the past; a previous undetected contamination event may have led to waterborne AGE infections. This study also did not examine human waste disposal or handwashing practices that might be associated with AGE. Furthermore, this study did not assess the level of arsenic, which is a known water contaminant on the Navajo Nation and can be associated with gastroenteritis (Hoover et al. 2016).

This is the first study examining water sources, quality, and availability among Navajo people that also examines the association of these factors and infection with pathogens that cause AGE. Our results highlight a need for additional detailed examinations concerning the use of unregulated hauled water for drinking, including drinking hauled water when community water sources are available. A detailed evaluation of the quality and integrity of existing community water systems and remedying any deficiencies in disinfection may be necessary.

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