THE GEOGRAPHY OF GROUNDWATER QUALITY AND CHILDHOOD DIARRHEAL
DISEASE IN BANGLADESH

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A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in
partial fulfillment of the requirements for the degree of Doctor of Philosophy in the
Department of Geography.

Chapel Hill
2011

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ABSTRACT

VERONICA ESCAMILLA: The Geography of Groundwater Quality and Childhood
Diarrheal Disease in Bangladesh
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Serre)

Childhood diarrhea persists in Bangladesh despite efforts to shift from surface water
to groundwater for drinking. It is unknown whether shallow aquifer groundwater extracted
through tubewells is a significant source of disease or if other sources such as surface water
and local sanitation are driving transmission. Using the disease ecology framework, this
study explores the influence of poor sanitation on diarrheal disease transmission. Specific
questions addressed in this study include: 1) Does poor sanitation influence shallow tubewell
water quality? 2) Does fecal contamination of tubewells influence diarrheal disease? 3) Does
the neighborhood water and sanitation infrastructure affect childhood diarrheal disease
incidence above and beyond household factors? 4) Does poor sanitation influence diarrheal
disease via bathing ponds? 5) Does obtaining drinking water from deep tubewells have a
protective effect against childhood diarrhea incidence?

This study integrates groundwater microbial data, health and demographic
surveillance data, and detailed spatial data of the water and sanitation infrastructure in six
villages in Matlab, Bangladesh. The relationship between groundwater quality and poor
sanitation is measured at multiple scales using geographic analysis tools. Direct and indirect
sanitation influences on childhood diarrheal disease (2002-2006) are explored using

neighborhood latrine metrics, and bathing pond latrine metrics. A deep tubewell arsenic mitigation intervention is also examined to determine whether children drinking from deep tubewells experience less diarrhea than children drinking from shallow wells.

Results suggest that poor sanitation is predictive of both groundwater contamination and diarrheal disease. Children living in neighborhoods with insufficient access to septic latrines experience higher diarrhea incidence. Additionally, children living near bathing ponds surrounded by latrines leaking effluent also have a higher incidence. While deep tubewells were installed for arsenic mitigation, they are also protective against diarrheal disease. These results shed light on the importance of integrating population and environment data to identify particular circumstances in which groundwater is compromised and children are at risk of contracting diarrheal diseases. These results suggest that poor sanitation diminishes the effect of improved drinking water sources and improvements to the built sanitation infrastructure are needed to reduce diarrheal disease incidence.

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CHAPTER 1

INTRODUCTION

Diarrheal diseases are the second leading cause of death in children under 5 worldwide responsible for 1.5 million annual deaths (1). Children living in impoverished areas with inadequate nutrition and poor health are most susceptible to severe diarrhea and dehydration. Diarrheal diseases remain endemic where improved water and sanitation sources are limited. Fifteen countries, including Bangladesh, account for nearly three quarters of child deaths caused by diarrhea. In response to high child mortality rates Bangladesh experienced a nearly universal shift from surface water to ground water consumption. Since the 1970's, millions of predominantly domestic shallow (<140 ft) tubewells have been installed throughout the country. Handpump wells are installed with a hand percussion drilling method (Figure 1.1) that bores a hole in the ground where Polyvinyl chloride (PVC) pipe is lowered to the shallow aquifer (2). Some tubewells are built with a concrete platform to prevent standing water from seeping around the annulus (Figure 1.2). Shallow tubewells are installed by local residents and are affordable to individual households or small groups of households. The mass installation of tubewells and groundwater consumption are attributed to the decline in diarrhea induced child mortality. Despite the decline in mortality, diarrhea morbidity remains high.

Figure 1.1: Tubewell installation

Delayed sanitation improvements can often reduce the effectiveness of improved water resource interventions. Simultaneous improvements in sanitation and water resources are synergistic and can reduce incidence of child and infant diarrhea (3, 4). In 2000, the United Nations set eight Millennium Development Goals (MDGs) for improving the human condition by 2015. The aim of the 7th goal is to reduce the proportion of people without sustainable access to safe drinking water and basic sanitation by half, by 2015. In 2010, it was suggested that Bangladesh is on track to meet this goal if changes are made to current policy and program efforts. While an estimated 72% of the rural population in Bangladesh

obtains drinking water from improved sources, less than 40% have access to improved

sanitation (5).

Figure 1.2 Shallow tubewell

Drinking water can be contaminated at the source or often becomes contaminated

between collection and point-of-use (6). However, it is unknown whether shallow aquifer

groundwater extracted through tubewells is a significant source of disease or if other sources

such as surface water are driving transmission. Few studies have measured the simultaneous

effects of the water and sanitation infrastructure on diarrheal disease incidence (7). This

study considers the varied environmental circumstances surrounding surface and

groundwater sources to better understand drivers of diarrheal disease. Diarrheal diseases are

often studied at the individual-level and do not account for neighborhood effects making it

difficult to distinguish the effects of the household and community infrastructure.

The objective of my dissertation is to measure how characteristics of the water and sanitation environment affect diarrheal disease and determine when tubewells are a source of transmission and when they are protective. This study also seeks to understand the effect of the neighborhood water and sanitation infrastructure on household diarrheal morbidity. This research is guided by the following questions and hypotheses:

(1) Does poor sanitation influence shallow tubewell water quality?

(2) Does fecal contamination of tubewells influence diarrheal disease?

(3) Does the neighborhood water and sanitation infrastructure affect

   childhood diarrheal disease incidence above and beyond household factors?

(4) Does poor sanitation influence diarrheal disease via bathing ponds?

(5) Does obtaining drinking water from deep tubewells have a protective effect

   against childhood diarrhea incidence?

These research questions were selected to address gaps in the current literature by utilizing an ecological framework with detailed geographic data: 1) This research incorporates groundwater microbial data, spatial data, and health data to explore the relationship between surface contamination from poor sanitation and drinking water quality. The novelty of this approach is the use of detailed data representing the quality and count of latrines at multiple spatial scales. It also remains unknown whether groundwater or surface water is more influential for diarrheal disease transmission, and this study explores these differences. 2) Existing research focuses predominantly on water quality interventions rather than simultaneously measuring the effects of improved or unimproved water and sanitation resources. This study incorporates detailed spatial data describing the quality of the water and sanitation infrastructure. Additionally, this research measures the role of community

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sanitation by exploring potential neighborhood boundaries. 3) Finally, this study measures the potential protective effect of deep public tubewells installed in a rural region of Bangladesh. While deep tubewells (>700ft) were installed in 2005 to mitigate the consumption of arsenic contaminated water, before this dissertation, it was unknown if this intervention provides a protective effect against diarrheal morbidity.

Background

Diarrheal Disease: Transmission and Treatment

Diarrhea is caused by various pathogens including viruses, bacteria, and protozoa. Diarrhea is defined as "having loose or watery stools at least three times per day" (1). Transmission most commonly occurs through fecal-oral routes usually by drinking water contaminated with fecal material from an infected person. Other forms of transmission include person-to-person contact and ingestion of contaminated food (8). Children living in economically disadvantaged areas that are densely populated with poor sanitation are exposed to a variety of organisms that cause diarrheal disease (9). Rotavirus and Enterotoxigenic *Escherichia coli* (ETEC) are the most common pathogens causing diarrhea in children under two years of age (10). Cases of childhood diarrhea are easily treated and often mild. However, acute cases can result in severe dehydration increasing the risk of malnutrition, stunted growth, and death (9, 11-14). The three main forms of acute diarrhea include acute watery, bloody, and persistent diarrhea. Infection from *Vibrio cholerae* or *Escherichia coli* (*E. coli*) bacteria, as well as rotavirus most often cause acute watery diarrhea. Bloody diarrhea is predominantly caused by the bacterial agent *Shigella*, and is the

most common cause of severe cases. Persistent diarrhea is defined as "an episode with or without blood that lasts at least 14 days" (1).

Escherichia coli, Rotavirus, and Vibrio cholerae agents cause watery diarrhea through varying levels of infectious pathogenic doses and incubation periods (10, 15). Enterotoxigenic E. coli requires a large infective dose ranging from 100 million to 10 billion organisms with an incubation period lasting 1 to 3 days. Rotavirus has an incubation period of approximately 2 days. Feces contaminated with rotavirus can contain more than 10 trillion infectious particles per gram, while 10-100 particles are sufficient to transmit infection (16, 17). The incubation period for cholera lasts from 2 hours to 5 days. Ingestion of a dose of 10,000 to one million V. cholerae bacteria can cause infection resulting in acute watery diarrhea that is often referred to as rice water diarrhea as flecks of mucus are expunged in the process (8). Shigellosis is caused by bacteria in the Shigella genus and causes diarrhea containing blood or mucus (18). The incubation period varies from 12 hours to 7 days but typically lasts 2-4 days and is inversely proportional to the load of ingested bacteria. As few as ten bacterial cells can infect an individual, causing fever, nausea, vomiting, stomach cramps, and dysentery (19).

The administration of oral rehydration solution (ORS), a mixture of glucose, sodium chloride, potassium chloride, and trisodium citrate, remains the most common form of rehydration treatment for diarrheal illness. Beginning ORS therapy at an early stage of infection lessens the severity of the effects. Severely dehydrated patients are treated with intravenous fluids and antibiotics. Beginning the course of antibiotic treatment on the first day of onset shortens the course of diarrhea. Currently, only 39% of children with diarrhea in developing countries receive the recommended treatment (1).

Diarrheal Disease in Bangladesh

Rotavirus, Enterotoxigenic *Escherichia coli*, *Shigella sp.*, and *Vibrio cholerae 01* are major pathogens of diarrheal disease in children under five in Bangladesh (20). Diarrheal disease incidence peaks at different times throughout the year. Bangladesh experiences two seasonal cholera outbreaks: pre-monsoon season between March and June, and post-monsoon season between September and December. Rotavirus incidence is constant throughout the year with a sharp winter peak and a small monsoon peak. The winter peak is observed worldwide while the monsoon peak is specific to temperate climates. The monsoon peak is associated with high water levels causing rivers to rise and inundate surrounding areas, thus increasing the chance of fecal contamination of ground and surface water (21). *E. coli* incidence is most common during the hot months when food is most contaminated due to higher bacterial growth caused by high temperatures (22, 23). Reported *Shigella* incidence is highest during the monsoon season with a smaller peak in winter months (24).

In all instances, contaminated fecal material from an infected person can contaminate water sources through various means. These include ground and surface water exposure to latrine effluent. If excreta disposal is absent, other measures of water treatment must be taken. Boiling water is a very effective method of killing microbial contaminants in water, but due to the cost of limited fuel resources this option is not currently practical in rural Bangladesh. Previous research identified a 25% reduction in diarrhea morbidity with improved water availability, a 22% reduction from improved excreta disposal, and a 16% reduction from water quality improvements, suggesting that water and sanitation improvements should occur simultaneously (25). Other transmission factors identified in

Bangladesh include population density, proximity to surface water, and living within a flood-controlled area (26, 27).

Groundwater Contamination

Access to safe water supply is conducive for the prevention of diarrheal disease transmission. In order to meet the World Health Organization (WHO) drinking water guidelines, *E. coli* should not be detectable in a 100ml water sample as *E. coli* is exclusively fecal in origin. Groundwater is generally of good quality and suitable for drinking but can become contaminated. The slow movement of groundwater makes prevention of microbial contamination easier than prevention of surface water contamination (28). Common sources of microbial contamination include on-site sanitation, open wells, and open surface water sources such as ponds. The WHO recommends that contamination sources, including latrines, be installed downhill at a minimum of 10 meters from the tubewell (28).

Shallow tubewell groundwater contamination can occur through direct and indirect localized pathways. Contamination from direct localized pathways occurs when pathogens migrate through subsoil from the base of a latrine into the water table. Lateral migration carries the pathogens to the base of the tubewell where entry occurs through defective casing (29). On-site sanitation systems, including pit and septic latrines, store waste at the point of disposal.[1] There is usually some degree of waste decomposition on site, but latrines require periodic emptying or construction of new facilities once full. Septic tanks typically hold solids in a sealed tank where matter decomposes anaerobically. Some septic tanks use a straight pipe to drain full tanks. Areas with pit latrines that are unsealed and leaking pose a

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[1] Pit latrines are constructed by digging a pit in the ground for feces disposal. Septic latrines are constructed by laying 3 or more concrete rings in a pit in the ground. A slab with an opening is placed above the rings and an outhouse is built over the tank.

contamination threat to groundwater covered by only a few meters of permeable soil (30). In some instances, pit latrines can microbiologically impact groundwater quality up to a 25 m lateral distance (31). Another potential source of tubewell water contamination is through direct human contact with the spout (29).

Indirect localized pathways develop as a result of poor tubewell construction. This provides a mechanism for contaminated surface water intake around the wellhead. Surface water seeps behind the tubewell casing contaminating shallow groundwater. Poor tubewell construction removes the opportunity for natural attenuation of microbes on the subsurface through die-off and predation. Survival and breakthrough of microbes on the subsurface vary and are dependent on local and seasonal conditions. Increased breakthrough following rainfall is widely recorded (29).

High quality well construction is essential for preventing groundwater pollution. This includes constructing wells with a concrete base, and maximizing the distance between groundwater and contamination sources (28, 29). Rainwater and other running water can easily contaminate tubewells lacking platforms (32). When space is limited and population is dense, tubewell depths should be greater to prevent lateral transfer of contaminated groundwater (29).

Groundwater and Diarrheal Disease in Bangladesh

In 1999, a massive campaign was initiated to test tubewells in areas of Bangladesh most affected by naturally occurring high levels of arsenic (33, 34). One major intervention was the installation of tens of thousands of deep wells funded by the government and non-government organizations (NGOs). However, in 2004, the National Policy for Arsenic Mitigation (NPAM) considered deep tubewells a low-priority intervention. The NPAM

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encouraged people to revert to drinking surface water (e.g. ponds, canals) or very shallow groundwater without sufficient consideration of the increased likelihood of exposure to microbial pathogens (34).

Shallow groundwater and surface water can become contaminated in areas with poor sanitation (35, 36). Currently over 90% of households in Bangladesh obtain their drinking water from tubewells, but diarrheal disease incidence persists. Households often drink from tubewells that are adjacent to a latrine because it is nearest to the dwelling despite the potential risk of ingesting contaminated groundwater. However it is possible that a threshold for ingesting microbial contamination exists, suggesting that the quality of groundwater, unless grossly contaminated, is not as important as other mechanisms of transmission (37).

In rural Bangladesh, people are aware that tubewell water is a safer source of drinking water, but continue to use surface water for non-drinking purposes including bathing, washing, and oral rinsing (38). Therefore, in addition to quality, the quantity of water from an improved source (tubewell) is also important for disease prevention (39-43). Significant water quantity improves overall hygiene by enabling households to use groundwater for other daily needs rather than relying on surface water that receives human waste from surrounding latrines, exposing people to fecal pathogens (40, 44).

Sanitation and Diarrheal Disease

An understanding of the efficacy of comprehensive intervention strategies remains low because studies predominantly focus on water quality rather than sustainable improvements in sanitation (7, 39, 45). Water interventions have limited health benefits when sanitation remains poor. Consequently, children living in households in close proximity to a tubewell that use a latrine for feces disposal have a lower risk of diarrheal morbidity (25, 42,

46). Previous studies have also noted that improvements in water quality and sanitation at the household level are not enough to reduce risk of diarrheal disease when the local environment has a poor sanitation infrastructure (47, 48). Lack of affordability contributes to unsanitary environments where households share latrines and practice open defecation. Sanitary latrines are characterized by a lack of bad smell, lack of flies and rodents, private, and have zero evidence of excreta polluting the ground (47, 49). Unsanitary latrines include open or hanging latrines, a dug hole, and septic latrines leaking human effluent (50). Sanitary latrines effectively prevent human contact with excreta while unsanitary latrines expose people to human effluent.

A sanitation intervention study conducted in Lesotho (51) found that the promotion and construction of improved latrines resulted in fewer diarrhea episodes in children under five. Improved latrines were most influential when better hygiene was practiced and more water was used in daily functions. Studies throughout the world have found higher levels of diarrheal disease among individuals using unsanitary latrines and among individuals living in areas lacking sufficient latrines for all residents (40, 47, 50, 52, 53). These studies suggest that the role of sanitation is integral to understanding diarrheal disease transmission and prevention.

The installation of household latrines has been identified as a cost-effective measure for preventing diarrheal disease transmission (54), however latrines require periodic emptying or construction of new facilities once they fill up (30) resulting in an economic concern for residents in rural Bangladesh (49). Open defecation by children in the family compound and inattention to proper disposal of garbage and feces increase the opportunity for young children to place waste products in their mouth (40). Since few people are able to

afford soap, alternative hand-washing practices are used. These include rubbing hands on the ground and scrubbing hands with soil or ash after defecation (39). Concentration of fecal coliforms in soil varied based on location. Soil near the kitchen was less contaminated than soil near a latrine and wet soil near a latrine had the highest level of fecal coliforms (39). Latrines discharging effluent on the ground contaminate soil, potentially enhancing the risk for transmission as people use this soil to cleanse their hands. Unsanitary latrines further expose people to microbial contaminants through surface run-off washing human excrement into surface water sources used for hand-washing (39). Contaminants in surface water used for hand-washing and other household purposes highlight the importance of sealed latrines, located a safe distance from water sources.

Indicators of Socioeconomic Status and Diarrheal Disease

The relationship between socioeconomic status (SES) and diarrheal disease is noted throughout the developing world (55). Socioeconomic status is interrelated with behavior and access to safe water and sanitation as the cost of resources is a concern for residents (56). For example, the cost of installing a private tubewell is the approximate equivalent of one month of a household's salary (34). Shallow domestic tubewells are installed using a hand percussion drilling method that is affordable for individual households however cost increases substantially as depth increases (57). Thus it is not economically feasible for residents to install deep tubewells that are several hundred feet deep and reduce the risk of both microbial and arsenic contamination. Tubewells that tap into the aquifer 200 m or more below the surface are much more expensive than shallow tubewells but generally provide safe drinking water. The cost of shallow tubewells (20-30 m depth) installed in Matlab,

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Bangladesh is between US$ 80-100 compared with the cost of wells deeper than 200 m between US$ 600-650 (58).

Maternal education status is a strong indicator of household SES. Higher levels of maternal education are also associated with improved hygiene, lower levels of childhood diarrheal morbidity, and greater likelihood of seeking medical attention when children experience acute illness (9, 52, 59). Households with higher SES are more likely to use soap and have relatively good hand-washing practices such as more vigorous hand scrubbing and an increased volume of rinsing water (39, 60, 61). Resource availability varies given particular socioeconomic contexts. Some neighborhoods may lack resources while others do not. Therefore, it is important to measure neighborhood influences on individual health (62).

Research Framework

This dissertation project lies within the conceptual framework of *disease ecology* and analytical framework of *neighborhoods and health*. Both bodies of work are motivated by the idea that health is an interaction of characteristics that are not purely individually-based. Within the framework of *disease ecology*, interactions between biological, cultural, and environmental traits have both positive and negative effects on health. The framework of *neighborhoods and health* complements *disease ecology* by measuring interactions between individual- and area-level characteristics within the boundary of a defined neighborhood. Thus, the principles of both frameworks provide the foundation for a more holistic understanding of diarrheal disease transmission.

Theoretical Framework: Disease Ecology

This research project measures the relationship between the local social and built environment and childhood diarrheal disease using the principles of *disease ecology* within the sub-discipline of medical geography. Dr. Jacques May, author of Ecology of Disease (1958), was the first to approach medical geography within the context of *disease ecology* by uniting the fields of medicine and geography. *Disease ecology* is concerned with "the ways human behavior, in its cultural and socioeconomic context, interacts with environmental conditions to transmit or prevent disease among susceptible people" (63). Disease is not the result of a specific etiology but rather the result of various interactions between host, environment, and culture (64, 65). For example, cholera transmission is not simply the result of ingesting water containing the bacteria, *Vibrio cholerae,* but rather the interaction of an individual's behavior, population, and environment characteristics such as poor hand-washing practices and bathing in contaminated surface water. Human health is a dynamic system in which humans are capable of impacting their own environment, which can in turn affect health. Varying degrees and types of hazards exist in the environment and impact health at different magnitudes (66).

The triangle of human ecology provides a structure in which the ecology of a disease is organized within three vertices representing the interaction between habitat, population, and behavioral traits (Figure 1.3) (63). An individual's habitat consists of the natural, social, and built environment. Habitat is the part of the environment that directly affects an individual's health including the home, workplace, schools, and transportation systems. The population vertex encompasses biological features including age, sex, and genetic characteristics that may cause susceptibility or resistance to certain infections. Behavioral

traits are comprised of cultural norms, mobility, roles in society, and technical interventions. Behaviors such as hand-washing or bathing in a pond can either protect or expose an individual to pathogens. In this sense, culture has a significant influence on individual and community level disease transmission and resistance (63).

The triangle of human ecology is used to explore potential factors contributing to childhood diarrheal disease transmission (Figure 1.3). The population vertex includes age because children under five are most susceptible to diarrheal disease and are most commonly infected by Rotavirus, followed by Enterotoxigenic *Escherichia coli* (ETEC) (9, 20). Nutritional status and previous diarrhea infections influence a child's susceptibility. Undernutrition is associated with diarrhea incidence and can also prolong the infection (67). In addition, cell-mediated immune deficiency is associated with increased diarrhea incidence as well as blood type(67) Diarrhea caused by ETEC is more common in children with blood types 'AB' or 'A' compared to children with blood type 'O' (13). Previous infections may serve as a protective buffer as children build immunity against subsequent infection and the severity of diarrhea is reduced with each new infection (68).

Several aspects of the built environment are hypothesized to influence diarrheal disease. Point source pollution sources such as unsanitary latrines and ponds directly expose individuals to contaminants. These point sources can also affect an individual's health by contaminating the shallow aquifer that provides drinking water pumped from shallow tubewells. The local water infrastructure is an integral component of the built environment that influences diarrheal disease. Specifically, the quantity and quality of tubewells available to a household or neighborhood impact health. Deep tubewells are typically less contaminated than shallow wells. Greater quantities of tubewells increase access to

groundwater and can influence hygienic behavior. Additionally, population density and area-level SES may negatively influence health outcomes. Low area-level SES may affect the nutritional status of the neighborhood and may limit the quantity and quality of water and sanitation resources. In addition, high population density places strain on already scarce resources and increases opportunities to interact with individuals that may practice poor hygiene.

Figure 1.3: Framework describing the disease ecology of childhood diarrheal disease transmission
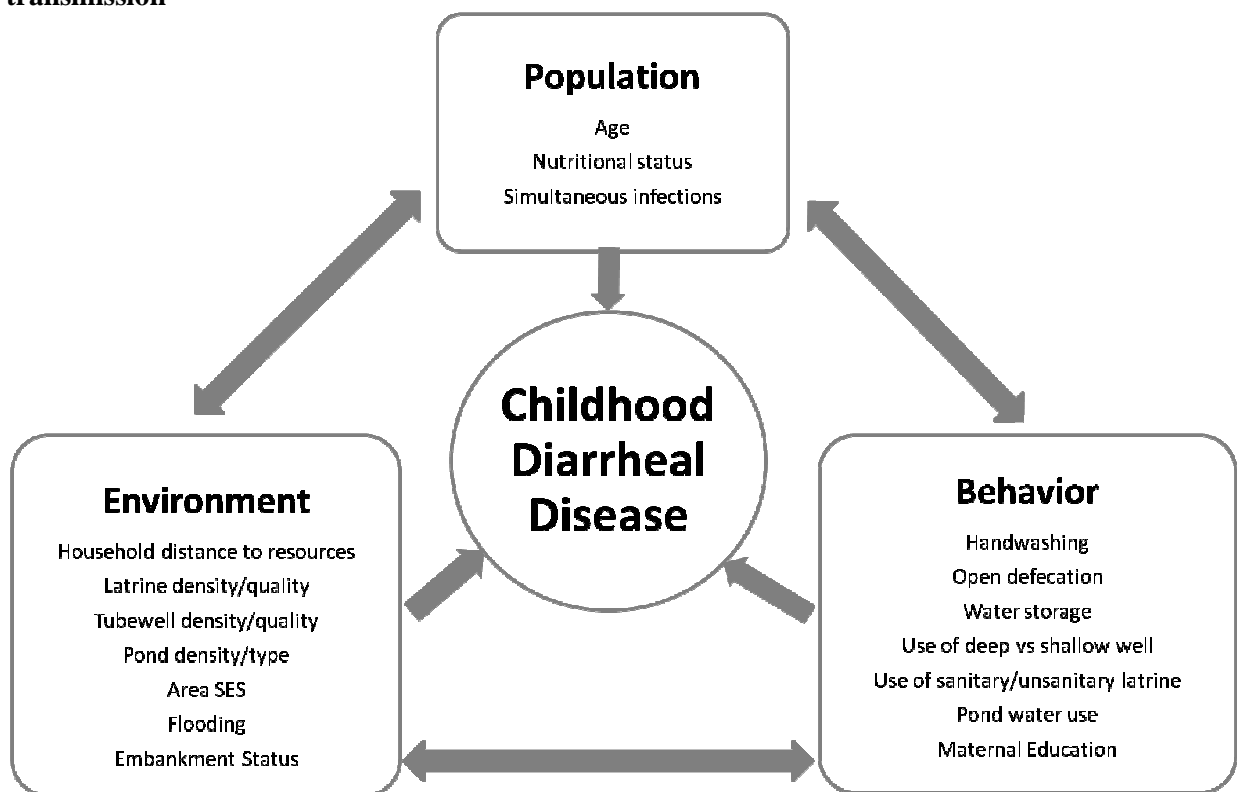
An important aspect of the natural environment is flooding during monsoon season. At this time ponds may overflow and spread water contaminated with human waste across the surface. Thus households located in areas with high pond and latrine density are expected to report higher incidence when flooding occurs. Nutritional impacts of flooding are expected to vary between households located inside and those located outside of the embankment.

Households living within the embankment do not experience flooding during the monsoon, allowing an additional annual rice crop, potentially improving nutritional status.

Cultural norms and behaviors influence individual- and neighborhood-level resistance and susceptibility to disease transmission. Many households obtain drinking water from the nearest tubewell. Tubewells are often shallow and poorly constructed, located in close proximity to a pit latrine. However, some households leave their dwelling to obtain drinking water from deep public tubewells. It is possible that persons obtaining drinking water from deep tubewells experience less diarrheal disease. Deep tubewells are expected to have a protective effect as levels of *E. coli* and fecal coliforms decrease with depth. Another important behavior to note is the practice of open defecation. In Bangladesh, very young children do not use latrines but defecate near the dwelling. The waste is often disposed into shallow ponds used for trash or latrine discharge. The practice of open defecation and improper disposal of feces increases the risk of young children coming in direct contact with human waste and ingesting contaminated fecal material (40, 69).

Bathing ponds provide water for multiple uses including washing clothes and dishes, cooking, and in some cases oral rinsing. In addition, ponds are often used to rinse fruit or vegetables. In these instances the fruit consumed immediately after rinsing becomes a transmission source. Pond water is also used for hand-washing. Hand-washing with surface water rather than tubewell water increases exposure to contaminated water. If a person handling food uses surface water for hand-washing they may expose others to diarrhea transmission. In all instances an individual is at risk of ingesting diarrhea pathogens because surface water is highly contaminated with fecal material. When children bath or swim in

ponds they are more likely to ingest microbial contaminated water compared with children bathing with tubewell water.

Two very important behaviors that are not captured in this study but have been noted in previous research are water storage and hand-washing practices. Water storage practices vary by household and can serve as buffers or exposures to transmission. Storing water in covered clay pots prevents individuals from placing hands in the container. Stored water can become contaminated if the utensil used is washed in pond water, however washing storage containers with soap and groundwater can prevent drinking water contamination. In some instances people use rain water storage bins for drinking water and other household needs. However, this practice is rarely used because it does not rain year round and people do not always clean the filter. If the filter is not cleaned properly this method of water collection and storage is no longer protective.

Improved hand-washing practices are also important for preventing the spread of fecal contamination through handling food and stored water. The frequency and quality of hand-washing is influenced by socioeconomic status and maternal education. Maternal education has a protective effect against childhood morbidity and has previously been associated with improved hygiene and higher levels of socioeconomic status (9, 52, 59). Furthermore, SES affects a household's ability to purchase soap, a sanitary latrine, and/or a tubewell. When people are unable to afford soap alternative hand-washing methods include rubbing hands on the ground and scrubbing hands with soil or ash after defecation (39). However, in some instances this soil is highly contaminated with fecal coliforms. While not all factors listed in Figure 1.3 are included in this research, the triangle of human ecology is

important for generating hypotheses based on potential cultural, biological, and environmental interactions.

Analytical Framework: Neighborhoods and Health

The importance of place and its impact on health has been acknowledged since at least the eighteenth century. However, the evidence, methods, and theories that capture these effects are relatively new. The *neighborhoods and health* framework lends itself to interdisciplinary health research and has been adopted by various disciplines including medical geography, epidemiology, demography, and policy studies (70). The study of infectious disease within the context of neighborhoods allows us to measure human and ecological interactions that result in various transmission routes (71).

Neighborhood studies account for both contextual (area-level) and compositional (individual-level) effects when measuring individual health outcomes. Contextual factors include the socioeconomic status of a neighborhood, and the distribution of resources such as health and education facilities. Compositional characteristics include an individual's income, age, and gender (62). Contextual and compositional interactions vary across space making contextual effects more influential in some neighborhoods than in others. People with similar characteristics tend to live in spatial clusters and certain group properties can affect health outcomes. For example, individuals with low socioeconomic status may be forced to live in a low-income neighborhood, lacking grocery stores, schools, clinics, or public transportation (72). Accounting for contextual traits provides a more comprehensive understanding of individual-level health.

Referring back to the triangle of human ecology (Figure 1.3), it is evident that n*eighborhoods and health* complements *disease ecology* by placing individuals within the

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context of a group, community, or neighborhood. *Neighborhoods and health* provides methodology that can be used to better understand diarrheal disease within the *disease ecology* framework. By studying health outcomes within both research frameworks, it is possible to measure relationships at varying scales. Previous diarrheal disease studies in Bangladesh found that improvements in household sanitation are not enough to avert risk of diarrheal disease when community sanitation is very poor (52, 73). While these studies recognized the potential influence of community sanitation, the authors did not conduct further analyses accounting for neighborhood characteristics. Additionally, these studies did not account for the spatial distribution of households and resources among neighborhoods. This research project measures neighborhood effects on diarrheal disease incidence by defining varying neighborhood boundaries and using contextual models. Contextual models investigate neighborhood- and individual-level effects on health outcomes (70).

The defined neighborhood varies with each study and is dependent on the research question and study population (74). Neighborhoods are often defined by political boundaries that are not local enough to study social processes and ecological influences (75, 76). Optimal neighborhood size may vary depending on the different ecological variables that are considered (75). In Matlab, households are nested within *baris* (patrilineal household clusters) and may have similar characteristics and health outcomes compared with individuals in the *bari.* While the *bari* may represent the neighborhood, neighborhood boundaries could also be defined by Euclidean distance.

Behavioral and cultural practices of neighboring households within the *bari* could negatively impact individual health. For example, if a household practicing good hygiene is surrounded by households that own unsanitary latrines, exposure to microbial pathogens

remains high. In other instances, neighbors may provide a protective buffer.   A household

with very low SES and poor hygienic practices surrounded by households with higher SES

and improved sanitation may have limited exposure to fecal pathogens. Beyond cultural and

behavioral practices, households within *baris* share resources. Shared resources include

ground and surface water, and less frequently latrines. In some instances multiple families

share a single dwelling. Neighborhood effects may exist at higher scales beyond the *bari*,

such as groups based on shared bathing ponds, or neighborhood buffers defined by Euclidean

distance.

Guided by the literature and the disease ecology framework, this research explores

the effects of poor sanitation on shallow tubewell water and diarrheal disease. This research

is presented in three empirical papers. The first empirical paper (Chapter 2), "Influence of

latrine proximity and type on tubewell water quality and diarrheal disease in Bangladesh"

measures the relationship between *E. coli* concentrations in shallow tubewell water and

surface contamination caused by leaking latrines. The relationship between *E. coli*

concentration in shallow tubewell drinking water and diarrheal disease is also measured. The

second paper "Influences of poor sanitation on childhood diarrhea in rural Bangladesh" is

presented in Chapter 4. This study explores poor sanitation effects on diarrheal disease

transmission using two separate analyses: the first measures the influence of neighborhood

sanitation (ie number and quality of latrines) on diarrheal disease and the second examines

the relationship between diarrheal disease and surface water contamination via bathing pond

exposure. The final paper (Chapter 6), "Impact of deep tubewells on childhood diarrhea in

Bangladesh" compares diarrhea incidence between households using deep tubewells and

households not using deep tubewells. These empirical papers build on one another and

identify circumstances in which shallow tubewell water and surface water quality are

compromised and children are at risk of contracting diarrheal diseases.

CHAPTER 2

INFLUENCE OF LATRINE PROXIMITY AND TYPE ON TUBEWELL WATER

QUALITY AND DIARRHEAL DISEASE IN BANGLADESH

Introduction

Diarrheal disease remains the second leading cause of death among children under 5 worldwide causing 1.5 million deaths annually (1). Access to a safe water supply and improved sanitation helps prevent diarrheal disease transmission but in densely populated places with high poverty rates such as Bangladesh is limited. Over the last several decades, Bangladesh experienced a widespread shift from surface to ground water consumption in response to high rates of child mortality due to diarrhea. An estimated 9 million tubewells are installed throughout the country (77). The majority are domestic shallow wells installed using a hand percussion drilling method that is affordable for individual households or *baris* (patrilineal household clusters) (2).

In Bangladesh, groundwater is generally considered safe for consumption but a survey conducted in the late 1990's identified high levels of arsenic (As) in tubewell water. Millions of residents were exposed to arsenic (As) levels exceeding Bangladesh (50 μg L^{-1}) and World Health Organization (WHO) (10 μg L^{-1}) standards (BGS and DPHE, 2001). Prolonged exposure places individuals at risk of developing skin lesions and chronic diseases such as lung and bladder cancer (78). As a result, millions of households abandoned their shallow high As wells for neighboring, predominantly shallow low As wells (79).

While well switching effectively reduces As exposure it can also increase exposure to microbial pathogens (80). Shallow low As wells are more likely to be contaminated with human waste than shallow high As wells resulting in a potential tradeoff between As and fecal contamination (80, 81). Contamination of the shallow aquifer could contribute to the slow decline in diarrhea morbidity over the last decade (82-86). It is possible that slow improvements in sanitation throughout Bangladesh compromise the shallow aquifer, exposing residents to fecal pathogens. Currently less than 40% of the population of Bangladesh uses septic latrines (1).

The relationship between the shallow aquifer and the sanitation infrastructure is complex. Residents build latrines in locations that are convenient for use and often near drinking wells and ponds. Construction and maintenance of the built drinking water and sanitation infrastructure can indirectly increase exposure to microbial pathogens if the wells or the shallow aquifer is compromised by surface contamination from unsanitary latrines, spilling effluent onto the open ground. Lateral migration then carries pathogens from the base of a latrine to a latrine pond (i.e., ponds with latrine effluent) or depression, shown to act as secondary point sources of fecal bacteria to the shallow aquifer, especially during the early monsoon when the water table is depressed and influxes of water and contamination are high (87). Alternatively, fecal waste may flow to a wellhead, and enter the well along an unsealed annulus or through a subsurface break in the PVC pipe (29). A third possible contamination pathway is direct vertical infiltration from below latrines to the unsaturated zone into an unconfined aquifer. In this third case subsurface contamination would presumably emanate from both unsanitary and sanitary latrines.

This study explores the relationship between surface contamination and *E. coli* concentrations in shallow tubewell water. Potential contamination point sources of human fecal waste include unsanitary and sanitary latrines and latrine ponds. Sanitary latrines are those with no evidence of leaking effluent onto the surface while unsanitary latrines expose individuals to human waste. Latrine ponds are measured as possible secondary point sources because they collect human waste from surrounding latrines, especially during heavy rainfall in the early monsoon when rapid overland flow washes human latrine waste into depressions. During the late monsoon, latrine ponds overflow, spreading fecal matter across the surface. The primary aim of this study is to explore the relationship between shallow aquifer contamination and surface contamination at varying scales accounting for differences in latrine quality.

A detailed spatial database, microbial data, and health data allowed us to explore these relationships. The influence of the sanitation infrastructure on tubewell microbial contamination measured at varying spatial scales and accounting for latrine quality, has to our knowledge not been systematically investigated. A secondary goal of this study is to explore the relationship between *E. coli* concentration in tubewell water and childhood diarrhea incidence. This study is guided by the following questions: 1) Does poor sanitation influence shallow tubewell water quality? 2) Does fecal contamination of tubewells influence diarrheal disease?

Research Design and Methods:

The study area, Matlab, Bangladesh, is a rural area located 50 km southeast of Dhaka. It is the field site for the International Center for Diarrhoeal Disease Research, Bangladesh

(ICDDR,B) which manages a hospital that provides free treatment for severe diarrhea to all residents. Hospital and community level records are maintained through a longitudinal Health and Demographic Surveillance System (HDSS). Community health workers visit households once per month and ask mothers if their child under 5 had diarrhea in the past 24 hours. Diarrhea is defined as a minimum of three loose or watery stools within a 24 hour period. Diarrheal events lasting several days are recorded as a single case.

An embankment, built for flood control runs through Matlab separating the six village study area with three villages on either side. The area outside of the embankment floods during the late monsoon however all villages are affected by heavy rain. Within the embankment, ponds can overflow and spread fecal contamination across the surface.

Tubewell water Microbial Survey

A subset of six villages located in the southwest region of Matlab were selected to monitor monthly variation of tubewell water microbial contamination (80). Duplicate 100 mL tubewell water samples were collected monthly between May 2008 and November 2009 (Data not collected in December 2008). Culturable *E. coli* was measured using the most probable number (MPN) based Colilert test kit (IDEXX Laboratories, Inc.). The MPN value reported here assumes that organisms are randomly distributed in the well water so that replicate samples contain the same "true" number of bacteria (88).

Geographic Database

A sub-meter Global Positioning Systems (GPS) survey of the water and sanitation infrastructure was conducted in 2008 and 2009 using Trimble GeoXH receivers. Data were differentially corrected to obtain the highest possible accuracy. Survey data collected include the location of all households, latrines, and ponds within 200 m of 92 monitored wells

(Figure 2.1). The presence of a concrete platform and whether the base was cracked or intact was recorded for all wells. Information provided by residents includes well depth, year of installation, and the households obtaining drinking water from the sampled well. The majority of survey wells are less than 120 ft deep, representative of the depth distribution of tubewells in the six village study area (Figure 2.2).

Figure 2.1: Study area geographic database
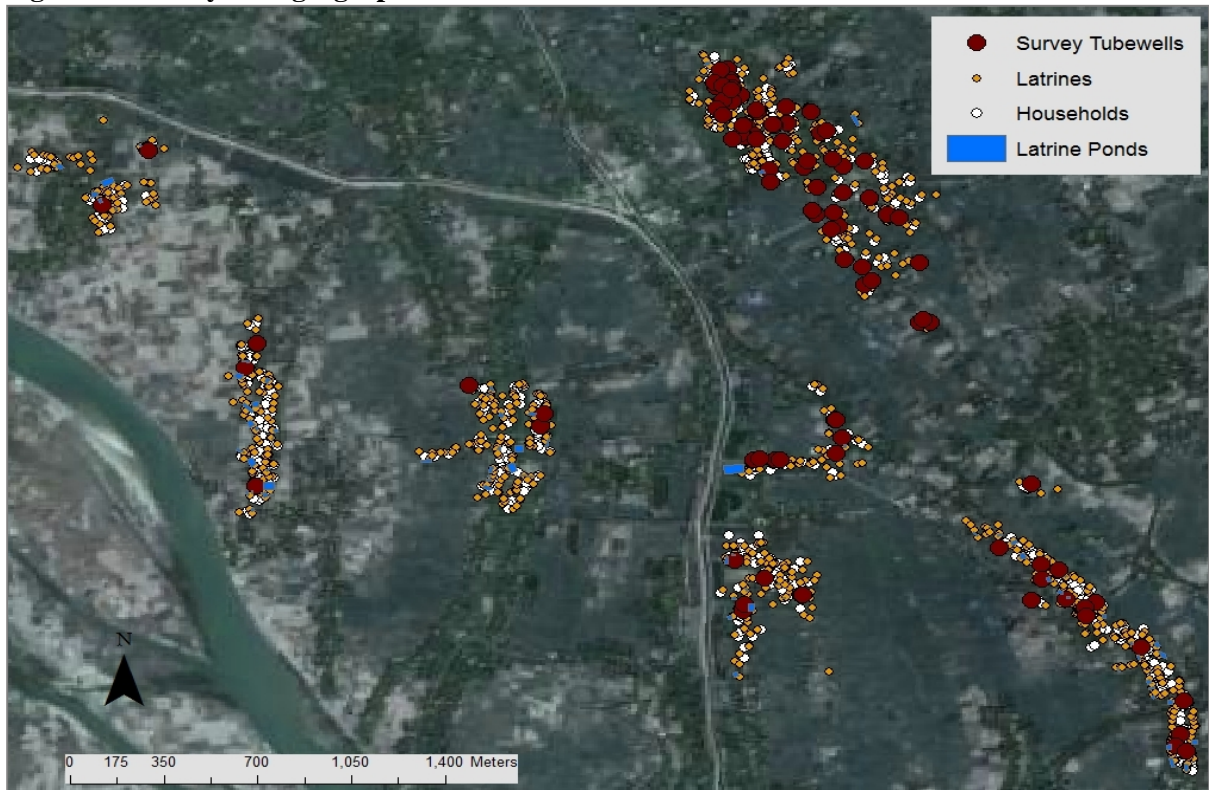
Residents also provided pond depth and pond use information. Long and short axes of ponds were measured using a sub-inch TruPulse Laser Rangefinder. Ponds were classified as bathing, fish-farming, latrine or no purpose. Digital pictures were also taken of each pond during the survey. Classification was done using pond pictures and information provided by residents during the survey. Ponds receiving direct latrine effluent that were not used for bathing or fishing were classified as 'latrine' ponds. Ponds that did not receive latrine effluent and were not classified as bathing or fishing were designated 'no purpose' ponds.

The majority of latrines in the study area are septic, comprised of concrete foundation rings used to prevent human effluent from leaking on the ground or into surface water. A small percentage (7.0%) of latrines are open, usually located over a shallow pond or near a septic latrine. Latrines were classified as unsanitary or sanitary. An unsanitary latrine is any latrine with visible effluent including open latrines, septic latrines with a broken base, and septic latrines draining effluent onto the ground or into surface water through a drain pipe. Septic latrines with an intact base and zero evidence of leaking effluent were classified as sanitary. Tubewell and spatial data were incorporated into a Geographic Information System (GIS) to explore the relationship between tubewell water quality and surface contamination.

Figure 2.2: Tubewell depth distribution
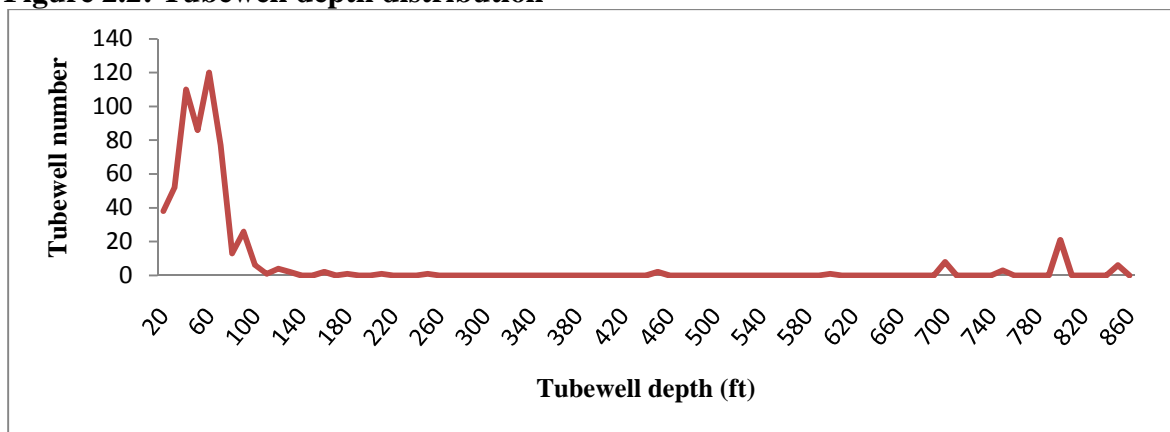
Variable Construction

Sanitation metrics were constructed to examine the association between contamination point sources and tubewell water quality at varying scales (Table 2.1). Circular windows were placed around individual tubewells to measure latrine and population counts between 10 m and 100 m in 5 m increments (89). Pond counts were measured between 10 m and 100 m in 10 m increments to account for the larger area covered by ponds.

In addition to surveying potential point sources of contamination, the information on the tubewells themselves were parameterized to evaluate the impact of well construction (intact concrete platform), age, and depth on microbial drinking water quality. Further, the population drinking from each tubewell was measured (Table 2.1). Testing these parameters helped to evaluate the possibility of rapid flow along unsealed tubewell annuli or through breaks in the casing as causing the observed contamination.

Table 2.1: Sanitation Variables

Sanitation Metrics	Tubewell Features
Latrine Count by type	Intact Concrete Platform
• Unsanitary/ Sanitary/ Total	Population drinking from well
Population Count	Age of well
Latrine Pond Count	Depth

Statistical Analysis:

The analysis was restricted to shallow tubewells (< 120 ft) because the majority of residents drink from domestic shallow wells (Figure 2.2) and the shallow aquifer might be compromised when sanitation is poor (30). The outcome measured is the frequency of *E. coli* detection from January through November (data not collected December 2008) from here on refers to as annual frequency. A sample was considered positive if both measurements contained detectable levels of *E. coli* $\geq$ 1 MPN/100 mL (80). An average was taken if the well was sampled the same month in 2008 and 2009. Statistical analyses were restricted to wells with data available for at least 10 of the 11 months. Seasonal frequency of *E. coli* detection was also calculated to show how relationships are affected by the monsoon.

Seasons were defined as winter (Jan-Mar), early and late monsoon (Apr-Jun and Jul-Sep respectively), and post monsoon (Oct-Nov, December data unavailable) (90).

Concentrations of annual and seasonal *E. coli* were compared with sanitation predictors using a correlation matrix. Pearson correlation coefficients |r| were reported for all predictors and sanitation metrics listed in Table 2.1. Significance was measured at p = 0.05. Multiple regression models were built using annual and seasonal *E. coli* outcomes. Significant (p < 0.05) and marginally significant (p < 0.1) predictors were included in the model. Marginally significant variables were included in the model to avoid dismissing small effects that may have a stronger influence when controlling for other predictors. For sanitation metrics, the distance with the strongest correlation coefficient was included in the regression model. The final model was selected using Akaike's Information Criterion (AIC). The test penalizes models with many variables that do not improve the fit much more than models with fewer variables. The model with the lowest AIC value is the most parsimonious.

Diarrheal Disease Analysis

Households participating in the community diarrhea survey obtaining drinking water from survey wells were identified. A Pearson correlation coefficient was calculated to measure the relationship between tubewell water microbial contamination and childhood diarrhea. Significance was measured at p < 0.05. This was a preliminary analysis as the data collection for households using survey wells is ongoing.

Results:

Annual frequency of culturable *E. coli* was detected in all 92 survey wells. Tubewells were contaminated 10% to 80% of the time across the entire study period. Seasonal detection varied with the lowest detection rates measured during winter months (Figure 2.3).

Contamination was most frequent during the post monsoon (Oct-Nov) and fluctuated during the early and late monsoon (Figure 2.3).

Figure 2.3: Frequency of *E. coli* detection by well count per season
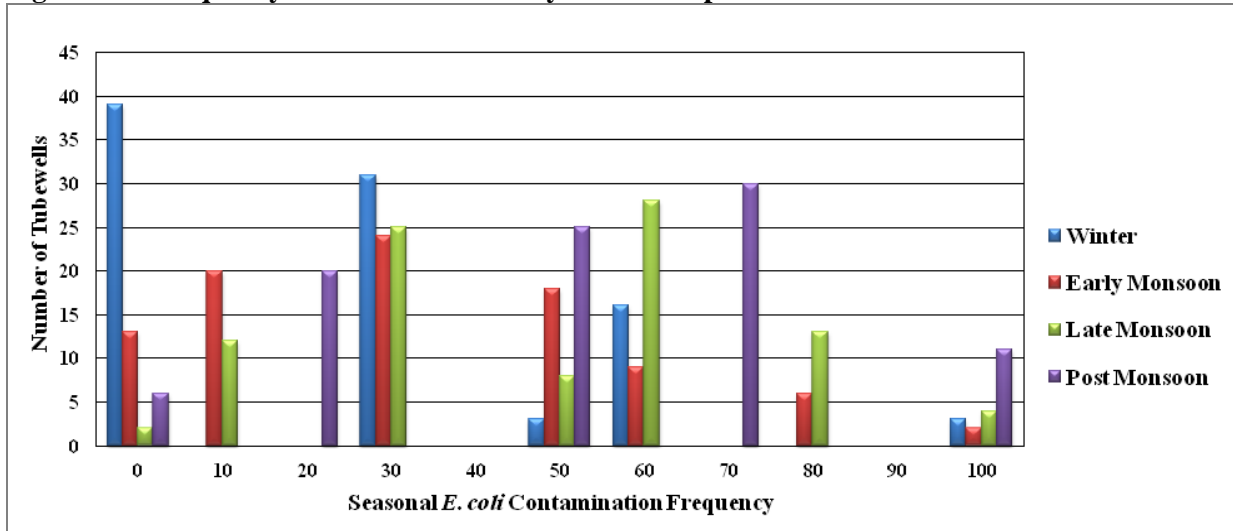
Annual E. coli - Correlation and Regression Results:

Pearson correlation coefficients show the relationships between annual contamination and sanitation metrics at multiple distances (Figure 2.4). The black bars demarcate the initial distance where the correlation becomes significant ($p < 0.05$). A single black bar indicates that the correlation is significant for the remaining distances. Two black bars on a single line identify the range of distances where the count of a given variable is significantly correlated with *E. coli*. The correlation between population count and *E. coli* was significant at 20 m to 100 m distances and peaked between 20 m and 25 m. Unsanitary latrine count was significantly correlated with *E. coli* at distances ranging from 10 m to 100 m, with the strongest correlation at 45 m (0.30). Sanitary latrine counts ranging from 50 m and 65 m were significantly correlated with *E. coli* (Figure 2.4). The presence of an intact concrete platform was marginally significant ($p < 0.1$) with a correlation coefficient of -0.19. Latrine

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pond count, age of well, depth and number of persons drinking from the well were not

significantly correlated with the annual frequency of detectable *E. coli*.

Figure 2.4: Annual *E. coli* frequency and latrine and population count correlation results. Correlation coefficients reported for distances 10 m – 100 m.
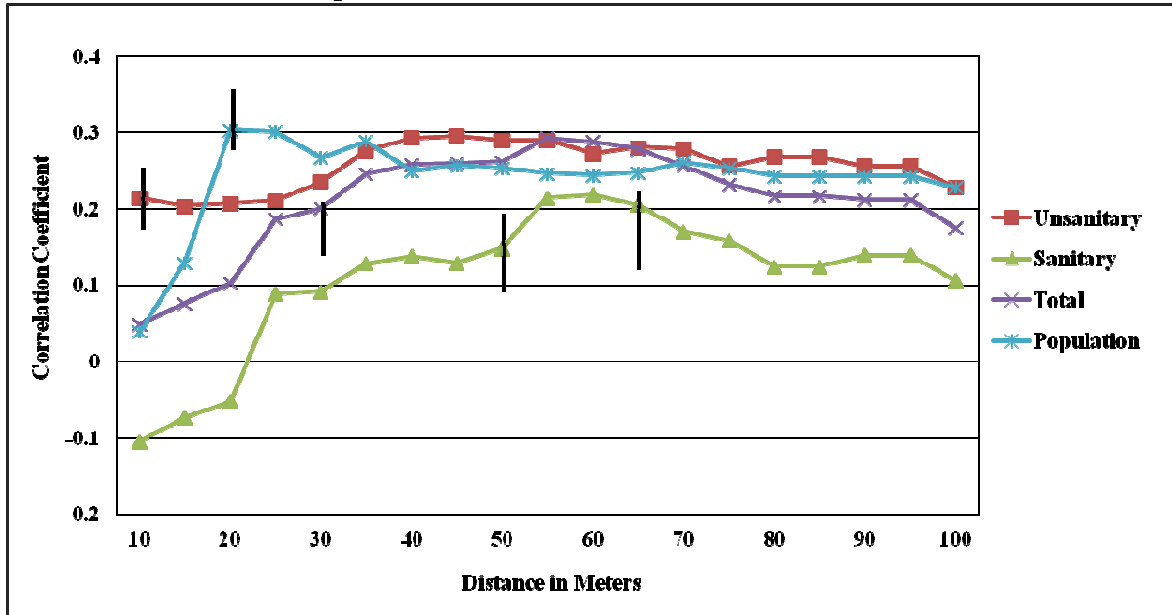
*Black bar identifies distance where correlation between *E. coli* and count of sanitation metric becomes significant. Two bars on a single line mark the range of distances where *E. coli* and predictor are significantly correlated.

Multiple regression models were built to measure interactions between sanitation

predictors that were significantly or marginally correlated with annual *E. coli*. The peak

correlation values for latrine and population count were included in the model. Variance

Inflation Factor (VIF) scores were measured to test for multicollinearity in the data. The

model with the lowest AIC includes 20 m population count, 40 m unsanitary latrine count,

and the presence of an intact platform (Table 2.2). Latrine and population count are

positively correlated while the presence of an intact concrete platform is protective.

Table 2.2: Multiple regression model for annual frequency of *E. coli* contamination

Predictors	Coef.	P value	95% CI	
Unsanitary latrine 40 m	0.015	0.012**	0.003	0.026
Population count 20 m	0.004	0.010**	0.001	0.006
Intact concrete platform	-0.067	0.023**	-0.125	-0.009

*$p \leq 0.1$ **$p \leq 0.05$, and ***$p \leq 0.01$
N=92
R-squared = 0.19
Adjusted R-square = 0.17

Seasonal correlation and regression results:

Correlation and multiple regression models were built using seasonal outcomes. Correlation coefficients were obtained for all sanitation metrics and predictors listed in Table 2.1. Multiple regression models were built including all significant ($p < 0.05$) and marginally significant predictors ($p < 0.1$) to explore interactions between predictors.

Significant correlations were not identified during winter months (Jan-Mar). Unsanitary latrine count within 20 m of a tubewell was marginally significant ($p < 0.1$). This could be due to the large number of tubewells that were below detection levels in winter. Significant relationships were not identified during the post monsoon period (Oct-Nov). Tubewell depth and the presence of an intact concrete platform were marginally significant ($p < 0.1$) with a negative correlation coefficient of -0.20.

Early Monsoon

Significant and marginally significant predictors of contamination during the early monsoon (Apr-Jun) are listed in Table 2.3. Population counts ranging from 20 m to 35 m are positively correlated with *E. coli*. Latrine pond counts ranging from 30 m to 40 m (peak at 40) are positively correlated with *E. coli*. Unsanitary latrine counts between 40 m to 60 m are positively and marginally ($p < 0.1$) correlated with *E. coli* (Figure 2.5).

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Table 2.3: Significant predictors of early monsoon contamination

Predictor	Correlation Coefficient	P value
Intact Concrete Platform	-0.304	0.003***
Population count 35 m	0.259	0.013**
Latrine pond count 40 m	0.229	0.028**
Unsanitary latrine count 45 m	0.194	0.064*

*p≤0.1 **p≤0.05, and ***p≤0.01

Figure 2.5: Early monsoon *E. coli* frequency and latrine, population, and latrine pond count correlation results. Correlation coefficients reported for distances 10 m - 100 m.
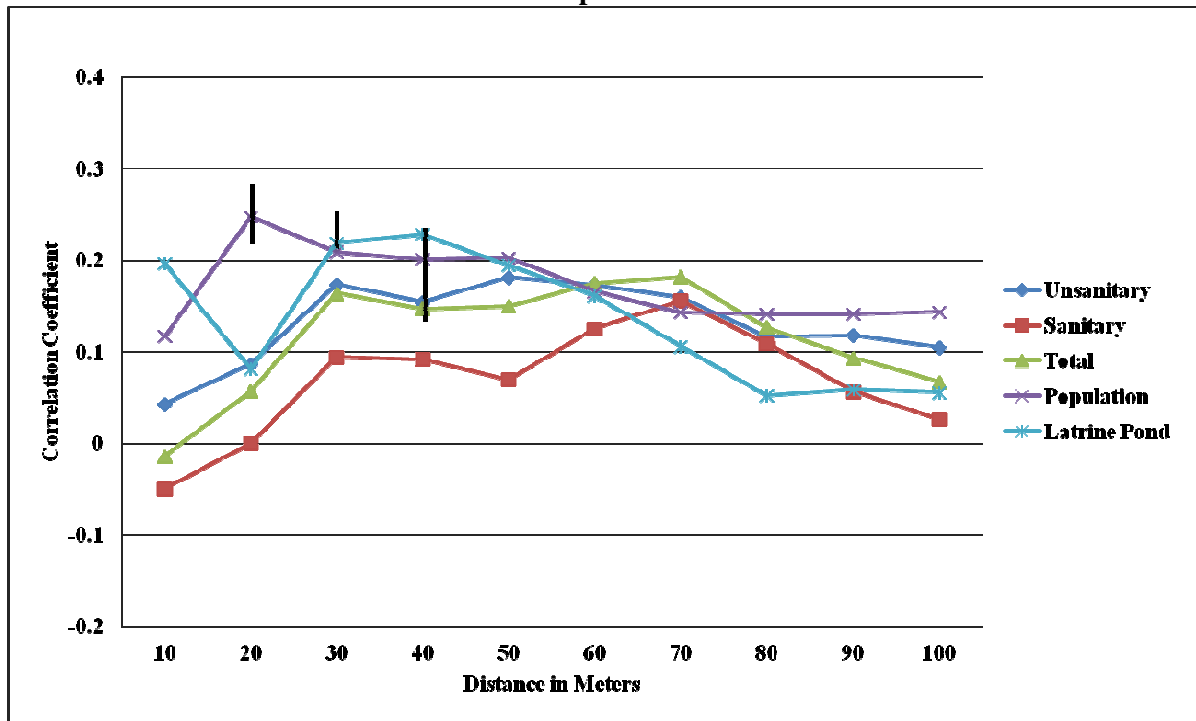
*Black bar identifies distance where correlation between *E. coli* and count of sanitation metric becomes significant. Two bars on a single line mark the range of distances where *E. coli* and predictor are significantly correlated.

Predictors in Table 2.4 were tested for multicollinearity and included in a multiple regression model predicting the frequency of *E. coli* contamination during the early monsoon. The most parsimonious model was selected using AIC (Table 2.4). Increases in population count increase risk of contamination, while the presence of a concrete platform

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remains protective. Latrine pond count is positively associated with *E. coli* contamination but only marginally significant. Unsanitary latrine count at 35 m was highly correlated with population count at 40 m and was not included in the final model. The correlation between population and latrine count increases with distance suggesting that in this model, population count also captures the effect of latrine count.

Table 2.4: Results for early monsoon multiple regression model

Predictors	Coef.	P value	95% CI	
Population count 35 m	0.004	0.003***	0.001	0.007
Intact concrete base	-0.164	0.001***	-0.265	-0.066
Latrine Pond count 40 m	0.084	0.078*	-0.009	0.176

*$p \leq 0.1$ **$p \leq 0.05$, and ***$p \leq 0.01$
N=92
R-squared = 0.21
Adjusted R-square = 0.19

Late Monsoon

During the late monsoon, both sanitary and unsanitary latrines were positively correlated with increased *E. coli* detection (Figure 2.6). However unsanitary latrines are influential at much shorter distances ranging from 30 m to 100 m while the correlation with sanitary latrines becomes significant at 55 m (Figure 2.6). Correlation coefficients for population count, latrine count, and latrine pond count metrics peak between 60 m and 70 m (Figure 2.6). During the late monsoon, correlation coefficients appear to converge as distance increases (Figure 2.6). One possible explanation is that during the late monsoon, the study area is so inundated with water that point sources contributing to surface contamination mix across a larger area than during the early monsoon. The presence of an intact concrete platform was not correlated with *E. coli* contamination in the late monsoon.

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Figure 2.6: Late monsoon *E. coli* frequency and latrine, population, and latrine pond count correlation results. Correlation coefficients reported for distances 10m – 100m.
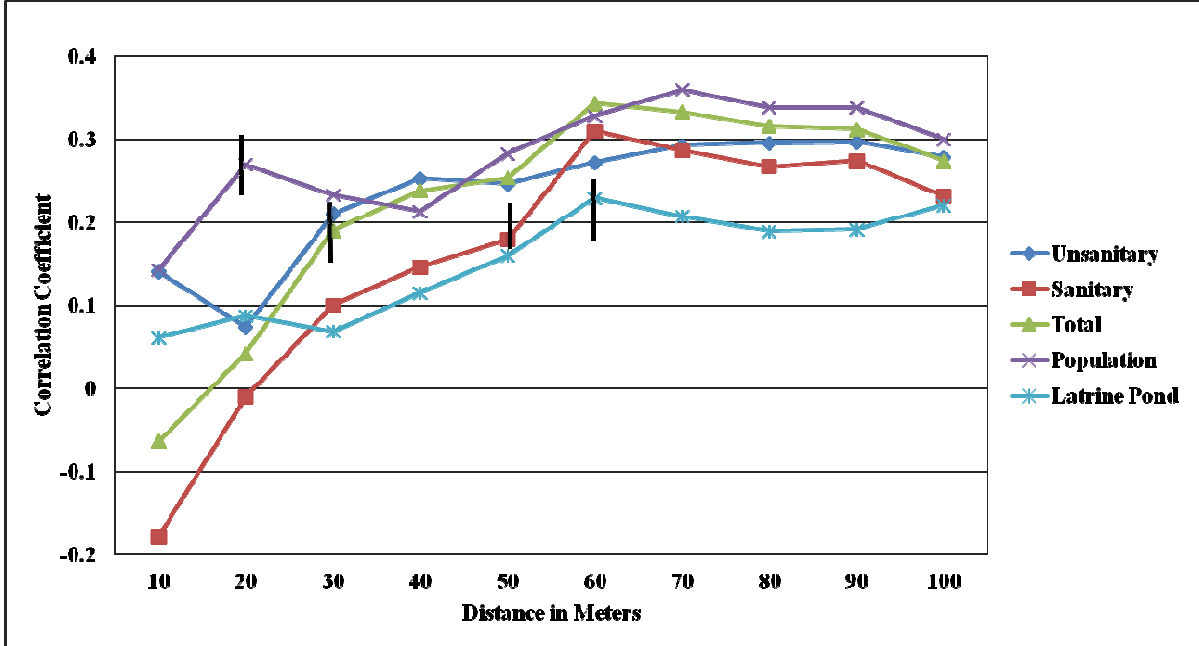
*Black bar identifies distance where correlation between *E. coli* and count of sanitation metric becomes significant. Two bars on a single line mark the range of distances where *E. coli* and predictor are significantly correlated.

This point was further supported by the high level of multicollinearity between all sanitation metrics at peak correlation distances. Two sets of multiple regression models were examined to account for the high collinearity between total latrine count at 60 m and population count at 70 m. Using AIC to select a model, total latrine count at 60 m was a slightly better fit however the predictors were nearly interchangeable (Tables 2.5 and 2.6).

Table 2.5: Results for late monsoon population count multiple regression model

Predictors	Coef.	P value	95% CI	
Population count 70 m	0.002	0.001***	0.001	0.003
Latrine pond count 60 m	0.050	0.080*	-0.006	0.106

*$p \leq 0.1$ **$p \leq 0.05$, and ***$p \leq 0.01$
N=92
R-squared = 0.16
Adjusted R-square = 0.14
AIC = -4.202

Table 2.6: Results for late monsoon total latrine count multiple regression model

Predictors	Coef.	P value	95% CI	
Latrine count 60 m	0.012	0.001***	0.005	0.019
Latrine pond count 60 m	0.056	0.047**	0.001	0.112

*$p \leq 0.1$ **$p \leq 0.05$, and ***$p \leq 0.01$
N=92
R-squared = 0.16
Adjusted R-square = 0.14
AIC = -4.271

Diarrheal Disease Analysis

Pearson correlation coefficients were calculated to measure the relationship between diarrheal disease and tubewell water microbial contamination. The sample consisted of 33 households obtaining drinking water from 13 survey wells. Childhood diarrhea data were not collected for the entire 18 month tubewell survey restricting the analysis from May 2008 - May 2009. Diarrhea data were aggregated over the 12 month period (December data unavailable) because of the small sample size. The outcome was whether a household reported diarrhea at least once during the study period. Tubewell water quality predictors included the frequency of *E. coli* detection over the study period, and the average level of *E. coli* contamination during the study period. The correlation between diarrhea and the frequency of *E. coli* detected in a tubewell was not significant. However, the correlation coefficient (0.39) reported for diarrhea and average *E. coli* levels was significant at $p < 0.05$ suggesting that tubewell contamination may contribute to childhood morbidity.

Discussion

The findings of this study suggest that the slow improvements to the drinking water and sanitation infrastructure may reduce the protective effect of groundwater consumption.

Increased population and unsanitary latrine count, latrine ponds, as well as the absence of an intact concrete platform around wellheads were predictive of *E. coli* contamination in tubewells during both the early and late monsoon seasons. The relationships varied by distance and unsanitary latrines were more highly correlated to fecal contamination in tubewells than sanitary latrines. This supports our hypothesis that surface contamination influences tubewell water quality via indirect pathways such as lateral transport to and leakage along unsealed annuli or infiltration from latrine ponds (87).

The stronger and yet further distance correlation between unsanitary latrines and *E. coli* contamination in tubewells in the late monsoon compared with *E. coli* detection during the early monsoon suggests that transport mechanisms vary by season. Overtopping of latrine ponds during the late monsoon would allow surface spreading of fecal contamination over much larger areas than when surface water is contained within discrete depressions early in the monsoon (89). Thus, fecal contamination in the late monsoon season in tubewells may result from sources aggregated across the neighborhood (70-100 m) scale, whereas in the early monsoon surface contamination is primarily from sources across the *bari* scale (20-40 m), and would include both subsurface transport from latrine ponds into the aquifer as well as surface flow to and rapid transport down unsealed tubewell annuli. The significance of population count and non-significance of unsanitary latrines within 20 m of a tubewell during the early monsoon could be a *bari* level effect. High counts of people in close proximity to tubewells may aid in the transport of contamination from latrines to unsealed tubewell annuli when there is less water spreading human waste across the surface. A previous study in Bangladesh found that inundation or standing water around a wellhead is predictive of microbial contamination, providing a path of least resistance for contaminated surface water

during the late monsoon (84). Inundation was also shown to be a significant predictor of well

water quality in Mozambique (91). This process provides an opportunity for surface

contamination from leaking unsanitary latrines and contaminated ponds to reach the water

table through rapid transport down the side of the well (92).

Identifying tubewells contaminated with fecal coliforms suggests that groundwater

treatment may be necessary (80, 81, 83-85). While the levels of contamination are often low,

water collected from a contaminated source is more likely to become highly contaminated

during storage (83). It has been suggested that a threshold of microbial contamination in

drinking water exists, therefore, the quality of groundwater, unless grossly contaminated, is

not as important as other mechanisms of transmission (37). However, even if such a

threshold exists this poses the question, "Is it acceptable to ignore the poor sanitation

infrastructure and the fact that people are ingesting water with levels of contamination

beyond what would be acceptable in other parts of the world?"

A preliminary analysis measuring the correlation between childhood diarrhea and *E.*

coli contamination was included in this study. As behaviors such as open defecation and

continued use of broken septic latrines result in surface contamination, the risk of shallow

aquifer contamination increases, and in turn influences health. The limited health data from

households drinking water from survey wells was problematic for this analysis. However the

significant correlation between diarrhea and *E. coli* contamination suggests that a relationship

exists and warrants further investigation.

This study highlights the importance of incorporating hydrological, spatial and

demographic data to understand population-environment interactions that influence tubewell

water quality and health. The study results suggest that an improved sanitation infrastructure

would enhance shallow tubewell water quality. It is unlikely that a universal shift to sanitary latrines will occur any time soon as poor sanitation is highly correlated with low socioeconomic status. Affordable modes of treatment or alternative drinking water sources are needed.

The ICDDR,B continues to introduce new methods to improve the quality of drinking water including rainwater harvest and a community piped water supply. While these methods provide safe water there are concerns with each technology and they are not universally applicable. Rainwater harvesting bins can provide safe drinking water but they do not provide a year round water supply and residents do not always clean the filter. A community piped water system that provides a water supply in the home twice a day was installed in one Matlab village (not part of our study area). The system requires a commitment from all community members to pay a fee to maintain the structure and to hire two staff members. While this is an effective system, it is only manageable if residents can afford to pay for maintenance. Another alternative recently tested in Matlab is a water purification mixture comprised of alum potash, bleaching powder, and lime. The mixture was found to be effective in purifying up to 15 l of surface water at a time and reducing diarrhea (93). It is unknown whether this practice will become widespread but it may provide an affordable alternative method for purifying water where sanitation is poor and the shallow aquifer is compromised. These alternatives may also be applicable in other regions with similar water and sanitation concerns. In the mean time, the results from this study can guide existing efforts for improving sanitation. Despite differences between sanitation influences during the late and early monsoon, the overall finding is the same. Placement of latrines near tubewells is convenient but affects water quality and likely health. Therefore, sanitation improvement

interventions should highlight the spatial separation of latrines and tubewells to limit

contamination.

CHAPTER 3

The previous chapter suggests that the quality of the sanitation infrastructure affects the microbial quality of drinking water obtained from shallow tubewells. Unsanitary latrines leaking effluent onto the surface are associated with groundwater contamination at varying spatial scales. The relationship between sanitation and groundwater contamination is much more prominent for unsanitary latrines compared to sanitary latrines. This suggests that improving the latrine infrastructure can reduce shallow tubewell contamination. The previous chapter also identifies a potential association between childhood diarrhea and increasing microbial contamination in tubewell water. This has important health implications because groundwater is generally considered safe for consumption in rural Bangladesh. However, shallow tubewell water is compromised in some environments, potentially resulting in diarrhea transmission. These findings highlight the importance of understanding behavioral and socioeconomic factors that result in poor latrine quality.

While findings from the previous chapter suggest that a relationship exists between groundwater quality and childhood diarrhea, it is unknown whether this mode of transmission is more influential than exposure to contaminated surface water. The following chapter further explores the relationship between diarrheal disease and the built sanitation infrastructure by measuring the effect of neighborhood sanitation. In addition, the relationship between bathing pond sanitation and diarrheal disease will also be analyzed.

CHAPTER 4

INFLUENCES OF POOR SANITATION ON CHILDHOOD DIARRHEA IN RURAL BANGLADESH

Introduction:

Although diarrheal diseases are no longer a major cause of mortality in developed countries, it remains one of the main causes of childhood mortality in the developing world. Diarrhea remains the second leading cause of death in children under 5 worldwide, killing 1.5 million children annually (1). Childhood diarrhea is preventable when access to improved sanitation and drinking water are available; however an estimated 2 billion cases occur each year with Asia and southern Africa carrying more than half of the burden. Oral rehydration therapy has proven successful in treating diarrhea and preventing death from dehydration however today only 39% of children receive the recommended treatment (1, 94). While diarrhea mortality rates have declined over the past few decades, limited progress has been made in reducing morbidity (UNICEF, 2009).

Diarrheal disease transmission is a complex process driven by the interaction of biological, behavioral and environmental factors varying across time and space (Emch, 1999; Meade, 2000). In Bangladesh, the interaction between high poverty rates, a dense population, limited access to improved water and sanitation and a tropical climate leave children in this area especially vulnerable to diarrhea outbreaks (21, 24). These factors may covary between and within multiple scales including but not limited to the household and neighborhood.

Neighborhoods can serve as buffers or increase risk as education and socioeconomic (SES) levels vary. Neighborhoods with higher levels of maternal education and SES are more likely to have improved sanitation resources and better hand-washing practices (Macintyre et al., 2002; Hoque et al., 1996; Levine et al., 1976; Ferrer et al., 2008; Pokhrel et al., 2004). Children living in neighborhoods with access to safe drinking water and sanitary latrines may have a lowered risk of diarrhea regardless of hygienic practices in their own household because the diarrhea pathogens are never introduced. Conversely, children in households with good hygienic practices may have a higher risk of diarrhea if overall neighborhood sanitation is poor. This study explores the relationship between childhood diarrhea and sanitation. This is explored by analyzing childhood diarrhea as it relates to the neighborhood water and sanitation infrastructure which is defined by the spatial arrangement of tubewells, latrines, and ponds. In another analysis childhood diarrhea is analyzed by the sanitation context around bathing ponds.

Background:

In Bangladesh, efforts by the United Nations Children's Fund, the Bangladesh Department of Public Health Engineering and non-governmental organizations (NGOs) led to a shift from surface to ground water consumption. Millions of tubewells were installed in Bangladesh over the last several decades in response to very high rates of diarrheal disease mortality and contaminated surface water used for consumption (95). The majority are domestic, shallow (<140 ft) wells usually located near the household. The shift from surface to ground water consumption has been attributed to the large decline in child mortality due to diarrhea. Despite this decline, diarrheal disease remains endemic in Bangladesh. One

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possible explanation is that slow improvements in sanitation reduce the effectiveness of improved drinking water sources. Simultaneous improvements in water and sanitation resources are often more effective in preventing diarrheal disease than improving water quality alone (25, 42, 46). An estimated 78% of the rural population in Bangladesh obtains drinking water from improved sources[2], however less than 40% of the rural population has access to improved sanitation (1).

Ground water is generally safe to drink but may be compromised in areas with poor sanitation and high population density, placing people at risk of ingesting human pathogens (35). Fecal coliforms must be absent from drinking water in order to meet the World Health Organization (WHO) standard, however multiple studies conducted in Bangladesh have found *Escherichia coli* (*E. coli*) in shallow tubewell water (28, 80, 81). While it is unknown what proportion of diarrheal disease incidence is attributed to contaminated tubewell water, these findings shed light on the importance of improved sanitation resources and a need to better understand behaviors that expose people to contaminated feces.

Open defecation by children in the family compound and inattention to proper disposal of garbage and feces increase the opportunity for young children to place waste products in their mouth (40). The use of septic latrines comprised of concrete foundation rings prevents human contact with excreta and effectively reduces childhood diarrhea (47, 49, 51). Septic latrines fill up and require maintenance such as periodic emptying or construction of an additional tank once full. This is a concern for some residents that are unable to afford installing a second tank (Taha et al., 2000). When maintenance is absent septic latrines can overflow or the concrete rings can break and expose children to human

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[2] This estimate would be closer to 97% of the population with access to an improved drinking water source however arsenic contamination has reduced safe water availability.

waste. In addition, improved sanitation is most effective when it occurs at a community level and all households have access to a sanitary septic latrine (1, 40, 47, 50, 53).

Children are further exposed to human feces when surface run-off washes excrement from unsanitary latrines into surface water (32, 34). Bangladesh has millions of ponds resulting from excavation practices used to build homes on raised land for flood protection (96). This makes surface water use convenient. Despite the shift from surface to ground water consumption, people are still exposed to contaminated surface water used for multiple daily practices including bathing, washing, hand-washing, and oral rinsing (38, 42).

Guided by the literature and framework of disease ecology, this study addresses the following questions:

1) Does the neighborhood water and sanitation infrastructure affect

childhood diarrheal disease incidence above and beyond household factors?

2) Does poor sanitation influence diarrheal disease via bathing ponds?

The research is carried out using three cumulative analyses. The first analysis identifies an optimal Euclidean distance based neighborhood to examine the ecological processes influencing diarrheal disease transmission in the study area. Next, the optimal neighborhood size defines the boundary for measuring neighborhood water and sanitation resources. The third analysis uses the optimal neighborhood size as a boundary for household connectivity to bathing ponds. We hypothesize that people living in households located in neighborhoods with inadequate access to improved latrines will be more likely to contract diarrhea regardless of household maternal education. We expect households surrounded by a greater number of bathing ponds with poor sanitation will experience higher diarrhea incidence.

Research Design and Methods:

Study Area and Community Level Survey:

Matlab is located approximately 50 km southeast of Dhaka and is the research site for the International Center for Diarroeal Disease Research, Bangladesh (ICDDR,B). The ICDDR,B Matlab hospital provides treatment for severe diarrhea free of charge to all residents. A longitudinal Health and Demographic Surveillance System (HDSS) of all Matlab residents maintained since 1966, includes a decennial population census and a socioeconomic census recording household assets and maternal education. Unique identifiers are assigned to individuals, households, and *baris* (partrilineally related household clusters). A comprehensive community level survey of unspecified diarrhea in children under five was carried out from 2000-2006. Community health research workers (CHRW) conducted monthly household visits and asked mothers if their children had three or more loose stills within the last 24 hours.

Geographic Database:

Six neighboring villages located in southwest Matlab were selected in 2008 to monitor monthly variations in fecal contamination of tubewell water (80). As part of this study, a Global Positioning Systems (GPS) survey of the water and sanitation infrastructure was conducted in the six village site during summers 2008-09. A sub-meter accuracy GPS receiver was used to record the spatial location and attributes of study area households, tubewells, latrines and ponds. Data were differentially corrected to maximize accuracy. Information provided by residents included tubewell depth and year of installation, and *bari* ownership of tubewells and latrines. Latrines were classified as sanitary or unsanitary based on physical characteristics observed during the survey. Sanitary latrines are septic latrines

comprised of intact concrete rings with zero evidence of leaking effluent. Open latrines and

septic latrines leaking effluent via broken rings or a drain pipe were classified as unsanitary.

A sub-inch laser rangefinder was used to measure proximity (in meters) between latrines and

the nearest pond in order to determine the number of latrines draining into individual ponds.

The rangefinder was also used to measure the long and short axes of ponds.

Residents provided information regarding pond depth and use, and images were taken. Ponds

were classified as bathing, no purpose and latrine ponds. A small number of ponds were

classified as fishing or cooking/washing only. Ponds receiving direct latrine effluent were

classified as latrine ponds unless otherwise designated as bathing or fishing ponds. All other

ponds were classified as no purpose. All spatial, health and demographic data were

incorporated into a Geographic Information System (GIS) of the study area (Figure 4.1).

Socioeconomic status and maternal education:

We constructed a categorical socio-economic status score using factor analysis. The

score reflects a composite of one ordinal variable representing house material and 26 binary

variables representing ownership household assets. Household assets include livestock,

telephone, radio, mattress and bed. The composite SES score was divided into quintiles with

higher quintiles reflecting higher SES (90). We grouped household maternal education into

the following categories: zero, 1 to 4, and ≥5 yrs of formal education (97).

Figure 4.1: Study area water and sanitation infrastructure
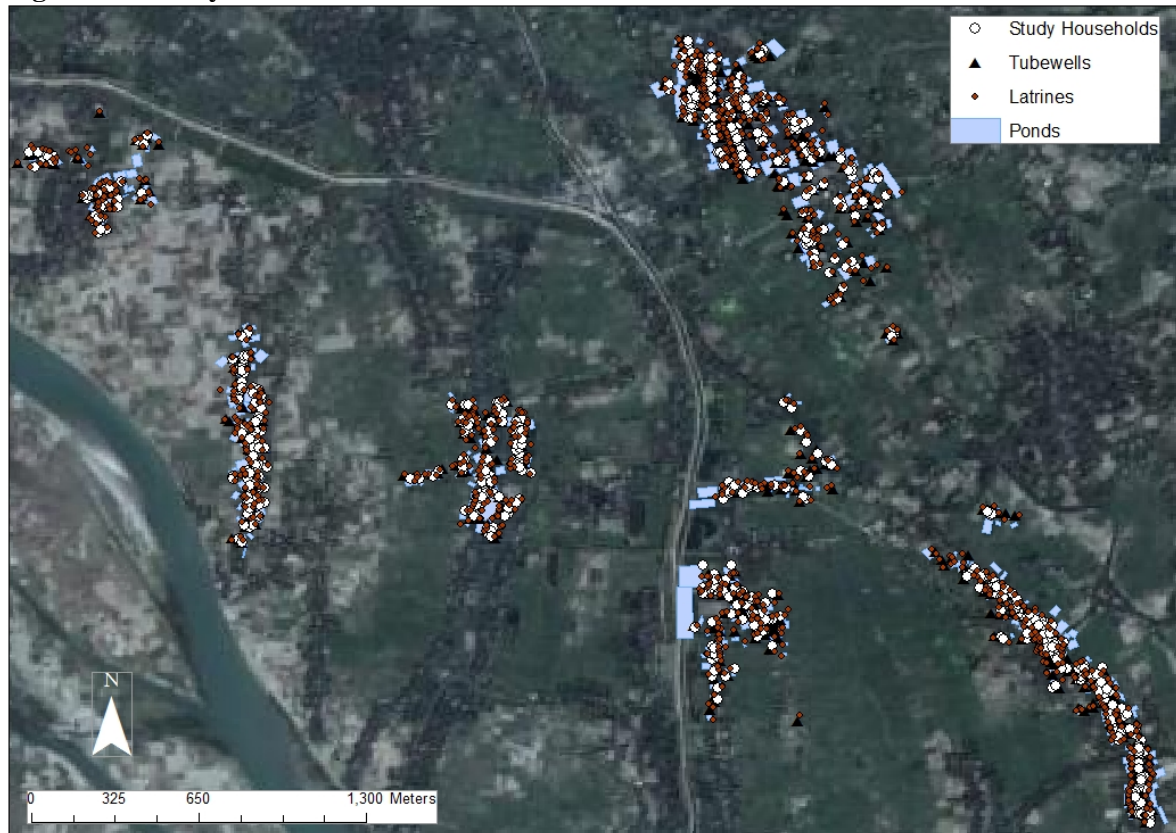
Neighborhood Selection:

The first step in this analysis was to define a neighborhood using Euclidean distance. Neighborhood boundaries are often difficult to define and are dependent on the research question and study population (Diex Roux, 2003). Political boundaries are often used to define neighborhood boundaries however these are often not local enough to capture social processes and ecological influences (Sampson et al., 2002; Ali et al., 2005). The *bari* is the closest unit to a pre-defined neighborhood within our study area. Clusters of patrilinealy related households are separated by invisible or physical boundaries. Households share resources including tubewells and latrines, and they interact on a daily basis. However two problems arise when considering the *bari* as neighborhood for our study: 1) more than half of the *baris* in our study sample have fewer than 5 households and in some cases only one

household, and 2) the boundaries of a *bari* are not representative of how far people are willing to walk on a daily basis to use a deep tubewell or bathing pond and interact with other neighbors. Based on this information and the area constraints of our surveyed villages we defined neighborhoods using Euclidean distance. While this is not a traditional neighborhood defined by cultural practices or observed by residents, it may be representative of the distance that individuals are willing to walk for resources on a daily basis and therefore interact with individuals within these distances. This is a spatial neighborhood, hereon referred to as neighborhood.

Multiple neighborhood sizes were measured by placing buffers around each household and measuring the variance of diarrhea incidence within various radii (Figure 4.2). The minimum size measured is a 100 m radius neighborhood because it encompasses an area larger than the average *bari*. Neighborhood sizes measured range from 100 - 500 m and increase in 50 m increments. The maximum is set to 500 m because the six study villages are non-contiguous and increased buffer sizes would encompass villages where data are unavailable.

A high variance of neighborhood diarrhea suggests that the data are too individualistic while a low variance suggests that data are global. An optimal neighborhood size ensures that the aggregated diarrhea data are neither local nor global. A 100 m sized neighborhood is expected to have a high variance while a 500 m sized neighborhood is expected to have a low variance. We utilized Hartley's test of homogeneity of variance to

identify an optimal neighborhood size to ensure that the aggregated diarrhea data are neither local nor global (75). The Hartley's test statistic, F_{MAX} is calculated by the following equation:

$$F_{MAX} = \frac{S^2_{max}}{S^2_{min}}$$

Where:

$S^2_{max=}$ maximum value of the variances among groups

$S^2_{min=}$ minimum value of the variances among groups

Under the null hypothesis, the F_{MAX} test assumes that variances are equal. Critical values are calculated under the F-distribution using (k, n_{max} - 1) degrees of freedom with significance measured at $\alpha = 0.05$. Here k represents the number of groups or neighborhoods and n_{max} represents the maximum sample size among groups.

The variance of each neighborhood is compared with both the highest neighborhood variance (upper, F_{max1}) and the lowest neighborhood variance (lower, F_{max2}). A significant value of F_{max1} suggests that the structure of the neighborhood data is not global while a significant value of F_{max2} suggests that the neighborhood data are not individualistic. Optimal neighborhood sizes fall between the lower and upper F_{max} limits and capture a variance of diarrhea incidence that is neither local nor global. The optimal neighborhood boundaries were used to guide variables constructed to address both research questions.

Figure 4.2: Euclidean distance based neighborhoods
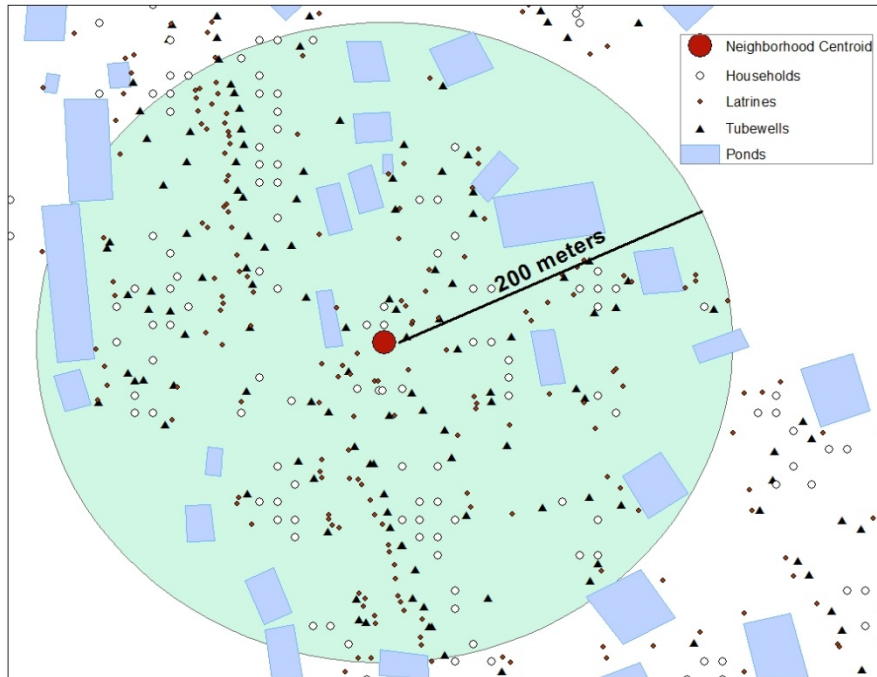
Neighborhood Sanitation Variable Construction

The first research question addressed in this study examines the relationship between diarrheal disease and the neighborhood sanitation infrastructure. A primary household latrine and tubewell were identified for each household prior to constructing neighborhood sanitation variables. Households typically obtain drinking water from the nearest tubewell within their *bari*. *Baris* that do not own a tubewell share a well from a neighboring *bari*, or use a public tubewell. Households were assigned to the nearest latrine within their *bari*, unless otherwise specified during the field survey.

Identifying an optimal neighborhood size(s) allowed us to measure neighborhood effects on household diarrhea. We constructed neighborhood level variables by placing buffers around households and aggregating data within optimal neighborhood radii (Figure 4.2). Variables include neighborhood population, average SES and maternal education, and sanitation infrastructure. The neighborhood sanitation infrastructure is defined by latrines,

tubewells, and ponds. We constructed variables for open, sanitary, and unsanitary latrine counts to measure the effect of latrine quality. We expected households in neighborhoods with higher counts of open and unsanitary latrines to report more diarrhea compared to households in neighborhoods using sanitary latrines. Neighborhood pond variables include counts of bathing, latrine, no purpose and total ponds. Pond variables were measured to examine the relationship between diarrhea and exposure to fecal contamination in surface water. Households located in neighborhoods densely populated with ponds were expected to have more diarrhea because of increased opportunity to interact with contaminated surface water.

Variables representing the ratio of people per tubewell and people per latrine were also measured. These variables were constructed to measure the relationship between diarrhea and sufficient access to improved water and sanitation resources. We expected to find lower diarrhea incidence among households in neighborhoods with fewer people sharing tubewells and sanitary latrines.

Bathing Pond Sanitation Variable Construction

The second part of this study measures the relationship between bathing pond sanitation and childhood diarrhea. Bathing ponds are a measure of disease exposure because they are often contaminated with fecal coliforms and are used daily. For this study, bathing pond sanitation is defined by the number and quality of latrines situated within the pond drainage basin, approximately 20 m (89). Bathing pond sanitation variables include: the count of sanitary latrines, total latrines, and latrines draining effluent within the basin, as well as the presence of a latrine draining directly into the pond. Latrine counts are separated by

type to identify any variation in relationships between diarrhea and the quality of latrines surrounding bathing ponds.

The optimal neighborhood size was also used to identify a distance for constructing bathing pond connectivity metrics. Households were linked to bathing ponds within a 250 m radius. Households were then connected via bathing ponds to estimate exposure to diarrhea pathogens from shared bathing pond use (Figure 4.3). Connectivity metrics were constructed using a distance decay function (98). The inverse distance squared weighting (IDW) function was used to assign more weight to bathing ponds within a shorter distance of the household. Bathing pond sanitation variables were also weighted so that the quality and quantity of latrines surrounding the closest bathing ponds were most influential. Variables were weighted based on the assumption that the likelihood of a household using a bathing pond decreases as distance increases. All weighted variables were aggregated to represent the quality and accessibility of bathing ponds within 250 m of each household.

Figure 4.3: Bathing pond sanitation and connectivity
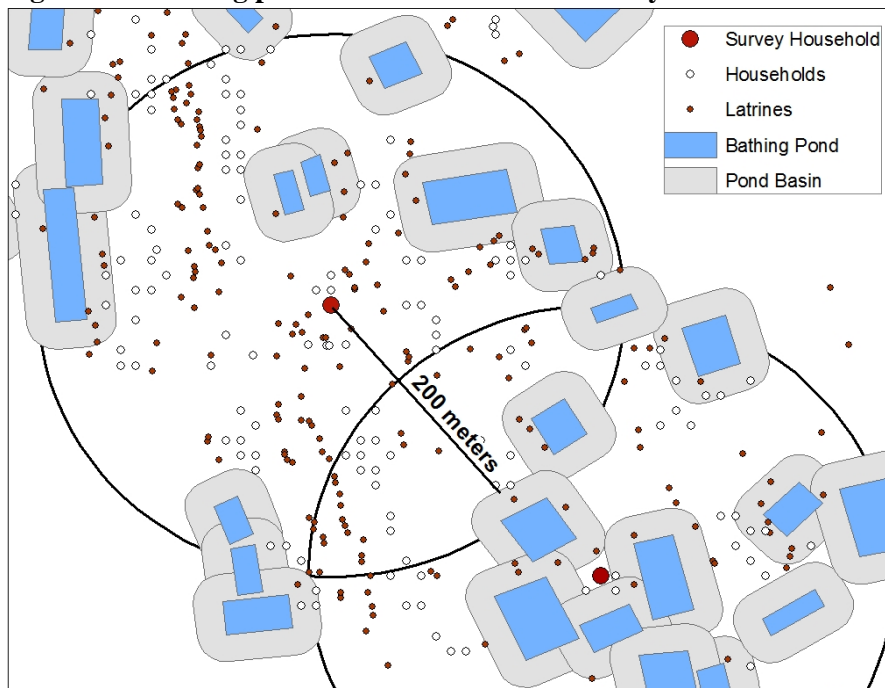
Random Effects Logistic Regression:

This study uses a repeated measures design to analyze the longitudinal community level diarrheal disease data for the 2002 -2006 period. The study period begins in 2002 to limit the effect of temporal changes to the built environment and ends in 2006 because the survey was not conducted in 2007. Monthly diarrhea cases reported by household are aggregated by season over the five year study period to account for seasonal patterns in the data. The seasons include early monsoon, late monsoon, and post monsoon with winter as the reference. The outcome for this analysis is the presence/absence of diarrhea reported by a household in a given season. The analysis is restricted to households with a child under 5 present during the study period resulting in a sample size of 737 households. We used a random effects specification to account for the clustered nature of the data due to the repeated measures design of the survey. Two sets of random effects logistic regression models were built to address each research question.

The first set of random effects logistic regression models was built to measure the relationship between neighborhood sanitation and childhood diarrhea (Table 4.1). Models were built for 150 m, 200 m and 250 m neighborhoods. Individual models were built to measure the relationship between childhood diarrhea and neighborhood SES and maternal education, as well as the number of open, septic, sanitary, and unsanitary latrines within a neighborhood. The final model built measured the combined effects of population per septic latrine, population per tubewell, and the number of neighborhood bathing ponds. All models were adjusted for season, year, number of children under 5 in a household, household level maternal education, and neighborhood population. We calculated Akaike Information Criterion (AIC) values for all models to select the best neighborhood size.

The second set of random effects logistic regression models were built to measure the relationship between childhood diarrhea and the sanitation quality of bathing ponds within a 250 m radius. Three models were built to measure the effect of the following weighted variables: the weighted sum of latrines leaking in the bathing pond drainage basin, the weighted sum of sanitary latrines within the basin, and the weighted sum of bathing ponds receiving direct effluent from a broken latrine. The three predictors were included in a final model to account for any interactions. All models controlled for season, year, number of children under 5 in a household, household maternal education, pond area, and the weighted sum of the population sharing bathing ponds.

Results:

Our sample included 9440 observations recorded for the 737 household sample during the study period. A total of 723 cases were reported between 2002-2006. The six study villages are non-contiguous and vary by size and population distribution. To account for these differences, and the possibility that optimal neighborhood size would vary by village, we conducted a separate F_{MAX} test for each village. Optimal neighborhood sizes were between 150 m, 200 m and 250 m.

Neighborhood Sanitation Analysis:

Random effects logistic regression models were built to measure the relationship between childhood diarrhea and neighborhood sanitation within 150 m, 200 m and 250 m neighborhoods. Models using a 250 m specification had the lowest AIC values representing the best fit. Results for the 250 m neighborhood models are presented below.

Models measuring neighborhood SES and maternal education were not significant and results are not shown. The majority of households in the study area own or have access to a septic latrine within their *bari*, however 13% of surveyed *baris* had at least one open latrine identified during the GPS survey. We measured the relationship between diarrhea incidence and open latrines to determine whether a mixed use of open and septic latrines within a neighborhood increases diarrhea (output not shown). We found a positive relationship between the likelihood of reporting diarrhea and the number of open latrines in a neighborhood. The reported odds ratio of 1.046 was significant at p<0.001and suggests that the likelihood of a household reporting diarrhea increases by 4.6% for each additional open latrine. Relationships between diarrhea and the number of septic, sanitary, or unsanitary latrines within a neighborhood were not significant.

While the relationship between diarrhea incidence and the number of septic, sanitary, and unsanitary latrines was not the significant, the ratio of people per latrines within a neighborhood was predictive of a household reporting diarrhea. Four models were built to measure the relationship between diarrhea and the ratio of the neighborhood population per latrine by type. Adjusted odds ratios for each model are listed in Table 4.1. We expected to find positive associations between diarrhea incidence and an increase in the ratio of people to latrines. As the ratio of the neighborhood population to latrines increases, a greater number of people must share latrines, placing increased strain on resources. The ratio of neighborhood population per unsanitary latrines was marginally significant suggesting that more people sharing latrines increases diarrhea. Similarly as the ratio of people per sanitary latrine increases so does the risk of diarrhea by 8.8%. The ratio of neighborhood population per total latrines was even more influential with an odds ratio of 1.312. The ratio of population per

septic latrine was the most predictive of reporting diarrhea with an odds ratio of 1.441.

Results suggest that the likelihood of reporting diarrhea increases as the number of people

sharing latrines increases. More specifically, the results suggest that a sufficient number of

septic latrines is more protective than a sufficient number of both septic and open latrines.

Table 4.1: Adjusted odds ratios for neighborhood population per septic latrines, unsanitary latrines, sanitary latrines and total latrines*

Neighborhood population per latrine type	Odds Ratio	P value	95% CI	
Unsanitary latrines	1.016	0.088*	0.998	1.034
Sanitary latrines	1.088	0.000***	1.040	1.138
Total latrines	1.312	0.000***	1.151	1.494
Septic latrines	1.441	0.000***	1.284	1.618

*$p \leq 0.1$ **$p \leq 0.05$, and ***$p \leq 0.01$
Results from 4 separate models*
Number of observations = 9940
Number of households=737
Models control for season, year, number of children under 5 per household, and household maternal education, neighborhood population

A random effects logistic regression model was built including multiple

neighborhood sanitation variables to measure any interaction between predictors. Results

presented in Table 4.2 suggest that as the ratio of population per septic latrine increases, so

does the risk of diarrhea regardless of tubewell access, emphasizing the importance of

neighborhood level access to septic latrines. The ratio of people per tubewells was not

significant. One possible explanation is that the abundance of tubewells throughout the study

provides sufficient access for all households eliminating variability. The likelihood of a

household reporting diarrhea increases 2.3% for each additional bathing pond in the

neighborhood. Additional models were built measuring the effect of neighborhood latrine, no

purpose and total ponds to determine whether living in a neighborhood densely populated

with visibly contaminated ponds increased diarrhea. Neither was significant, possibly

because people do not directly interact with 'no purpose' ponds or 'latrine' ponds. However,

people do interact with bathing ponds and as the number of bathing ponds increases, the

likelihood of a person using surface water increases. The following section builds on this

finding and explores the relationship between bathing pond sanitation and diarrheal disease.

Table 4.2: Neighborhood sanitation random effects logistic regression model

Predictors	Odds Ratio	P value	95% CI	
Neighborhood water and sanitation infrastructure				
Population per septic latrine	1.548	0.000***	1.374	1.745
Population per tubewells	0.983	0.120	0.963	1.004
Neighborhood bathing ponds	1.023	0.003***	1.007	1.043
Controls				
Household Maternal Education	0.887	0.102	0.769	1.024
Children under 5 per household	1.752	0.000***	1.478	2.076
Early Monsoon	2.074	0.000***	1.619	2.656
Late Monsoon	1.731	0.000***	1.344	2.230
Post Monsoon	1.247	0.105	0.955	1.627
Year	0.657	0.000***	0.613	0.704

*$p \leq 0.1$ **$p \leq 0.05$, and ***$p \leq 0.01$
Number of observations = 9940
Number of households=737
Odds ratios adjusted for all other predictors listed in the table

Bathing Pond Sanitation Results

The number and type of latrines within a 20 m bathing pond drainage basin were measured. Households were linked to bathing ponds within a 250 m radius using an inverse distance squared function. A total of 135 bathing ponds were identified in our study area. Of the 135 bathing ponds, 11 had a latrine draining directly into it, with one pond receiving effluent from multiple latrines. Households were connected to an average of 10 bathing ponds and shared these ponds with a weighted average of 482 people.

Random effects logistic regression models were built to measure the relationship between bathing pond sanitation variables and diarrhea. All pond sanitation variables were weighted with the assumption that people are less likely to use bathing ponds that are further away. The relationship between diarrhea and bathing pond sanitation variables did not vary between models measuring predictors separately or combined. Table 4.3 shows the results for the model including all predictors.

The presence of a latrine draining directly into the pond and the number of sanitary latrines within the pond drainage basin were not significant. The likelihood of a household reporting diarrhea increased by 50% for every unit increase of the weighted sum of latrines draining in pond basins. Controls for pond area and number of people sharing bathing ponds were not significant.

Table 4.3: Bathing pond sanitation random effects logistic regression model

Predictors	Odds Ratio	P value	95% CI	
Bathing Pond Sanitation				
Latrines draining in 20 m basin	1.493	0.000***	1.227	1.818
Latrine draining directly in pond	0.673	0.137	0.400	1.135
Sanitary latrines in basin	1.059	0.472	0.906	1.239
Controls				
Area	1.000	0.056*	1.000	1.000
Population sharing ponds	1.000	0.506	1.000	1.001
Household Maternal Education	0.857	0.035**	0.742	0.990
Children under 5 per household	1.789	0.000***	1.506	2.124
Early Monsoon	2.073	0.000***	1.619	2.655
Late Monsoon	1.731	0.000***	1.344	2.229
Post Monsoon	1.247	0.105	0.955	1.627
Year	0.666	0.000***	0.622	0.713

*$p \leq 0.1$ **$p \leq 0.05$, and ***$p \leq 0.01$
Number of observations = 9940
Number of households=737
Odds ratios adjusted for all other predictors listed in the table

Discussion:

This study demonstrates that even with the transition from surface to ground water consumption, poor sanitation continues to play a significant role in diarrhea transmission. The Fmax test statistic identified 150 m, 200 m and 250 m as optimal neighborhood sizes. Previous studies in Matlab have identified 500 m as an optimal neighborhood size for exploring shigellosis transmission and cholera vaccine efficacy (98, 99). The difference in

optimal neighborhood size could be a result of the different scales at which the data were collected and analyzed. In previous neighborhood studies the *bari* was the unit of analysis and Matlab region was the study area. For this study, we utilized household level data as the unit of analysis to identify neighborhoods within six villages. By exploring neighborhoods within a village, optimal neighborhoods could be representative of the distances people are willing to walk for water and sanitation resources. All households in our study area are within ~220 m of a bathing pond and it has been shown in other rural areas of Bangladesh that some villagers are willing to walk up to ~150 meters several times a day to obtain drinking water (100, 101)

Neighborhood Sanitation Infrastructure

The majority of households in our study area have access to a septic latrine; however some households continue to use both open and septic latrines. It is not surprising that households living in neighborhoods where open latrines remain an option experience more diarrhea. Open latrines are closely related to low SES and maternal education potentially influencing other sanitary practices that are not captured in this study. In addition, an increase of people sharing septic latrines is associated with diarrhea. This suggests that beyond repairing broken septic latrines, there is a need for complete abandonment of open latrine use and sufficient access to septic latrines is needed.

The non-significant relationship between diarrheal disease and neighborhood latrine ponds was unanticipated. We expected latrine ponds to affect overall neighborhood sanitation, especially during the monsoon when surface water bodies flood and inundate the surrounding area exposing people to fecal matter. However, the number of bathing ponds was positively associated with diarrhea. These relationships demonstrate the importance of

looking beyond the built sanitation infrastructure and exploring the behaviors that place people in direct contact with fecal contamination. Villagers do not collect surface water from latrine ponds for daily use; however they do come in direct contact with bathing ponds. We assume that similar to tubewell and latrine use, households tend to use the closest bathing pond. While we are unable to identify the exact bathing pond(s) used by individual households, utilizing a distance weighted connectivity metric allowed us to measure the quality of multiple ponds potentially being used.

Bathing Pond Sanitation

Results displayed in Table 4.3 suggest that the maintenance of latrines surrounding a bathing pond is important to prevent exposure to fecal contamination. This was expected as unsanitary latrines are more highly correlated with bathing pond fecal contamination than sanitary latrines as latrine effluent is washed directly into the pond by rain and draining tubewells (89). The protective effect of household level maternal education suggests that despite the use of contaminated bathing ponds, improving education may influence other protective behaviors that are not captured in this analysis.

Conclusion:

Latrine installation is considered a cost-effective measure for preventing diarrhea, however latrines require periodic emptying or construction of new facilities once they fill up becoming an economic concern for some residents (30, 49, 54). This is a problem because residents consume untreated ground water and continue to use surface water. If sanitary excreta disposal is absent, other measures of water treatment must be taken. Boiling water is

an effective method for treating water however this also places an economic burden on rural residents.

The main limitations of this study are the lack of pond water quality data and information linking households to their preferred bathing pond(s). However water collected from a small sample of bathing ponds in our study area was highly contaminated with fecal coliforms (Feighery, unpublished data). By measuring bathing pond fecal coliform levels and asking households where they bathe, we could more accurately identify surface water sources that cause diarrhea.

It is evident that behaviors such as discontinued use of open latrines and regular maintenance of household septic latrines reduce diarrhea. Given the extreme poverty in the area it is unlikely that many households will immediately change their latrine practices. Therefore, the question raised is what can be done to reduce exposure to contaminated feces. One alternative is abandoning surface water use and relying strictly on ground water. During the GPS survey, we observed that some residents living further away from bathing ponds preferred to bath with tubewell water. While this practice has been shown to reduce diarrhea, it is not feasible on a broad scale (102). A recent study conducted in Matlab measured the effect of a water purification mixture comprised of alum potash, bleaching powder and lime. The mixture was found effective in purifying up 15 l of surface water at a time and reducing diarrhea (93). It is unknown whether this practice will become widespread but it may provide an alternative method for purifying water where sanitation is poor and people use surface and ground water contaminated with fecal coliforms.

CHAPTER 5

Findings reported in Chapters 2 and 4 suggest that the quality of the sanitation infrastructure influences diarrheal disease via contaminated groundwater and surface water. Results also suggest that open latrine practices should be abandoned entirely and septic latrines should be used exclusively. It is unlikely that improvements in sanitation will occur rapidly and high poverty and a lack of fuel resources makes it difficult for residents to boil water. Thus, there is a need for safe water alternatives that are not affected by poor sanitation.

The World Health Organization recommends that tubewells be installed a minimum distance of 10 m from latrines. Similarly, results in Chapter 2 suggest that unsanitary latrines are associated with contaminated tubewell water and septic latrines should be sealed and installed away from tubewells. High population and latrine density make it difficult to install tubewells a minimum of 10 m from a latrine. When the population is dense and it is impossible to install tubewells at great distances from latrines the WHO suggests increasing the depth of the tubewell.

The Bangladesh Department of Public Health and Engineering installed deep tubewells (> 500 ft) in areas of Bangladesh with high arsenic contamination. It is unknown whether these deep tubewells have a protective effect against diarrheal disease transmission. However a protective effect is possible given the lower levels of microbial contamination in the deep aquifer and the relationship between childhood diarrhea and fecal contamination in

shallow tubewells (Chapter 2). The following chapter explores this relationship to determine whether households obtaining drinking water from shallow wells experience more diarrhea than households drinking from deep wells.

CHAPTER 6

IMPACT OF DEEP TUBEWELLS ON CHILDHOOD DIARRHEA IN
BANGLADESH

Introduction

Diarrheal diseases are the second leading cause of death in children under 5 worldwide (103). Children living in poor areas with inadequate nutrition are most susceptible to severe diarrhea and dehydration. An estimated 2.5 million cases of diarrhea occur annually in children under five, with Asia and southern Africa accounting for more than half of the cases (86). Diarrheal diseases remain endemic where water and sanitation infrastructure is limited in countries such as Bangladesh.

Efforts by UNICEF, the Bangladesh Department of Public Health Engineering (DPHE), and non-governmental organizations (NGOs) have lead to a nearly universal shift from surface water to groundwater consumption in Bangladesh (104). These efforts were in response to the severe burden of diarrheal disease and the widespread contamination of surface water with human pathogens. Since the 1970's, the number of tubewells is thought to have doubled roughly every 5 years throughout rural Bangladesh (79). The majority are private shallow domestic wells that were installed using a hand percussion drilling method that is affordable for individual households (2). Currently over 90% of households in Bangladesh obtain drinking water from a total of approximately 10 million mostly shallow tubewells.

Whereas the proliferation of tubewells provided access to drinking water that is much less contaminated with microbial pathogens than surface water, it caused a severe health problem of a different nature due to frequently high levels of arsenic (As) in groundwater. A survey carried out in the late 1990's showed that a third of the population of 130 million at the time was drinking water that did not meet the Bangladesh standard for As in drinking water of 50 µg L^{-1} and nearly half the population to levels that exceeded the WHO guideline of 10 µg L^{-1} (78). Beyond early signs of arsenicosis such as skin lesions (105), exposure to As by drinking tubewell water has increased all-cause mortality (106) and cancers of the lung, liver, and bladder in adults (107).

In response to As testing of nearly 5 million wells throughout the affected regions of Bangladesh under the Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP), millions of households have stopped drinking from their shallow high As wells and switched to a neighboring well that is low in As, and often also shallow (34, 79). It was recently shown, however, that groundwater pumped from shallow low-As wells is more likely to be contaminated with human waste due to the imprint of the local hydrogeology combined with high population density and poor sanitation than groundwater from a shallow high-As well (80, 81). This raises the concern that the response of households to well-testing for As might have increased exposure to microbial pathogens. More generally, fecal contamination of shallow groundwater may be one reason for the persistence of diarrheal disease in Bangladesh (84, 108).

After switching to a nearby household well, the next most effective means of reducing As exposure from drinking water has been the installation throughout the country of ~165,000 deep wells by DPHE and NGOs over the past decade (34, 109). These deep wells

tap older strata that either retain As within aquifer sands or have been flushed of their initial

As content (57, 110). Most of the deep wells installed by DPHE and NGOs are over 500 feet

deep. Deep public tubewells are typically installed near a road in a central location of a

village to maximize access. It has been shown that some villagers are willing to walk up to

~150 meters several times a day to obtain drinking water from these deep tubewells (100,

101). While such deep tubewells were installed to reduce exposure to As, the impact of

switching to such, often more distant, wells has to our knowledge not systematically been

investigated. One potential source of concern is that water pumped from a distant well may

be stored for longer in the house, hereby increasing the risk of microbial contamination, even

if the depth of public wells might be expected to offer some additional protection against

microbial contamination (83, 108, 111). The impact of access on hygiene is less likely to be

significant because villagers have been encouraged to continue to rely on their household

well for uses other than drinking and cooking. The extensive set of diarrheal disease data

collected in the Matlab study area of the International Center for Diarrhoeal Disease

Research, Bangladesh (ICDDRB, B) offers a unique opportunity to measure the relationship

between diarrheal disease and obtaining drinking water from deep tubewells within a

population that drinks primarily untreated groundwater.

Methods

Study Setting and Design

The rural study area of Matlab, Bangladesh, is located 50 km southeast of Dhaka

(Figure 6.1). This ICDDR,B field site has a hospital that provides in-patient treatment for

severe diarrhea free of charge to all residents. The study area's Health and Demographic

Surveillance System (HDSS) is a longitudinal surveillance system that has maintained health

and demographic records for all Matlab residents since 1966. People are assigned a unique

identification number upon entry into the area via birth or migration. Individual identification

numbers are used to link demographic, health, and other data. In addition to the monthly

collection of household-level population under the HDSS, a detailed household census that

included measures of socio-economic status (SES) and maternal education was conducted in

2005. Monthly diarrhea incidence data were collected for children under five by female

community health workers who asked mothers whether their child had diarrhea during the

previous 24 hours. A case is defined as three loose stools in a 24-hr period and episodes

reported to last several days are recorded as a single case (23).

Figure 6.1.(a) Map of ICDDR,B's study of Matlab in Bangladesh. (b) Enlarged view of the six villages where surveys were conducted in 2008-09 to determine which households had switched to a deep tube well and which had not.
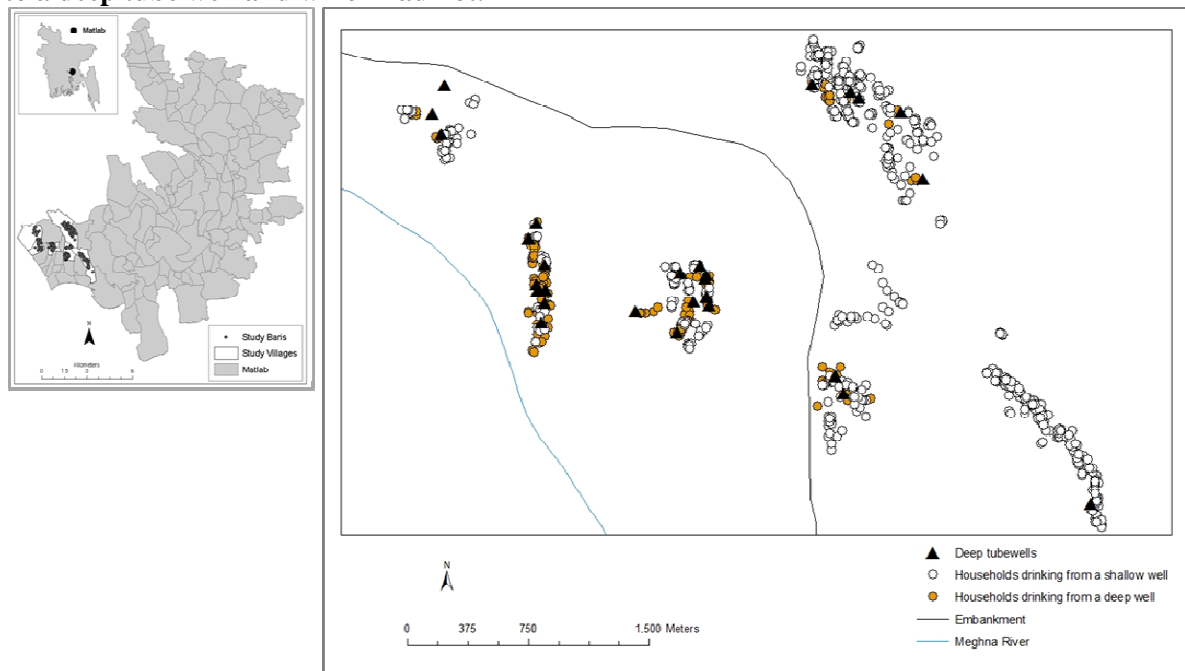
Geographic Database and Study Variables

On the basis of its high proportion of shallow wells that are low in As, the village of

Bara Haldia and five neighboring villages were selected to monitor variations in fecal

contamination of tubewell water (80). As part of this study, drinking water resource

information was obtained in 2008-09 for 543 households with a population of 2700. A field

survey was conducted to map the water and sanitation infrastructure of the 6 village study

area and the data were incorporated into the study area geographic information system (GIS).

Sub-meter accuracy global positioning system (GPS) receivers were used to collect spatial

data that were differentially-corrected through post-processing to ensure high accuracy. All

tubewells, latrines, and household locations were mapped and during the survey, residents

provided information regarding which tubewells they use for drinking water. Households

generally obtain drinking water from the nearest tubewell within their cluster of patrilineally-

related households called *baris*. *Baris* that do not own tubewells identified drinking wells that

are owned by neighboring *baris*, mosques, or are public. Some households own a tubewell

but identified a deep public tubewell as their source for drinking water. Using tubewell age

and information provided by residents, we determined which households obtain drinking

water from deep tubewells installed in 2005 and which households drink water from private

shallow wells.

Four time invariant control variables are included in this study: the number of latrines

within 30 meters of a household, the population density, SES, and household maternal

education level. The GIS was used to calculate the number of latrines around each household

as well as the number of people living within a 30 meter radius of a household. The adjacent

latrine variable controls for local-level sanitation effects and population density controls for

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local use of water resources as well above ground transmission and contaminant source strength. A categorical SES score was developed using principal components analysis. The score reflects a composite of five dichotomous variables representing ownership of various household assets (bed, bicycle, blanket, lamp, watch), and one ordinal variable representing household wall material. The composite SES score was divided into quintiles to represent a range of economic levels with higher quintiles reflecting higher SES (90). Household maternal education represents years of education, with an average of 3.4 years per household.

Statistical Analysis

This is a repeated measures study that uses data from the six-village study area of reported household-level childhood diarrhea from 2005 to 2006. To study the effect of obtaining drinking water from a deep tubewell on childhood diarrhea, we consider the number of cases reported in children under five, 12 times per year during our study period, aggregated for years 2005 and 2006. Although diarrheal disease data are available starting in 2000, the majority of deep tubewells in our study area were installed in 2005, making it difficult to separate the effect of time from the effect of deep tubewell use on diarrhea. The analysis did not extend beyond 2006 because the comprehensive collection of diarrheal disease data in Matlab ended.

Because our outcome is a count variable with a skewed distribution we first determine whether a negative binomial or Poisson distribution best supports our data by comparing the mean and the variance of the outcome. An unequal variance and mean suggests that the data are overdispersed and a negative binomial regression model is preferred over Poisson. The negative binomial model allows for overdispersion with an

additional parameter and assumes a Gamma distribution. We use a random effects specification to account for the clustered nature of the repeated measures.

Data are arranged by unique identifiers over time representing n cases over t time periods for a total of $n \times t$ observations. The negative binomial regression model below measures the probability mass function for y_{it}:

$$\Pr(y_{it} = r) = \frac{\Gamma(\theta + r)}{\Gamma(\theta)\Gamma(r+1)} \left(\frac{\lambda_{it}}{\lambda_{it} + \theta}\right)^r \left(\frac{\theta}{\lambda_{it} + \theta}\right)^\theta, \quad r = 0, 1, 2, \ldots$$

Where r represents success (diarrhea) and y_{it} represents the diarrhea count for household i at time t. In this equation λ_{it} is the expected value of y_{it}, θ is the overdispersion parameter, and $\Gamma(\cdot)$ is the gamma function. Next, we assume that the expected value y_{it} is described by a log-linear regression. This is measured in the equation below where the $\log \lambda_{it}$ is a function of the predictor variables:

$$\log \lambda_{it} = \mu_t + \beta x_{it} + \gamma z_i + \alpha_i$$

Where β and γ represent the vectors of coefficients. The outcome is a function of the following: the time specific intercept μ_t, time variant factors x_{it}, time invariant factors z_i, and an individual specific error term α_i that represents unobserved variables assumed to be uncorrelated with the observed variables.

The random effects negative binomial model provides coefficients for both time variant and time invariant predictors. Use of a deep tubewell as the primary source of household drinking water is the predictor of interest. Additional time invariant predictors included in the model are maternal education, SES, and latrine and population density. The model also includes time variant controls for the number of children under five in a given household, and a dummy for year to capture the effect of time on decreasing incidence. All statistical analyses were carried out using Stata 11.0 (StataCorp. 2007).

Results

Of the 543 households within the study area, a subset of 179 obtain drinking water

from a deep well located at a median distance of 41 meters (Figure 6.1). The median distance

to the nearest deep tubewell of 153 meters for the remaining 364 households indicates that

this was probably a factor in their decision to use a private shallow tubewell. Diarrhea

incidence was lower for households drinking from a deep well compared to those drinking

from a shallow well in 2005 and 2006. The key feature for this analysis is the proportional

decrease in diarrhea incidence between 2005 to 2006 which was nearly twice as large for

households using a deep tubewell.

A total of 122 diarrhea cases were reported between 2005 and 2006. The difference in

the outcome mean (0.13) and variance (0.17) suggests that a negative binomial distribution is

appropriate for these data. The negative binomial random effects model includes

observations for 543 households, with an average of 1.3 children. The model is restricted to

households with children under five present during the study period. The model is

unbalanced due to children aging in and out of the community diarrhea survey, thus

households contribute one or two observations over the two year period and a total of 927

observations are included in the model.

 Results for the random effects negative binomial model are displayed in Table 6.1.

Coefficients were exponentiated to report incident rate ratios (IRR). While incidence rate

ratios of one indicate no effect of an independent variable, incidence rate ratios of above one

indicate positive and below one negative effects. The risk of diarrhea incidence significantly

decreased for households using a deep tubewell (IRR 0.541). Thus households using a deep

tubewell had a 46% lower risk of diarrhea than households using a shallow tubewell,

controlling for number of children under five, and holding all other variables constant.

Household maternal education was marginally significant (p value < 0.1) suggesting that an

increase in education is associated with a decrease in diarrhea. Controls for year, household

SES, maternal education, and population and latrine density were not significant. The

findings from the random effects negative binomial are consistent with the observation that

diarrhea incidence is lower and decreasing more rapidly for households using a deep

tubewell.

Table 6.1. Random effects negative binomial regression results for the association between childhood diarrhea and deep tubewell use in 2005-2006

Predictors	IRR	95% CI		P value
Deep Tubewell Use	0.541	0.308	0.949	0.032*
Children Under 5	1.988	1.434	2.755	0.000***
Maternal Education	0.932	0.858	1.012	0.094
SES	0.983	0.840	1.151	0.835
Latrine Density	0.977	0.882	1.082	0.650
Population Density	0.999	0.987	1.012	0.911
Year	1.371	0.914	2.058	0.128

Significance values: 0.0001 '***' 0.001 '**' 0.05 '*'
Number of Observations = 927
Number of Households = 543

Discussion and implications

The overall decline in the incidence of childhood diarrhea from 2005 to 2006 is

dramatic but beyond the scope of this analysis (Figure 6.2). The main result presented here is

that obtaining drinking water from a deep public well is associated with a significant

reduction in diarrheal disease in children under five, even if that well was typically further away than the household's own well. Less convenient access to the main source of drinking water, or potentially longer storage of drinking water within the home, as result of using deep well evidently did not have a major impact on diarrheal disease (83). One possible explanation is that household wells, regardless of their As content, continue to be used for personal hygiene (3). Although this would have to be determined more rigorously, it appears that the microbial quality of low-As water pumped from deep public wells might be higher than that of shallower household wells. The reason for this is not entirely clear but might be related to the protective effect of greater separation of deeper wells from the strong surface sources of microbial contamination such as latrines and ponds (78, 81).

Figure 6.2. Comparison of the average annual incidence of diarrheal disease with children under five in 2005-06 for the six study villages.
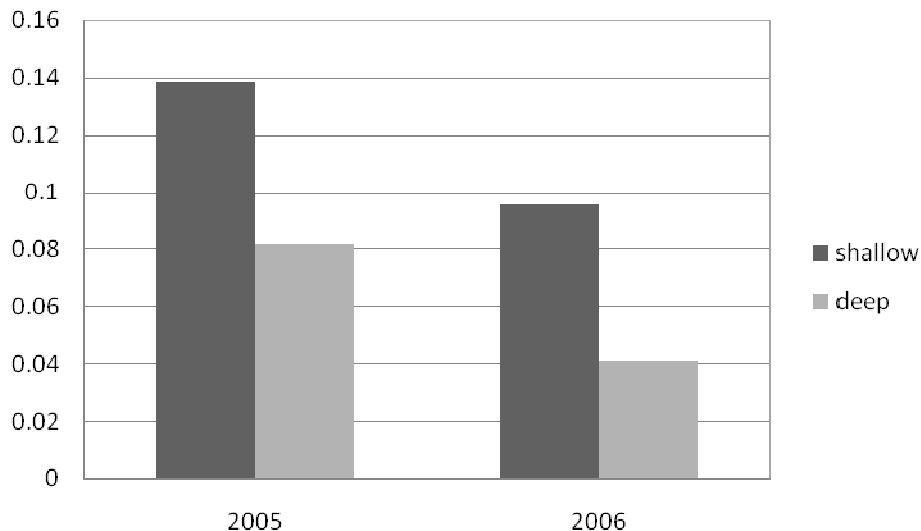
The practical implication of our finding is that the installation of 165,000 deep wells through the country to reduce As exposure may have had the added benefit of decreasing exposure to microbial pathogens. Given the high cost of a deep well, it is unlikely that many will be installed privately in the future. The question raised, therefore, is whether even

households with shallow wells that are low in As should instead use deeper public wells as their main source of drinking water. Before making such a recommendation, however, it is important to consider that deep public wells should be periodically tested for As. The limited time series data available indicate that As concentrations in groundwater pumped from deep public wells remain low in the vast majority of cases, but a small yet significant proportion is likely to fail over time due to broken or disconnected PVC pipes (112). Even a modest failure rate of 5% translates into a total of more than 8,000 deep public wells throughout the country that a population of 2,000,000 should not be drinking from, assuming conservatively that 250 villagers on average drink from deep public well (100).

The main limitation of this study is the limited number of households and deep public wells that were considered. By asking households if they use a deep tubewell as their primary source of drinking water, the analysis of the available diarrheal disease data could be expanded to all 142 villages of Matlab.

CHAPTER 7

CONCLUSION

This research provides evidence that the interaction between human behaviors and the environment can expose individuals to diarrhea pathogens. Interactions between human biology, behaviors, and the natural and built environment are dynamic and continuous. The decision to drink water from shallow wells surrounded by unsanitary latrines or the continued practice of rinsing dishes or bathing in ponds surrounded by failing latrines increases an individual's risk of diarrhea. The built environment is constructed by residents and varies based on SES, preferences, and is influenced by policy.

The overarching finding of this research is that the slower improvements to the sanitation infrastructure compared with improved water resources is an important contributor to childhood diarrheal disease. Poor sanitation exposes individuals to fecal pathogens through various avenues. In Chapter 2 we saw that not only the proximity of latrines to tubewells but also the quality of latrines is predictive of shallow tubewell water quality. The significance of this finding is that it suggests that surface contamination from unsanitary latrines compromises drinking water quality at the point of collection. Additionally, while the WHO recommends that tubewells be placed a minimum of 10 m from a latrine to prevent contamination, the relationship is much more complex. Beyond placing latrines at greater distances from tubewells, maintaining the latrine structure is also important as sanitary latrines in close proximity to tubewells were not predictive of microbial contamination.

These findings have important health implications. During the 18 month sampling period in this study, all 92 survey wells were contaminated with *E. coli* at least once. While the levels of *E. coli* often placed people in the low risk category of diarrheal disease transmission (28), drinking water contaminated at the source is more likely to have higher levels of fecal contamination after storage increasing risk of ingesting fecal pathogens (39). The contribution of point source contamination to diarrheal diseases in Bangladesh remains unclear however results from this study suggest that increased levels of *E. coli* in shallow tubewell water are associated with childhood diarrhea.

Findings presented in Chapter 4 further demonstrate the importance of improved sanitation. Children living in neighborhoods where open latrines are used in conjunction with septic latrines are more likely to experience diarrhea. Additionally, it is not only the use of septic latrines that is protective, but having a larger number of latrines for the neighborhood population is also protective. The increased risk of diarrhea associated with more people sharing a latrine could be caused by overflowing septic latrines resulting from overuse. We see in Table 4.1 that sufficient sanitary latrines and sufficient total latrines (including open) are not as protective as simply having enough septic latrines for all residents. In addition, children living near bathing ponds surrounded by latrines leaking waste into the pond drainage basin experience more diarrhea. These results suggest that it is important to: 1) abandon the use of open latrines, and 2) to increase the proportion of sanitary septic latrines.

In Chapter 6 we see that one possible way of dealing with a limited sanitation infrastructure is to obtain drinking water from deep tubewells. This analysis demonstrates the importance of policy implementation in preventing diarrheal disease. While the primary role

of the installation of deep public tubewells was to provide arsenic-free groundwater, an unanticipated benefit of an additional protective effect for diarrhea transmission exists.

While sanitation and hygiene practices such as hand-washing and water storage are important for estimating diarrheal disease risk (3, 111), the quality of the source of water remains integral for ensuring safe drinking water (83). Our findings suggest that deep tubewells are protective, however further development of the deep tubewell infrastructure in rural Bangladesh requires several considerations. Increased involvement of NGOs and the government is needed as it is not economically feasible for most rural Bangladeshi families to install deep tubewells (58). Community training on deep tubewell maintenance is also needed to avoid unsafe practices such as priming with water from a contaminated source (108). The sustainability of deep groundwater quality must also be evaluated (100). Groundwater flow modeling of the Bengal basin suggests that deep irrigation pumping could induce downward flow from high arsenic regions resulting in deep groundwater As contamination (113, 114). However, these studies also suggest that deep hand-pumped wells could provide As free water for hundreds of years if use is restricted to domestic supply (113, 114). If deep groundwater quality is sustainable, deep tubewell interventions could potentially target low As regions with poor water quality and high diarrhea incidence. It is possible that the findings to this research could be extrapolated to similar locations but several factors need to be considered including climate, geology, and water and sanitation infrastructure. More importantly, this study provides a framework for similar interdisciplinary research involving field data collection.

Additional interventions to provide safe drinking water were initiated in Matlab, Bangladesh. The first is a community piped water supply where water is extracted from the

deep aquifer (800 ft), providing households with water that is drawn from a faucet inside the home twice a day. This system currently serves two villages in Matlab. The project was funded by ICDDR,B and the Bangladesh Rural Advancement Committee (BRAC) and the community is responsible for maintaining the quality of the structure and paying the salary for two staff members. While this is an effective form of obtaining a safe water supply, and residents are happy with the system, villages with low SES are unable to afford a community piped water supply. This suggests that water and sanitation interventions may vary based on community SES and affordable alternatives are needed. A recently developed alternative providing a safe water supply is the use of a water purification mixture recently found effective in reducing diarrhea (93). The mixture can purify up 15 l of surface water at a time and is inexpensive. It is unknown whether this practice will become widespread but it may provide an alternative method for purifying water where sanitation is poor and SES is low.

This research demonstrates how disease ecology provides a holistic framework that can guide interdisciplinary research and geographic methods including fieldwork. Interdisciplinary work can help move the field of medical geography forward as studies arise incorporating spatial data and both social and environmental data. By incorporating hydrological, spatial, health and demographic data it was possible to explore poor sanitation influences on shallow tubewell water quality. This analysis is an important part of this research because it demonstrates how the built environment can affect drinking water and consequently affect health. This would not have been possible without interdisciplinary collaboration, providing access to groundwater data.

Fieldwork conducted for this research was also an important component that was guided by the disease ecology framework. Beyond providing the necessary spatial data, field

observations provide insight into details of daily life that would otherwise go unnoticed. These observations informed my hypotheses, methods, and interpretation of results. One important observation was that some households chose to walk longer distances to use a deep tubewell rather than a nearby low arsenic shallow tubewell. Exploring the protective effect of a deep tubewell arsenic intervention was possible because specific households obtaining drinking water from deep tubewells were identified.

Another important field observation that informed this research was the notable difference in household SES in areas using open latrines. One of the six villages appeared to be significantly poorer and had the greatest number of open latrines. This prompted me to explore the relationship between diarrheal disease and types of latrines, specifically neighborhood open latrines. The non-significant relationship between latrine pond count and diarrheal disease presented in Chapter 4 was unexpected. I initially expected latrine ponds to function as an indicator of poor neighborhood sanitation and increase the likelihood of children coming in contact with human waste. However, it was not apparent that children interacted with these ponds. Bathing pond count was a positive predictor of diarrheal disease however because children interact with these ponds. This field survey could provide an example for future field surveys conducted in similar areas.

Limitations and Future Direction

Additional research is needed to better understand the extent at which consumption of contaminated shallow tubewell water influences diarrheal disease transmission. The main limitation of this study is the lack of diarrhea data available for households obtaining drinking water from survey wells (Chapter 2). The study was restricted to 33 households and 12 months of data. Findings suggest that a relationship exists between increasing *E. coli*

contamination and diarrhea, however research with a larger sample size would be beneficial. The community level diarrheal disease survey is ongoing providing an opportunity for future research. One possibility is to identify additional households obtaining drinking water from survey wells and incorporate these households into the community level diarrhea survey. If additional households are incorporated into the study and monthly groundwater samples continue to be collected it would be possible to analyze the relationship between monthly diarrheal disease and monthly tubewell contamination levels. This would provide a more accurate representation of the relationship between diarrheal disease and shallow tubewell water.

Another potential area for future research is conducting a more detailed bathing pond survey. Asking households to identify specific ponds they use for bathing and other daily practices could provide a clearer picture of how surface water quality influences diarrhea transmission. Additionally, incorporating microbial surface water samples from bathing ponds would help identify any fluctuations in diarrhea associated with varying levels of surface water contamination.

This research explored the ecology of childhood diarrheal disease at a very local scale accounting for household and neighborhood level influences. While predictive factors were identified at these scales, it is possible that 'upstream' factors are also influential and should be considered in future research. The importance of understanding the political ecology of diarrheal disease may rise as concerns over the amount of groundwater abstracted in Bangladesh increase. The current rate of groundwater being drawn throughout Bangladesh for irrigation and urban water supplies is not sustainable (115). As the government becomes more involved in response to these concerns, policy changes regarding groundwater

consumption will make it necessary to explore diarrheal disease transmission using both disease ecology and political ecology frameworks.

As we 2015 it is unclear whether the safe water and sanitation access millennium development goal will be met. Strong efforts have been made by the government, NGOs and residents of Bangladesh to improve access to improved drinking water sources. A large shift from open or hanging latrines to more sanitary septic latrines has also occurred, however this shift has been much slower. This research suggests that this uneven shift is a large contributor to endemic childhood diarrhea in Bangladesh. This study explored the effects of poor sanitation using various approaches and the results suggest these efforts are not enough. While there are notable improvements more needs to be done to ensure that all residents have access to improved sanitation and drinking water and that the use open and unsanitary latrines is abandoned. As the shift to groundwater from surface water was nearly universal in Bangladesh, a universal shift to improved sanitation is also needed to reduce diarrheal disease incidence.

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