

AN INVESTIGATION OF COLIFORM CONTAMINATION IN PRIVATE WELL
WATER ON THE CROW RESERVATION

by

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ABSTRACT

The Crow reservation has a rural population that depends on home well water for domestic use. Many of the home wells do not have a suitable well cap, allowing a potential pathway of bacterial contamination of groundwater. Fecal coliform is associated with acute health problems, such as gastrointestinal illness, diarrhea, and cramps. Therefore, total coliform contamination of well water is an important health concern among Crow home well users. This research examines patterns in total coliform contamination among home well samples with respect to a suite of well and local aquifer characteristics thought to influence vulnerability to contamination, including well protection factors. Well and aquifer characteristics considered in this research include: the geologic production formation, local land cover, and distance to the nearest river. Well protection factors include: cap type, cap condition, depth of completion and time since completion (or age). One hundred water quality samples were collected from home wells along the Little Big Horn River in 2017, and available data on the character of those wells and aquifers were collected for comparison with the patterns in fecal coliform contamination among the samples. Presence/absence of coliform contamination was assessed using the Colilert IDEXX Quanti-Tray 2000 method. Spatial variations in the characteristics of wells and aquifers were characterized through a combination of well logs, the National Land Cover Dataset, and the National Hydrography Dataset. Logistic regression was used to identify potential relationships between probability of coliform contamination and characteristics of associated wells and aquifers. Logistic regression models suggested two notable and statistically significant ($\alpha = 0.05$ level) relationships: (1) wells completed in alluvium and farther from the river had a higher probability of total coliform contamination, and (2) wells with old style caps had a higher probability of total coliform contamination. The government of the Crow tribe can decide how to use the results for mitigation efforts and awareness for homeowners with contaminated wells. Also, the Crow Water Quality Project should archive and consider these results for future research, planning, development, and management.

CHAPTER ONE

APSÁALOOKE STORY

Water is Life

Water is of great importance to the Apsáalooke (Crow) people as we believe it has spiritual and healing power. Because of this belief, along with our history of dependence on buffalo, it has long endured throughout the history of the Apsáalooke (Crow) people from the time of the migration story to the present day. One story that portrays this power told by Chief Plenty Coups (Plenty Coups and Linderman, 2002), is a story about a man and how he was able to heal people with water. The story is mystical and respected as it is narrated by the Chief. When Plenty Coups was young he remembers the Apsáalooke (Crow) being in the Bighorn basin near the Wind River in Wyoming. In this area there is a spring that heals the ailing and they called it Medicine Water, which is present day Thermopolis Hot Springs. The hot spring was below a small hill with a small island at the center of the hot spring and this young man decided to dream on the island. To dream, is to fast in the hopes of experiencing a vision for help or power. This young man also had a few companions with him and they left him to go high into the mountains to go dream themselves and were instructed by the young man not to go near the spring until the fourth day. Listening to orders these men went to their high points on the mountain and they noticed on the third day he was gone. As instructed the men did not go to the spring until the fourth day and found the young man was not on the island but on shore. The young man told the men to go back to the village and instruct the wise ones to make

preparations for his arrival. The instructions were to build four medicine sweat lodges and to build them in a specific way. When this was complete the young man came to the village and gathered the wise ones to go into the four sweat lodges. When inside the fourth sweat lodge he told them his dream. In his dream he said that on the first and second night the Medicine Water had cleansed and burned his body. On the third night a person came to him and told the young man to follow him. The person went into the Medicine Water and the young man followed him with no pain. They came to a big red and black painted lodge with many horses close by and there was an otter on one side of the lodge and a white bear on the other, looking angry. The person spoke to them and said "this young man is my son." When they entered the lodge the young man could see across from the fire a kindhearted woman and the young man looked around and the person said "this is it you can go now." As the young man was about to leave the lodge, the woman said "are you not going to give something to your son to help his people?" The person then gave the young man a strip of otter skin and a picket pin and told him if the Apsáalooke (Crow) wished to use it this water will heal his people. When the villagers packed up camp and left they dropped beads and other personal things into the water for the person and his woman to have. This young man became powerful after his dream. One instance is during a serious battle with the Lakota. The young man was in love with a young woman and her father was a prominent warrior. During the battle this young woman's brother was struck with an arrow below the armpit and the father took his son to a lodge. The father went to the young man and asked to heal his son, professing he was willing to give all that he had to save his son. The young man said, "I just want

one thing” and he looked at the father’s daughter and the father agreed. The young man wasted no time prepared himself gathered his otter skins and grabbed his medicine bundle, which contained his medicine skin of an otter and with the stuffed head. He dipped the otter skin in some water and sprinkled onto the man who sat up. The young man whistled four times like an otter and proceeded to the river with the wounded man and the young man dove twice upstream into the water and twice downstream. The otter skin seemed to take on life and swimming and soon its nose was at the man’s wounds with its tail wiggling. As soon as the otter was done, dark blood could be seen in the river. The young man said “you are healed” and there were two scars under the man’s armpit. To this day Apsáalooke (Crow) members give offerings to the Medicine Water when passing through that area.

This story depicts how sacred and divine water is to the Apsáalooke (Crow) people in a time of adhering to nature’s laws, hunting the buffalo, survival and inter-tribal warfare. Despite the many years since that time, water has not lost its significance and spiritual healing power among the Apsáalooke (Crow). Water continues to be an obvious source of spiritual and cultural importance to Indigenous nations globally (McGregor, 2012).

This thesis is organized into two additional chapters. Chapter two is an introduction to water quality on the Crow reservation. Chapter three is an analysis of water quality samples based on well protection factors and physical characteristics of the well locations.

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CHAPTER TWO

INTRODUCTION

Water Quality on Crow Tribal Land

The Crow reservation, now reduced to its current 930,777 ha in south-central Montana (Figure 1) (Montana State Governor's Office, 2013). The Crow reservation has three scenic mountain ranges - the Wolf Mountains, the Pryor Mountains and the Big Horn Mountains that tower above the plains and supply three major river systems - Pryor Creek, the Little Big Horn River and the Bighorn River (Figure 2) (Eggers et al., 2015). The approximate enrollment of the tribe is 12,000 members with 8,000 residing on the reservation (MDPHHS, 2017). The traditional customs on the reservation are still strong with 3,000-4,000 native language speakers (Golla et al., 2007). A portion of tribal members are still actively involved in ceremonies and maintaining customs with all elements of nature including fire, earth, wind and water (Cummins et al., 2010; Eggers et al., 2015).

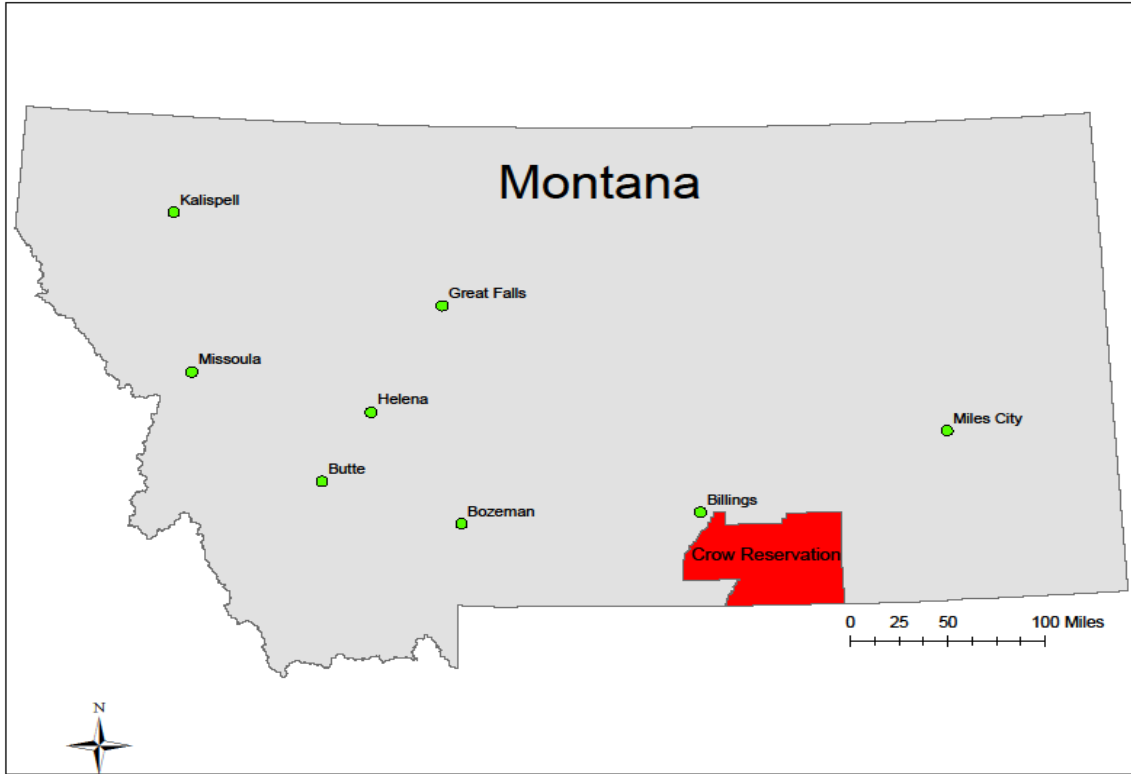


Figure 1. Map of the Crow Reservation and the state of Montana

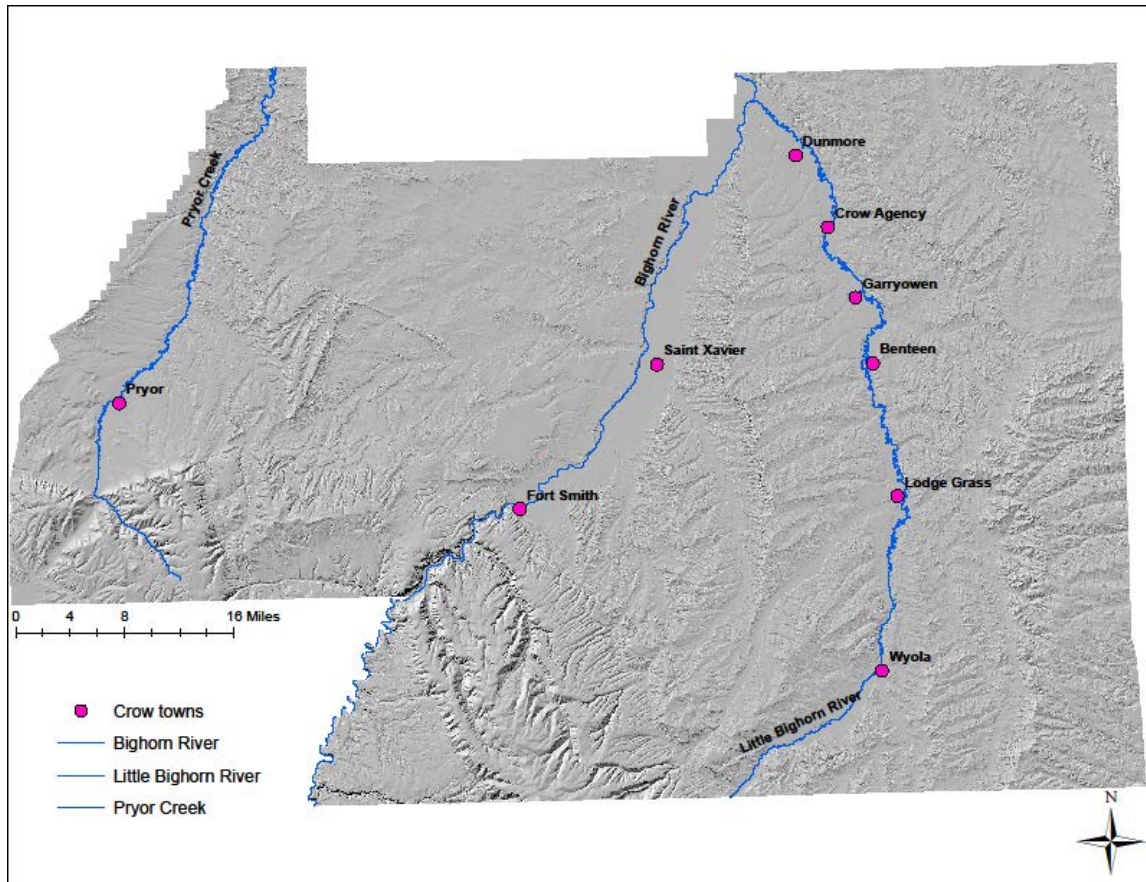


Figure 2. Towns on the Crow Reservation and three major rivers, the Pryor Creek, Big Horn River and the Little Big Horn River.

The families on the Crow reservation who do not have access to municipal drinking water generally use private well water. An estimated 1,020 homes on the Crow reservation have a private well for domestic uses that include drinking, bathing and washing dishes or clothes (Eggers et al., 2018). In these instances, well water is typically the only source of water that families use to drink, bathe, wash dishes, and wash clothes. In the United States, an estimated 15 percent of the population (approximately 40 million people) depend on private well water for their source of water for everyday use

(DeSimone et al., 2009; Maupin et al., 2014). Since the 1950s, Apsáalooke (Crow) water quality has been degraded. A lengthy struggle for water suitable for drinking or recreational beneficial use and ceremonial use has affected the cultural well-being and health for tribal members (Cummins et al., 2010; Eggers et al., 2013). Concerns regarding contaminants in drinking water on the Crow reservation have continued to increase among homeowners, with little resolution. In response, community members with collaborators from Montana State University and the University of New Mexico have led efforts since the 1990's to gain an understanding of the potential sources of contaminants in surface water and groundwater on the Crow reservation (Cummins et al., 2010; Doyle, Redsteer & Eggers, 2013; Hamner et al., 2013; Eggers et al., 2015; Richards et al., 2018; Doyle et al., 2018; Eggers et al., 2018). These efforts have been instrumental in improving understanding of the contaminants that affect the water of homeowners and tribal members who are culturally connected to water. Well owners for whom water was found unsafe for consumption have been given a home water cooler with a refillable five gallon jug. Optimistically, additional mitigation efforts that will slow the rate of contamination or alleviate current contaminated sites will evolve from these efforts.

The major concern about water quality on the Crow reservation is of health issues for families that drink well water containing metal, nitrate or bacterial contaminants (Cummins et al., 2010). Among the many contaminants of drinking water are metals or metalloids or other elements such as uranium (U), arsenic (As) and manganese (Mn) are (USEPA, 2009). Uranium exposure increases the risk of liver and kidney cancers and the regulatory maximum contaminant level (MCL) defined to minimize these risks in public

water supplies is 0.03 mg/L (EPA). Arsenic, with a MCL of 0.01 mg/L, also increases the risk of various cancers, along with causing skin damage and circulatory complications (USEPA, 2009). Manganese is a secondary drinking water quality contaminant. This means the U.S Environmental Protection Agency (EPA) does not enforce the standard level, however, the level is used as a guideline for public water systems. The secondary maximum contaminant level for manganese is 0.05 mg/L and a Health Advisory of 0.30 mg/L, incurring significant health risks especially to the nervous system of children and infants (USEPA, 2003; USEPA, 2004).

The EPA regulates microbial contamination in public supplies of drinking water based on concentrations of total coliforms, *Cryptosporidium*, *Giardia lamblia*, and *Legionella* (USEPA, 2009). The health effects of bacterial coliform contamination are usually short term, including vomiting, cramps and diarrhea. Total coliform regulation is listed as a treatment technique, which requires implementation of a mitigation strategy to reduce the levels of microbial contaminants in drinking water. Fecal coliform and *Escherichia coli* are indicator bacteria, which means their presence in drinking water indicates potential contamination by animal or human feces and a subsequent co-occurrence of fecal pathogens. The focus of bacterial contamination in home well water has guided efforts for this study on the Crow reservation.

The overarching goal of this research was to examine the potential drivers of total coliform contamination across a large sampling of private wells of the Little Big Horn River Valley on the Crow reservation. The hope is that this knowledge will be used to

identify wells with bacterial contamination and to provide mitigation efforts. This goal was achieved through the following objectives:

- 1) Collected and analyzed 100 samples from private wells.
- 2) Worked with a mentor and IHS to obtain and abstract relevant information from driller logs.
- 3) Compiled primary and secondary data into a GIS for spatial analysis.
- 4) Developed a process for extracting key information needed to answer research questions and assess the likelihood of total coliform contamination according to various well protection factors, including well depth, well cap type and condition and well age.
- 5) Developed a process for extracting key information needed to answer research questions and assess the likelihood of total coliform contamination according to various physical characteristics of well locations, including the geologic formation, land cover, and distance to the nearest river.

These goals were achieved by application of logistic regression models to objectively characterize patterns in the relationship between probability of contamination by coliforms and the characteristics of the aquifer and well.

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CHAPTER THREE

AN INVESTIGATION OF COLIFORM CONTAMINATION IN PRIVATE WELLS
WITH RESPECT TO WELL AND AQUIFER CHARACTERISTICS AND
CONTAMINATION PROTECTION FEATURES

Introduction

Total Coliform Contamination

Groundwater is an essential source of water for rural families in developed and developing countries. The potential of pathogens in drinking water is a major health concern for these communities (Adhikary, 2010; Baba and Tayfur, 2011; Saba et al., 2015). Total coliforms are indicator bacteria that can be analyzed from a sample to determine risk of fecal pollution in a water source. Indicator bacteria refers to the contaminant possibly being from human or animal feces with potential pathogens in the water source (Rompré et al. 2002; Scott et al. 2002; Yates 2007). Total coliforms may directly include pathogenic bacterial species or indicate the presence of other pathogenic microbes (e.g. *Cryptosporidium* and *Giardia*). All of these pathogens can cause acute gastrointestinal symptoms including diarrhea, cramps, nausea and headaches (USEPA, 2009). Coliforms are represented by a wide range of genera and species in the *Enterobacteriaceae* family (Rompré et al. 2002). Franson (1975), defines coliforms as:

1. All aerobic and facultative anaerobic, gram-negative, non-spore forming, rod-shaped bacteria that ferment lactose with gas and acid formation within 48 h at 35 °C.
2. All aerobic and many facultative anaerobic, gram-negative, non-spore forming, rod-shaped bacteria that develop a red colony with a metallic sheen within 24 h at 35 °C on an endo-type medium containing lactose.

There are no federal standards for coliform contamination for rural private wells.

This prompts many homeowners to adopt standards available from the United States Environmental Protection Agency (EPA) for public water systems (USEPA, 2009).

According to the EPA standards (USEPA, 2009), samples collected in one month may not contain more than 5 percent contaminated with total coliform, or up to 40 samples collected in one month may have no more than one sample contaminated. Monitoring of domestic wells is at the discretion of homeowners, and therefore national-level water quality standards are only guidelines for homeowners (DeSimone et al., 2009).

Public Health Issue

Gastrointestinal illnesses related to drinking water supplies from private wells can cause severe diarrhea, vomiting or cramps (Payment et al. 1997; USEPA, 2009). Over 1,400 infectious organisms are known to cause gastrointestinal illnesses; they stem from animal or human feces and are naturally occurring in aquatic environments. Waterborne pathogens are comprised of bacteria (including *Salmonella typhi*, some strains of *Escherichia coli*, *Vibrio cholera* and *Legionella spp*), enteric viruses (including rotaviruses and adenoviruses), and protozoa (including *Cryptosporidium hominis* and

Giardia lamblia), (Ashbolt, 2004). Extensive literature has examined relationships between bacteria and well water in relation to gastrointestinal illnesses. These studies have acquired data from various sources that include: water samples, questionnaires or diaries of symptoms or public data if available (Knobeloch et al. 2013; Raina et al. 1999; Stauber et al. 2016; Strauss et al. 2001). Awareness of the causal relationships between gastrointestinal illnesses and pathogens in water resources is generally increasing, but far less research in this area has been focused on native and other minority communities.

Water Quality Disparity in Minority and Tribal Communities

Minority communities have challenges in overcoming poor water quality and other disparities in risks to health. In a review of racial disparity in water quality by Craun et al. (1993), gastrointestinal death rates were found to be higher among Native Americans than non-native Americans, with six percent of distribution systems contaminated by microbes on reservations. The review concluded that minority populations rely on water resources of poorer quality. A study identified a North Carolina African American population outside the jurisdiction of the city municipal system. The population had poor water quality with high microbial contamination and a higher risk of gastrointestinal illnesses than their neighbors who were connected to the municipal system (Stillo and MacDonald, 2017). Racial disparity also affects municipal water and sewer services in North Carolina. One study found that in a census block with a small percentage of African American population had more municipal services as opposed to census blocks with 100 percent African American population.

Additionally, a white majority population with municipal services was unwilling to extend water and sewer services to neighboring black populations or mixed populations (Leker and MacDonald, 2018).

With poor water quality evident in minority communities, research is being conducted to understand and highlight water quality problems on tribal reservations throughout the United States. The Navajo Nation has dealt with extensive contamination of water sources that has affected community, livestock, and wildlife health, which is likely to continue into future generations. Abandoned uranium mines have created substantial contamination of water resources and community health risks because mining companies did not clean up uranium tailings or mill waste after mine operations closed (Beisell, 2009).

Failures in infrastructure have the potential to send waste directly into water ways and aquifers, such as a dam failure at Church Rock in the late 1970's that released large amounts of radioactive uranium downstream. This disaster killed 10,000 sheep and contaminated a nearby river. Since the 1980's, birth defects have begun to be noticed in the Shiprock area. By the early 2000's, some organizations were providing funding for research assessments of water quality around the abandoned uranium mines, and other reclamation efforts were underway, including the removal of eight inches of top soil in some areas. Some consider these efforts "too little, too late" (Beisell, 2009). Hoover et al., (2018), were able to identify water quality clusters of high concentrations of metals and

metalloids in water sources on the Navajo reservation using a variety of clustering methods.

McGinnis and Davis (2002) examined water quality in private wells on the Omaha and Santee reservation in Nebraska. They conducted chemical and bacterial analyses, finding that 38 percent of wells were contaminated with coliform across both reservations. In Oklahoma, the Concho Reserve is tribal land shared by Cheyenne and Arapaho tribes. They used a wellhead protection area model combined with GIS to identify contamination from different sources in wellhead protection areas and discovered this tool is helpful in identifying contamination around wellhead areas (Vieux et al., 1998)

Drivers of Groundwater Contamination

Water quality from agriculture, mining, industrial and anthropogenic contamination in rural areas is of global concern. In Turkey, a study of natural and anthropogenic pollution of groundwater found that septic system waste seeped into groundwater and the study revealed that shallow groundwater in alluvium was more likely to be contaminated by overlying septic systems (Babe and Tayfur, 2011).

Felipe et al. (2018) sampled 53 home wells in a rural area of Brazil and found that nearly 68 percent of samples were contaminated by bacteria, total coliforms or *E.coli*. They also tested for protozoans and found 33 percent of samples were contaminated with *Giardia* and *Endolimax nana*. Physical and chemical factors were also analyzed, specifically pH, temperature, salinity and dissolved oxygen, and temperature and salinity were found to be significantly correlated with bacterial colonization and growth.

Saba et al. (2015) examined microbial presence in groundwater in Moradabad City, India. They tested samples from private wells and the local municipal system for total and fecal coliforms and *E.coli* using plate count and Most Probable Number (MPN). They tested differences between pre- and post-monsoon seasons. The study revealed 58 percent of samples were contaminated with fecal coliforms post-monsoon compared to 16 percent pre-monsoon, indicating that changes in hydrologic transport in response to monsoons increase the risk of unsafe drinking water (Saba et al., 2015).

Finally, a study in China examined samples collected from untreated water at a water treatment plant for total coliforms and *E.coli* using plate count and MPN (Ye et al., 2013). The study revealed a range between non-detect and 1600 MPN per 100 mL for both total coliforms and *E.coli*, with shallow groundwater and inadequate wellheads as contributing factors to contamination (Ye et al., 2013).

Many studies point to well protection factors as the main driver of contamination. For example, Gonzales (2008), examined the relationship of total coliform contamination to wellhead protection and to well depth. In their study, categorical classes were identified for well head condition (poor, fair and good) and for three ranges of well depths. They found that 71% of wells less than 199 ft deep were contaminated and 71% of wells with poor and fair condition well heads were contaminated (Gonzales, 2008). Additionally, they found that 100% of wells located within 100 ft of a nearby tributary were contaminated with total coliform. Swistock and Sharpe (2005) investigated effectiveness of mitigation of bacterial

contamination in home wells by disinfecting wells and installing sanitary well caps. Their findings indicated that 45% of mitigated wells were still contaminated with total coliform. They tested the wells both short term (30-60 days) and long term (1 year) and concluded that wells may be at risk of ongoing contamination due to contaminated groundwater (Swistock and Sharpe, 2005).

Other studies point to physical characteristics of the well and aquifer as dominant drivers of contamination (O'Dwyer et al., 2018; Oosting & Joy, 2011). O'Dwyer et al (2018) developed a hierarchical logistic regression model that evaluated the influence of a variety of factors on the presence/absence of *E.coli* in wells. They found that wells located in sand and gravel aquifers in their study area were less likely to have contamination than wells located in bedrock aquifers. Another study developed a GIS model to rate risk factors that were divided into geologic, terrain and on-site systems risk factors (Oosting and Joy, 2011). Soil type and the on-site system age were factors that had the highest risk. They also determined that if a system was 25 years or older it was considered high risk. Proximity to a river or water supply was also evaluated, however, it was found to have low risk (Oosting and Joy, 2011).

Despite the number of studies on fecal contamination of groundwater and wells, variation in local conditions and the intertwined complexity of potential drivers of contamination lead to substantial uncertainty in the ability to predict and mitigate water quality issues in rural landscapes. Therefore, continued investigations of the potential drivers of contamination are important to further

improve our understanding of this growing risk to human health. Mitigation efforts need to be guided by the best available science and local knowledge. This study contributes a groundwater fecal contamination analysis that is critical both to mitigation efforts by the Crow tribe and to the understanding of the broader scientific community.

Objectives

The overall objective of this study was to investigate potential drivers of total coliform contamination of private well water on the Crow Reservation. Expected outcomes of this research are to increase health awareness among homeowners and generate mitigation efforts. More specifically, the goal of this study was to conduct statistical tests on observational data of total coliform contamination in home wells along the Little Big Horn River. Total coliform and *E. coli* Most Probable Number (MPN) were measured using the EPA-approved IDEXX Quanti-tray 2000 method (idexx.com). The predictor variables were divided into two major categories – well protection factors and physical characteristics of the well location and aquifer. Specific variables included in the statistical models were the type and condition of the well cap, the well depth and the well age data derived from well logs, a binary classification of the well production formation derived from well logs, land cover derived from the National Land Cover Database, and distance to the nearest river derived from the National Hydrography Dataset. Logistic regression models were developed to address the following predictions based on hypothetical mechanisms of contamination in the study system:

1. Home well water is more likely to be contaminated by total coliform bacteria in shallow wells that pump directly from alluvium located proximal to the Little Big Horn River or other major tributaries.
2. Water from older wells is more likely to be contaminated by total coliform bacteria.
3. Home well water is more likely to be contaminated by total coliform bacteria when the well cap is damaged or of a less effective older style (lacking a sanitary seal).
4. Home well water is more likely to be contaminated by total coliform bacteria, when there is majority agricultural land cover in the vicinity of the well.

Methods

Study Site

The study area was located within the Little Bighorn River watershed located within the Crow reservation boundary in southeastern Montana (Figure 1). The Crow reservation covers 930,777 ha with vegetation ranging from grasslands to wetlands. The Crow reservation has three mountain ranges and includes Pryor Creek, the Little Big Horn River and the Big Horn River valleys (Figure 2) (Doyle et al., 2013). The study area is a drainage area approximately 110,000 ha that follows the Little Bighorn River (Figure 3) flowing south to north (Tuck, 2003). The tribe has more than 12,000 enrolled members with roughly 8,000 members living on the reservation in the three major river valleys.

Most of the population resides in the Little Big Horn River Valley, which is therefore the focus area of this study (Doyle et al., 2003).

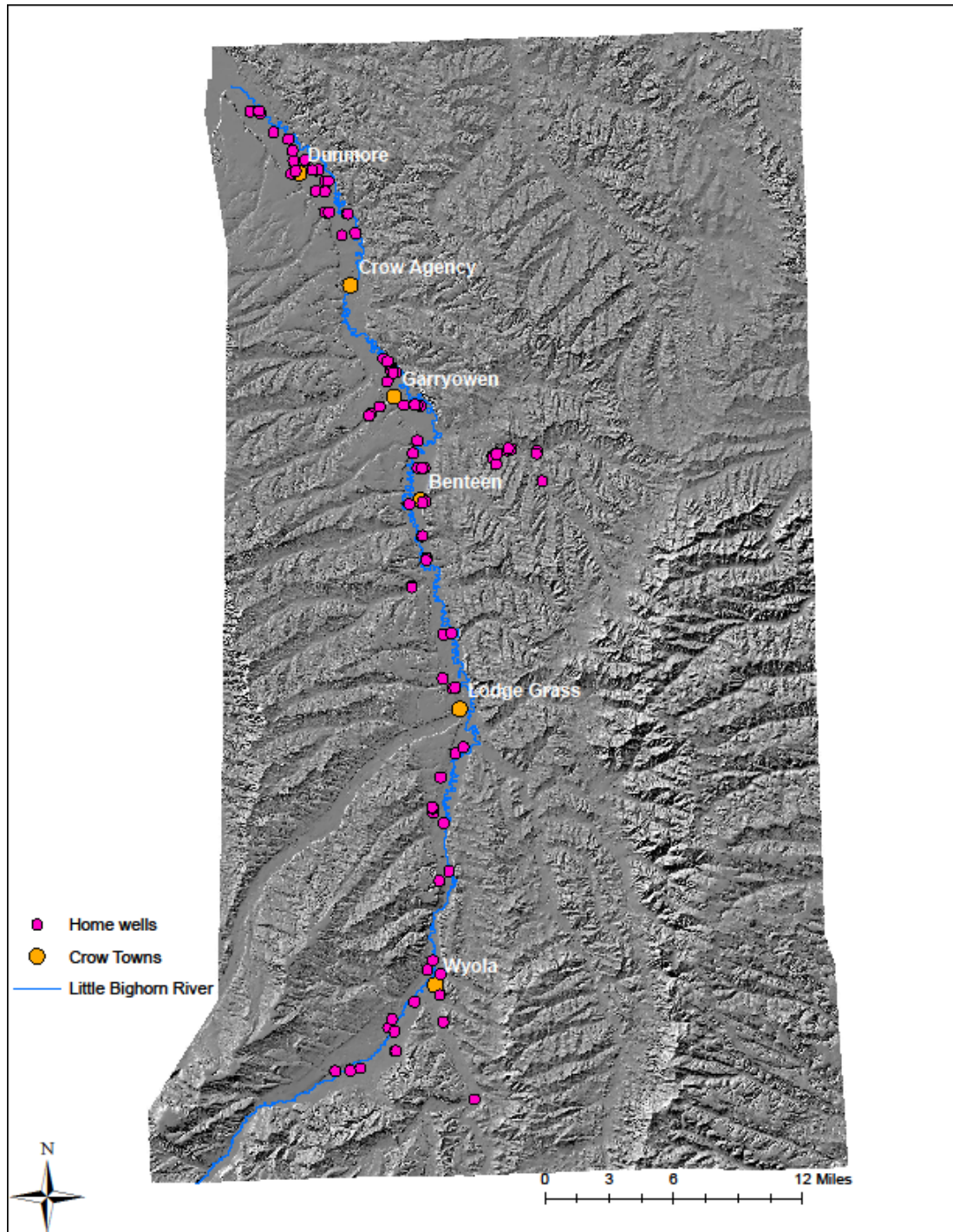


Figure 3. Study area along the Little Big Horn River with home well sites and Crow towns.

Data Collection

A sampling of 100 home wells was conducted along the Little Big Horn River in May and June of 2017. Samples were analyzed for microorganism analysis and water chemistry. Data characterizing the protection factors for the wells were collected along with a suite of physical characteristics for each well location.

Sample Collection and Analysis

At each of the 100 sample locations, water samples were collected and water temperature, pH and conductivity were immediately measured and recorded (Multimeter, Oakton, and Vernon Hills, IL, USA). Sampling procedures included calibrating the multimeter at the beginning of each day of sampling, using rubber gloves, wiping down the faucet with alcohol pads, letting the tap run for a few minutes to clear water which had been sitting in the pipes, collecting water samples from the sink or outside faucet using sterile 100 mL bottles without touching the inside of cap or bottle and otherwise following sterile procedure, and using a sterile control sample for each day of sampling (Egger et al., 2018). Three to four sample bottles were used to collect water for coliform, *E.coli* and MPN analyses. Samples were transported and held in a cooler with ice until processing.

The water samples along with the field blank control were processed within three to four hours of collection using IDEXX Colilert® QuantiTrays® (IDEXX Laboratories, Westbrook, Maine). The trays and bottles were incubated for 24 hours. After incubation, the trays were recorded using the Quanti-Tray method for MPN results. Bottles were analyzed for presence or absence of coliform that was compared to an IDEXX

comparator standard tray. Also, to detect for *E.coli* both trays and bottles were placed under a UV light, with fluorescence indicating tray cells or the bottled sample contained *E. coli* (Vermeulen et al., 2008).

Characterization of Well Protection

At each well location, GPS was used to record the latitude and longitude when receiving a signal from a minimum of four satellites. Well protection factors were either recorded on site (e.g. well cap type and condition) or obtained from well logs (e.g. well age and well depth). The well cap type, old style or new style and condition, damaged or not damaged were recorded. For instance, when a bolt was missing, or the cap was missing entirely, it was recorded as damaged, with the intent to have as much information about the cap type and condition as possible.

To simplify the cap type classification, a binary type was recorded: “old style” versus “new style,” with “new style” being a sanitary well cap with a watertight seal. The well cap condition was recorded as either damaged (including missing cap or bolts) or not damaged (Figure 4). Well caps were considered damaged if they were missing bolts, had visible damage or were entirely absent. During sampling other observations were evident and were recorded such as uncapped wells, wells that were connected to a pressure tank, wells that had pump houses and wells with pumps which were not observable due to small structures built around the wells. The number of these observations was 9, which was minimal. However, three uncapped wells were assigned as damaged but did not receive a style (old style or new style); rather they were recorded as NA’s.

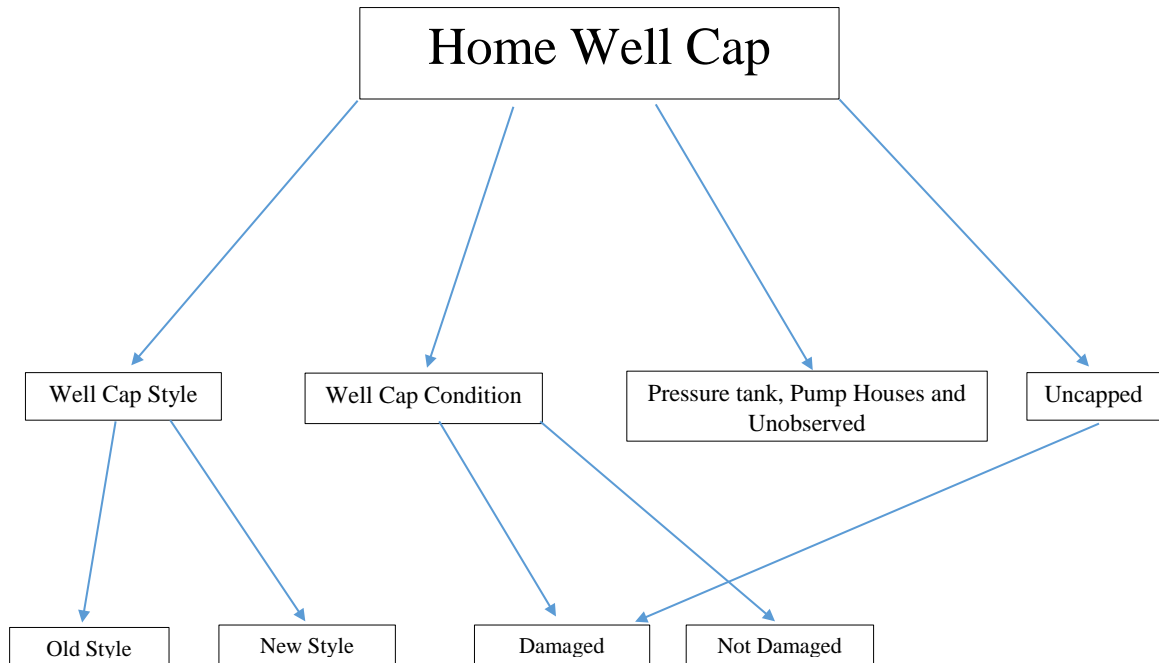


Figure 4. Flow chart of classification of well cap style (oldstyle and new style) and well cap condition (damaged and not damaged).

Characterization of Well and Aquifer Physical Characteristics

Physical characteristics that were recorded included the production formation of the well, land cover near the well, and distance from the well to the nearest location on the Little Big Horn River or a major tributary. These observations were derived using a variety of sources including well logs and existing geospatial data layers in a Geographic Information System (GIS).

Classifying Wells Completed in Alluvium

A classification system was developed to systematically identify home wells that were drawing water from the alluvial aquifer associated with the river. This classification was based on well logs that were obtained from the Indian Health Services (IHS) in Crow Agency. Well logs included well depth, screen depth, and a description of the production formation (rock, gravel, sand or clay), though some logs were incomplete.

In addition to the information from well logs, a report by Tuck (2003) was used to provide hydrogeologic information and water quality for 39 wells in the Little Big Horn River Valley.

A three-step classification approach was then used. In the first step, 74 wells were identified with logs that contained a description of the production formation (rock, gravel, sand or clay) and the well depth. For this group, a home well was assigned to the alluvium category if the production formation was described as having alluvium characteristics including gravel, silt or sand. Home wells were determined to be not

alluvium if the production formation descriptions indicated blue sand stone, shale, blue clay or brown shale.

The second classification step was identification of 10 wells with logs that lacked a description of the production formation, but well depth was known. From the wells with a known production formation description, a threshold of 40 feet was designated as the limiting depth for the alluvial aquifer. Only 2 wells deeper than 40 feet exhibited substrate characteristics typical of the river alluvium. Therefore, wells where only depth was known were characterized as alluvial if they were shallower than 40 ft, and not alluvial otherwise.

The final classification step included identification of 16 wells with logs that did not provide production formation or well depth. These wells were compared with nearby wells that have depth and formation characteristics reported in the literature (Tuck, 2003). A home well was classified as alluvium if a nearby well had a hydrogeologic type of alluvium and was otherwise considered not alluvium.

Estimation of Distance to River

Stream data were obtained from the National Hydrography Dataset to determine the distance to the nearest river or major tributary. A shapefile was created of all the streams and rivers on the Crow reservation. ArcMap was used to calculate the distance in meters from the home well locations to the closest shape representing the river or major tributary using the “near” tool.

Land Cover Classification

The National Land Cover Dataset is data on land cover at 30 m resolution. The vegetation class relevant to Crow reservation consist of pasture/hay, grassland, woody wetlands, shrubs and forest land cover. The land cover type at each home well location was extracted from the 2011 National Land Cover Dataset (Homer et al., 2012), using the Spatial Analyst extraction tool in ArcMap.

The majority land cover class was determined within four buffer distances for each home well location (200 m, 90 m, 60 m and 30 m). These four buffer distances were selected to investigate the potential significance to coliform contamination, because no prior information was available to determine the best buffer size for this analysis. The four buffer distances were developed using the buffer tool that is part of the proximity toolset and analysis toolbox in ArcMap. The zonal statistics tool was then used to determine the majority land cover class within each of the four buffer distances around each home well location.

From the detailed land cover classifications, the majority land cover was simplified into a binary agricultural v. non-agricultural cover. The agricultural cover class consisted of pasture/hay or cultivated crops and the non-agricultural cover class consisted of all other classes.

Logistic Regression Models

The logistic regression models were evaluated based on the significance of predictor variables at the $\alpha = 0.05$ level and the ability to interpret the models. The response variable for all logistic regression models was a binary measure of contaminated

vs. not contaminated wells based on the Most Probable Number (MPN) of fecal indicator coliform bacteria. Three subsamples were taken at each of the home wells and analyzed for MPN. A well was classified as contaminated when any of the subsamples had an MPN greater than 1 and otherwise classified as not contaminated.

Logistic regression models were developed through consultation with the Statistical Consulting and Research Services (SCRS) at Montana State University to address the four predictions. All models included an intercept coefficient (β_0) and linear coefficients (β_1 through β_n) that each quantified the influence of an associated predictor variable on the log-odds (or logit probability) of well contamination. Coefficients were considered independently for each model (i.e. the β_0 coefficient for the first model was independent of the β_0 coefficient for the second model). Values of these coefficients were numerically optimized to maximize the likelihood of the model fit to data, assuming that observations of contamination were independent and followed a Bernoulli distribution as follows:

$$y_i \sim \text{Binomial}(1, \pi_i)$$

where y_i is the binary response variable for contamination of well i :

$$y_i = \begin{cases} 0 & i^{th} \text{ well is classified as not contaminated} \\ 1 & i^{th} \text{ well is classified as contaminated} \end{cases}$$

and π_i is the modeled probability that a well is contaminated. Predictor variables were considered to have significant effect on the probability of well contamination when the 95% confidence intervals for the associated β coefficients did not include zero (or the 95% confidence intervals for e^β did not include unity).

To facilitate derivation of a model, the first prediction was rephrased as a pair of empirical questions.

- 1 A) How are the odds of coliform contamination related to well depth, after accounting for distance to the nearest river and whether the well was completed in alluvium?

- B) How are the odds of coliform contamination related to distance to the nearest river, after accounting for well depth and whether the well was completed in alluvium?

Based on these questions the following logistic regression model was derived:

$$\text{logit}(\pi_i) = \beta_0 + \beta_1 WD_i + \beta_2 DR_i + \beta_3 I_{alv,i} + \beta_4 DR_i * I_{alv,i}$$

- WD_i is the depth of the i^{th} well in feet.
- DR_i is the distance to the nearest river of the i^{th} well in feet.
- $I_{alv,i}$ is a binomial variable indicating well substrate:

$$I_{alv,i} = \begin{cases} 0 & i^{th} \text{ well is not completed in alluvium} \\ 1 & i^{th} \text{ well is completed in alluvium} \end{cases}$$

For a well not in alluvium, the model simplifies to:

$$\text{logit}(\pi_i) = \beta_0 + \beta_1 WD_i + \beta_2 DR_i$$

For a well in alluvium, the model simplifies to:

$$\text{logit}(\pi_i) = (\beta_0 + \beta_3) + \beta_1 WD_i + (\beta_2 + \beta_4) DR_i$$

Therefore, this model allows for independent intercepts and effects of DR for wells that are completed in alluvium vs. those that are not completed in alluvium.

The second prediction was similarly rephrased as an empirical question.

2. How are the odds of coliform contamination related to well age?

The corresponding model was then derived:

$$\text{logit}(\pi_i) = \beta_0 + \beta_1 WA_i$$

- WA_i is the age of the i^{th} well in years.

The third prediction was similarly rephrased as an empirical question.

3. How do the odds of coliform contamination compare between wells with undamaged new style caps and other well cap types and condition.

Based on these questions the following logistic regression model was derived:

$$\text{logit}(\pi_i) = \beta_0 + \beta_1 I_{DN_i} + \beta_2 I_{DO_i} + \beta_3 I_{PHPTNO_i} + \beta_4 I_{UC_i} + \beta_5 I_{UDO_i}$$

- I_{DN_i} is an indicator function of whether the i^{th} well has a damaged new style well cap ($I_{DN_i} = 1$ if the well has a damaged new style cap and $I_{DN_i} = 0$ if the well has a different well cap categorization).
- I_{DO_i} is an indicator function of whether the i^{th} well has a damaged oldstyle well cap ($I_{DO_i} = 1$ if the well has a damaged oldstyle cap and $I_{DO_i} = 0$ if the well has a different well cap categorization).
- I_{PHPTNO_i} is an indicator function of whether the i^{th} well has pump house, pressure tank, or unobserved well cap ($I_{PHPTNO_i} = 1$ if the well has pump house, pressure tank, or unobserved well cap and $I_{PHPTNO_i} = 0$ if the well has a different well cap categorization).
- I_{UC_i} is an indicator function of whether the i^{th} well is uncapped ($I_{UC_i} = 1$ if the well is uncapped and $I_{UC_i} = 0$ if the well has a different well cap categorization).

- I_{UDO_i} is an indicator function of whether the i^{th} well has a undamaged oldstyle well cap ($I_{UDO_i} = 1$ if the well has a undamaged oldstyle cap and $I_{UDO_i} = 0$ if the well has a different well cap categorization).

The fourth prediction was similarly rephrased as an empirical question.

4. How are the odds of coliform contamination related to whether the majority land cover type is agriculture within a 30 m, 60 m, 90 m, and 200 m radius of the well?

Based on these questions the following logistic regression model was derived:

$$\text{logit}(\pi_i) = \beta_0 + \beta_1 I_{NotAg_i}$$

- I_{NotAg_i} is an indicator function for the i^{th} well of whether the majority land cover type at a 30 meter radius is not agriculture ($I_{NotAg_i} = 1$ if the majority land cover type at a 30 meter radius is not agriculture and $I_{NotAg_i} = 0$ if the majority land cover type at a 30 meter radius is agriculture.)

A separate model was developed for each buffer distance, based on the radius used to derive I_{NotAg_i} values. All data were imported into the programming software Rstudio for data organization.

Results

For the 100 home well samples, the mean MPN was 81.5 per 100 mL. In terms of a binary classification, 58% of wells were classified as contaminated and 42 % of wells were classified as not contaminated.

Well depths averaged approximately 65 ft and ranged from 16 to 360 ft (Table 1).

Well age averaged 27 yr and ranged from 1 to 51 yrs (Table 1).

Table 1. Summary statistics of well protection factors and physical characteristic: well depth, well age and stream distance.

	Minimum	Maximum	Median	Mean	Std. Deviation
Well Depth (ft)	16	360	48	65	55.3
Well Age (yr)	1	51	29	27	12
Stream Distance (m)	7	1660.9	249.4	344.9	325.6

Eight wells had old style caps that were damaged and 45 wells had old style caps that were undamaged. A total of 8 wells had new style caps that were damaged and 27 wells had new style caps that were undamaged (Table 2).

Table 2. Categorical well protection factors.

Well Protection Factors	n
Undamaged New Style Cap	27
Damaged New Style Cap	8
Damaged Old Style Cap	8
Undamaged Old Style Cap	45
Pump House, Pressure Tank, Not Observed	9
Uncapped	3

The distance from the wells to the nearest stream or river averaged 344.9 m and ranged from 7 to 1660.9 m (Table 1).

A total of 53 wells were completed in alluvium and 47 wells were completed in other formations (Table 3).

Table 3. Categorical physical characteristics.

Physical Characteristics	n
Alluvium	53
Not Alluvium	47

The logistic regression models were evaluated based on the following assumptions: multicollinearity, no extreme influential values and predictor variables were linearly related to the log odds. Assumptions were evaluated by diagnostic plots and scatter plots that were considered acceptable.

For the 47 wells that were not located in the alluvial aquifer, 24 of them (51%) were contaminated (Table 5). The logistic regression models indicated that for wells that are not located in the alluvial aquifer, the odds of coliform contamination decrease by 0.33% for each additional meter of distance between home wells and the nearest stream or river (95% CI: -0.7%, -0.08%), (Table 4; Figure 5), (Table 6).

For the 53 wells that were located in the alluvial aquifer, 34 of them (64%) were contaminated (Table 5). The logistic regression models indicated that for wells that are located in the alluvial aquifer, the odds of coliform contamination increase by 0.08% for

every additional meter of distance between home wells and the nearest location on a stream or river (95% CI: 0.14%, 0.32%), (Table 4; Figure 5), (Table 6).

Table 4. Predictor variables, parameter estimates, exponentiated parameter estimates, exponentiated confidence intervals and P-value used for each interpretation.

Predictor variables	Parameter Estimate	Exponentiated Parameter Estimate	Exponentiated Confidence Interval	P-value
Model 1				
Well Depth (β_1)	0.0047	1.0047	(0.9919, 1.0175)	0.4529
Intercept (not in alluvium) (β_0)				
Distance to the Nearest River (not in alluvium) (β_2)	-0.0033	0.9967	(0.9930, 0.9992)	0.0325
Intercept (not in alluvium) ($\beta_0 + \beta_3$)				
Distance to the Nearest River (in alluvium) ($\beta_2 + \beta_4$)	0.0008	1.0008	(1.0007, 1.0084)	0.0311
Model 2				
Intercept (β_0)				
Well Age (β_1)	0.0419	1.0428	(1.0050, 1.0856)	0.0315
Model 3				
Intercept (β_0)				
Damage New Style (β_1)	1.0415	2.8335	(0.5720, 16.3534)	0.2106
Damage Oldstyle (β_2)	2.4765	11.8995	(1.7595, 240.0228)	0.0300
Pump house				
Pressure Tank Unobserved (β_3)	0.7538	2.1251	(0.4599, 10.4559)	0.3340
Uncapped (β_4)	1.2238	3.4001	(0.2898, 78.8444)	0.3420
Undamaged Oldstyle (β_5)	1.1253	3.0811	(1.1633, 8.5529)	0.0261
Model 4a				
Intercept (β_0)				
30 meter radius (β_1)	0.0556	1.0572	(0.5364, 2.0532)	0.870

Model 4b				
Intercept (β_0)				
60 meter radius (β_1)	-0.2376	0.7885	(0.3186, 1.8925)	0.599
Model 4c				
Intercept (β_0)				
90 meter radius (β_1)	-0.1178	0.8889	(0.3660, 2.1105)	0.791
Model 4d				
Intercept (β_0)				
200 meter radius (β_1)	-0.5008	0.6060	(0.2325, 1.4982)	0.2878

Table 5. Number of contaminated, not contaminated and percent contaminated in alluvium and not in alluvium.

	Percent contaminated	Contaminated	Non-contaminated
Alluvium	64%	34	19
Not in Alluvium	51%	24	23

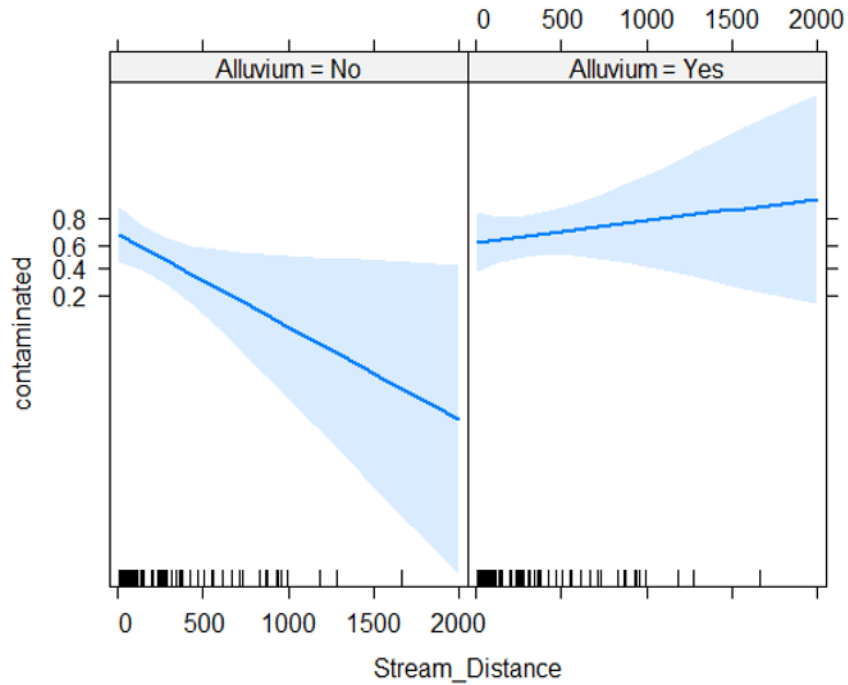


Figure 5. Logistic regression effects plot, probability of contamination (axis labeled “contaminated”) as a function of distance to the nearest stream (axis labeled “Stream_Distance in units of meters), for wells located in alluvium (right side) versus wells not located in alluvium (left side).

Table 6. Significant predictor variables and associated percent effect of parameter on odds of contamination and percent confidence intervals.

Significant predictor variables	Percent Effect of Parameter on Odds of Contamination	Percent Confidence Interval
Distance to the Nearest River (not in alluvium)	-0.33% m ⁻¹	(-0.7%, -0.08%)
Distance to the Nearest River (in alluvium)	0.08% m ⁻¹	(0.14%, 0.32%)
Well Age	4.28% yr ⁻¹	(0.50%, 8.65%)
Damage Oldstyle	1090%	(76%, 23902%)
Undamaged Oldstyle	208%	(16%, 755%)

The logistic regression model indicated that the probability of coliform contamination increases with well age (Table 4; Figure 6). Specifically, each year of increase in well age is associated with an estimated 4.28% increase in the odds of coliform contamination (95% CI: 0.50%, 8.65%) (Table 6).

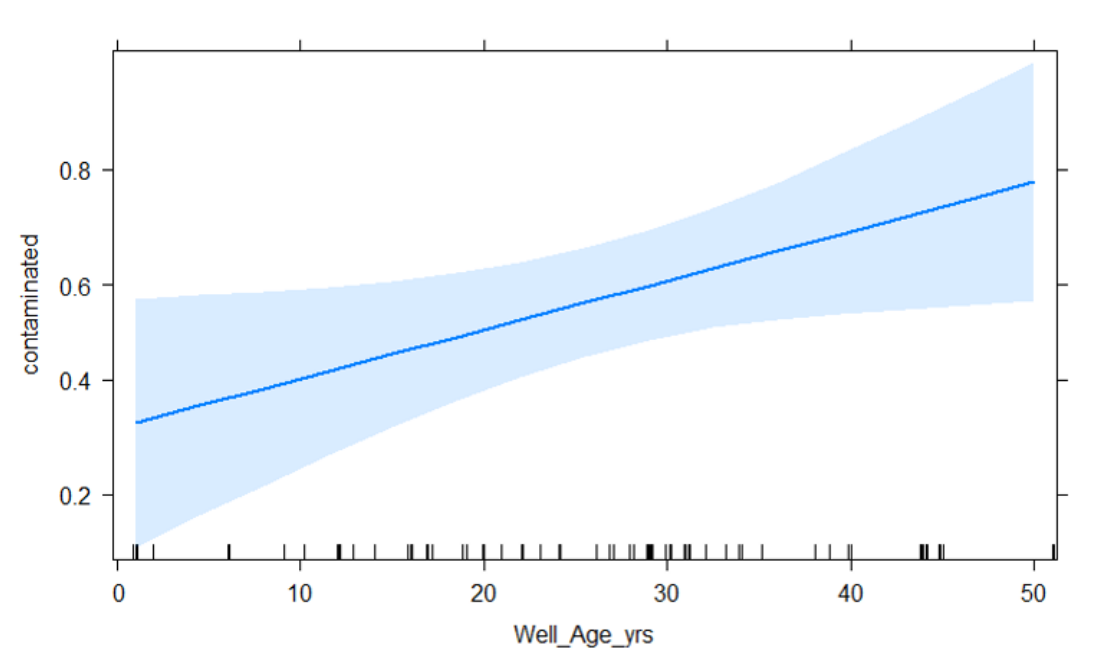


Figure 6. Effects plot of the model for probability of contamination (axis labeled “contaminated”) versus well age (axis labeled “Well_Age_yrs” in units of years).

Logistic regression models indicated that the probability of coliform contamination increases dramatically for wells with damaged old-style caps (Table 4; Figure 8). Similarly, the probability of coliform contamination also increases for wells with undamaged old-style caps. The estimated probability of contamination for wells with a damaged old-style cap is associated with 1090% (or eleven-fold) increase in the

odds of contamination (95% CI: 76%, 23902%) (Table 6). The estimated probability of contamination for wells with an undamaged old-style cap is associated with 208% (or two-fold) increase in the odds of contamination (95% CI: 16%, 755%) (Table 6).

Lastly, logistic regression indicated no significant relationships between coliform contamination and proximal agricultural land cover for any radius of area considered (Table 4).

Discussion

Our findings suggest that both well protection factors and physical characteristics are significantly related to coliform contamination in home wells on the Crow reservation. Significant relationships were especially evident between distance to the stream and coliform contamination in home wells, though perhaps in an unexpected direction. Of the 53 wells that were located in the alluvial aquifer, 34 were contaminated with coliform (64%), suggesting that wells located in alluvial aquifers were highly likely to be contaminated, and were more likely to be contaminated if further from a river or stream (Figure 5). In contrast, Gonzales (2008), found that wells located closer to a water source were more likely to be contaminated. Perhaps the difference in results indicates a difference in the source of contamination, i.e., the difference between alluvial aquifers that are contaminated by the river vs. alluvial aquifers that are contaminated by local land use.

For wells not located in alluvium, the odds of contamination decreased with distance from the river (Figure 5). These findings are consistent with Gonzales (2008), who found less interaction between wells and surface water at distances of 100 ft or

greater and more interaction with surface water at distance of 100 ft or less. However, our findings indicate that there may be some interaction between the river and wells located in the alluvial aquifer at further distances, possibly due to the ease of bacterial movement through alluvial aquifers (Entry and Farmer, 2001; West and Chilton, 1997). We speculate that wells in proximity to the river may experience more frequent water exchange and mixing with less contaminated river water, and therefore, less likelihood of contamination. Conversely, wells more distant from the river, may experience less water exchange and therefore, greater likelihood of sustaining contamination from sources associated with land use overlying the alluvial aquifer. Using the modeled probability of well contamination in alluvium, we developed an example of a risk map for a specific area on the Little Bighorn River based on the aquifer types and the distance to the river. The risk map illustrates the degree to which the model predicts an increase in probability of contamination with increased distance from the river for alluvial aquifer types (Figure 7).

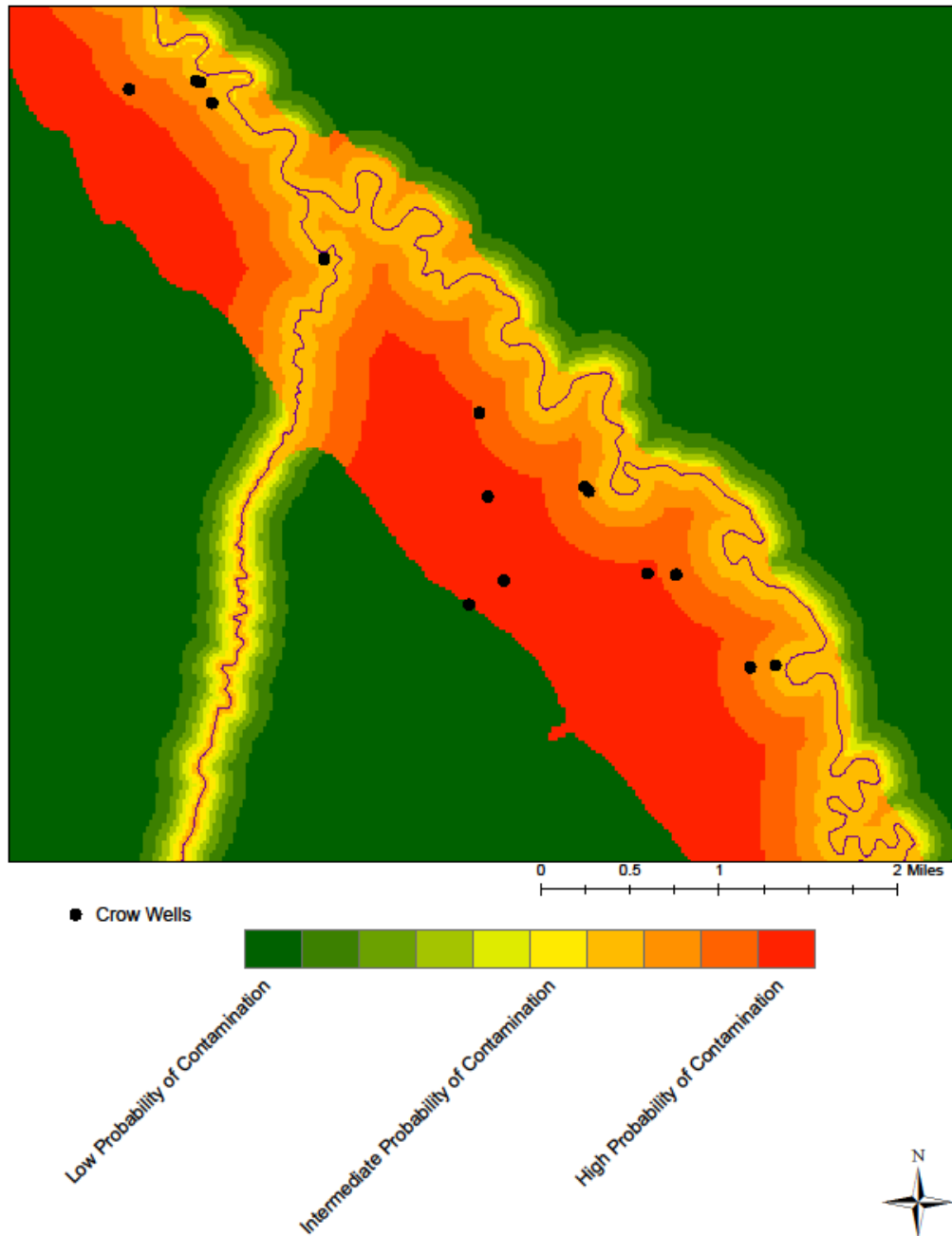


Figure 7. Risk map illustrating that for wells located in alluvium, risk increases as the distance from the river increases; and conversely, for wells not located in alluvium, the risk increases as the distance from the river decreases.

Older wells 25 years or older were more likely to be contaminated than younger wells (Figure 6). This finding is in contrast to that of Won et al. (2013) who found that

coliform contamination did not have a relationship with the well age. However, in yet another study the results indicated that on-site septic systems that were greater than 25 years had a high risk of failure (Oosting and Joy, 2013). Based on our results, however, we might conclude that homeowners examine the ages of their well and their septic system and consider replacement of older systems.

Old style well caps, whether damaged or undamaged were associated with wells more likely to have coliform contamination. Gonzales (2008), revealed that wellhead protection plays a role in coliform contamination, with higher risk for wellheads in poor condition. Our study findings suggest that identifying old style cap types throughout the Crow reservation should be continued to be monitored over time for remediation when the time is appropriate. Oldstyle caps are broadly distributed throughout the Little Bighorn Valley (Figure 8). While well protection appeared to be an issue, we could not directly tie contamination to local land use around wells. Our study findings did not reveal any significant relationships with agricultural cover radius of 30, 60, 90, 200 m. We speculate that this may be from a scale-disconnect between the classification of NLCD data and the true vegetation around the well perimeter.

Given that these data are observational, the results cannot be used as causal evidence that wells being in alluvium, being older, having an old style cap (damaged or undamaged) or being further from the river in alluvium directly causes home wells to be contaminated. Confounding variables that can influence the results cannot be ruled out.

For example, we did not measure distance of septic systems from wells or locations of septic systems relative to the gradient of the landscape or wells, and more accurate means of recording presence of livestock on the property were not included in the analysis. Furthermore, since the 100 wells were not sampled at random from the population of all wells on the Crow reservation, inference to the larger population of wells on the Crow reservation is not justified. Subsequently, the evidence cannot be used to draw direct statistical inference on cause and effect. However, the results allow further hypothesis generation regarding the potential sources of groundwater contamination on the Crow reservation, and interpretation of results can still benefit home owners as a tool to identify older wells located in alluvium, with old style caps and hence by association are more likely to have coliform contamination.

Conclusion

Native communities have challenges in improving drinking water quality in rural areas with private wells. One challenge is there are no regulations regarding bacterial contamination of wells owned by rural homeowners, urging homeowners to adopt the regulation of having no bacterial contamination in their wells (USEPA, 2009). There are acute health issues relating to having bacterial contamination, including diarrhea, cramps and vomiting (USEPA, 2009). Health issues are still of concern to homeowners that do not know to test their wells, and this lack of testing is attributable to insufficient funding, the inability to read and understand the consequences of the results, or the lack of perception of a potential problem because the taste and smell of the water are satisfactory (Eggers et al., 2018). A major challenge for native communities is the funding to upgrade

well structures and septic systems to mitigate water quality issues (Doyle et al., 2018). Another major challenge is that there are no data to support these health and water quality issues when attempting to find funding in grant proposals (Doyle et al., 2018). This underscores the need for research conducted in native communities to produce data usable for research grant proposals (Doyle et al., 2018; Hamner et al., 2014; Richards et al., 2018). Research studies in tribal communities create awareness of these issues generating an effort to find short term and long term solutions for native communities (Doyle et al., 2018).

This study found that observational data and physical characteristics data and well logs provided the analytical basis for modeling well age, well cap type and condition, production formation (alluvium, not alluvium) and distance to river, as they relate to the probability of coliform contamination. Although, the findings cannot be used for causal evidence, the results could guide mitigation efforts for homeowners with private wells on the Crow reservation. Identifying wells with different aquifer types was difficult due to insufficient data provided by well logs, therefore a binary classification system was developed to classify aquifer type. Also, complete curation of well logs by drill technicians would be instrumental in having that type of data available. The logistic regression models detected significant relationships between coliform contamination and aquifer type, distance to the river, well age and cap type. Future work on evaluating water quality in private wells might consider other variables to include in modelling, such as identifying locations of on-site septic systems and more complex bacterial analyses to identify if the contamination is from human and/or animal feces. This would provide a

more accurate indication of factors contaminating home wells and the ability to identify the source (s). In turn, it will help governing bodies with a more precise solution to implement for well owners with poor drinking water quality.

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