EVALUATING MICROBIAL RISKS IN PRIVATE WELLS AND RECREATIONAL WATERS

A Dissertation

by

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ABSTRACT

Microbial contamination of water systems continues to be a significant public health concern. Evaluating human health risks associated with these contaminants and how communities perceive risks are imperative for protecting human health. This study estimated human health risks associated with exposure to contaminated well water after Hurricane Harvey flooding and at public beaches contaminated by human and non-human fecal sources. Well owner perceptions of well water safety and well stewardship practices three years after flooding were also evaluated.

Concentrations of the fecal indicator bacterium, *Escherichia coli,* and the opportunistic pathogen, *Legionella pneumophila* (*L. pneumophila*)*,* in well water after Hurricane Harvey were incorporated into a quantitative microbial risk assessment (QMRA) to estimate the risk of infection for exposure scenarios involving either ingestion or inhalation. Derived reference pathogen doses indicated that norovirus and *Cryptosporidium* posed the greatest health risk for gastrointestinal infections, as the estimated median infection risk exceeded the U.S. Environmental Protection Agency (U.S. EPA) modified daily risk threshold of 1×10^{-6}. The human health risks associated with exposure to *L. pneumophila* also exceeded U.S. EPA risk thresholds. Private well owners who participated in the survey, regardless of education, income, or county of residence, generally perceived their well water to be safe, while well stewardship practices (well water testing and well disinfection) were not routinely completed. Lastly, QMRA was utilized to assess health risks at two recreational beaches impacted by human and non-human fecal sources. Concentrations of the microbial source tracking markers-human (HF183), dog (DogBact) and gull (Gull2)-were detected at varying concentrations, yet health risk estimates at both beaches did not exceed the U.S. EPA risk of illness threshold of 0.036.

A microbial risk assessment for Texas well owners following exposure to flood-impacted wells has not been previously conducted. Evaluating well owner perceptions and well stewardship practices three years after flooding in context with estimated health risks is instrumental for risk mitigation and communication. Similarly, conducting a site-specific risk assessment characterizing human health risks at recreational beaches impacted by both human and non-human fecal sources is a targeted approach to identify pollution mitigation measures that are appropriate and effective for beach management.

DEDICATION

I dedicate this work to my late father, Dr. Andrew Gitter. Your love for the outdoors and your career in medicine inspired me to pursue my research passion in environmental health.

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NOMENCLATURE

DNA	deoxyribonucleic acid
E. coli	*Escherichia coli*
FIB	fecal indicator bacteria
GI	gastrointestinal
L. pneumophila	*Legionella pneumophila*
mL	milliliter
mm	millimeter
MST	microbial source tracking
NOAA	National Oceanic and Atmospheric Association
OP	opportunistic pathogen
qPCR	quantitative polymerase chain reaction
RBT	risk-based threshold
SDWA	Safe Drinking Water Act
TWON	Texas Well Owner Network
U.S. EPA	United States Environmental Protection Agency

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1. INTRODUCTION

1.1. **Problem statement**

Exposure to microbial contaminants in drinking and recreational waters continues to be a significant public health concern. Detection, disinfection, and regulatory standards have assisted in protecting human health from both fecal and opportunistic pathogens, but outbreaks and pathogenic infections and illnesses still occur (1,2). Microbial risk assessment and surveys can be instrumental in identifying behaviors that may influence health risks and identifying exposure pathways of greatest health concern.

Approximately 13 million American households rely on private wells to supply their daily drinking water, however, these wells are exempt from Safe Drinking Water Act (SDWA) regulations (3,4). A variety of different contaminants have been studied in well water, including nitrates, fertilizers, organic wastes, and heavy metals, with contamination most commonly occurring through surface water entry and poor construction and maintenance of the well system (5). However, the human health risks associated with well contamination after a natural disaster event, especially for microbial contaminants, remains poorly characterized (6,7). Hurricane Harvey flooding impacted nearly 526,000 well users in Texas (7). Within the United States, groundwater is presumed to be relatively safe, but pollutants from naturally occurring and human sources still contaminate private wells, often with well owners unaware of such contamination.

Individuals managing or relying on private wells are responsible for ensuring the safety and quality of their own well water; however, after a flood event, well owners may not be aware of the specific water treatment practices and preventive measures, including routine well maintenance, disinfection, and testing, that should be implemented (8,9). Increases in the frequency and magnitude of natural disaster events, specifically flooding, emphasizes the importance of well users to implement measures to ensure the safety and integrity of their wells and well water. Understanding well owner knowledge gaps and risk perceptions regarding their well water use and well maintenance is critical for developing effective communication and training efforts to mitigate health risks. Characterizing health risks associated with flooding and private wells is only one component of addressing the public health issue, which also requires identifying the concerns, perceptions, and practices that well owners currently have regarding their wells.

Similar to the practices implemented to protect drinking water sources, recreational water quality management strives to manage fecal pollution in waterbodies to mitigate the human health risks for a variety of different ailments, including gastrointestinal (GI) illnesses. Advancements in water quality management to evaluate health risks based upon specific fecal pollution sources, as described by using alternative indicators of microbial source tracking (MST) and molecular markers, is informative for site-specific water quality evaluations and human health risk assessments (10). The 2012 Recreational Water Quality Criteria indicated that future water quality management could be based upon specific levels of human health risk instead of traditional detection of fecal indicator bacteria (FIB) in water bodies (11). While no specific threshold exists for molecular marker concentrations in recreational waters, integrating risk assessment with MST data to assess the potential for these thresholds, is needed. Future water quality management that is targeted at the site-specific level (as indicated by molecular marker concentrations for specific fecal sources) can greatly assist with identifying management practices that not only target the fecal sources of greatest human health concern but also maximizes the cost-effectiveness of management implementation.

Identifying and quantifying microbial risks in well water used for drinking and recreational waters is imperative for protecting human health. Evaluating these health risks, but also identifying how those risks are perceived by users is necessary for effective water management.

1.1.1. **Hurricane Harvey and well water flooding**

Hurricane Harvey caused unprecedented flooding, resulting in over 60 inches of rain in southeastern Texas. The impacts of floodwaters from a hurricane driven event can be devastating, resulting in hazardous conditions that result in infrastructure damage, but also adversely impacts the environment, society, and public health (12). The linkage between rainfall events, enteric disease outbreaks and surface water flooding are relatively well documented, but how those factors affect private wells and potential human health risks remains limited (12,13). While microbial contaminants have been sampled in floodwater and wells post-flood in previous studies, the potential risks for human health have not been estimated. Hurricanes and many other natural disaster events have destroyed communities throughout the United States, further strengthening the need for risk-based research to improve response measures and future planning (12). Understanding environmental conditions and their influence on water quality is a multifaceted issue, especially in the context of flood events. An increase in acreage used for urban and agricultural uses influences the types and concentrations of microbial contaminants in the environment, therefore potentially affecting human health. While several environmental health concerns may exist from flood events, understanding the impacts on drinking water sources, especially for wells, is critical, as well as essential for improving public health responses following natural disasters.

Emergency response planning for contaminated drinking water typically focuses on municipal drinking water systems, with little guidance for contaminated private wells (14). Following a flood event, the United States Environmental Protection Agency (U.S. EPA) advises that different steps should be taken to protect the wellhead and its components. Such steps include well and pump inspection, emergency disinfection of flooded wells, and sampling and testing well water (15). All steps are to be completed by the well owner or by a hired well or pump contractor. The risks of not knowing if a wellhead has been flooded, if the well water has been contaminated, or if the well water was not properly disinfected (when a well-owner completes it on their own) can pose severe health risks for those drinking and using the water for daily activities.

A few prior reports of heavy precipitation influencing groundwater and consequently causing human illnesses do exist. Nearly 2,300 cases of gastroenteritis, which included 65 hospitalizations and seven deaths, occurred after a groundwater supply in Walkerton, Ontario, Canada was contaminated with *E. coli* O157:H7, following a heavy rainfall (16). A statistically significant relationship was identified between years with flooding (including 2005 and 2013) and *E. coli* contamination in private drinking water wells in Calgary, Alberta, Canada (13). High levels of verotoxigenic *E. coli* were documented in private wells in the Republic of Ireland during the summer of 2008, following flooding from summer rains (17). Lastly, a 2008 review of waterborne diseases in the United States identified 19.5 million illnesses to occur annually in the US. Within the 12-year study period, 76% of the 183 documented outbreaks and 33% of estimated waterborne illnesses were estimated to be from groundwater drinking systems (18,19).

Contaminated drinking water remains a significant concern for private well owners in rural areas, especially with the risks associated with surface water flooding, groundwater contamination of enteric pathogens, and GI illnesses (12). Microbial pollutants can reach private drinking water systems via a variety of pathways, most commonly from the entry of surface water, often carrying pollutants, directly into the well or through the outside well casing with damage resulting from poor maintenance or construction. Often heavy rainfall and flooding can submerge wellheads, enabling surface water to enter shallow, older or improperly capped wells or water and contaminants to move through the soil profile, infiltrating groundwater sources (20). Microbiological well contamination may also result from the improper land application and management of manure, leaking septic tanks, failing water treatment systems, lack of well sanitation, and poor maintenance (18). Guidance by the U.S. EPA primarily includes information on the importance of testing and appropriate technologies that can help treat and remove pollutants (15). Best management practices to ensure safe drinking water for private well owners include testing well water and comparing results with the federal drinking water standards. The well owner bears the financial responsibility for this testing and well maintenance, potentially creating another limitation for safe drinking water and increasing the risk of exposure to contaminated water.

1.1.2. Microbial source tracking in tropical waters

The primary objective of recreational water quality management is protecting human health. Historically, the U.S. EPA has provided recommendations for FIB concentrations in recreational waters, which are required to be adopted by states to be implemented as protective water quality standards for human health (11). Epidemiological studies that were first utilized to determine that increasing FIB concentrations consequently resulted in an increased occurrence of GI illnesses for swimmers, were primarily focused on health risks associated with waters impacted by municipally treated wastewater effluent (21,22). However, water bodies can be affected by a wide array of fecal pollutant sources that can include not only human, but wildlife and livestock. Recently, it has been determined that human health risks likely vary depending on the fecal contaminant source (10,23,24).

MST has become a common water quality management tool to identify specific fecal sources polluting water bodies of concern. While previous MST methods have included comparing microbial DNA fingerprints between environmental samples and reference libraries, advances in methodologies have transitioned to quantitative polymerase chain reaction (qPCR) MST analyses (25–27). Molecular assays in MST analyses target specific bacterial genes that are unique to specific hosts, enabling fecal contaminants in a water body to be identified at the source-specific level. Many MST markers target *Bacteroidales*, specifically the genus *Bacteroides*, since these bacteria serve as an important indicator of recent fecal contamination, are often host-species specific, and represent a substantial portion of the present bacteria in the mammalian intestinal system (27). HF183 has become the most predominantly used human MST marker and is considered highly sensitive marker for human sewage (28). Markers also exist for a variety of animals hosts, including but not limited to, gulls, dogs, ruminants, poultry, and porcine sources (28,29).

Monitoring water quality for traditional FIB, such as *E. coli* or enterococci, is useful, but falls short of providing targeted source specific information of pollutant sources. Previous work that utilized MST marker data for water quality management, in conjunction with traditional FIB measurements, resulted in best management practices that included installing dog waste stations at a national recreation area in Georgia to implementing gull abatement practices at a public California beach (30,31). Relationships between MST markers and pathogens remains limited, emphasizing the need for further investigation, yet correlations have been identified for human and non-human fecal sources (32). Evaluating water quality at the source-specific level, though, has greatly advanced the array of management measures that can be implemented and increased the cost-effectiveness of such measures.

The integration of MST marker concentrations for water quality management can extend beyond informing only best management plan implementation, but also for evaluating fecal source-specific human health risks. Recreational waters are often impacted by a variety of both human and non-human fecal sources, emphasizing the utility of MST to guide effective and appropriate water quality and public health decision-making. Prior risk assessments have identified that health risks do vary, depending on whether the fecal source is of human origin (secondary wastewater effluent or raw sewage) or non-human (e.g., wildlife or livestock) (10,23,24,33–35). The utility of MST, while having its limitations, provides an opportunity to evaluate recreational water quality management beyond that of identifying impairments based solely on traditional FIB recreational water quality standards.

1.1.3. **Quantitative microbial risk assessment**

The Quantitative Microbial Risk Assessment (QMRA) framework utilizes four different phases, hazard identification, exposure assessment, dose-response assessment, and risk characterization, to estimate the potential human health risks following exposure to a microbiological contaminant. More specifically, QMRA derives a risk estimate for developing an infection and when information is available, an illness, from a pathogen based upon a specific exposure scenario and dose-response model. QMRA is commonly used in drinking and recreational water studies. Water companies in the Netherlands are required to apply the approach to estimate the infection risks in their drinking water systems (36–38).

The hazard characterization of QMRA aims to identify the pathogen of interest in the specific risk assessment. Often, when only FIB or molecular marker data are available, reference pathogens will be used to develop potential pathogen dose estimates

(10,24,34,35,39,40). The exposure assessment develops the scenario and dose of a pathogen that an individual may encounter. An appropriate dose-response model must be selected that fits the pathogen of interest and exposure scenario (i.e., ingestion of the pathogen and not inhalation). Lastly, the risk characterization utilizes the dose calculated during the exposure assessment in the dose-response model to gather an estimated risk of infection. Often a percentage of infections that result in a specific illness for a pathogen is available and can be used to estimate the risk of illness for a disease.

1.1.3.1. Escherichia coli

The USEPA has identified nearly 500 waterborne pathogens that are a potential concern in drinking water sources yet sampling for all specific pathogens is nearly impossible (41). FIB are microorganisms that survive in the digestive systems of endotherms, therefore serving as an "indicator" of fecal pollution and potential pathogens when detected. Fecal contamination of drinking water is a significant concern for diarrheal diseases and other illnesses. Total coliforms and *E. coli* are used as the FIB for testing of fecal contamination in drinking water with a standard "non-detectable" concentration for a 100 milliliter (mL) sample. For private well owners, when sampling their drinking water, no *E. coli* should be detected, which is often indicated by a presence/absence test.

E. coli is a member of the thermotolerant coliform family and indigenous to the intestinal flora of warm-blooded animals and currently the best bacterial indicator for fecal contamination in drinking water (42). Only six strains of *E. coli* are pathogenic, and the majority of strains are not harmful. In tropical sand and water environments, *E.*

coli has been found to persist with no known source of fecal contamination, potentially questioning its utility as an indicator in specific scenarios (43). For private well owners, testing for *E. coli* or fecal coliforms is recommended practice to ensure the integrity of their drinking water. In QMRA, FIB data is often used to develop reference pathogen doses for specific exposure scenarios (23,24,33,35,44,45).

1.1.3.2. Molecular markers

FIB limitations (e.g., different environmental persistence than pathogens and ability to grow in the environment (46,47)), led to using MST to evaluate fecal sources in water bodies. Advances in MST to detect specific sources of fecal contamination utilizing host-associated fecal DNA markers provides significant opportunity to directly target pollutant sources of concern for water quality management. qPCR MST assays can provide a quantification of a specific fecal marker that can not only inform management practices, but be utilized in QMRA studies (10,34,35,40,48). Application of fecal markers to estimate associated pathogen doses is not new, given that previous studies have evaluated the contact recreation health risks in a QMRA for specific fecal sources using FIB (24,33). Limitations of using MST marker concentrations in QMRA does exist, given that molecular methods, such as qPCR, do not consider microbial viability and assumptions must be made regarding the marker gene and specific pathogens for each host (48). Specific marker thresholds do not exist either (although they have been proposed), but health risks, based upon U.S. EPA guidance, can be applied for risk-based assessments and comparisons.

1.1.3.3. Opportunistic pathogens

Opportunistic pathogens (OPs) are becoming an increasing source of waterborne disease outbreaks in the U.S. with a greater health burden than waterborne enteric pathogens (49,50). Disinfection practices have reduced the health risks of diarrheal diseases, shifting awareness to an increase in OP related illnesses. These pathogens are more likely to cause illnesses in immunocompromised individuals, children, or the elderly than in healthy adults (51). OPs are not easily identified by the presence of FIB, since they naturally grow in environmental waters and can proliferate in biofilms, such as in plumbing and distribution systems. Persistence in drinking water distribution and premise plumbing most likely occurs due to the disinfection resistance, biofilm formation, ability to grow at low oxygen and carbon levels, and survival and growth in phagocytic free-living amoebae (52). *Legionella* cases tend to be the greatest number of documented OP cases per year. From 2000-2009, the incidence of infections from *Legionella* spp. was reported to have increased from 0.39 cases per 100,000 individuals to 1.15, a 200% increase (53). While over 50 species of *Legionella* exist, many of which are human pathogens, *Legionella pneumophila* (*L. pneumophila*) is the most common species and is known to cause Legionnaire’s Disease, a severe infection that includes pneumonia, as well as Pontiac Fever, a milder illness (54–56).

1.1.4. **Well Water Protection and Risk Mitigation**

Safe and secure drinking water is essential for public health, but for the nearly 43 million Americans who rely on private sources of drinking water (including wells, springs, and cisterns) proper technical training and education of well maintenance and operations may not always be provided or available (4,57). Often, private well owners in rural communities will consider their wells to provide better quality water than their municipal counterparts (58,59). However, the widespread prevalence of various pollutants measured in drinking water wells indicate that the potential human health effects could be significant (60). Informing, educating, and training private well owners regarding the significance of well maintenance, and potential sources of contamination and preventive measures can assist in mitigating potential health risks.

Only sixteen states and few localities have established regulations for well construction and testing for specific contaminants, including nitrates and coliform bacteria (61–63). Several states have programs and resources to educate and assist private well owners, such as the Texas Well Owner Network (TWON). In Texas, TWON was established in 2010 with state and federal funding to educate landowners about well water quality testing, management, and protection of private well systems (64). Information delivered through this program aims to mitigate the transport of contaminants to surface water and to underlying aquifers as well protect the health of well owners and others dependent on private water wells. Educational materials and trainings are delivered to private landowners with wells with the goal of protecting water quality and human health. However, in Texas, with nearly one million private drinking water wells in the State, reaching all well owners is challenging (64).

1.2. **Research approach**

The research objectives aimed to improve understanding of microbial risks in private drinking water and public recreational waters, as well as evaluate well owner perceptions regarding well water safety. The objectives evaluated included:

1. To characterize human health risks associated with microbially contaminated well water after Hurricane Harvey,
2. To evaluate well owner perceptions of well water safety and well stewardship three years after Hurricane Harvey,
3. To estimate human health risks associated with human and non-human sources of fecal pollution at a public beach used for primary contact recreation.

Human health risks associated with exposure to microbial contaminated well water is presented in Chapter II. Estimated risks for a GI and respiratory infection in a variety of exposure scenarios were compared to daily and annual U.S. EPA risk thresholds for drinking water.

An analysis of survey responses regarding well owner perceptions of the safety of their well water and their well stewardship practices are assessed in Chapter III. Statistical analyses were conducted, which included descriptive summary statistics, Pearson's chi-squared, and T-test/ANOVA analyses to determine if any associations existed between socio-demographic variables or perceptions regarding well water safety.

Chapter IV includes a risk assessment evaluating human health risks associated with human and non-human fecal sources at a public beach for both children and adults. Risk estimates were compared to the U.S. EPA risk threshold for contact recreation.

In Chapter V, findings from all three objectives and their relevance for evaluating microbial water quality and risk perceptions are discussed. Information gained from each of the studies indicate the utility of microbial risk assessments for characterizing health risks in water, both drinking and recreational, and the importance of evaluating well owner perceptions and practices to inform future outreach and public health management. Future needs for this type of research are also presented in the chapter.

2. ASSESSING HEALTH RISKS ASSOCIATED WITH CONTAMINATED WATER WELLS AFTER HURRICANE HARVEY

2.1. **Introduction**

The frequency of flooding in coastal areas has dramatically increased since the 1950s, especially along the United States Gulf Coast region due to climate change (65). An increase in the frequency and magnitude of floodwaters results in an increased risk for drinking water contamination and waterborne diseases (12). Public water utilities regulate their water sources under the requirements of the federal Safe Drinking Water Act (SDWA), striving to ensure the safety of their drinking water or notifying consumers of public health advisories. However, for private well owners, their exemption from the SDWA poses an increased risk for gastrointestinal and respiratory infections, especially during natural disaster events.

Over 60 inches (1524mm) of precipitation from Hurricane Harvey resulted in extensive flooding and damage to the City of Houston and coastal counties (66,67). According to the National Groundwater Association, approximately 215,906 wells were impacted by Hurricane Harvey floodwaters (68). Not only are private wells exempt from any regulations under the SDWA, but they also often lack continuous disinfection, therefore presenting a significant health risk for pathogen exposure during flooding. In response to a flood event, the U.S. EPA advises that steps should be taken to protect the wellhead and its components, including inspecting the well and pump, disinfecting and sampling well water; however, post-flood well water practices are not always implemented (9,15,69). The lack of proper well stewardship post-flood or lack of awareness that a well may have been contaminated can present severe health risks for those drinking and using the water for daily activities.

Traditionally, well contamination is evaluated via the detection of FIB (FIB), including total coliforms and/or *E. coli*. According to TWON programming with well water screening in Gulf Coast counties, baseline contamination rates include: 19.6% of samples testing positive for total coliforms and 3.9% samples testing positive for *E. coli*. After Hurricane Harvey, 29.6% of samples tested positive for total coliforms and 11.0% tested positive for *E. coli* (7). Assessing well water for fecal contamination post-flooding is imperative given that reports of rainfall and flooding affecting groundwater and resulting in gastrointestinal illnesses, while limited, do exist (13,16,17).

The presence and persistence of OPs in private wells is becoming an increasing area of interest due to their limited characterization in well water and well system plumbing. The OP, *Legionella,* has been found to occur naturally in the environment (rivers, streams, and groundwater) and likely presents a risk for private well owners, especially during flood events (6,71–73). Infections and illnesses from OPs are more likely to occur in children, the elderly, or in individuals who are immunocompromised or have chronic medical conditions, than in healthy adults (56,74). FIB, such as *E. coli*, are typically not found to be an appropriate indicator for OPs since *Legionella* are more resistant to chlorine, can be protected from disinfection by phagocytosis of amoebae, and can grow and persist in biofilm growth (75). *L. pneumophila* is the most common species of *Legionella* known to cause Legionnaire’s Disease, a severe infection that includes pneumonia, as well as Pontiac Fever, a milder illness (76,77). Recently, *Legionella* has become the leading cause of waterborne pathogen drinking water associated outbreaks (78).

Health risks regarding the presence of FIB and *Legionella* in private well water can be evaluated using the mathematical modeling framework of quantitative microbial risk assessment (QMRA). The framework includes four phases (hazard identification, exposure assessment, dose-response assessment, and risk characterization) to estimate the risk of infection following exposure to a specific microbiological contaminant (79). QMRA studies examining human health risks associated with private well water remains limited compared to studies assessing recreational and other drinking water sources.

Private well owners should maintain and ensure the quality of their drinking water, but under flood conditions, well owners may not be aware if flood waters have inundated their well heads or if groundwater has been contaminated with pathogens from floodwaters. The scope of the research was to determine the human health risks associated with exposure to contaminated well water for microbial contaminants and to further improve risk management solutions. Few well water quality-human health risk assessments have been conducted in the United States following a flood event. Researchers with Virginia Tech, Texas A&M AgriLife Extension Service, and Louisiana State University Health Sciences facilitated the collection and analysis of well water samples following flooding in the central and upper Gulf Coastal region of Texas for both FIB and *Legionella*. Microbial data retrieved from these sampling efforts was utilized in a comprehensive risk assessment to assess the human health risks associated with exposure to contaminated well water.

2.2. **Methods**

2.2.1. **Study area and sample collection**

Samples were gathered from private wells located in 18 counties along the Gulf Coast region of Texas that were impacted by Hurricane Harvey. Groundwater in this area is characterized as the Coastal Lowlands aquifer system which is consolidated to unconsolidated and composed of clay, silt, sand, and gravel, with local variation (79). Virginia Tech University, Louisiana State University, and the Texas Well Owner Network, which is part of the Texas A&M AgriLife Extension Service, and county extension agents, coordinated sampling kit distribution and pick-up for private well owners who chose to participate in the voluntary and free well water sampling and testing.

Sample collection for this study should be considered “citizen science”. Participants were provided instructions regarding how to properly collect their own well water samples for laboratory analysis. The specific round of the sampling campaign that is used in this risk assessment was conducted between September 11, 2017 and October 22, 2017 with n=630 samples. A description of the sampling campaign and procedures can be found in Pieper et al. (2021).

2.2.2. **Microbial analysis**

Samples were analyzed for *E. coli* and *L. pneumophila* (other indicators and pathogens were also enumerated and are described in Mapili (2019) and Pieper et al.

(2021)). *E. coli* was enumerated using the IDEXX Colilert 2000 method (Westbrook, MN), with a detection limit of 1.01 MPN/100 mL. Samples were initially analyzed by personnel at Virginia Tech University. Of those samples collected, most samples (n=403) were collected in 250 mL containers, while a subset of samples (n=61) were collected in 1000 mL containers (7). 120 mL of each sample was used to quantify for total coliforms and *E. coli*. Samples analyzed by Virginia Tech included laboratory blanks. Information regarding detailed analysis of microbial water quality data is further described in Pieper et al. (2021). The subset of samples collected in 1000 mL containers were for OP analysis. *Legionella pneumophila (mip* gene*)* gene copies (gc) were quantified via qPCR. Further details regarding sampling design and analysis, including DNA extraction and standards, are described in Mapili (2019). The limit of quantification for *L. pneumophila* was 10 gc/mL.

2.2.3. **QMRA methodology**

The hazard characterization of QMRA aims to identify the pathogen of interest in the specific risk assessment. Often when only FIB data are available, reference pathogens will be used to assess a potential dose (39,44,81). The exposure assessment evaluates the scenario and potential pathogen dose an individual may be exposed to and requires an appropriate dose-response model that fits the pathogen of interest and exposure scenario. Lastly, the risk characterization utilizes the dose calculated during the exposure assessment in the dose-response model to gather an estimated risk of infection.

2.2.3.1. Exposure Models

Using *E. coli* concentrations to estimate the potential health risks associated with exposure to specific reference pathogens in a water source requires assumptions regarding parameter values and exposure characteristics. The reference pathogens of concern for drinking water, and used in the risk scenario, include *Cryptosporidium*, *Giardia*, *Campylobacter jejuni*, norovirus, *Salmonella* spp. and *E. coli* O157:H7. Each of these reference pathogens are found in human sewage and are known to be pathogens of concern in recreational and drinking water sources (45,82). All reference pathogens can result in a gastrointestinal infection. Since *E. coli* concentrations were measured at indoor water sources, including the faucet in the kitchen, bathroom, or bathtub, no fate and transport of the FIB or reference pathogens were included in the assessment. Different exposure pathways of well water were evaluated, including ingestion from drinking, showering, bathing, brushing teeth, washing food and dishes, and toilet flushing (Figure 2.1). Differences in *E. coli* concentrations between filtered and unfiltered water were evaluated (analyses not included) and were determined to not be statistically different; therefore all *E. coli* measurements collected from water samples (from indoor sources that were either filtered or unfiltered) were included in the risk analysis. Since the kit instructions specified the water sample needed to be collected indoors, it was assumed that any sample with location of collection labeled “NA” was collected from an indoor water source and therefore included in the study.

L. pneumophila was directly enumerated from water samples collected from indoor water sources, and therefore no fate or transport of the pathogen is included in the risk assessment either. The *L. pneumophila* primers target the *mip* gene, which is present as a single gene copy in the genome, therefore it was assumed that the one gene copy was equivalent to one viable, infectious microorganism. Three scenarios were evaluated for *L. pneumophila* exposure which included inhalation of aerosols via showering, running a hot-water faucet, and toilet flushing. All exposure pathways have been identified to transmit low numbers of *Legionella* during routine use (83,84).

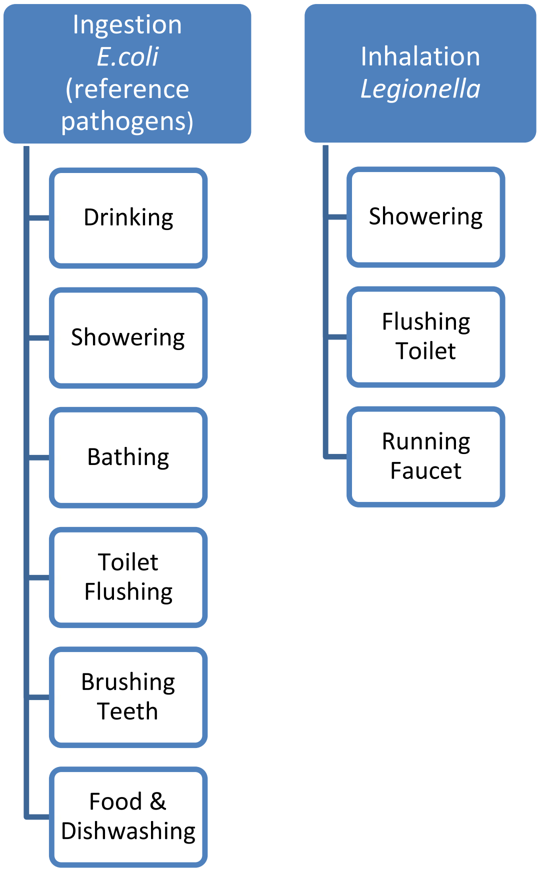


Figure 2.1. Exposure pathways for well water consumption

2.2.3.2. Ingestion and inhalation exposure models

A dose for each reference pathogen can be calculated using the measured *E. coli* concentrations (Equation 1). Concentrations of each reference pathogen in raw wastewater were collected from the literature (85–100). Due to the variable water ingestion rates for different age groups, exposure scenarios were calculated for four different age categories: infant to less than two years old; two years old to six years old; six years old to 16 years old and lastly, the adult category (over the age of 16 years) (101).The indirect ingestion exposure scenarios (showering, toilet flushing, brushing teeth, and food and dishwashing) were evaluated for adults while only bathing was considered for child-specific exposure.

To incorporate variability into the risk assessment, probabilistic distributions were utilized for the parameters as appropriate and if the information was available. The estimated dose for the ingestion exposure model is described in Equation 1 (81,102).

Eq. 1

$$Dose_{RP} = \frac{C_{E.coli}}{C_{E.\,coli\ in\,WW} \times 100} \times C_{RP\ in\,WW} \times V$$

Where RP refers to reference pathogen; $C_{E.coli}$ is the concentration *E. coli* as measured in well water samples (MPN/100mL); $C_{E.coli\ in\ WW}$ is the concentration of *E. coli* measured in raw wastewater (CFU/L); $C_{RP\ in\ WW}$ is the concentration of the specified reference pathogen in raw wastewater (number of organisms/L); and V is the volume of water ingested (L).

For the *Legionella* risk assessment, daily and annual risks of infection were estimated given the potential persistence of the OP in well water distribution systems. The inhalation dose was developed by first estimating the concentration of *L. pneumophila* in the air during each exposure scenario (Equation 2), followed by calculating the inhalation exposure dose (Equation 3) (103,104). An inhalation rate for light activity and a single daily exposure was assumed for showering or bathing (105). Assumptions regarding exposure durations, emission factors and exposure frequency for the toilet flushing and running faucet (sink) exposures are described in Table 2.1.

Eq. 2

$$C_{air} = C_{water} \times EF$$

where C_{air} is the concentration of *L. pneumophila* estimated in the air (gc/m^3); C_{water} is the concentration of LP measured in well water samples (gc/mL); EF is the emission factor (L/m^3). A conversion factor of 1000 is needed to convert ml to L.

Eq. 3

$$Dose_{LP} = C_{air} \times I \times ED \times FR$$

where $Dose_{LP}$ is the concentration of *L. pneumophila* inhaled (gc); C_{air} is the concentration of *L. pneumophila* estimated in the air (gc/m^3); I is the inhalation rate (m^3/min); ED is the exposure duration (min); FR is the fractional retention rate of aerosols in human alveoli.

Lastly, this QMRA only evaluates the individual risk of exposure in a static model and does not consider immunity or secondary transmission (106).

Table 2.1. Input parameters for Monte Carlo simulations of both ingestion and inhalation exposure scenarios

Parameters	Unit	Concentration	Source
Ingestion Exposure Model			
E. coli **concentration in well water**	log MPN/100 mL	-4.835, 3.824[a]	Environmental data
E. coli **concentration in raw wastewater**	log10 CFU/L	6.7, 8.0[b]	(107)
Norovirus concentration in raw wastewater	log10 copy/L	4.7,1.5[c]	(85)
Cryptosporidium **concentration in raw wastewater**	log10 oocysts/L	-0.52, 4.7[b]	(40,89–91,100)
Giardia **concentration in raw wastewater**	log10 cysts/L	0.51, 4.2[b]	(40,89,90)
Salmonella **spp. concentration in raw wastewater**	log10 CFU/L	0.5, 5[b]	(40,97,98)
E. coli **O157:H7 concentration in raw wastewater**	log10 CFU/L	-1, 3.3[b]	(40,95)
Campylobacter jejuni **concentration in raw wastewater**	log10 MPN/L	2.9, 4.6[b]	(40,96)
Volume of Water Ingested (L)			
	Infants <2	0.82[d,e]	(101)
	Children 2-<6	0.76[d,e]	
	Children 6-<16	1.3[d,e]	
	Adult	2.5[d,e]	
Indirect Ingestion (mL)	Showering	0.058,1.9[f,g]	(108)
	Bathing	0.81, 63[h,i]	(109)
	Brushing Teeth	1,5[f,j]	(110)
	Toilet Flushing	0.01, 0.3[f,k]	(111–113)
	Food and Dish Washing	(0.007,0.008,0.071)[l]	(114)

Table 2.1 Continued

Parameters	Unit	Concentration	Source
Inhalation Exposure Model			
***Legionella* concentration in well water**	gene copies/mL	(0,0.014,0.163)[m]	Environmental data
Inhalation rate, light activity (adult)	m^3/min	(0.013,0.017)[f]	(105)
Inhalation rate, light activity (child)	m^3/min	(0.014,0.016)[f]	
Fractional retention rate		0.5	(115–117)
Showering			
Exposure duration	min	15	(118)
Emission factor	liter/m^3	3.4 x 10^{-4}	(119,120)
Toilet Flushing			
Exposure frequency	flushes/day	5	(113)
Exposure duration	min/flush	(1,5)[f]	(121)
Emission factor	liter/m^3	1.3 x 10^{-6}	(122,123)
Sinks (running faucet)			
Exposure frequency	times/day	adult: (5,10.3)[f] child: (4.7-8.3)[f]	(124)
Exposure duration	seconds	7	(125)
Emission factor	liter/m^3	5.6 x 10^{-4}	(83,123)

[a]lognormal distribution (log mean, log standard deviation); [b] $\log_{10}$-uniform distribution (minimum, maximum); [c]$\log_{10}$-normal distribution (mean, standard deviation); [d]point-estimate (90th percentile); [e]l/day; [f] uniform distribution (minimum, maximum);[g]mL/day assuming one 10 minute shower; [h]gamma distribution (r, λ);[i] mL/day assuming one bath;[j] mL per event and assumed to occur twice a day; [k]assumed 5 flushes per day; [l]triangle distribution (minimum, likeliest, maximum; [m]Weibull distribution (location, scale, shape).

Following the calculation for the estimated dose of the pathogen, a dose-response equation is needed to calculate the risk of infection for each reference pathogen. The dose-response equations utilized are based upon feeding studies and outbreak data and include exponential, Beta-Poisson, and Fractional Poisson mathematical models. Feeding and outbreak data for *Salmonella*, *Campylobacter jejuni,* and *E. coli* O157:H7 have been fit to a Beta-Poisson dose-response model (79,126–128). An exponential model has been fit to data to estimate the dose-response relationships for *Cryptosporidium*, *Giardia*, and *Legionella* (129–132). Lastly, a Fractional Poisson model has been used to describe the probability of infection for norovirus (133). Table 2.2 summarizes the dose-response parameters for each pathogen.

Table 2.2. Dose-response models utilized in the QMRA

Pathogen	Probability of Infection	References
Salmonella spp.	1-(1+dose/2884)^-0.3126	(128,134)
Campylobacter jejuni	1-(1+(dose/7.59))^-0.145	(126)
***E. coli* O157:H7**	1-(1+(dose/48.8))^-0.248	(127)
Cryptosporidium	1-exp(-0.09*dose)	(131)
Giardia	1-exp(-0.01982*dose)	(129,130)
Norovirus	0.72*(1-exp(-dose/1))	(133,135)
Legionella	1-exp(-0.0599*dose)	(132)

A norovirus dose response model that assumed full particle disaggregation was used as a conservative approach to assessing infection risks (132,134,135). Untreated drinking water, which is representative of private wells, generally have lower norovirus concentrations than recreational waters. Certain models, including the Messner et al. dose response model (135), tend to yield higher probability of infection risks, but are frequently used in other risk assessments. The other dose-relationships presented have all been used in previous water quality related QMRA studies (24,33,34,92).

The probability of infection due to cumulative daily exposure to indirect routes of water ingestion (showering, bathing, brushing teeth, flushing the toilet, and washing food/dishes) was estimated using equation 4. The cumulative daily (equation 4) and annual (equation 5) exposure risks were estimated for inhalation of *L. pneumophila* aerosols during daily tasks (showering, flushing the toilet, and running the faucet). The cumulative risk of infection combines statistically independent exposures (24,136).

Eq. 4

$$P_{inf,daily} = 1 - \prod(1 - P_{inf,S})^{n}$$

where $P_{inf,daily}$ is the daily probability of a reference pathogen or *Legionella* infection per each exposure scenario (ingestion: showering, bathing, flushing toilet, brushing teeth and food and dishwashing; inhalation: showering, flushing toilet and running faucet); $P_{inf,S}$ is the calculated probability of a single exposure for each scenario; *n* is the daily exposure frequency.

Eq. 5

$$P_{inf,annual,LP} = 1 - \prod(1 - P_{inf,S})^{365}$$

where $P_{inf,annual,LP}$ is the annual risk of infection probability for *L. pneumophila*; $P_{inf,S}$ is the daily risk of infection for each exposure scenario.

Crystal Ball Pro® Software (Oracle Corp., Redwood Shores, CA, USA) was used to conduct the Monte Carlo simulations (10,000 simulations for each exposure parameter). For each simulation, the QMRA model used input parameters that are described by statistical distributions (when appropriate) to include inherent variability in the model (Table 2.1). Probability plots were developed for the interval censored *E. coli* concentrations using Minitab® software (Minitab LLC, State College, PA, USA). Utilizing maximum likelihood estimation (MLE), the dataset was fit to the Weibull, lognormal, exponential, loglogistic and normal distributions. Best fits for the dataset and the fitted distribution were based upon the Anderson-Darling (A-D) and Kolmogorov-Smirnov (K-S) tests.

The daily risks of infection were compared to the modified U.S. EPA threshold of 1 infection per 1,000,000 individuals and annual risks were compared to the annual U.S. EPA threshold of 1 infection per 10,000 individuals (136,137). These risk thresholds have been utilized to provide guidance for safe drinking water, and while the same drinking water standards are not required for private wells, these risk guidelines are informative for evaluating public health concerns (141). Different risk thresholds were utilized depending on the exposure scenario and pathogens. For exposure scenarios involving reference (fecal) pathogens, the daily risk of infection was compared to the daily risk threshold due to the limited duration of risk associated with floodwaters contaminating private wells. The risk of infection associated with exposure to *Legionella* was evaluated for both daily and annual risks due *Legionella* potentially persisting in premise plumbing, resulting in continuous exposure to the pathogen. Risk estimates for each exposure scenario are described in Figures 2.2 through 2.5 with brief summaries of the findings.

2.3. **Results**

The risk scenarios evaluated include: direct ingestion of drinking water, indirect ingestion of water via showering or bathing, brushing teeth, washing food and dishes, and flushing the toilet; and inhalation of aerosols while showering, flushing the toilet and running the faucet. The risk of infection corresponding to each pathogen was evaluated using the concentrations of *E. coli* and *L. pneumophila* measured in indoor water sources after any type of filtration or treatment had been used. For the drinking water exposure, a range of ages were evaluated; however, for the indirect ingestion exposure scenarios, ingestion values were used for adults, except for the bathing scenario which was assumed for a young child. For *L. pneumophila*, each exposure scenario was evaluated for both adults and children. The risks associated with each daily exposure were evaluated with the daily and annual U.S. EPA risk threshold.

2.3.1. **Scenario 1: drinking water**

The risk of infection for an array of bacterial, protozoan, and viral reference pathogens were assessed to identify which pathogen(s) may pose the greatest health risk for private well water. Human sewage was assumed to be the pollution source given the potential for floodwaters to damage septic systems and transport wastewater from nearby wastewater treatment facilities. Assuming the pollution source was of human origin also provided a conservative approach for this specific exposure scenario, given that fecal pollution from non-human sources have been identified to have a lower health risk for a GI infection and illness (10,24). Across all reference pathogens and age groups assessed, the median risk values for norovirus and *Cryptosporidium* (adult and child subgroups) exceeded the 1×10^{-6} risk of infection threshold (137) (Figure 2.2). Overall, norovirus appears to have the greatest median risk for infection, compared to the other bacterial and protozoan reference pathogens by exceeding the threshold 1-2 orders of magnitude (Table A-1). The only parameter that varied between age groups was the daily ingestion volume of water. Adults were assumed to ingest 2.5 L of water daily, which is nearly three times greater than the volume of water assumed to be ingested by infants under the age of 2. The ingestion volumes were protective assumptions that were applied in this risk assessment (90th percentile) (101). Both bacterial pathogens, *E. coli* O157:H7 and *Salmonella*, had the lowest median health risks. The findings indicate that specific enteric pathogens, such as viruses, may be of greater concern than other enteric pathogens in well water and should be considered an increased health risk during flood events involving septic and wastewater contamination.

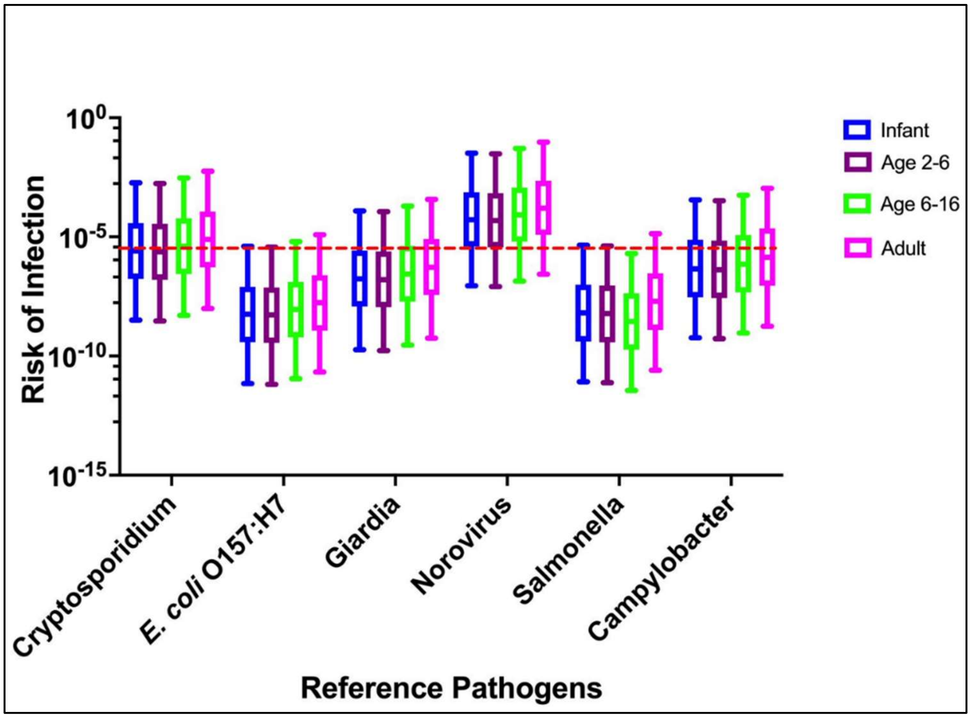


Figure 2.2. Daily risk of a GI infection for ingesting private well water assumed to be impacted by flooding. Box plots show median (centerline), 25th and 75th percentiles (edges of box), and 5% and 95% percentiles (whiskers). The red dashed line indicates the modified USEPA daily risk of infection standard of 1 x 10^{-6}.

2.3.2. **Scenario 2: indirect ingestion**

The same six reference pathogens were evaluated for indirect ingestion exposures, which included bathing (children only), showering (adults only), flushing the toilet, brushing teeth and food and dish washing (all considered only for adults). Daily infection risks for each reference pathogen and exposure pathway are depicted in Figure 2.3 and described in detail in Table A-2. The median daily infection risk of 1 $x10^{-6}$ was not exceeded in any of the scenarios, but the median risk of a GI infection from norovirus did meet the risk benchmark for bathing (1.78×10^{-6}) and food and dish washing (1.79×10^{-6}). The exposure scenarios that tended to have a greater risk of infection included bathing, showering and food and dish washing. Toilet flushing and brushing teeth were identified as the exposure pathways with the lowest risk. For *Giardia* and *Salmonella*, the 95th percentile risks were four orders of magnitude below the risk benchmark. The risks per exposure pathway were not consistent for each reference pathogen. For example, the risk of infection from brushing teeth exceeded the risk of infection for showering for *Cryptosporidium*, *Giardia*, and norovirus; however, the risk of infection from brushing teeth was lower than the risk from showering for *Campylobacter*, *E. coli* O157:H7, and *Salmonella*. Given that there are inconsistencies in risk among exposure pathways and that norovirus was determined to be the greatest pathogen of concern, certain pathways, including bathing, showering and food and dishwashing, might need to be avoided if there is a concern that floodwaters may have contaminated a well.

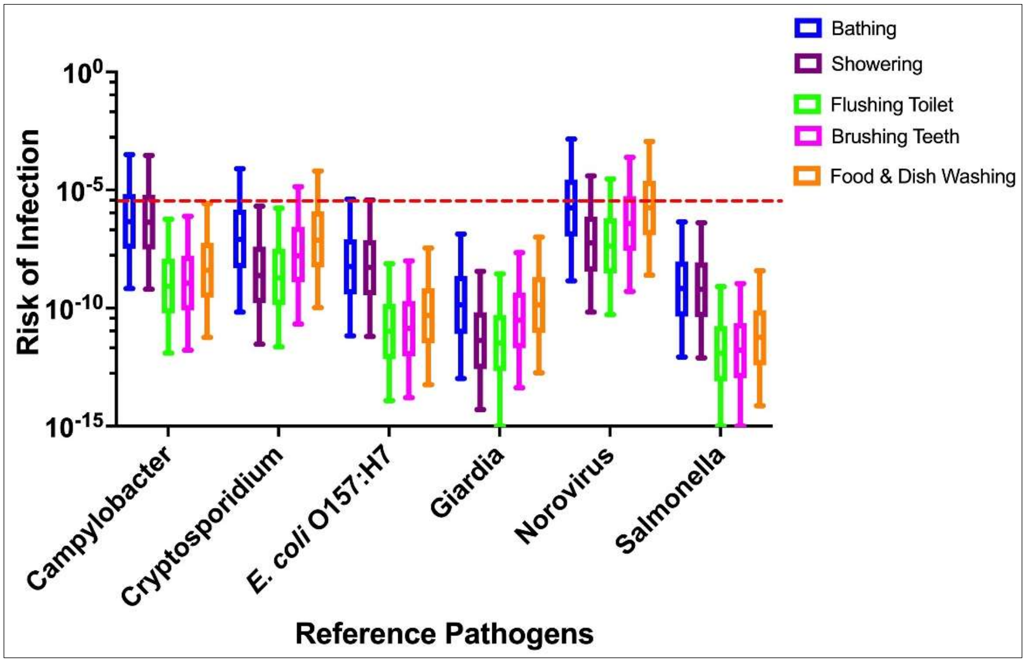


Figure 2.3. Daily risk for a GI infection for indirect exposure to well water assumed to be impacted by flooding. Exposure scenarios include bathing (children only), showering, flushing the toilet, brushing teeth, and food and dishwashing (all scenarios adult only). Box plots show median (centerline), 25th and 75th percentiles (edges of box), and 5% and 95% percentiles (whiskers). The red dashed line indicates the modified USEPA daily risk of infection standard of 1 x 10^{-6}.

2.3.3. **Opportunistic pathogen exposure**

Both daily and annual risks of a *Legionella* infection were evaluated for exposure via showering, toilet flushing and running a faucet in an enclosed area (Figure 2.4 and Table A-3). For both daily and annual median health risks, showering (adult: 2.4 x 10^{-6} (daily) and 8.45 x 10^{-4} (annual); child: 2.43 x 10^{-6} (daily) and 8.58 x 10^{-4} (annual)), posed the greatest health risk, exceeding the 1 x 10^{-6} daily and 1 x 10^{-4} annual risk thresholds for both adults and children. Running the faucet had a median health risk (adult: 3.10 x 10^{-7} (daily) and 1.10 x 10^{-4} (annual); child: 2.82 x 10^{-7} (daily) and 9.82 x 10^{-5} (annual)) that was greater than toilet flushing (adult: 1.19 x 10^{-8} (daily) and 4.34 x 10^{-6} (annual);

child: 1.18 x 10^{-8} (daily) and 4.28 x 10^{-6} (annual)), but both exposure scenarios did not exceed the daily and annual risk thresholds. While the shower exposure scenario and overall exposure risks (adult: 5.56 x 10^{-5} (daily) and 1.94 x 10^{-2} (annual); child: 5.27 x 10^{-5} (daily) and 1.83 x 10^{-2} (annual)) were elevated, it is important to note that this risk assessment was an overly protective approach of assessing the relative risks of different exposure scenarios for *Legionella*.

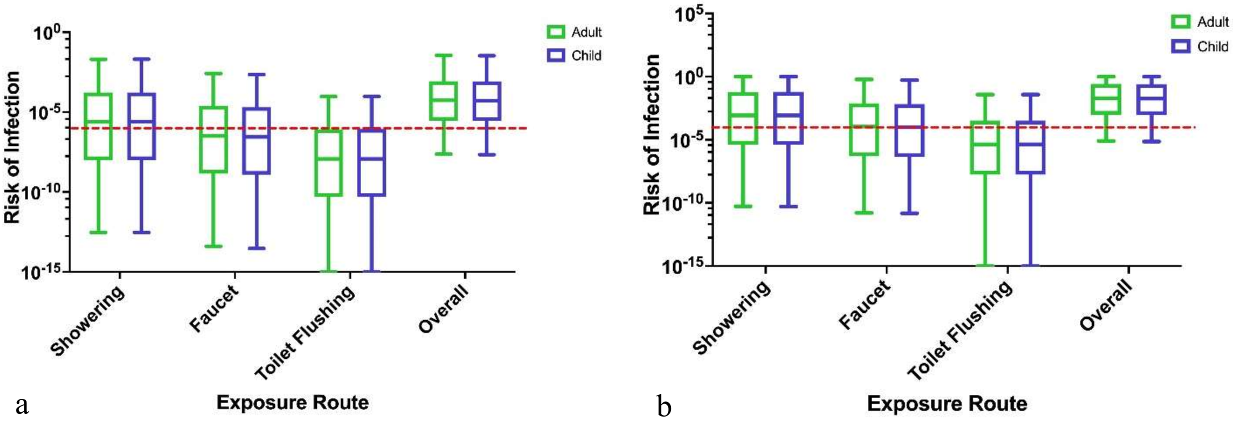


Figure 2.4. a) Daily risk of a *Legionella* infection through different exposure pathways, including showering, running the faucet in a sink, and toilet flushing. b) Annual risk of a *Legionella* infection through different exposure pathways, including showering, running the faucet in a sink, and toilet flushing. The green boxes indicate adult risks and the blue boxes indicate child risks. The overall risk from cumulative exposure of each pathway for both daily and annual exposure is also displayed. Box plots show median (centerline), 25th and 75th percentiles (edges of box), and 5% and 95% percentiles (whiskers). The red dashed line indicates the modified U.S. EPA daily risk of infection threshold of 1 x 10^{-6} in Figure a and the U.S. EPA annual risk of infection threshold of 1 x 10^{-4} in Figure b.

2.3.4. **Sensitivity analysis**

Sensitivity analyses were conducted on the risk of infection output for each model parameter in the following QMRA simulations: risk of infection from drinking water as represented by reference pathogens, risk of infection from indirect ingestion, and risk of infection from *Legionella*. The sensitivity analysis of all six different reference pathogens for drinking water and indirect ingestion indicated that the *E. coli* distribution in well water parameter contributed the greatest influence and variability on all risk of infection estimates. Other parameters that had influence on the risk of infection for indirect ingestion included the concentration of each reference pathogen in raw sewage and the rate of ingestion for each exposure scenario. Lastly, for the *Legionella* exposure scenarios, the *Legionella* concentration parameter had the greatest influence on daily and annual exposure risks. When evaluating the overall health risk for daily and annual exposures, the exposure durations were also found to influence the risk of infection estimates. Other parameters (as described in Table 2.1) were determined to not be significant contributors to variability in risk estimates. As identified by the sensitivity analysis, the concentration of pathogen is the greatest driver of health risk for the specific exposure scenarios presented in this study.

2.4. **Discussion**

Hurricane Harvey adversely impacted coastal communities that spanned across 41 counties in the Gulf Coast region of Texas, including nearly 526,000 private well users (7). This study identified elevated risks for GI infections for private well owners who may have experienced flooding and well water contamination from Hurricane Harvey floodwaters. While exposure to *Legionella* in private drinking water sources may pose a respiratory health risk as well, further evaluation is warranted, given the distribution of this OP in well water and private well systems is weakly characterized.

2.4.1. **Well water health risks for enteric and opportunistic pathogens**

While drinking water risks likely exist, especially for viral pathogens, well water may not be directly used for drinking during a flood disaster event. However, indirect exposure routes, such as showering, bathing, brushing teeth, washing dishes and food, and toilet flushing, could potentially be of concern. Norovirus, under all exposure scenarios, was the pathogen of greatest health risk. Besides that of drinking exposure (all health risks for the reference pathogen, norovirus, exceeded the daily risk benchmark of $1x10^{-6}$), bathing and washing dishes and produce nearly exceeded the daily risk benchmark as well (1.78×10^{-6} and 1.79×10^{-6}, respectively). The bacterial reference pathogen, *Campylobacter*, and the protozoa, *Cryptosporidium*, could also pose a risk if well water is used for drinking. The increased risk of infection from *Cryptosporidium* and norovirus parallels the estimates of Murphy et al. (2016) which identified *Cryptosporidium* and norovirus as the predominant pathogens likely causing illnesses attributable to private wells.

While preliminary findings indicated that risks for respiratory infections may exist for specific exposure routes, based upon the detected concentrations of *Legionella*, this risk analysis was completed in a conservative manner. Daily and annual risk benchmarks were assessed given that *Legionella* can often persist in premise plumbing and well systems for a prolonged period of time and naturally occurs in groundwater (73). Private well systems lack continuous disinfection and have the potential for water to stagnate in the system or for hot water heaters to not be hot enough, potentially increasing the risk for *Legionella* exposure and infection. Showering for both adults and children reached the daily (adult: 2.41×10^{-6}; child: 2.43×10^{-6}) and annual (adult: 8.45 x

10^{-4}; child: 8.58 x 10^{-4}) median risk thresholds, while for the “running the faucet” exposure scenario, only the annual median risk for adults (1.11 x 10^{-4}) met the threshold. Recent efforts to characterize microbial contaminants in private well systems have indicated substantial detection of *Legionella (*and other OPs). Approximately 15% of wells evaluated following the 2016 Flood in Louisiana had detectable concentrations of *L. pneumophila*, while 77% had detectable concentrations of *Legionella* spp. (72). A comprehensive survey of private wells in North Carolina (under ambient and non-natural disaster conditions) had 100% and 65.5% of samples positive for *Legionella* spp. DNA and *L. pneumophila* DNA (73). Baseline conditions for private wells are often unknown, yet comprehensive microbial surveys have indicated that *Legionella*, specifically *L. pneumophila*, may present a health concern for Legionnaire’s disease.

Previous QMRA studies, while extremely limited, have indicated that enteric pathogens, including norovirus and *Cryptosporidium*, likely contribute an increased risk for GI infections and illnesses (3,138,139). Given that these private wells are not monitored under ambient or natural disaster conditions and well water treatment is only implemented by the well owner, the health risks of exposure to enteric and opportunistic pathogens are likely underreported. Widespread and affordable testing and disinfection or filtration/treatment protocols should continue to be offered to well owners, especially following flooding.

2.4.2. **Indicators for evaluating health risks in well water**

Indicator organisms are critical for rapidly and cost-effectively assessing well water quality; however, traditional indicators, including total coliforms and *E. coli*, may not be appropriate for representing all enteric pathogens. Given that both total coliform and *E. coli* concentrations were elevated in well samples following Hurricane Harvey, compared to baseline conditions, these microbial indicators were useful in identifying environmental contamination of wells, possibly from floodwater (and fecal contamination) (7). Often, baseline conditions regarding these indicator organisms in private wells are unknown, limiting the knowledge gained from emergency and rapid response well testing. Numerous factors can potentially influence the likelihood of a well being contaminated, whether impacted by floodwater or not, including well maintenance, amount of rainfall, climate, season, land use, and geology (7,72,143). The extensive screening and outreach provided by TWON has helped to provide baseline monitoring data of wells across the state and can assist future work that aims to characterize well contamination, in regards to flooding and other environmental factors. However, the utility of *E. coli* to represent the potential presence of all fecal pathogens, specifically viruses, is limited. Coliphages, a group of viruses that can infect coliform bacteria and serve as viral indicators of fecal pathogens, have been approved for groundwater monitoring by the U.S. EPA. Of 122 wells sampled in North Carolina, total coliforms and *E. coli* were detected in approximately 20% of samples, while male-specific and somatic coliphages were detected at a higher frequency (66% and 54% of samples, respectively) (141). Incorporating coliphage testing into well water surveys can improve current knowledge regarding viral pathogens in drinking water sources.

Utilizing total coliforms to predict *Legionella* spp. and *L. pneumophila* is not appropriate, given the lack of correlations being identified between traditional indicators and OPs. Total bacteria levels have been identified to have a correlation with both *Legionella* spp. and *L. pneumophila* positivity in well water, potentially acting as an indicator for these OPs (72,73). The increase of total bacteria in well water may represent environmental conditions favorable to the growth and persistence of *Legionella* (72,145,146). Well testing efforts that include total bacteria counts may help inform the well owner of their well water quality and integrity of their distribution system, as total bacteria counts may indicate deteriorating water quality or favorable conditions for microbial growth.

2.4.3. **Barriers to testing**

Given the potential health risks associated with microbial contaminants in flood-impacted wells, outreach and well testing during and following disaster events are imperative. However, it is well known that well owners may not be able to seek testing or disinfection services due to an array of barriers, which can include cost, transportation, inconvenience, and lack of access (144,145). To address cost and transportation barriers in Marquette County, Wisconsin, the health department provided free testing for 150 households and assisted with sample drop-off and shipping (144). Well testing initiatives in Ontario identified that providing sample bottle pick-up and drop-off and dedicated resources for well water testing can assist with increasing testing participation (145). Public education regarding the importance of water quality in private wells is critical to facilitate routine testing, as well as increasing the initiative for well owners to seek testing after natural disaster events. Outreach personnel, such as TWON, are instrumental for identifying and mitigating barriers for private well testing in Texas.

2.4.4. **Challenges**

This study did not distinguish samples from wells that were characterized by specific factors that may have influenced the likelihood of a well being contaminated or flooded (e.g., proximity to floodwaters). All samples collected between September 11 and October 22 were included in the risk assessment to provide a preliminary characterization of the risks for a GI infection for private wells impacted by Hurricane Harvey. *Legionella* samples were collected during the same timeframe. Future risk assessments may incorporate indicator or pathogen decay and assess how health risks may change over time. The scope of this risk study, given that samples were collected directly from the faucet and not from floodwaters or well tanks, did not incorporate microbial decay or transport. Refining future approaches that assess pathogen concentrations and risks across time (e.g., risks during flooding and number of days after flooding) can inform emergency response communication, management, and well stewardship post-natural disaster. The QMRA presented in this study applied environmental data to characterize immediate health risks following contamination that resulted from flooding up to two months prior.

The risk assessment utilized input parameters and dose-response relationships that were gathered from the literature and based upon the best available knowledge at the time. The pathogen and indicator concentrations and ingestion volumes for each exposure scenario likely vary among different environments, age groups, and communities. While the assumptions presented in this study incorporated variability as best as possible, the risk of infection estimates should be evaluated as preliminary characterization of health risks for private wells.

Lastly, characterizing health risks utilizing FIB does present challenges. *E. coli* is the standard FIB utilized in drinking water testing, but it has been known to regrow and become naturalized in the environment (46). Further, the specific fecal sources contaminating the well (whether human or non-human) remains unknown unless MST techniques are utilized. However, *E. coli* testing is relatively rapid and low-cost, especially during a natural disaster event. Future work targeting specific MST markers to assess fecal contamination or fecal pathogens for a subset of samples can be informative to assess sources and pathways of contamination; however, given the vast amount of data that was gathered by citizens and researchers, the utility of FIB to assess water quality and health risks should not be disregarded.

2.5. **Conclusion**

The preliminary findings help to characterize the exposure risks for individuals who rely on private wells that are impacted by a hurricane (or natural disaster) and consequently contaminated by flood waters. While norovirus has been identified to be the reference pathogen of greatest concern due to the risk of infection estimates that exceed the risk benchmark for public water systems, further exposure scenarios and conditions remain to be evaluated. Respiratory infections from opportunistic pathogens are poorly characterized and warrant further exposure and risk analysis. Research evaluating well owner behavior in context of this risk assessment may identify gaps in knowledge regarding exposure risks. Infection risks for individuals relying on private water supplies is weakly understood and needs further investigation. Improved characterization of these health risks can assist in providing effective outreach and emergency response measures to private well owners.

3. EVALUATION OF WELL OWNER PERCEPTIONS AND PRACTICES AFTER HURRICANE HARVEY

3.1. **Introduction**

The increasing frequency and intensity of extreme weather events affecting coastal communities poses a significant public health threat for individuals relying on private well water (146,147). The Texas Gulf Coast experienced extensive flooding after Hurricane Harvey made landfall on August 25, 2017 resulting in damages to and contamination of some public and private water systems (66). While residents in that region were predominantly served by public water systems (approximately 93.9%), a significant number of individuals were dependent on private wells (148). Approximately 526,000 private well users (6.1% of the region's population) or 215,906 private wells, are estimated to have been impacted by floodwaters (7,68). Private wells are exempt from the water quality protections of the 1974 Safe Drinking Water Act, resulting in well owners being responsible for ensuring the safety of their own drinking water. Before natural disaster events, well owners are encouraged to implement precautionary measures to protect the integrity of their well, such as sealing the top of the well, and disinfecting and testing their well for bacteria after flooding. Well owners in rural areas are also encouraged to be self-sufficient for a minimum of 72 hours after a natural disaster event due to the limited availability and access of emergency services (149). Well water contamination, especially by flooding, can pose a significant health risk for consumers, oftentimes with well users not knowing their well water has been contaminated (13,16–19).

While precautionary measures regarding well maintenance and preparation for natural disasters are critical for well owners, research has indicated that well users often lack the knowledge regarding these measures, including sealing the top of the well, well water disinfection and testing post-flood, and well maintenance (9,150,151). The risk perceptions and behaviors of well users who had previously experienced flooding, such as for the private well owners impacted by Hurricane Harvey, remains poorly understood. Common barriers to proper well stewardship include a lack of knowledge regarding what testing and treatment entails, the inconvenience of testing, lack of resources to successfully test or treat, and complacency (60,153). However, well water education has been documented to assist in motivating well owners to implement well maintenance practices (152,153).

The goal of this study was to characterize well owner behaviors and perceptions regarding well water quality after experiencing a significant flood event three years prior. Specifically, the study assessed well owner perceptions regarding the safety of their well water for specific uses (drinking, cooking, and bathing), and if well stewardship practices were being implemented (e.g., testing and disinfecting). Knowledge gained from this study can identify how well owners previously impacted by flooding perceive future risks to their well water and if prior well education outreach, especially after a natural disaster, has influenced well stewardship practices.

3.2. **Methods**

3.2.1. **Survey development and distribution**

A questionnaire was initially distributed along with sampling kits for well owners impacted by Hurricane Harvey in the fall of 2017 through a citizen science sampling campaign that was organized by researchers from Virginia Tech University, Louisiana State University Health Sciences, and TWON, part of the Texas A&M AgriLife Extension Service. The four-page questionnaire asked well owners questions regarding their well's characteristics, maintenance of their well, water use behaviors, and knowledge regarding well water management assistance (7). The survey discussed in this study is based upon the 2017 questionnaire template. A follow-up survey that was administered was updated to include questions regarding recent well water testing and disinfection, current uses of well water, management and well adaptations made following Hurricane Harvey. The survey was administered electronically via Qualtrics (Qualtrics XM, Utah, USA) and included 28 questions, taking less than 15 minutes to complete. Survey distribution and communication procedures followed online survey administration methods, including four points of contact, as described in previous work (154). An initial pre-contact email was sent to participants to notify them of the study, followed by an email including the link to the survey, and then two reminder emails (which included the survey link) were each following week for two weeks. Individuals who completed the original survey in 2017 was the targeted audience for the follow-up survey. The follow-up survey was conducted under Texas A&M University Institutional Review Board approval (IRB2017-0760M).

Of the original survey participants who completed the 2017 questionnaire (n=630), there was only a subset emails that were unique (n=498). Of those email addresses, several were determined to no longer be valid (n=62), leaving a total number of 436 email addresses successfully working for survey distribution. In October 2020, the follow-up survey (Appendix B) was delivered electronically to the 436 active email addresses. Follow-up reminders with invitations to complete the survey were sent once a week for the three-week duration of the survey. In total, 69 surveys were completed, resulting in a submission rate of 15.8%. There were seven surveys that were started and not completed (for a total of n=76 surveys), and therefore omitted from data analysis. The survey was administered during the COVID-19 pandemic, and while delivered electronically in an effort to mitigate any public health concerns, the delivery method may have been a factor influencing participation.

This survey study aims to evaluate current well owner concerns and behaviors regarding well water safety and risks three years after major flooding from Hurricane Harvey. Responses to the following questions for the Fall 2020 survey were the focus of this paper.

Does anyone in your home drink the water from your kitchen tap? (Yes, with filter/treatment; Yes, but not with filter/treatment; or No)

- *If yes, about how much well water do you and your family drink on average for each person in a day?* Answer choices included 2 cups, 4 cups, 6 cups, 8 cups and I don't know.

Please indicate your level of agreement by circling the appropriate number (1=disagree; 5=agree).

- I feel my well water is safe to drink.
- I feel my well water is safe for cooking.
- I feel my well water is safe for bathing.
- I am comfortable managing my well (testing, treating, and maintaining).
- I know where to find information about well water testing services.
- I know where to find information about well water treatment systems.

Have you ever had your well system disinfected? Answer choices included: Yes, we did it ourselves; Yes, someone else did it; No; Don't know.

Do you test your water more frequently since the flood? Answer choices included: Yes, No, or Don't know.

Do you feel your water is safe? Answer choices included: Yes, No or Don't know.

3.2.2. **Statistical analyses**

Descriptive statistics were used to evaluate responses from the follow-up survey. Socio-demographic data (county of residence, education, ethnicity, and annual income) for the respondents was gathered by matching the key number linked to the current survey with the original survey (which had asked participants for that information). Pearson's chi-square tests of independence and Fisher Exact tests were utilized to assess if any associations existed between specific socio-demographic characteristics and responses regarding well water stewardship and perceptions of well water quality. The t-test for independent samples and analyses of variance (ANOVA) were used to determine if there were differences of means among counties, income or education groups and their perceptions of well water safety and well stewardship practices. Likert scale data were not evaluated for normality, since previous work utilizing Likert scale data to measure differences of means have indicated that the t-test and the Wilcoxon signed-rank or Mann-Whitney tests result in similar error rates or that the t-test produced appeared to reject false hypotheses better (155,156). When conducting the statistical analyses, missing responses were omitted. The statistical package for Social Sciences (SPSS) Version 28 was used for all data analyses. The significance level was defined as $\alpha<0.05$.

3.3. **Results**

Survey question response rates for individual questions varied since some respondents selected to skip specific questions (none of the survey questions were required to be completed). Only 11.6% (n=8) of participants completed the final free response question regarding well-related concerns or issues that were not discussed in the survey. Cronbach's coefficient alpha was calculated for variables pertaining to perception of well water safety (for drinking, cooking, and bathing), comfort managing well, and knowledge of where to find information for well water treatment and well system disinfection. An alpha of 0.82 was measured, indicating good reliability. Responses to questions regarding perceptions of well water, well stewardship, and well water uses were evaluated to characterize well owner behavior and concerns three years after flooding from Hurricane Harvey.

3.3.1. **Socio-demographics and water usage**

Survey participants predominantly identified as white (84.8%) with only 4.5% and 1.5% identifying as Hispanic and African American, respectively (Table 3.1). Participants from fourteen different counties completed the follow-up survey, with 33.8% living in Wharton County, followed by Victoria (19.1%) and Harris Counties (10.3%). Nearly two-thirds of respondents had a bachelor's degree or post-college education (61.2%), while 34.3% reported having a high school diploma or completing some college. Specifically, 13.4% reported having a high school diploma, 20.9% reported having some college, 41.8% had a college degree, and 19.4% had a post-college degree (MS, PhD). Information regarding annual income is less informative, given that 35.8% of participants provided "prefer not to answer." Of the information available, 14.9% reported an income of $45,000 or less, 29.9% reported an income between $45,001 and $85,000, and 16.4% reported an income of $85,001 or greater.

Regarding drinking water from the kitchen tap, participants were nearly evenly split among whether they drank water with filtration or treatment (36.2%), drank water without filtration or treatment (34.8%), or did not drink water from the tap (29%). When assessing exposure to drinking water in human health risk assessments, a common assumption used to estimate the volume of water consumed daily is approximately one to two liters of water per day

(157). The majority of participants (45.8%) reported drinking 8 cups of water per day, verifying a key assumption utilized in human health risk assessments.

Table 3.1. Socio-demographics and water consumption of respondents

Variable		% (#)
County (n=68)	Wharton	33.8% (23)
	Victoria	19.1% (13)
	Harris	10.3% (7)
	Hardin	8.8% (6)
	Liberty	5.9% (4)
	Waller	4.4% (3)
	Orange	4.4% (3)
	Tyler	2.9% (2)
	Chambers	2.9% (2)
	Other[1]	7.5% (5)
Education (n=67)	Less than a bachelor's degree	34.3% (23)
	Has a bachelor's degree or post college education	61.2% (41)
	Prefer not to answer	4.5% (3)
Income (n=67)	$45,000 or less	14.9% (10)
	$45,001-$85,000	29.9% (20)
	$85,001 or greater	19.4% (13)
	Prefer not to answer	35.8% (24)
Ethnicity (n=66)	Black or African American	1.5% (1)
	Hispanic or Latino	4.5% (3)
	White or Caucasian	84.8% (56)
	Prefer not to answer	9.1% (6)
Drink Water from Kitchen Tap? (n=69)	Yes, with filter/treatment	36.2% (25)
	Yes, but not with filter/treatment	34.8% (24)
	No	29.0% (20)
Average Number of Cups Consumed (n=48)	2 cups	6.3% (3)
	4 cups	18.8% (9)
	6 cups	16.7% (8)
	8 cups	45.8% (22)
	I don't know	12.5% (6)

[1] Other includes the counties, Calhoun, DeWitt, Goliad, Gonzales, and Refugio. These counties each had 1 respondent each (1.5%)

The categories-education, annual income, and county- were evaluated for an association with several variables regarding drinking well water and well stewardship (Table B-1). No statistically significant associations were identified. However, the lack of associations likely indicates that differences in education, income, or location do not appear to affect well owner perceptions regarding drinking their well water or practicing well stewardship.

3.3.2. **Well stewardship**

Well stewardship activities, including well water testing and disinfecting a well system, are often under implemented by private well owners. Nearly half of respondents (46.27%, n=31) indicated that they or someone else have disinfected their well system, while approximately 44.78% (n=30) reported never disinfecting their well (and 8.96% (n=6) did not know if they had ever disinfected their well) (Figure B-1, Table B-2). Of the respondents who indicated they had disinfected their well system, 41.94% (n=13) reported disinfecting due to a “concern for contamination from flooding/heavy rains”, while 22.58% (n=7) disinfected due to a positive bacteria test or for routine maintenance (Table B-3). Only 12.90% (n=4) disinfected due to taste or odor issues.

Well water testing occurred at relatively similar percentages as well system disinfection. The majority of respondents (53.73%, n=36) reported not testing their well water since Hurricane Harvey, while 44.78% (n=30) reported that they had tested their well water (Figure B-2, Table B-4). When asked how frequently they have tested since Hurricane Harvey, 83.33% (n=25) reported only testing once, while 16.67% (n=5) indicated they had tested 2-3 times since then. There was a lack of an association when evaluating if respondents who tested their well water since the flood also had their well systems disinfected (p=0.333; Table B-5). Approximately 53.3% of respondents who reported testing their well since the flood, also reported having their well system disinfected, while 40.5% of respondents who reported not testing their well since the flood did report having disinfected their well system.

When respondents were asked if they had a water treatment device installed on their home drinking water system, 27.36% responded not having any treatment system, while 25.47% indicated having a water softener and 16.98% indicated having a sediment filter (Figure B-3, Table B-6). Treatment systems that would help mitigate bacteria contamination, including a chlorinator (0.94%), reverse osmosis (6.60%), and ultraviolet light (0.94%), were not reported to be widely used.

3.3.3. **Well water safety and drinking**

Respondents were asked if they felt that their well water was safe. Overall, 77.6% (n=52) of well owners responded that they felt their well water to be safe, with 19.4% responding “don’t know” and only 3% (n=2) reporting they felt their water to be unsafe. The greatest percentage of respondents who reported feeling their water was safe also drank their well water from the kitchen tap (76.93%). Of the respondents who reported not drinking their well water, most reported “don’t know” regarding their well water safety. Of the two participants who indicated that they do not feel their well water is safe, both reported drinking their well water without filtration/ treatment (Figure 3.1).

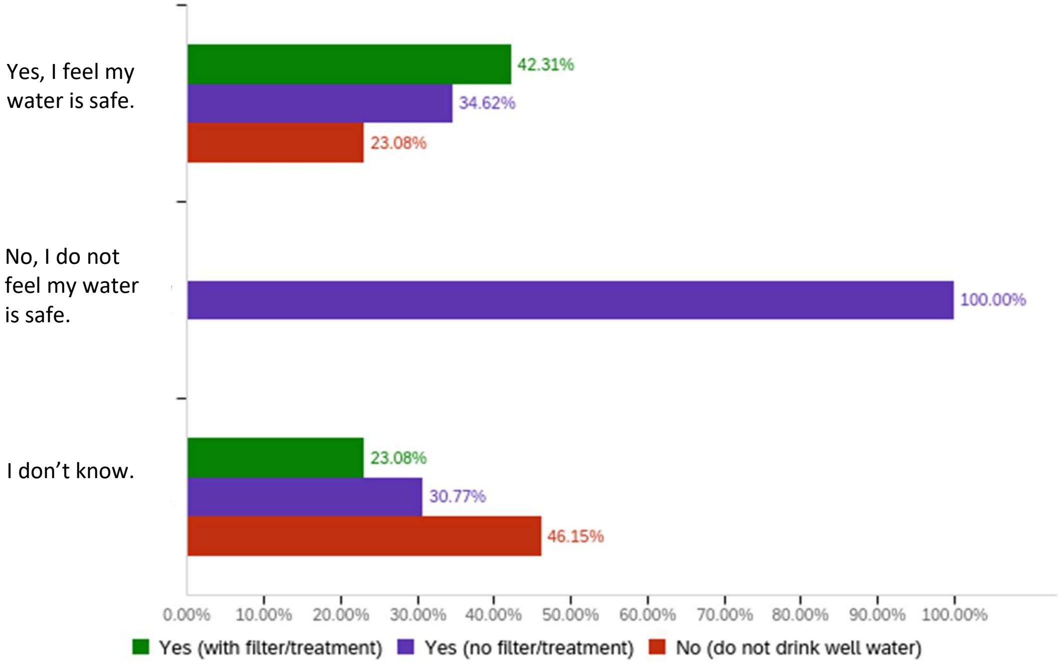


Figure 3.1. Perceived safety and use of well water for drinking

3.3.4. **Perceptions of water safety and well stewardship**

A Likert scale ranking was used for questions asking about feelings of well water safety for drinking, cooking, and bathing, and for comfort/knowledge regarding well management and resources. Rankings on the Likert scale were as follows for statistical analysis: rankings from 1-2 were categorized as disagree, 3 was neutral, and 4-5 was agree. Perceptions of well water safety and well stewardship activities (including testing and disinfecting) were evaluated for associations.

Individuals who reported feeling that their well water was safe for drinking and cooking were associated with feeling comfortable managing their well (drinking: $p<0.002$ and Cramer's $V=0.312$; cooking: $p<0.001$ and Cramer's $V=0.295$) (Table 3.2).

There was a lack of association for respondents regarding whether they felt their water was safe for drinking, cooking, or bathing, and if they tested their well since Hurricane Harvey flooding or if they had ever disinfected their well. No significant association was identified for well water safety (drinking, cooking, and bathing) and knowing where to find information regarding well water treatment or testing.

Table 3.2. Perceptions of well water safety and well stewardship

Variable[1]	Do you feel that your well water is safe?		p-value	I feel my water is safe to drink.			p-value	I feel my water is safe for cooking.			p-value	I feel my water is safe for bathing.			p-value
Have you tested your well since the flood?	Yes	No/ Don't Know	0.99	Dis-agree	Neu-tral	Agree	0.105	Dis-agree	Neu-tral	Agree	0.573	Dis-agree	Neu-tral	Agree	0.881
Yes	44.6% (29)	50% (1)		14.3% (1)	25% (2)	51% (25)		60% (3)	28.6% (2)	47.2% (25)		50% (2)	33.3% (2)	45.6% (26)	
No	55.4% (36)	50% (1)		85.7% (6)	75% (6)	49% (24)		40% (2)	71.4% (5)	52.8% (28)		50% (2)	66.7% (4)	54.4% (31)	
Have you ever had your well disinfected?	Yes	No/ Don't Know	0.495	Dis-agree	Neu-tral	Agree	0.76	Dis-agree	Neu-tral	Agree	0.128	Dis-agree	Neu-tral	Agree	0.99
Yes	47.7% (31)	0% (0)		57.1% (4)	37.5% (3)	46.9% (23)		0% (0)	57.1% (4)	49.1% (26)		50% (2)	50% (3)	45.6% (26)	
No	52.3% (34)	100% (2)		42.9% (3)	62.5% (5)	53.1% (26)		100% (5)	42.9% (3)	50.9% (27)		50% (2)	50% (3)	54.4% (31)	
I am comfortable managing my well.	Yes	No/ Don't Know	0.096	Dis-agree	Neu-tral	Agree	**0.007**	Dis-agree	Neu-tral	Agree	**0.006**	Dis-agree	Neu-tral	Agree	0.362
Disagree	11.5% (7)	1 (50%)		33.3% (2)	37.5% (3)	6.1% (3)		25% (1)	33% (2)	9.4% (5)		0% (0)	20% (1)	12.5% (7)	
Neutral	31.1% (19)	50% (1)		50% (3)	37.5% (3)	28.6% (14)		75% (3)	50% (3)	26.4% (14)		50% (1)	60% (3)	28.6% (16)	
Agree	57.4% (35)	0% (0)		16.7% (1)	25% (2)	65.3% (32)		0% (0)	16.7% (1)	64.2% (34)		50% (1)	20% (1)	58.9% (33)	

Table 3.2 Continued

Variable[1]	Do you feel that your well water is safe?		p-value	I feel my water is safe to drink.			p-value	I feel my water is safe for cooking.			p-value	I feel my water is safe for bathing.			p-value
…information[2] about well water treatment systems.	Yes	No/ Don't Know	0.123	Disagree	Neutral	Agree	0.474	Disagree	Neutral	Agree	0.121	Disagree	Neutral	Agree	0.686
Disagree	28.8% (17)	100% (2)		66.7% (4)	28.6% (2)	28.3% (13)		80% (4)	33.3% (2)	25% (12)		0% (0)	40% (2)	32.7% (17)	
Neutral	18.6% (11)	0% (0)		0% (0)	14.3% (1)	21.7% (10)		0% (0)	16.7% (1)	20.8% (10)		25% (1)	20% (1)	17.3% (9)	
Agree	52.5% (31)	0% (0)		33.3% (2)	57.1% (4)	50% (23)		20% (1)	50% (3)	54.2% (26)		75% (3)	40% (2)	50% (26)	
…information[2] about well water testing services.	Yes	No/ Don't Know	0.525	Disagree	Neutral	Agree	0.866	Disagree	Neutral	Agree	0.187	Disagree	Neutral	Agree	0.964
Disagree	31% (18)	100% (1)		50% (2)	37.5% (3)	28.9% (13)		75% (3)	50% (3)	25% (12)		25% (1)	50% (2)	32.4% (16)	
Neutral	20.7% (12)	0% (0)		0% (0)	25% (2)	22.2% (10)		0% (0)	0% (0)	25% (12)		25% (1)	0% (0)	21.6% (11)	
Agree	48.3% (28)	0% (0)		50% (2)	37.5% (3)	48.9% (22)		25% (1)	50% (3)	50% (24)		50% (2)	50% (2)	47.1% (24)	

[1] All tests for association done with Fisher Exact tests; significance is defined as $p<0.05$

[2] I know where to find…

Independent sample t-tests and ANOVA were used to determine if there were any differences in perceptions of well water (for drinking, cooking, and bathing) and knowledge of well stewardship for respondents, specifically regarding education, annual income, and county of residence. Responses were in the categories: 1=disagree, 2=neutral, and 3=agree. For all three socio-demographic variables, only one variable, "I feel my water is safe for cooking", was identified to significantly differ between the two educational categories (Table 3.3). The means evaluated for the other variables and categories did not significantly differ.

Generally, individuals who identified as living in Wharton or Victoria Counties were more likely to feel comfortable managing their well (2.5), having knowledge of where to find resources for well water testing (2.23) and well system treatment (2.22), and feeling their water is safe for cooking (2.82) and bathing (2.83). Individuals who identified as living in "other counties" identified as being slightly more likely to feel that their water was safe for drinking (2.7). Wharton County residents dropped off 462 samples between September 18th, 2017 and March 8th, 2018, potentially influencing the increased knowledge of well stewardship practices and confidence in water quality.

For all variables, respondents who reported having an education that was either a high school diploma or some college (categorized as less than a bachelor's degree) were more likely to report that they felt their water was safe for drinking (2.75), cooking (2.91), and bathing (2.82), and responded as feeling more comfortable/knowledgeable regarding well management practices than for respondents who identified as having a "bachelor's degree or greater" (Table 3.3). There was a significant difference for the perception, “I feel my water is safe for cooking” between the two educational categories (Cohen’s D= 0.441). For the variable regarding “I am comfortable managing my well”, both groups (less than a bachelor’s degree=2.45 and bachelor’s degree or greater=2.42) were nearly the same average.

Trends regarding perceptions of well water quality and knowledge of water management are not as consistent for the annual income category. Generally, respondents in the income category, $45,001-$85,000 were more likely to report a lower feeling of safety for drinking (2.56), cooking (2.45), and bathing (2.65), and for comfort in managing their own well system (2.17). Individuals in the income category, $45,000 or less, indicated that were less likely to know where to find information regarding well water testing (2.00) and well water treatment systems (2.00).

Overall, perceptions of well water safety tended to have a greater average (more likely to agree) among respondents, than perceptions regarding well management knowledge. Knowledge regarding where to find information for well water testing and well water treatment systems had the lowest averages (amongst all variables) for all three categories, indicating a need to further evaluate limitations that may be affecting respondents.

Table 3.3. Perceptions of well water and well stewardship based on county of residence, education, and annual income

Variable	Category					
	Counties	**N**	**Mean**	**SD**	**F-value**	**p-value**
I feel my water is safe to drink	Victoria & Wharton Counties	33	2.64	0.699	0.439	No significant difference
	Other Counties	30	2.70	0.651		
I feel my water is safe for cooking.	Victoria & Wharton Counties	33	2.82	0.465	4.378	No significant difference
	Other Counties	31	2.68	0.701		
I feel my water is safe for bathing.	Victoria & Wharton Counties	35	2.83	0.453	0.985	No significant difference
	Other Counties	31	2.77	0.617		
I am comfortable managing my well.	Victoria & Wharton Counties	32	2.50	0.762	0.833	No significant difference
	Other Counties	30	2.33	0.661		
I know where to find information about well water testing services.	Victoria & Wharton Counties	30	2.23	0.858	0.384	No significant difference
	Other Counties	28	2.04	0.922		
I know where to find information about well water treatment systems.	Victoria & Wharton Counties	32	2.23	0.906	0.142	No significant difference
	Other Counties	28	2.14	0.891		
Variable	**Category**					
	Education	**N**	**Mean**	**SD**	**F-value**	**p-value**
I feel my water is safe to drink	Less than a bachelor's degree	20	2.75	0.639	2.021	No significant difference
	Has a bachelor's degree or greater	39	2.59	0.715		
I feel my water is safe for cooking.	Less than a bachelor's degree	21	2.91	0.301	13.827	Significant (Cohen's D= 0.441)
	Has a bachelor's degree or greater	39	2.64	0.707		
I feel my water is safe for bathing.	Less than a bachelor's degree	22	2.82	0.501	0.39	No significant difference
	Has a bachelor's degree or greater	40	2.78	0.577		

Table 3.3. Continued

Variable	Category					
	Education	**N**	**Mean**	**SD**	**F-value**	**p-value**
I am comfortable managing my well.	Less than a bachelor's degree	20	2.45	0.686	0.539	No significant difference
	Has a bachelor's degree or greater	38	2.42	0.758		
I know where to find information about well water testing services.	Less than a bachelor's degree	18	2.22	0.808	2.939	No significant difference
	Has a bachelor's degree or greater	36	2.14	0.931		
I know where to find information about well water treatment systems.	Less than a bachelor's degree	18	2.39	0.85	0.553	No significant difference
	Has a bachelor's degree or Greater	38	2.13	0.906		
Variable	**Category**					
	Income	**N**	**Mean**	**SD**	**F-value**	**p-value**
I feel my water is safe to drink	$45,000 or less	9	2.67	0.707	0.075	No significant difference
	$45,001-$85,000	18	2.56	0.705		
	$85,001 or greater	13	2.62	0.768		
I feel my water is safe for cooking.	$45,000 or less	9	2.78	0.441	3.108	No significant difference
	$45,001-$85,000	20	2.45	0.826		
	$85,001 or greater	12	3.00	0.0		
I feel my water is safe for bathing.	$45,000 or less	9	2.89	0.111	0.724	No significant difference
	$45,001-$85,000	20	2.65	0.15		
	$85,001 or greater	13	2.85	0.154		
I am comfortable managing my well.	$45,000 or less	9	2.33	0.289	1.698	No significant difference
	$45,001-$85,000	18	2.17	0.167		
	$85,001 or greater	12	2.67	0.188		

Table 3.3. Continued

Variable	**Category**					
I know where to find information about well water testing services.	$45,000 or less	8	2.00	0.327	1.384	No significant difference
	$45,001-$85,000	18	2.06	0.235		
	$85,001 or greater	10	2.60	0.221		
Variable	**Category**					
	Income	**N**	**Mean**	**SD**	**F-value**	**p-value**
I know where to find information about well water treatment systems.	$45,000 or less	8	2.00	0.926	0.207	No significant difference
	$45,001-$85,000	18	2.11	0.964		
	$85,001 or greater	11	2.27	0.905		

3.4. **Discussion**

Characterizing well owner concerns and perceptions of well water quality, especially in the years following flooding, is imperative to provide baseline information that can inform future risk communication efforts. The data evaluated in this follow-up survey to well owners nearly three years after Hurricane Harvey flooding assessed perceptions regarding well water safety and knowledge of well stewardship and management practices. The majority of respondents indicated that they did drink their well water from the kitchen tap (71%) and overall, 77.6% indicated that they believed their well water was safe. However, in terms of well management practices, only 44.8% indicated that they test their well water and 46.3% indicated they have disinfected their well system. For all respondents who participated in the survey, 53.3% indicated that they have both tested their well water again since their previous testing immediately following the flood in 2017 and have had their well system disinfected. An estimated 3,765-7,530 private wells were likely inundated by flood water and while this is relatively a small percentage of the overall total of wells estimated to be impacted by Hurricane Harvey (215,906 wells), there are several pathways for microbial contamination of well water, besides that of direct contamination by inundation (7,12). Study results indicate that prior experience with Hurricane Harvey in 2017 has not resulted in significant concerns about well water safety or influenced well water stewardship activities.

3.4.1. **Well stewardship after a natural disaster**

Well stewardship practices, under both disaster and non-natural disaster conditions, are critical for drinking water quality awareness and protecting public health. Similar to previous work (9), most well users did not report testing their well water or conducting well system disinfection following Hurricane Harvey. A greater proportion of well owners reported feeling that their well water was safe and had not tested their well water since the flood (55.4%), than for well owners who reported feeling that their well water was safe and had recently tested it (44.9%). Given that well users indicated a lower rating (on a Likert scale) regarding comfort maintaining their well system, and knowledge of well testing and disinfection, unfamiliarity may play role in the lack of well stewardship activities.

Even without the recent experience or concern for flooding, well owners are known not to regularly test or disinfect their well water. Studies of private well owners in Wisconsin have estimated that only 10% of private well owners test their well water as recommended by public health guidelines (150,158). A significantly greater percentage of well users reported having tested their well water in the last three years in the Gulf Coast region of Texas (44.8%); however, such testing could have occurred immediately after Hurricane Harvey flooding during Rounds 1 or 2 of well water sampling and educational outreach provided by TWON and local health departments. The survey did not distinguish in the question whether testing after the flood occurred during one of the testing campaigns or was conducted during another TWON educational workshop, by a local health department or under other circumstances.

Risk perception may also affect well stewardship following a natural disaster. Not all well owners who participated in the study had well heads that were inundated by floodwater or were significantly impacted by flooding from Hurricane Harvey. Not experiencing significant damage after enduring a risk may influence individuals into thinking they will not be impacted by future risks (i.e., natural disasters) (153,159). While all survey participants had previously been a part of post-Hurricane Harvey well testing campaigns, prior experiences to flooding did not appear to influence well stewardship practices.

3.4.2. **Perceptions of well water safety and well stewardship practices**

The only statistically significant association relating feelings of well water safety and well stewardship was between the categories of "I am comfortable managing my well (testing, treating, and maintaining)" and "I feel my water is safe for drinking" and "…cooking" (p-values= 0.007 and 0.006 respectively). However, an association was not evident between the categories of "I am comfortable managing my well (testing, treating, and maintaining)" and "[I] feel my well water is safe"; nor with the variables regarding well water testing, disinfection or knowledge of well water testing or treatment services. While it would be assumed that comfort managing a well would have an association with feeling safe drinking and cooking with well water, what "comfortable managing a well" implies may still be unclear. The lack of association with other variables regarding well stewardship (well water testing, well system disinfection and knowledge of services for testing and disinfection) seem to indicate that a well owner's comfort of managing their well may not directly indicate that appropriate well stewardship practices are being implemented. A common barrier to testing and treatment has been identified as a lack of understanding or knowledge regarding the components of well water testing and well system disinfection (150). While educational outreach may not directly resolve this disconnect in knowledge and practice, it is a critical component towards facilitating behavioral change.

Motivations and barriers for well owners regarding well stewardship have been described as: knowledge and information, risk perception, social norms, and convenience (153). In the context of this study, the lower level of comfort reported for managing well systems and for having the knowledge of well water testing and well system disinfection, emphasizes the importance of knowledge and information barriers. Informational messaging concerning well water testing and disinfection may not clearly communicate the necessary frequency and timing of testing for well maintenance (160,161). Despite receiving written information, respondents who chose to provide comments in open-answer sections of the survey indicated that they did not know when or where to get a test or how often they should get their well tested. It is known that knowledge is imperative for affecting behavior (153,162). The frequency of well owner engagement or educational workshops, or type of material presented when natural disasters occur may need to be reviewed and expanded, given that well owners who participated in this study had previously received well water results and received written information regarding well testing and disinfection after Hurricane Harvey.

Perceived risk can directly influence well stewardship practices. A well owner's perception of their water's safety or quality can affect decisions on whether to test or treat well water; for example, a low perceived risk will often result in well owner's not testing or treating their water (153,163). Further, well water quality is often determined by its aesthetic properties (e.g., smell, color, and taste), even though many contaminants (e.g., bacteria) have no noticeable changes on the water's aesthetics. The average rating regarding safety of well water for drinking (2.66), cooking (2.74), and bathing (2.79) was relatively high (max=3), supporting that well owners likely feel their water is safe and therefore do not see a need to test and disinfect their systems regularly.

3.4.3. **Socio-demographics and well water perceptions and stewardship**

Previous work has indicated that education and income are significant predictors impacting well water testing and management (150,158,164,165). However, perceptions of well water safety and well stewardship practices were not significantly different among the socio-demographic factors of residence, education, and annual income assessed in this study. Only the variable "I feel my water is safe for cooking" was determined to be significantly different between the two educational groups (less than a bachelor's degree or has a bachelor's degree or greater). The lack of a relationship between these two variables may indicate that the experiences from the previous flooding of Hurricane Harvey did not differentially affect well owners, in terms of income or education. All those affected generally had similar perceptions of their well water safety, and knowledge, comfort and stewardship practices regarding their well systems. The lack of differences or associations among these sociodemographic characteristics are not unusual, given that others have found demographic factors to be unrelated to water testing practices (163). Location of residence has also been found to influence health risks and well water management but was not identified to be a predictor for this specific group of well owners (166,167).

3.4.4. **Study limitations**

This study, albeit with its limitations, provided an assessment of well owner perceptions three years after flooding from a category 4 hurricane. Respondents to the follow-up survey had participated in the original survey administered in the Fall of 2017 after Hurricane Harvey, and while all previous participants were contacted, a small proportion decided to voluntarily participate in this study. Fourteen different counties were represented in the study, providing a broad representation of the Texas Gulf Coast area. Given the follow-up survey was not in the original study design following the distribution of the first survey, it is likely inappropriate to apply pre- and post-study analyses between the two surveys. This survey is an example of a cross-sectional study, and while informative, does have its limitations regarding the ability to infer respondent behavior and motivations.

The survey was administered online during the COVID-19 pandemic in October-November 2020. While online surveys are relatively inexpensive to administer, can gather data quickly and minimize survey error, there are limitations that should be considered (168). Online surveys require respondents to have access to the internet. Given that all participants were contacted with email addresses provided from the first survey (administered in 2017), it was assumed all contacted individuals would have internet access. However, due to the nature of most private well owners living in rural areas, this assumption may not have been entirely accurate. The survey allowed participants to easily skip questions and was shorter than the first survey to increase completion (154,168).

While the study attempted to identify associations among perceptions of well water safety and well stewardship, very few statistically significant findings were discovered. However, the lack of associations between the variables evaluated or differences in means among socio-demographic categories were still informative. Well owners, regardless of county of residence, annual income, or education, indicated that they perceive their well water to be safe, and after experiencing a natural disaster, did appear to have increased rates of water testing or well treatment.

Future work regarding well owners impacted by natural disasters and their perceptions of well water safety and well stewardship is still needed. This study was unique to a specific region of the Gulf Coast of Texas and could differ from well water perceptions for well owners in the Texas Hill Country who have experienced massive flooding or for well owners in different regions of the United States. Evaluating why well users believe their well water is safe for different uses should also be investigated. Lastly, as extreme weather events continue to occur due to climate change, evaluating well owner perceptions and behaviors over time may be informative for educational outreach and risk communication.

3.5. **Conclusion**

Well owners who participated in this study had been previously impacted by Hurricane Harvey flooding and had participated in a well water testing campaign and educational outreach. Participants in this study indicated that they perceive their well water to be safe, appear to practice well water testing and disinfection at rates higher than previously reported in the literature (150). Information gained from this study is informative for well water outreach efforts in Texas and other coastal areas in the United States that are impacted by natural disasters. Texas well owners in the Gulf Coast region indicated minimal concern for their well water safety, suggesting that even though they endured a significant natural disaster event, perceptions of well water were not adversely impacted. These perceptions and well stewardship practices were generally consistent across income, education, and location of residence.

Knowledge and educational outreach are critical components for overcoming barriers to well stewardship and have been previously presented to these participants. Future outreach should consider perceptions and social norms for well owners and consider targeting and simplifying messaging regarding why well water testing and disinfection is necessary and important. Due to their proximity to the Gulf of Mexico, these participants will likely experience flooding again in the future, further emphasizing the critical importance of educational outreach. The lack of testing and disinfection coupled with believing that their well water is safe poses a public health concern for well users in this region. Survey evaluations are useful tools to inform of gaps or disconnects of well water perceptions and well management practices, which is needed to identify opportunities for future educational outreach.

4. QMRA OF RECREATIONAL BEACHES IMPACTED BY DOG, GULL, AND HUMAN FECAL SOURCES

4.1. **Introduction**

Recreational water bodies, such as rivers, inland lakes, and beaches, are required to meet U.S. EPA standards for FIB to minimize risk and protect public health (11). Epidemiological studies indicating an increase in swimmer GI illnesses with increasing FIB concentrations have historically been the basis for establishing water quality criteria or public health recommendations for recreational water management (22,169). However, most of these studies have focused primarily on municipally treated wastewater effluent, which is not always reflective of actual environmental conditions. These water bodies can be influenced by a wide array of microbial contaminants originating from different sources, including both human and non-human fecal sources. Non-human sources, specifically from agricultural animals and wildlife, typically have lower risks than water bodies impacted by human sewage due to different mixes and densities of FIB and pathogens (23).

Limitations of general FIB, such as with *E. coli* and Enterococci, have increased the need to identify and utilize alternative indicators to assess fecal contamination in different water systems (27). The ideal surrogates for fecal contamination should meet several different requirements, which include but are not limited to: host species specificity, high abundance in feces of host species, pathogen co-occurrence, inexpensive cost to monitor and detect, not be naturalized to the environment nor multiply outside of the host, similar fate and transport as pathogens in the environment and in treatment processes, nonpathogenic; and correlate with human health risks (27,170). While not a single fecal indicator has been identified to meet all the requirements, alternatives have been proposed, albeit with their own limitations.

MST has been used as a method to identify specific sources of fecal contamination, which can inform risk assessments and direct targeted practices for coastal water quality management. MST protocols have advanced in the past several years and are generally defined as library-independent or library-dependent. Library independent MST uses host associated fecal DNA markers, also known as MST markers, to identify FIB sources, and unlike library-dependent methods, do not require comparing samples with a reference library (27,171). Among the many methods used in MST, qPCR MST assays are frequently used to detect specific fecal sources. Many qPCR markers target *Bacteroides*, which are bacteria that exist in warm-blooded animals, but do not survive in the environment and therefore indicate recent fecal contamination. The *Bacteroides* HF183 marker has been identified to be associated with human sewage (172), while other markers, including dog-associated *Bacteroidales* (DogBact) and *Catellicoccus marimammalium* (*C. marimammalium*) (Gull2) for dogs and gulls respectively, have been utilized in assessing source-specific fecal contamination (173–175). All three markers target the 16S rRNA gene. Both dog and gull feces are known to transmit zoonotic bacterial pathogens and are therefore a concern for human health (176–180).

While no established standards exist for MST markers in recreational waters, QMRA has been utilized to estimate potential benchmark thresholds to interpret measured concentrations (10,35,40,48,183). QMRA is composed of four phases, which includes hazard identification, exposure assessment, dose-response, and risk characterization (79). Collectively, the four phases identify the microorganisms assumed to be a health risk and ultimately quantify those associated health risks within a specific exposure scenario. Concentrations of MST markers can be used in a QMRA to inform and estimate reference pathogens of concern that are known to pose a risk for GI illnesses. Previous QMRA studies regarding risk-based thresholds (RBTs) for molecular markers have focused on human and gull associated fecal sources and incorporated differential decay of pathogens and fecal indicators, varying mixtures of human and gull feces and different ages of feces (10,35,40,181).

This study utilizes previous QMRA approaches to apply a site-specific risk assessment for two popular recreational beaches impacted by human, gull, and dog fecal pollution (24,35). The scenario presented here evaluates potential fecal sources likely common at most urban public beaches and applies a framework that could be considered for different MST markers and fecal sources. This approach is an applied risk assessment utilizing field environmental MST marker data to assess human health risks that can ultimately provide guidance for beach management and protection of public health for swimmers.

4.2. **Methods**

4.2.1. **Sample collection and DNA extraction**

Researchers with the National Oceanic and Atmospheric Association (NOAA) Atlantic Oceanographic and Meteorological Laboratory and the University of Miami collected water samples at three time points daily (morning, mid-day, and late afternoon) from June 27-29, 2019 at Haulover Park and June 21-24, 2018 at Crandon Park Beaches. The samples were retrieved using a sterile 1L bottle at knee-high depth in water. Samples were then transported on ice in a cooler and delivered to the lab, upon which they were immediately filtered onto a 0.45 micron mixed cellulose ester 47mm diameter filter and stored at -80°C until processing. The FastDNA SPIN Kit for Soil (MP Biomedicals, Irvine, CA) was used for genomic DNA extraction from the filter, following the manufacturer's instructions. DNA was then eluted into 100µL of elution buffer and stored at -80°C.

4.2.2. **MST analyses**

The fecal markers, which included the human specific *Bacteroides* marker, HF183, the dog specific *Bacteroidales* marker, DogBact, and the gull specific *C. marimammalium* marker, Gull2, were enumerated using qPCR (173,175,182,183). qPCR standards for the markers were prepared utilizing stock solutions of 1e25 target sequence copies (tsc) per µL of synthetic DNA gBlock fragments (Integrated DNA Technologies, Skokie, IL). Serial dilutions of 1e6, 1e5, 1e4, 1e3, 1e2, and 1e1 tsc/ µL were performed on the stock solution for each marker. The 25µL reaction volumes included 12µL of Qiagen 2x QuantiTect Probe qPCR Master Mix, 3µL of the corresponding primers-probe mix specific for each assay, 7.5µL of PCR-grade H_2O, and 2µL DNA template (either unknown sample or quantitation standard, or the no template negative control) for each well. Samples were run in duplicates and inhibition controls were performed for the first marker tested (HF183). Each plate was run on an Applied Biosystems StepOnePlus qPCR System (Thermo Fisher Scientific, Waltham, MA) as per the cycling conditions referenced for each assay. The concentration of marker per each sample was calculated from the multiple composite qPCR standard curve data for each assay. All field work and laboratory analyses were conducted by researchers from the NOAA Atlantic Oceanographic and Meteorological Laboratory and the University of Miami.

4.2.3. **QMRA**

A QMRA was utilized to assess the risk of a GI infection and illness associated with ingestion of seawater during recreational exposure at both Crandon and Haulover Park Beaches. The MST markers, HF183, Gull2 and DogBact, identified in seawater indicate a mixture of fecal contamination sources and can be used to assess health risks in a QMRA.

Seawater can be impacted by a variety of waterborne fecal pathogens depending on the different fecal sources contaminating the recreational area. For this study, the scope was focused on a human and two non-human fecal sources, specifically from gulls and dogs. Previous work has evaluated RBTs for human and gull fecal contamination from MST markers, using HF183 for human and *C. marimammalium* for gulls (10,35,40,184). Reference pathogens were selected based upon their environmental prevalence and health risks in recreational waters and are often applied in QMRA studies (10,35,81,187,188). The specific reference pathogens used to represent the different fecal sources, human sewage, gull and dog feces, were identified from previous studies. Human sewage was selected to represent the human fecal component since no permitted or identified wastewater treatment facilities were identified to discharge at Haulover and

Crandon Beaches. A potential source likely contributing to the human fecal marker measured is bather shedding. The reference pathogens representing human sewage, norovirus, adenovirus, *Cryptosporidium*, *Giardia*, *Campylobacter*, *Salmonella* spp. and *E. coli* O157:H7, have been used in several QMRAs assessing the health risks associated with recreational waters (24,34,45,187). Gull feces have been represented by *Salmonella* and *Campylobacter* in other QMRA studies assessing non-human fecal sources (10,35,185). Canine fecal waste has not been assessed in a QMRA study before, but *Campylobacter* is identified as a pathogen of concern for pet owners and can result in pet-associated human campylobacteriosis (178,188,189). All reference pathogens selected have the health endpoint of a gastrointestinal infection and illness, commonly known as gastroenteritis.

A reference pathogen dose can be calculated from the MST marker concentration detected in recreational waters for the three different fecal sources. Concentrations of HF183, Gull2 and DogBact in raw sewage and feces were obtained from the literature (175,184,190). This study quantified the environmental concentration of *C. marimammalium* using the Gull2 marker and the concentration of *C. marimammalium* had been previously quantified in gull feces using the LeeGull MST marker (184). Both the Gull2 and LeeGull MST markers target the same region of *C. marimammalium*. LeeGull2 utilizes a different primer/probe set which amplifies a smaller PCR product (174). Concentrations of each reference pathogen in each respective fecal source was also retrieved from previous studies (84–97,99,191). Incidental ingestion of ambient seawater was distinguished between both adults and children and followed a normal distribution (192). Since pathogens from non-human fecal sources are known to not be as infectious to outside hosts, a fraction for pathogenicity for humans was used for the gull and dog pathogens (139,187,188). The input parameters utilized in the dose equation are listed in Table 4.1. This QMRA evaluates the individual risk of exposure in a static model and does not consider immunity or secondary transmission (106).

Table 4.1. Parameters and their distributions used to estimate the reference pathogen dose

Parameter	Units	Concentration	Source
HF183 measured in the environment	copies/100mL	Interval Censored: Haulover (4.38822, 2.02544)[a]; Crandon (3.78605, 1.54293)[a]	Environmental data
		Substitution: Haulover (4.50538, 1.91507[a]; Crandon (3.88925, 1.46944)[a]	
Gull2 in environment	copies/100mL	Interval Censored: Haulover (3.26340, 1.39613)[a]; Crandon (679.841, 0.388813)[b]	Environmental data
		Substitution: Haulover (67.31681, 0.93997)[b]; Crandon (835.67521, 0.44577)[b]	
DogBact in environment	copies/100mL	Interval Censored: Haulover (21.1045, 0.423840)[b]; Crandon 0 or 25[c]	Environmental data
		Substitution Haulover (63.18327, 0.90705)[b]; Crandon 0 or 25[c]	
HF183 in human sewage	copies/mL	(5.212, 0.566)[d]	(175)
Gull2 in gull waste	copies/g	(8.7,8.3)[e]	(184)[i]
DogBact marker in dog waste	copies/g	(5,9)[f]	(190)
***Campylobacter* in Dog Feces**	organisms/g	(3, 8)[f]	(198)
***Campylobacter* in Gull Feces**	CFU/g	(3.3, 6)[f]	(191)
***Salmonella* in Gull Feces**	CFU/g	(2.3, 9.0)[f]	(191)
***Salmonella* in Sewage**	CFU/L	(0.5,5)[f]	(97,98)
***Campylobacter* in Sewage**	MPN/L	(2.9,4.6)[f]	(96)
***E. coli* O157:H7 in sewage**	CFU/L	(-1,3.3)[f,j]	(95)
***Cryptosporidium* in sewage**	oocysts/L	(-0.52, 3.7)[f]	(90–92,94,100)
***Giardia* in sewage**	cysts/L	(0.51, 4.2)[f]	(89,90)
Norovirus in sewage	copy/L	(4.7, 1.5)[d]	(85)
Adenovirus in sewage	IU/L	(1.75, 3.84)[f]	(87,88,189)
Volume water ingested	adult (mL)	(32.3, 70.5)[g, k]	(192)
	children (mL)	(67.7, 160)[g, l]	(192)

Table 4.1. Continued.

Parameter	Units	Concentration	Source
Fraction of Pathogenic Species	gull	0.01-0.4[h]	(95)
	sewage	1	(95)
	dog	0.02- 0.1[h]	(178)

[a] Lognormal distribution (log mean, log standard deviation); [b] Weibull distribution (scale, shape); [c] Point estimate; [d] Log_{10}-normal distribution (mean, standard deviation);[e]Log_{10}-weibull distribution (scale, shape);[f] Log_{10}-uniform distribution (minimum, maximum);[g] normal distribution (mean, 90%); [h] uniform distribution (minimum, maximum);[i] The *C. marimammalium* concentration was estimated using the LeeGull marker in (184), but the Gull2 marker which is used in this study, identifies the same target region of *C. marimammalium*.; [j] The lower range was not detected and -1 is used as a lower bound for *E. coli* O157:H7.; [k] Ingestion value for adults age 35 and over recreating in marine water.; [l] Ingestion values for children age 6-12 recreating in marine water.

Each reference pathogen dose following incidental ingestion during contact recreation was calculated using Equation 1 (24,35,101):

Equation 1

$$dose_{RP}^{S} = \frac{C_{MST}}{F_{MST}^{S} \times 100} \times R_{RP}^{S} \times P_{S} \times V$$

where S represents each fecal source as indicated by the MST markers (human, gull and dog); MST indicates each MST marker (HF183, Gull2 and DogBact); RP refers to reference pathogen; C_{MST} is the concentration of the specific MST marker as measured in the environment (copies/100mL); F_{MST}^{S} is the concentration of the specific MST marker in sewage or feces for each fecal source (copies/mL or copies/g); R_{RP}^{S} is the concentration of the reference pathogen in the sewage or feces of each fecal source (n/g or n/L); P_{S} is the fraction of human-infectious species or serotypes; and V is the volume of water ingested (mL). A conversion factor of 0.001 is needed when calculating the reference pathogen dose for the sewage source since the R_{RP}^{S} is measured in L and the V of water ingested is measured in mL.

4.2.4. **Dose response**

A dose-response equation was used to estimate the probability of the risk of infection (P_{inf}) per an exposure event. The dose-response equations utilized were based upon feeding studies and outbreak data and included exponential, Beta-Poisson, and Fractional Poisson mathematical models. Feeding and outbreak data for *Salmonella*, *Campylobacter* and *E. coli* O157:H7 have been fit to a Beta-Poisson dose-response model (126–128,134). An exponential model has been fit to data to estimate the dose-response relationships for *Cryptosporidium*, *Giardia,* and adenovirus (131–133,199–202). Lastly, a Fractional Poisson model has been used to describe the probability of infection for norovirus (133).

Table 4.2 summarizes dose-response parameters for each reference pathogen. The probability of illness (P_{ill}) for each pathogen was estimated by multiplying the P_{inf} and the morbidity of each respective pathogen. When applicable, the morbidity or proportion of infections that result in illness was described as a value drawn from a uniform distribution.

Table 4.2. Dose-response relationships and morbidities for each reference pathogen.

Pathogen	Probability of Infection	Probability of Illness|Infection	References
Salmonella spp.	1-(1+dose/2884)^-0.3126	0.17-0.4[a]	(128,134)
Campylobacter	1-(1+(dose/7.59))^-0.145	0.1-0.6[a]	(126)
E. coli O157:H7	1-(1+(dose/48.8))^-0.248	0.2-0.6[a]	(127)
Cryptosporidium	1-exp(-0.09*dose)	0.3-0.7[a]	(131)
Giardia	1-exp(-0.01982*dose)	0.2-0.7[a]	(129,130)
Norovirus	0.72*(1-exp(-dose/1))[c]	0.3-0.8[a]	(133,135)
Adenovirus	1-exp(-dose *0.4172)	0.5[b]	(199,202)

[a] uniform distribution (minimum, maximum); [b] point estimate; [c] Full particle disaggregation is assumed with $\mu=1$

For the norovirus dose-response model, a conservative version of the model was utilized assuming full particle disaggregation (133,135,136). There is no definitive consensus on which norovirus dose-response model is most appropriate for specific environmental situations. However, for recreational waters, which tend to have higher norovirus concentrations than untreated drinking water, most norovirus dose response models predict similar values for the probability of infection (135). The other dose-relationships presented in Table 4.2 have all been used in previous recreational or drinking water QMRA studies (33,34,80,92).

The probability of illness due to exposure to a combination of the three different fecal sources, as represented by reference pathogens, was estimated using equation 2. For mixed sources that shared the same reference pathogens, the $dose_{RP}^{S}$ was calculated independently for each fecal source and then summed together to find the total $dose_{RP}$. The cumulative risk of illness combines statistically independent exposures (24,136).

Equation 2

$$P_{ill}^{S} = 1 - \prod_{RP}(1 - P_{ill,RP})$$

Crystal Ball Pro® Software (Oracle Corp., Redwood Shores, CA) was used to conduct the Monte Carlo simulations (10,000 simulations for each exposure parameter). For each simulation, the QMRA model used input parameters that are described by statistical distributions (when appropriate) to include inherent variability in the model (Table 4.1). Probability plots were developed for the interval censored MST marker concentrations using Minitab® software (Minitab LLC, State College, PA, USA). Utilizing maximum likelihood estimation (MLE), the datasets were fit to the Weibull, lognormal, exponential, loglogistic and normal distributions. Best fits for the datasets and the fitted distributions were based upon the Anderson-Darling (A-D) and Kolmogorov-Smirnov (K-S) tests. Probability plots and MLE for best fitted distributions based upon the A-D and K-S tests were also conducted using a substitution technique for the non-detects. Non-detect values were substituted with ½ the detection limit (25 copies/100 mL).

4.3. **Results**

4.3.1. **Risks based on each fecal source**

The risk of illness corresponding to each fecal source was evaluated utilizing the environmental concentrations of the MST markers and assuming an exposure scenario that included swimming or similar recreational activities for both children and adults. The risks associated with each fecal source were evaluated to see if they exceed the U.S. EPA risk standard of 0.036 (11). Both Haulover and Crandon Beaches were evaluated in this QMRA. However, since Crandon Beach did not have any detected dog fecal contamination (as indicated by non-detects for the DogBact MST marker), a scenario that assumed a concentration of the dog marker, which was represented by ½ the detection limit was included. For abbreviations, interval censored data that was fitted to a probability distribution are identified as INT and datasets that had non-detects substituted with ½ the detection limit and fitted to a distribution are identified as DL. Boxplots depicting the risk of illness for adults and children at both Crandon and Haulover Beaches are depicted in Figure 4.1 and Table 4.3.

For both beaches, the human fecal source was determined to pose the greatest risk for human health. Dog and gull fecal sources had similar overall median health risks which was at least one order of magnitude less than the health risks posed by the human source. For Haulover Beach, the median health risks for dog (7.96×10^{-5} for adults and 2.10×10^{-4} for children) and gull (4.19×10^{-5} for adults and 1.08×10^{-4} for children) were approximately one to two orders of magnitude lower than the median health risks associated with human sewage (3.15 x 10^{-3} for adults and 7.73 x 10^{-3} for children) (for the INT data). Alternatively, the health risk for the dog fecal source (4.03 x 10^{-4} for adults and 1.01 x 10^{-3} for children) was slightly greater by one order of magnitude than the health risks estimated for the gull source (6.69 x 10^{-4} for adult and 1.70 x 10^{-4} for children) when estimated with the DL data. Under both scenarios of data fitting (INT and DL), the health risks from human sewage (3.40 x 10^{-3} for adults and 8.47 x 10^{-3} for children using DL data) were one to two orders of magnitude greater than the non-human fecal sources (Figure 4.1 and Figure C-1). The overall health risks for both data methods were estimated to be 1 x 10^{-3} for adults and 1 x 10^{-2} for children.

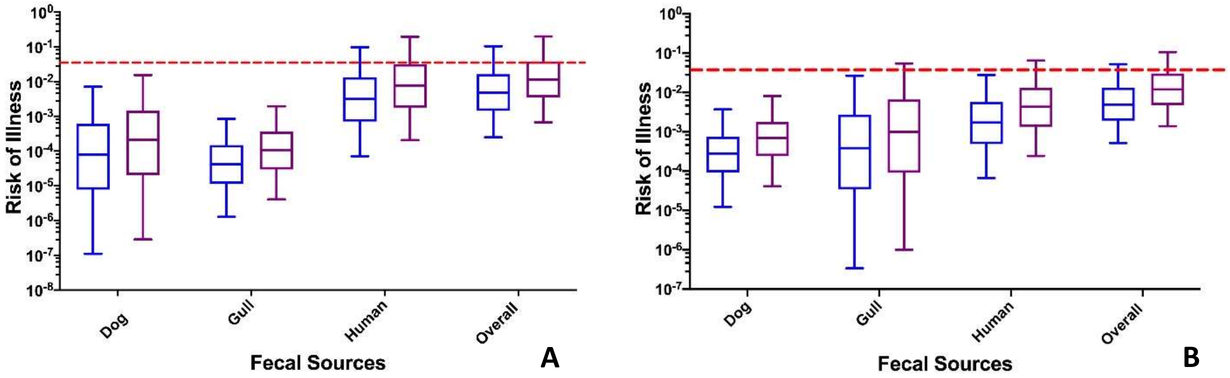
For Crandon Beach, the DogBact MST marker was not detected during sampling. Two QMRA scenarios were simulated including no dog fecal source and assuming the dog fecal source was present by utilizing a DogBact marker concentration of 25 copies/100 mL. When assuming no dog marker was present (and therefore absent of dog fecal contamination), the median health risk from the gull source (3.97 x 10^{-4} for adults and 9.97 x 10^{-4} for children) was one order of magnitude lower than the human source (1.74 x 10^{-3} for adults and 4.45 x 10^{-3} for children) (INT data) (Figure 4.1). When using the DL method for the data, the median risk of illness from the gull source (4.93 x 10^{-4} for adults and 1.32 x 10^{-3} for children) was either one order of magnitude lower or in the same order of magnitude as the median health risk from the human source (1.96 x 10^{-3} for adults and 4.77 x 10^{-3} for children) (Figure C-2). When including the dog fecal source in the QMRA, the median health risks for dog (2.78 x 10^{-4} for adults and 6.93 x

10^{-4} for children) were within the same order of magnitude as the gull fecal source (3.83 x 10^{-4} for adults and 9.90 x 10^{-4} for children) for the INT data (Figure 4.1). The health risks from human sewage (1.70 x 10^{-3} for adults and 4.31 x 10^{-3} for children) still exceeded the non-human fecal sources (INT data). Similarly, the health risk from human sewage was at least one order of magnitude greater (1.95 x 10^{-3} for adults and 4.77 x 10^{-3} for children) than the risks from dog (2.77 x 10^{-4} for adults and 6.73 x 10^{-4} for children) and gull (5.51 x 10^{-4} for adults and 1.40 x 10^{-3} for children) for the DL data (Figure C-3). Between the two scenarios which either did or did not include the dog fecal source, the overall median human health risk was estimated around 1 x 10^{-3} for adults and ranged between 1 x 10^{-2} and 1 x 10^{-3} for children.

The overall median health risk, when considering a mixture of fecal sources, was below the U.S. EPA risk threshold of 0.036. A slight difference in health risks were evident between adults and children, which is likely due to the assumed greater ingestion volume of seawater for children compared to adults (192). The health risks from the human fecal source likely drives the overall health risk when exposed to a mixture of fecal sources.

Table 4.3. Median probability of illness for both adults and children (adult|child) per each fecal source at both Haulover and Crandon Park Beaches.

Beach	Fecal Source	Median Risk of Illness (INT method)	Median Risk of Illness (DL method)
Haulover	Dog	7.96×10^{-5}|2.10×10^{-4}	4.03×10^{-4}| 1.01×10^{-3}
	Gull	4.19×10^{-5}| 1.08×10^{-4}	6.69×10^{-5}| 1.70×10^{-4}
	Human	3.15×10^{-3}|7.73×10^{-3}	3.40×10^{-3}|8.47×10^{-3}
	Overall	4.75×10^{-3}| 1.14×10^{-2}	5.73×10^{-3}|1.38×10^{-2}
Crandon	Dog	2.78×10^{-4}| 6.93×10^{-4}	2.77×10^{-4}| 6.73×10^{-4}
	Gull	3.83×10^{-4}|9.90×10^{-4}	5.51×10^{-4}| 1.40×10^{-3}
	Human	1.70×10^{-3}| 4.31×10^{-3}	1.95×10^{-3}| 4.77×10^{-3}
	Overall	4.90×10^{-3}|1.19×10^{-2}	5.47×10^{-3}| 1.30×10^{-2}
	Overall (excluding Dog)	4.07×10^{-3}| 9.95×10^{-3}	4.45×10^{-3}| 1.07×10^{-2}



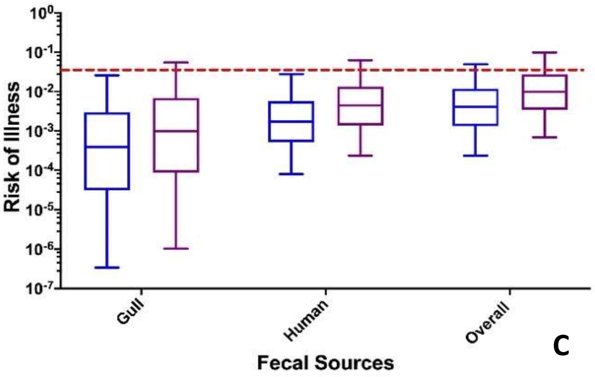


Figure 4.1. A. The risk of a GI illness per each fecal source at Haulover Beach (HF183, Gull2 and DogBact INT method for marker concentrations). B. The risk of a GI illness per each fecal source at Crandon Beach assuming a DogBact concentration of 25 copies/100 mL (HF183 and Gull2 INT method for marker concentrations). C. The risk of a GI illness per each fecal source at Crandon Beach assuming the dog fecal source is absent (HF183 and Gull2 INT method for marker concentrations). The blue boxplots represent adults and the purple boxplots represent children. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

4.3.2. **Reference pathogens**

The risk of illness for each reference pathogen was estimated to determine which pathogens may pose the greatest risk for human health. The human fecal source was represented by the greatest diversity of reference pathogens, but for gulls and dogs, only bacterial pathogens known to infect humans were evaluated. For Haulover Beach, the median risk of illness from *Campylobacter* from the dog fecal source (7.96 x 10^{-5} for adults and 2.10 x 10^{-4} for children) was estimated to be slightly greater than the median risks posed by *Campylobacter* in gull feces (6.41×10^{-6} for adults and 1.62×10^{-5} for children) and similar to the median health risks posed by *Campylobacter* in human sewage (1.49×10^{-5} for adults and 3.65×10^{-5} for children) for the INT data (Figure 4.2). For gulls, the human health risks for a GI illness associated with *Salmonella* (6.51×10^{-7} for adults and 7.96×10^{-5} for children) were greater than risks from *Campylobacter*. The human source was represented by bacteria, protozoa and viruses with norovirus having the greatest median health risk (2.97×10^{-3} for adults and 7.34×10^{-3} for children). Norovirus has been identified to dominate the health risk in other recreational and drinking water studies (33,95,139,190,203). Adenovirus has the second greatest median health risk for the human source (9.22×10^{-5} for adults and 2.24×10^{-4} for children), while *Salmonella* (2.0×10^{-9} for adults and 4.47×10^{-7} for children) and *E. coli* O157:H7 (3.0×10^{-9} for adults and 5.75×10^{-7} for children) had the lowest median health risks. The health risks associated with adenovirus were within the same order of magnitude as the health risks associated with the *Campylobacter* reference pathogen for the dog source. The median health risks for each pathogen utilizing the DL method were within an order of magnitude as the estimated health risks using the INT method (Figures 4.2 and C-4).

For Crandon Beach, when assuming the dog fecal source was present, the relative risks were similar to those identified with Haulover Beach (Figures 4.2, C-4 and C-5). When using the INT data, the risk of illness for norovirus (1.61×10^{-3} for adults and 4.10×10^{-3} for children) was again the reference pathogen with the greatest median risk. However, the median health risks from *Campylobacter* for dog (2.79×10^{-4} for adults and 6.93×10^{-4} for children) and gulls (5.55×10^{-5} for adults and 1.44×10^{-4} for children) and *Salmonella* for gulls (2.74 x 10^{-4} for adults and 7.10 x 10^{-4} for children) were within the same order of magnitude as the median health risks associated with adenovirus (4.92 x 10^{-5} for adults and 1.25 x 10^{-4} for children). For the human reference pathogens, both *Salmonella* (1.0 x 10^{-7} for adults and 2.49 x 10^{-7} for children) and *E. coli* O157:H7 (1.27 x 10^{-7} for adults and 3.23 x 10^{-7} for children) had the lowest median health risks, similar to Haulover Beach. The risk of illnesses for each reference pathogen that were estimated using the DL method were within the same order of magnitude for the health risks estimated using the INT method (Figures C-5 and C-6). The estimated health risks for each reference pathogen (under each specific fecal source) were the same under the scenarios with and without dog (Figures 4.2 and C-5). The median health risks associated with each reference pathogen for adults and children at both beaches are described in Table C-1.

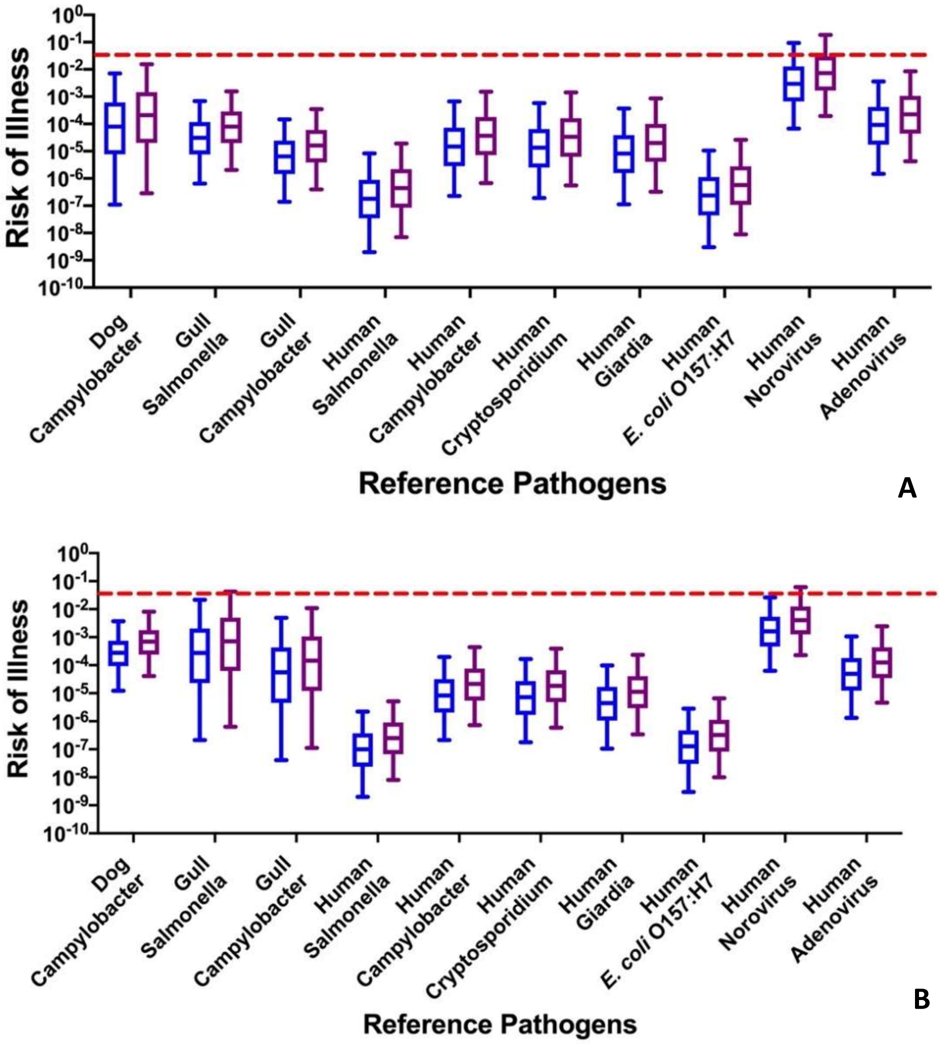


Figure 4.2. A. The risk of illness associated with each reference pathogen (using the INT data for HF183, Gull2 and DogBact MST markers) at Haulover Beach. B. The risk of illness associated with each reference pathogen at Crandon Beach and assuming a concentration of 25 copies/100 mL for the DogBact MST marker to represent the dog fecal source (HF183 and Gull2 concentrations were estimated using the INT data). The blue boxplots represent adults, and the purple boxplots represent children. The dashed red line indicates the USEPA risk threshold of 0.036.

4.3.3. **Sensitivity analysis**

A sensitivity analysis of all QMRA simulations indicated that the model is most sensitive to the concentration of the HF183 marker in seawater. For Haulover Beach, the

QMRA model was also sensitive to the adult and child ingestion rates and the DogBact concentration in the environment. However, for the Crandon Beach models, the Gull2 marker in seawater and adult and child ingestion rates were identified as being the second and third most sensitive parameters. Among all simulations for both beaches, the input parameters describing the concentrations of pathogens and MST markers in different fecal sources (i.e., in human sewage, gull or dog feces) did not appear to have as great of an influence on the risk output. The consistency in HF183 being identified as the most sensitive parameter to the risk assessment indicates that the concentration of a fecal marker or other indicator, such as a fecal indicator organisms or pathogen, likely has the greatest effect on the overall risk estimate.

4.4. **Discussion**

As indicated in this study, the GI risk from swimming or playing in water containing a mixture of human and non-human fecal sources will be driven by the human fecal source. Library-independent MST fecal markers, specifically HF183, Gull2 and DogBact, were used to represent the potential fecal contamination from sewage, gull, and canine feces. This risk study, albeit a conservative method for assessing risk at two popular recreational beaches, is an application of using MST markers to evaluate the GI risk associated with swimming or other contact activities, while utilizing a methodology that applies a ratio of MST markers in the environment and in sewage/feces to estimate pathogen concentrations (35,203).

4.4.1. **QMRA application for beach management**

Based on the environmental data, the estimated median GI risk for both Crandon and Haulover Beaches did not exceed the U.S. EPA risk threshold. However, identifying which reference pathogens and fecal sources have the greatest influence on risk is imperative for effective beach management and protecting human health. While the human source did appear to “drive” the overall health risk, both the dog and gull fecal sources had similar risks. The gull source was detected more frequently than the dog source at both beaches. The dog fecal source, while not detected at as high concentrations as the gull source, still presented a health risk as indicated by the reference pathogen *Campylobacter*. Non-detects for the DogBact marker was not surprising given that both beaches did not permit dogs. However, the presence of dog feces is still possible and may pose a health risk for individuals recreating at a beach. Gull management may be challenging to implement but limiting dogs on or upstream of recreational beaches would not only reduce potential fecal loads into the water body, but also lessen any potential health risks.

Gull feces, while not considered as great of human health risk as human sewage, should not be disregarded in beach management for public health protection. Attempts at curtailing gull presence at beaches have been implemented with successful reduction of FIB and pathogen densities (179). Dogs are often used to curtail gulls on beaches and while effective, the potential risks associated with dog feces in seawater at those beaches should be considered as well.

The human fecal source was represented by sewage, in which the human HF183 marker in sewage is predicted to have a greater median health risk than when detected in treated effluent (35). Crandon and Haulover Beaches were not determined to have any permitted wastewater outfalls, therefore assuming human sewage as the contamination source was determined appropriate for this study. This assumption also provided a conservative and protective approach for evaluating the human health risks at both beaches (10). The frequent detection of HF183 in daily samples at both beaches also indicates that the prevalence of this fecal marker is likely resulting from bather shedding.

The sensitivity analysis indicated that the MST marker concentration, specifically for HF183 and Gull2, had the greatest influence on the QMRA model. Managing the specific fecal sources, such as the human source, will likely have the greatest impact on reducing the uncertainty on the risk of illness estimates. Although frequency typically drives microbial infection risks, this study demonstrates the importance of source identification when addressing GI illnesses from predicted infections. Therefore, beach management should continue to target minimizing contamination from human and non-human fecal sources, if possible, given those are primary factors influencing risk.

Lastly, a revised RBT for fecal contamination of unknown age was determined to be 525 copies/100 mL for HF183 and 200,000 copies/100 mL for gull feces (10). Both beaches had individual HF183 sample concentrations that exceeded the 525 copies/100 mL risk threshold, but their geometric averages were identified to be below that threshold value (Table C-2). Similarly, the geometric averages for the Gull2 marker were below the recommended RBT. This study assumed fresh contamination of sewage, gull, and dog feces (three contributing fecal sources), which could indicate why the overall median risk of illness may be only one order of magnitude less than the risk threshold of 0.036. The risk of illness outcomes estimated in this study do align with published RBTs (10). Applying these proposed RBTs in a real-world context is not only informative for evaluating site-specific recreational water quality, but useful in assessing the appropriateness of these thresholds for beach management.

4.4.2. **Study limitations**

Certain assumptions and limitations in the study design and QMRA may have had an impact on the overall risk output. It was assumed that the fecal sources of human sewage, dog, and gull feces, were all fresh with no aging, which is a similar approached used in other QMRAs (24,35). Recent QMRAs have incorporated fecal aging but have indicated that fecal sources are likely composed of a mixture of ages and overall risk estimates may be sensitive to the decay rate constant used for certain pathogens, such as norovirus (10). Future risk assessments utilizing environmental data could be refined to include pathogen and MST marker decay, and those ratios of decay may influence health risk outcomes. Refining approaches of risk analyses that are conservative and have incorporated unknown and mixed ages of fecal sources could help develop a robust risk simulation for beach managers. However, the approach presented in this study provides a conservative risk estimate and protection for human health.

This QMRA study relied upon input parameters and dose-response relationships gathered from the literature. The pathogen and MST concentrations, ingestion volumes and range of morbidity for pathogens, likely vary among different environments.

Assumptions must be made to incorporate these values into the risk assessment and are assumed to be the best available information at this time.

Utilizing MST markers for site-specific risk assessments is an advancement in recreational water quality monitoring, but there are limitations associated with these markers. MST markers are not 100% host specific and sensitive, such as with the Gull2 marker, which has expressed limited cross-reactivity with other seabird species (171,182). However, assessing health risks associated with MST markers-as opposed to FIB concentrations-provides greater insight into the variety of fecal sources impacting a water body, better informing targeted application of best management practices. Personnel with skilled training, laboratory infrastructure and funding are necessary for this approach of utilizing molecular markers for beach monitoring. While these are limitations, if molecular data are available or the resources are available for site-specific MST, this approach should be pursued.

4.4.3. **Future studies**

While seawater was assessed as a route of exposure in this study, beach sand is another environmental component that could cause an array of health issues, besides that of GI illnesses. MST markers were evaluated in dry sand at both beaches and all three fecal markers were detected, especially HF183. Few QMRA studies have examined human health risks from exposure to beach sand (201), indicating the need for future work. Besides oral ingestion, dermal abrasions can be another area of concern for beach sediment. Future work assessing microbial risks from beach sands, especially in the context of MST markers, may provide insight into the relative health risks associated with different environmental media. While GI illnesses were the health risk of interest in this study, other pathogens can originate from human sewage and dog and gull feces that cause adverse health outcomes, such as skin rashes. *Pseudomona*s and adenovirus are fecal pathogens known to cause skin irritations in marine waters and have been documented to co-occur with FIB (202).

4.5. **Conclusion**

This risk study is the first approach of utilizing environmental MST marker data for different fecal sources at popular recreational beaches in a QMRA. The QMRA study can serve as a starting point for beach managers to assess health risks from not only human sewage and gull feces, but also dog feces. While the detection of traditional FIB has been useful for managing water quality-limitations, such as with environmental regrowth and persistence-have posed challenges for adequately assessing recreational water quality and safety. Applied approaches of utilizing site-specific environmental MST data in QMRA studies that can be developed not only by public health practitioners, but also by water quality and beach managers, will ultimately help direct budgeted resources and implementing management strategies that are most protective for the public. The benefit of targeting specific fecal sources in risk analyses for beach management should not be overlooked, given the economic importance of marine tourism for coastal communities.

5. SUMMARY

The studies conducted in this dissertation evaluated microbial risks in different water systems via QMRA and a survey. The health risks associated with exposure to pathogens in both drinking and recreational waters are still a significant threat to public health and require both analytical and social science driven approaches to mitigate risks. The research presented in this dissertation conveyed the importance of characterizing exposure pathways, whether via direct or indirect ingestion of water, and understanding community concerns and perspectives regarding water management to inform public health practices.

5.1. **Evaluating microbial health risks of flood-impacted private wells**

Characterizing human health risks associated with exposure to microbial contaminants in flood impacted private wells is a critical step towards mitigating exposure risks for private well owners. Well water management is exempt from the water quality requirements of the Safe Drinking Water Act, therefore requiring well owners to ensure the safety and quality of their own water. This study was the first application of utilizing QMRA to evaluate the human health risks associated with exposure to fecal pathogens, as represented by *E. coli*, and opportunistic pathogens, as indicated by *L. pneumophila*, in Texas wells. Reference pathogen doses developed from *E. coli* concentrations were utilized in the risk assessment. The two reference pathogens associated with the greatest health risk for a GI infection included norovirus and *Cryptosporidium*. Under the drinking water exposure scenario, those two reference pathogens had median risk values that exceeded the U.S. EPA risk of infection threshold for both adult and child subgroups. Compared to the other bacterial (*Salmonella*, *Campylobacter*, and *E. coli* O157:H7) and protozoan (*Giardia* and *Cryptosporidium*) reference pathogens, norovirus dominated the overall human health risk and exceeded the median risk by 1-2 orders of magnitude compared to the other pathogens. Similar to several other recreational and drinking water studies, norovirus was the reference pathogen of greatest public health concern for a GI infection (3,10,24,187,203,204)

Indirect exposure risks, defined as incidental ingestion of well water while either bathing (child), showering (adult), brushing teeth, flushing the toilet, and rinsing food and dishes were not identified to be a significant health risk that exceeded U.S. EPA risk thresholds; however, the median risk of a GI infection from norovirus was identified to meet the risk threshold for bathing (1.78×10^{-6}) and food and dish washing (1.79×10^{-6}). The other reference pathogens were not identified to contribute to human health risks that exceeded the risk threshold. However, specific exposure pathways, particularly bathing, showering, and food and dishwashing, may pose a greater health risk if floodwaters have contaminated a well, given the health risks associated with norovirus.

While a conservative risk assessment framework was utilized to evaluate exposure to *L. pneumophila,* daily and annual risks for a respiratory infection exceeded the U.S. EPA risk threshold for both adults and children in the showering exposure scenario (adult: 2.4×10^{-6} (daily) and 8.45×10^{-4} (annual); child: 2.43×10^{-6} (daily) and 8.58×10^{-4} (annual)). Toilet flushing and running a faucet in an enclosed area were not identified to be exposure pathways that would result in an elevated health risk. The overall human health risk estimate (including exposure to all three pathways) exceeded daily and annual risk thresholds for both adults and children (adult: 5.56×10^{-5} (daily) and 1.94×10^{-2} (annual); child: 5.27×10^{-5} (daily) and 1.83×10^{-2} (annual)); while the risk assessment presented in the study was conservative, it provided a preliminary characterization of exposure risks for well owners to this specific opportunistic pathogen.

Overall, the study provided a broad characterization of human health risks associated with fecal and opportunistic pathogens that may be present in flood-impacted well water. Evaluating these risks in context of well owner concerns and stewardship practices can assist in identifying research opportunities to better understand the public health risks associated with flood-impacted wells. Further, these health risk estimates can help inform emergency response and educational outreach to well owners impacted by not only floods, but other natural disaster events.

5.2. **Evaluation of well owner perceptions and practices after Hurricane Harvey**

The previous study estimated associated health risks for well owners potentially exposed to contaminated well water, while this study surveyed well owners regarding their perceptions of their well water safety and well stewardship practices three years after Hurricane Harvey. Participants in the study had previously received well water testing immediately after Hurricane Harvey and received educational information regarding well testing and well system maintenance after a natural disaster.

The majority of participants (77.6%) indicated that they believe their well water is safe, especially for drinking, cooking, and bathing, and well water testing (44.8%) and well system disinfection (46.3%) were reported at relatively greater proportions than previously published well stewardship rates (150). Similarly, a greater proportion of participants indicated that they felt their well water was safe without recently testing their well water since the flood (55.4%), than well owners who recently tested their well water since the flood and felt that their water was safe (44.9%). Contrary to many studies, socio-demographic characteristics, specifically for education and annual income, were not identified to be significant predictors impacting well water testing and disinfection (150,158,164,165). Only the perception regarding "I feel my water is safe for cooking" was identified to be different between the two educational groups (Table 3.3). Similarly, well owner perceptions regarding well water safety did not differ significantly for annual income, education, or county of residence, indicating that the effects of flooding on private wells from Hurricane Harvey did not differentially impact well owners who had participated in this study.

The information gained from this study generally indicated that well owners perceived their well water to be safe. Slightly less than half of participants had completed recommended well water testing and disinfection (if necessary), emphasizing the critical public health need for continued educational outreach. Improving well owner awareness, especially in areas likely to be impacted by natural disasters, is necessary to help mitigate potential well water contamination risks and waterborne infections. The survey administered in this study was an informative tool to gage well owner concerns and practices, which is necessary to strengthen risk communication and outreach to these vulnerable communities.

5.3. **QMRA of recreational beaches impacted by dog, gull, and human fecal sources**

Site-specific human health risk assessments at recreational beaches have the potential to improve watershed management in a more targeted approach. Two public beaches in Miami, FL, Haulover and Crandon Beaches, were identified to be impacted by human, dog, and gull fecal sources, based upon on the detection of fecal markers utilizing MST techniques. The QMRA that was developed did not identify an elevated human health risk (for a GI illness) at either beach (or for either adults or children), according to the U.S.EPA risk threshold of 0.036 (Table 4.3). However, the work built upon prior QMRA studies completed that evaluated human health risks at beaches impacted by human and gull fecal contamination (10,34,35,40).

Of the three fecal sources that were represented in the study, the human source posed the great human health risk for a GI infection. The reference pathogen, norovirus, much like in the in the first study, dominated the overall health risk estimate. Dog and gulls were identified to have similar risks, although the risks of infection were at least one order of magnitude lower than the risks posed by the human fecal source. Children were identified to have a slightly elevated health risk for a GI infection than adults, which is likely due to a greater assumed ingestion volume of water while recreating than for adults (Table 4.3 and Figure 4.1). Ultimately, the health risks presented by the human fecal source appeared to "drive" the overall risk estimate for a GI infection for both adults and children.

Library independent MST markers, as presented in this study, have the potential to better inform watershed and beach management practices, potentially influencing beach advisories in the future. Targeting sources of human fecal contamination may be more practical than attempting to manage wildlife sources. Fecal sources, such as from domestic pets, could be a manageable pollutant source as well. The detected concentrations of MST markers were compared to the MST marker thresholds presented in previous work (10), and while this study was a conservative and applied approach of utilizing environmental molecular marker data in a QMRA to evaluate site-specific risks at public beaches, they were identified to align with the risk of illness estimates gathered in this study.

Future work should include further application of previously published RBTs of MST marker concentrations at other recreational sites to better evaluate the appropriateness of these thresholds. QMRAs that evaluate the health risks associated with beach sand and other environmental media remains limited and warrant further investigation as health risks from recreational waters do not occur in isolated environments. Lastly, other fecal pathogens exist, including *Pseudomonas* and adenovirus, that can result in non-GI illnesses, such as skin rashes, and are likely underestimated.

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APPENDIX A

APPENDIX FOR ASSESSING HEALTH RISKS ASSOCIATED WITH CONTAMINATED WATER WELLS AFTER HURRICANE HARVEY

Table A-1. Daily risk of infection for each age group and reference pathogen for drinking water

	Reference Pathogen					
Age Group	***Cryptosporidium***	***E. coli* O157:H7**	***Giardia***	**Norovirus**	***Salmonella***	***Campylobacter***
Infant	2.5591E-06	5.73E-09	1.73E-07	5.2501E-05	6.54E-09	4.53E-07
Age 2-6	2.3718E-06	5.31E-09	1.60E-07	4.8659E-05	6.06E-09	4.20E-07
Age 6-16	4.057E-06	9.08E-09	2.74E-07	8.3231E-05	2.84E-09	7.18E-07
Adult	7.802E-06	1.75E-08	5.28E-07	1.6005E-04	1.99E-08	1.3817E-06

Table A-1. Daily risk of infection for indirect ingestion exposure scenarios

Reference Pathogen	**Bathing**	**Showering**	**Brushing Teeth**	**Toilet Flushing**	**Washing Produce and Dishes**
Campylobacter	4.66137E-07	4.3203E-07	1.13692E-09	8.52691E-10	3.97923E-09
Cryptosporidium	8.13062E-08	2.38696E-09	1.65132E-08	1.892E-09	7.56823E-08
***E. coli* O157:H7**	5.68574E-09	5.26971E-09	1.3868E-11	1.0401E-11	4.8537E-11
Giardia	1.37434E-10	4.295E-12	3.0841E-11	3.392E-12	1.36576E-10
Norovirus	1.77669E-06	5.76636E-08	3.82443E-07	4.25618E-08	1.78795E-06
Salmonella	6.69518E-10	6.20529E-10	1.63292E-12	1.22458E-12	5.7154E-12

Table A-2. Daily and annual risks of infection for *Legionella*

Exposure	**Daily Median Risk of Illness**		**Annual Median Risk of Illness**	
	Adult	Child	Adult	Child
Showering	2.40185E-06	2.43355E-06	8.45066E-04	8.58219E-04
Faucet	3.18725E-07	2.82277E-07	1.10662E-04	9.82467E-05
Toilet Flushing	1.18662E-08	1.17843E-08	4.34201E-06	4.27745E-06
Overall	5.55831E-05	5.26602E-05	1.941289E-02	1.8299298E-02

APPENDIX B

APPENDIX FOR EVALUATION OF WELL OWNER PERCEPTIONS AND PRACTICES AFTER HURRICANE HARVEY

Howdy,

You are receiving this e-mail since you completed an initial survey and had your well water tested after Hurricane Harvey between September and October 2017. Your participation in the initial survey helped us learn how to better serve well owners affected by hurricanes. Researchers with the Texas Well Owner Network and Texas A&M AgriLife are conducting a follow-up study on how perceptions of well water quality and well management have changed in the three years since Hurricane Harvey.

We would be very grateful for your continued assistance by completing the follow-up survey at your earliest convenience. The deadline for responses is the end of the day on [month] [date], [year]. The survey will take no longer than 10-15 minutes to complete.

Your survey responses will help inform researchers about well owner concerns and behaviors. This information is critical for assessing communication and education needs for future natural disaster preparation and response.

All personal information and survey responses will be kept anonymous and confidential.

If you would like to participate in the follow-up study, the survey can be completed by clicking this link: Take the Survey
Or copy and paste the URL below into your internet browser: https://agrilife.az1.qualtrics.com/jfe/preview/SV_cYHSHyKrWNvoNSd?Q_CHL=preview
Please feel free to ask questions regarding this study. You may contact us by reaching out to Anna Gitter at anna.gitter@ag.tamu.edu or Dr. Diane E. Boellstorff at dboellstorff@tamu.edu.

Thank you,

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IRB Number: IRB2017-0760M
IRB Approval Date: 06/07/2020
IRB Expiration Date: 12/06/2022

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TWON
TEXAS
Well Owner
NETWORK

Texas A&M
AgriLife
Extension

TEXAS A&M
AGRILIFE
EXTENSION

DEPARTMENT OF SOIL AND CROP SCIENCES

Thank you for volunteering to participate in our research study. Your participation in this study will help us better understand private well water quality and perceptions about water quality a couple years after a major flooding event. Results from this effort will be published to document the patterns and trends observed, but your survey responses will be kept strictly confidential. By submitting the online survey, you consent to participate in this study.

Participation in this study entails:

- Completing an online survey about your perceptions of your well water quality and well management practices (will take approximately 15 minutes).

For questions about your rights as a research participant, to provide input regarding research, or if you have questions, complaints, or concerns about the research, you may call the Texas A&M University Human Research Protection Program office by phone at 1-979-458-4067, or by email at **irb@tamu.edu.**

If you have any questions or would like to discuss details of this study further, please contact me at dboellstorff@tamu.edu or (979) 458-3562.

Thank you.

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IRB NUMBER: IRB2017-0760

IRB APPROVAL DATE: 12/07/2017 IRB EXPIRATION DATE: 12/06/2022

WELL SYSTEM INFORMATION

1. Does anyone in your home drink the water from your kitchen tap?
   ☐ Yes, with filter/treatment ☐ Yes, but not with filter/treatment ☐ No

   <u>IF YES</u>, about how much well water do you and your family drink on average for each person in a day?

   ☐ 2 cups ☐ 4 cups ☐ 6 cups ☐ 8 cups ☐ I don't know

   ☐ Other amount: ____________________________

2. What water treatment devices are currently installed? ***Check all that apply*:**
   ☐ None ☐ Iron removal ☐Chlorinator ☐ Sediment filter

   ☐ Acid neutralizer ☐ Water softener ☐ Reverse osmosis

   ☐ Ultraviolet (UV) light ☐ Activated carbon (charcoal) filter

   ☐ Other (please describe):_________________________________

   If you have treatment, is it: ☐ tap-mounted unit ☐ whole house filter ☐ mixture ☐ not applicable

   If you have treatment, was it added after Hurricane Harvey: ☐ Yes ☐ No ☐ Don't know

FLOODING AFTER HURRICANE HARVEY

3. If your well head was submerged under floodwater during Harvey, has the casing of the well been raised to above the level of the previous flood?
   ☐ Yes, have raised the casing ☐ No, haven't raised the casing

☐ Well head wasn't submerged ☐ I don't know if the well head was submerged

4. List all the ways in which you use(d) your well water. ***Check all that apply:***
   <u>BEFORE FLOOD</u>: ☐ Cooking ☐ Drinking ☐ Bathing ☐ Pets ☐ Other: ___________

   <u>AFTER FLOOD</u>: ☐ Cooking ☐ Drinking ☐ Bathing ☐ Pets ☐ Other: ___________

5. What were (or are) your family's primary sources of drinking water? ***Check all that apply:***
   <u>BEFORE FLOOD</u>: ☐Unfiltered well water ☐Bottled or purchased water
   ☐ Filtered/treated well water ☐ Other: ___________________

   <u>AFTER FLOOD:</u> ☐Unfiltered well water ☐Bottled or purchased water
   ☐ Filtered/treated well water ☐ Other: __________________

<u>If you chose "bottled or purchased water", is it due to taste or odor issues?</u>

☐ Yes ☐ No ☐ Don't know

6. Please indicate your level of agreement by circling the appropriate number **(<u>1 = disagree; 5 = agree</u>)**.

CURRENTLY		
Disagree	Neutral	Agree

I feel my well water is safe to drink

1	2	3	4	5

I feel my well water is safe for cooking

1	2	3	4	5

I feel my well water is safe for bathing

1	2	3	4	5

WELL WATER TESTING AND WELL MAINTENANCE

7. Have you ever had your well system disinfected?

☐ Yes, we did it ourselves ☐ Yes, someone else did it ☐ No ☐ Don't know

<u>IF YES</u>, when was the last time? ______________________________

<u>IF YES</u>, why did you disinfect?

☐Concern for contamination from flooding/heavy rains ☐Taste/odor issues ☐Routine maintenance

☐Positive bacteria test

<u>IF NO</u>, why not? ***Check all that apply*:**

☐ Too expensive ☐ Don't drink or cook with well water ☐ Not a priority

☐ Not a concern ☐ Don't know how to ☐ Meant to but didn't

☐ Not sure of benefit ☐ Other (please describe): ______________________________________

8. Do you test your water more frequently **SINCE THE FLOOD?**
   ☐ Yes ☐ No ☐ Don't know

IF YES, what did you test for?

☐ Chemicals ☐ Bacteria ☐ I'm Not Sure ☐ Other, please list: _____________________________

IF YES, roughly when was your well last tested? _____________________________

IF YES, how many times have you tested your water **SINCE THE FLOOD (SEPTEMBER 2017)**?

☐ once ☐ 2-3x ☐ greater than 3x

IF NO, or you do not test as often as you would like, why not? ***Check all that apply***:

☐ Too expensive ☐ Don't drink or cook with it ☐ Not a priority or concern
☐ No Transportation ☐ Don't know where to get it tested ☐ Other:
____

9. Do you feel that your water is safe?
   ☐ Yes ☐ No ☐ Don't know

IF NO, what concerns do you have about your water's quality?

☐ Bacteria in water
☐ Nutrients (nitrate)
☐ Chemicals or metals (lead or arsenic) in water
☐ Taste, odor or appearance problems
☐ Too expensive to treat water
☐ Too expensive to fix well
☐ Not sure how to treat water
☐ Not sure how to have water tested
☐ Myself or someone else became ill from the water
☐ Other: ____________

KNOWLEDGE, RESOURCES, INFORMATION AND BEHAVIOR

10. Please indicate your level of agreement by circling the appropriate number **(1 = disagree; 5 = agree)**.

Disagree **Neutral** **Agree**

I am comfortable managing my well (testing, treating, and maintaining)

1	2	3	4	5

I know where to find information about my well characteristics (e.g., depth, year constructed)

1	2	3	4	5

Disagree **Neutral** **Agree**

I know where to find information about well water testing services

1	2	3	4	5

I know where to find information about well water treatment systems

1	2	3	4	5

11. What is the best way to contact you to provide you with information? ***Check all that apply***
☐Television ☐Radio ☐Phone calls ☐ Text messages ☐ Email
☐ Newspaper ☐ US Mail ☐ Twitter ☐ Facebook ☐ News websites ☐ Government website
☐ Leave info at stores ☐ Leave info at gas stations ☐ Leave info at post offices
☐ Community members ☐ Other: ____

FAMILY

12. Do you believe anyone in your house got sick from consuming your well water **SINCE THE FLOOD**?
☐ Don't know ☐No ☐Yes ☐Not applicable

IF YES OR DON'T KNOW: Identify symptoms you observed in household members you suspect may have gotten ill from consuming the well water: ***Check all that apply***.

☐Diarrhea ☐Weight loss ☐Fatigue ☐Bloating ☐Fever

☐Increased gas ☐Nausea ☐Cramps ☐Vomiting ☐Muscle aches

☐Other (Any other symptom that is not listed above. Please list any other symptoms that you believe you may experienced.): ______________________________

13. Any well-related issues or concerns we haven't discussed?

Table B- 1. Perceptions of well water and well stewardship by annual income, education, and county of residence of well owners

Variable	Annual Income				Education			Location		
	$45,000 or less	$45,001-$85,000	$85,000 or greater	P-value	Less than a bachelor's degree	Greater than a bachelor's degree	P-value	Victoria and Wharton Counties	Other Counties	P-value
Does anyone in your home drink well water from the kitchen tap?				0.112[1]			0.108[1]			0.936
Yes, but with filter/treatment	50% (5)	20% (4)	53.8% (7)		21.7% (5)	41.5% (17)		36.1% (13)	34.4% (11)	
Yes, but not with filter/treatment	20% (2)	55% (11)	15.4% (2)		52.2% (12)	26.8% (11)		33.3% (12)	37.5% (12)	
No	30% (3)	25% (5)	30.8% (4)		26.1% (6)	31.7% (13)		30.6% (11)	28.1% (9)	
Do you feel that well water is safe?				0.569[1]			0.984[1]			0.99[1]
Yes	100% (9)	95% (19)	100% (13)		77.3% (17)	77.5% (31)		97.1% (34)	96.8% (30)	
No/Don't Know	0% (0)	5% (1)	0% (0)		22.7% (5)	22.5% (9)		2.9% (1)	3.2% (1)	
Have you had your well tested since the flood?				0.495[1]			0.903[1]			0.620[1]
Yes	55.6% (5)	45% (9)	30.8% (4)		40.9% (9)	42.5% (17)		40% (14)	48.4% (15)	
No or Don't Know	44.4% (4)	55% (11)	69.2% (9)		59.1% (13)	57.5% (23)		60% (21)	51.6% (16)	
Have you ever had your well system disinfected?				0.496[1]			0.706[1]			0.99[1]
Yes (by myself or someone else)	33.3% (3)	35% (7)	53.8% (7)		50% (11)	45% (18)		45.7% (16)	45.2% (14)	
No or Don't Know	66.7% (6)	65% (13)	46.2% (6)		50% (11)	55% (22)		54.3% (19)	54.8% (17)	

[1] Fischer's exact test; significance is defined as $p<0.05$

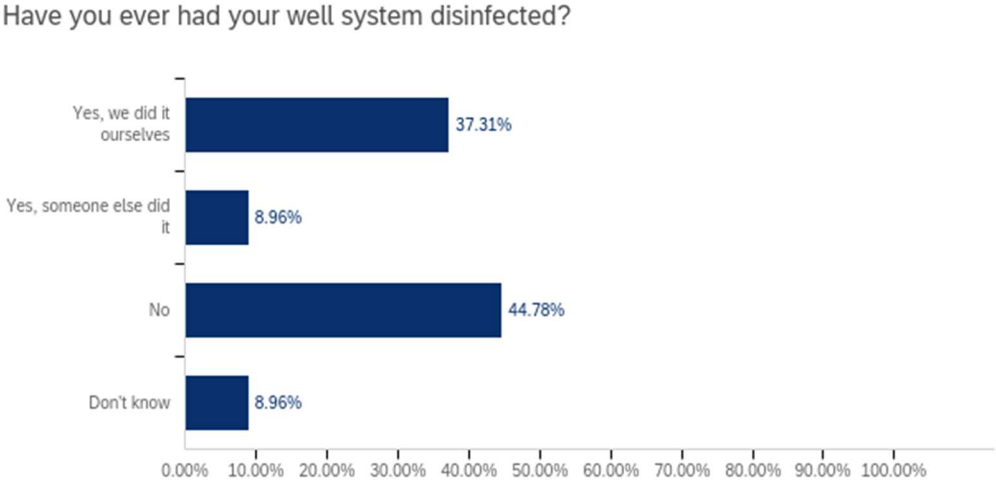

Figure B- 1. Well system disinfection practices

Table B- 2. Well system disinfection practices as reported by well owners

Well system disinfected	Percentage	Count
Yes, we did it ourselves	37.31%	25
Yes, someone else did it	8.96%	6
No	44.78%	30
Don't know	8.96%	6
Total	100%	67

Table B- 3. Reported reasons for disinfecting wells

Reason for disinfecting	Percentage	Count
Concern for contamination from flooding/heavy rains	41.9%	13
Positive bacteria test	22.6%	7
Taste/odor issues	12.9%	4
Routine maintenance	22.6%	7
Total	100%	31

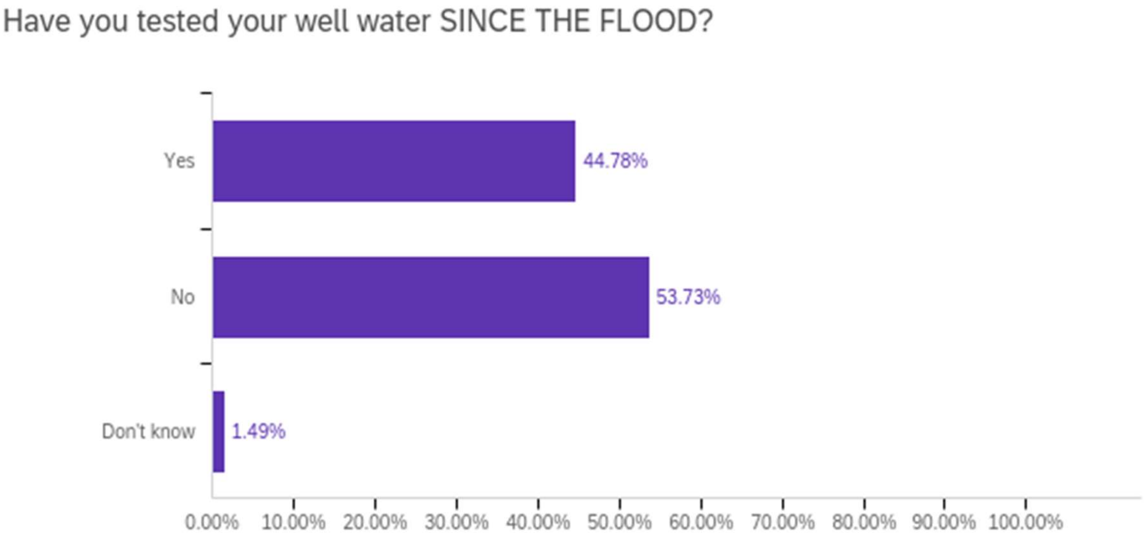

Figure B- 2. Well testing after Hurricane Harvey flooding

Table B- 4. Well water testing after Hurricane Harvey flooding

Well Water Tested	Percentage	Count
Yes	44.78%	30
No	53.73%	36
Don't know	1.49%	1
Total	100%	67

Table B- 5. Crosstabulation of well water testing and well system disinfection by well owners

		Tested Well Since the Flood?		Total
		Yes	No or Don’t Know	
Ever have well disinfected?	Yes, by self or someone else did it	16 (53.3%)	15 (40.5%)	31 (46.3%)
	No or Don’t Know	14 (46.7%)	59.5% (22)	36 (53.7%)
Total		30 (100%)	37 (100%)	67 (100%)

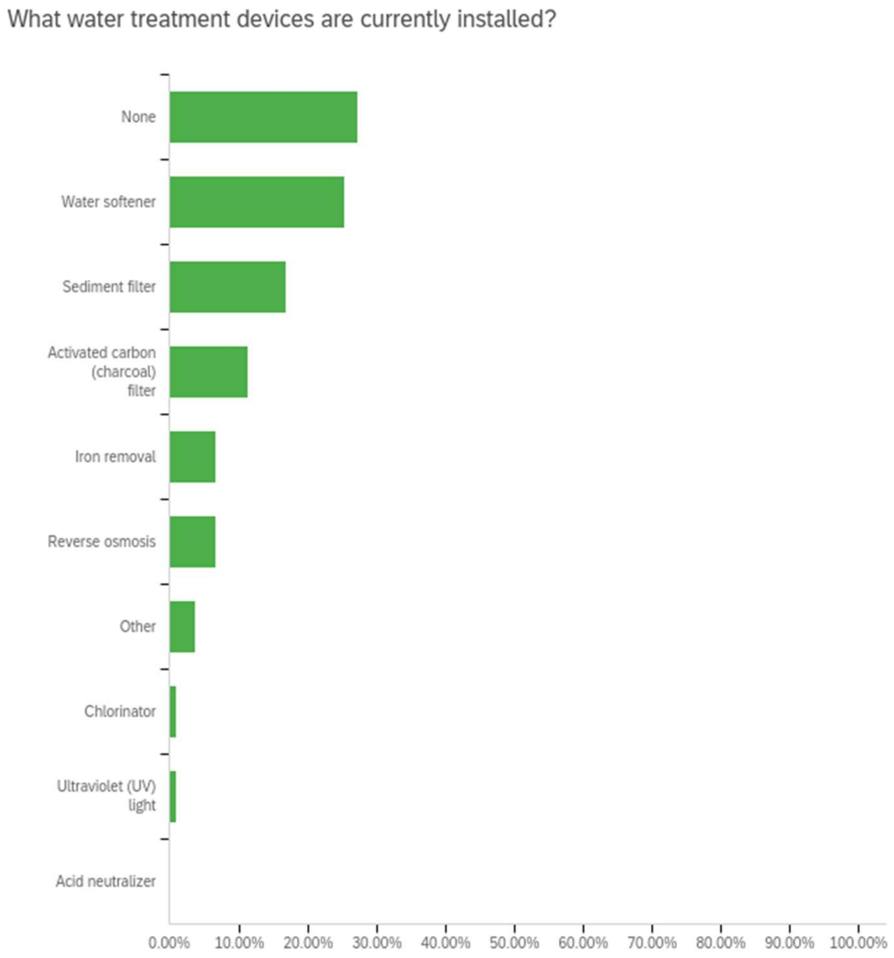

Figure B- 3. Water treatment devices reported to be used by well owners

Table B- 6. Well water treatment devices reported to be used by well owners

Treatment Device	Percentage	Count
None	27.36%	29
Iron removal	6.60%	7
Chlorinator	0.94%	1
Sediment filter	16.98%	18
Acid neutralizer	0.00%	0
Water softener	25.47%	27
Reverse osmosis	6.60%	7
Ultraviolet (UV) light	0.94%	1
Activated carbon (charcoal) filter	11.32%	12
Other	3.77%	4
Total	100%	106

APPENDIX C

APPENDIX C FOR QMRA OF RECREATIONAL BEACHES IMPACTED BY DOG, GULL AND HUMAN FECAL SOURCES

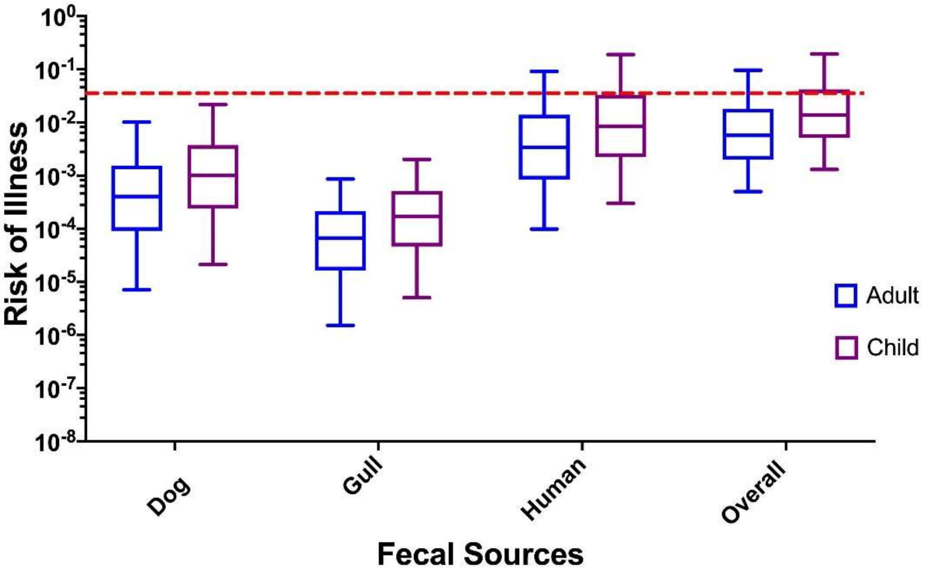

Figure C- 1. The risk of a GI illness per each fecal source at Haulover Beach. HF183, Gull2 and DogBact marker concentrations were estimated using the DL approach. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

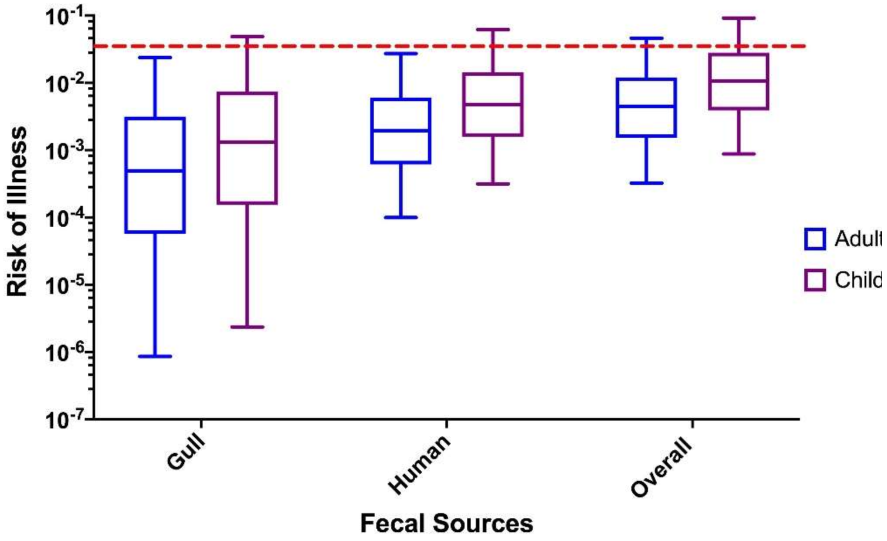

Figure C- 2. The risk of a GI illness per each fecal source at Crandon Beach (without the dog fecal source present). HF183 and Gull2 marker concentrations were estimated using the DL approach. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

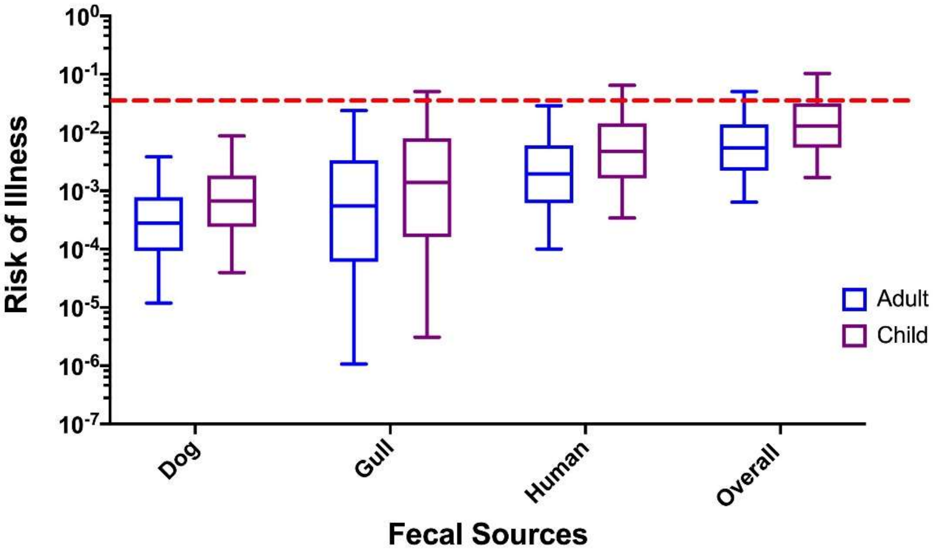

Figure C- 3. The risk of a GI illness per each fecal source at Crandon Beach. HF183 and Gull2 marker concentrations were estimated using the DL approach. DogBact marker concentration was assumed to be 25 copies/100 mL. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

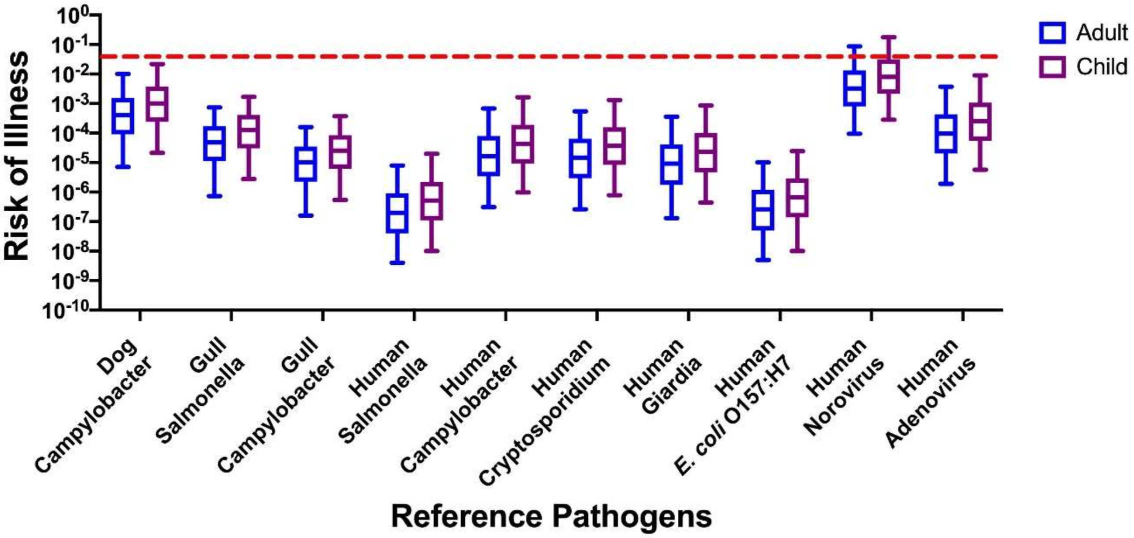

Figure C- 4. The risk of illness associated with each reference pathogen at Haulover Beach. HF183, Gull2 and DogBact marker concentrations were estimated using the INT method. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

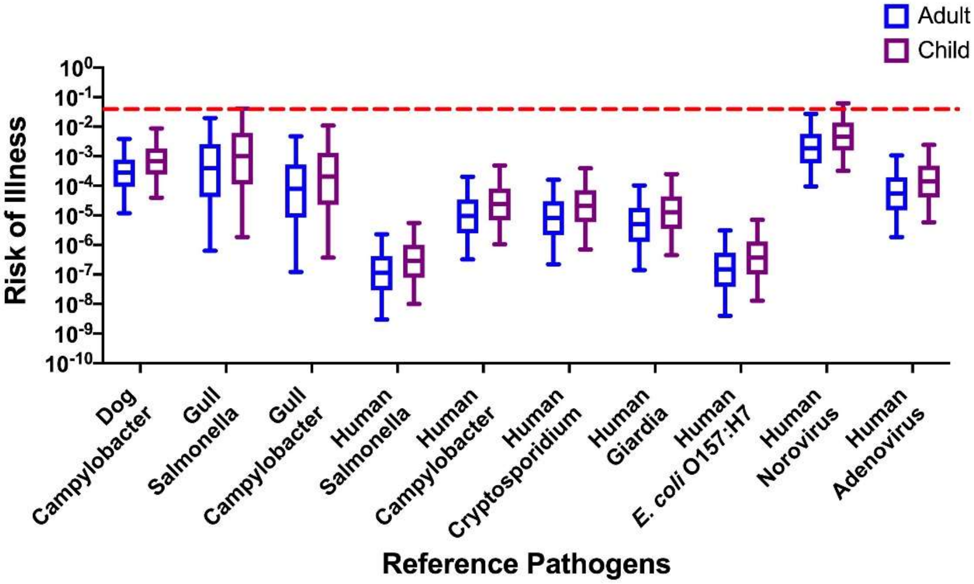

Figure C- 5. The risk of illness associated with each reference pathogen at Crandon Beach and assuming a concentration of the DogBact MST marker (25 copies/100 mL) to represent the dog fecal source. HF183 and Gull2 marker concentrations were estimated using the DL method. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

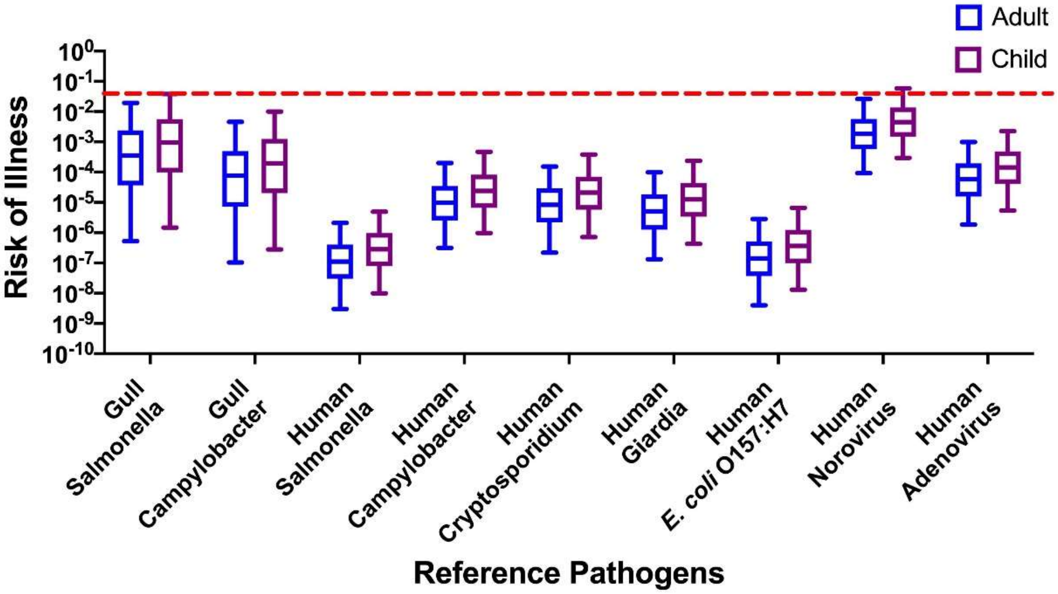

Figure C- 6. The risk of illness associated with each reference pathogen at Crandon Beach assuming no dog fecal source was present. HF183 and Gull2 marker concentrations were estimated using the DL approach. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

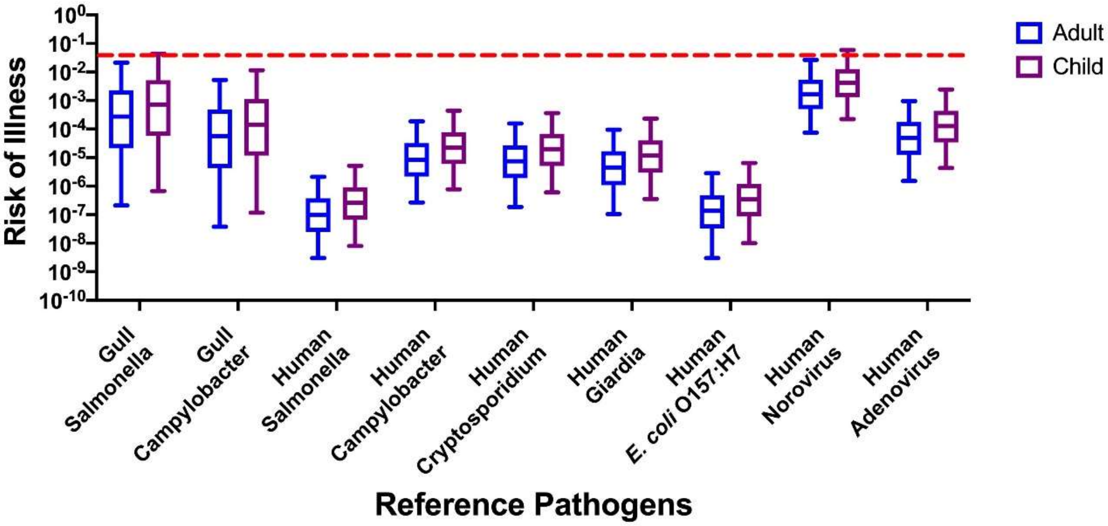

Figure C- 7. The risk of illness associated with each reference pathogen at Crandon Beach, assuming no dog fecal source was present. HF183 and Gull2 marker concentrations were estimated using the INT method. The dashed red line indicates the U.S. EPA risk threshold of 0.036.

Table C- 1. Median risk of GI illness for each reference pathogen at both Haulover and Crandon Beaches

		Median Risk of Illness (INT method)		**Median Risk of Illness (DL method)**	
Beach	**Reference Pathogen**	**Adult**	**Child**	**Adult**	**Child**
Haulover	Adenovirus	0.000092208	0.000223712	0.00009588	0.00025212
	Norovirus	0.002972967	0.007339024	0.00322231	0.00796983
	Campylobacter (Human)	0.000014867	0.000036516	0.00001639	0.00004307
	Cryptosporidium	0.000013475	0.000033542	0.00001462	0.00003687
	Giardia	0.000008259	0.000020064	0.00000921	0.00002297
	E. coli O157:H7	3.00E-09	5.75E-07	2.60E-07	6.60E-07
	Salmonella (Human)	2.00E-09	4.47E-07	4.00E-08	5.20E-07
	Campylobacter (Dog)	0.000079576	0.000209643	0.00040279	0.00101076
	Campylobacter (Gull)	0.000006411	0.000016195	0.00001007	0.00002533
	Salmonella (Gull)	6.51E-07	0.000079613	0.00004841	0.00012546
Crandon (excluding Dog)	Adenovirus	0.000049188	0.000127453	0.000058258	0.000143577
	Norovirus	0.001642857	0.004202154	0.001841371	0.004497322
	Campylobacter (Human)	0.000008395	0.000022085	0.000009709	0.000024083
	Cryptosporidium	0.000007486	0.000019762	0.000008383	0.000020988
	Giardia	0.000004487	0.000011902	0.000005066	0.000012582
	E. coli O157:H7	1.37E-07	3.42E-07	1.41E-07	3.65E-07
	Salmonella (Human)	9.90E-08	2.59E-07	1.10E-07	2.83E-07
	Campylobacter (Gull)	0.000056362	0.000143246	0.000076009	0.000196587
	Salmonella (Gull)	0.000276472	0.00072579	0.000352556	0.000951991
Crandon (with Dog)	Adenovirus	0.000049198	0.000125108	0.000055332	0.000139558
	Norovirus	0.001606472	0.004063127	0.001854772	0.004546536
	Campylobacter (Human)	0.000008239	0.000021557	0.000009626	0.000023862
	Cryptosporidium	0.000007248	0.000018374	0.000008222	0.000020657
	Giardia	0.000004444	0.000011213	0.000005029	0.000012659
	E. coli O157:H7	1.27E-07	3.23E-07	1.49E-07	3.69E-07
	Salmonella (Human)	1.00E-07	2.49E-07	1.14E-07	2.88E-07
	Campylobacter (Dog)	0.000278493	0.000692811	0.000277155	0.000673204
	Campylobacter (Gull)	0.000055542	0.000144378	0.000079719	0.000206656
	Salmonella (Gull)	0.000273707	0.000706906	0.000396627	0.000997568

Table C- 2. Geometric averages of MST markers (gene copies/100 mL) measured in recreational waters at Haulover and Crandon Beaches

Fecal Marker	**Haulover Beach**	**Crandon Beach**
HF183	84.66	48.87
Gull2	79.77	265.71
DogBact	34.61	ND