ANALYSIS OF DRINKING WATER QUALITY AND SANITATION IN A PERI-URBAN AREA OF DAR ES SALAAM, TANZANIA

By

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ABSTRACT

ANALYSIS OF DRINKING WATER QUALITY AND SANITATION IN A PERI-URBAN AREA OF DAR ES SALAAM, TANZANIA

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While the Sustainable Development Goal 6 called for universal access to water and sanitation by 2030, the challenge of achieving this goal seems daunting in the context of the bourgeoning peri- urban communities of the developing world. These areas are often in a regulatory grey area, receiving municipal water on an irregular basis and lacking sanitation and other basic services. And yet, SDG 6 recognizes that improving global health and wellbeing is critically linked to addressing this problem. A multi-method study of the peri-urban area of Dar es Salaam was conducted to determine the extent of the problem and to make recommendations for system-wide approaches to alleviate the risk of waterborne disease. Existing water sources in the area were identified. Water collection and storage practices were assessed at the household level to determine how water from relatively clean sources becomes contaminated. Escherichia coli (*E. coli*), nitrate, and total dissolved solid (TDS) were analyzed as indicators for the sewage contamination. Bivariate correlation and univariate regression analyses were used to identify the sources of contamination. The assessment focused on the relationship and association of water contamination with site-specific variables. The variable that had the highest negative impact to the water source was analyzed by using a groundwater flow and contaminant transport model as a tool to make recommendations for proper site-specific sanitation practices. Of the three water sources identified (city water, vendors, and domestic wells), water quality analysis showed that city water at the point of collection (POC) was deemed excellent, whereas it diminished at the point of use (POU) for all three water sources. Reasons for change in water quality at POU and POC were due to mixing of water from different water sources at homes during storage. Using a multinomial regression model, the main reason for mixing water was determined to be the dilution of the salty taste of well water ($p < 0.05$) and insufficient storage containers ($p < 0.05$). Of the three water sources identified, domestic wells were found to be the most contaminated. Further analysis on the domestic wells showed a significant contamination, where 80% of wells tested contained E. coli. Also, 58% and 81% of wells tested had concentrations of nitrate and TDS, respectively, that exceeded the WHO guidelines. Univariate regression analysis confirmed the association of contaminants with distance of a well from a sanitation system and well depth ($p < 0.05$). Groundwater transport modeling showed a strong correlation between the tracer and contaminants and the tracer and distance and helped identify the safe well setback distance that is specific to site conditions, soil type, and aquifer properties. Groundwater modeling was shown to be a good assessment tool for contamination within an aquifer system in urban overpopulated areas of developing countries. Our findings also indicate that the risk of exposure to waterborne disease comes from a combination of factors that involve multiple actors, from improved awareness and sanitation practices to improved regulatory oversight, supply practices, and sanitation technologies.

I dedicate this thesis to my three beautiful girls, Atuganile, Rachael and Serena.
You are the reason I didn't give up!
You too, can do all things through Christ who strengthens you (Philippians 4:13)

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

CCF: Community Capitals Framework

CDC: Centers for Disease Control and Prevention

DAWASCO: Dar es Salaam Water and Sewerage Corporation

E. coli: Escherichia coli

EPA: Environmental Protection Agency

GIS: Geographic Information System

IWRM: Integrated Water Resources Management

KAP: Knowledge, Attitude and Practices

MCL: Maximum Contaminant Level

MODFLOW: Modular Three-Dimensional Finite-Difference Groundwater Flow Model

MT3DMS: Modular Three-Dimensional Multispecies Transport Model for Simulation

NO_3^-: Nitrate

POC: Point of Collection

POU: Point of Use

TANROADS: Tanzania National Roads Agency

TDS: Total Dissolved Solids

UNDP: United Nations Development Programme

UNICEF: Nations International Children's Emergency Fund

WQI: Water Quality Index

WHO: World Health Organization

CHAPTER 1: Introduction

1.1 Background

Approximately 663 million people around the world do not have access to potable drinking water, with half of these people living on the continent of Africa and 23 million living in Tanzania (Water Aid, 2016; WHO & UNICEF, 2015). Safe drinking water is considered a basic human right and a crucial part of implementing an effective health protection policy (WHO, 2011). It is recognized that the availability of potable water is key to achieving the UN Millennium Development Goals (MDGs) (Murphy & Fukuda-Parr, 2004; UNICEF, 2004). Inadequate access to water and sanitation is responsible for ~829,000 deaths a year, and debilitating illness for millions (WHO, 2019). Goal 6 of the Sustainable Development Goals (SDGs) focuses on ensuring the availability of water and the sustainable management of water and sanitation by 2030, with the main goal of eliminating waterborne disease. It is critical to tackle the problem of poor access to water and sanitation in order to achieve improvements in quality of life and meaningful development gains.

Many peri-urban communities in the developing world have a particular challenge, as they often have a deeply inadequate supply of municipal water, inadequate or nonexistent sanitation systems, and other basic services such as lack road access in informal settlements. The risk of contracting waterborne diseases in these environments is high. Within these communities, the use of pit latrines and the reliance on groundwater is high and it is expected to increase as Sustainable Development Goals for safe sanitation are increasingly being met (Graham & Polizzotto, 2013; Ravenscroft et al., 2017). In Dar es Salaam City where this study was conducted, the main source of city water supply has been the surface water, however, in the recent years, these sources have become unreliable due to declining in water levels due to human activities, including climate change (Mato, 2002; Ngoye & Machiwa, 2004). As a result, the city is unable to supply water to all residents resulting in increased reliance on groundwater. The majority of homes in this area use unimproved pit latrines. The lack of access to well-designed and operating sewerage systems along with poor management of wastewater results in the contamination of ground and surface water (Ngasala et al., 2019).

1.2 Objectives

The main objective of this study was to use multi-method study of a peri-urban area of Dar es Salaam to determine the extent of the problem and make recommendations for system-wide approaches to alleviate the risk of waterborne disease. Specific objectives were to:

1. Identify and assess the implications of poor water scarcity, water quality, household water management, water hygiene practices issues, as well as environmental concerns that lead to poor sanitation practices.
2. Asses the aspect of cross contamination of domestic water from the use of multiple water sources at the household level
3. Determine the association and the relationship of domestic water contamination with site-specific variables.
4. Use groundwater modelling contaminant transport model as a tool to make recommendations for proper site-specific sanitation practices.

Building on prior studies of poor sanitation practices and domestic water contamination (e.g., Kyessi, 2005; Schouten & Moriarty, 2003), this study uses an interdisciplinary approach to identify the barriers to improving water quality, household hygiene practices, and general environmental conditions related to water sanitation in the densely populated, peri-urban area community. A multi-method study of the peri-urban area of Dar es Salaam was conducted to determine the extent of the problem and to make recommendations for system-wide approaches to alleviate the risk of waterborne disease. It was argued that the action of reducing the severity of this risk in the African peri-urban community context must involve an approach that simultaneously addresses infrastructure upgrades, and improvement of governance, individual and household knowledge about water quality, hygiene, and sanitation. Such an approach can involve better insights about how best to assess and plot public health responses to frequent outbreaks of waterborne diseases. The study draws on results from a field study about water quality, sewage contamination, and water supply in a densely-populated neighborhood of Dar es Salaam. The complete analysis was done in 4 different stages.

The first chapter explored cross-cultural perceptions of environmental risks of water contamination, water sanitation, and water quality in an urban community. It provided an insight on how best to assess public health responses to frequent outbreaks of water borne diseases in the city of Dar es Salaam. Specifically, it focused on the implications of water scarcity for water quality issues, household water management, water hygiene practices, and environmental concerns arising out of poor sanitation practices. The analysis built on two arguments, first, health communication that improves household knowledge, attitudes and practice, should be combined with initiatives to create community level management structures and infrastructure investments (Schouten & Moriarty, 2003). Second, ultimately communities can improve access to potable water through a combination of advocacy and implementation by community-level non-governmental organizations and political parties (Kyessi, 2005). An asset-based approach was used that identifies deficits, but also investment opportunities at the neighborhood level.

The second chapter focused on the aspect of cross contamination of domestic water from the use of multiple water sources at the household level. Jensen et al. (2002) and Wright et al.

(2004) provided much information about the importance of community education to address the issue of contamination during water storage and the impact of poor water storage practices on water quality at the household level. The focus of this study was to assess how water becomes contaminated between the point of collection (POC) and the point of use (POU) due to practices such as mixing and storage at POU.

The third chapter expanded on chapter 2, which provided an insight into the origins of water contamination and identified the most contaminated water sources. The analysis went further to assess the relationship and association of water contamination with site-specific variables. Numerous studies have analyzed the impact of contamination in surface and ground water sources by focusing on each factor individually, but this chapter uniquely identified the sources and used statistical methods to evaluate the correlation between site-specific parameters and levels of contamination. It was hypothesized that positive bivariate correlations exist between nitrate, TDS, and *E. coli* levels, which means that all three contaminants originate from the same sources.

The last chapter used groundwater modelling contaminant transport model as a tool to make recommendations for proper site-specific sanitation practices. The variables (based on chapter 3 results) that had the highest negative impact to the water source were analyzed using a groundwater flow and contaminant transport model. A numerical tracer was used to represent contaminant transport and find its correlation with distance and the contaminants (nitrate, *E. coli* and TDS).

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CHAPTER 2: Risk Perceptions of Environmental and Health Impacts of Water Contamination in Dar es Salaam, Tanzania

Abstract

Much has been written about the urgent need to address the public health implications of water in peri-urban communities in developing countries. Issues related to water supply in peri-urban communities are often quite different compared to those rural water communities in developing countries. This is due to the fact that peri-urban residents often have partial access to water and sanitation services, but these supplies may be significantly compromised. Conventional approaches to improving access to water and sanitation have been siloed. Additionally, agencies tended to look either at the provision of centralized infrastructure (water delivery systems, for instance), the implementation of decentralized systems for service delivery, regulatory mechanisms or at programs to improve individual and household knowledge, management, and practices. We found that these sectoral attempts to address water and sanitation concerns ultimately fail to adequately capture both the full scope of the problem, and to propose the full range of activities that might address persistent community risk of waterborne disease. Based on a multi-method used in the peri-urban area of Dar es Salaam, we argue that more system wide approaches are needed to alleviate the risk of waterborne disease. Our findings indicate that the risk of exposure to waterborne disease comes from a combination of factors that involve multiple actors, from improved awareness and sanitation practices to improved regulatory oversight, supply practices, and sanitation technologies.

Keywords:

Risk perception, developing country, Dar es Salaam, water supply, community

2.1 Introduction

Sustainable Development Goal 6 (SDG 6) calls for universal access to water and sanitation by 2030, specifically with the laudable goal of eliminating waterborne disease among other benefits (United Nations, 2019). Inadequate access to water and sanitation is responsible for millions of deaths a year, and debilitating illness for countless others (Water Aid, 2016; WHO & UNICEF, 2015). Tackling this problem is critical to achieving improvements in quality of life and meaningful development gains. The peri-urban communities in the developing world present a particular challenge, as they often have partial but a deeply inadequate supply of water, and marginal sanitation, at best. In these environments, the risk of contracting waterborne diseases, including cholera, dysentery, and typhoid, all of which can be fatal, is high. This chapter will assess the sources of risk in a case study of access to water supply in a densely populated, peri-urban, Tanzania community.

This chapter builds on a decade's old literature on community water supply and sanitation (e.g., Schouten & Moriarty, 2003). We argue that mitigation of this risk in the African peri-urban community context must involve an asset-based approach that simultaneously addresses infrastructure upgrades, improvements in governance in terms of actions and decisions, and improved individual and household knowledge about water quality, hygiene, and sanitation. Such an approach can involve better insights about how best to assess and plot public health responses to frequent outbreaks of waterborne diseases. We employ the community capitals framework (CCF) as an analytical tool (Flora et al., 2016). This integrated asset-based framework, allows us to see the integrated nature of addressing the challenge of waterborne disease by identifying the integrated issues of governance, infrastructure, hygiene behavior, and individual. We explore how cross-cultural perceptions of environmental risks about water contamination, water sanitation, and water quality in an African urban community provide valuable insight about how best to assess and plot public health responses to frequent outbreaks of waterborne diseases in the city of Dar es Salaam, Tanzania. This research draws on results from a field study about water quality, sewage contamination, and water supply in one of the densely populated, informal settlements of Dar es Salaam.

2.1.1 Using the Community Capitals Framework to Assess Water and Sanitation

Schouten & Moriarty, (2003) documented community water management as a viable strategy for addressing the rural water challenges. The crux of the strategy was to build on participatory frameworks for the development of systems that would ensure improved water supply to communities (Chambers, 1983). Their point was that rural water systems would not be improved through the application of technologies such as hand pumps, borehole wells, etc. The application of these technologies, specifically in the context of Africa, rather has had an inglorious history of the short-term success that left communities without basic services. The proposed solution was a development approach that aimed to engage the community in identifying issues, finding solutions, and managing the implemented water systems. The results were systems for water delivery in rural communities that built into the design community management structures often in the form community-level water committees that oversaw maintenance, collection of user fees to finance management, and rules and regulations (e.g. Lockwood, 2004). A key insight from this work was that communities themselves could identify the community concerns, including the issues with water delivery and the exposure to risk.

A recurring problem, however, was that community water committees found themselves lacking both the resources and the necessary expertise to manage the water supply. Over time, it became increasingly clear that both the discovery of community water issues and work toward developing solutions to those issues could be facilitated through repeated engagement by outside organizations. We draw from this literature the importance of taking an approach that is simply not technology-focused, and the importance of working with the community to address issues and solutions. We argue here that this community- level analysis can help inform how to address issues of water and sanitation in the peri-urban context. Given the need to assess water and sanitation as integrated issues in the community, we chose an analytical framework through which we could look at these issues as integrated assets. The CCF conceptualizes community development as occurring through the interaction of seven integrated stocks and flows of assets as described in Table 2-1:

Table 2-1. Community Capitals

Community Capital	**Description**
Social	Networks of trust and reciprocity between close friends and relations (bonding social capital) and those with whom people have fewer intimate relationships (bridging social capital)
Political	Access to financial capital and other resources through the political process
Cultural	Worldview and attributes or assets associated with the community
Human	Skills, knowledge, and abilities
Natural	Natural assets, ranging from air quality to biodiversity and open space
Financial	Available monetary resources – investment capital
Built	Housing stock, industrial stock, transportation, water, and wastewater infrastructure

The capitals are conceptualized as interrelated. As one capital changes, others will also change. The key to development is when community investments can lead to positive changes across capitals. Emery and Flora (2006) described this process as “spiraling up” in describing a community in Nebraska, USA, that invested in built capital that created inviting spaces for youth in the center of town, which led to greater engagement of youth in the community (cultural capital), which improved community interaction (social capital), and ultimately the willingness of youth to stay in the community (human capital).

2.1.2 Case Study: Water and Sanitation Challenges in a Dar Es Salaam Neighborhood

The study area is home to people of different ethnicities representing multiple cultural groups. As with many developing countries, water scarcity, poor water quality, and wastewater management are complex and on-going challenges facing low-income and underserved communities. Whereas water scarcity and its implications for environmental health is a global problem, the situation is particularly dire for several countries in sub-Saharan Africa. Recent studies estimate that as many as 4 billion people worldwide may be facing serious water shortages. While China and India are most seriously affected, as many as 250 million people in Africa may be impacted by water scarcity (Mekonen et al., 2016; UN Water, 2016). The World Wildlife Fund (WWF) says "Fourteen countries in Africa are already experiencing water stress; another 11 countries are expected to join them by 2025 at which time nearly 50 percent of Africa's predicted population of 1.45 billion people will face water scarcity or stress" (World Wildlife Fund, 2016). Tanzania has been listed among those African nations suffering from multiple forms of water scarcity (Kitundu, 2016; Kyessi, 2005; Mbani, 2017).

Specifically, of interest to our study, new research indicates that access to a consistent and reliable water supply is a widespread problem for households in Dar es Salaam, Tanzania (Reweta & Sampath, 1998; Smiley, 2016, 2017). At a micro level, the impact of water scarcity on environmental health is evident in peri-urban areas of Dar es Salaam, where scarcity is compounded by poor environmental sanitation, poor household and public health hygiene practices, poor water quality, and poverty. Residents of the area are low and middle-income wage earners who spend a high proportion of their income on purchasing water for domestic use and for wastewater management. Human waste from the area is discharged into poorly constructed septic tanks and pit latrines that subsequently contaminate groundwater sources, affect drinking water quality, and pose significant environmental and human health hazards. Consequently, preventable waterborne diseases like cholera, diarrhea, and typhoid occur in the study area and Dar es Salaam city every year (Ngasala et al., 2018). Additionally, the burden of finding clean water and averting the health impacts of waterborne diseases falls disproportionately on women and children who constitute the most vulnerable segments of the study area.

Building on prior studies of poor sanitation practices and domestic water contamination (Kyessi, 2005), the study adopts an interdisciplinary approach for identifying the barriers to improving water resource management, water quality improvement, household and public health hygiene practices, and general environmental conditions related to water sanitation. Furthermore, the study explores how local capacity for managing water sanitation and water quality issues can be developed from existing community resources and household assets related to water supply, water storage, and water usage.

In reporting our findings to-date, we focus specifically on the implications of water scarcity for water quality issues, household water management, and water hygiene practices, as well as the larger environmental concerns arising out of poor sanitation practices in the community. Using the CCF, we identify strategies to address these water quality challenges. Building human capital through improved health communication is critical, as it can address risk perception about water quality and sanitation practices in the study area. These improvements must also be combined with improved social and political capital in the form of regulatory systems to ensure that: a) city water supplies are delivered in ways that mitigate risk; b) when communities are hit by water stoppages, an alternate and quality supply of water is ensured; and c) social systems and the necessary infrastructure are developed to improve wastewater management. Such a holistic approach must not exceed financial feasibility, especially keeping in mind the current constraints to addressing water and sanitation issues this context:

1. There are not immediate infrastructural solutions to Dar es Salaam's water scarcity problem, as population growth has exceeded the capacity of water storage systems, a situation compounded by financial shortfalls (Smiley, 2016).
2. To prevent waterborne disease outbreaks, residents must be aware of the risks that inadequate water supply and related poor water quality pose to the health of individual households and neighborhoods.
3. It is essential for those who suffer from water scarcity problems to know how to protect their own health and the health of their community in spite of acute water shortage problems.
4. It is crucial for public health workers to take advantage of the cultural knowledge, beliefs, practices, and assets already present in the community so as to create effective public health communication and education programs to alleviate the public health crises that frequently plague the community.

We underscore these four issues because existing literature shows that risk perception, '*principles knowledge*,' coupled with self-efficacy, and cultural knowledge, as well as cultural beliefs, all play important roles for attitude formation, behavioral intentions, and behavioral practice. It is known that perceptions of risk, knowledge about risk, the means to protect oneself from risk, and protecting oneself from risk are all quite complicated. There is some evidence to show that when people perceive they have little control over their own situation (*a low self- efficacy condition),* they are less likely to act to protect themselves from risk (Bandura, 2004; Flammer, 2001; Witte & Allen, 2000). Moreover, people sometimes refuse to protect themselves from *functional risk (fear and doubt)* because they do not believe in the effectiveness of recommended measures (*low response self-efficacy*) (Lattimore et al., 1992; Rimal, 2001; Thrasher et al., 2016).

Finally, we cannot minimize the importance of what Felt and others have termed the importance of *cultural beacons* and *overlooked grassroots wisdom* (Felt, 2014). By this, they emphasize the importance of ground-level field observation, user-defined, and user-generated cultural referents, coupled with external indicators that could validate assumptions. This cultural framework is essential for health communication practice and for people's attitude toward health, well-being, and disease states. If people are to have buy-in to public health messages that are addressed to them, the messages must not only be culturally appropriate, the messages must be crafted in ways that create self-efficacy and self-empowerment for the intended audience of the message. In other words, people are more likely to act to protect their health if they believe they can best impact their health status and have some control over their health outcomes.

2.2 Related Studies

Diarrheal diseases kill 1800 children under the age of five each day worldwide, with nearly half of these occurring in sub-Saharan Africa (Mattioli et al., 2015). Areas that have water scarcity also tend to have poor water quality. One of the main sources of contamination is poor sanitation practices. According to Kotloff et al. (2013), sanitation infrastructure and management ranks among the most deficient in Sub-Saharan Africa and southern Asia compared with the rest of the world. The practice of open defecation in the fields and uninhabited spaces is widely practiced in many African and South Asian countries. In Africa alone, 26% of the population are reported to practice open defecation while 44% are said to use shared defective sanitation facilities that were constructed without following approved local engineering design standards (Kotloff et al., 2013).

About one-third of the population of the countries are said to use poorly constructed septic tanks or pit latrines. In Bagamoyo, Tanzania, children between ages 3-5 years are reported to ingest water that is contaminated with high levels of feces, thus highlighting the importance of examining the sources of water contamination at the household level (Mattioli et al., 2015).

Public officials and technical experts often conceive technical solutions as ways to minimize water contamination problems in developing countries through investments of public funds and resources in the construction and maintenance of septic tanks and septic systems. While properly constructed and operated, decentralized systems (e.g., septic tanks) can protect public health and the environment, septic tanks are sometimes placed too close to domestic wells that also serve as sources of drinking water as was shown by Ngasala et al. (2019). Similarly, a study in Zanzibar, Tanzania demonstrated the seasonal microbial and nutrient contamination in domestic wells. Out of 19 water samples tested, only 5% of the collected water samples met WHO drinking water standards (Kiptum & Ndambuki, 2012).

In areas where water is scarce, people often rely on multiple water sources (Ngasala et al., 2018). As shown by Ngasala et al. (2019), in the study area, the common water sources of water supply are domestic wells, rainwater harvesting, vendors, and city water. The quality of water varies with the source of supply. Similarly, water quality can be compromised at the household level because of household usage and water storage practices (Ngasala et al., 2019). Water consumers at local levels are typically unaware of the variations in quality depending on the source of the supply, many believing that when water looks *"clear"* it means it is *"clean"*. By not knowing the quality of water from these sources, clean water becomes contaminated simply by mixing it with contaminated water (Ngasala et al., 2018).

As emphasized in the work of Ngasala et al. (2019), it is important to not only improve health education but also people's knowledge, attitudes, and practices about water sanitation (WHO, 2013). The success of this approach has been demonstrated by several researchers (Crocker et al., 2017; Garn et al., 2017; Woode et al., 2018). For example, researchers in Bangladesh reported that households that received health education showed significant improvements when compared to those that did not receive education in water and sanitation practices (WHO, 2013). In Zimbabwe, there was a significant improvement in the hygiene behavior of those who were involved in community health clubs (Waterkeyn & Cairncross, 2005). These health clubs are a good resource for community members and usually provide training that focuses on health and well-being. Cutler & Miller (2005) show that improving a city's water supply can potentially reduce the mortality rate due to waterborne diseases by about half.

Schouten & Moriarty (2003) note that sustainable solutions must move beyond health communication. Focusing their work on rural communities, they argue that health communication that improves household knowledge, attitudes, and practice, should be combined with initiatives to create community-level management structures and infrastructure investments. Kyessi (2005) applies this approach to two peri-urban ("fringe") neighborhoods of Tungi and Yombo Dovya in Dar es Salaam. He argues that these two settlements have been disadvantaged by the "spaghetti-like" implementation of water infrastructure in Dar, owing to a combination of persistent water scarcity and lack of financing to improve water delivery infrastructure. He argues ultimately that communities improve access to potable water through a combination of advocacy and implementation by community level, non-governmental organizations, and political parties. Our analysis builds on these insights by taking an asset-based approach that identifies deficits, but also investment opportunities, at the neighborhood level.

2.3 Methodology

The pilot study in Dar es Salaam, Tanzania, uses a multi-method investigation. We implemented a combination of a household survey, interviews with women, key informant interviews, and field observations. These methods were implemented to make deductions about household water storage and hygiene practices, as well as assess the level of knowledge, attitudes, and behavioral practices by household members on water and sanitation issues.

The household survey of the study area involved a stratified cluster sampling technique that combines a random starting point with a standard assessment interval to select households from which survey respondents were chosen. In developing countries where population lists are not readily available, such cluster sampling techniques have been considered adequately represent community profiles (Henderson & Sundaresan, 1982). The research team conducted face-to-face interviews with adult women from 63 households (aged 18 years and above), representing 6% of the households in the community. Women have the primary responsibility for procuring water and managing household water supply. The response rate was 97%; two households were not interviewed because there was no adult (under 18 years) in the home. The interview was designed to assess respondents' knowledge, attitudes, practices (KAP), and perceptions as they relate to water sanitation, water quality, and water management issues. We also attempted to assess the degree of self-efficacy in the study area.

Additionally, we interviewed 15 key informants representing community and religious opinion leaders, water vendors, public health workers, water and wastewater management officials, and local government officials with responsibility for the city water supply and wastewater management. They were interviewed about the status of water quality, water supply, water sanitation, and what they know about household water storage practices, as well as community environmental conditions. The findings from these interviews and household surveys are presented in this paper. The research team used field observations to verify interview responses. After each household interview, the team conducted field observations with additional questions to the residents if needed. The observations included the location of water sources as well as environmental pollution caused by poor sanitation practices and poor water and wastewater management.

2.4 Findings

The results from the study were divided into three main issues: water scarcity, sanitation practices, and water quality. Additionally, we report some observed behaviors and narratives from the field about the water and sanitation problem in the study area.

2.4.1 Water Scarcity

Household Interview Responses

The built capital for water delivery in the study area facilitates an extreme natural capital deficit. Our survey indicates that 87% of household respondents reported water scarcity issues. Municipal water supply did not provide sufficient supply for household needs and community members reported that they have to use a combination of sources to meet their needs. This combination consists of connections to city water supply system, water sourced from city vendors, rainwater harvesting, shallow wells, and deep wells (boreholes). The majority of interviewees (i.e., households) (51%) said they prefer to get their water from the city supply system (Figure 2-1), but as this is not frequently available, they rely on other sources. Thirty-nine percent of respondents reported having a connection to city water supply lines operating as standpipes. Of those, one-half reported that water flows through the pipes infrequently. Respondents reported many reasons for the unreliability of city water supply, including poor design of city water infrastructure; inefficiency of city water management, and suspicion of corruption by city officials. In other words, household respondents associated the deficit in water supply (natural and built capital) with weak political capital (management and governance) and poor design of the infrastructure. More than 50% of households surveyed rely on domestic wells (Figure 2-2).

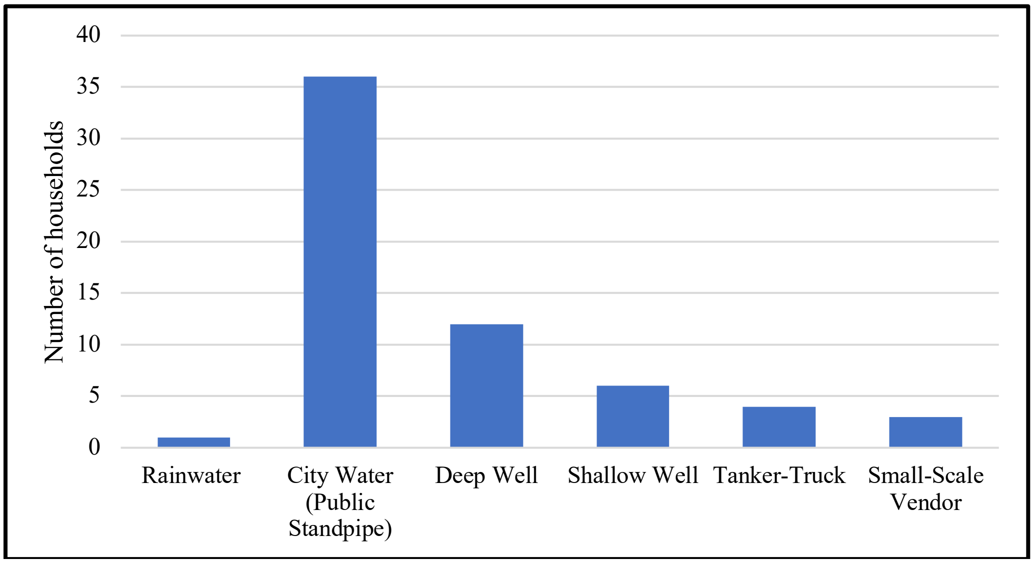

Figure 2-1. Preferences of water sources by the interviewees, considering its availability (N = 60).

One consequence of the water scarcity problem is that women spend a disproportionate portion of their day fetching water. In 9 of 10 households surveyed, women were primarily responsible for fetching water. They spend an average of 20 minutes a day (waiting time) fetching water (Figure 2-3). Households use between 7.5 and 12.5 liters of water per day per person on average for their cooking, bath, laundry, and cleaning (44% of sample). The recommended WHO standard is 20 liters per person per day for food and drinking only. The lack of reliable water has significant detrimental effects on human capital at the community level.

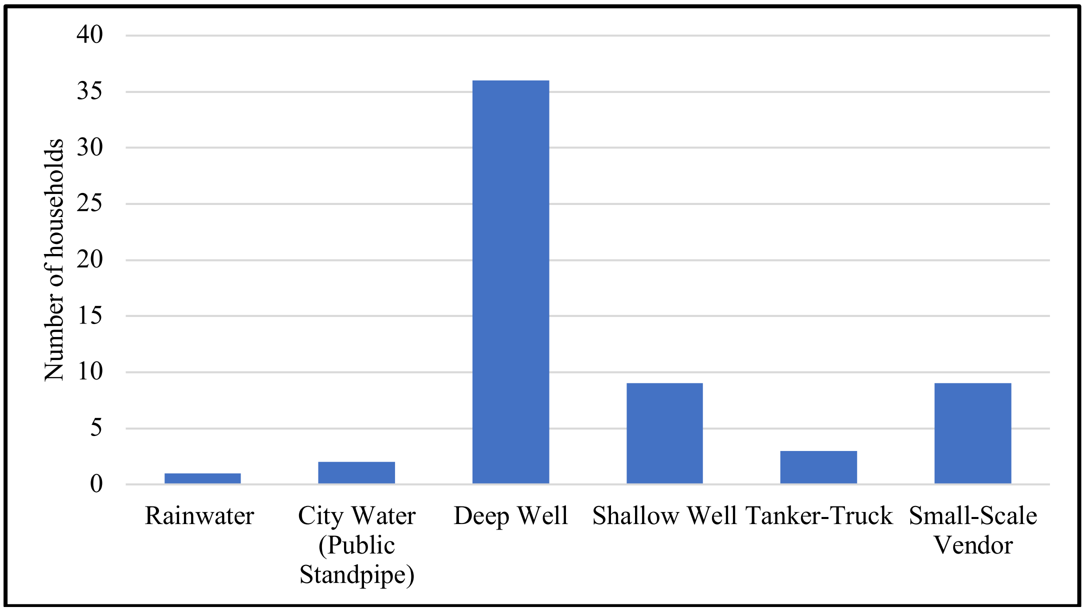

Figure 2-2. The immediate alternative water sources used by the interviewees, considering its availability (N = 60)

Key Informants and Field Observations

Interviews with key informants such as city officials and local water vendors confirm the reports from the households about the infrequency of city water supply in the study area. City water is available from once a week to once a month from public standpipes located within the community. As shown on Figure 2-3, woman waiting to collect city water from one of the public standpipes. The officials attributed the instability of the water supply to frequent breakages and leakages of the city water piping system. Our field observations and investigation show that water scarcity has other impacts on sanitation, proper hygiene, disease prevention, and general public health management. For example, medical practitioners who spoke about hygiene practices in the community said few people wash their hands after using the toilet, thus heightening the likelihood of infections and disease outbreaks. The water scarcity also compromises the quality of sanitation in public hospitals and clinics and it was reported that the recurrence of waterborne diseases is frequent. The health officials interviewed stated that 80% of school-aged children who miss school because they contracted a waterborne disease. Urinary Tract Infections (UTI) are prevalent, especially among women.

Figure 2-3. Woman waiting to collect city water from one of the public standpipes

2.4.2 Sanitation Practice

Household Interview Responses

Our household surveys indicate that more than 50% of respondents report that they dispose of wastewater from household cleaning, laundry, and dishwashing on the surface of the ground outside their premises or in septic systems. As shown in Figure 2-5, the area surrounding more than half of the homes visited had swampy areas, stagnant pools, soap residues, green slime, and foul odors within their yards. Nearly 51% of the homes surveyed had toilets that collect sewage in a single pit, 39% had an outside pit latrine, and 8% had an unimproved pit latrine. About 23% stated that they separate bathing water from sewage but that they release shower water on the ground surface outside their homes. Furthermore, more than 50% of households state their sewage pits fill up between 6 months and 2 years. In comparison, a properly designed and constructed septic tank should take between 3 and 5 years to fill up with solids, depending on household size and frequency of use (US EPA, 2015). Also, 23% of households surveyed said their pits overflow, especially during the rainfall season, and 18% reported that shower water runs freely in front of their yard. When asked if public health inspectors visit their households for sanitation inspection, 50% say they do so occasionally (once a month on average). The other one-half say they had never been visited by public health inspectors.

Key Informants and Field Observations

Our field observations indicated that none of the homes are connected to the city sewer system. Wastewater management officials from the city reported that all residents rely on private companies that use tanker trucks to empty the sewage from their septic tanks/pit latrines. In some cases, the homes do not have access to roads, thereby preventing truck access. The officials also stated that the contamination of well water with sewage is the result of poor municipal planning and the close proximity of water sources to septic systems, which was confirmed by Ngasala et al. (2019). Sewage management officials stated that the sewage management practices used by private contractors pose significant risks to water sources.

Public health officials reported that due to a lack of resources, inspections are infrequently conducted unless it has been reported to the official agencies that wastewater is being discharged improperly. When public health officials visited homes, they would only alert health authorities or local government through filing reports to official agencies that wastewater was being discharged improperly. These often did not result in action, but even more rare were efforts to provide technical assistance to improve household wastewater management. Another recurring issue that was mentioned with representatives of private waste management companies is that the impoverished residents placed a low priority on waste removal, including the evacuation of pit latrines because they cannot afford the cost. Consequently, pit latrines are allowed to fill beyond capacity, overflow, and pose visible health risks (Figure 2-4). Furthermore, the waste stabilization ponds that service the community are quite distant from the community, which increases disposal costs.

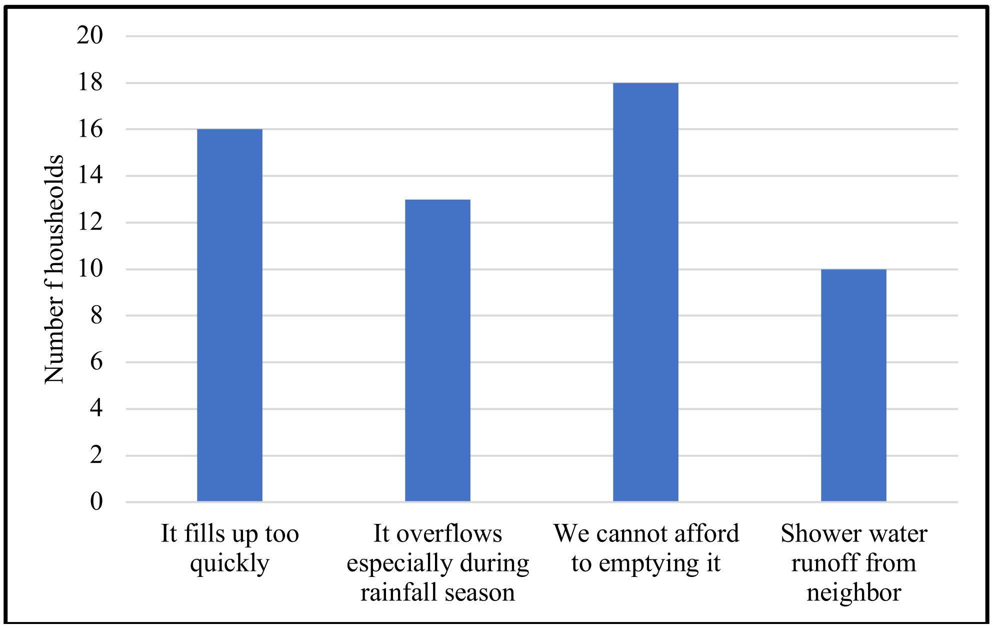

Figure 2-4. Challenges related to the maintenance of their sanitation systems reported by interviewees (N = 57)

2.4.3 Water Quality

Household Interview Responses

As indicated by the survey responses and shown by Ngasala et al. (2018), poor sanitation practices impair water quality. To determine the level of sensitivity and the implications of poor sanitation practices for water quality in the study area, we assessed the KAP and perception of respondents with regards to water quality issues. Forty percent of survey respondents reported wastewater overflowing septic and storage tanks during rainy seasons, thereby contaminating both surface and groundwater. As shown in Figure 2-5 (and discussed earlier), more than one-half of the households surveyed had wastewater discharges, soapy residues, and green slimes outside their premises. Nearly 7 in 10 had never repaired their septic systems, thus increasing the likelihood of sewage leakages into groundwater. Most respondents rated the quality of city water as average even though the supply is poor. Well water, which is the most common alternative source of supply, was rated as average as well, but respondents stated that it tasted very salty. Most respondents reported that they do not treat their water before drinking because of the high associated cost.

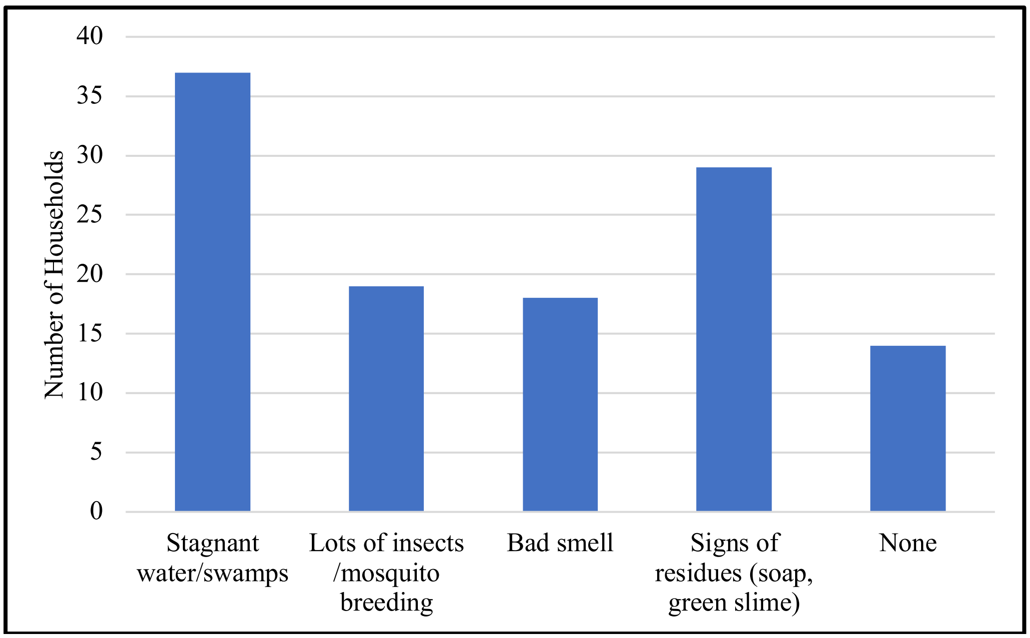

Figure 2-5. Observed site condition of household interviewed.

Key Informants and Field Observations

Community leaders made four main observations:

- Well water is readily available, safe to drink, but the taste is poor.
- Water from shallow wells is not safe to drink because the wells are too close to the septic system/pit latrines and is likely contaminated by sewage.

- Aware that deep wells are preferable to shallow wells as a source of drinking water, but they say most people cannot afford the cost of installing deep wells in their homes, so they resort to installing shallow wells.
- Recognize that the quality of city water is sometimes compromised by dirt and sewage contamination because of frequent breakages of the pipe network and leakages, which expose the pipes to contamination.

Our field observation shows that the pipe network is often exposed above ground and sometimes the pipes were located near sewage disposal. Interviews with water vendors (N = 8) that serve the community show that there is a great deal of uncertainty about the source of the waters sold. Some of them admit that they collect water from water leakages and retail the likely contaminated water to unsuspecting households. One informant vendor put it this way:

> *"We think water is clean but because our containers are dirty, we end up contaminating clean water. Our customers complain because most of the contamination is coming from our containers."*

Small-scale vendors admit that their customers complain about the quality of water they supply (Figure 2-6). The vendors suspect some of these complaints may be legitimate because they are uncertain about the provenance of the water that they purchase from the wholesale water distributors. Vendors also say the quality of city water is very poor after a long interruption in the supply, with city water being heavily tainted by dirt, malodorous compounds, and the taste of chlorine, especially during the rainy season. Vendors also cast doubt about the quality of well water that they retail to their customers because they say wholesale distributors sometimes mix city water with well water to dilute the taste so that the wholesalers can sell more to increase their profit margins.

The problems of affordability extend beyond drinking water. Most of the household respondents stated that they cannot afford to pay a private company to empty their septic tanks. Residents of the study area reported that they commonly discharge their overflowing septic tanks and toilet pits into the Ng'ombe River, especially at night or during the rainy season.

Figure 2-6. Small scale water-vendor delivering water to a customer

2.4.4 Additional Field Observations

There are other endemic but structural and systemic issues that affect water quality and water sanitation in the study area beyond those previously mentioned. Local officials and some community leaders say these issues are no less important and represent intrinsic factors for managing and improving the overall environmental conditions of the neighborhood. At the individual level, they point to the unwholesome character of some residents who engage in illegal practices that threaten public health. They point to the example of a resident who connected a sewage pipe to the water supply pipe network of the city at a time when water was not flowing through the pipes. The resident was caught, prosecuted, and jailed. Officials at the city water agency, DAWASCO, also say water pipes are frequently damaged during road and street construction projects. They regard such damages as avoidable if road building projects are properly coordinated between the water management agency and the city road building authority, TANROADS.

2.5 Discussion

Summary of Findings

The goal of this research was to comprehensively address the barriers to meeting SDG 6 in a peri-urban neighborhood of Dar es Salaam, Tanzania. The occurrence of waterborne disease remains a significant challenge for this community, with significant effects on health. Recognizing the integrated nature of this challenge, we took community assets approach to address the issue. In setting out our objectives for this pilot study and reporting the data, we wanted to explore the extent to which assets, knowledge, attitudes, and practices about water use have resonance for the ways people in the study area obtain and use water. Another objective was to understand how the residents perceive and assess risk as it relates to water scarcity, water quality, and sanitation, and how such risk perception affects personal health, household well-being, public health, and general environmental conditions in the study area.

From the findings, we have reported in this chapter, the residents of the study area appear highly vulnerable to the outbreak of serious waterborne diseases, some of which might spread rapidly because of a host of problems that are related to water supply, water quality, and sanitation. We have reported that although more than 80% of the households say they rely on water sourced from domestic wells, the quality of this water is not just average, it is also salty and contaminated with bacterial matter, some of which might be human waste from septic tanks as reported by Ngasala et al. (2019). The contamination of domestic wells in the study area is due to the depth and proximity to septic tanks or pit latrines (Ngasala et al., 2019). Furthermore, we reported that even though only one-third of the households are connected to the city water pipe network, the availability of this water is not reliable, and its quality was also judged as average by community residents.

We reported that city water is also often contaminated because of exposure of the pipes above ground level. These findings are consistent with those of Ngasala et al. (2019), who found that city water in this area is contaminated at home during storage and the main source of contamination of city water is the mixing of it with water from domestic wells that are located too close to septic tanks and pit latrine. The finding that sewage and wastewater disposal practices at the household level contribute in a significant way to the contamination of groundwater supply and freshwater that people depend on for drinking, cooking, and bath is alarming and particularly troubling because there appears to be no discernible sense of urgency on the part of public health and local government authorities to do something about the situation in order to prevent disaster. Treatment cost appears to be a significant barrier to consuming relatively clean water even though we are yet to isolate what most people mean by "treatment cost", including whether a significant portion of the population regards boiling water before drinking as a cost barrier.

2.5.1 Risk Perception from the Household Interviews

Risk perception in the community is very low with regard to the safety of the water they use for drinking, cooking, bathing, and general household hygiene maintenance. We reported data that show that because of scarcity, people's water use is not only much less than recommended WHO daily use standards for drinking and cooking, the quality of the water is also very poor due to a combination of factors. Some of these factors have to do with water source and supply issues, household water storage and distribution practices, and physical infrastructure issues such as the siting of septic tanks and septic systems much closer to water supply facilities. Community members have a low risk perception in regard to the quality of their water, equating quality to whether the water looks *clear* or not, or to how it *tastes*. We also found that despite the suspect quality of the water and knowledge that some of the water may be from highly contaminated sources, a substantial proportion of our study population reported that they do not treat their water before use. The few households that reported treating their water, reported that they did so by boiling. The main reason reported of not boiling is the high cost of fuel irrespective of the suspected quality of the water.

2.5.2 Risk Perception from the Key Informants

Responses from key informants show high risk perception especially when it comes to water quality. They agree that water taste from deep domestic wells is poor and that there is a difference in the quality of water from shallow wells and deep wells because of the proximity of the wells to septic systems. Community leaders also recognize that many of the city water pipe network leakages are exposed above ground which increases the risk of contamination compromised by soil and sewage. Responses from water vendors show that there is a great deal of uncertainty about the source(s) of water that they sell. Some of them admit that they collect water from pipe leakages and retail the likely contaminated water to unsuspecting households.

2.5.3 Attitude Towards Change

Although not definitive, we suspect that these results clearly point to both high risk and low risk perception from the study area. Frequent outbreaks of cholera, diarrhea, and urinary tract infections occur every year and unless there are changes in household hygiene practices, improvements in infrastructure, and/or wastewater management practices, these problems will continue to occur. The urgency for the need to do something about the household and public hygiene situation related to water safety, sanitation, and household hygiene practices is highlighted by the finding that 80% of school age children who miss school each year in this area do so because of illness attributed to waterborne diseases. The solution(s) to the problem will require massive commitment of public investments for urban planning, urban redesign and renewal, engineering assessments, and reconstruction of the area. Additionally, it is imperative that more manageable and cost-effective approaches like public health education, communication, and disease management be explored to change household practices and behaviors in ways that ensure buy-in by target communities.

To succeed, the communities must see a need for change, they must be willing to do something about change, and must feel empowered in doing so. This is why we incorporated self-efficacy theory in our analysis and why we also explore the role that field observation and grassroots folk wisdom might play in the change process. Our discussion of the theory of self-efficacy and risk perception shows that if change is to occur, people must be armed with the right kind of knowledge, they must be able to perceive risk, know they can do something about it, they must believe in recommended measures, know they have control over their own situation, and must be willing to act to protect their health and the health of their families and neighbors. The literature is fairly well established about this process being at the heart of the change process in behavior change scenarios involving health communication practice.

2.6 Conclusion

To conclude, we want to stress that although our results are based on small-scale pilot data representing 6% of households, we believe we have established the case that there is a need for urgency in addressing the public health and environmental problems related to water scarcity, sanitation, water quality, and household hygiene practices. Our data and our discussion show that absent major urban renewal project(s) that will immediately relocate the entire population of the study area, it is imperative that we to invest in programs that will educate, and inform the residents to take the kind of actions that will protect their own health, the health of their neighbors, and their own community. In the absence of large-scale surveys and controlled studies, we are not definitive about how serious problems like poor risk perception, low self-efficacy, and low response self-efficacy are, but we have shown enough evidence to support the view that this might be a problem in this community.

Finally, we were able to draw much from our field observations and the ground-level, grassroots, official and folk wisdom of people and the wider Dar es Salaam city. This is important for providing context for our findings and assumptions made during field observation. This is a crucial point because data is neither value-neutral nor one-dimensional. Unless put in its proper context, an outsider's perception of risk, might be colored by assumptions and pre-existing frames that may be alien to the lived reality of residents. Since context matters, this is why health communication theorists believe that people who are targets of attitude and behavior change programs must be active participants in the conception and design of solutions to problems that seek to address their health situations. We hope that based on our work so far, we have provided some insight into the way forward to address some of the enduring and endemic public health and environmental conditions affecting the study area.

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CHAPTER 3: Linking Cross-Contamination of Domestic Water with Storage Practices at the Point of Use in Urban Areas of Dar es Salaam, Tanzania

Abstract

In this study, water samples from 123 households were collected from the point of collection (POC) to the point of use (POU) in Dar es Salaam, Tanzania. The objectives were to assess water collection and storage practices at the household level and to determine how water becomes contaminated. Household interviews revealed three main mixing combinations used in households: (1) city water with well water (CW); (2) water purchased from vendors with city water (VC); and (3) city, vendor, and well water (WVC). The quality of city water at the POC was deemed excellent (low water quality index), whereas it diminished at the POU for all water sources. Statistical analysis showed that the main reason for mixing well water with city water was to dilute the well water's salty taste ($p < 0.05$). It was found that the practice of mixing all three water sources was due insufficient storage containers ($p < 0.05$). These impairments to water quality require an integrated response that combines hygiene education and improvements to water storage, water treatment, and regulation of vendors.

Keywords:

Developing country, Tanzania, water quality index, city water, water vendors, domestic well, storage practices

3.1 Introduction

About 780 million people worldwide still do not have access to safe water and it is estimated that 2.5 billion people in the world lack access to adequate sanitation (CDC, 2014). Nearly 88% of the deaths in sub-Saharan Africa are caused by waterborne diseases from drinking or ingestion of water contaminated by pathogenic organisms (CDC, 2014; Montgomery & Elimelech, 2007). These diseases include cholera, typhoid, and amoebic dysentery. According to Montgomery and Elimelech (2007), the estimated annual morbidity due to diarrheal diseases (~1 billion episodes) and the estimated annual mortality (~2.2 million) are caused by the improper disposal of human and animal excreta, contaminated drinking water, and poor hygiene. While these general pathways to morbidity and mortality are well documented, this paper will aim to better specify the drivers of these pathways and to recommend ways of mitigating those drivers.

In areas where water is scarce, people tend to rely on more than one source of water for domestic use. Examples of the types of water sources that people commonly use in water-limited areas include: rain water, publicly piped water (also known as city water), domestic wells, and private water vendors. Past research suggests that the predominant factor determining water quality in a household is the type of water source (Trevett & Carter, 2008). Source water quality is likely to vary significantly over time and depends on the location and how each source is maintained, stored and/or distributed. Water usage and storage practices likely contribute to the contamination of drinking water, especially at the household level. In many cases, water users are not aware of how water quality can vary from one source to another and many users believe that "clear" means "clean"; however, this is unlikely and requires investigation. Consequently, a lack of community awareness of the variability of water quality with its source likely leads to clean water being mixed with contaminated water during household storage.

Some studies (Brick et al., 2004; Steele et al., 2008) highlight that certain storage practices and storage container characteristics are directly associated with the contamination of household drinking water. In a town in south India, 67% of water samples collected from "treated" municipal water were contaminated by *E. coli* during household storage (Brick et al., 2004). The researchers also tested different storage container materials, and brass proved to decrease contamination levels, as compared to other materials (Brick et al., 2004). This is likely due to the antimicrobial properties of zinc and copper (components of brass) (Yasuyuki et al., 2010). The positive impacts of health education and efforts to improve knowledge, practices, and attitudes to prevent contamination from poor water storage practices are well-known in places where such programs were implemented. For example, a study in Bangladesh demonstrated that households that received health education showed significant improvements in water and sanitation compared to those that did not (Mascie-Taylor et al., 2003). In Zimbabwe, researchers described significant improvement in the hygienic behaviors of members of community health clubs compared to those who were not involved in such groups (Waterkeyn & Cairncross, 2005). Such health clubs raise awareness amongst members, thus allowing them to help make their households and communities healthier.

In the last ten years, most of the work in the area of water usage and storage behavior has focused on interventions to reduce drinking water contamination in the household (Davis et al., 2011; Kamara et al., 2017). The Centers for Disease Control and Prevention (CDC) and the Pan American Health Organization (PAHO) developed the following intervention guidelines to reduce water contamination: (i) disinfect water using sodium chloride manufactured locally through electrolysis of brine; (ii) use proper water storage vessels or containers that help minimize or prevent contamination; and (iii) distribute community hygiene education and training materials for families (CDC, 2000; Clasen & Bastable, 2003). Studies of intervention programs showed reductions of 44% in the incidence of diarrhea in Bolivia and up to 62% in Uzbekistan post-intervention (Rangel et al., 2003). In rural Malawi, improved water collection and storage methods were associated with a 69% reduction in fecal coliform counts in drinking water and a 31% reduction in diarrhea in children under five years, despite the lack of use of disinfectants such as chlorine (Roberts et. al., 2001). In the late nineteenth and early twentieth centuries in America, the availability of clean water reduced the mortality rate by about half in large cities (Cutler & Miller, 2004).

Integrated approaches are necessary to address domestic water quality issues. Everard (2014) calls for system-wide, integrated approaches to water quality assessment and management (Everard, 2014). Participatory management initiatives are seen as a key tool in integrated approaches in as much as they can systematize governance, including the assessment and maintenance of technologies (Adams & Zulu, 2015; Schouten & Moriarty, 2003). One of the key challenges to ensuring widespread water access in peri-urban Africa is the number of sources of water that residents must utilize, given the unreliability of the city water supply. The World Bank (2004) argued that this necessitated the overhaul of regulatory frameworks, ensuring that they are compatible with facilitating quality service from private sector actors. Alternatives have included the facilitation of vendor unions that self-police quality service standards (Wutich et al., 2016).

This study was conducted in one of the peri-urban areas of Dar es Salaam, Tanzania, where water is relatively scarce compared to other tropical areas. People in Dar es Salaam rely on three different water sources for household consumption. The first source is domestic wells, which are often privately or publicly owned, from which people can purchase water. Due to water scarcity and a lack of regulatory control in this area, there are a relatively high number of private and public domestic wells. The average density is 12 wells per square mile, however, the cost associated with purchasing water from domestic wells is high. Water from most domestic wells is contaminated by household sewage due to the wells' close proximity to poorly constructed septic tanks and pit latrines (Arwenyo et al., 2017). Additionally, water from domestic wells is typically salty to the taste, which is perhaps due to salt water intrusion from the nearby Indian Ocean (Mtoni et al., 2013). A second water source in Dar es Salaam is provided by the City. Water from the Ruvu River is treated by coagulation, flocculation, sedimentation, filtration, and disinfection and then distributed to the community through shared standpipes.

City water is the only source that is considered safe to drink; however, due to aged and poorly constructed and maintained water infrastructure, city water is highly unreliable. Complicating water availability even further, in Dar es Salaam, city water is usually available intermittently (up to once every two weeks). When city water is available, however, the costs associated with purchasing it are less compared to water from domestic wells (Smiley, 2013). The cost of water from domestic wells is high because well owners charge what the market will bear while city water is subsidized. The third community source is water provided by private vendors. These are individuals who sell water in the city. The source of this water is highly varied and often unknown. As such, the quality of water from such sources is also varied and questionable. Water from vendors is often expensive because vendors take economical advantage of customers during the dry season when water is extremely scarce.

While city water is the only source that is considered to be safe for consumption, because it is unreliable, people rely on the other water sources. This aspect of cross contamination of water in areas that rely on multiple water sources has not yet been investigated comprehensively until now. In the published literature (Jensen et al., 2002; Wright et al., 2004) there is much information about the impact of poor water storage practices on water quality at the household level as well as the importance of education provided to communities in need to address this issue. However, correlations between water storage practices and the extent of water contamination in households due to poor storage practices have not yet been studied in detail. Therefore, to help fill this key knowledge gap, the objectives of our study were to (1) assess water collection and water use practices at the household level and (2) determine how water becomes contaminated because of practices such as mixing and storing water. The hypothesis is that poor water storage practices and non-hygienic behaviors are the main cause of contamination of city water at the household level in Dar es Salaam.

3.2 Methods

3.2.1 Study Area and Data Collection

The study area is one of the densely populated, informal settlements in Dar es Salaam, Tanzania, which is located on the East African coast and borders the Indian Ocean to the east (Figure 3-1). The city is the major seat of government institutions and the largest urban center in Tanzania. Dar es Salaam is highly populated with significant economic development. Residents of this settlement are low-income wage earners who spend a significant portion of their income to purchase water for domestic use and for wastewater management. The study was conducted during the dry season when water is usually scarce.

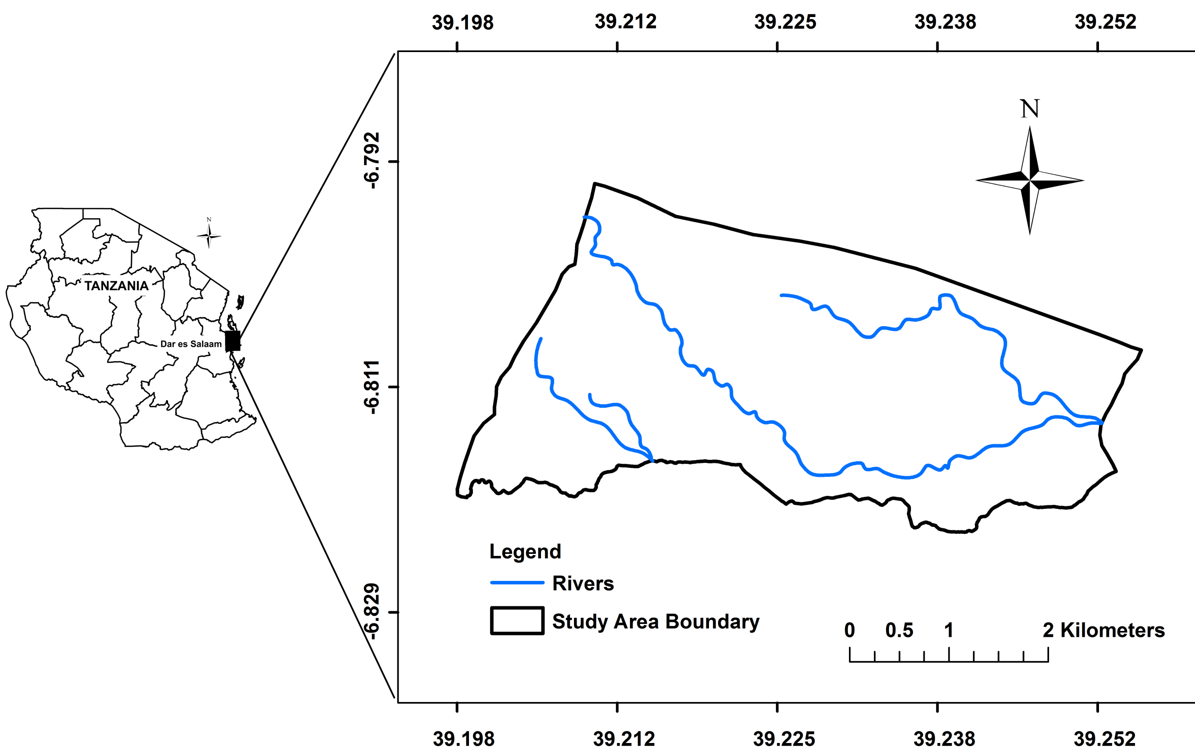

Figure 3-1. Location of the study area in Dar es Salaam, Tanzania

Before data collection, the study received exempt status from the Institutional Review Board (IRB) at Michigan State University and the Tanzania Commission of Science and Technology (COSTECH). The researchers conducted qualitative and quantitative surveys of 123 Dar es Salaam households in July 2016 to identify water storage practices, hygienic behaviors, and the extent of water contamination at the household level. The household survey involved a stratified cluster sampling technique that combined a random starting point with a standard assessment interval to select households from which survey respondents were chosen (Teddlie & Yu, 2007). In developing countries where population lists are not readily available, such cluster sampling techniques have been considered to provide adequate representation of community profiles (Henderson & Sundaresan, 1982). The team utilized a household survey, interviews with adult women who are responsible for water collection, and field observations to make preliminary deductions about household water storage and hygiene practices related to water and sanitation issues. From each household, detailed information on the type of water source commonly used, location of water source(s), costs associated with purchasing water, typical water usage and storage practices, and location of nearby sanitation facilities for wastewater management were obtained. In addition, water samples were collected from each household's disclosed water source and storage container(s) for subsequent analysis for general quality.

3.2.2 Water Quality Analysis

The term point of collection (POC) refers to the location (or water source) where water is collected and carried to a household for domestic use. In this peri-urban area of Dar es Salaam, water is not distributed into the home by transmission lines. On the contrary, point of use (POU) is the location where water is used at the household level for different purposes, such as drinking, cooking and bathing. Water samples were collected at the POU from covered storage containers stored either in the kitchen (about 30% of the households) or from one of the storage rooms in the home (about 70% of the households). All samples (POC and POU) were collected in the afternoon between 12 pm and 3 pm. More than 80% of the households visited were observed to have water stored in 20 L plastic buckets with lids. The rest were stored in 20 L jerry cans that have small opening with lids. The average length of time that water is usually stored depends on the type of source from which the water was collected, household size, and water usage. However, when residents had water stored in the home, it was likely well water, because well water is more easily accessible than city water, which is available only once or twice a week.

Water sampling and laboratory storage techniques followed WHO standards and the US Environmental Protection Agency (U.S. EPA) Interactive Sampling Guide for Drinking Water System Operators (U.S. EPA, 2015). Water samples were analyzed for seven different parameters:

nitrate, nitrite, ammonia, chloride, total dissolved solids (TDS), pH, and *Escherichia coli* (*E. coli*). Nitrate, nitrite, and chloride were analyzed by using ion chromatography. Ammonia was tested using U.S. EPA Method 350.1 via semi-automated colorimetry (Pfaff, 1993). TDS concentrations were quantified using Method 8163, the Gravimetric Method (Total Filterable Solids) (U.S. EPA, 2012), which was adapted from Standard Methods for the Examination of Water and Wastewater, Part 2540C. Finally, *E. coli* concentrations was measured using Method 1603, by Membrane Filtration using modified membrane-thermotolerant *Escherichia coli* Agar (Modified mTEC) (U.S. EPA, 2009). See Table 3-1 for details of the laboratory testing methods and measuring units.

Table 3-1. Summarized laboratory methods used for water quality testing

Parameter	**Methods of Analysis**	**Measurement units**
Turbidity	Turbidometric/Turbidity tube	NTU
Chloride	Ion chromatography	mg/L
Ammonia (NH_3-N)	Titration by H_2SO_4	mg/L
Nitrate -N (NO_3-N)	Ion chromatography	mg/L
Nitrite-N (NO_2-N)	Ion chromatography	mg/L
E. coli	Membrane Filtration	*E. coli* count/100 mL
pH	Electrometric/pH meter	N/A

Water Quality Index (WQI) was used to assess source water quality by comparing values estimated with maximum contaminant levels (MCL) according to Tanzania or World Health Organization (WHO) guidelines. The WQI is a way of calculating a single score from multiple water quality parameters and is also one of the criteria for water classifications with respect to standard parameters for water characterization (Mophin-Kani & Murugesan, 2011; Ngasala et al., 2018). WQI were computed using the seven water contaminants mentioned previously. Each contaminant was assigned a weight based on its perceived effect on primary health or the relative importance of the parameter in terms of the overall quality of water for drinking purposes (Vasanthavigar et al., 2010). The assigned weight ranged from 1 to 5. An assigned weight of 1 indicates the parameter has low negative impact on human health and 5 indicates that the detrimental impact is high. The relative weight of each parameter was calculated using equation (1) where, RW is the relative weight, AW is the assigned weight of each parameter and n is the number of parameters. The RW values are shown in Table 3-2.

Table 3-2. Assigned and relative weight of the water quality parameters (Al-Barakah et al., 2010; Ramakrishnaiah et al., 2009; Saana et al., 2016)

Parameters	Water Quality Standard	Assigned Weight	Relative Weight
Total Dissolved Solids (TDS)	500	4	0.129
Nitrate (mg/L)	10	5	0.161
Nitrite (mg/L)	3	4	0.129
Ammonia (mg/L)	1.5	5	0.161
Chloride (mg/L)	250	5	0.161
pH	6.5-8.5 (7.0)	3	0.097
E. coli (CFU/100mL)	0	5	0.161

The quality rating scale *(Q_i)* for all the parameters was calculated using equation (2), where, Q_i is the quality rating, C_i is value of the water quality obtained from the test conducted in the laboratory, S_i is the recommended maximum contaminant level according to WHO standards. Before calculating WQI, equation (3) was used to calculate sub-indices *(SI_i)* for each contaminant, then equation (4) was used to calculate the WQI for each water sample (Ramakrishnaiah et al., 2009). The overall water quality based on the computed WQI is classified into five categories and these are shown in Table 3-3.

$$RW = \frac{AW_i}{\sum_{i=1}^{n} AWi} \tag{1}$$

$$Q_i = \frac{C_i}{S_i} \times 100 \tag{2}$$

$$SI_i = RW \times Q_i \tag{3}$$

$$WQI = \sum_{i=1}^{n} SI_i \tag{4}$$

Table 3-3. Water Quality Index classification adopted and modified (Ramakrishnaiah et al., 2009)

Classification	***Range***	***Description***
Excellent	<50	Water quality is protected with no impairment; This range can be obtained if all measurements meet recommended guidelines
Good	50-200	Water quality is protected with only a minor degree of impairment; conditions rarely depart from recommended guidelines.
Poor	200-300	Water quality is usually protected but occasionally impaired; conditions sometimes depart from recommended guidelines.
Very Poor	>300	Water quality is almost always impaired; conditions usually depart from recommended guidelines.

3.2.3 Statistical Analysis

Survey responses were analyzed by using a multinomial logistic regression model. The goal of the analysis was to understand why people mix water during storage. Multinomial regression is a generalization of the binary logistic model that predicts binary outcomes with two levels only (e.g., pass/fail) to include categorical or qualitative variables with more than two levels (e.g., a person's political affiliation or the state they live in). Given a *mixing combination* (X) such as WC (well water mixed with city water), the model predicts the most likely *reason* (Y) for that mixing combination which is represented as a categorical variable with one of three possible values (e.g., 1, 2, or 3 to denote the three possible reasons why residents mix water). Therefore, multinomial logistic regression is usually used when the categorical dependent outcome has more than two levels (Chan, 2005). For this analysis, the model used water *mixing combination* as the independent variable and the *reason* for mixing (1, 2 or 3 as described above) as the dependent variable. Multinomial logistic regression was used to model the nominal outcome variable (i.e., water storage behavior was coded as a categorical variable with three levels; see below), in which the log-odds of outcomes are modeled as a linear combination of predictor variables (equation 5).

Out of 123 households surveyed, 63 households reported mixing water from different sources during storage. Therefore, 63 households that reported mixing water were analyzed. The model provides *p*-values and 95% confidence intervals for model predictors as well as odds ratios that characterize the log-odds of outcomes for the households (Hosmer & Lemeshow, 2004; Monyai et al., 2016).

Three pairs of water mixing combinations were identified: well water, vendors and city water *(WVC)*, well water and city water *(WC),* and vendors and city water *(VC)*. Residents were also asked to select one or more main reasons for mixing water during storage, which were used as predictors of different water mixing combinations. This increased the total number of responses from 63 to 133. The mixing combination of the water sources is thus a categorical dependent variable with three predictors as describe above: 1) insufficient number of water storage containers, 2) no perceived difference in the quality of water, and 3) dilution of the salty taste from well water ($J = 3$; see equation 5). The independent variable mixing combinations (k) are *WVC*, *WC* and *VC* ($k = 1$, 2 and 3). Each individual survey observation was counted as one response, which resulted in a total of 133 observations ($i = 1 \ldots 133$). For a categorical dependent variable with J categories, the multinomial regression model estimates (J - 1) logit equations. One category was picked as a baseline and used to calculate the odds that a member of group i falls in category j as opposed to the baseline. Odds ratio was used to measure the association between the *mixing combinations* with the *reasons* by using equation 6. Finally, statistical package for the Social Sciences (SPSS version 22) was used for all of the statistical analyses.

$$log\left(\frac{\pi_{ij}}{\pi_{iJ}}\right) = \sum_{k=1}^{3} \beta_{kj} x_{ik} \quad , \qquad j = 1 \dots \dots , J-1 \; and \; i = 1 \dots .133 \tag{5}$$

$$Odds\ Ratio = \frac{\pi_{ij}}{\pi_{iJ}} = e^{\sum_{k=1}^{3} \beta_{kj} x_{ik}} \tag{6}$$

Where:

π_{ij} = Probability that the i-th response falls in the j-th category

β = Regression coefficient

x_{ik} = The binary predictor variable that describes whether the i-th individual belongs to the kth outcome.

3.3 Results

3.3.1 Water Quality

A total of 20 POCs were identified based on the survey responses - seven public standpipes that intermittently deliver city water, six public wells and seven vendors. Water samples collected from these sources were tested. A total of 101 samples were identified by families as being mixed in the home during storage, 45 were reported to have been obtained from public wells, 48 from city water standpipes, and 8 from water vendors. Figure 3-2 through 3-4 show the comparison between the quality of water at the original source with water collected and that stored at home for all three water sources. The calculated WQI of each sample was used to determine the average value for samples that were collected from the same source. As shown on Figure 3-2, the WQI of the city water at the standpipes is excellent whereas the WQI indices for city water stored at home range from “good” to “very poor”. Although WQI for water from domestic wells and vendors does not fall under the category “excellent”, there is a noticeable difference between water quality at the POC and POU, as shown in Figure 3-3 and 3-4.

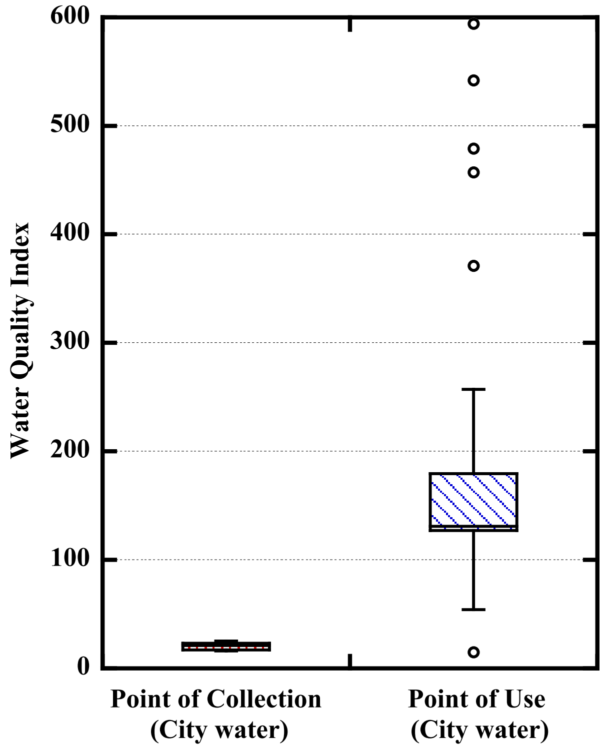

Figure 3-2. WQI comparison of (a) city water samples tested at the point of collection (POC, n = 7) and at the households (i.e., the point of use, POU, n = 48)

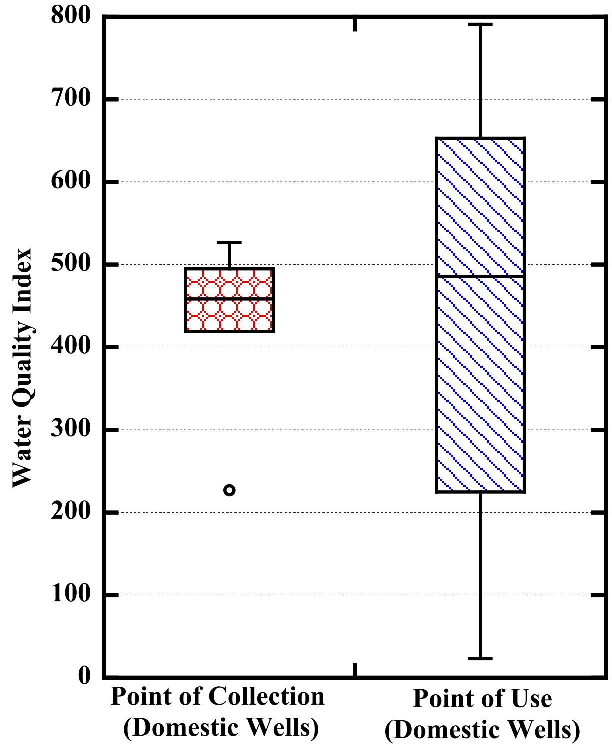

Figure 3-3. WQI comparison of *domestic well* water samples tested at the POC (n = 6) and at the households (i.e., the POU, n = 46).

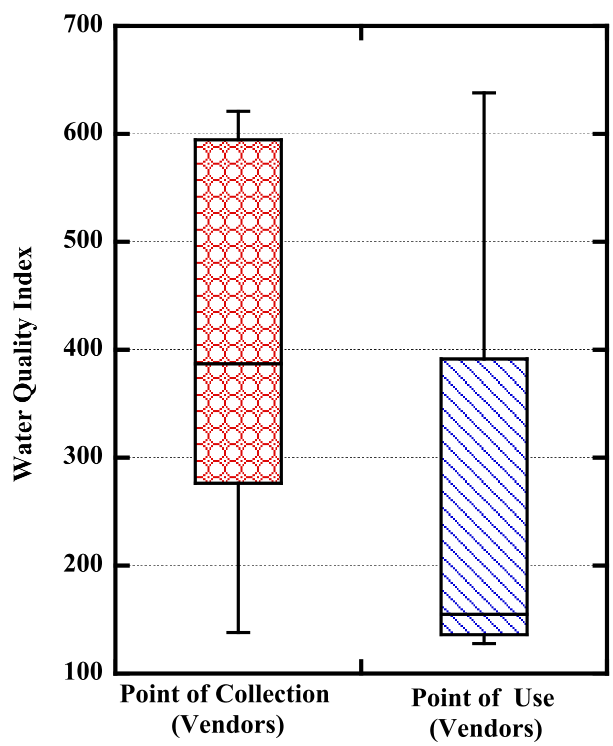

Figure 3-4. WQI comparison of *water from private vendors* water samples tested at the POC (n = 7) and at the households (i.e., the POU, n = 8).

Overall, water from domestic wells had the poorest quality, followed by water from vendors. City water had the best quality. However, the quality of city water from samples collected at the households is poor compared to city water at the POC. Figures A3-1 through A3-7 in Appendix show a series of box plots depicting the variation of all seven contaminants tested for city water, domestic wells, and private vendors collected from POC, which can be compared ith the red dotted line indicating the maximum contaminant level (MCL) according to WHO guidelines. Concentration levels above the dotted lines indicate violations of drinking water standards. On average, water from the domestic wells exceeded WHO's guideline levels for all seven contaminants. Water from vendors also exceed MCLs, except for nitrite, ammonia and chloride. City water shows high variation for all seven contaminants whereas about 50% of the city water samples were above MCLs and the other 50% were below MCLs.

3.3.2 Impact on Water Storage Practices

Household interviews revealed that in this informal settlement, one family of between 5-7 people uses 2-4 twenty-liter buckets of water per day. On average, one household stores 6 to 10 twenty-liter buckets of water. Survey questions allowed interviewees to select more than one response; therefore, the total number of responses were greater than the number of households that reported that they mix water during storage. Approximately 50% of households interviewed indicated that they mix water from different sources during storage. Survey responses showed that individuals of various households use two different mixing combinations (*WC* and *WVC*) more commonly than the combination of city water and vendor water (*VC*) (see Figure 3-5). Most people reported that the main reason they mix water during storage is due to a lack of a sufficient number of containers followed by the need to dilute the salty taste of well water (Figure 3-6). Only 25%

of participants reported that they did not know the difference in the quality of water from one water source to another. Nearly 75% of individuals mix city water with at least one water source and less than 25% exclude well water when mixing (Figure 3-5).

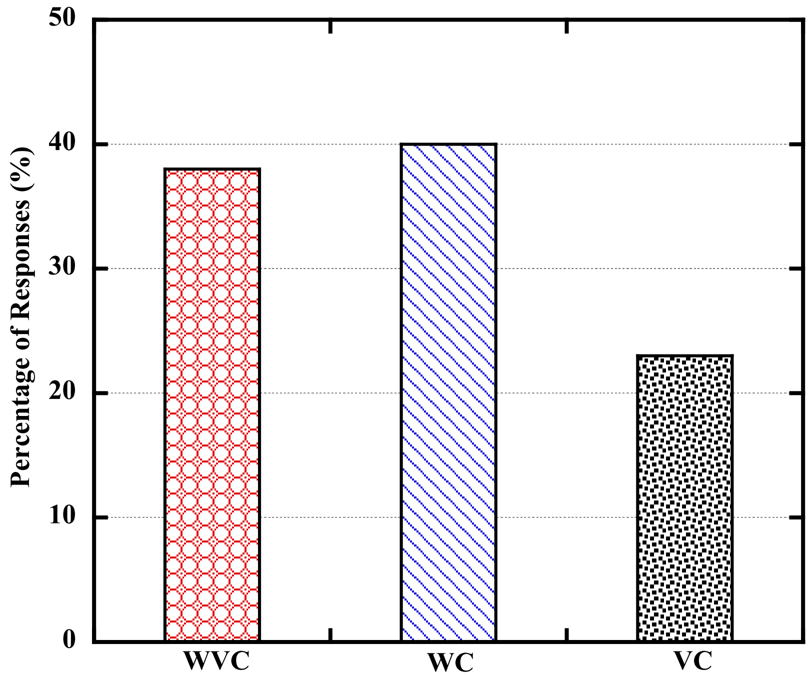

Figure 3-5. Percentages of survey responses showing three different mixing combination of water sources during storage at the household.

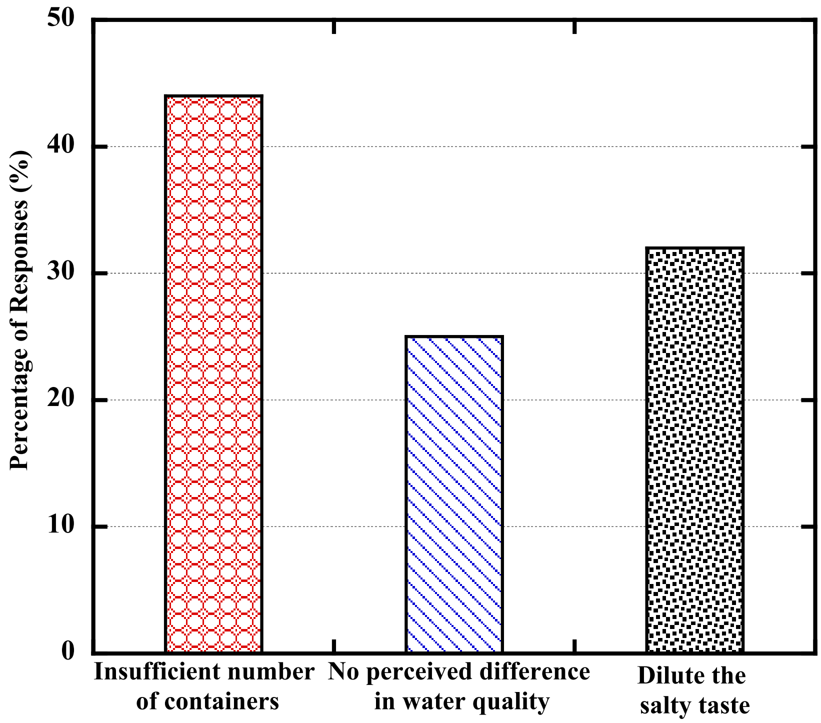

Figure 3-6. Percentage of survey responses for residents' tendency to mix water during storage.

Multinomial logistic regression analysis was used to evaluate patterns of water storage behaviors. The results indicate that people will more likely mix water from all three water sources (city water, vendors, and well water), and this pattern is best explained by having an insufficient number of containers with p-values of 0.035 and 0.001, respectively (Table 3-4). Those who mix water to dilute the salty taste are more likely to mix well water and city water (p-values = 0.001 and 0.000) than those who mix all three sources. Results also showed that people are more likely to mix water from vendors with city water when they believe that there is no difference in the quality of water between those two sources (p-value = 0.028). In summary, it was found that two main reasons that indicate why individuals mix WVC or WC in households are: insufficient number of water storage containers and the need to dilute the salty taste of well water. Also, most people believe the quality of water from vendors is similar to city water, and their reason for mixing

VC was that they did not know the difference in water quality. From these results, it is possible that the main source of contamination at the point of consumption is poor storage practices.

Table 3-4. Multinomial logistic regression showing the relationship between type of *mixing combination* and the *reasons* for mixing water during storage

Reasons for mixing water during storage	**β**	***p*-value**	**95% CI for Odds Ratio**		
			Lower	Odds Ratio	Upper
WC vs WVC (n =133)					
Insufficient number of containers	-0.633	0.035*	0.295	0.531	0.957
No perceived difference in water quality	-0.511	0.323	0.218	0.600	1.651
Dilute the salty taste	1.322	0.001*	1.719	3.750	8.180
VC vs WVC (n=133)					
Insufficient number of containers	-1.269	0.001*	0.134	0.281	0.589
No perceived difference in water quality	0.531	0.183	0.778	1.700	3.713
Dilute the salty taste	-0.693	0.258	0.151	0.500	1.660
VC vs WC (n=133)					
Insufficient number of containers	-0.636	0.123	0.236	0.529	1.188
No perceived difference in water quality	1.041	0.028*	1.117	2.833	7.186
Dilute the salty taste	-2.015	0.000*	0.047	0.133	0.378

**Regression is significant at the 0.05 level*

3.4 Discussion

Our water quality analysis showed that there is a significant difference in water quality between the POC and POU. At the POC, city water was consistently of high quality as shown in Figure 3-2 and well water had the poorest quality (Figure 3-3). However, the quality of the water from vendors was highly variable, ranging from very poor to very good. This difference of water quality at POC and POU indicates the possibility of mixing water during storage at the household. During the interview process, the interviewer recorded observations regarding water use and storage. In addition, interviewees were asked about sources of water, storage practices, and water usage. The length of water storage varied, depending on the type of water source, household size, and water usage. Interviewees reported that they clean the containers before collecting and storing water; however, it is impossible to confirm these reports. We observed that all water storage containers were covered.

Statistical analysis of the survey responses about mixing combinations and the reasons for mixing explain the ways in which household members mix water during storage. Multinomial logistics regression analysis supports the fact that the main reason for mixing water from all three sources (city, wells, and vendors) during storage is an insufficient number of containers, and the main reason of mixing water from the city and vendors is the perception that there is no difference in the quality of water.

3.4.1 Extent of Contamination

While the nitrate concentrations exceeded MCLs in domestic well water, nitrate levels did not exceed MCLs in water obtained from vendors and the city. WHO (2017) recommends that the concentration of nitrate in drinking water not exceed 11 mg/L as N (50 mg/L as nitrate ion). The U.S. EPA has set the MCL of 10 mg/L as N for the regulatory limit. High levels of nitrate in drinking water are usually associated with human activities, and the presence of nitrate might indicate presence of other contaminants that originate from human and animal waste, and agricultural activities. Ammonia and nitrite are other forms of inorganic nitrogen. Results also show both ammonia and nitrite did exceed the MCL in domestic well water tested from the POU. Common sources of inorganic nitrogen are fertilizers, human waste, and animal waste from feedlots, septic systems, and leaky pit latrines. In the study area, due to close proximity of wells and septic tanks, the main source of nitrogen compound is thought to be from sewage seeping from septic tanks (Elisante & Muzuka, 2017).

Extremely high TDS levels were found in water from domestic wells as compared to city water and water from vendors. TDS levels in Dar es Salaam city water, tested at the POC, were >50 mg/L, whereas the TDS levels at most of the domestic wells were above the secondary standard of 500 mg/L set by the U.S. EPA. However, the TDS measured at the POU ranged from very low (23 mg/L) to very high (2,030 mg/L), possibly due to the mixing water from multiple sources. One of the reasons for high TDS levels in domestic wells is likely due to salt water intrusion, due to the proximity of the wells to the ocean (Mtoni et al., 2013). It is also possible that TDS levels are high because of the proximity of wells to septic tanks. High concentration of TDS might indicate the possibility of other chemical contaminants such as calcium, chlorides, nitrate, phosphorus, iron, sulfur, and other ions particles (WHO, 2017). Further testing is necessary to determine the ions that contribute to TDS.

Similar to TDS levels, high concentrations of chloride, especially in domestic wells, also suggest possible saltwater intrusion from the Indian Ocean. One of the reasons that people mix well water with city water during collection and storage is because of high salinity. Our results show very low chloride content in city water at the POC, but a few samples had high chloride content when tested at the POU. High concentrations of chloride can give a salty taste to drinking water; however, to date, no health-based guideline exists for evaluating levels of chloride in drinking water (WHO, 2017). Chloride can increase the electrical conductivity of water and increases its corrosivity, which may also influence the levels of heavy metal compounds in drinking water distributed by city water through metal pipes due to the chemical reaction of chloride and metals.

Our results showed that all samples at the POU were contaminated with *E. coli*, a type of gram-negative non-spore forming bacterium that is found in the intestines of mammals. *E. coli* is used as an indicator of sewage and animal waste in water because this bacterium can be easily and inexpensively detected. No *E. coli* were detected in city water samples at the POC, however, that water is treated and disinfected, unlike the well water. On the contrary, domestic well and vendor samples were already contaminated by *E. coli* at the POC (Figure A3-1 in Appendix), *E. coli* were detected in all POU water samples at levels in exceedance of the MCL, irrespective of the water sources suggesting that city water became contaminated in the household level.

The pH of all water sources tested at the POC and POU was between 6.5 and 8.5, except for in the water from few domestic wells (about 10%) where the pH was <6.5. These wells were located in the east side of the study area. The reason for the reduced pH is unknown at this point. Acceptable pH levels are usually in the range 6.5–8.5. pH levels below 7 may be corrosive but there are no health-based guidelines proposed for pH (WHO, 2017).

3.4.2 Water Storage Practices

The main focus of our study is to analyze the storage practices at the household level. Our study collected POU samples from water storage containers stored in the homes only and therefore our water storage practices findings reflect what was observed at home. The main reason residents identified for mixing different water sources during storage was the lack of availability of a sufficient number of water storage containers. The lack of containers is due to the inability of the residents to purchase additional containers. As such, regardless of community awareness about the quality of their water, to our knowledge, the fact that most residents have limited income, restricts the ability of the residents of this settlement in Dar es Salaam to practice safe water storage at the household level.

Our results also show that the TDS levels in most water samples and the chloride levels in some of the water samples were above WHO guidelines, likely contributing to a salty taste to well water. Therefore, to make well water less salty and more palatable, residents tend to dilute salty well water by mixing it with more palatable city water. To some extent, this storage practice appears to be purposeful. Unbeknownst to the residents, the disadvantage of this approach is that well water is often highly contaminated. Most people interviewed did not know that city water and vendor water differed in quality. However, some residents did report that vendors claim that their water originates from the city water supply even if this is not true. As shown by our water quality results (Figures 3-2 and 3-4), water from vendors tested at the POC is poorer in quality as compared with water obtained from the city. However, residents who choose to believe that the vendors' water is obtained from the city supply commonly mix that water with city water thinking that it is from the same source. For them, the salty taste of water from vendors did not seem to be a concern.

Findings from this study did not show a big difference from those conducted in other parts of the world with similar challenges. In Sierra Leone, water samples from 20 unimproved water sources and 100 from the stored household water were collected and analyzed for pathogenic bacteria in 13 different villages in the Kailahun district along with 85 household interviews on demographics, hygiene practices, sanitation, water collection and storage practices (Clasen & Bastable, 2003). Results from unimproved water sources showed that all samples were contaminated by pathogenic bacteria and 92.9% of samples that were collected from households had high levels of fecal contamination (Clasen & Bastable, 2003). In Bagamoyo, Tanzania, a study involving hand-to-mouth contacts found out that a child consumes a total 0.098 mg or 0.93 mg of feces per day through drinking water stored and hand-to-mouth contacts (Mattioli et al., 2015). Children 3 to 6 months old consumed more feces per day from hand-to-mouth transfer while older children (3-5 years) consumed feces mainly through drinking water. Results from this study show the importance of focusing on interventions to minimize diarrhea by addressing hygiene in addition to water itself (Mattioli et al., 2015).

Regardless of other circumstances such as economic status, education and capacity building are important in these communities. In places such as Upper Egypt, where four districts (Itssa, Nasser, Samalot and Abou-Korkas) were monitored to observe how the behavior at the community level changes from education on personal hygiene and environmentally-appropriate water usage and sanitation (WES) (Metwally et al., 2007). The education focused on personal hygiene such as hand washing, especially after using the toilet, before eating, before preparing food and serving food and personal hygiene for children. Other relevant practices that were taught were proper drinking water storage and proper use and maintenance of pour flush latrines, for example, covering the latrine while not using it and pouring water in the latrine before and after use. The progress was monitored over a three-year period by conducting household surveys. Results from this study showed improvements in human behaviors towards water handling after hygiene health education increasing from the baseline, midterm and final survey which can highly minimize water contamination at the household level (Metwally et al., 2007).

3.5 Conclusion

The main objective of this study was to assess the water collection and storage practices at the household level and to analyze the extent of contamination of city water, which is safe at the POC but becomes contaminated at the households due to poor storage practices. The hypothesis tested positive by confirming that poor water storage practices in this community are the main cause of city water contamination at the household level. The study was able to identify existing water sources and determine the quality of water at the POC and at the POU. WQI classification demonstrated the level of contamination in a comprehensive manner based on scientific criteria for water quality. Water quality varied depending on the type of water source and storage practices. WQI results showed different levels of water quality in a given water source and the statistical analysis results indicated that, there are reasons why people mix water during storage. Under conditions where safe water is available, it should not matter whether one mixes water or not during storage. However, this informal Dar es Salaam community is largely unaware of the variations in quality of their water between sources and therefore are likely to use storage practices that lead to the contamination of higher quality city water.

Financial limitations and low-economic conditions prevent the residents from practicing proper water storage (Clasen & Bastable, 2003). The default for addressing household water quality concerns is often to either demand for more reliable city water service, and/or more attention to hygiene education. These either wholly institutionalize or individualize the problem. Our findings, however, indicate that addressing household water quality in the peri-urban context necessitates a combination of actions. Given the challenges of municipal water supply in a place like Dar es Salaam, it would be naïve to simply demand consistency of supply. Our data indicate that peri-urban household water quality concerns involves a) blending water; b) inadequate storage; c) misplaced trust in vender water; d) use of contaminated groundwater. The survey analysis indicates that people make these choices because of both lack of education and because of what amount to institutional constraints.

This implies a need for an integrated approach that addresses education, technology, and governance. Better (and more) storage facilities could be about education, yes, but also improving the availability of inexpensive and functional storage containers. Likewise, given frequency of discontinuation city water, water vendors provide an important service for households. It seems then, that a key to better household water quality is to develop mechanisms that ensure better standards of practice and labels. In other words, regulations of vendors. While the World Bank

(2004) proposed such regulation as the role of the state, Wutich et. al. (2016) suggest that such regulation could be ensured through unionization of vendors.

The data indicate that wells are badly contaminated and are also salty. Because our study examined POC and POU, it was clear that poor quality of water was coming from domestic wells and end up contaminating other sources at POU, specifically city water. Observations from site visits at these wells during water collection showed how close domestic wells were to septic systems, which suggests the likelihood of well contamination (Arwenyo et al., 2017). Education about the proper placement of domestic wells to lower groundwater contamination, proper wastewater management as well as proper construction of septic tanks should be emphasized. At the household level, education about better choices of water treatment technologies will help improve the quality of drinking water (Rajasingham et al., 2018).

Basic education about household water management as well as water treatment through use of inexpensive water filters could provide knowledge that may lead to a multi-barrier system to protect water quality. Also, knowledge about the sources of water and their quality is the key component to improving water quality and human health. When residents become aware of the differences in water quality from different sources, it will change their perspective and can encourage them to pay more attention during storage. Once the community is aware of the condition of their water, education about proper water storage practices can be implemented along with cost effective household drinking water treatment methods. Beyond education and awareness, however, there are additional actions that would be important to implement the multi-barrier approach, including: 1) improving the access to and availability of adequate numbers of containers so that water can be segregated; 2) developing a feasible regulatory system so that tankers and other suppliers are held to account for the quality of water that they provide; 3) better access to and management household filtering and treatment systems to improve water quality; and 4) improved systems for waste disposal and management to minimize contamination in the first place.

In other words, we argue that addressing water quality concerns, such as we document in peri-urban Dar es Salaam, must be addressed through an integrated domestic water management approach. Future research needs to address how to implement such an integrated approach.

3.6 Acknowledgments

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APPENDIX

APPENDIX

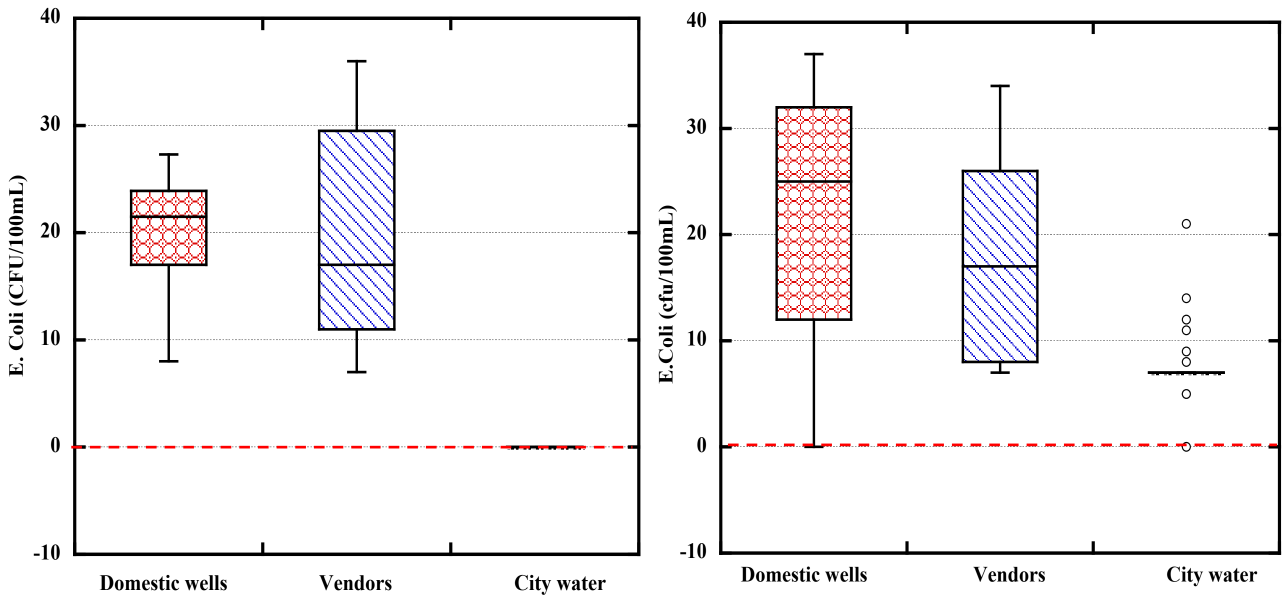

Figure A3-1. *E. coli* concentration comparison at the Point of Collection (POC) on the left, and Point of Use (POU) on the right

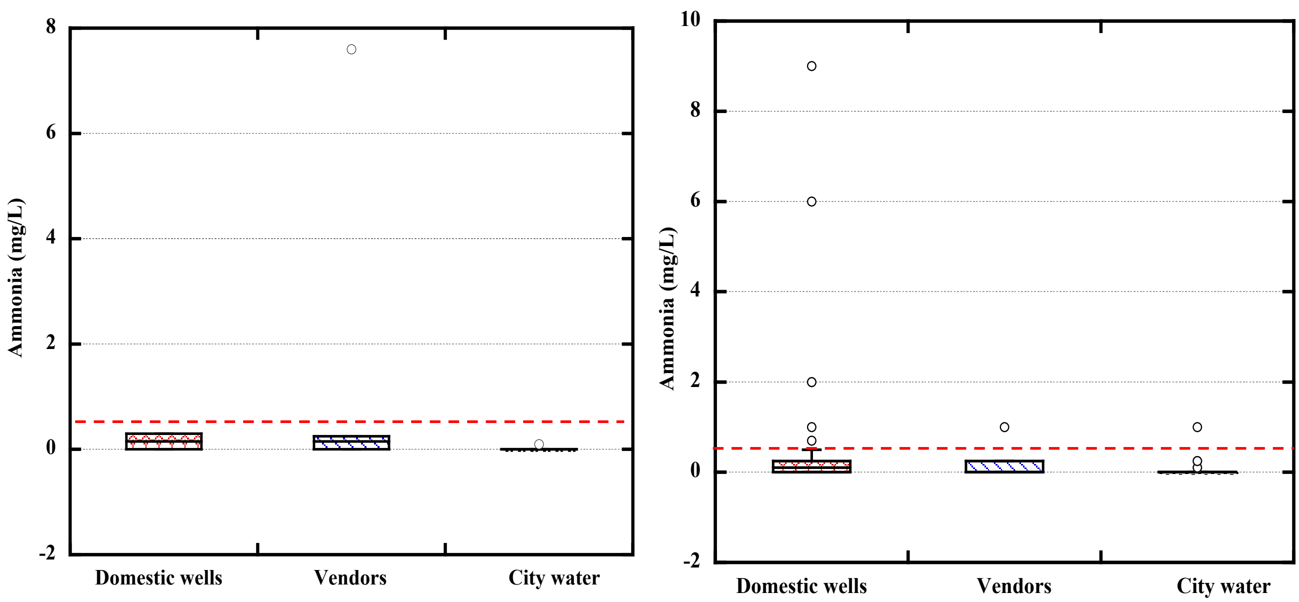

Figure A3-2. Ammonia concentrations comparison at the Point of Collection (POC) on the left and Point of Use (POU) on the right

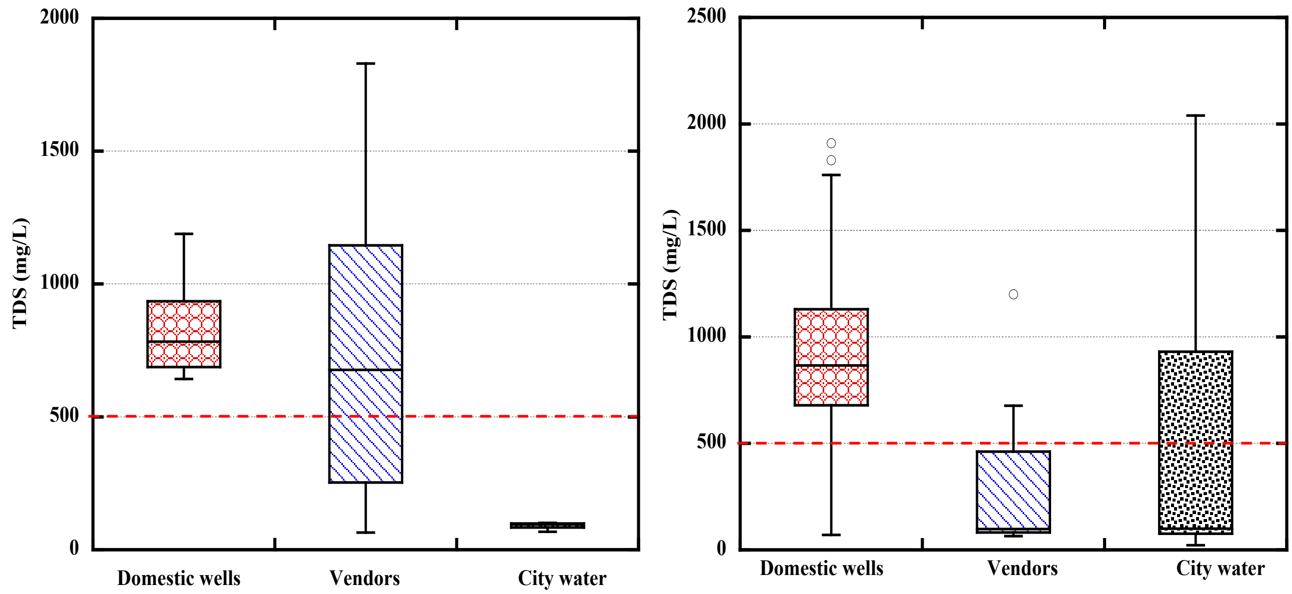

Figure A3-3. Total Dissolved Solids (TDS) concentrations comparison at the Point of Collection (POC) on the left, and Point of Use (POU) on the right

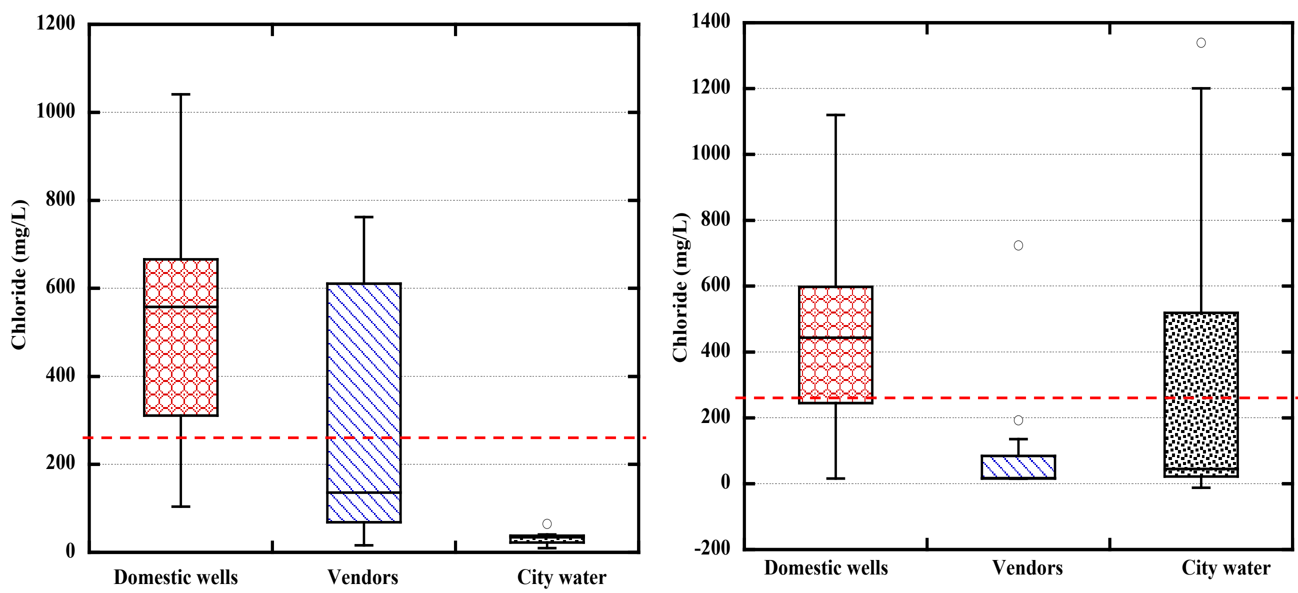

Figure A3-4. Chloride concentrations comparison at the Point of Collection (POC) on the left, and Point of Use (POU) on the right

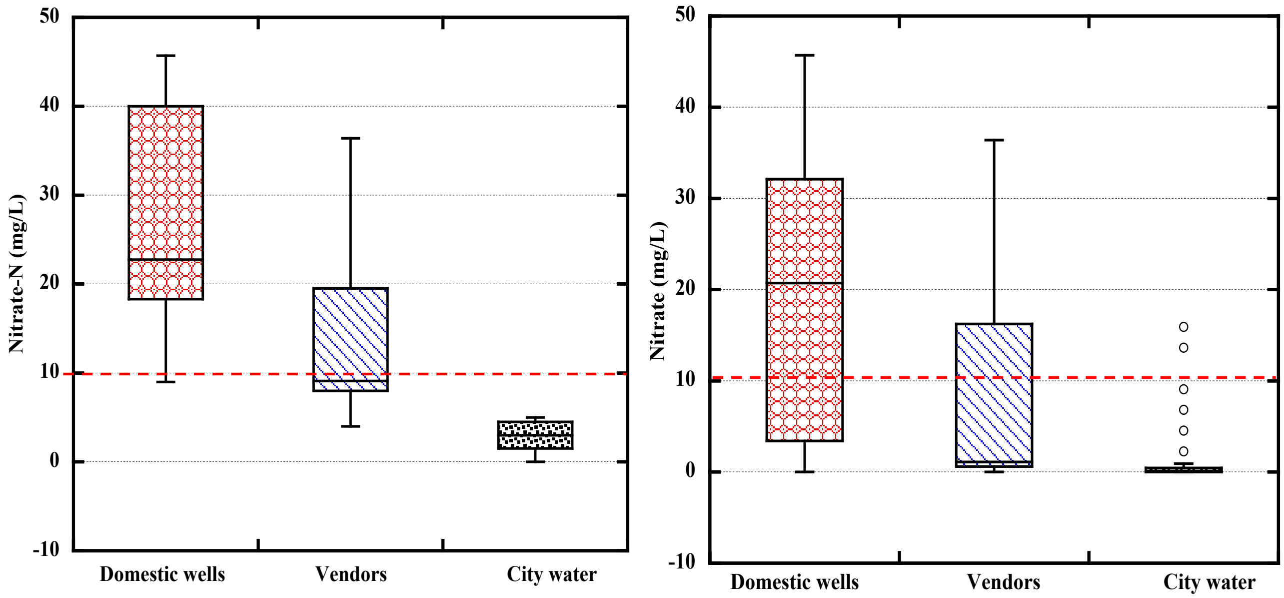

Figure A3-5. Nitrate concentrations comparison at the Point of Collection (POC) on the left, and Point of Use (POU) on the right

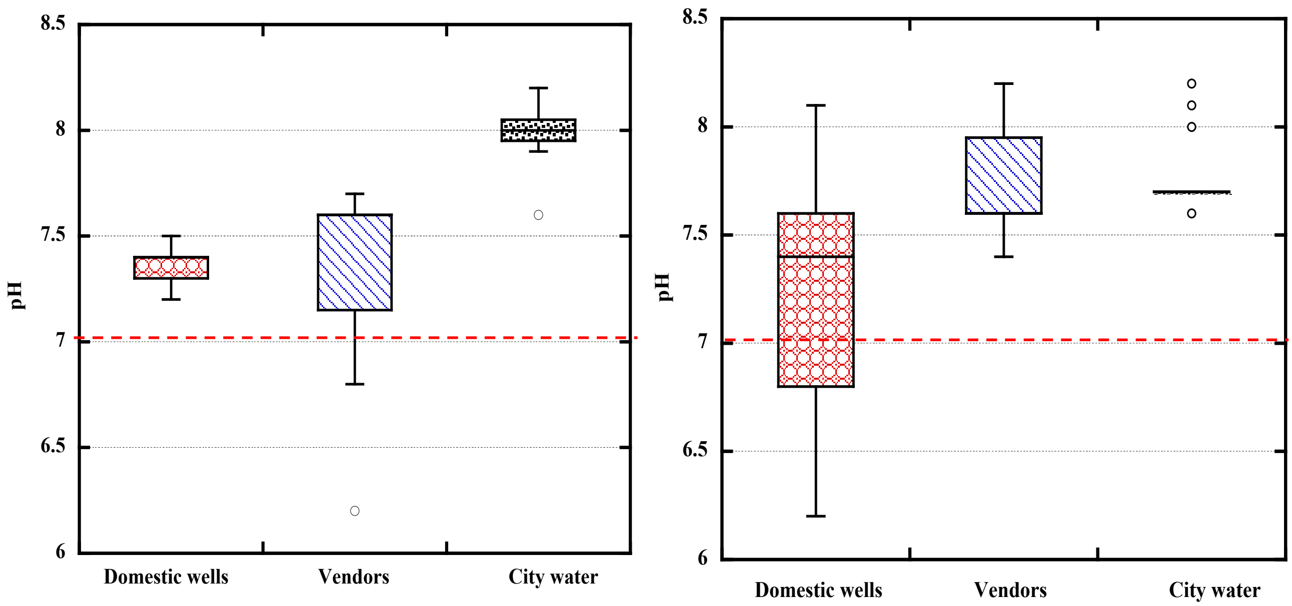

Figure A3-6. pH levels comparison at the Point of Collection (POC) on the left, and Point of Use (POU) on the right

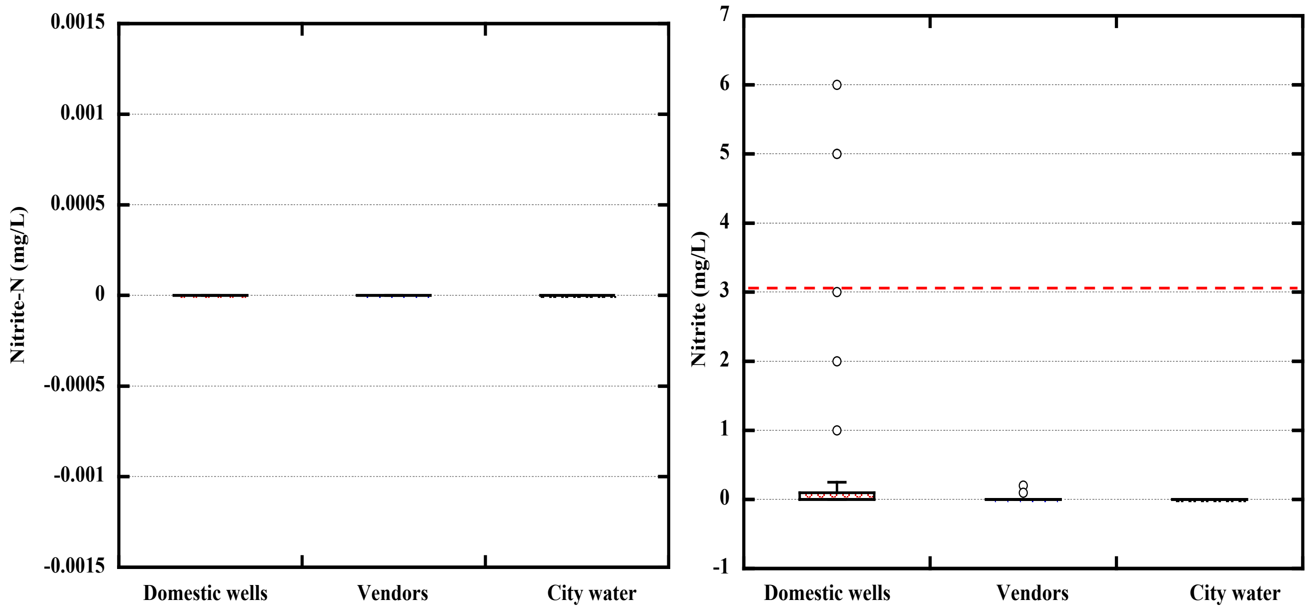

Figure A3-7. Nitrite concentrations comparison at the Point of Collection (POC) on the left, and Point of Use (POU) on the right

Table A3-1. Number of households reported different mixing combinations and the reasons for mixing water during storage.

Reason for Mixing	**N**	**Percentage (%)**
Insufficient number of containers	58	44
No difference in the quality of water	33	25
Dilute the salty test	42	32
TOTAL	**133**	**100**
Mixing Combination	**N**	**Percentage (%)**
Well, Vendors & City water	50	38
Well & City water	53	40
Well & Vendors	30	23
TOTAL	**133**	**100**

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CHAPTER 4: Impact of Domestic Wells and Hydrogeologic Setting on Water Quality in peri-urban Dar es Salaam, Tanzania

Abstract

In densely populated urban areas of many low-income countries, water scarcity, poor water quality, and inadequate wastewater management present complex challenges to ensuring health and wellbeing. This study was conducted in an impoverished peri-urban community in Dar es Salaam, Tanzania that experiences water scarcity and relies on domestic wells for drinking water. The objective of this study was to identify the sources of domestic well water contamination and assess the relationship and association of water contamination with three variables 1) the proximity of the well to a sanitation system, 2) well age, and 3) well depth. Out of the 71 wells tested, samples from >80% of wells contained Escherichia coli (*E. coli*) and 58% had nitrate levels above WHO guidelines. The average concentration of total dissolved solids (TDS) was 882 mg/L, which exceeded the WHO guideline of 600 mg/L. Bivariate correlation analysis showed a strong correlation between water contamination and proximity of the well to a sanitation system along with well depth. Univariate regression analysis confirmed the association of contaminants with distance of a well from a sanitation system and well depth ($p<0.05$) but age of the well did not show any significant influence on water quality. Our findings indicate significant contamination of wells from nearby septic tanks and pit latrines. New regulatory mandates for the distance of domestic wells from sanitation systems are essential to prevent groundwater contamination and to protect human health.

Keywords:

Low-income countries, water quality, pit latrine, shallow and deep well, public health, sanitation

4.1 Introduction

Water scarcity and poor water quality are major issues facing densely populated urban communities in developing countries. Contamination of groundwater as a result of poor sanitation practices represents a major threat to the safety of drinking water resources throughout the world. Urban areas are of particularly high risk due to population growth rates of greater than 5% per year. This rapid population growth results in the concentration of poverty, which together result in the rapid spread of waterborne disease (WHO, 1992). A major challenge for those concerned with environmental health is the design and introduction of excrete disposal systems appropriate to these high-density, low-income communities. Untreated groundwater is a major source of enteric diseases causing significant morbidity and mortality globally. An estimated 1.77 billion people worldwide use pit latrines and global reliance on groundwater and pit latrines is only expected to increase as Sustainable Development Goals for safe sanitation are increasingly being met (Graham & Polizzotto, 2013; Ravenscroft et al., 2017). Previous research has demonstrated that trade-offs exist between the SGD goals of water supply (SGD 6.1) and sanitation (SGD 6.2) with increased latrine coverage and adoption linked to increased contamination (Sorensen et al., 2016).

In Dar es Salaam City, where this study was conducted, the main source of city water supply has been the Ruvu River. However, the water level in Ruvu River has been declining in recent years due to human activities (Mato, 2002; Ngove & Machiwa, 2004). As a result, the water supply from Ruvu River has been unreliable and the City is unable to supply water to all residents. Population growth, surface water contamination, and dwindling surface water supplies have resulted in heavy reliance on groundwater. More than 50% of residents in Dar es Salaam rely on groundwater for their daily use (Mtoni et al., 2013). There are more than 7,500 active boreholes/wells in the city and annual withdrawals from the aquifer exceeds 69 million cubic meters of water (Mtoni et al., 2011).

As Graham and Polizzotto (2013) pointed out, despite the global reliance on groundwater and issues surrounding groundwater contamination by pit latrines, few studies directly examined the links between groundwater pollution and contamination from pit latrines and one of the objectives of this work is to address this gap in the context of urban areas in Dar es Salaam, Tanzania. Over-extraction of groundwater often leads to detrimental effects, such as seawater intrusion into freshwater aquifers and contamination from improper sewage and industrial waste disposal. Improper human waste management is known to result in the contamination of groundwater with contaminants such as nitrate (NO_3^-), enteric bacteria i.e., *Escherichia coli* (*E. coli)*, viruses, and total dissolved solids (TDS). There are several factors that can result in the contamination of domestic wells. In our study, we focused on three factors – well depth, age of the well, and proximity of the well to a septic system.

The first variable assessed is the well depth. Several studies such as Elisante and Muzuka (2016) found that the depth of the well can affect the level of contamination. In our study area, the depth of shallow wells ranges from 1 to 15 m. Deep wells extend to depths up to 120 m. The extent of contamination of shallow wells depends on the depth and the condition of sanitation facilities in the area. In our study area, nearly 90% of the homes use either an unventilated pit latrine or a single unlined septic tank without a soakaway pit. Herein the two types of units will be referred to as "pit latrines". On the contrary, residents typically refer to these facilities as septic tanks although many of them are not constructed to meet the definition of a properly constructed septic tank (See Appendix A in the Appendices for more details). More than 50% of residents in the study area have to mechanically empty their pit latrines between 1 to 24 months (Ngasala et al., 2016). This compares to typical times of between 3 and 5 years to fill the pits (Orner, 2018).

The rate of contaminant migration is a function of soil type. The soil type in our study area is sandy clay (Mtoni et al., 2012). The permeability of this type of soil is relatively high and is estimated to be between 0.5 - 15 cm/hr (USEPA, 1980). More than 50% of the study area has a shallow water table that is less than 5 m below ground surface. During the rainy season, when the water table rises, many “pit latrines” in this area fill with groundwater because they are not sealed, thereby potentially contaminating the nearby shallow wells, as shown by (Mkude & Saria, 2012). These researchers observed extensive contamination of nine shallow wells (1.5 to 8 m deep) with total and fecal coliform bacteria in three districts of Dar es Salaam. The main source of contamination in those wells was reported to be improper on-site waste disposal.

The second factor studied is the age of the well. Well age is an important factor in predicting the likelihood of well contamination. High pumping rates, the high-water demand, along with the high permeability of soils in the study area exacerbate the risks of well contamination which increase over time. For example, 35,000 private rural wells in Ohio, Indiana, Illinois, West Virginia, and Kentucky, U.S.A., were tested for different contaminants including nitrate. Concentrations were found to be higher in wells that are shallower, older, located in sandy soils or in close proximity to feedlots, or chemical mixing sites (Richards et al., 1996). Wells constructed in urban areas are likely to be surrounded by many potential sources of contamination. For example, older well pumps are more likely to leak lubricating oils, which can seep into the well. Corroded and perforated casings can also result in well contamination. In areas where water is scarce, privately owned domestic wells supply water to the public, which results in high pumping rates and increases the rate of well contamination overtime (Mtoni et al., 2013).

The third factor is the proximity (or distance) of the well to a pit latrine. According to WHO (1997), septic tanks or pit latrines should be placed down gradient from the well. If latrines and septic tanks are poorly sited, they can lead to the contamination of drinking water sources (WHO 2017a). The distance from the well to septic systems has been reported to be at least 15 meters (Sphere Project, 2011; CDC, 2009; US EPA, 2002), although the actual distance will depend on the aquifer properties along with the rate of transport of microbiological and chemical contaminants in the aquifer (Graham & Polizzotto, 2013). Vinger et al. (2012) noted that wells are most likely to be contaminated where the separation distance between pit latrines and wells is less than 12 m. In Zanzibar, Tanzania, the study assessed seasonal microbial and chemical contamination in domestic wells, where 50% of the domestic wells were located less than 15 m from a septic tank or pit latrine. Only 5% of water samples tested from these wells met WHO drinking water guidelines (Vuai, 2012). Although the study did not clearly establish a correlation between microbial and chemical contaminants, the researchers concluded that the major sources of contamination were septic systems and pit latrines. The decision on the safe distance from the well to the septic tank is site specific and it varies depending on the soil type and aquifer properties.

Numerous studies have analyzed the impact of contamination in domestic wells by focusing on each factor individually. Most research focused on the proximity of the well to the source of contamination and used a simple correlation analysis. The objective of this study is to identify sources of drinking water contamination and analyze the relationship and association of water contamination with all three variables 1) the proximity (distance) of the well to a sanitation system, 2) age of the well, and 3) well depth. Herein, we test two main hypotheses. First, we hypothesized that positive bivariate correlations exist between nitrate, TDS, and *E. coli* levels; in other words, we propose that all three contaminants exist simultaneously because they originate from the same sources. Also, we hypothesize that negative bivariate correlations exist between contaminants and the three well variables mentioned in drinking water from domestic wells in the study area. Second, we propose that meaningful linear relationships exist between contaminants and the three variables previously mentioned. The location of domestic wells near a sanitation system influences the level of contamination, especially in places (such as the study area) where the hydraulic conductivity of the aquifer material is high as this promotes the seepage of sewage into nearby wells.

4.2 Methods

4.2.1 Study Area Description

The study area is located on the East African coast in Dar es Salaam City, Tanzania. The country borders the Indian Ocean to the east (Figure 4-1). Dar es Salaam is the major seat of government institutions and the largest urban centre in Tanzania. It is highly populated (~6 M) with significant economic development. The climate of Dar es Salaam region is tropical with high temperatures (up to 35 ºC) in November through February and cooler temperatures between May and September with annual average temperature about 22°C. There are two wet seasons in a year, short rains and long rains. Long and heavy rains occur from March to May, while short rain storms occur in October to December. The dry season is typically from June to September. The average monthly rainfall during the long rainy season is 253 mm and 117 mm during the short rainy season (Mtoni et al., 2012)

The study area is one of the densely populated, informal settlements in Dar es Salaam. The wards within the study area are Mabibo, Mburahati Makurumla, Kigogo, and parts of Mzimuni, Makuburi, Manzese and Ubungo (Figure 4-1). The population density of the study area is about

14,250/km^2 (United Republic of Tanzania, 2013). Residents are low-income wage earners who spend a significant portion of their income to purchase water for domestic use and for wastewater management (Ngasala et al., 2019). The houses are in close proximity to one another and none of the households are connected to the sewer system. Human waste from this area is discharged to "pit latrines", most of which have been poorly constructed with little or no regard for human health or the environment.

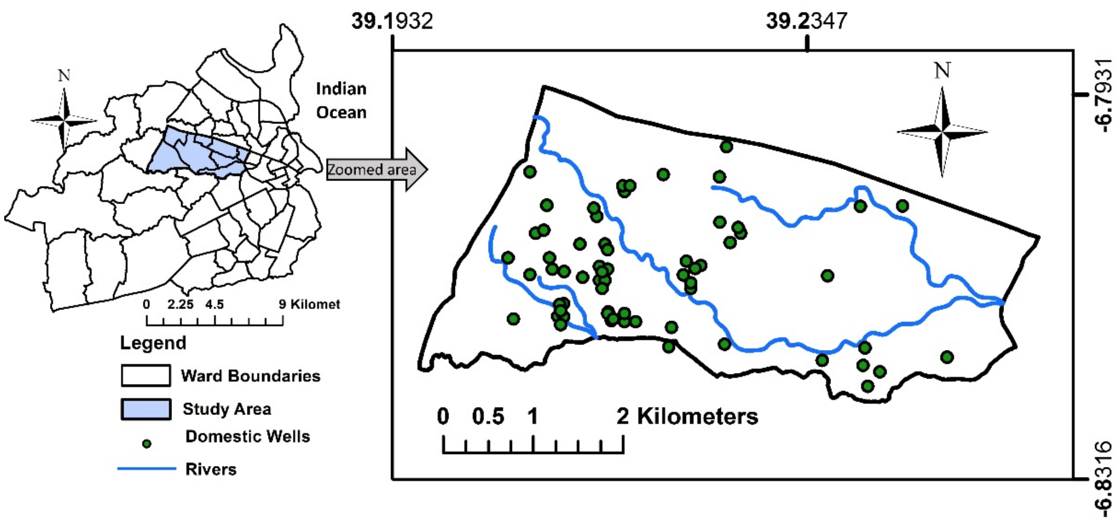

Figure 4-1. Location of the study area in Dar es Salaam, Tanzania showing 71 domestic wells that were used for water quality testing and statistical analyses. Our study area is located about 7 km from the Indian Ocean.

The Dar es Salaam City consists of mainly two aquifers: an upper unconfined sand aquifer and a lower semi-confined sand aquifer that are separated by a clay aquitard of between 10 and 50 m (Mtoni et al., 2012). Details of the aquifer systems and the hydrogeology of the region are provided in Appendix B in the Appendices. Figure 4-2 shows the hydrogeology of our study area. The uppermost water-bearing unit in the study area is the unconfined sand aquifer. The majority of the wells in our study area draw water from the upper and the lower semi-confined sand aquifers. The depth of the water table in the unconfined aquifer averages tens of meters below the land surface. The average static water table level in the 71 wells in the study area is about 15 m. The average yield of these wells is approximately 130,000 L/d. The average hydraulic conductivity (k) of the aquifer material was 0.14 m/d and the average drawdown at the well was 8.15 m during pumping. More than 90% of all wells in this study area are privately owned, but they are considered public wells because residents purchase water from the owners for their daily use. About 20% of the wells are shallow wells. Water is typically pumped from these wells between 5 to 6 hours per day.

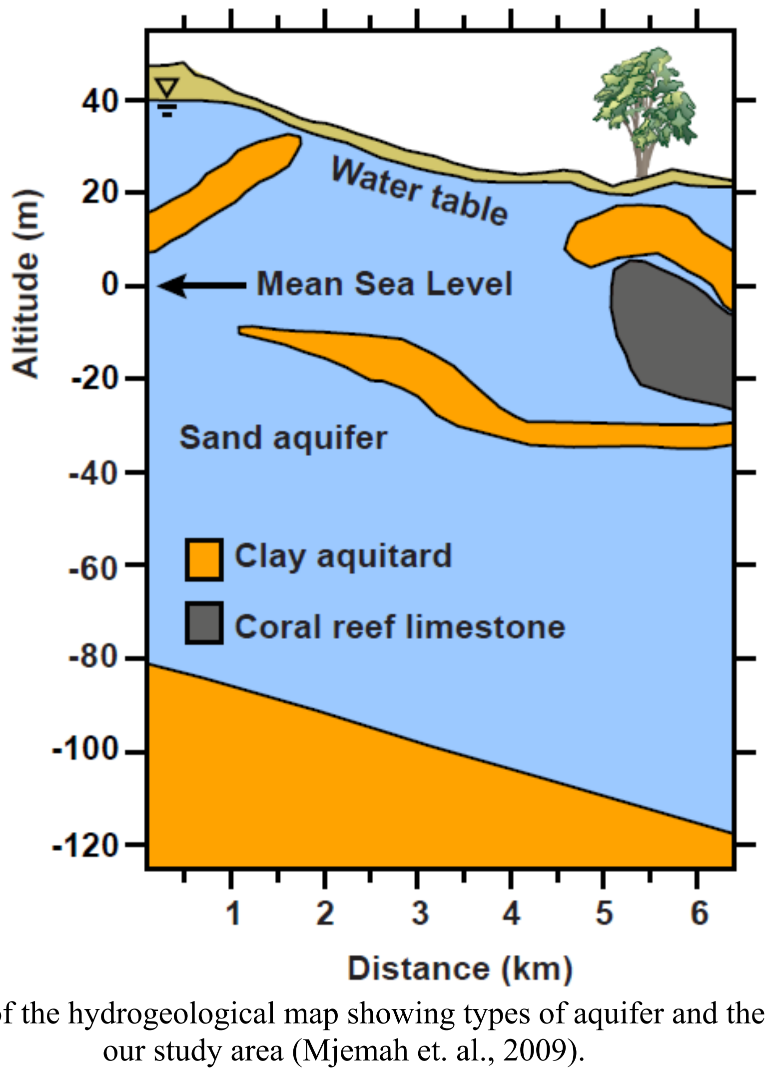

Figure 4-2. Profile of the hydrogeological map showing types of aquifer and the water level in our study area (Mjemah et. al., 2009).

Water supply and sewerage system in Dar es salaam is managed by Dar es Salaam Water and Sewerage Corporation (DAWASCO). EWURA (2013) reports that 40.7% of the population obtains water directly from DAWASCO, however, being connected to a DAWASCO piped water system does not guarantee access to water supply. According to the Ministry of Water, 49% of water produced is lost due to old infrastructure and illegal water connections (URT, 2013), although Nganyanyuka et al. (2014) suggested that the figure may be closer to 80% with only 18% of the total number of households receiving this service. In Dar-es-Salaam, most people purchase water from either public standpipes, private boreholes, or fetch water from shallow open wells (Kjellén, 2006). Similarly, in our study area, the majority of the population relies on domestic wells, public standpipes and small scale vendors (Ngasala et al., 2018), although some residents access water from DAWASCO by making illegal connections into the distribution network (Nganyanyuka et al., 2014).

4.3 Data Collection

Prior to data collection, we obtained permission from the Tanzania Commission for Science and Technology (COSTECH) in Dar es Salaam, Tanzania and from the Human Research Protection Program (IRB) at Michigan State University to conduct this investigation. Seventy-one domestic wells were located in the study area (as shown in Figure 4-1). The official well reports were collected from the Drilling and Dam Construction Agency (DDCA) in Dar es Salaam, with information such as the date the well was drilled and the depth of the well. The latitude and longitude for each well was recorded using a GPS unit. The distance from the well to the closest "pit latrine" was measured. Water samples were collected from each well during the dry season (June - August 2016). While much work has been done during the rainy season when the water table is higher, very few studies have been conducted during the dry season. Additionally, the several cholera outbreaks that occurred during the dry seasons in the two years prior to our study indicate the importance of understanding water quality issues in both the wet and dry seasons. The concentrations of nitrate, TDS and *E. coli* were determined in all water samples obtained from the wells. Details of the sampling and analysis are provided in Appendix C of the Appendices.

4.3.1 Radius of Influence

The radius of influence R of a pumping well is defined as the radial distance from the well, where the drawdown is a maximum, to a point where the drawdown is negligible. Although R is time-dependent, the Thiem equation (Bear, 1979) shows that the piezometric head, which depends on $\ln(R)$, is not very sensitive to errors in R. One of the most commonly used empirical equations for R, known as the Sichardt formula (equation 1 below), where the number 3000 is an empirical constant) is used to estimate R in the present work (Bear, 1979):

$$R = 3000\, s_w \sqrt{k} \tag{1}$$

Where:

R = influence radius (m)

k = hydraulic conductivity (m/s)

s_w = drawdown in the borehole (m)

4.3.2 Statistical Analysis

To understand the relationships between water contaminants and well characteristics, two statistical analysis methods were applied to water quality data 1) bivariate correlation to determine the empirical relationship between contaminants and the three explanatory variables (distance, depth, and age) and 2) multiple linear regression to confirm whether meaningful linear relationships exist between contaminants and the three well characteristics (distance, depth and age). IBM Statistical Package for the Social Science (SPSS) version 24.0 (IBM Corp, 2016) was used for all analyses.

Bivariate Correlation

Pearson's *r* correlation was used to characterize linear relationships between contaminants: 1) *E. coli* and nitrate, 2) nitrate and TDS, and 3) *E. coli* and TDS. We then explored the linear relationships between contaminants and well characteristics. Based on results from Pearson's *r* correlation (bivariate correlation), we focused our investigation on the relationship between contaminants and well characteristics by using multiple linear regression models.

Multiple Linear Regression for Nitrate

With respect to the regressions, a general (Gaussian) linear model (Univariate General Linear Model) was fit to nitrate concentrations as a function of all three well characteristics. The multiple linear regressions (MLR) were used to evaluate nitrate concentrations due to the continuous nature of the dependent data (DeMaris, 2004; Cleophas & Zwinderman, 2012). All possible model parameter combinations were evaluated in order to identify the MLR models that best explained the data based on the adjusted R^2 and residual diagnostics. Three factors were used to select the best MLR model. First, we examined the collinearity of data. Collinearity happens when one predictor variable in a MLR model can be linearly predicted from the others. High collinearity between predictors indicates that variables share significant amount of information. This can be a problem for parameter estimation for any descriptive data set because it increases the variance of regression parameters which can cause the wrong identification of predictors (Dormann et al., 2013). Second, the Variance Inflation Factor (VIF) was used to measure the degree of multi-collinearity of the *i*-th independent variable with the other independent variables

(O'Brien, 2007). We tested whether any pairs of variables are correlated at all (negative or positive) such that they can be considered numerically redundant with one another (Zuur et al., 2010). Independent predictor variables with VIF < 3.0 were used for data analysis.

The second factor is adjusted R^2. This is a measure of the accuracy of linear models to identify the percentage of variance in the input(s). The closer the adjusted R^2 is to 1.0, the more the variation in the dependent variable can be explained by the independent variables in the regression model (Kvålseth, 1985). Last, is the significance where *p*-values less than 0.05 indicated the significance of the relationship of that combination. Additionally, model residual patterns were used to visually confirm the single best fitting model to each dependent variable, including 1) histogram plots of raw residuals whereas the histogram should emulate the shape of a normal (bell-curved) distribution, 2) quantile plots of observed versus expected cumulative probability of raw residuals whereas the points need form a nearly linear pattern, and 3) standardized Pearson residuals model versus predicted values whereas residuals should be randomly spread above and below $y = 0$ without any funnel shape or linear patterns in residuals that could indicate heteroscedasticity. If the residuals have a stark funnel or linear pattern to them, then re-fitting the model was considered with a transformed y variable. This visual confirmation procedure was employed to identify any residual departures from model assumptions of normality and homoscedasticity.

Multiple Linear Regression for TDS and E. coli

In contrast to general linear model, a generalized linear model (univariate generalized models with a log-link function) was used to evaluate the remaining dependent variables, *E.coli* and TDS, which represent positive-definite discrete data (Molenberghs & Verbeke, 2006). As mentioned above, all possible model parameter combinations were assessed to identify the best explanatory negative binomial models based on the adjusted R^2 and residual diagnostics. Three factors were used to select the best model. First, the omnibus test was used to assess whether or not the model fit (with *x* predictors) outperforms a null (intercept-only) model in terms of its explained variance about *y*. Overall, when significant, the fitted model better explains variability in *y* than an intercept-only model [i.e. $y \sim 1$]) (Epps & Singleton, 1986; IBM Corp, 2011). Second, the Akaike's Information Criterion (AIC) score was used to report model quality in terms of interpolative prediction accuracy and model deviance (the log-likelihood) (Burnham & Anderson, 2002). This value was used to compare the 8 models (per *y* variable) to each other. The model with the lowest AIC (of its 7 other complements) is the best-fitting model to the data (Yamaoka et al., 1978) as the AIC penalizes models with a large number of explanatory variables. Third, *p*-values less than 0.05 indicated the significance of the relationship of that combination. Residual diagnostics with plots of histograms and standardized Pearson residuals were also used for generalized liner model. The same criteria were used for linear regression to determine the best-fit model. Equations 2 and 3 formulaically describe the general form of the regressions considered:

$$Y = \beta_0 + \beta_1 x_1 + a\beta_2 x_2 + \beta_3 x_3 + \varepsilon \tag{2}$$

$$Y = \beta_0 + a\beta_1(distance) + \beta_2(depth) + \beta_3(age) + \varepsilon \tag{3}$$

Where:

Y= Dependent variables (contaminant concentrations)

β_{1-3} = Linear regression coefficients

β_0 = an intercept

x_{1-3} = Independent variables (well characteristics)

ε = Unexplained error variance

4.4 Results

In sparsely-populated areas and where pumping is infrequent or sporadic, subsurface contaminant plumes travel following the natural gradient flow direction. To determine if septic systems are located within the area influenced by a pumping well, we computed the radius of influence, R using the drawdown values measured at the wells with hydraulic conductivity values obtained from site-specific aquifer tests. The Sichardt formula used in our analysis produced the smallest R values compared to other empirical and semi-empirical equations described in Bear (1979) and estimates obtained from groundwater modeling results (e.g., Hatari Water, 2016). The median radius of influence in our study area was calculated to be 84.1 m. All "pit latrines" used to measure distance to domestic wells were therefore within the radius of influence (R). All wells were located within 35 m of a latrine. Considering the long periods (5 to 6 hours) of pumping and the proximity of wells to latrines, the direction of groundwater flow due to the natural hydraulic gradient is expected to have minimal effect on well contamination. As a result, natural groundwater flow direction was not considered as one of the metrics in our analysis and will be examined in a future groundwater modeling study, which is beyond the scope of the present chapter. Figure 4-3 shows one of the domestic wells in the study area located only 3 meters away from the "pit latrine". Although the well is 40 meters deep, the radius of influence was significantly larger than the distance to the "pit latrine".

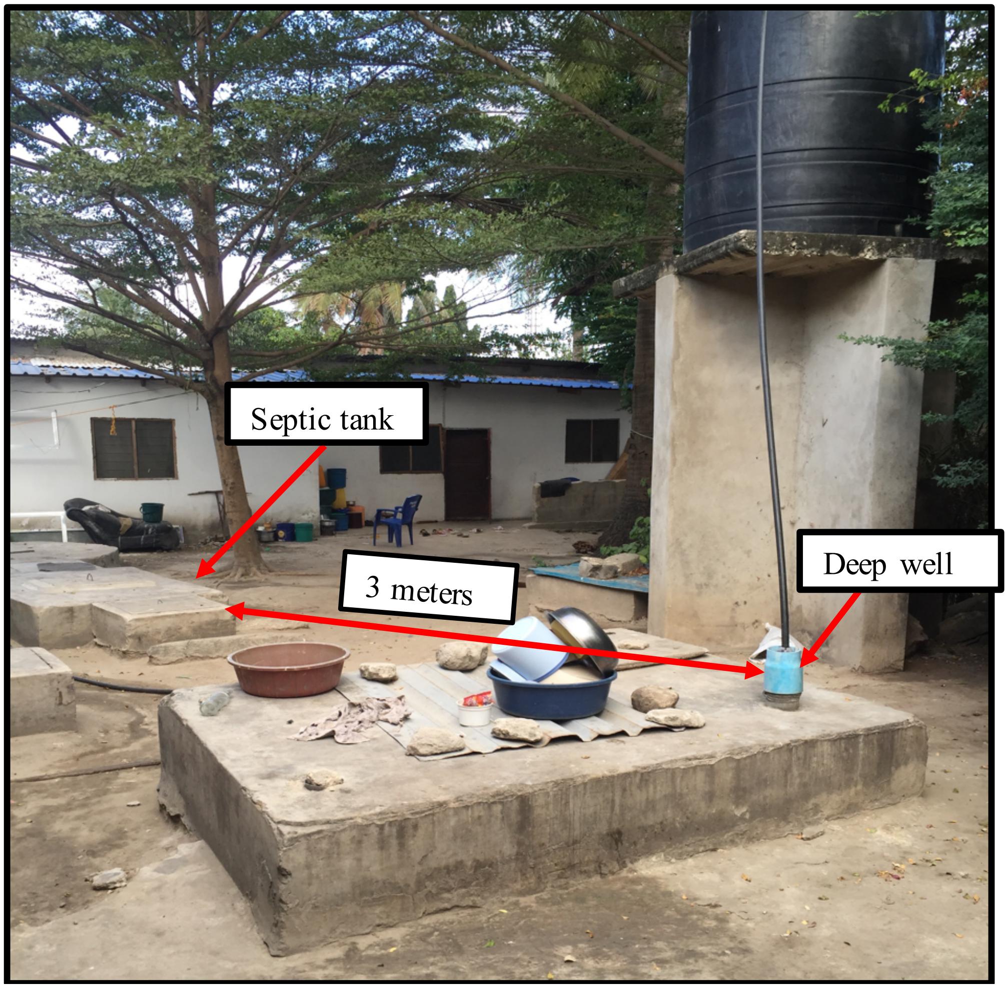

Figure 4-3. Photograph of a domestic well in Dar es Salaam, Tanzania. Herein, the well, though deep, is positioned only 3 m from the nearest "pit latrine", which may influence well water quality

4.4.1 Bivariate Correlations

Water samples collected from all 71 domestic wells were found to have nitrate levels between 0 – 45.7 mg/L as N with an average of 19.5 mg/L as N (Figure 4-4a). Nearly 58% of these samples were above the WHO drinking water guideline of 10 mg/L as N. TDS concentrations were between 71-1910 mg/L with an average of 882 mg/L (Figure 4-4b). The WHO guideline for TDS is 600 mg/L (WHO, 2017). More than 80% of these samples were contaminated with *E. coli* (Figure 4-4c).

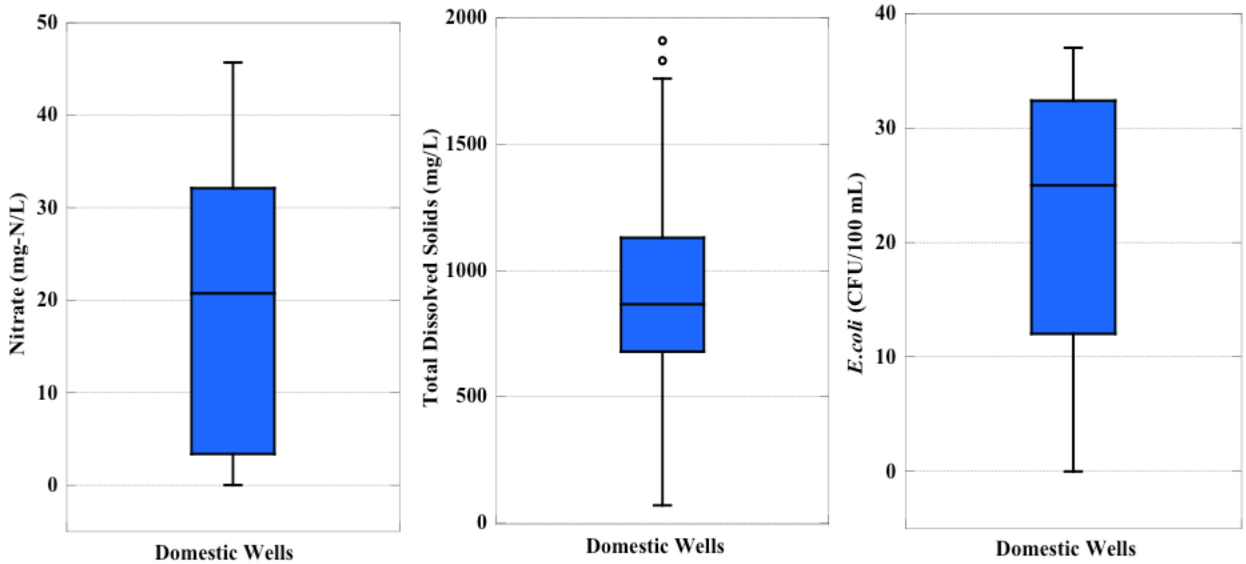

Figure 4-4. Box plots showing the upper adjacent, median and lower adjacent values of nitrate (4-4a), TDS (4-4b) and *E. coli* (4-4c) for all domestic wells analyzed.

Figure 4-5 shows the spatial mapping of the nitrate, *E. coli,* and TDS concentrations in all wells in the study area. The wells located on the north and the west side of the study area had higher nitrate and *E. coli* contamination levels than those on the east and southern areas. TDS levels were a concern on the east and west side of the study area. The reason could be to the proximity of pit latrines in that area. Spatial maps for nitrate and *E. coli* correlate with scatter plots in Appendix D (Figures A4-10 and A4-11). TDS levels were highest on the southwest side of the study area, which is different compared to *E. coli* and nitrate. Distance did not appear to be a factor for high TDS levels as is shown in Figure A4-12 in Appendix D.

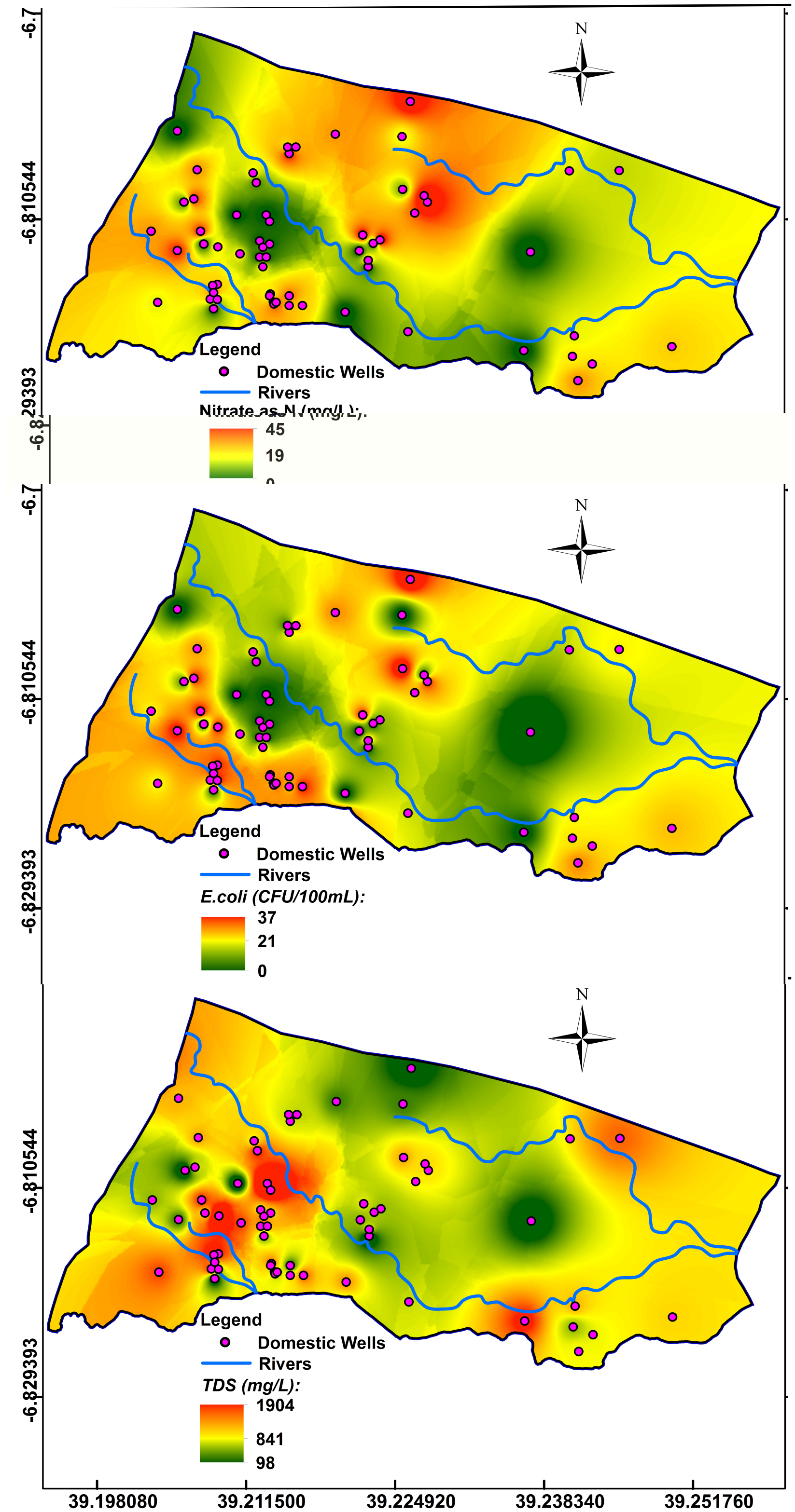

Figure 4-5. The spatial distribution of nitrate, *E. coli,* and TDS concentrations from the wells analyzed within the study area.

Pearson's *r* correlations from three combinations of contaminants: 1) *E. coli*- nitrate, 2) nitrate - TDS, and 3) *E. coli*-TDS revealed that nitrate and *E. coli* are positively correlated with an *r* of 0.806 (Table 4-1). Nitrate-TDS and *E. coli*-TDS combinations had *r* values of -0.082 and 0.058 respectively, suggesting that these parameters are not well correlated. Figures A4-1, A4-2 and A4-3 in Appendix D show the scatter plots from Pearson's *r* correlation between *E. coli*-nitrate, TDS-nitrate and TDS- *E. coli* with R^2 values of 0.651, 0.007 and 0.004 respectively for all 71 wells analyzed to support values in Table 4-1.

Table 4-1. Pearson's r values from linear correlation analysis of three combination of contaminants

Independent Variable	**Pearson Coefficient**		
	Nitrate	*E. coli*	TDS
Nitrate	1.000		
E. coli	0.807*	1.000	
TDS	-0.082	0.058	1.000

**Correlation is significant at p<0.01 level (2-tailed test)*

Out of 71 wells analyzed, 26% were found to be less than 30 meters deep. The depth for both shallow wells and deep wells ranges between 2 and 120 meters with an average of 51.1 m (Figure 4-6a). The age of most wells at the time of sampling was between 1 year and 26 years, with an average of about 9 years, with one outlier that was 56 years old (Figure 4-6b). Field investigations found that 65% of domestic wells were located less than 15 m from septic tanks. The maximum distance was found to be 35 m and minimum was 3 m with an average of 13.4 m (Figure 4-6c).

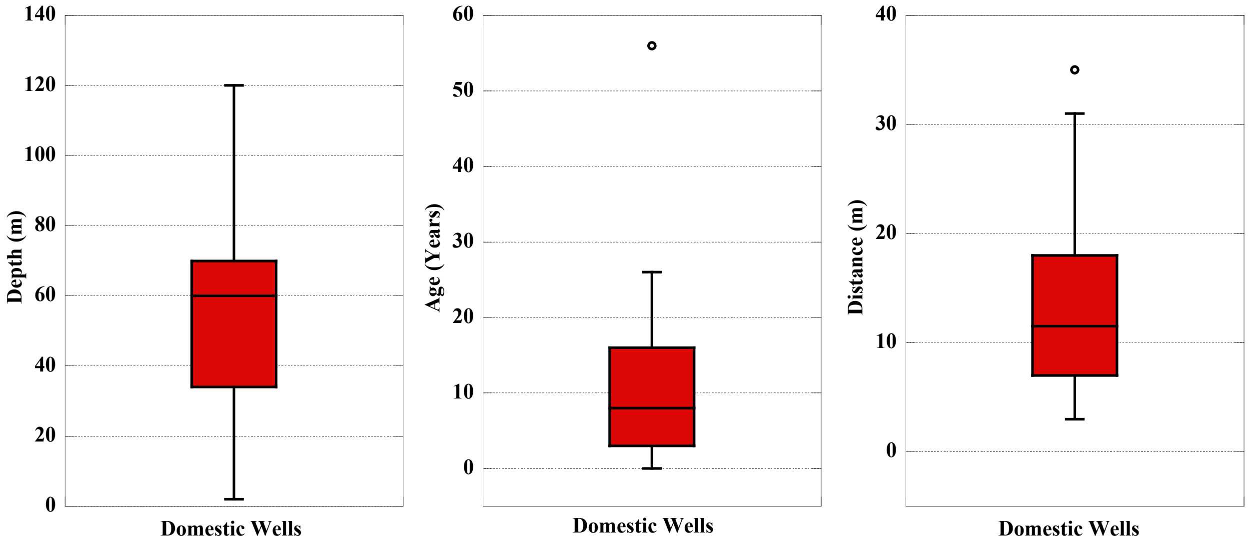

Figure 4-6. Box plots showing the upper adjacent, median and lower adjacent values of well depth (4-6a), well age (4-6b) and distance (4-6c) from a well to the nearest pit latrine for domestic wells

Bivariate correlation of well distance, age, or depth with TDS showed no correlation. However, when paired with well age, there was a weak negative correlation with Pearson's *r* value of -0.156 (Table 4-2). Correlative comparisons showed that nitrate and distance between wells and pit latrines (hereafter, distance) and *E. coli* and distance exhibit strong negative correlations with Pearson's *r* coefficients -0.846 and -0.794, respectively. Bivariate combinations of well age for nitrate and *E. coli* (-0.047 and 0.025 respectively) showed no correlation but showed weak negative correlation for well depth with Pearson's *r* coefficients of 0.0391 and -0.472, respectively (as shown in Table 4-2).

Table 4-2. Bivariate correlation of distance, age, or depth of the well with water quality

Independent Variable	**Pearson's r Coefficient**		
	Nitrate	*E. coli*	TDS
Age	-0.047	0.025	-0.156
Depth	-0.391*	-0.472*	-0.093
Distance	-0.846*	-0.794*	-0.007

**Correlation is significant at p<0.01 level (2-tailed test)*

Figures A4-4, A4-5 and A4-6 in Appendix D show the scatter plots for Pearson's *r* correlation of *E. coli*, nitrate and TDS respectively with R^2 values of 0.153, 0.223 and 0.009 respectively for well depth. Figures A4-7, A4-8 and A4-9 in Appendix D show Pearson's *r* correlation for nitrate, *E. coli* and TDS with R^2 values of 0.002, 5.267E-40 and 0.024 respectively, for well age. Figures A4-10, A4-11 and A4-12 in Appendix D show the scatter plots for Pearson's *r* correlation of nitrate, *E. coli*, and TDS with distance from the well to a pit latrine with R^2 values of 0.715, 0.632 and 0.000548 respectively.

4.4.2 Univariate Multiple Linear Regressions

General Linear Model

Table 4-3 summarizes the multiple linear regression results for all 7 combinations of independent variable tested for nitrate. *Nitrate-depth* and *nitrate-age-depth* combinations showed significant differences with *p*-values of 0.001 and 0.000, respectively, as well as the best observed cumulative probability and expected cumulative probability plots (see Figures A4-13 through A4-30 in Appendix D). Water quality results for wells that were < 40 m deep had the highest levels of contamination compared to wells deeper than 40 m. When *nitrate-distance*, *nitrate-age-distance, nitrate-distance-depth, nitrate–age-distance-depth,* combinations were analyzed, they showed significant difference with *p*-value of 0.000 for all of them as well as the best histogram plot (see Figure 4-7 and Figures A4-22, A4-25, and A4-28 in Appendix D). Regression standardized residual plot for nitrate and distance, showed heteroscedasticity because the dependent variable is not equal across the values of independent variables (Figure 4-8) and the plot of observed cumulative probability and expected cumulative probability show nearly linear patterns, which indicates that the normal distribution is a good model for this data set (Figure 4-9). Since distance is the common variable for all four combinations, it indicates that the proximity of the well to the pit latrine seems to explain the high nitrate levels in water samples. The figures showing histograms and scatter plots for depth and age can be found in Appendix D.

Table 4-3. General Linear Model analysis results from 7 combinations of independent variables of nitrate with four independent variables.

Independent Variable	Adjusted R^2	*p*-value			Variance Inflation Factors (VIF)
		Age	Depth	Distance	
Age	-0.012	0.700			1.000
Depth	0.141		0.001*		1.000
Distance	0.711			0.000*	1.000
Age & Depth	0.154	0.152	0.000*		1.082
Age & Distance	0.707	0.694		0.000*	1.001
Distance & Depth	0.708		0.667	0.000*	1.230
Age, Distance & Depth	0.705	0.579	0.560	0.000*	1.112, 1.265, 1.367

Note: Adjusted R^2 and p-values in bold are significant at 0.05 level and VIF are all less than 3 which shows that distance and depth explains the high nitrate levels.

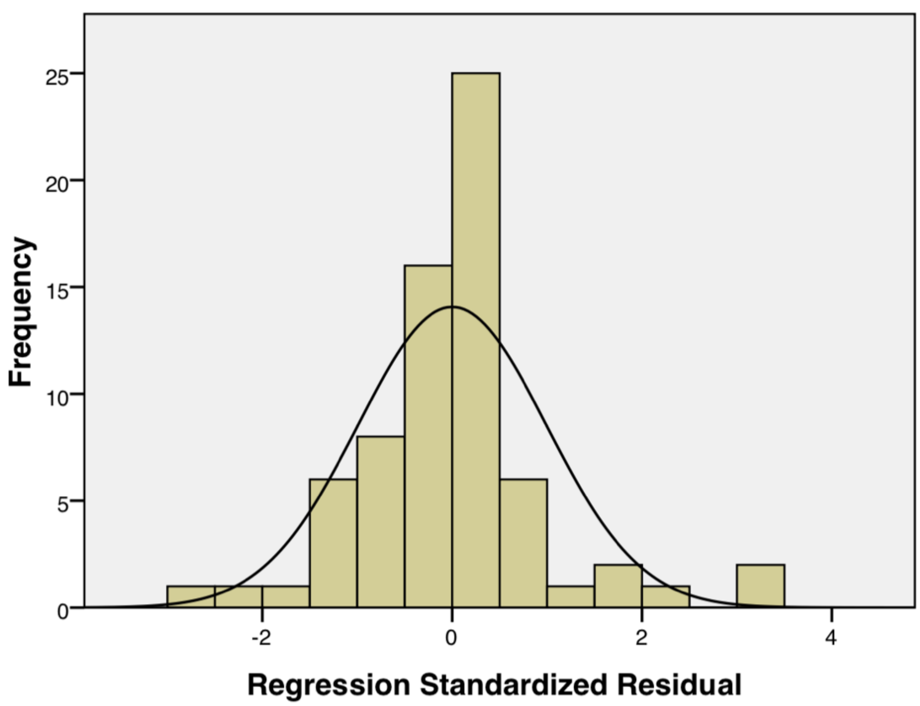

Figure 4-7. Plot of histogram of raw residual for nitrate and distance of well from “pit latrine”

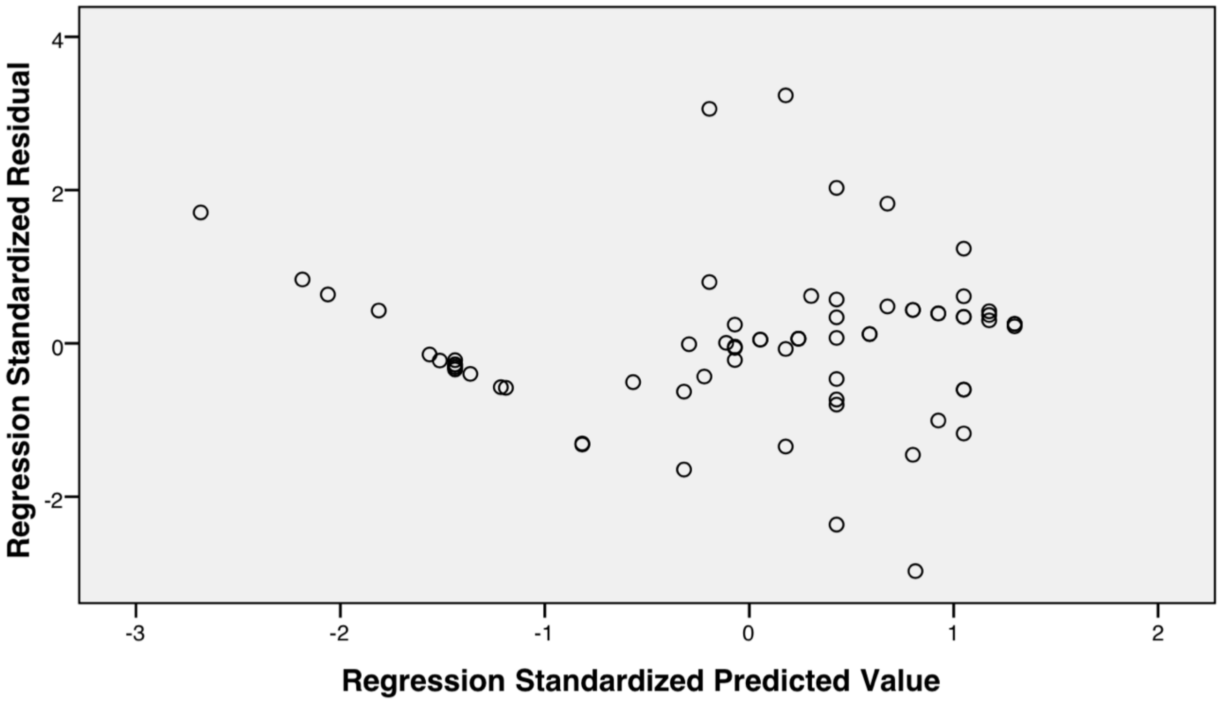

Figure 4-8. Plot of Regression Standardized Residual for nitrate and distance

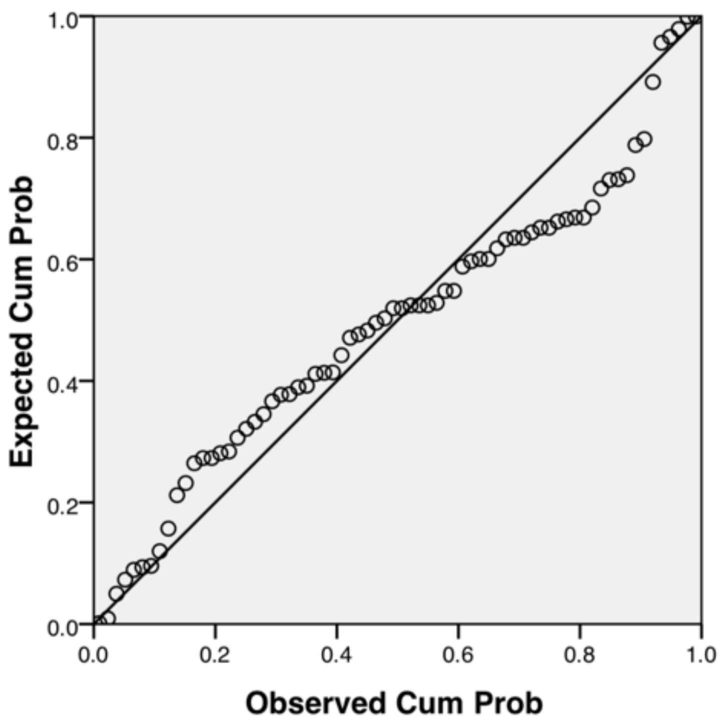

Figure 4-9. Plot of Observed Cumulative Probability and Expected Cumulative Probability for nitrate and distance of well from the “pit latrine”.

Generalized Linear Model

Table 4-4 summarizes the generalized linear model results for all 8 combinations of independent variable tested for *E. coli* and TDS. When the following combination were analyzed: *E. coli-distance*, *E. coli-age-distance, E. coli-distance-depth, E. coli–age-distance-depth*, results indicated a statistically significant correlation between *E. coli* and the independent variables (see Table 4-4 for *p*-values), as well as the best histogram of raw residual residuals (Figures 4-10(a) and A4-37, A4-39 and A4-41 in Appendix D) and regression standardized residuals (Figures 4-10(b) and A4-38, A4-40, and A4-42 in Appendix D). Figures 4-10 (a) shows a histogram of raw residuals for *E. coli* and distance which does not emulate the shape of a normal (bell-curved) distribution. The distribution is slightly multimodal instead of being normal. Figure 4-10(b) is a plot of standardized Pearson residuals for *E. coli* and distance showing dependent variable is equal across the values of independent variables which means there is no heteroscedasticity.

Since distance is the common variable for all four combinations, the proximity of the well to the "pit latrine" best explains the high level of *E. coli* in the water samples. As shown in Table 4-5, TDS results for all seven combination factors did not show the best model fit except for histogram of raw residual and regression standardized residual plots for *TDS-distance* and *TDS-distance-depth* (Figure 4-11(a) and (b) and Figures A4-51 and A4-52 in Appendix D). Figure 4-11 (a) is a plot of histogram of raw residuals for *TDS - distance* which doesn't emulate the shape of a Normal (bell-curved) distribution - it shows a slightly multimodal distribution instead of a normal distribution. Figure 4-11(b) is a plot of standardized Pearson residuals for *TDS-distance* showing no heteroscedasticity because the dependent variable is equal across the values of independent variables. Figures A4-43, A4-45, A4-47, A4-49, A4-53 in Appendix D show the histograms of raw residual and figures A4-44, A4-46, A4-48, A4-50, A4-54 show regression standardized residual for *TDS-age, TDS-depth*, *TDS-age-depth, TDS-age-distance, and TDS-age-depth-distance* respectively.

Table 4-4. Generalized linear model results from 8 combinations of independent variables with *E. coli*.

Independent Variable	Omnibus Test	*p*-value				Akaike's Information Criterion (AIC)
		Intercept	Age	Depth	Distance	
Intercept (null)	-	0.000	-	-	-	-
Age	0.213	-	0.201	-	-	364
Depth	0.661	-	-	0.658	-	366
Distance	0.003*	-	-	-	0.002*	357*
Age & Depth	0.460	-	0.237	0.972	-	366
Age & Distance	0.013*	-	0.809	-	0.007*	359
Distance & Depth	0.012*	-	-	0.579	0.003*	360
Age, Distance & Depth	0.027*	-	0.616	0.484	0.005*	361

Note: Here in, omnibus test values show four independent variables fitted that are significantly different from a null model, p-values are significant at 0.05 level and Akaike's Information Criterion (AIC) scores report the quality of the model fit with distance showing the lowest AIC as the best-fitting model.

Table 4-5. Generalized linear model results from 8 combinations of independent variables with TDS.

Independent Variable	Omnibus Test	*p*-value				Akaike's Information Criterion (AIC)
		Intercept	Age	Depth	Distance	
Intercept (null)	-	0.000	-	-	-	-
Age	0.561	-	0.551	-	-	1093
Depth	0.733	-	-	0.733	-	1094
Distance	0.977	-	-	-	0.977	1094
Age & Depth	0.772	-	0.671	0.516	-	1095
Age & Distance	0.844	-	0.996	N/A	0.551	1095
Distance & Depth	0.931	-	-	0.706	0.872	1095
Age, Distance & Depth	0.899	-	0.493	0.616	0.792	1097

Note: Here in, omnibus test values show four independent variables fitted that are significantly different from a null model, p-values are significant at 0.05 level and Akaike's Information Criterion (AIC) scores report the quality of the model fit with age showing the lowest AIC in bold as the best-fitting model.

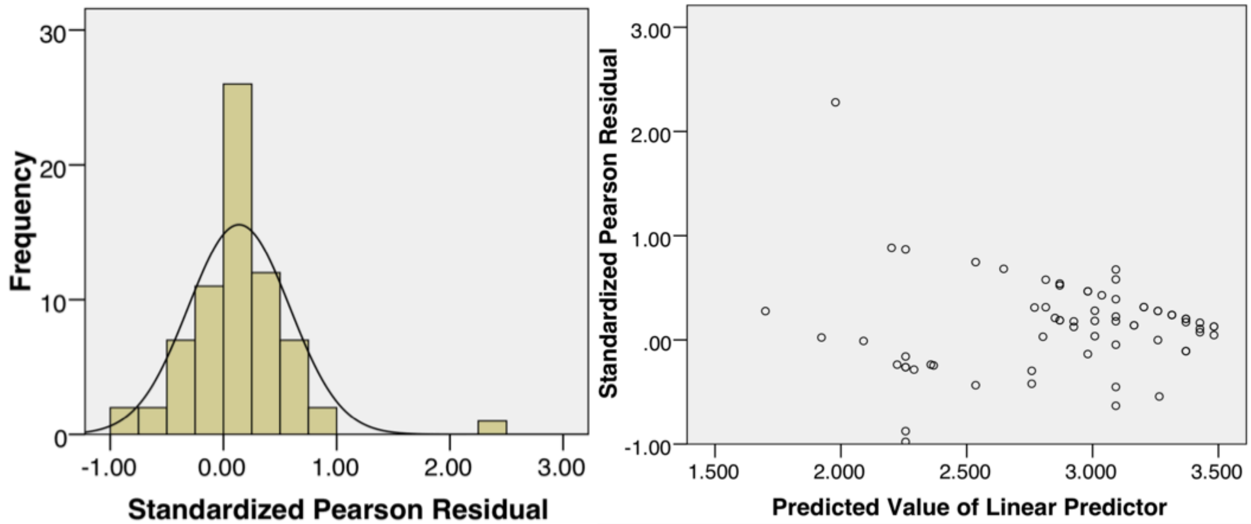

Figure 4-10. (a) Histogram of raw residuals for *E. coli* and distance, (b) plot of standardized Pearson residuals for *E. coli* and distance.

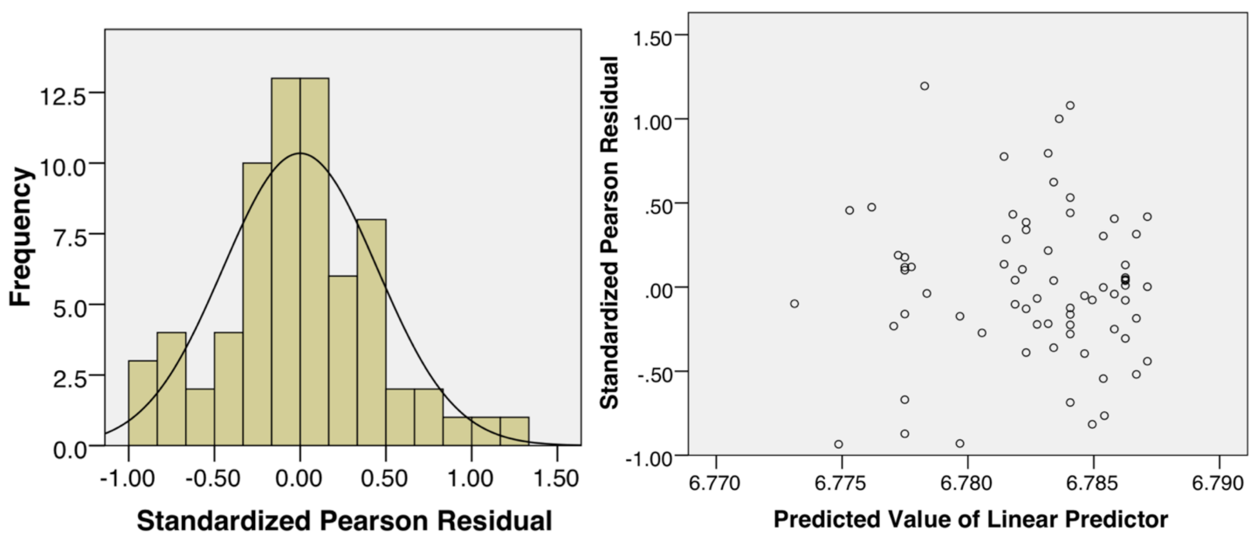

Figure 4-11. (a) Plot of histogram of raw residuals for TDS and distance, (b) Plot of standardized Pearson residuals for TDS and distance.

4.5 Discussion

Bivariate correlations between contaminants partially supported our first hypothesis that there is a common source of nitrate, TDS, and *E. coli* in the wells. Results showed a strong correlation between nitrate and *E. coli* but a very weak correlation between TDS with both nitrate and *E. coli*. Such positive strong correlations between nitrate and *E. coli* suggest that nitrate and

E. coli might originate from the same source. As mentioned in the study area description, our study area is peri-urban and there are no agricultural activities or known waste dumping, therefore, the only source of nitrate and *E. coli* is expected to be from human waste. Residents reported that water from most of these wells has a salty taste, which is not surprising as the average TDS concentration from all 71 wells was 882 mg/L. As the study area is located within 7 km of the Indian Ocean, the source of the TDS could be the result of salt water intrusion rather than from sewage contamination.

Bivariate correlation of distance from the well to the septic tank and well depth with all three contaminants showed a negative correlation for nitrate and *E. coli* but no correlation from TDS, which suggests that TDS levels may not have any relationship with distance, age, or depth. No correlation was found from well age with any of the contaminants, which means, it is likely that there is no relationship between well age and contaminants, however, it is likely that there is a relationship with the existence of the contaminants and the location of the well and the well depth. Nearly 65% of the wells were located less than the recommended safe distance of 15 meters or more (CDC, 2009; US EPA, 2002). Strong correlations for both distance and depth indicate that, the risk of domestic well contamination increases with the decrease of depth and distance.

Univariate MLR analysis supports the second hypothesis by showing linear relationships between contaminants and two well characteristics: distance from a nearest pit latrine and the well depth. Results strongly explain the relationship between water quality and well characteristics because they support the bivariate correlation analysis. Our findings clearly demonstrate how poor sanitation practices contribute to groundwater contamination. Linear regression and generalized linear model analyses indicated that there is a relationship between nitrate and distance as well as *E. coli* and distance from a pit latrine and depth of the well. TDS did not show any relationship with any of the three variables. High nitrate levels and the presence of *E. coli* in domestic water sources indicate the possibility of contamination from nearby septic tanks and pit latrines. Water quality did not appear to be influenced by well age.

More than 90% of the wells sampled in this study operate as public wells by supplying water to the community. Additionally, hydraulic properties such as hydraulic conductivity of the soil, discontinuity of clay aquitard, and depth of groundwater table could affect significantly the levels of contaminants. Islam et al. (2016) made similar conclusions regarding their study in Bangladesh where they conclude that the minimum safe distance of a tube well from a pit latrine is a function of hydrogeological conditions and horizontal and vertical distances of the well from the latrine. Some studies have shown that certain soil types can be used to filter and decontaminate water during seepage. For example, in a study conducted in Maputaland, South Africa, Still and Nash (2002) found that fine sandy soil is an effective filter medium and that pit latrines pose a very small health risk as long as they are at least 20 m from the nearest septic system. In our study area, which is also in a fine to medium sand aquifer, the average distance measured from wells to latrines in is 10 m, with only 15% of wells located greater than 20 meters (Figure 4-6). Additionally, because these wells are used to supply water to the public with pumping times of up to 6 hours per day, it is unlikely that the soil type will effectively act as a filter medium. Our findings are supported by the work of Foppen and Schijven (2006), who demonstrated that even with the soil types that can act as filter media, bacteria can still be detected up to 10 meters from the source. With viruses, these distances can be expected to be even longer due to their smaller size compared to bacteria.

Our findings are similar to a study in Uganda that investigated the impact of the proximity of septic systems to spring wells on water quality. The researchers found that as the distance between spring wells and septic systems increased, a decrease in both coliform counts and nitrate concentration was observed (Elisante & Muzuka, 2016; Arwenyo et al., 2017). Arnade (1999) also found a statistically significant correlation between domestic well contamination and distance from the septic system in a research study she did in Palm Bay, Florida. In Zanzibar, Tanzania, researchers assessed microbial and chemical contamination of domestic wells and found that many of the wells were located near pit latrines, and 95% of sampled wells violated WHO drinking water guidelines (Vuai, 2012).

As shown in Figures A4-4 and A4-5 in Appendix D, the depth of the well is correlated with the level of contamination. The highest levels of contamination were detected in the shallow wells. This is similar to other areas such as rural Zimbabwe where (Dzwairo et al., 2006) found that water quality was impacted in shallow wells that were located up to 25 m from a pit latrine (Dzwairo et al., 2006). Based upon to our field observations, majority of shallow wells were unprotected from contamination by surface runoff. The infiltration of contaminated surface runoff into the well is one way in which shallow wells could become polluted. An example of this is through “flooding out”, which is common method of emptying sewage especially for the above ground pits in unplanned areas of Dar es Salaam. Another method is the flow of contaminated groundwater from under pit latrines to wells (Jenkins et al., 2014). Although pit flooding can be a concern during the rainy season, because our study was conducted during the dry season, it is unlikely that this procedure would have resulted in the contamination of the wells. The most likely cause of contamination is from contaminated groundwater. Well water quality did not appear to be influenced by well age. Because the extent of pollutant travel was likely less in newer wells as compared to older wells, it was anticipated that contamination would be less extensive than in old wells.

4.6 Recommendations

From our findings, we concluded that the contamination of domestic wells in the study area is due to the depth and proximity to septic tanks. The problem is exacerbated because the soil type in the study area is fine to medium sand (Mtoni et al., 2011). The age of the well did not appear to have any impact on the water quality but the depth of the wells impacted the quality of water, especially for shallow wells because most shallow depths are very close to the depth of the pit latrines. Detailed statistical analyses show a clear association between more than one well characteristic and water quality. Based on the findings of our analyses, we offer several recommendations to protect and improve local water quality in the study area as well as in similar low-income countries and communities.

4.6.1 Sanitation

In Tanzania, standards for septic systems or latrine siting are not enforced, especially in urban and peri-urban areas. In slums or unplanned urban areas of Dar es Salaam, where the vast majority of residents are impoverished, it is a challenge to manage sewage due to poor road access and lack of sewerage systems. Septic tanks and pit latrines are poorly constructed, which leads to the contamination of domestic wells. Improved sanitation is desperately needed.

One potential improvement is the use of Container Based Sanitation (CBS), where toilets collect human excreta in sealable, removable containers (also called cartridges). These containers can then be collected and transported to a treatment system. An empty container is delivered to the latrine at the same time. CBS could help to minimize drinking water contamination in slums or unplanned urban areas where it is a challenge to manage sewage due to poor road access. CBS has several advantages including: it can be used in water-scarce areas since it requires a low amount of water, is hygienically safe with proper handling, and is affordable (World Bank, 2019). As discussed previously, many of the pit latrines in the study area are unlined and lack soakaway pits. Improved construction of latrines would greatly improve public health. Proper training of local masons in the construction of raised, lined, and ventilated improved pit latrines is also recommended.

Sanitation could also be improved the through the development and enforcement of standards to the siting of latrines. This is especially true in peri-urban areas across sub-Saharan Africa. Results from our study and other similar studies (e.g., Graham & Polizzotto, 2013) show that site specific distances for the separation of domestic wells from pit latrines are necessary due to variations in hydrogeological conditions. Therefore, these standards for safe distance should be specific based on the depth of the proposed wells, the type of sanitation system, and the pumping rate and frequency of the wells.

Where latrines operate at greater than their design capacity, additional latrines should be constructed. However, in peri-urban areas where latrines and drinking water wells are already in close proximity, this poses significant challenges. However, as Ravenscroft et al. (2017) noted, fears of increased groundwater pollution should not constrain expanding latrine coverage. On the other hand, it is imperative that pit latrines are constructed properly and at a sufficient depth and distance from wells to minimize contamination.

4.6.2 Water Supply

One of the most significant improvements to public health in the developed world has been well-operated public water supplies. The construction and operation of public water supplies will discourage the use of contaminated water from domestic wells for drinking water. However, the water must be affordable and accessible. The Tanzanian and city governments should invest in improving the water distribution system to meet the demand of the population of Dar es Salaam, eliminating illegal connections into the water distribution system, and charging those who tap illegally into the supply.

Until the water distribution system can be improved, water vendors and local residents will continue to supply the needs of the community. As such, it is imperative that methods be developed to improve service to residents. This could be accomplished through regular and random (unannounced) testing of both well water and vendor-provided water. The testing results need to be available to residents in an accessible and understandable format. Water quality apps or sensors for early warning of contamination, monitoring, and the operation of water supply systems, along with general notifications to the public could provide residents with critical information (Aisopou et al., 2012). The local and national governments could develop a certification system for vendors and local suppliers whose water meets all WHO guidelines.

Educational programs about sanitation and public health should be developed and available to residents and public health officials. This could include simple and affordable methods for testing and treating water to ensure that it meets the basic criteria for consumption. Where well water from domestic wells is not fit for human consumption, residents could be taught about its other uses, such as for toilet flushing, irrigation of forage crops, and domestic cleaning. Wash stations could be constructed at schools and children can be taught about the importance of proper handwashing. Capacity building for public health workers is also essential. As discussed in detail by Heller et al. (2007), this could include educational initiatives that are based on open resources available online. Educational efforts should include regular community members, local independent providers and water vendors, etc. As Ivey et al. (2006) noted, in developed countries, community participation and advocacy, along with public education, can results in the protection of water sources and improved public health.

4.6.3 Water Resources Management

Although much needs to be done in many low-income countries, learning about the proper management of water resources from developed countries can be highly beneficial (Wang & Yu, 2014). Stricter laws and governmental regulations that are enforced are critical to the proper management of water sources. In developed countries such as the United States, laws and regulations for managing and protecting water sources have resulted in significant improvements in air and water quality (Smail et al., 2012). Proper management of water sources require interdisciplinary approaches that can easily be available through involving people from different backgrounds including water users themselves, institutions, and even stakeholders in order to help identify problems and help solve different water issues.

Our study focused on a few key predictors, but we acknowledge that other factors may have impacted contamination, such as the size of the well opening, means of collecting water such as using buckets, seasonal variations in rainfall patterns, and spatially variable soil and aquifer material characteristics. Future work should focus on detailed groundwater modelling in the area to further understand and quantify the links between pit latrines, sanitation practices and groundwater contamination in a changing climate. Additionally, given the frequency of pit latrine use in our study area, future studies should focus on additional contaminants beyond standard indicators, monitor temporal changes in water quality parameters, climate change, and evaluate alternative technologies.

4.7 Acknowledgements

We are grateful to the Environmental Science and Policy Program at Michigan State University (ESPP-MSU) and the Miriam J. Kelley African Scholarship Grant Program at Michigan State University for financial support. Special thanks to the MSU Centre for Statistical Training and Consulting (CSTAT) for their assistance with our statistical analyses.

APPENDICES

Appendix A: Sanitation Facilities in Dar-es-Salaam

A typical septic system has two section chambers, the first tank is designed to allow the decomposition of organic matter in the sewage. The tank is usually sealed to prevent seepage of contaminants into the ground; the second tank is a soakaway pit, from which septic tank effluent is allowed to seep into the ground. The average depth of many septic tanks is 1.2 m (EPA, 2000). There are two types of pit latrines that are commonly used; traditional (unventilated) pit latrines and ventilated improved pit latrine (VIP). The recommended typical pit latrine for better sanitation practices is VIP. The average size of the pit is 1.3 m x 1.3 m x 2.5 m (L x W x D) with a PVC vent pipe to prevent odors and flyscreen to prevent flies and other disease-carrying insects from entering (Ryan & Mara, 1983; Mara, 1984). The pit is usually lined with cement mortar to prevent collapsing and seepage in groundwater. The unventilated pit latrines are usually single-pit that must be desludged every 3 - 10 years but too often left unlined and unprotected from collapsing or constructed with openings in it for infiltration to purposely allow seepage (Mara, 1984). The lack of ventilation results in odors and the proliferation of flies and other insects in the latrine.

Appendix B: Hydrogeology and Domestic Wells

The Dar es Salaam City consists of mainly two aquifers: an upper unconfined sand aquifer and a lower semi-confined sand aquifer that are separated by a clay aquitard of between 10 and 50 m (Mtoni et al., 2012). The unconfined aquifer consists of fine to medium sand that contains varying amounts of silt and clay and it extends down to the second clay layer towards the Indian Ocean (Mjemah et al., 2009). The lower semi-confined aquifer overlies the clay-bound sands and gravels with a thickness of several hundred meters (>740 m in borehole at Kimbiji) and the kaolinitic Pugu Sandstone (Mjema et al., 2009; Mjemah, 2007). Some of the boreholes are drilled into semi unconfined aquifer but not through its maximum thickness. The majority of the city overlays a sand aquifer and clay aquitard (Mjemah et. al., 2009). The main supply of groundwater in Dar es Salaam is from sand aquifers and it is referred to as the main producing zone.

Groundwater has been used as a source of water supply for the Dar-es- Salaam City since 1943 (Mjemah et. al., 2009). According to Baumann et. al. (2005), about 1000 boreholes (shallow and deep wells) are drilled every year. In Dar es Salaam, deep wells are usually drilled by the Drilling and Dam Construction Agency (DDCA) or by hiring a private geological survey contractor. Common drilling equipment used are either power augers or rotary drills with steel or plastic (PVC) casings depending on the type of soil in the area. Water from deep wells is usually extracted using installed submersible pump and stored in either underground or aboveground storage tanks. Water quality testing is performed right after drilling process is completed for chemical and microbiological contaminants. Shallow wells are usually hand dug by using simple tools, such as picks and short shovels or using augers. Water from shallow wells is collected by using a bucket, by a manually operated hand pump, or using jet pumps. There are three main types of shallow wells, those that are 1) protected with lids, 2) unprotected without lids, and 3) protected with installed handpump (Martínez-Santos et al., 2017). It is not common to perform water quality testing in shallow wells to avoid cost because they are usually dug by well owners themselves.

Appendix C: Methodology for Sampling and Analysis

Our water sampling techniques followed the U.S. EPA interactive sampling guide for drinking water system operators. Samples were collected by hand directly from the well tap from deep wells, and at the sampling depth of 6-12 inches below the water surface from shallow wells. Samples tested for nitrate were preserved with H_2SO_4 to a pH. < 2 and cooled to 4°C at the time of collection. All samples were stored in the water cooler during transit to the laboratory and they were analyzed for TDS and nitrate in the lab within 24 hours and *E. coli* within 2 hours receipt at the laboratory. The nitrate concentration was determined by U. S. EPA Method 353.2 via automated colorimetry (US EPA, 2012). The TDS concentrations were quantified using Method 8163, the Gravimetric Method (Total Filterable Solids), which is adapted from Standard Methods for the Examination of Water and Wastewater, Part 2540C (Hach, 2017). *E. coli* concentrations were assessed by membrane filtration using modified membrane-thermotolerant *Escherichia coli* Agar (Modified mTEC Method 1603) (EPA, 2009). Water testing and analysis was done at the Muhimbili University of Health and Allied Sciences (MUHAS) microbiology laboratory located 3-5 miles from the study area.

Appendix D: Statistical Analysis

Bivariate Correlations

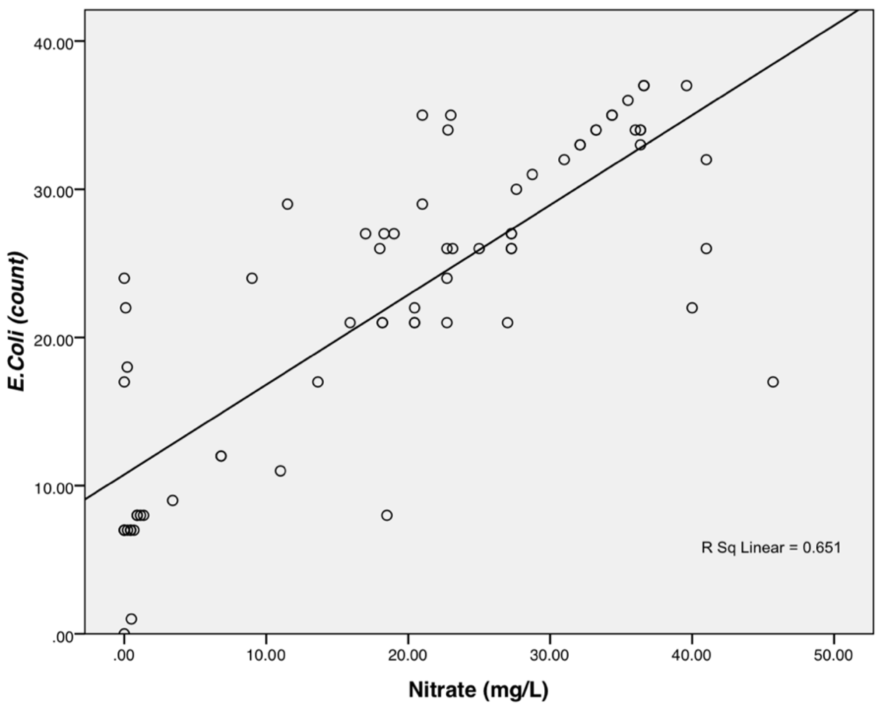

Figure A4-1. Pearson's r correlation between nitrate concentration and *E. coli* count

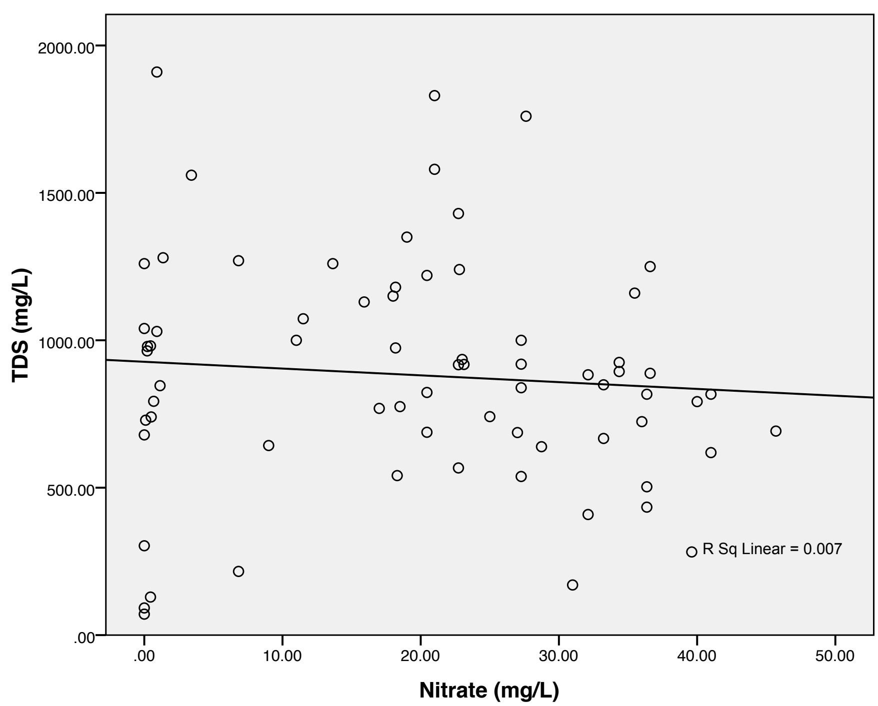

Figure A4-2. Pearson's r correlation between nitrate and TDS concentration

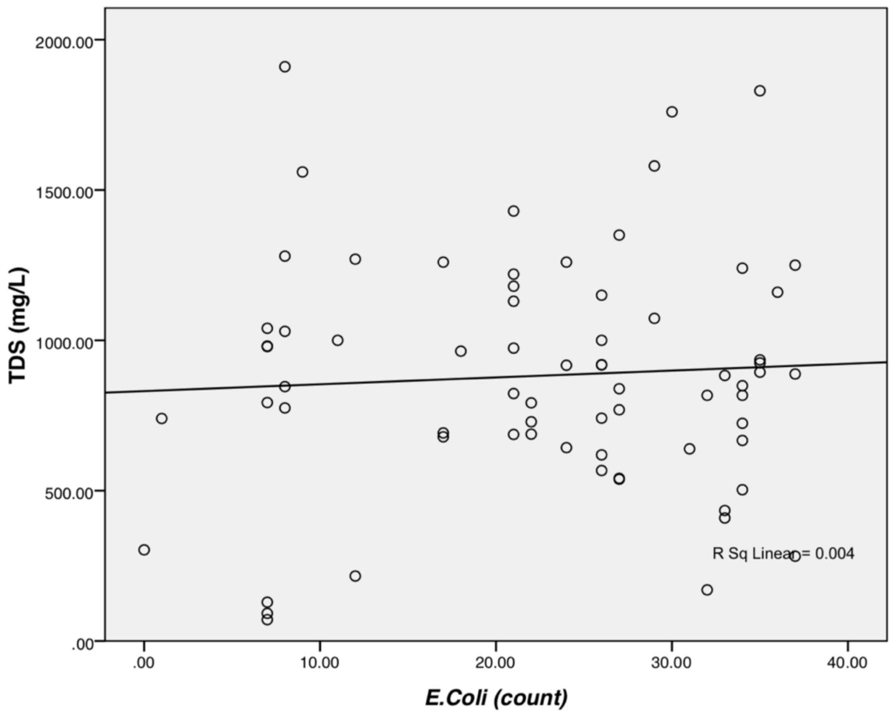

Figure A4-3. Pearson's *r* correlation between TDS concentration and *E. coli* count

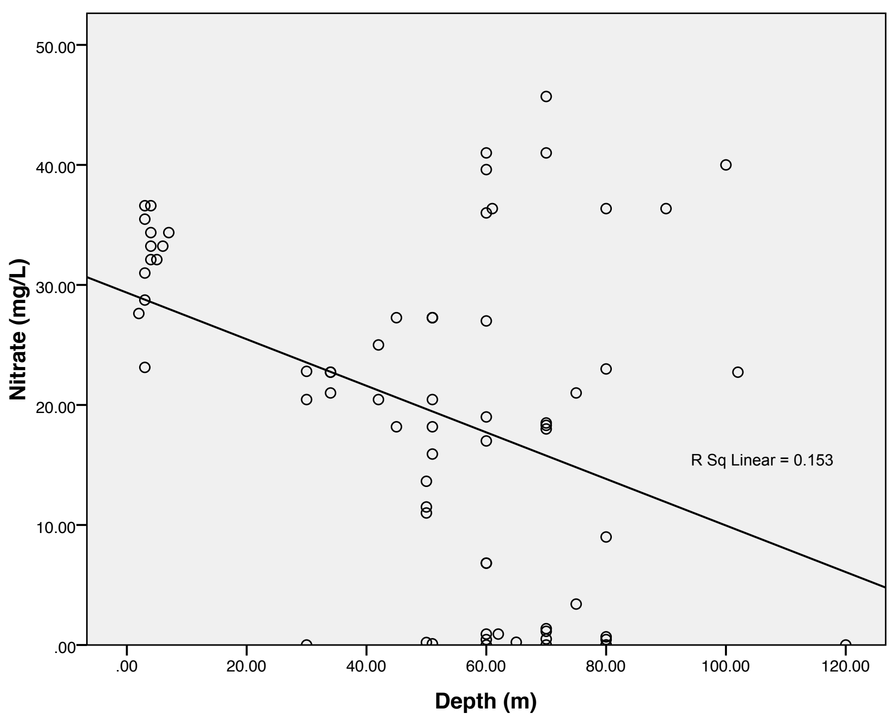

Figure A4-4. Pearson's *r* correlation between nitrate concentration and depth of the well

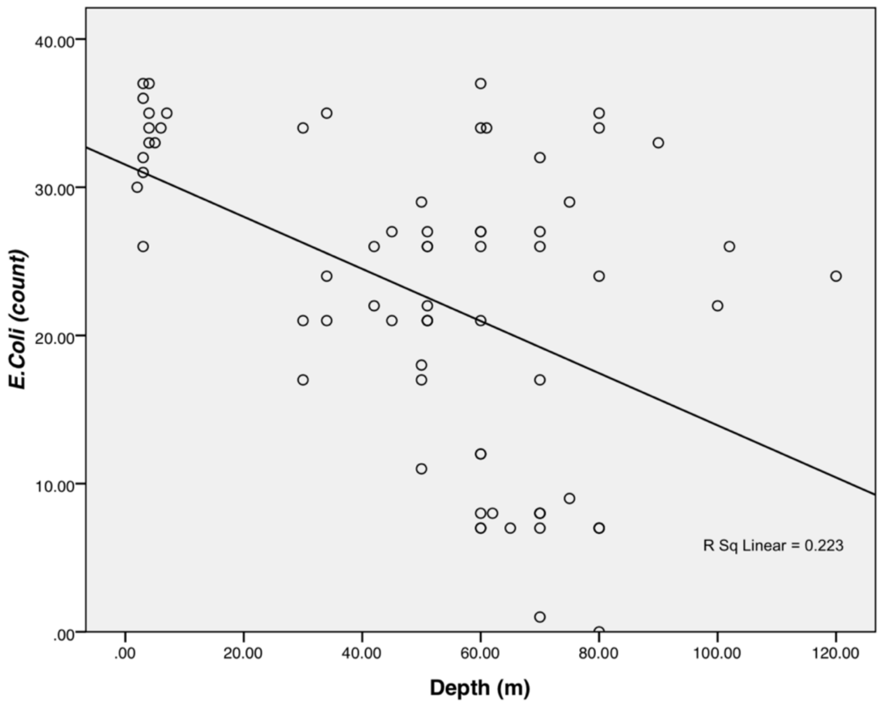

Figure A4-5. Pearson's *r* correlation between *E. coli* count and depth of the well

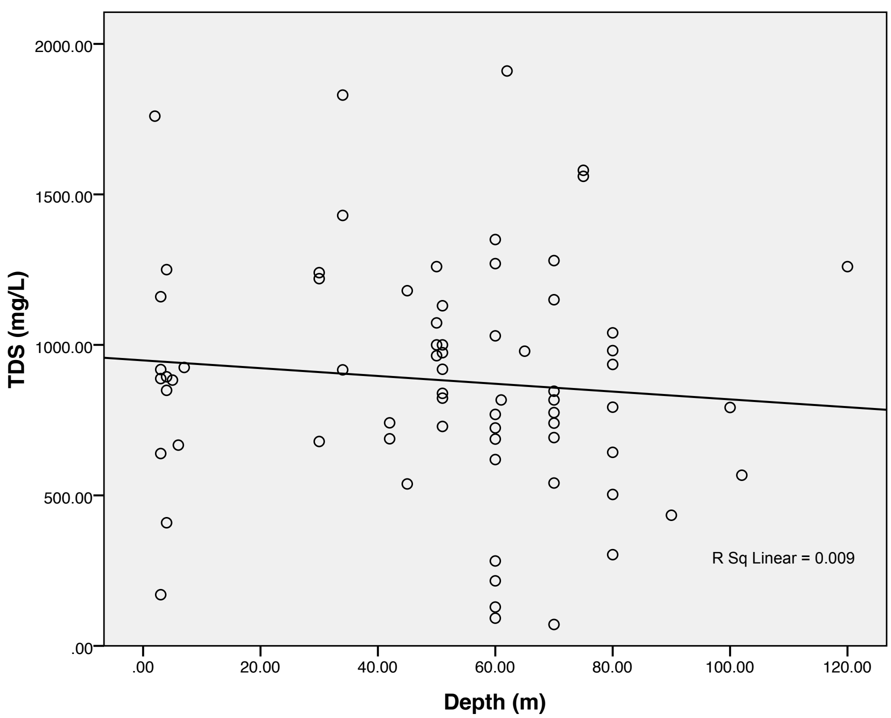

Figure A4-6. Pearson's *r* correlation between TDS concentration and depth of the well

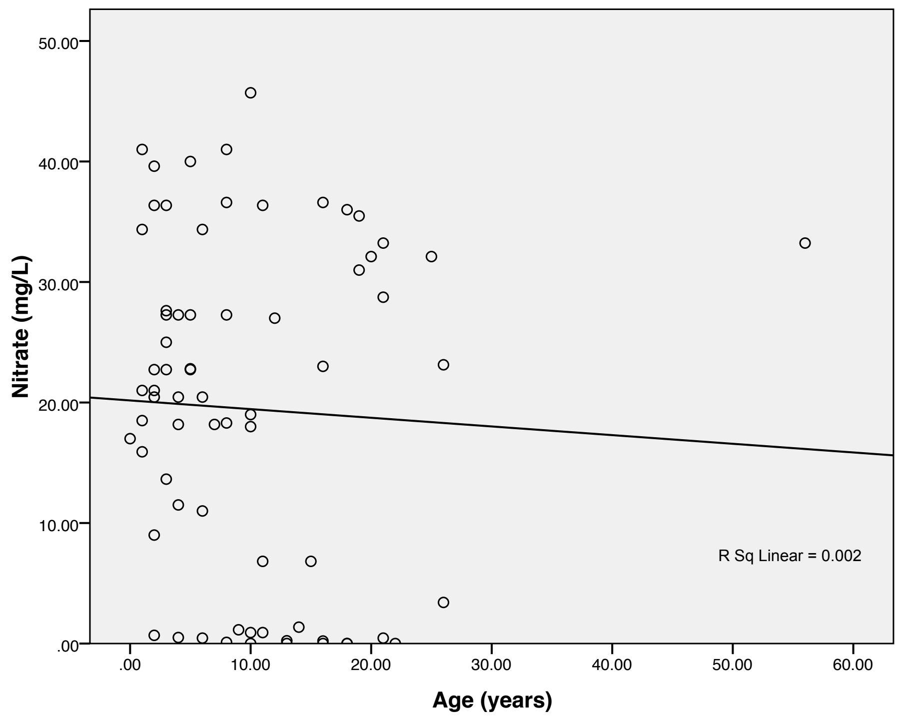

Figure A4-7. Pearson's *r* correlation between nitrate concentration and age of the well

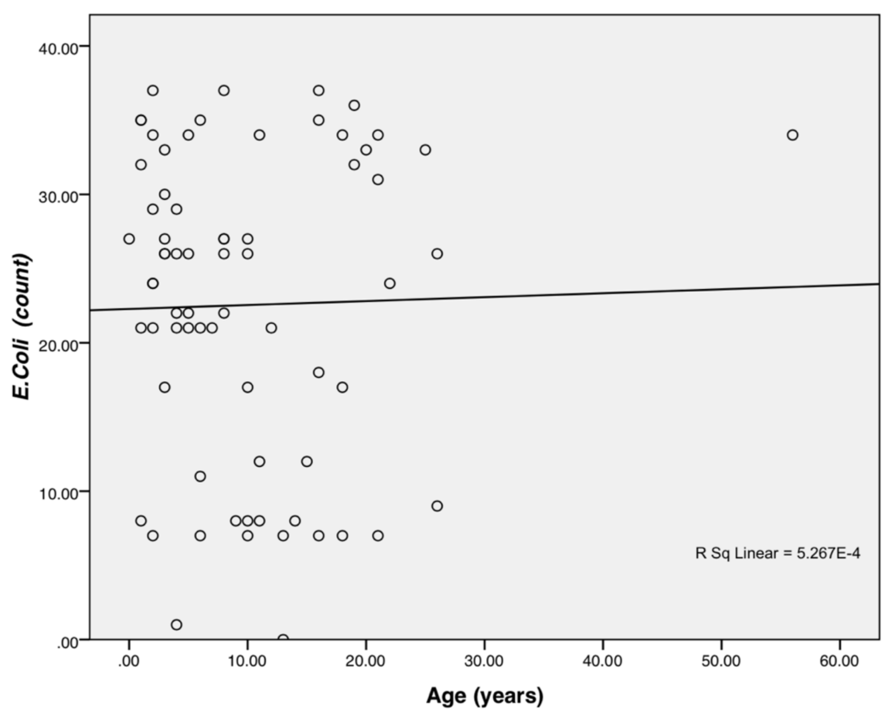

Figure A4-8. Pearson's *r* correlation between *E. coli* and age of the well

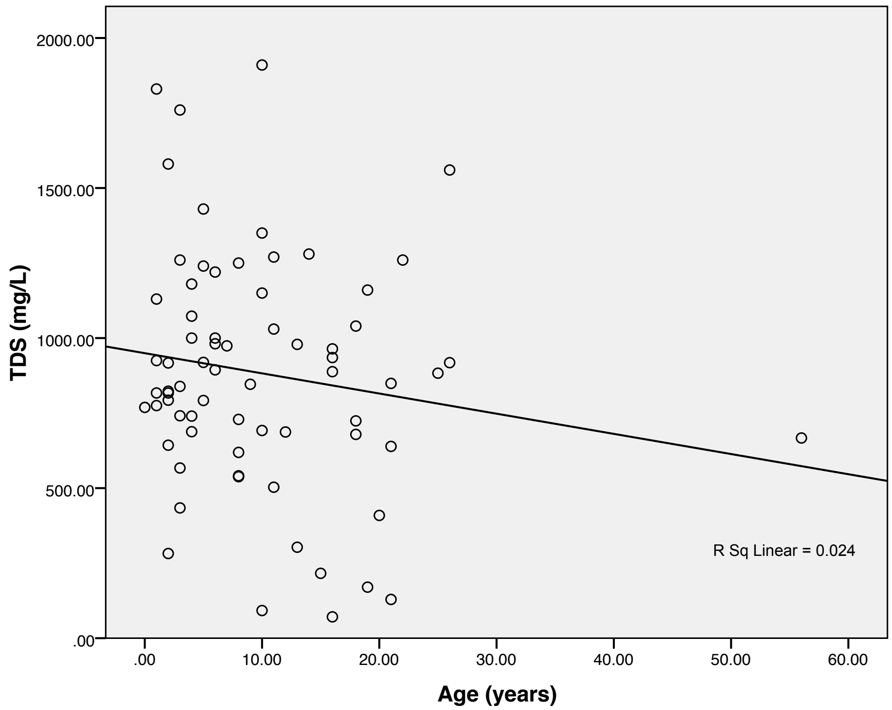

Figure A4-9. Pearson's *r* correlation between TDS concentration and age of the well

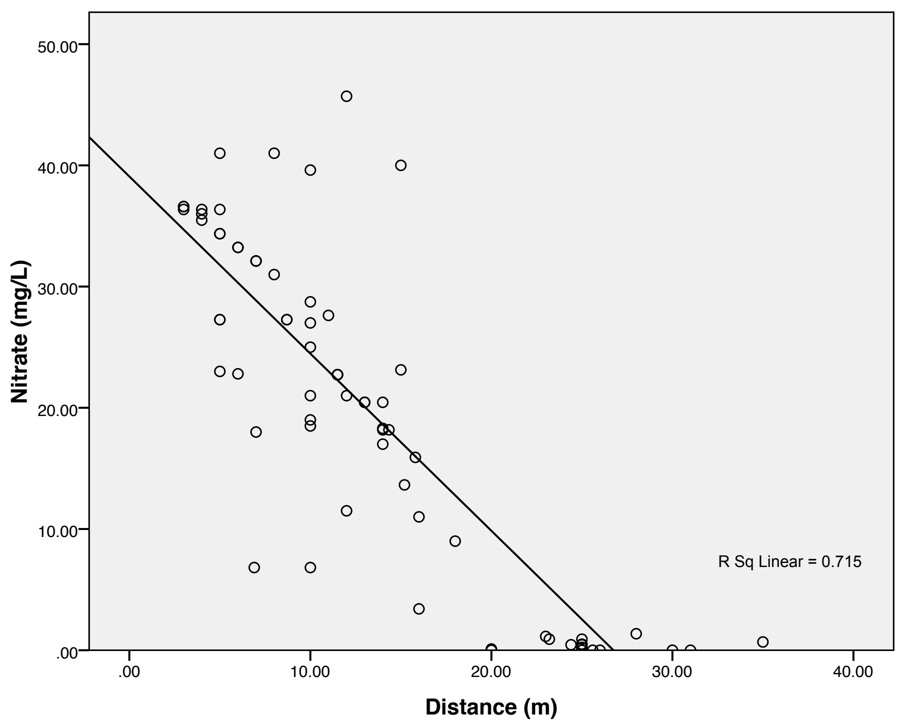

Figure A4-10. Pearson's r correlation between nitrate concentrations with distance from a domestic well to its nearest "pit latrine"

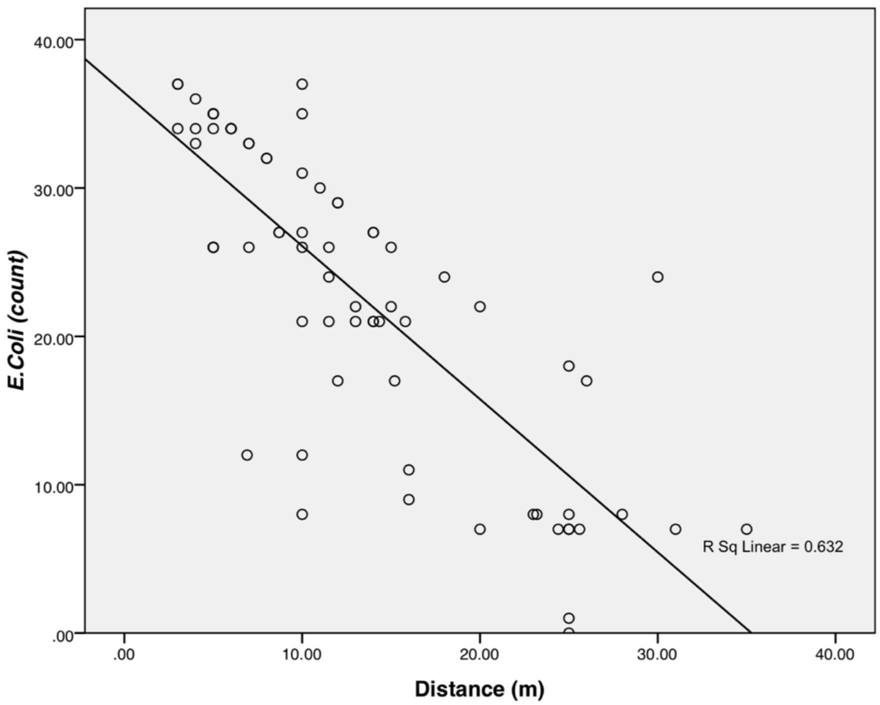

Figure A4-11. Pearson's r correlation between *E. coli* with distance from a domestic well to its nearest "pit latrine"

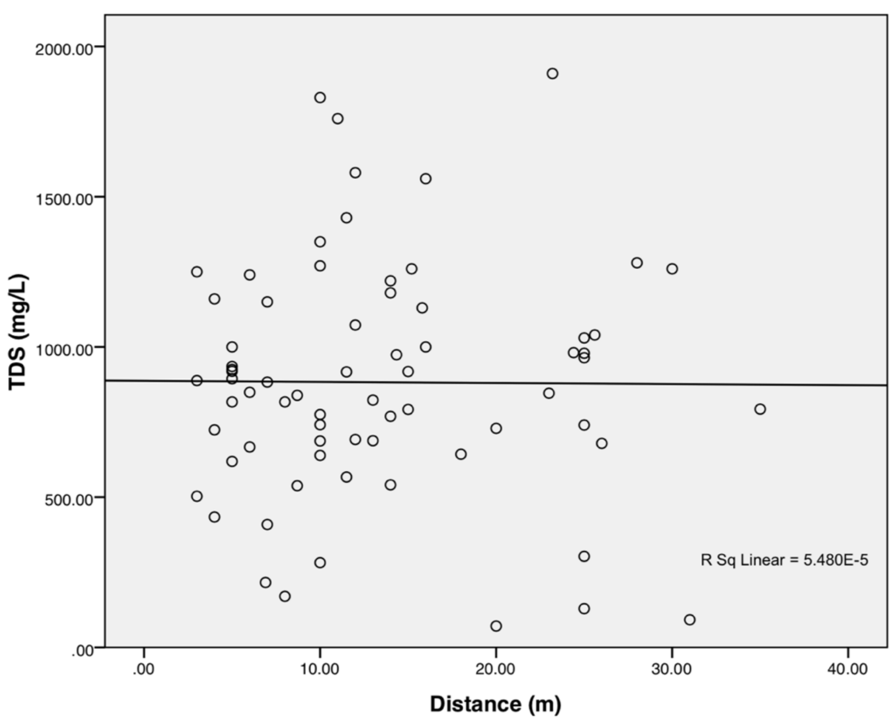

Figure A4-12. Pearson's r correlation between TDS concentrations with distance from a domestic well to its nearest "pit latrine"

Univariate Multiple Linear Regressions

Table A4-1. General Linear Model analysis results from 7 combinations of independent variables of nitrate that describe the graphs for *nitrate*

Independent Variable	Histogram of Raw Residuals	Standardized Pearson Residuals × Model Predicted Values	Raw Residual Sample × Theoretical-Quantiles
Intercept (null)			
Age	Poor	Poor	Fair
Depth	Poor	Poor	Good*
Distance	Good*	Poor	Fair
Age & Depth	Fair	Fair	Good*
Age & Distance	Good*	Poor	Fair
Distance & Depth	Good*	Poor	Fair
Age, Distance & Depth	Good*	Poor	Fair

Table A4-2. General Linear Model analysis results from 7 combinations of independent variables of nitrate that describe the graphs for *E. coli*

Independent Variable	Histogram of Raw Residuals	Standardized Pearson Residuals × Model Predicted Values
Intercept (null)		
Age		Poor
Depth	Poor	Good*
Distance	Poor	Good*
Age & Depth	Good*	Poor
Age & Distance	Good*	Poor
Distance & Depth	Good*	Fair
Age, Distance & Depth	Good*	Poor

Table A4-3. General Linear Model analysis results from 7 combinations of independent variables of nitrate that describe the graphs for Total Dissolved Solids (TDS)

Independent Variable	Histogram of Raw Residuals	Standardized Pearson Residuals × Model Predicted Values
Intercept (null)		
Age	Fair	Poor
Depth	Good*	Good*
Distance	Good*	Good*
Age & Depth	Good*	Poor
Age & Distance	Good*	Poor
Distance & Depth	Good*	Good*
Age, Distance & Depth	Good*	Poor

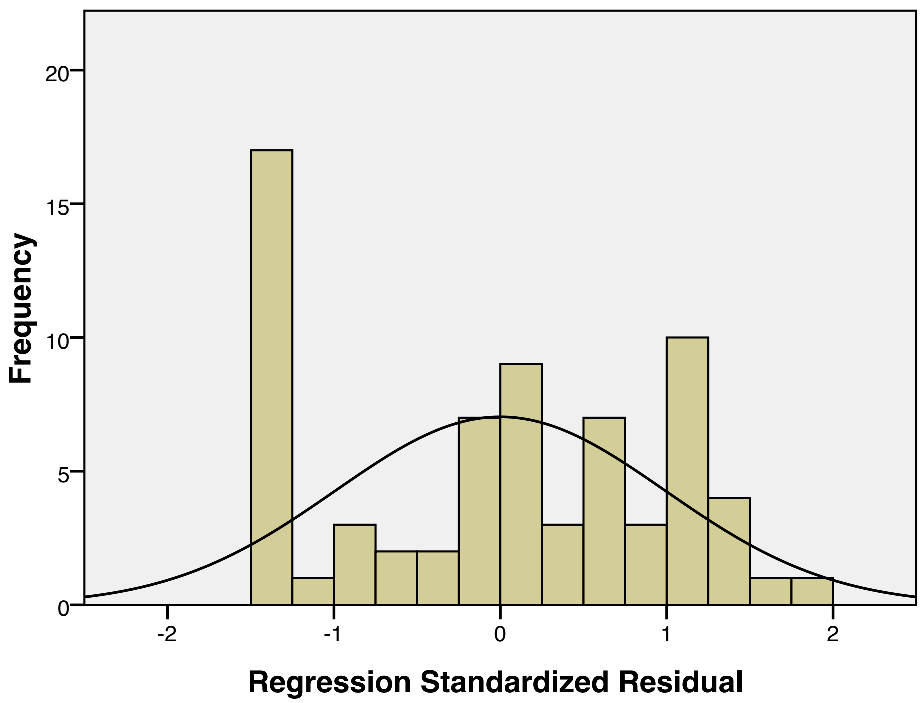

Figure A4-13. Plot of histogram of raw residual for *nitrate and age*, herein, the figure does not emulate the shape of a Normal (bell-curved) distribution

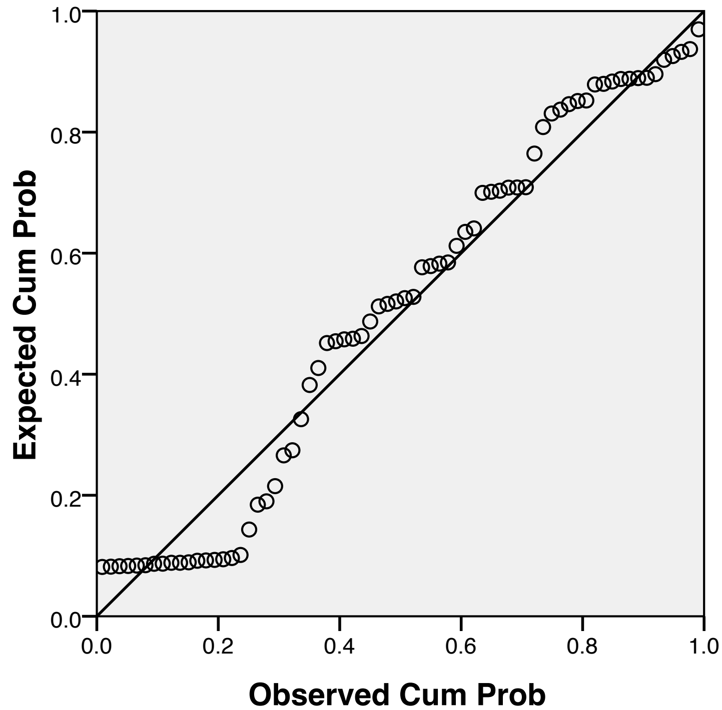

Figure A4-14. Plot of Observed Cumulative Probability and Expected Cumulative Probability for *nitrate and age*, the points here partly form linear pattern, which indicates normal distribution is a poor model for this data set

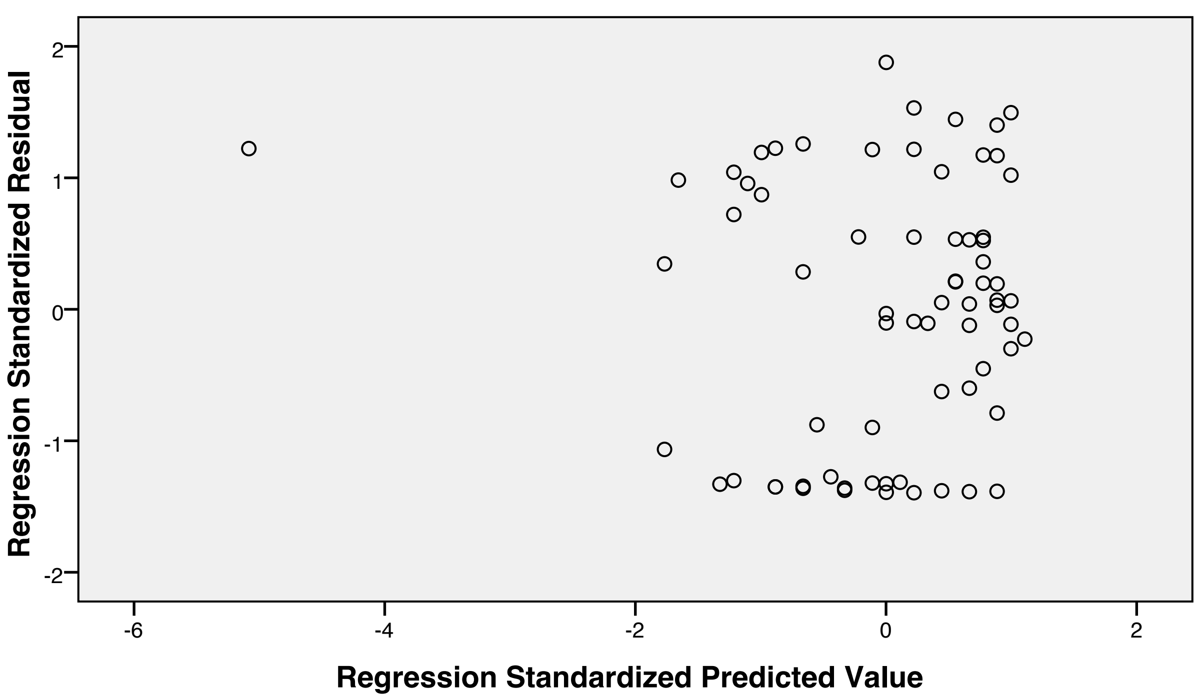

Figure A4-15. Plot of Regression Standardized Residual for *nitrate and age* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

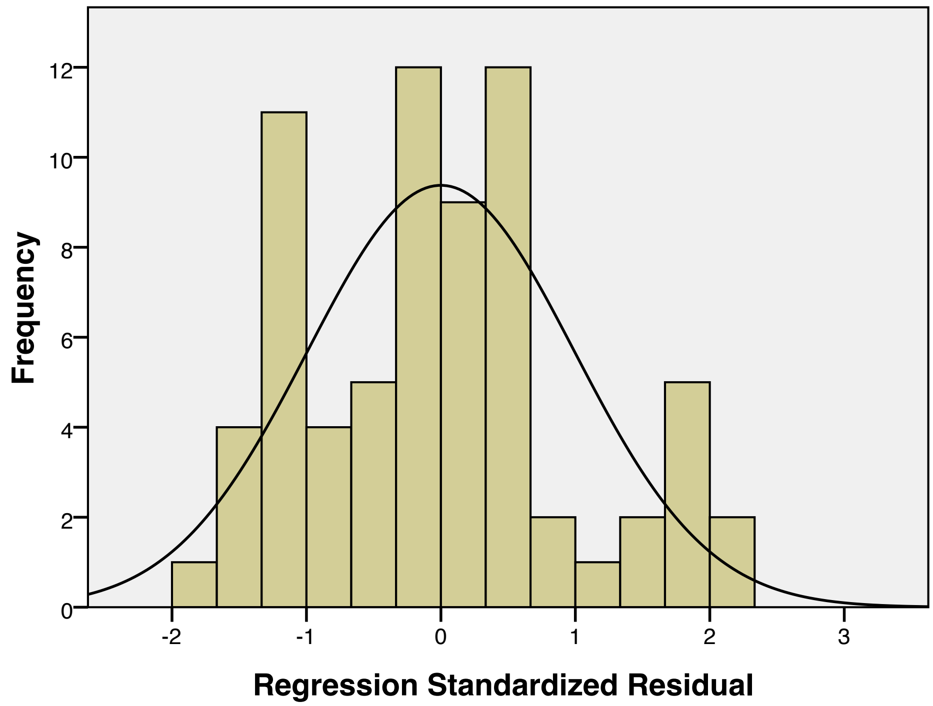

Figure A4-16. Plot of histogram of raw residual for *nitrate and depth*, herein, the figure does not emulate the shape of a Normal (bell-curved) distribution

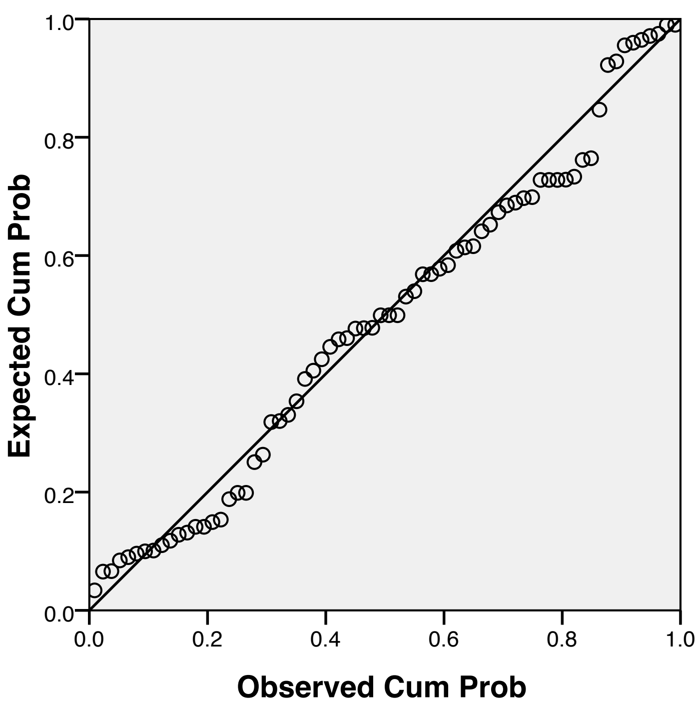

Figure A4-17. Plot of Observed Cumulative Probability and Expected Cumulative Probability for *nitrate and depth*, the points here form linear pattern, which indicates normal distribution is a good model for this data set

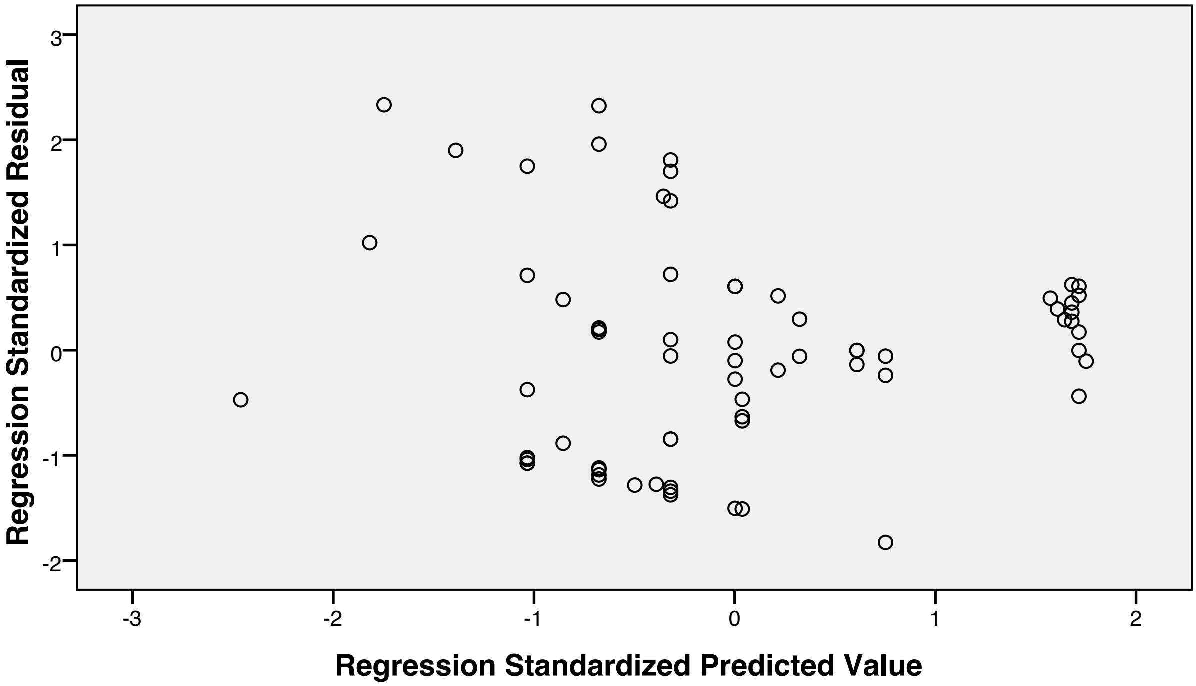

Figure A4-18. Plot of Regression Standardized Residual for nitrate and depth which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

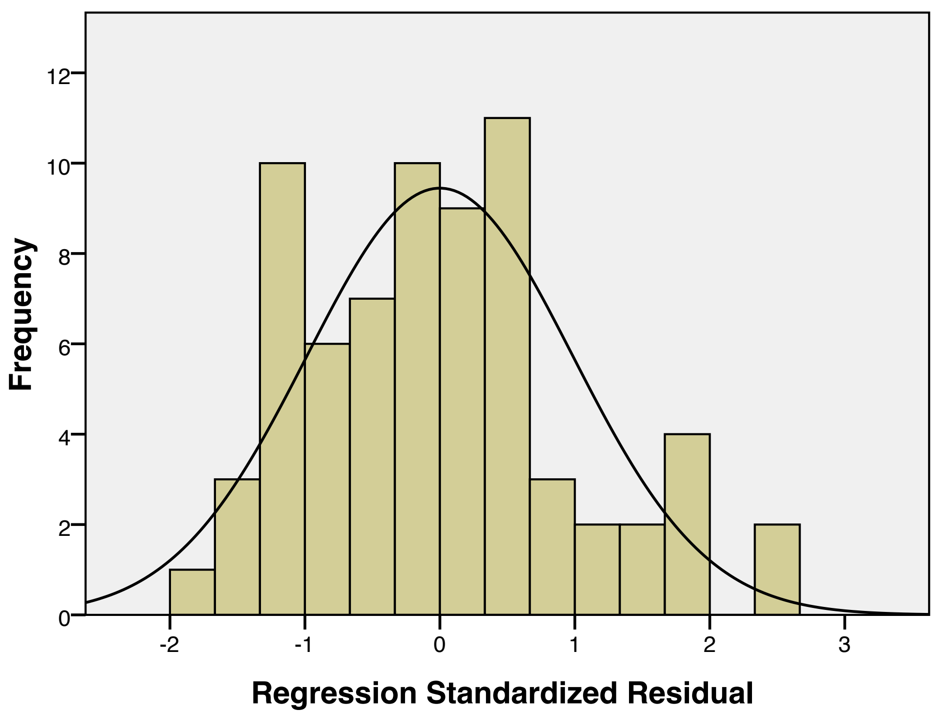

Figure A4-19. Plot of histogram of raw residual for *nitrate with age and depth*, herein, the figure somehow emulates the shape of a Normal (bell-curved) distribution

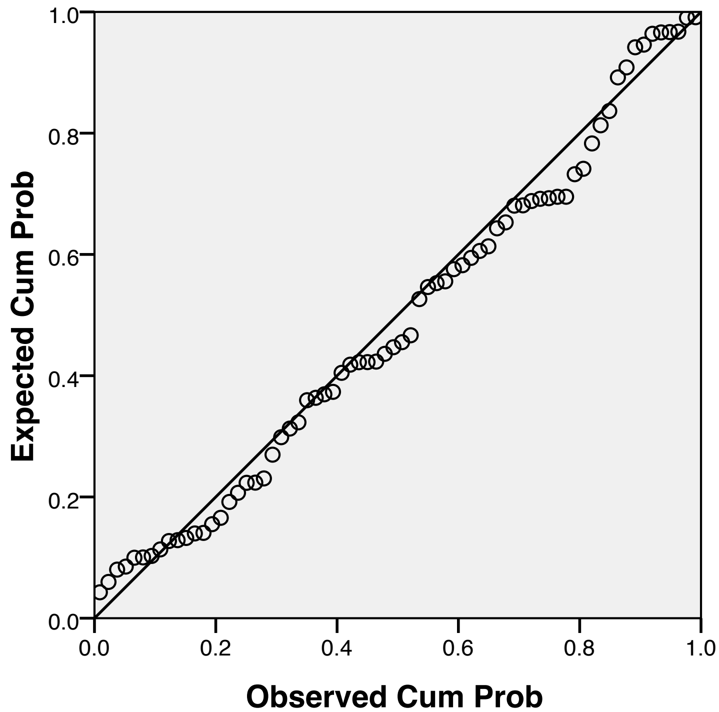

Figure A4-20. Plot of Observed Cumulative Probability and Expected Cumulative Probability for *nitrate with age and depth*, the points here form linear pattern, which indicates normal distribution is a good model for this data set

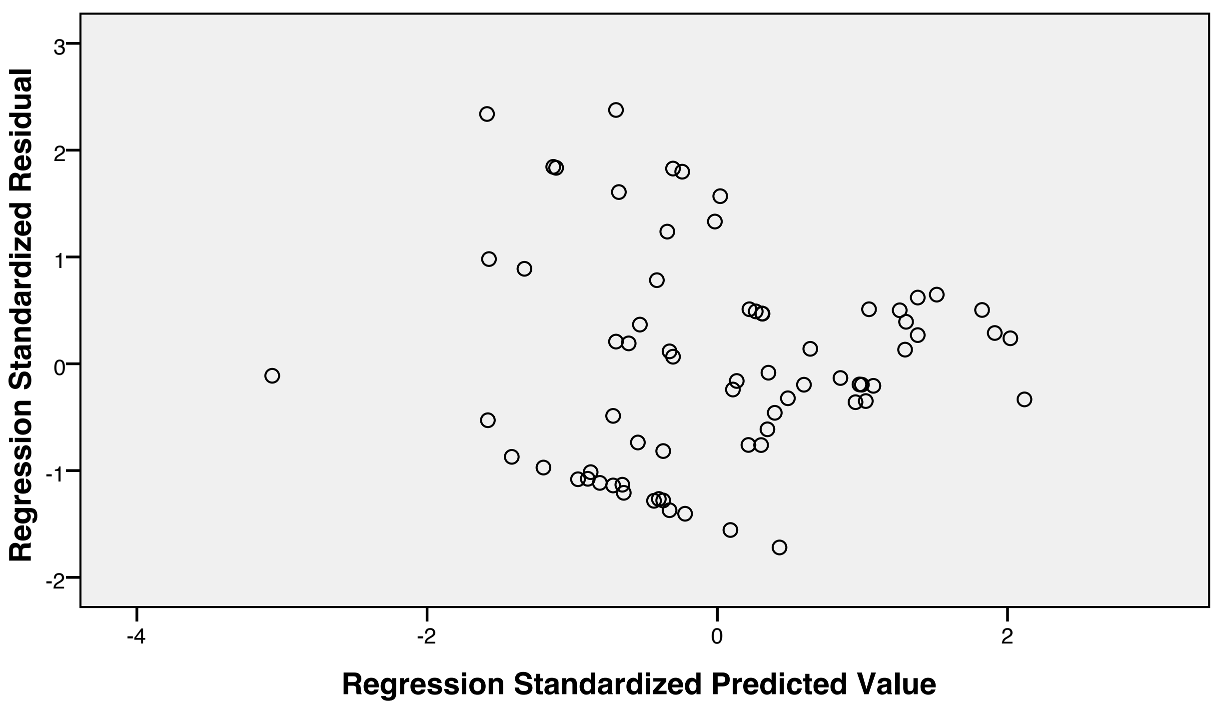

Figure A4-21. Plot of Regression Standardized Residual for *nitrate with age and depth* which shows no heteroscedasticity because dependent variable is equal across the values of independent variables

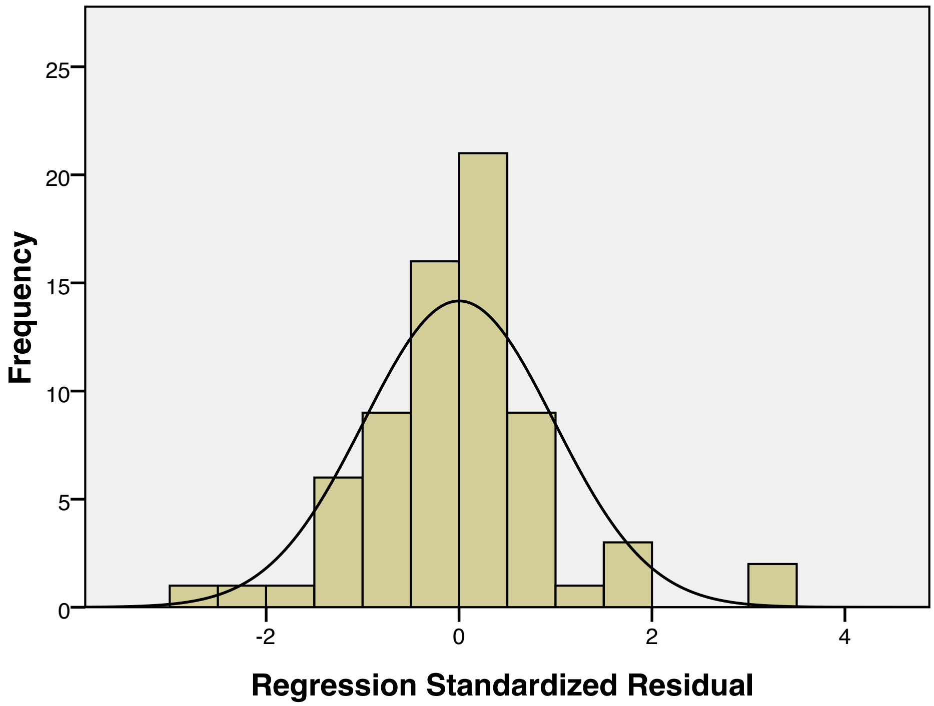

Figure A4-22. Plot of histogram of raw residual for nitrate with age and distance, herein, the figure emulates the shape of a Normal (bell-curved) distribution

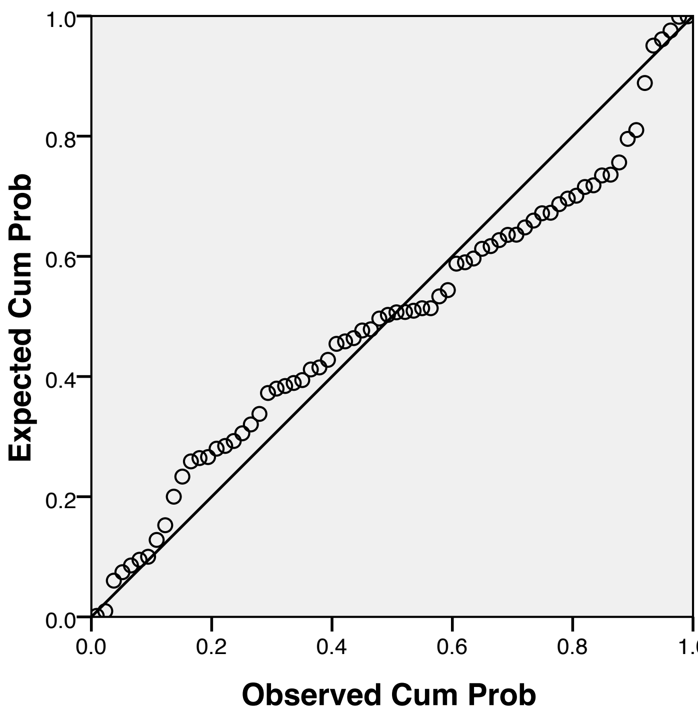

Figure A4-23. Plot of Observed Cumulative Probability and Expected Cumulative Probability for *nitrate with age and distance*, the points here partly form linear pattern, which indicates normal distribution is a fair model for this data set

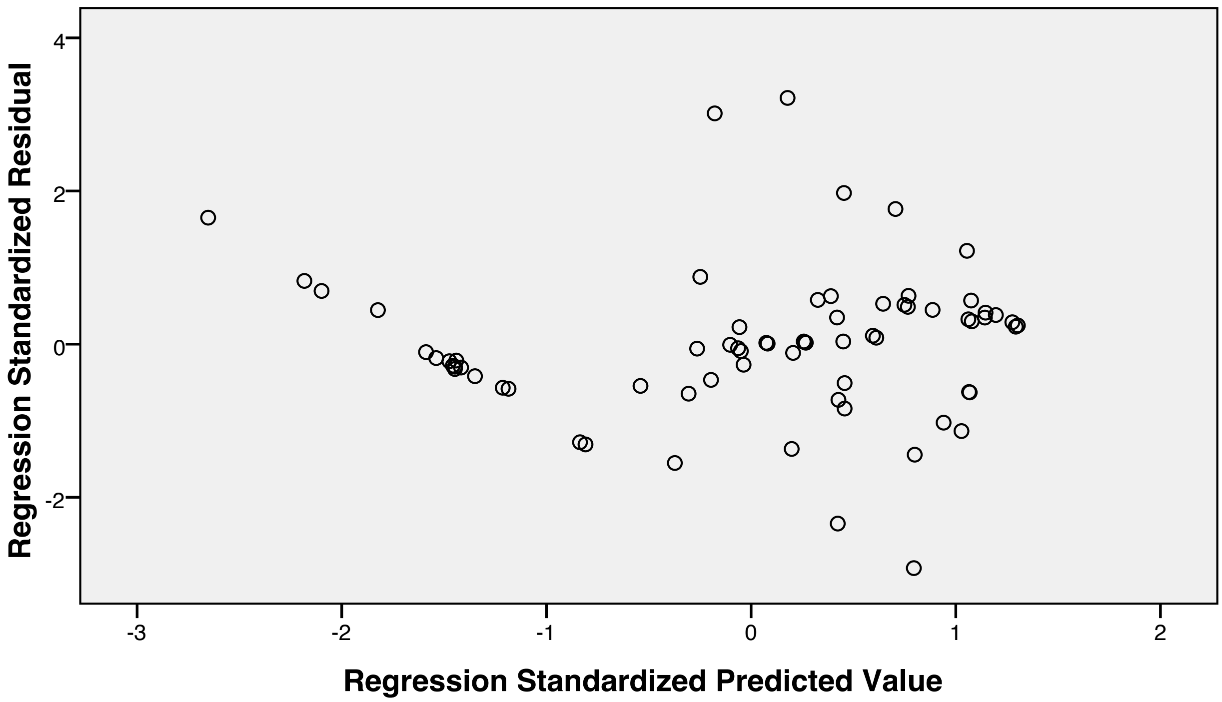

Figure A4-24. Plot of Regression Standardized Residual for *nitrate with age and distance* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

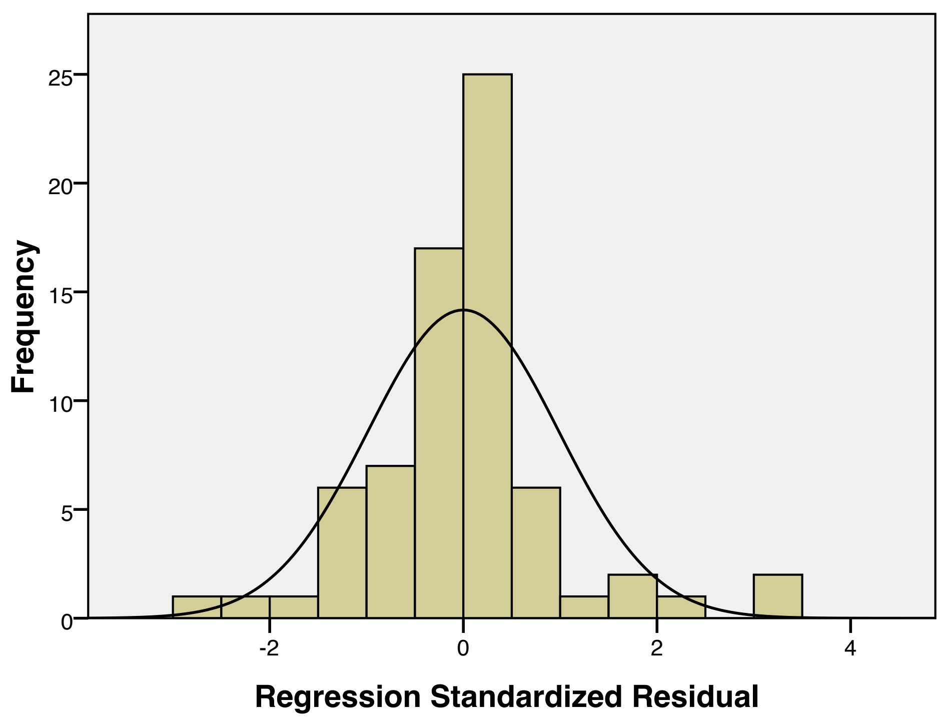

Figure A4-25. Plot of histogram of raw residual for *nitrate with distance and depth*, herein, the figure emulates the shape of a Normal (bell-curved) distribution

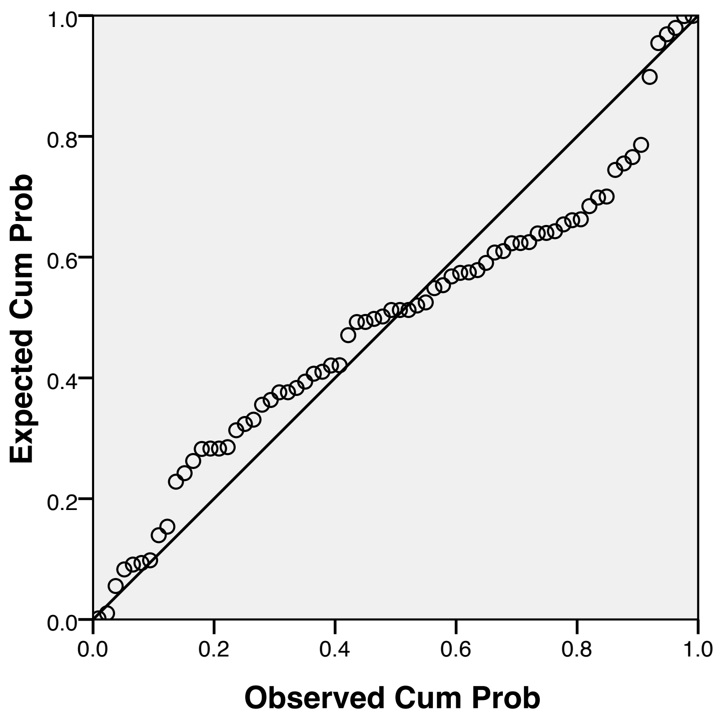

Figure A4-26. Plot of Observed Cumulative Probability and Expected Cumulative Probability for *nitrate with distance and depth*, the points here partly form linear pattern, which indicates poor normal distribution is a fair model for this data set

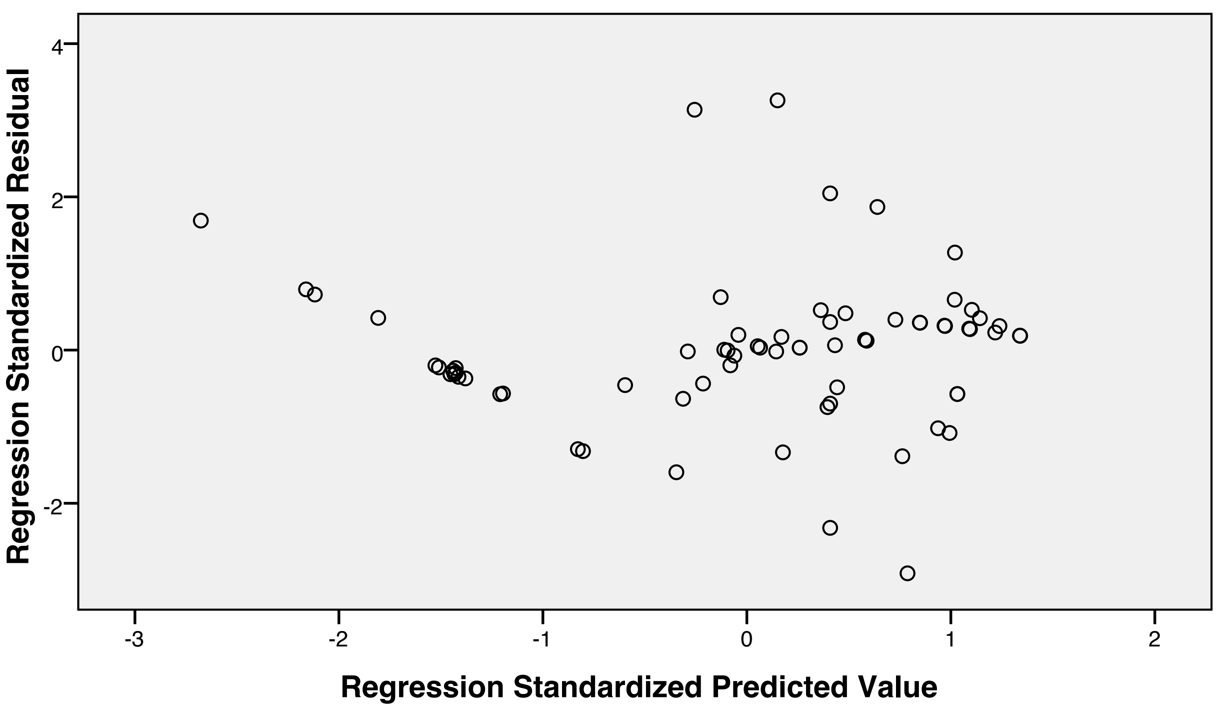

Figure A4-27. Plot of Regression Standardized Residual for *nitrate with distance and depth* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

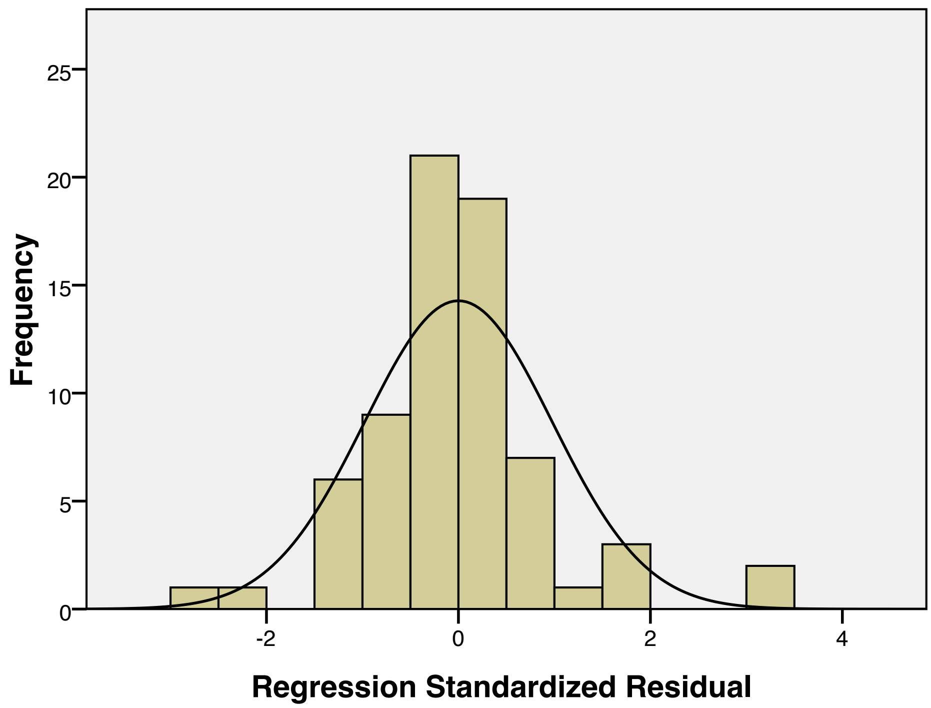

Figure A4-28. Plot of histogram of raw residual for *nitrate with distance, depth and age*, herein, the figure emulates the shape of a Normal (bell-curved) distribution

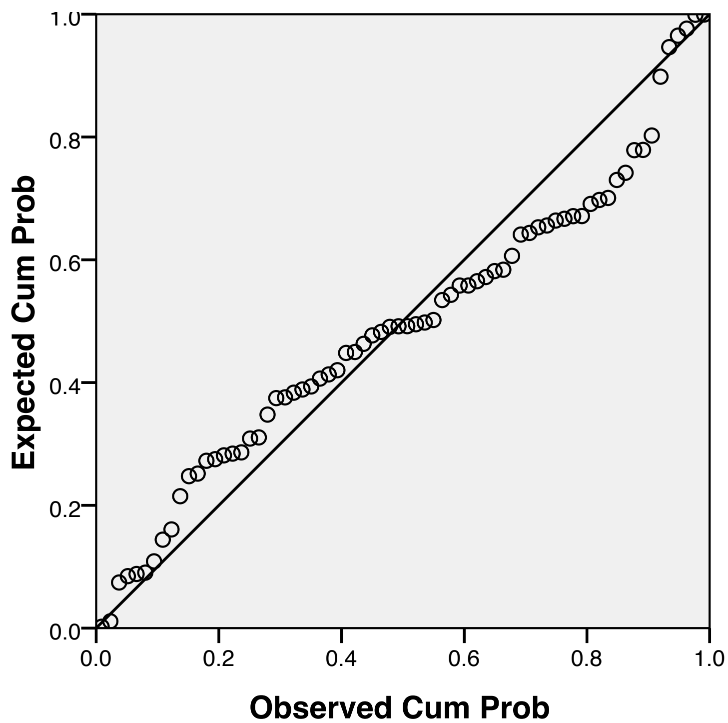

Figure A4-29. Plot of Observed Cumulative Probability and Expected Cumulative Probability for *nitrate with distance, depth and age* the points here partly form linear pattern, which indicates poor normal distribution is a fair model for this data set

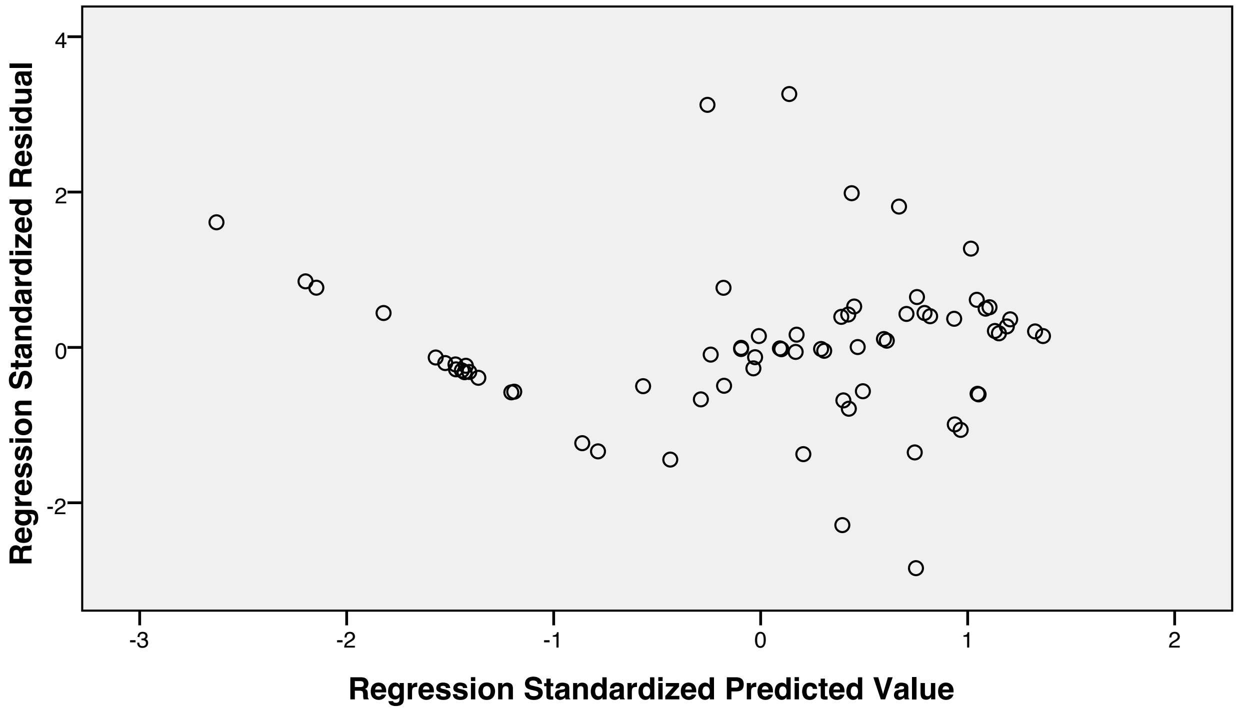

Figure A4-30. Plot of Regression Standardized Residual for *nitrate with distance, depth and age* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

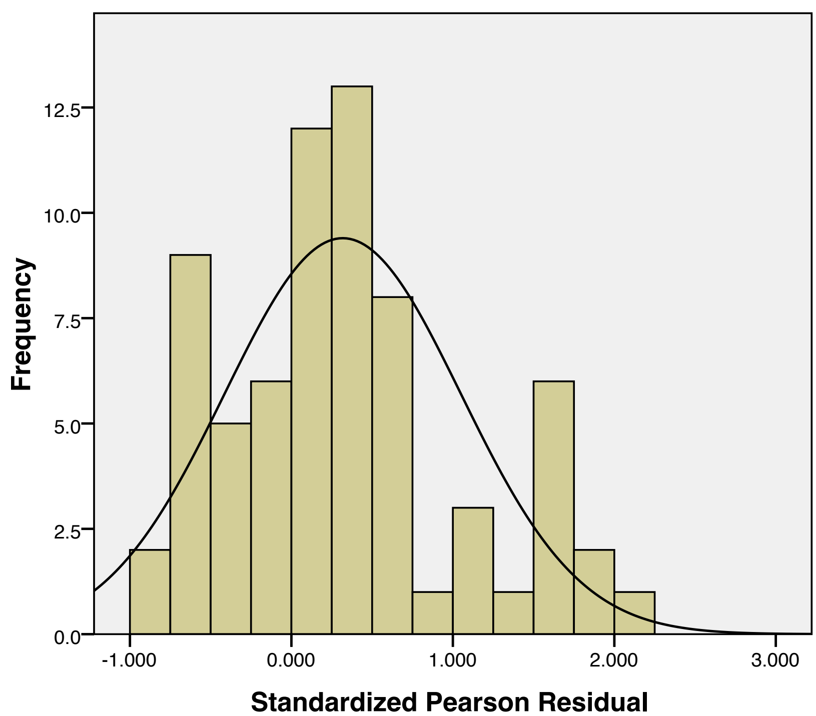

Figure A4-31. Plot of histogram of raw residual for *E. coli and age*, herein, the figure doesn't emulate the shape of a Normal (bell-curved) distribution

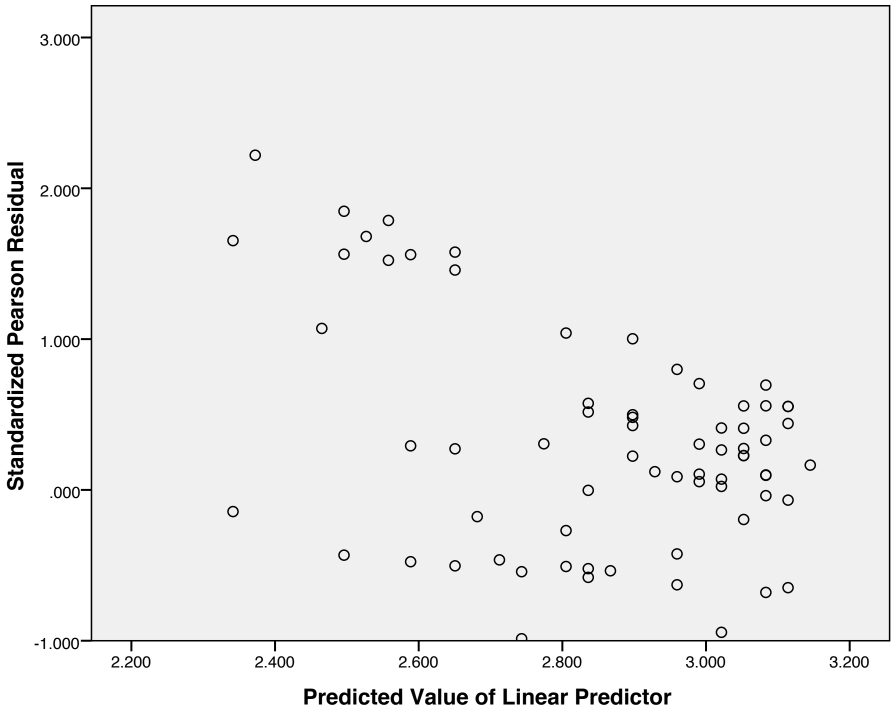

Figure A4-32. Plot of Regression Standardized Residual for *E. coli and age* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

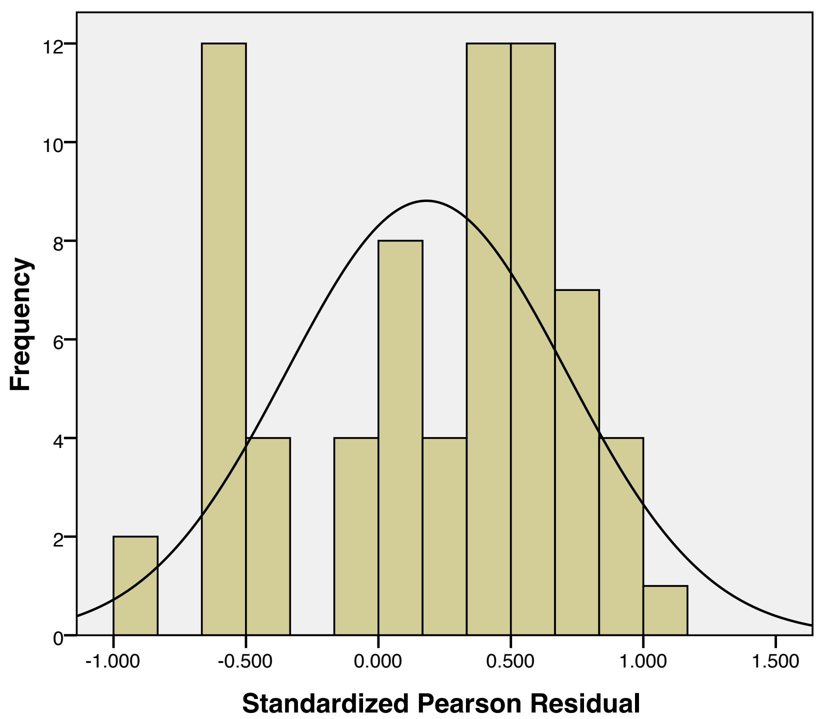

Figure A4-33. Plot of histogram of raw residuals for *E. coli and depth* which doesn't emulate the shape of a Normal (bell-curved) distribution, it shows slight multimodal instead of normal distribution

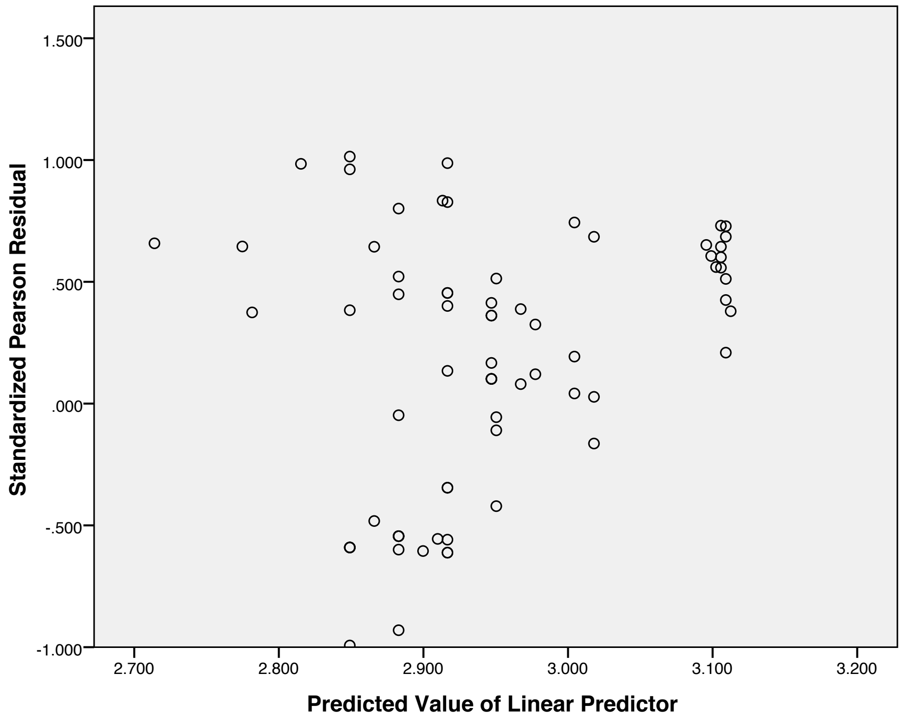

Figure A4-34. Plot of Regression Standardized Residual for *E. coli and depth* which shows no heteroscedasticity because dependent variable is equal across the values of independent variables

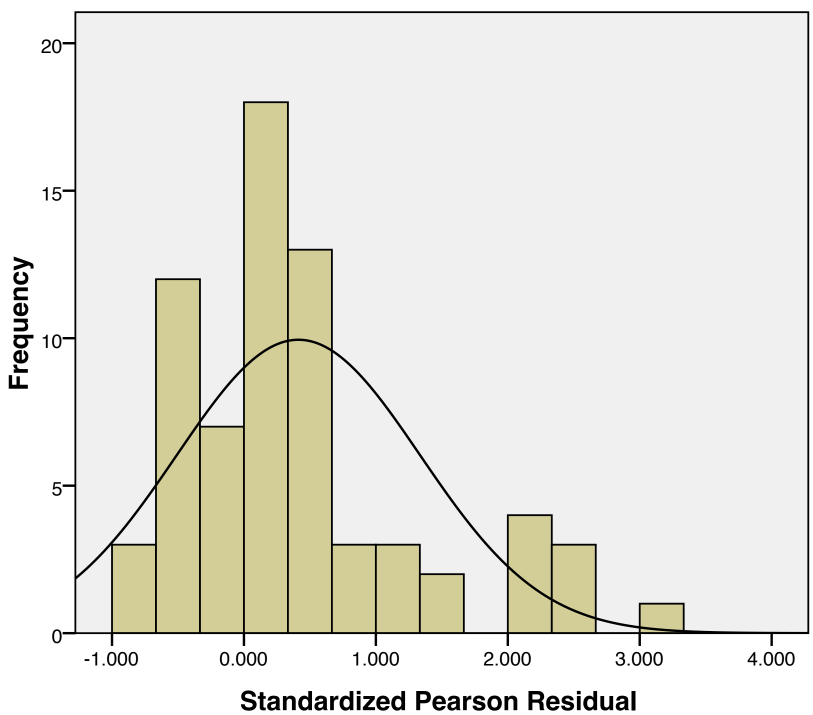

Figure A4-35. Plot of histogram of raw residuals for *E. coli with age and depth* which doesn't emulate the shape of a Normal (bell-curved) distribution, it shows slight multimodal instead of normal distribution

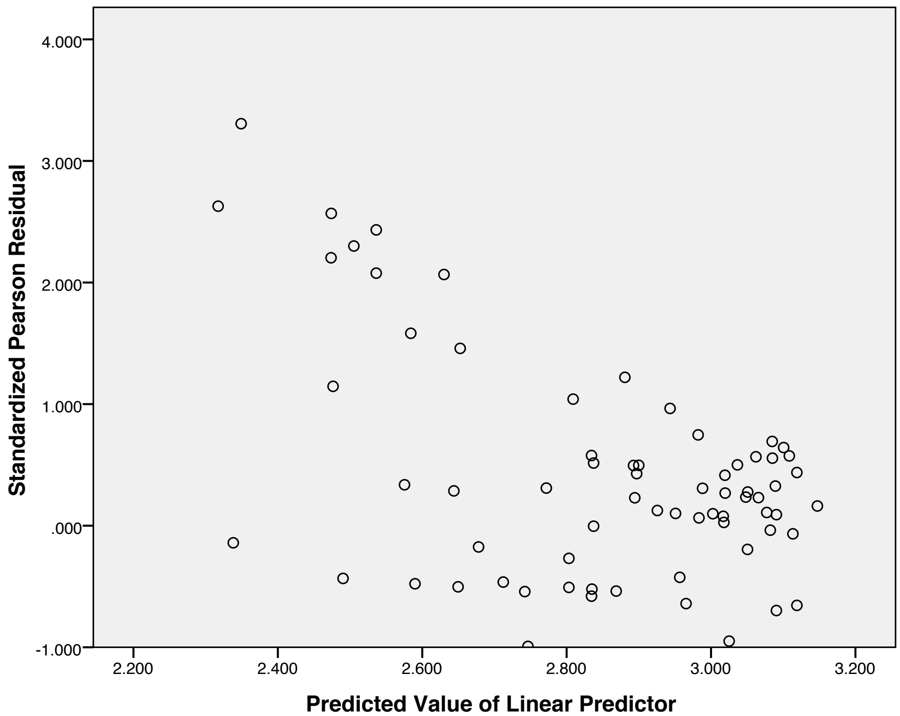

Figure A4-36. Plot of Regression Standardized Residual for *E. coli with age and depth* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

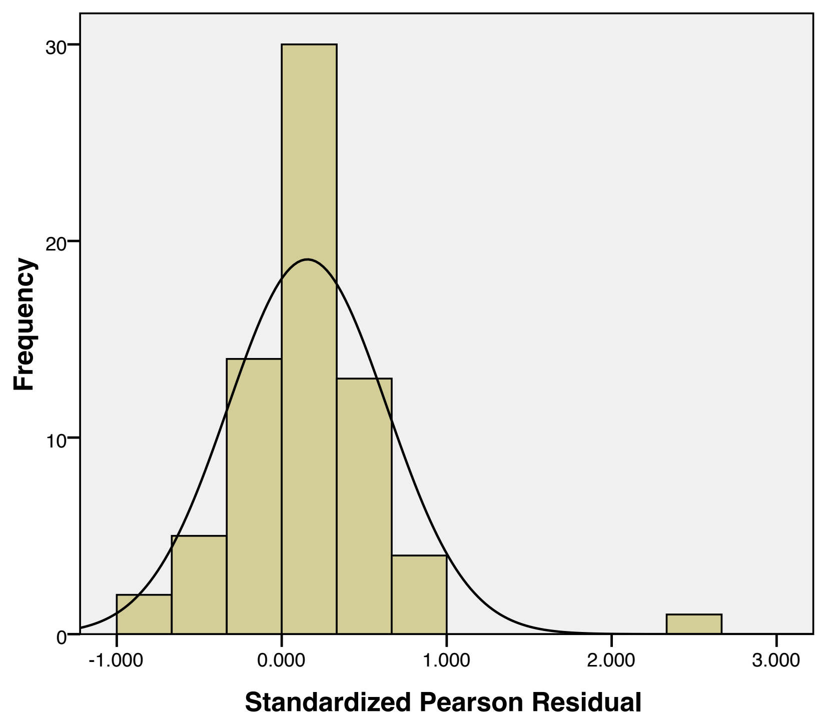

Figure A4-37. Plot of histogram of raw residuals for *E. coli with age and distance* which emulates the shape of a Normal (bell-curved) distribution

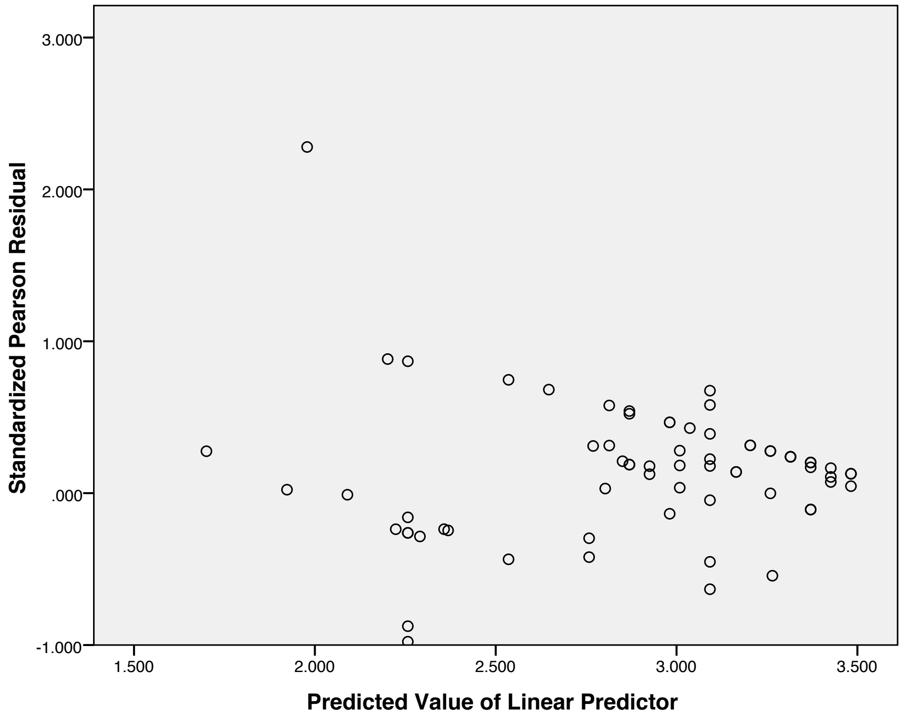

Figure A4-38. Plot of Regression Standardized Residual for *E. coli with age and distance* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

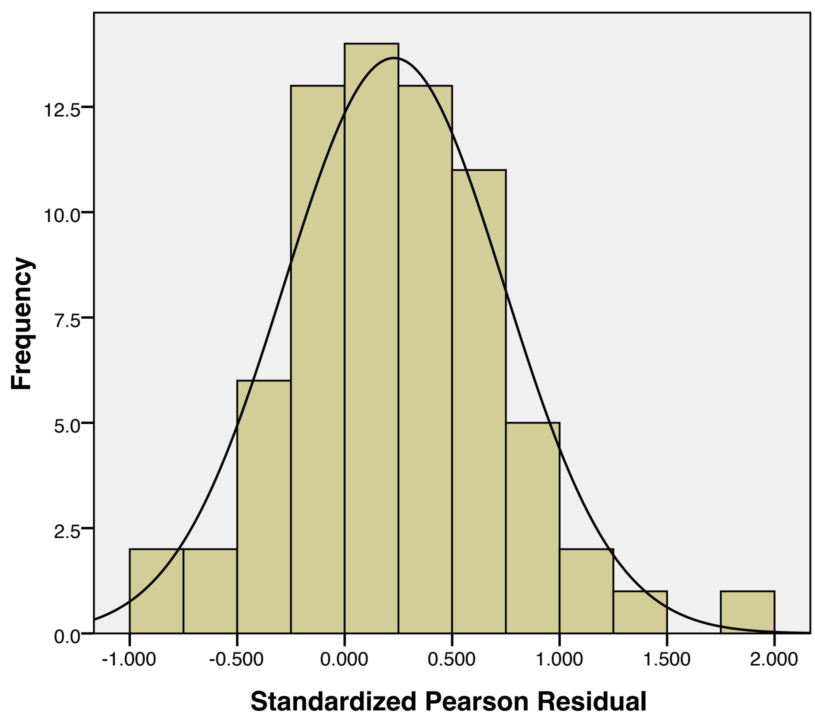

Figure A4-39. Plot of histogram of raw residuals for *E. coli with depth and distance* which emulates the shape of a Normal (bell-curved) distribution

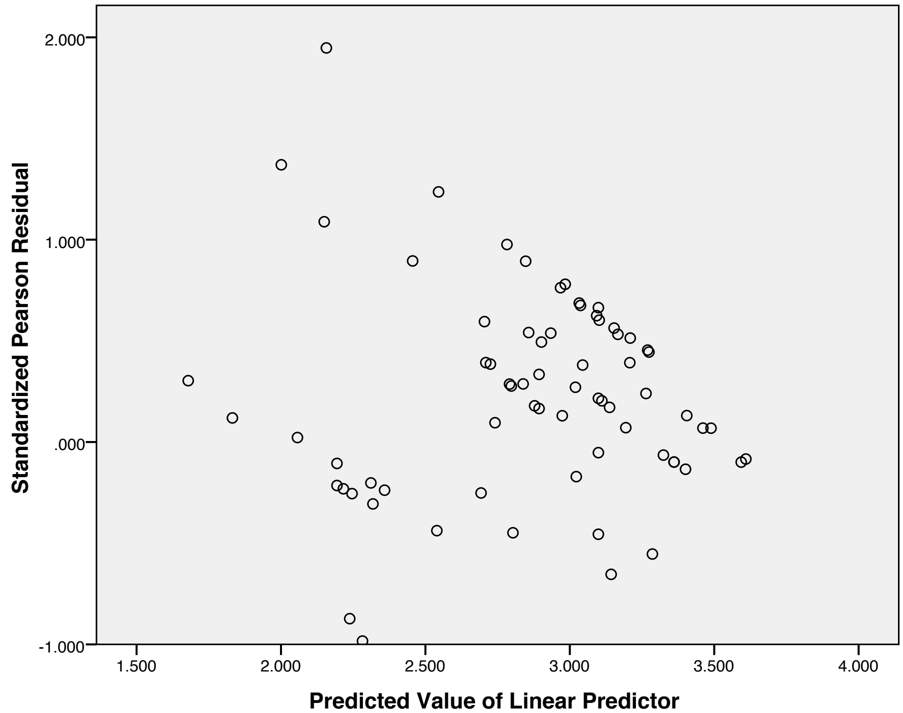

Figure A4-40. Plot of Regression Standardized Residual for *E. coli with depth and distance* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

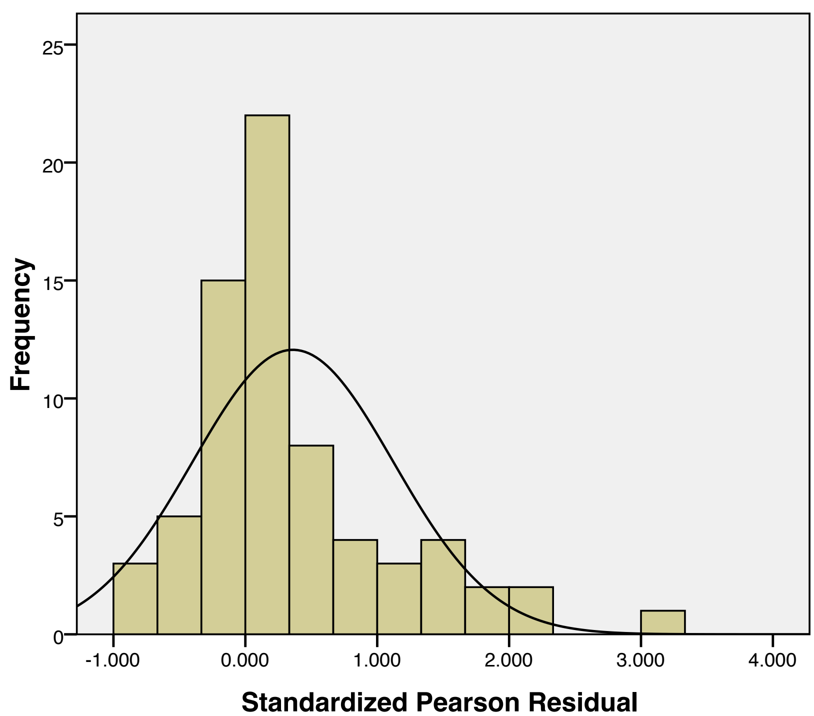

Figure A4-41. Plot of histogram of raw residuals for *E. coli with age, depth and distance* which doesn't emulate the shape of a Normal (bell-curved) distribution, it shows right skewed distribution

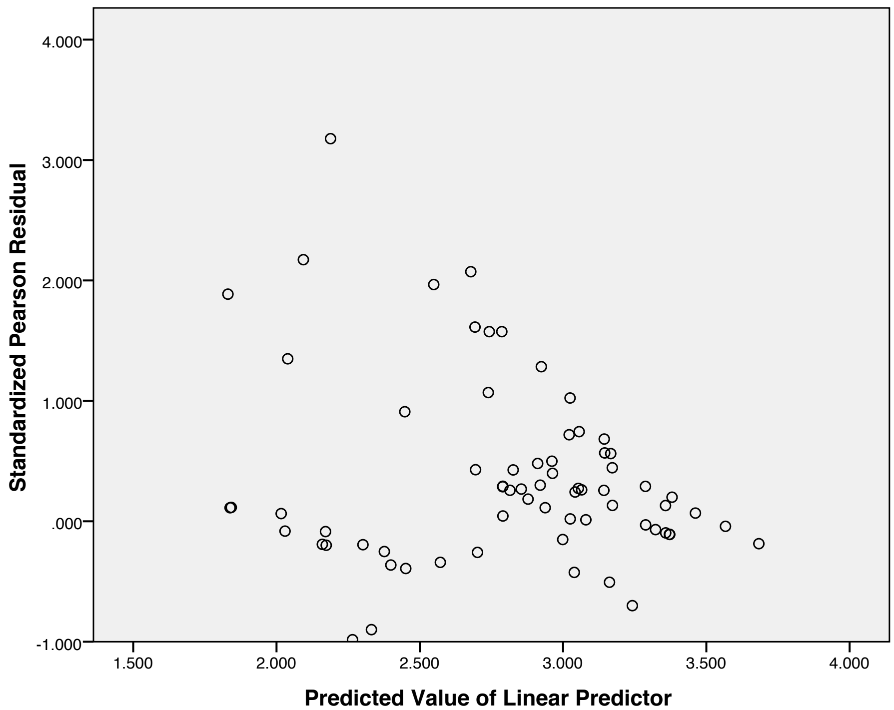

Figure A4-42. Plot of Regression Standardized Residual for *E. coli with distance, depth and age* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

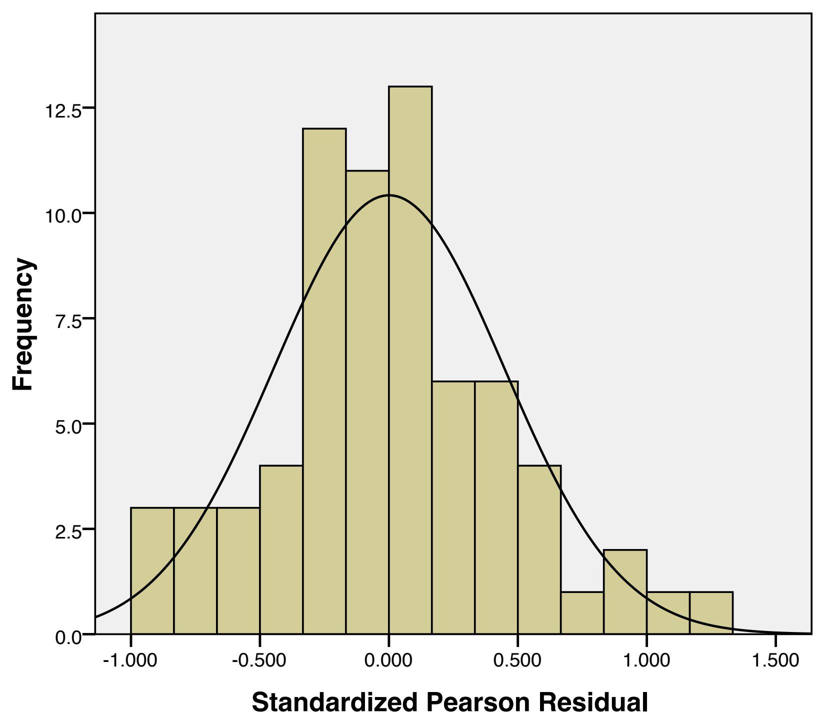

Figure A4-43. Plot of histogram of raw residuals for *TDS and age* which doesn't emulate the shape of a Normal (bell-curved) distribution, it shows slight multimodal instead of normal distribution

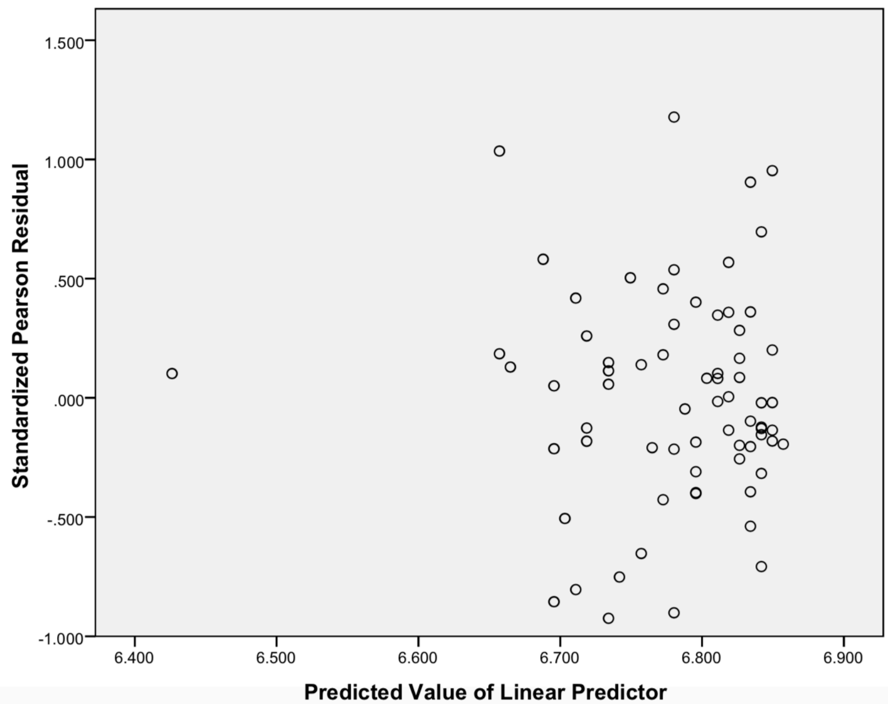

Figure A4-44. Plot of Regression Standardized Residual for *TDS and age* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

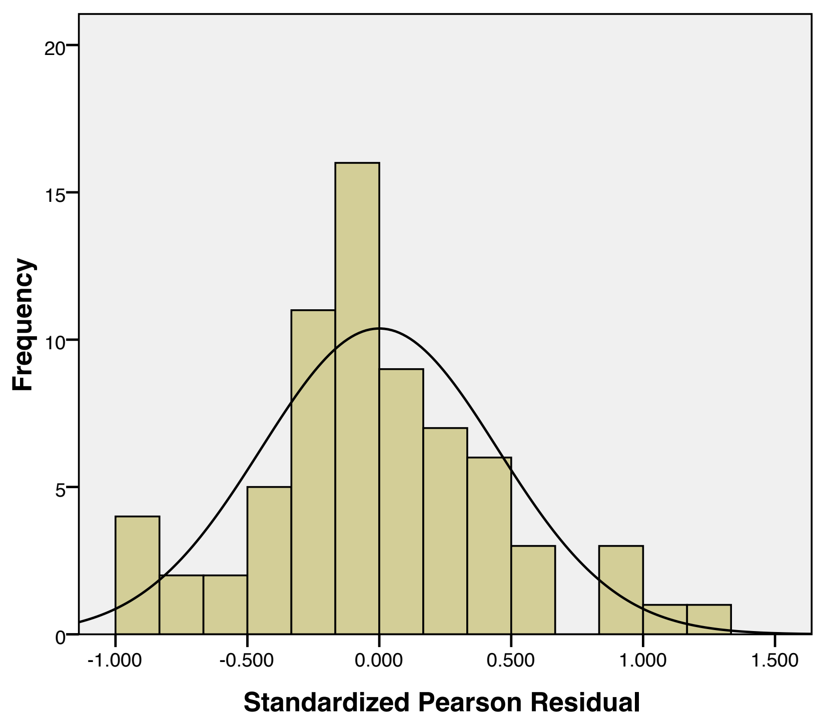

Figure A4-45. Plot of histogram of raw residuals for *TDS and depth* which doesn't emulate the shape of a Normal (bell-curved) distribution, it shows slight multimodal instead of normal distribution

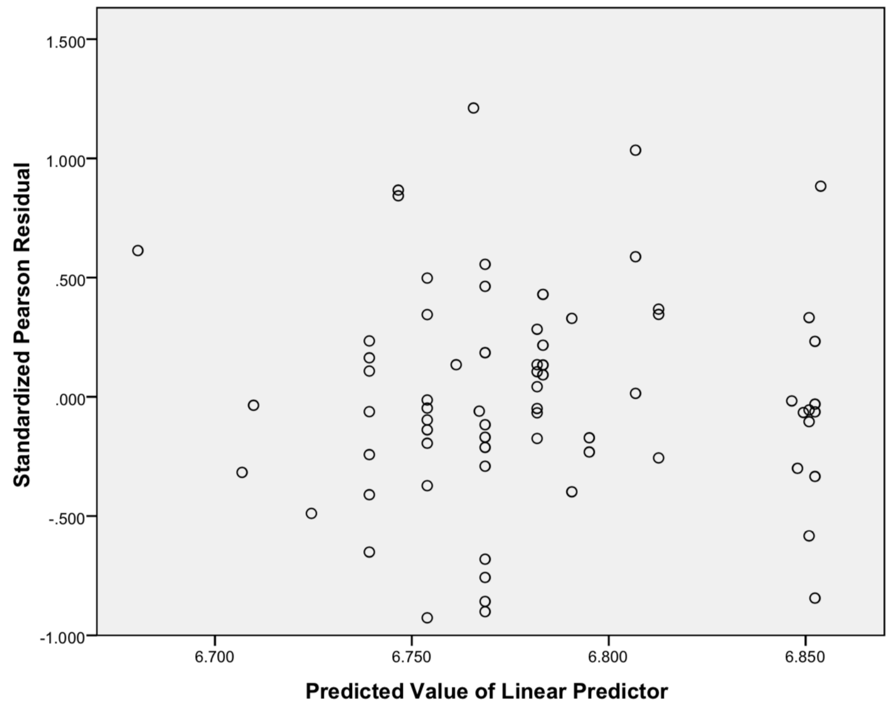

Figure A4-46. Plot of Regression Standardized Residual for *TDS and depth* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

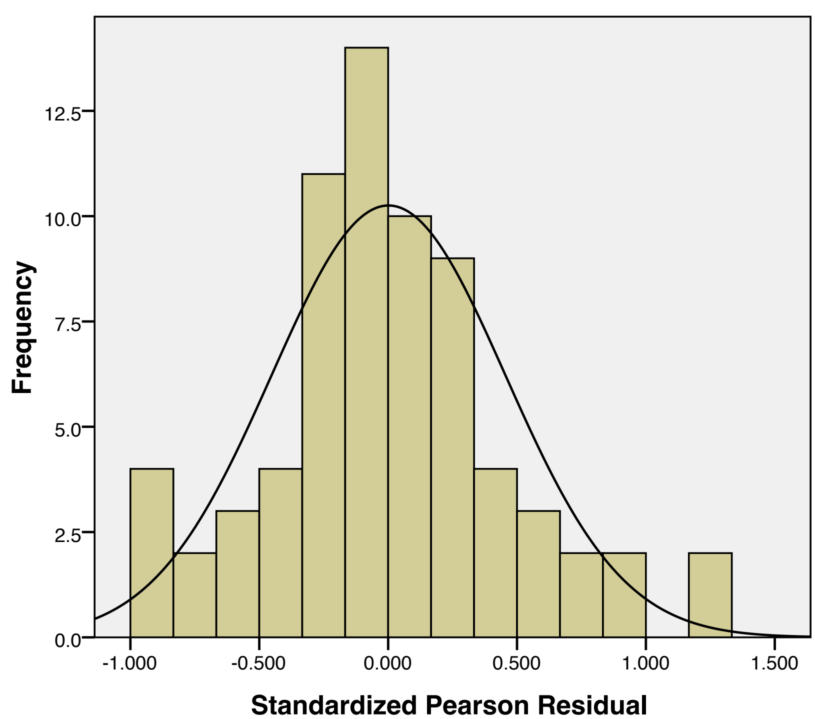

Figure A4-47. Plot of histogram of raw residuals for *TDS with age and depth* which doesn't emulate the shape of a Normal (bell-curved) distribution, it shows slight multimodal instead of normal distribution

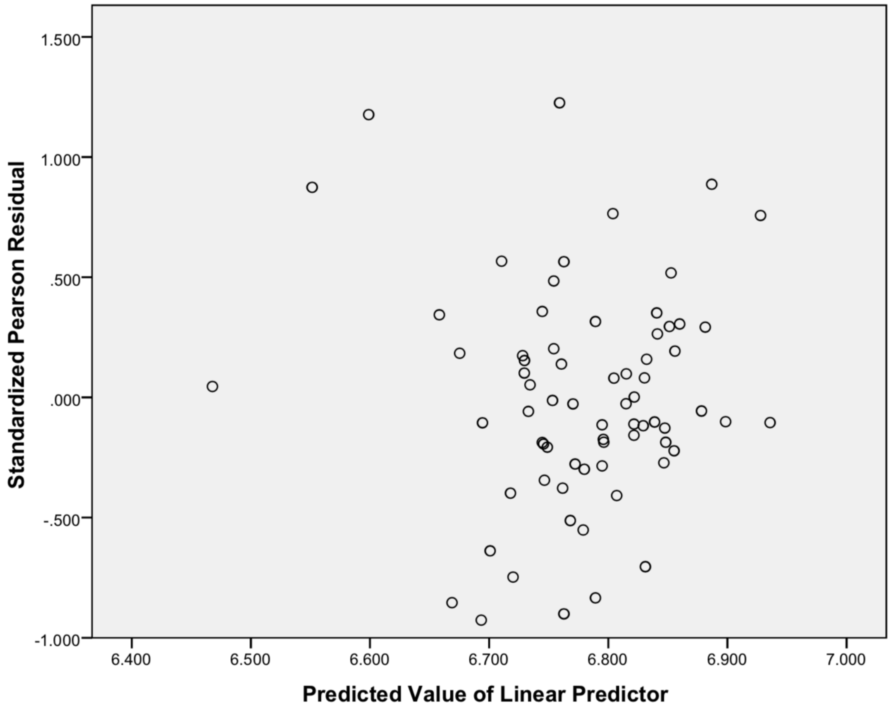

Figure A4-48. Plot of Regression Standardized Residual for *TDS with age and depth* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

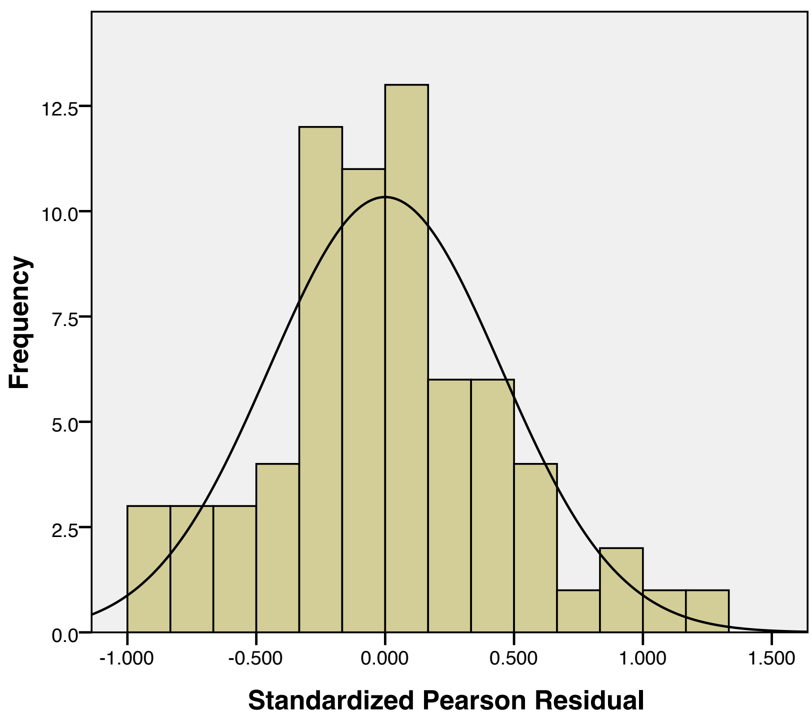

Figure A4-49. Plot of histogram of raw residuals for *TDS with age and distance* which doesn't emulate the shape of a Normal (bell-curved) distribution, it shows slight multimodal instead of normal distribution

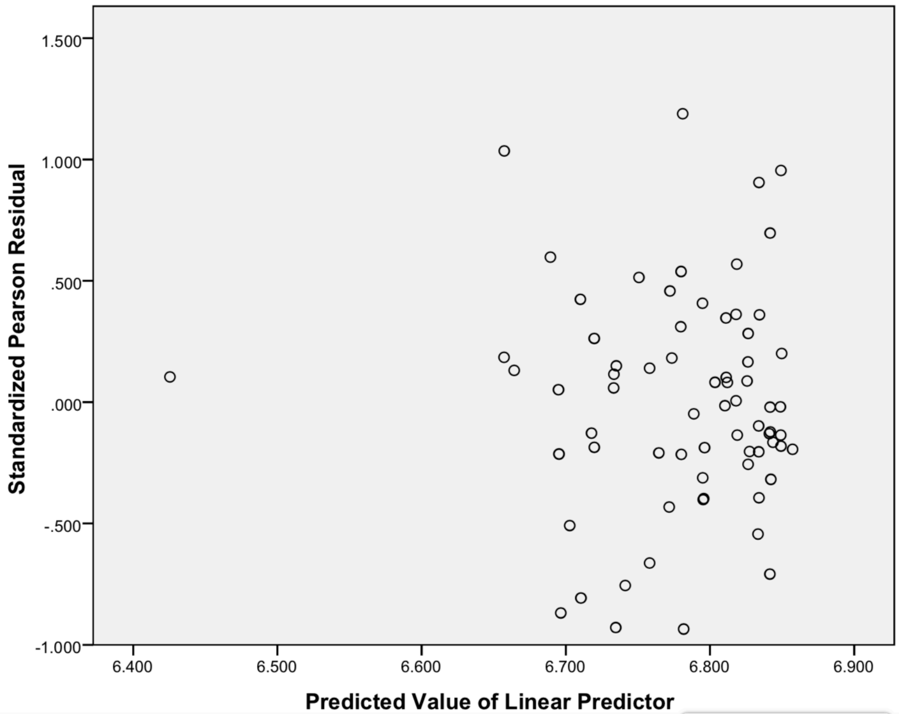

Figure A4-50. Plot of Regression Standardized Residual for *TDS with age and distance* which shows some heteroscedasticity because dependent variable is not equal across the values of independent variables

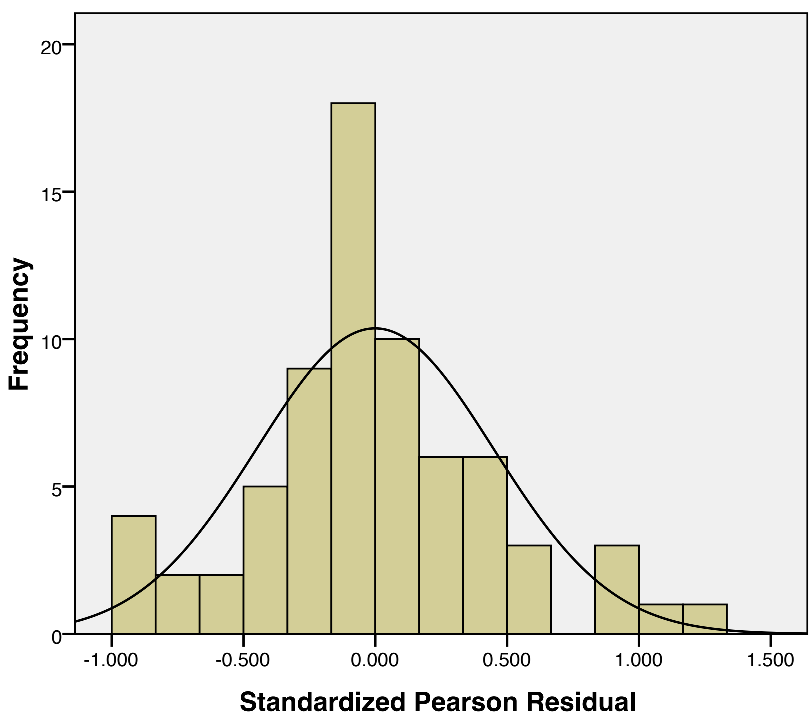

Figure A4-51. Plot of histogram of raw residuals for *TDS with depth and distance*

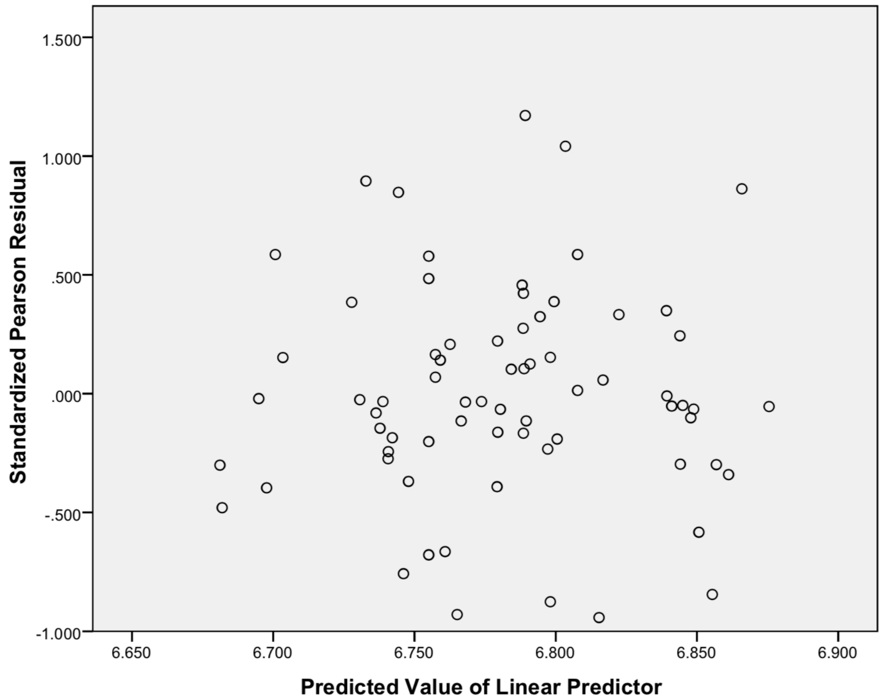

Figure A4-52. Plot of Regression Standardized Residual for *TDS with depth and distance* which shows no heteroscedasticity because dependent variable is equal across the values of independent variables

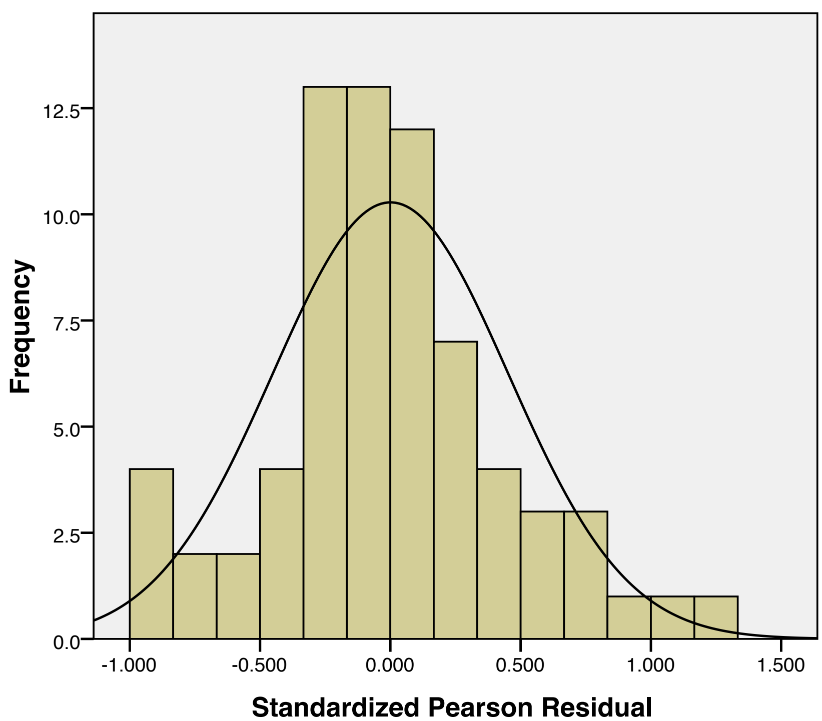

Figure A4-53. Plot of histogram of raw residuals for *TDS with age, depth and distance*

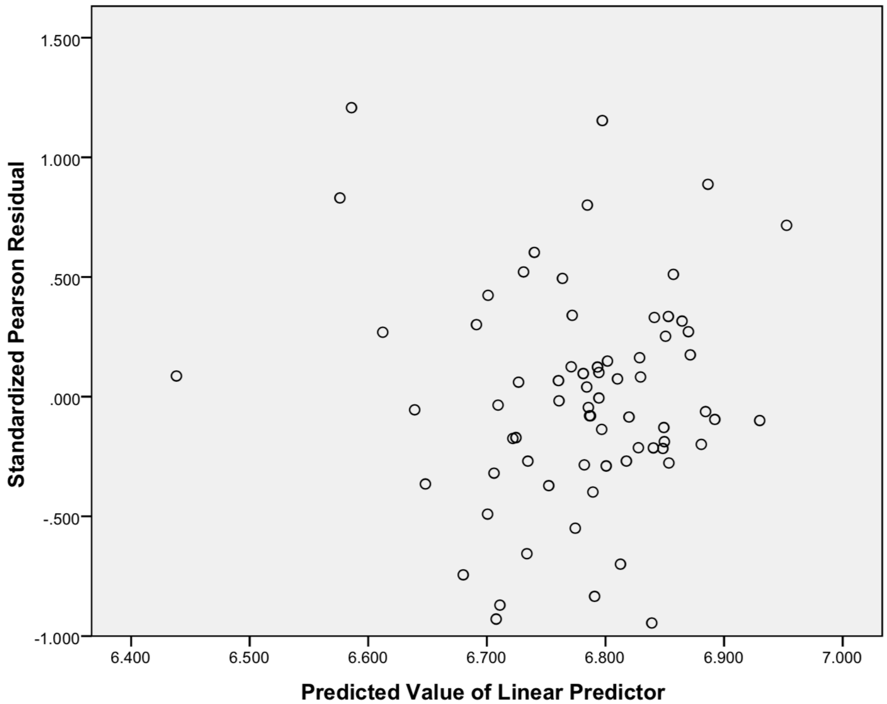

Figure A4-54. Plot of Regression Standardized Residual for *TDS with age, depth and distance* which shows no heteroscedasticity because dependent variable is equal across the values of independent variables

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CHAPTER 5: Identifying Safe Sanitation Practices in Dar es Salaam, Tanzania using Groundwater Transport Modeling and Water Quality Monitoring Data

Abstract

Groundwater flow and transport simulations were carried out in the peri-urban areas of Dar es Salaam, Tanzania to determine the association between simulated tracer concentrations and observed levels of contaminants in order to identify the site-specific minimum distance(s) for pit latrines to prevent or minimize contamination based on the soil types and aquifer properties in the region. Bivariate correlation and linear regression models were used to find the associations and relationship between 1) tracer and contaminants (nitrate, *E. coli* and total dissolved solids) and 2) tracer with distance measured from the well to the pit latrines. The flow model was successfully calibrated with an R^2 value of 0.95 between observed and simulated heads. The results showed a strong positive correlation between the tracer with nitrate and *E. coli* with Pearson coefficient (r) values of 0.80 and 0.79, respectively, but weak correlation with TDS with an r value of 0.23. As expected, a strong correlation between tracer with distance was found with r value of 0.84. Domestic wells that met WHO guidelines were found to be located between 32m and 35 m from the pit latrines. In conclusion, based on the soil types and aquifer properties of our study area, the minimum recommended distance that the well can be placed to minimize contamination is ~33 m. However, in the peri-urban area studied, this distance exceeded the distance between a well and the closest pit latrine for 68% of the wells. The challenge in urban overpopulated areas of developing countries is to develop strategies to protect the public when wells are closer to pit latrines than the distances determined to be safe. Integrated modeling of multiple contaminants of interest from a public health point of view may call for large datasets and detailed site characterization which is expensive. Linking simulated tracer with observed contaminant levels may provide a reliable alternative approach for assessing human health risks associated with groundwater contamination.

Keywords: *Developing country, domestic wells, groundwater flow, minimum distance, MODFLOW, MT3DMS, pit latrine*

5.1 Introduction

Contamination of groundwater as a result of poor sanitation is one of the major threats to the safety of drinking water resources throughout the world. People are affected greatly by water scarcity mainly due to unpredictable rainfall patterns, prolonged dry seasons, and limited options to access water caused by climate change and human activities (Haddeland et al., 2014; US EPA, 2017). The urban areas of many developing countries are at high risk due to large population growth rates, increased urbanization, and abject poverty, along with poor sanitation and inadequate water supply, which together result in the rapid spread of waterborne diseases (WHO, 1992). As the population in developing countries continues to increase, it is expected that the global reliance on groundwater and pit latrines will increase (Graham & Polizzotto, 2013; Ravenscroft et al., 2017).

In densely populated cities such as Dar es Salaam where this study was conducted, the main source of city water supply has been the Ruvu River. However, in recent years, the water supply from the Ruvu River has been unreliable and the city is unable to supply water to all residents due to the decrease in water levels (Mato, 2002; Ngoye & Machiwa, 2004). More than 50% of residents rely heavily on groundwater for their daily use (Mtoni et al., 2013). It is estimated that annual withdrawals from the aquifer exceeds 69 million water m^3 (Mtoni et al., 2011). Over-extraction of groundwater often leads to devastating effects, including seawater intrusion into freshwater aquifers and contamination from improper sewage. Poorly constructed septic tanks and pit latrines can lead to groundwater contamination with contaminants, including nitrate (NO_3^-), *Escherichia coli* (*E. coli*), viruses, and total dissolved solids (TDS) (e.g., see Chen et al., 2016).

Groundwater modeling (Anderson & Woessner, 1992) is a useful tool to understand how population growth and climate change are likely to impact both groundwater quality and quantity.

Contaminant transport modeling can be used to understand the spatiotemporal dynamics of contaminant plumes in real-life situations, including from landfills, hazardous waste sites, and contaminated aquifers (Zheng & Bennett, 2002) and to assess risks to human health. The conceptual model can be used to provide a qualitative framework for designing a numerical model and represent a groundwater system based on what is known about the modeled area. In the constructed model, as shown in Figure 5-1, proposed features such as pumping wells, injection wells and pit latrines can be included. For areas where groundwater has been contaminated, these models can be used to estimate the time required for the plume to reach water source and to determine the minimum distance a drinking water well can be placed from a pit latrine.

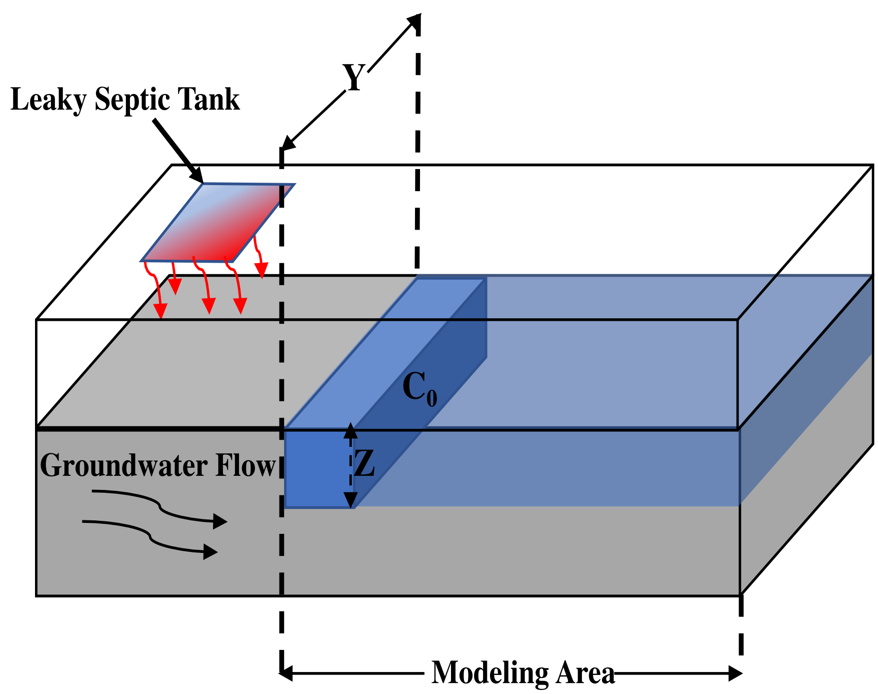


Figure 5-1. Conceptual model of contaminant transport in groundwater with C_0 representing the initial source concentration of the contaminant, Z is the soil layer thickness, and Y as the width of the modeling area.

This study was conducted in one of the peri-urban areas of Dar es Salaam, Tanzania. As water is scarce, residents of this area rely on multiple water sources for household consumption

(Ngasala et al., 2018). One of the most common water sources used is domestic wells, often privately or publicly owned, from which people can purchase water. The average density of wells in this area is 4.6 wells/km^2. Residents are low-income earners who spend a significant portion (> 50%) of their income to purchase water for domestic use and for wastewater management (Ngasala et al., 2018). While the cost of purchasing water from private wells is high, residents often have few options other than this or purchasing water from street vendors. Water from most domestic wells is contaminated by household sewage due to the close proximity of the wells to poorly constructed septic tanks and pit latrines (Ngasala et al., 2019)

About 90% of the homes in this area use unimproved pit latrines, which are not constructed to meet the definition of a properly constructed pit latrine. Due to lack of access to both a sewer system and roads, more than 50% of residents have to manually empty their pit latrines. Typically these pits are emptied every 1 to 24 months, whereas the typical time to fill a pit latrine is between 3 and 5 years (Orner, 2018). The soil type in this area is sandy clay, which has a high soil permeability (Mtoni et al., 2012). The majority of the study area has a water table that is ~5 m below ground surface, which causes the poorly constructed pit latrines to fill with groundwater especially during the rainy season (Mkude & Saria, 2012).

Ngasala et al. (2018) linked the cross contamination of domestic water with mixing during storage practices at the point of collection and at the point use in this area. The study focused on the water quality analysis of three different water sources used by the community (city water, domestic wells and water vendors) and found out that domestic wells have the highest level of contamination. Ngasala et al. (2019) used statistical analyses to further analyze the impact of these wells and hydrogeologic setting on water quality and examined three possible factors that can cause well contamination - well depth, age of the well, and distance from the well to a pit latrine.

They found that distance had the highest impact to the quality of the wells. Additionally, results revealed that more than 65% of the wells were located less than the recommended safe distance of 15 m (CDC, 2009; Sphere Project, 2011; US EPA, 2002), although Graham & Polizzotto (2013) suggested that the actual distance for the well to be placed depends on the aquifer properties along with the rate of transport of microbiological and chemical contaminants in the aquifer.

Several researchers came up with various recommended well setback distances ranging from 15-30 m (see Table A5-1 in Appendix). Although there is widespread use of groundwater modeling in hydrologic sciences, especially in developed countries, their use is less common in many developing countries (Wilcox et al., 2010). Very few studies have used ground water models to estimate the recommended minimum distance based on specific site conditions such as soil type and aquifer properties in the context of urban areas such as Dar es Salaam, Tanzania. If multiple contaminants such as bacteria, viruses, nutrients, and suspended solids relevant to human health are involved, a holistic assessment calls for multi-component groundwater transport modeling. An additional complicating factor is the need for integrated modeling across multiple domains to include relevant processes such as runoff, infiltration, and transport in the vadose zone before contamination moves to the fully-saturated groundwater domain. While significant progress has been made in the development of subsurface and integrated transport models (e.g., Bradford et al., 2014; Dwivedi et al., 2016; Niu & Phanikumar, 2015), such efforts tend to be expensive due to the need for large datasets, computational times and detailed site characterization that often precedes the modeling effort. A novel aspect of the present work is that it combines groundwater flow and tracer transport modeling with water quality monitoring data to identify setback distances and the approach can be used within a risk assessment framework to identify best practices for future developments in the region (e.g., to identify setback distances for an acceptable level of risk). By linking simulated tracer concentrations with distance from pit latrines and developing relations between observed water quality and simulated tracer, transport modeling can be simplified significantly while still relying on local conditions such as soils and geology to drive decisions.

This work is an attempt to assess the existing regulations for domestic wells and pit latrines or septic systems. Specifically, we have used a groundwater model to the estimate site-specific minimum recommended distance that a well can be located to prevent or minimize contamination by combining tracer transport modeling with water quality data. The ultimate goal is to develop additional drinking water protection strategies for unsewered highly populated peri-urban area of Dar es Salaam. We have expanded upon the work of Ngasala et al. (2019), by using a numerical tracer that represents contaminant transport and determined its association with distance and contaminant levels (nitrate, *E. coli* and TDS). In this study, two main hypotheses are tested, first, we hypothesized that there is a strong correlation and association between the tracer and water contaminants (nitrate, TDS, and *E. coli*). We also hypothesize that, based on the soil types and aquifer properties in our study area, the minimum recommended distance in our study area is greater than the recommended well setback distance of 15 m (CDC, 2009; Sphere Project, 2011; WHO, 1992) and the distance between a vast majority of wells and pit latrines.

5.2 Methods

5.2.1 Study Area

The study area is one of the densely populated low-income, peri-urban areas in Dar es Salaam city with the population density of about 14,250/km^2. The city is located in Tanzania on the East African coast bordering the Indian Ocean to the east (Figure 5-2). The climate of the city is tropical with average temperature about 22 °C. The country has two rainy seasons, short rains of October-December with an average rainfall of 117 mm and long rains between March-May with an average rainfall of 253 mm (Mtoni et al., 2012). As none of the homes in this area are connected to a sewer system, human waste from this area is discharged to septic tanks or pit latrines, most of which have been poorly constructed with no regard for human health or the environment.

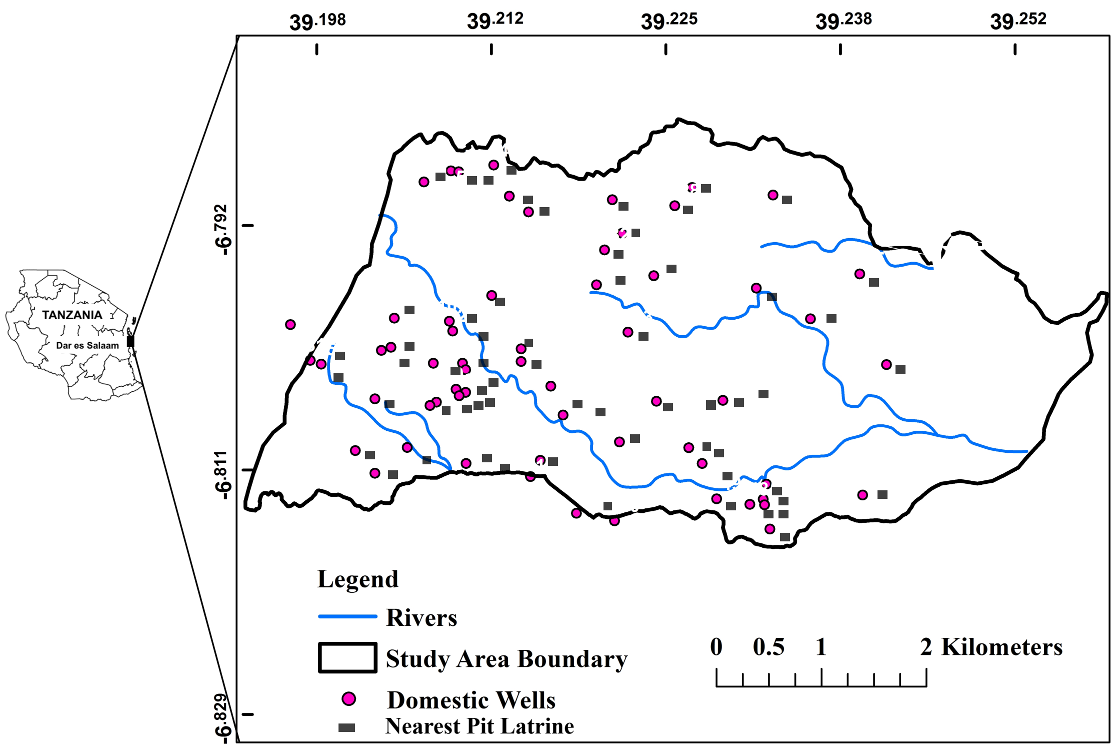


Figure 5-2. Location of the study area in Dar es Salaam, Tanzania showing 63 domestic wells and 64 pit latrines that were used for groundwater modeling

5.2.2 Data Collection

The site was surveyed to identify existing domestic wells and wastewater systems (pit latrines). The information about these systems including construction method, size, depth, and age of pit latrine, and sewage discharge schedule was collected. For homeowners who also have domestic wells, additional information was obtained, such as the distance between the well and the closest pit latrine. GPS coordinates of each pit latrine and domestic well locations were recorded for mapping and modeling purposes. Additionally, we obtained official well records from the Drilling and Dam Construction Agency (DDCA). The records included soil profiles, well logs, and water quality analyses associated with all wells that were drilled in the study area. Groundwater recharge rates and rainfall patterns were collected from the literature (Mjemah et al., 2009; Mtoni et al., 2011). Hydraulic head and groundwater flow direction data were calculated using the well log information provided and digital elevation model (DEM) data (112 pixels/inch) from Michigan State University library.

5.2.3 Hydrogeology

There are two main aquifers in the city: an upper unconfined sand aquifer and a lower semi-confined sand aquifer that are separated by a clay aquitard (Mtoni et al., 2012). The unconfined aquifer consists of fine to medium sand with traces of silt and clay, which extends to the second clay layer towards the Indian Ocean (Mjemah et al., 2009). The lower semi-confined aquifer overlies the clay-bound sands and gravel with a thickness of several hundred meters (Mjemah, 2007; Mjemah et al., 2009). The majority of the city including the study area overlays a sand aquifer and a clay aquitard, which are the main sources of groundwater (Mjemah et al., 2009). Figure A5-1 in Appendix shows the top view (a) and side view below that (b) of the 3D conceptual model of the study area. The uppermost water-bearing unit is the unconfined fine sand aquifer with a depth of approximately 50-60 m. The second layer is a clayey sand aquitard having a depth of ~20 m. The third layer is comprised of sandy clay with a depth of ~30 m and also consists of a clay lens with a depth of ~7 m.

5.2.4 Groundwater Flow and Transport Modeling

Groundwater Modeling System (GMS, 2019) interfaced with MODFLOW-2000 (Harbaugh et al., 2000) and MT3DMS (Zheng & Wang, 1999) was used to simulate flow and conservative solute transport in the fully-saturated groundwater domain within the study area.

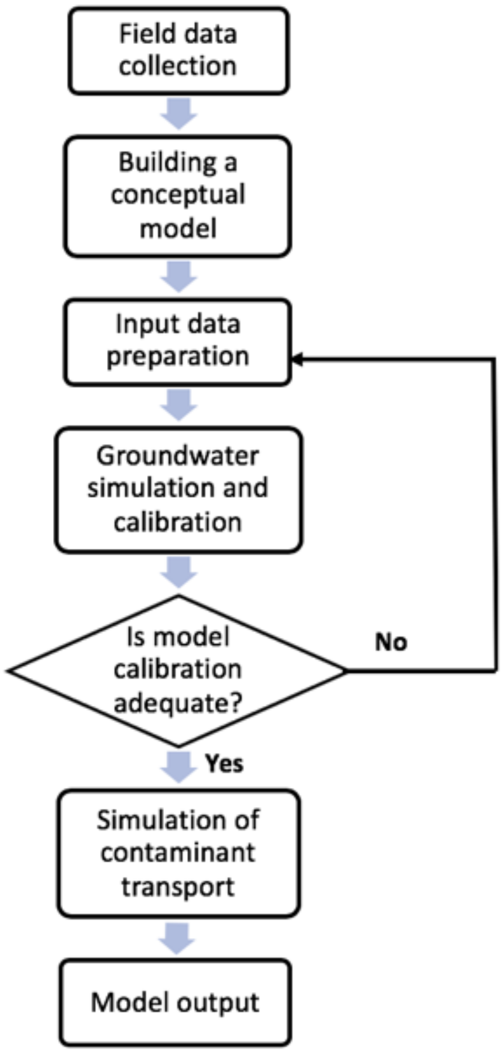


Figure 5-3. Step by step procedure for the groundwater simulation process

A MODFLOW numerical model was constructed from the conceptual model using appropriate properties, boundaries, and data from field observations. The conceptual model and grids were the same for both the groundwater flow and the transport models. The study area covered was about 36 km^2 and a horizontal model grid of 100 (x) × 100 (y) cells was used with three layers in the vertical z-direction. The boundary conditions for the upper aquifer were the constant head boundary in the north, east and south of the domain. No flow boundary conditions were incorporated in the western part of the domain and the variable head boundary is in the middle locations.

Input parameters for running the steady state MODFLOW simulation include time steps, sources and sinks such as rivers, wells and recharge, hydraulic parameters and boundary conditions. Three layers were simulated; fine sand (thickness = 60 m), clayey sand (thickness = 20 m), and sandy clay (thickness = 30 m). The soil materials for each layer are classified as described in the *Hydrogeology* section above and as shown on Figure A5-1 in Appendix. The average hydraulic conductivity values used for all three layers; fine sand, clayey sand and sandy clay were 15.14, 0.15, and 0.0022 m/day, respectively, with porosity value of 0.3 for all three layers (EPA, 1984; Mjemah et al., 2009; Sarki et al., 2014). Vertical and horizontal anisotropy values were estimated to be 4 and 1, respectively (Chapuis & Gill, 1989; Mualem, 1984). The starting head was 60 m. The average annual recharge value for the Dar es Salaam is 184 mm/year, which is equivalent to 0.0005 m/day (Mtoni et al., 2011). MODFLOW packages used were Time Variant Specified Head, Drain, Recharge, Well, LPF - Layer Property Flow. Hydrogeological properties information used were soil types, hydraulic conductivity, porosity and observed hydraulic head. The summary table of input parameters is provided in Table 5-2 in Appendix.

Lastly, the model was run to simulate groundwater heads and flows. Model calibration was performed using the observed heads and flow rates obtained from field data. All wells analyzed are located downstream from the source (pit latrines). The calibration process was done until model simulations matched the field observations to a reasonable degree. Heads and fluxes were computed by MODFLOW during the flow simulation then read by MT3DMS to simulate tracer transport. The longitudinal dispersivity (α_L), horizontal (α_H) and vertical transverse dispersivity (α_V) values were estimated to be 20, 2 m and 0.2 m respectively for all three layers based on Engesgaard et al. (1996). A conservative numerical tracer with an arbitrary initial concentration (C_o) of 100 mg/L was "released" into the aquifer from each of the 63 pit latrines. The contaminant transport model was run for 1825 days (5 years). The plume migration from the source region was observed at 64 monitoring wells.

5.2.5 Statistical Analyses

The predicted heads obtained using MODFLOW were compared to the observed heads to assess the accuracy of the model and appropriateness of the initially input parameters. Both the goodness of fit, R^2 and the root mean square error (RMSE) were calculated to assess model performance. To understand the relationships between tracer concentration and distance from the well to pit latrines, the results from the transport model were used to determine the linear relationship and predict the relationships between the tracer, distance, and the contaminants. Wells were divided into two groups - wells that are less than 15 m deep (shallow) and wells that are more than 15 m deep as deeper wells tend to follow different flow paths (Wilcox et al., 2010). Two statistical analysis methods were applied to the results from the transport model 1) bivariate correlation to determine the strength of the linear relationship between tracer and the distance and 2) linear regression to confirm whether a linear relationship exists between the tracer and distance from the well to pit latrines. SPSS version 24.0 (IBM Corp, 2016) was used for all analyses.

Bivariate Correlation and Regression Analysis

Bivariate correlations were used to determine the relationships between the tracer, distance and the contaminants. Pearson's *r* correlation was used to characterize the linear relationships between the *tracer concentration and distance* from the well to the pit latrines for shallow wells and deep wells as well as for the following combinations: 1) *tracer concentration with nitrate,* 2) *tracer concentration with E. coli,* and 3) *tracer concentration with TDS*. The association between two variables was measured by the correlation coefficient with values between -1 and 1. Results from Pearson's *r* correlation were used to find the relationship between contaminants and distance by using linear regression model.

After confirming that there is a significant association between the tracer, water contaminants, and distance of the well from the pit latrines from the bivariate correlations, linear regression analysis was used to model the relationship between contaminants and distance, see equations (1) through (4). For equation 1, distance was a dependent variable, whereas tracer concentration was a dependent variable. For equation 2, 3 and 4, contaminants were dependent variables, whereas tracer concentration was an independent variable. Results were used to estimate the minimum well setback distance for this peri-urban area of Dar es Salaam for both shallow wells and deep wells.

$$Tracer = \beta_1 + \alpha_1(Distance) \tag{1}$$

$$Nitrate = \beta_2 + \alpha_2(Tracer) \tag{2}$$

$$E.coli = \beta_3 + \alpha_3(Tracer) \tag{3}$$

$$TDS = \beta_4 + \alpha_4(Tracer) \tag{4}$$

where:

α_i = Slopes of the lines

β_i = Intercepts, the values of y when $x = 0$

The adjusted R^2 was used to measure the accuracy of linear models to identify the percentage of variance in the input (s). The closer the adjusted R^2 is to 1.0, the more the variation in the dependent variable can be explained by the independent variables in the regression model (Kvålseth, 1985). The significance of the relationship of the combination was indicated when p-values were less than 0.01.

5.3 Results

5.3.1 Groundwater Flow Model Simulation and Calibration

Figure 5-4 shows the computed hydraulic heads in all three layers. The model was calibrated manually by adjusting the hydraulic conductivities and recharge values that are within the acceptable range to find an optimal set of values. Figure A5-2 in Appendix shows a flow vector map corresponding to these heads. Groundwater flow model output was used to simulate transport. The R^2 value was 0.95 between observed and simulated heads and the RMSE was 1.3 m, which indicates good overall agreement and model performance.

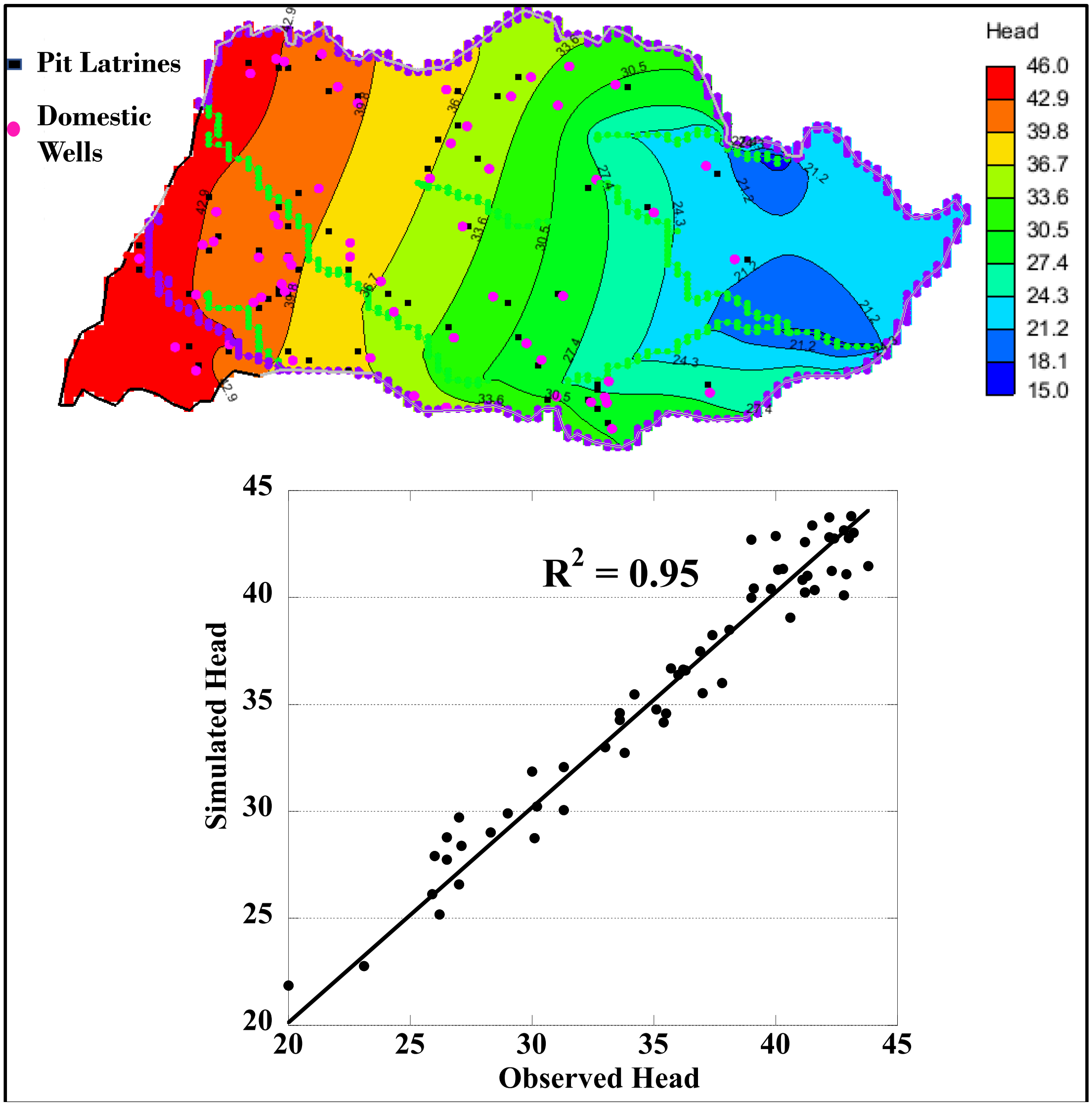


Figure 5-4. Groundwater flow (top) and calibration of the hydraulic head (bottom)

5.3.2 Tracer Transport

Tracer breakthrough curves generated for some of the wells are shown in Figure A5-3 in Appendix. The minimum distance the plume travelled to reach the monitoring well with maximum normalized tracer concentration of 100 mg/L ($\frac{C}{C_0} = 1$) was 3 m, corresponding to a travel time of 4.5 days. The longest distance the plume travelled to the well was 35 m, which had the maximum tracer concentration of 10 mg/L ($\frac{C}{C_0} = 0.1$). The average velocity of 0.67 m/day, resulting in a travel time of 52 days.

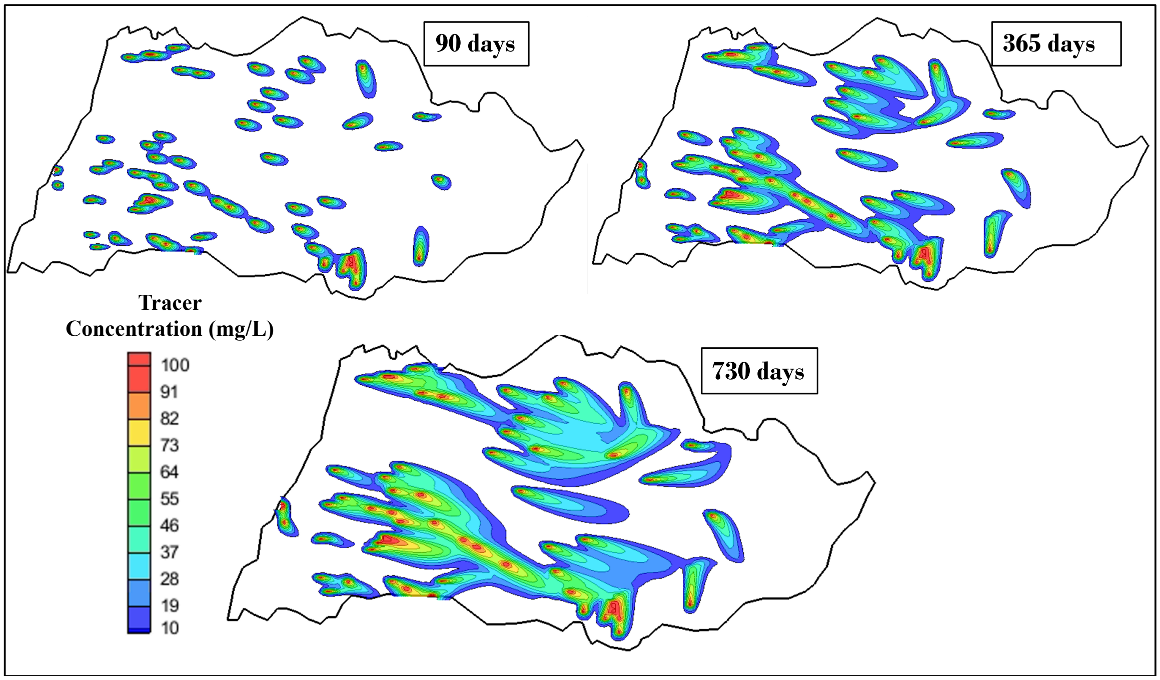


Figure 5-5. Plume transport at 90 days (top left), 365 days (top right) and 730 days (bottom) with red dots representing monitoring wells receiving contamination from the source (pit latrines)

Figure 5-5 shows the tracer transport modeling results in the top layer after 90 days (three months), 365 days (1 year) and 730 days (2 years). After 90 days, the transport model showed the plumes moving towards the east side of the study area. The tracer transport model also showed that, at the maximum simulation time of 1825 d, very few wells were predicted to have concentrations less than 50% of the initial concentration seeping from the pit latrines. This was irrespective of distance and included wells within the 15 m radius assumed to be "safe" according to WHO guidelines. In reality, the wells that were located upstream of the pit latrine should have the less contamination, but according to the model results showed otherwise possibly due to the proximity of wells from latrine. All domestic wells were within 35 m of a pit latrine.

Figure A5-4 in Appendix shows the plume transport for all three layers after 2 years for a well that was located about 9 m from the pit latrine. After 2 years (730 days), that well had already a tracer concentration of 90 mg/L. After 2 years, just on the first layer, the plume has already travelled more than 175 m. The plume travel distance decreased to about 90 m in the second layer and about 55 m in the third layer.

5.3.3 Bivariate Correlations

Nitrate, *E. coli,* and TDS concentrations detected through sampling and analysis at the drinking water wells were used for bivariate correlation analysis with the tracer from the contaminant transport model. Pearson's r correlations from three combinations of contaminants: 1) *tracer with nitrate,* 2) *tracer with E. coli, and* 3) *tracer with TDS* revealed that nitrate and *E. coli* are positively correlated with tracer transport with Pearson coefficient, r of 0.80 and 0.79, respectively. Tracer with TDS showed a weak positive correlation with r of 0.23, suggesting that these parameters are not well correlated. The summary of the r values for tracer and contaminants is provided in Table 5-1.

Table 5-1. Bivariate correlations of tracer transport with water quality parameters.

Independent Variable	**Pearson Coefficient, r**
	Tracer
Tracer	1.00
Nitrate	0.80*
E. coli	0.79*
TDS	0.23

**Correlation is significant at 0.01 level (2 tailed)*

Field investigations revealed that, out of 64 wells analyzed, 56% of domestic wells were located less than 15 m from a pit latrine, which is the WHO guideline for the distance of a drinking water well from pit latrines. The maximum distance was found to be 35 m and minimum was 3 m with an average of 17.1 m. Wells were then cataloged into two clusters, shallow wells with depth less than 15 m and deep wells with depth more than 15 m. Bivariate correlation results between *tracer with distance* for shallow wells showed a strong negative correlation with value of -0.96 and for deep wells was -0.76. Correlative comparisons showed that *nitrate and distance* as well as *E. coli and distance* exhibit strong negative correlations with r values of −0.95 and −0.93, respectively for shallow wells and −0.85 and −0.83, respectively for deep wells. Correlative comparisons for *TDS and distance* showed a weak negative correlation with r values of −0.41 and −0.17, for shallow wells and for deep wells respectively as shown in Table 5-2.

Table 5-2. Bivariate correlations of distance from shallow and deep wells to pit latrines with tracer transport and water quality parameters.

	Pearson Coefficient, r			
	Tracer	**Nitrate**	**E. coli**	**TDS**
Distance for shallow wells ($d < 15m$)	-0.96*	-0.95*	- 0.93*	-0.41
Distance for deep wells ($d > 15m$)	-0.76	-0.85*	-0.83*	-0.17

**Correlation is significant at 0.01 level (2 tailed)*

5.3.4 Linear Regression

WHO drinking water guidelines were used as the threshold to compare contaminants with the tracer concentration at the well to determine the minimum setback distance from the linear regression analysis results. According to WHO guidelines, the acceptable concentration of nitrate is 10 mg/L as N, for *E. coli* it is 0 CFU/100 mL and for TDS it is 500 mg/L. Results showed that only 32% of the wells tested for nitrate met the WHO guidelines, 6 % for *E. coli* and only 17% for TDS. Linear regression was used to fit the tracer concentration with distance for shallow wells and deep wells. Results showed shallow wells had higher R^2 value (0.92) compared to deep wells (0.62) as shown in Figures A5-5 and A5-6 in Appendix. When linear regression was used to fit the tracer concentration for all wells combined with distance, nitrate, *E. coli* and TDS, results showed R^2 values of 0.71, 0.65, 0.62 and 0.05 respectively as shown in Table 5-3. Figures 5-6, 5-7 and 5-8 show the scatter plots of the linear regression model results of tracer as dependent variable with distance, nitrate and *E. coli* as independent variables. Figure A5-7 in Appendix shows scatter plot for TDS.

Table 5-3. Linear regression summary results from all wells with tracer transport and distance, nitrate, *E. coli* and TDS

Variables	**Tracer**		
	R^2	**Adjusted R^2**	***p*-value**
Distance	0.71	0.705	**0.000***
Nitrate	0.65	0.640	**0.000***
E. coli	0.62	0.618	**0.000***
TDS	0.05	0.036	0.074

**Correlation is significant at 0.01 level (2 tailed)*

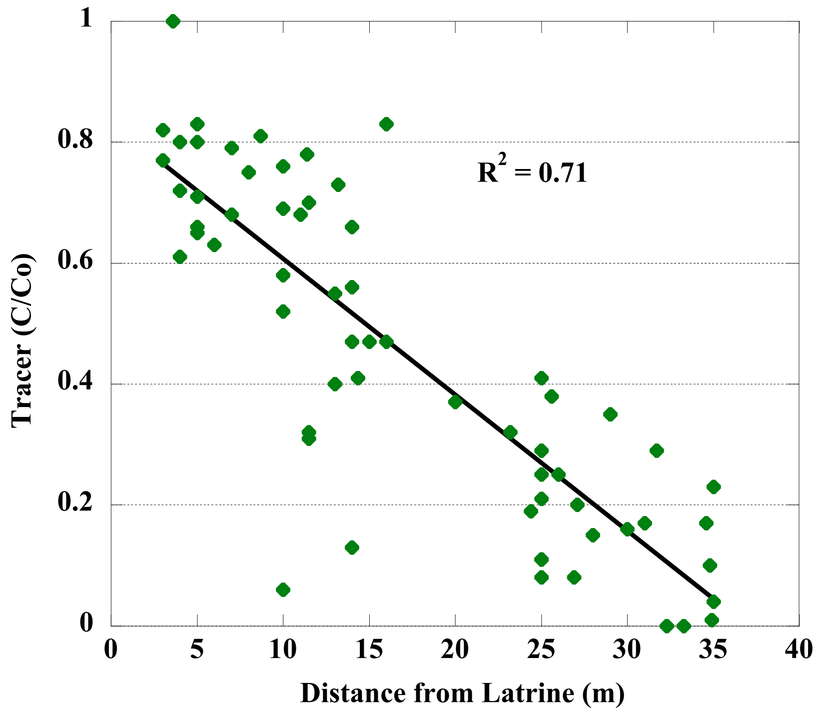


Figure 5-6. Linear regression model results of distance measured with numerical tracer concentration for all wells combined (shallow and deep)

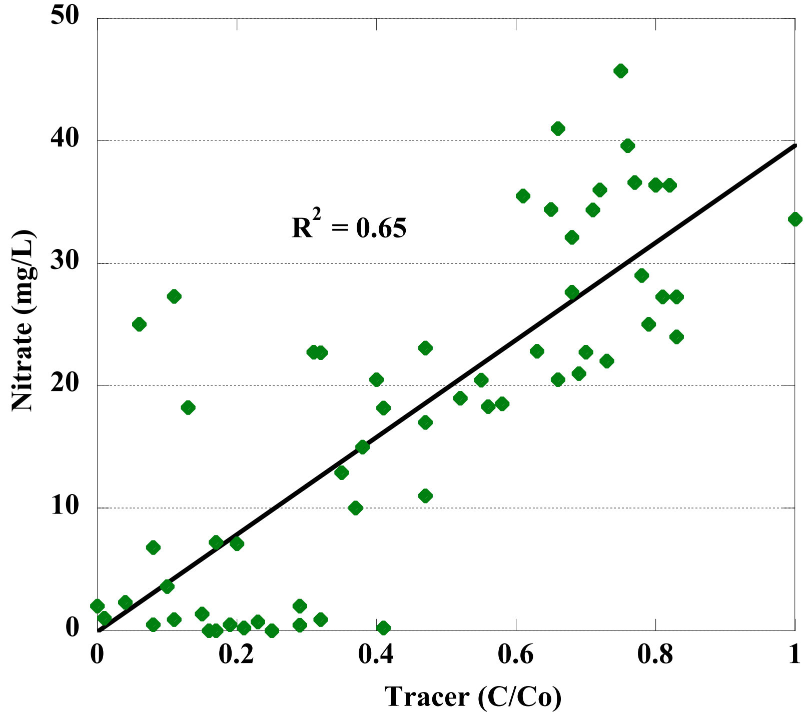


Figure 5-7. Linear regression model results of nitrate with numerical tracer concentration for all wells combined (shallow and deep).

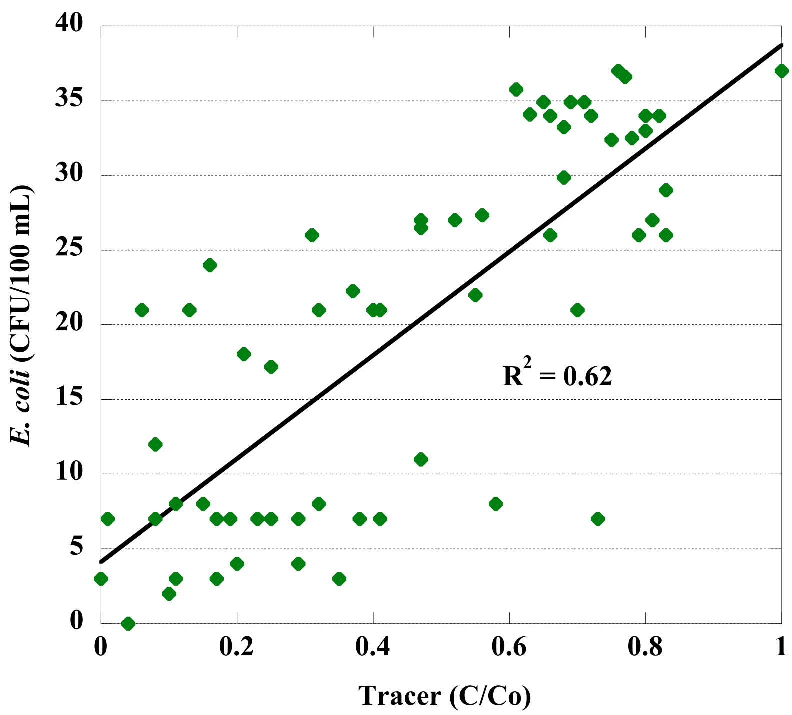


Figure 5-8. Linear regression model results of *E. coli* with numerical tracer concentration for all wells combined (shallow and deep)

To understand how *E. coli* and nitrate concentrations change with distance and to identify safe distances based on the concentrations of these variables, new values of "fitted distances" for *E. coli* and nitrate were obtained using (a) the regression equation between distance and simulated tracer concentration (Figure 5-6) and (b) regression equations between simulated tracer and observed *E. coli* and nitrate concentrations. The new distance values were referred as "fitted distance". New linear regression results with fitted distance are shown in Table 5-4. R^2 values for nitrate and *E. coli* are close to 1 but for TDS it didn't explain the variance. The scattered plots supporting results from Table 5-4 are shown in Figures A5-8, A5-9 and A5-10 in Appendix. From the fitted distance results, minimum setback distances of wells that met WHO guidelines for all three contaminants were identified as shown in Figure 5-9.

Table 5-4. Linear regression summary results from all wells with tracer transport and distance, nitrate, *E. coli* and TDS

Dependent Variable	**Fitted Distance**		
	R^2	**Adjusted R^2**	***p*-value**
Tracer	1.00	1.00	**0.000***
Nitrate	0.65	0.64	**0.000***
E. coli	0.63	0.62	**0.000***
TDS	0.05	0.04	0.075

Figure 5-9 shows the distance comparison between all 64 wells analyzed (red boxplots) with those wells that contaminants levels are within the WHO guidelines (blue boxplots). The minimum fitted distances for nitrate, *E. coli* and TDS were found to be 18.4 m, 32.3 m and 4.0 m respectively (Figure 5-9). Results for TDS do not show a large variation between fitted distances for TDS for all wells with those wells that were within WHO guideline which is due to weak correlation and regression results as shown earlier. The recommended minimum distance was selected from the largest value between nitrate and *E. coli* for concentration levels that met WHO guidelines, thus, the minimum distance was found to be 32.3 m (Table 5-5).

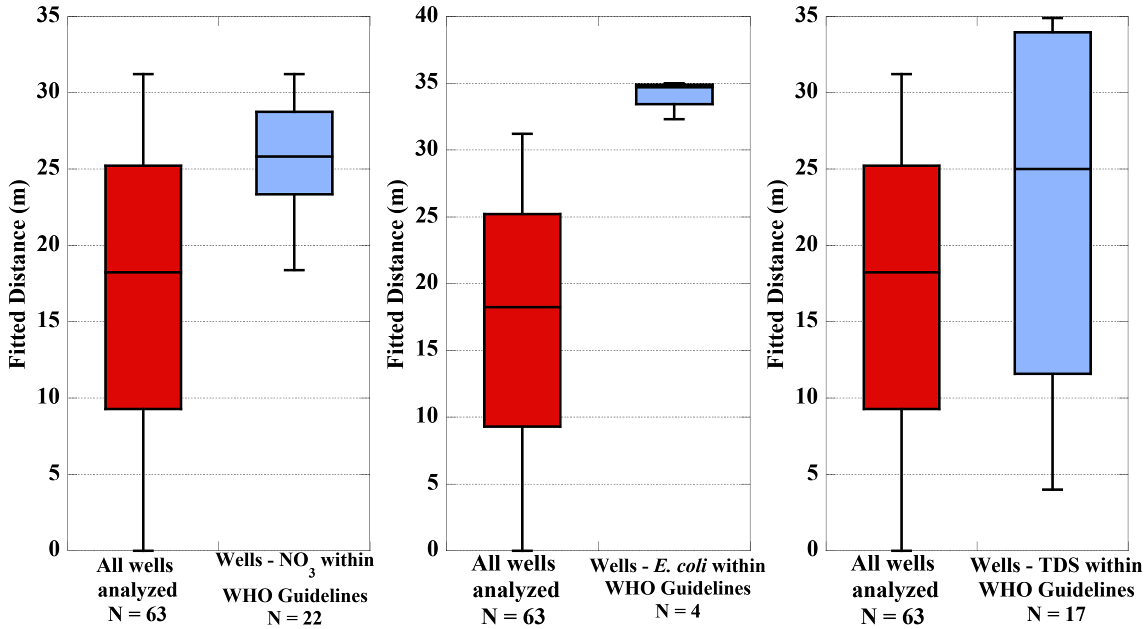


Figure 5-9. Box plots showing the upper adjacent, median and lower adjacent values of fitted distance for all wells analyzed (blue box) with wells that met WHO standard (red box) for nitrate, *E. coli* and TDS levels

Table 5-5. The recommended minimum distance based on the fitted distance from the wells to pit latrines

Water Quality Parameter	**Fitted well setback distance within WHO guidelines (m)**	
	Max	Min
Nitrate	31.2	26
E. coli	35.0	**32.3****
TDS	**34.9***	**4.0***
Recommended minimum distance 32.3 m		

**Not relevant due to weak correlation and with distance and tracer*
***Maximum number among the minimum setback distances*

5.4 Discussion

Bivariate correlations between contaminants and tracer concentration supported our first hypothesis that there is a strong correlation between tracer and water contaminants (nitrate and *E. coli*). However, TDS did not show a significant correlation. Linear regression analysis showed that there is relationship between distance with the tracer and contaminants. This is consistent with the statistical analysis reported by Ngasala et al. (2019), which indicated that it was plausible that the three contaminants (nitrate, *E. coli* and TDS) originated from pit latrines, but the results present here provide further evidence that nitrate and *E. coli* originate from the same source while TDS does not. Since the study area is peri-urban and there are no agricultural activities or known waste dumping, the only source of nitrate and *E. coli* is believed to be from human waste. The reason of weak correlation with TDS could be because the source of the TDS is due to saltwater intrusion rather than from sewage contamination since the study area is located within ~7 km of the Indian Ocean.

Our results also supported the second hypothesis that based on the soil types and aquifer properties in our study area, the distance simulated from the groundwater model is greater than minimum well setback distance of 15 m according to CDC (2009), Sphere Project (2011) and WHO (1992). Bivariate correlation between distance from the well to the pit latrines and tracer showed a strong negative correlation. These results are similar to that presented by Ngasala et al. (2019) who found that there was a strong negative correlation between distance and nitrate and *E. coli* but weak correlation for TDS, suggesting that TDS levels may not be related to distance. Out of 64 wells analyzed, 68 % of the wells were located less than recommended distance of 15 m, with an average of 10.6 and the shortest distance was 3 m. Additionally, 24% of all wells were shallow wells with a depth less than 15 m, and the rest are deep wells with up to 120 m deep. Linear regression results showed a significant difference between shallow wells and deep wells although as combined, the showed high R^2 which explained the results.

Only 32%, 6% and 27% of the wells had nitrate, *E. coli* and TDS levels that met WHO drinking water guidelines. The minimum residual tracer concentration ($\frac{C}{C_0}$) detected in wells that met WHO standards was 0.01 (1%) and the maximum was 0.41 (41%) with an average 0.19 (19%). Results from linear regression analysis showed the maximum fitted distance from pit latrines to be 32.3 m. Strong correlations for distance and tracer suggest that contaminants are originating from nearby pit latrines and the risk of domestic well contamination increases as the distance to the pit latrine decreases. Our findings support those of Kiptum and Ndambuki (2012) who determined that the minimum distance a well should be placed from a latrine is 48 m. The study was conducted in Langa, Kenya, where residents rely on groundwater sources. Using MODFLOW modeling with the particle tracking tool (PMPATH), they found that an average velocity that a particle can travel is 1.2 m/day. The longer it takes for a particle to travel, the better the filtration process that will minimize the contamination of wells.

Not surprisingly, our results also showed that deep wells are less likely to be contaminated by seepage from proximate pit latrines than are shallow wells. Based on our modeling results, wells that had depth of were 15 m or less were more contaminated and distance had more influence in those wells than deep wells. Water quality in shallow wells were significantly impacted by pit latrines within the study area. Results are consistent with Ngasala et al. (2019) that showed the correlation between contamination levels and depth. Although shallow wells showed to be more impacted, results also showed that some of the deep wells were impacted by the distance because they had high concentrations of contaminants. As found by Glanville et al. (1997), deeper wells do not always guarantee a high-quality water supply. There is other possible reason for this if the historical land use surrounding this per urban area was agriculture, and if the use of agricultural fertilizers (nitrogen fertilizers in particular) was significant. In our case, close proximity of wells to latrines could be one of the factors especially if septic tanks or pit latrines are placed upgradient from the well. Deep wells might have good quality of water at the beginning, then with time decrease the quality if sewage contaminants introduced at upgradient locations in the flow system reach deeper into the aquifer overtime (Wilcox et al., 2010). According to WHO (1997), septic tanks or pit latrines should be placed down gradient from the well. For public shallow wells serving multiple households, they can be drilled deeper to minimize the chance of being contaminated. The source-water protection can be more easily accomplished for a single well that serve multiple homes and for numerous wells scattered throughout a subdivision.

Groundwater modeling can be applicable in highly populated cities where groundwater contamination is common. Contaminants such as nitrate have been researched more in both surface water and groundwater modeling due to the nature of its source. Obviously, in areas with high number of pit latrines have shown the higher nitrate load as it was found by Rios et al. (2013) who compared two neighborhoods, and found that there was a big difference between the two areas due to a smaller number of pit latrines and higher denitrification rate at one of them.

According to the model results presented, the present regulations nationally and internationally regarding private well construction and setback distances are insufficient to protect drinking water quality in unsewered overpopulated peri-urban areas of Dar es Salaam. One of the challenges for implementing drinking-water protection measures in per urban areas of Dar es Salaam is government regulations do not explicitly give local entities the authority to regulate well construction or setback distances at the local level. As noted by Wilcox et al. (2010), since literature has not covered site-specific variables such as soil type, geology, or groundwater flow direction, therefore these findings are not surprising. In Tanzania, groundwater is heavily used not only in urban areas, also in rural areas where both shallow and deep wells are common. The major benefit of the approach we have used in this study is that it can be applied to in other peri-urban areas or in regions with different hydrologic information and provide a scientifically based method for designing private water supplies.

5.5 Conclusion

In this paper, we expand upon the work of Ngasala et al. (2019, 2018) that assessed the water quality from various sources and then evaluated the factors affecting water contamination in domestic wells. In this work, using numerical modeling we were able to estimate the site-specific minimum distance that drinking water wells can be placed from pit latrines by incorporating site specific data such as hydrogeology, soil properties, and rainfall, and then used a tracer to represent sewage contaminants emanating from the leaky pit latrine. Simulated tracer concentrations were correlated with well contaminants (nitrate, *E. coli* and TDS) to determine the recommended minimum well setback distance.

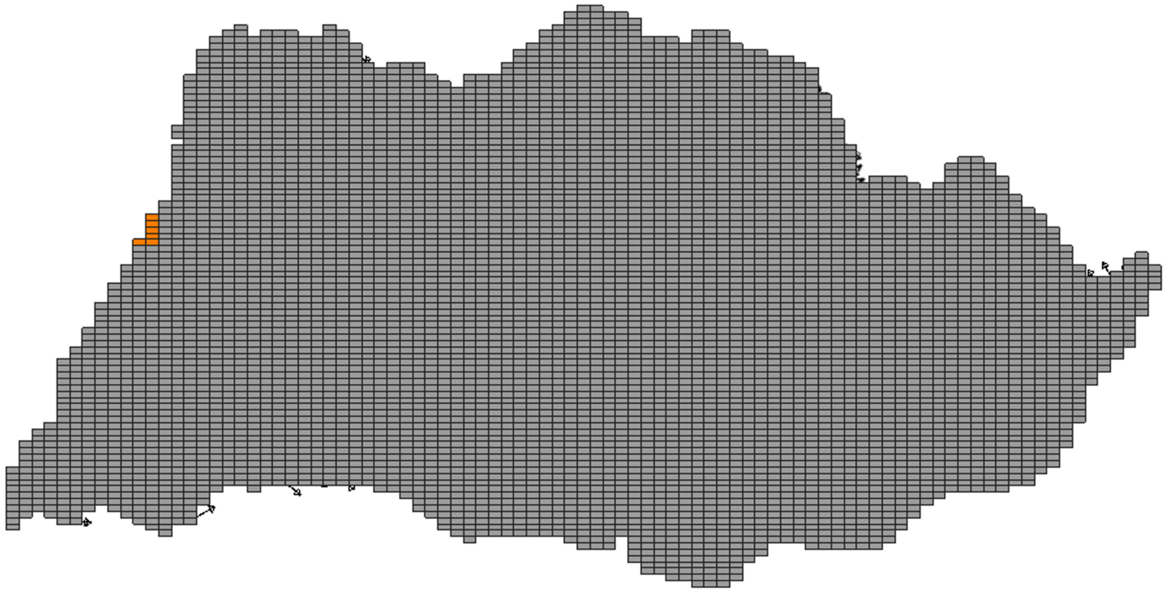
According to the results of contaminant transport modeling, the wells showed to be contaminated significantly. The minimum "safe" distance to place the drinking water well was found to be 32.3 m. The results also indicated that groundwater flows at an average rate of 0.67 m/day. The distance can aid in reduction of contamination because it subjects the contaminants to a longer travel time from a latrine to a drinking water well which will allow the filtration process of any pollutants (Kiptum & Ndambuki, 2012). To prevent contamination of water in the wells, it is recommended that lining to the wells especially for shallow wells and concrete covering be done to prevent surface runoff and spillage from entering the well. For the wells that are already too close to pit latrines, it is critical for the residents to treat that water before drinking by using affordable household treatment methods such as boiling or chlorination.

In the future, if at all possible, the wells should not be placed less than 32.3 m (~33 m). In areas where it is impossible to meet this standard due to close proximity of houses, decentralized water supply systems such as having community wells that will serve small enough number of homes instead of having too many wells in the community will help minimize the contamination. Additionally, treatment systems can be applied to points at or near these community points where drinking water is consumed, at either the household or community level. This can be done through community water committees, community members themselves as well as the leaderships of local governments. Proper wastewater and sewage management can help minimize contamination significantly. We highly recommend proper construction of the pit latrines and septic tanks in the area by following the engineering requirements and standards in order to reduce sewage leakages into groundwater and overflows into surface water sources. Additionally, decentralized wastewater collection and treatment systems can be introduced in communities to serve small number of households at a time. The capital costs associated with decentralized systems for both water and wastewater can be significantly lower than centralized systems which will results in savings for individual families and to the agencies responsible for water distribution networks (Ali, 2010).

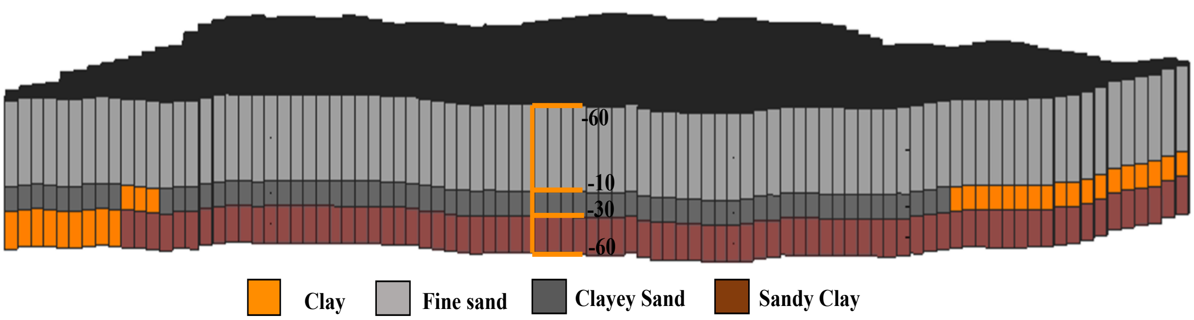
To conclude, groundwater modeling has proven to be a useful tool to understand contamination within an aquifer system in urban overpopulated areas of developing countries. Although the model only considers point sources, nonpoint sources could also contribute to groundwater contamination. The future work for groundwater modeling should consider non-point sources as well as seasonal variations (rainy vs dry seasons).

APPENDIX

APPENDIX



(a) The top view of the 3D conceptual model



(b) The side view of the 3D conceptual model

Figure A5-1. The top view (a) and side view (b) of the 3D conceptual model of the study area with three soil layers, fine sand aquifer, clayey sand with layers of clay aquitard and the sandy clay mixed with clay lenses

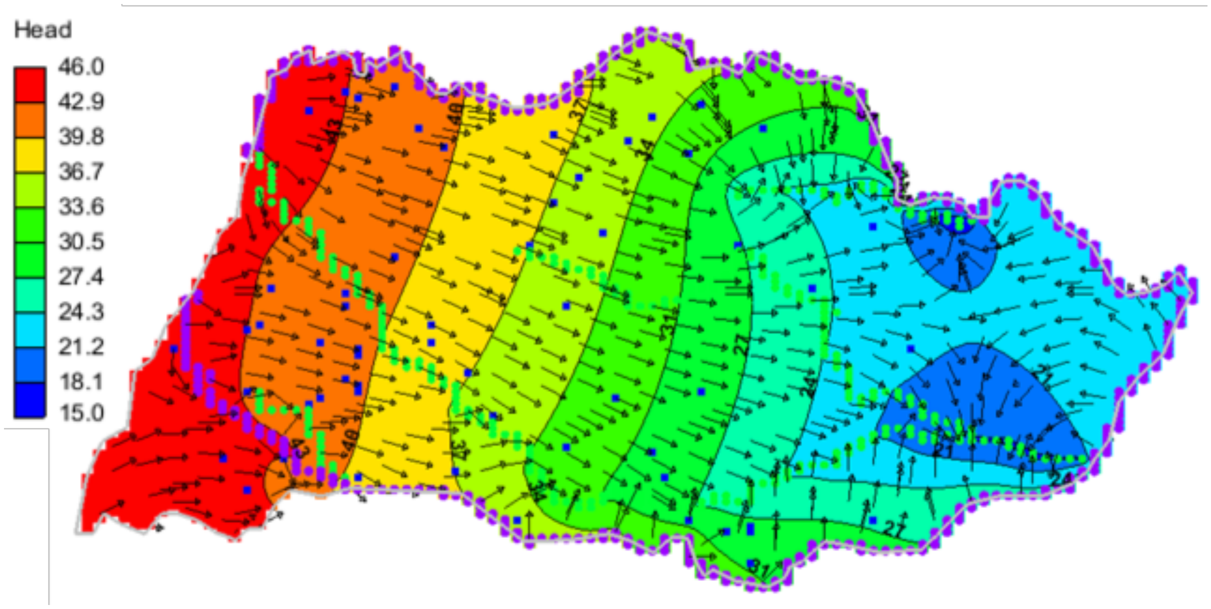


Figure A5-2. A flow vector map corresponding to groundwater flow and calibration of the hydraulic head

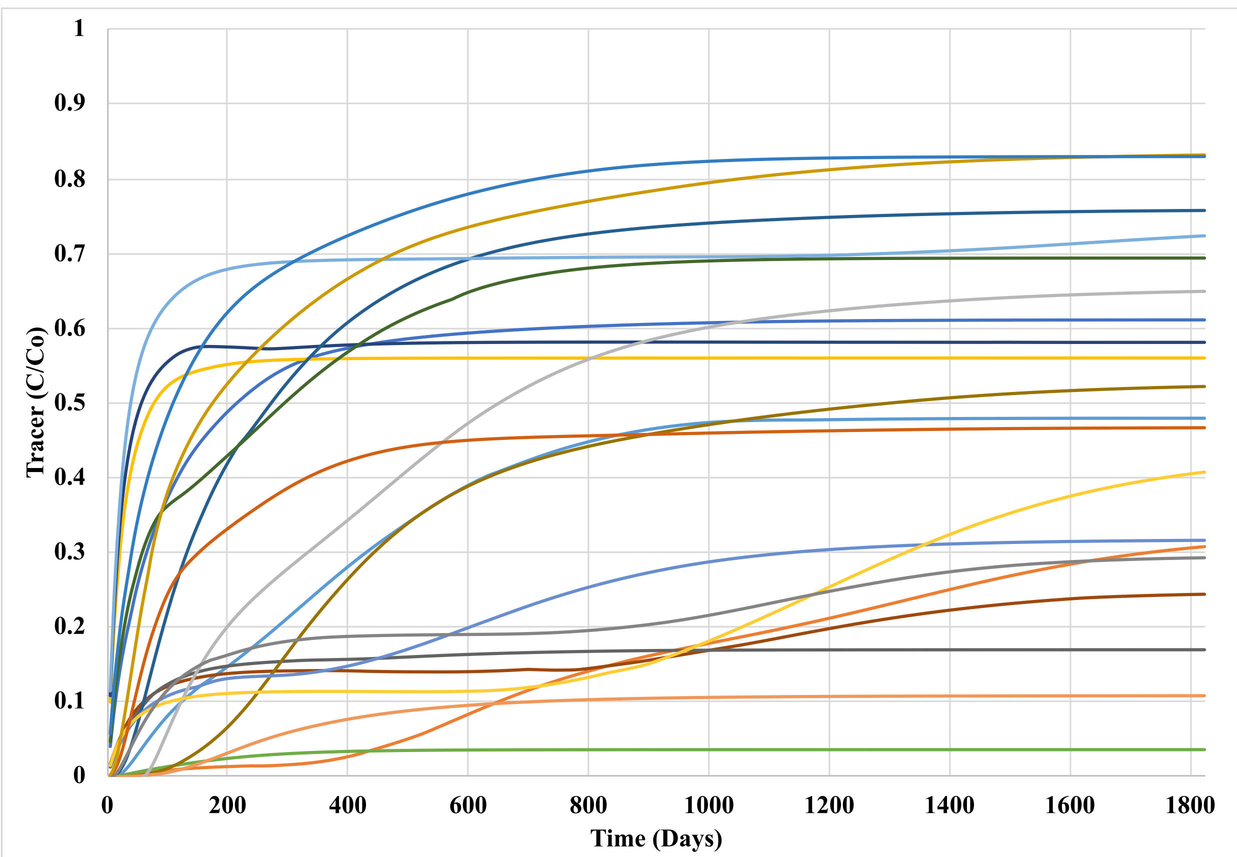


Figure A5-3. Tracer breakthrough curves generated for selected domestic wells

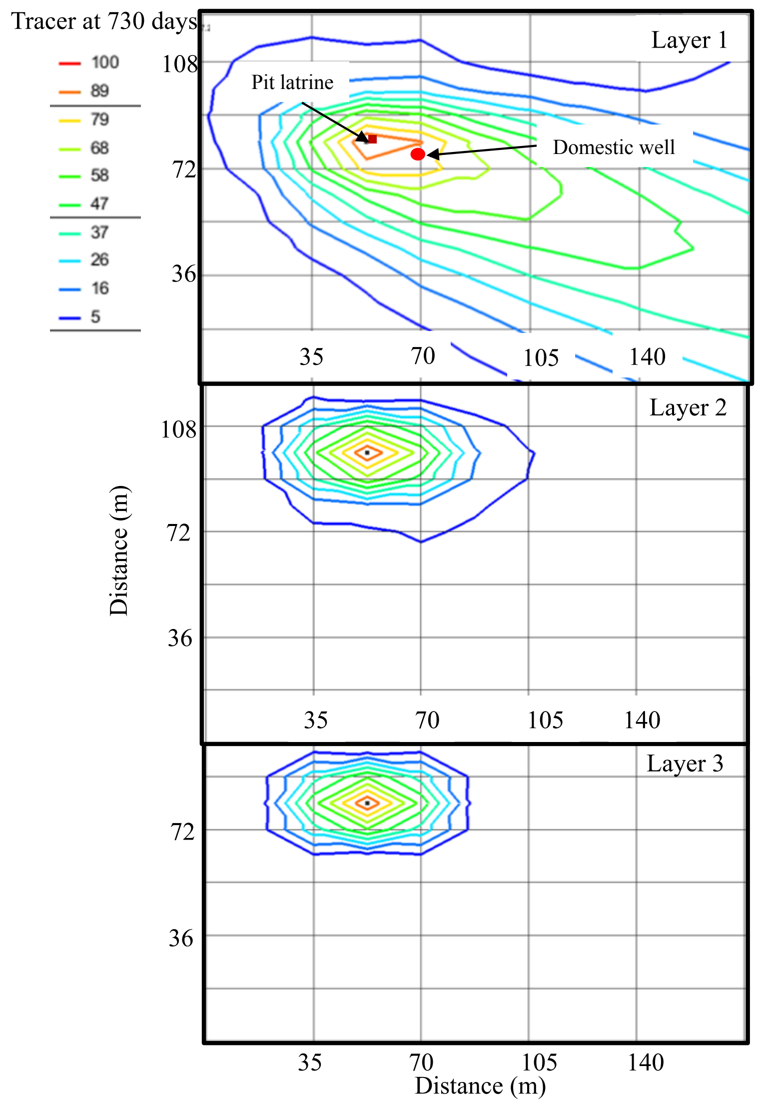


Figure A5-4. Plume migration at 1st, 2nd and 3rd layers after 730 days, showing a well located about 9 m from the pit latrine

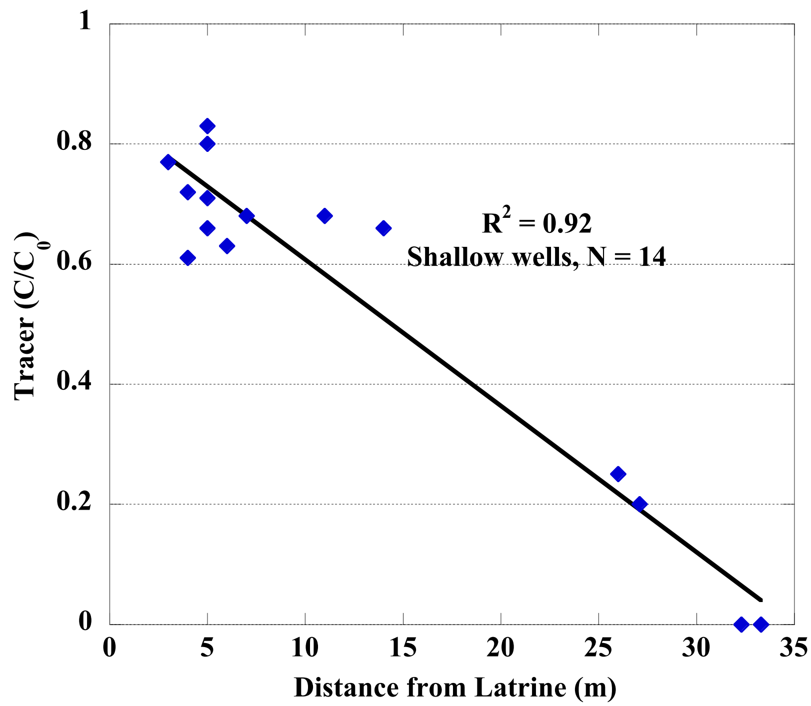


Figure A5-5. Linear regression model results of the measured distance from pit latrine with numerical tracer concentration for shallow wells

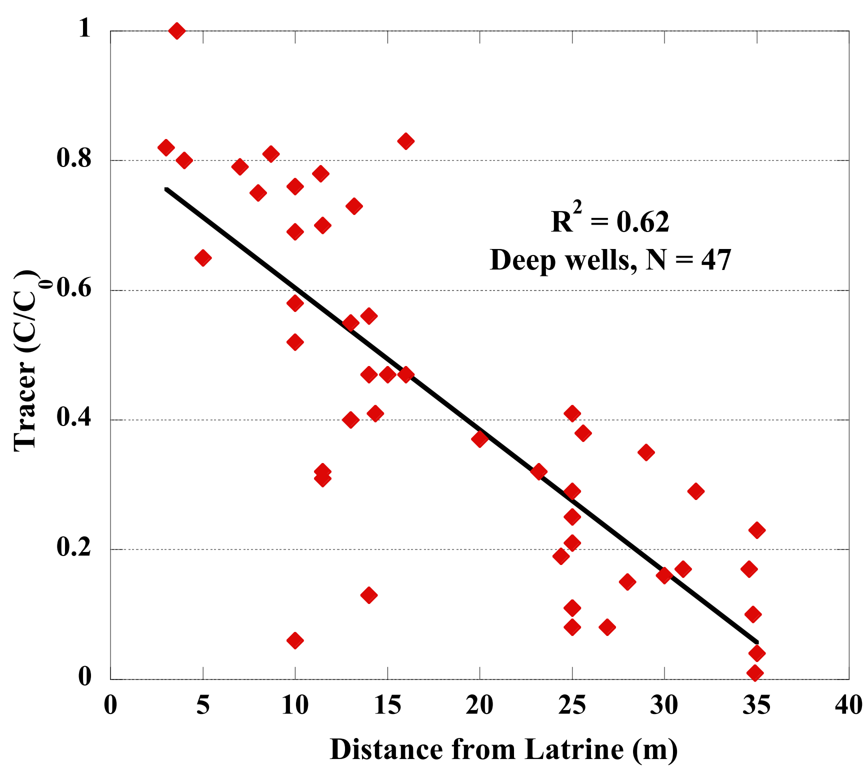


Figure A5-6. Linear regression model results of the measured distance from pit latrine with numerical tracer concentration for deep wells

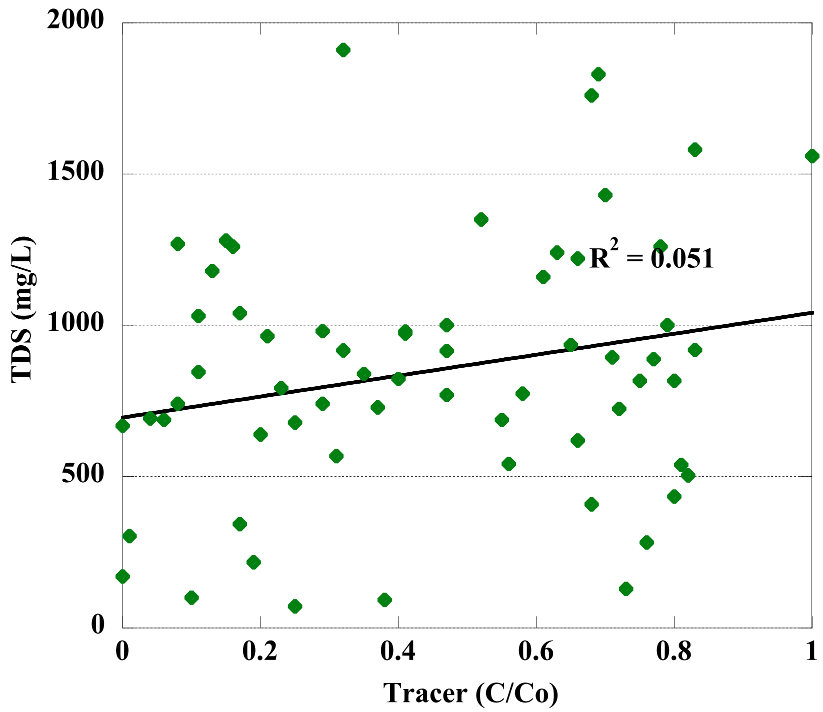


Figure A5-7. Linear regression model results of TDS with numerical tracer concentration for all wells combined

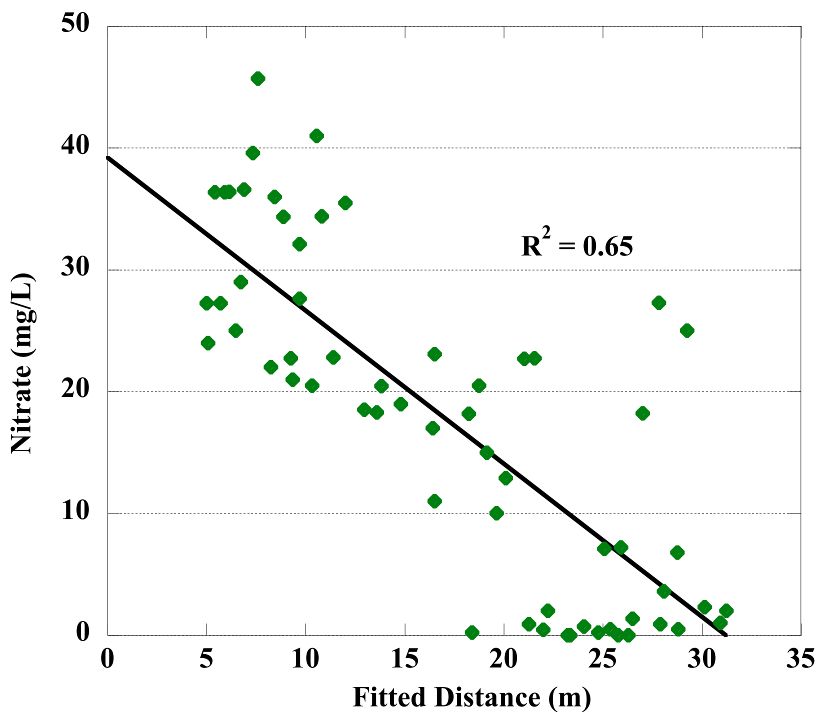


Figure A5-8. Linear regression model results of fitted distance with nitrate for all wells combined

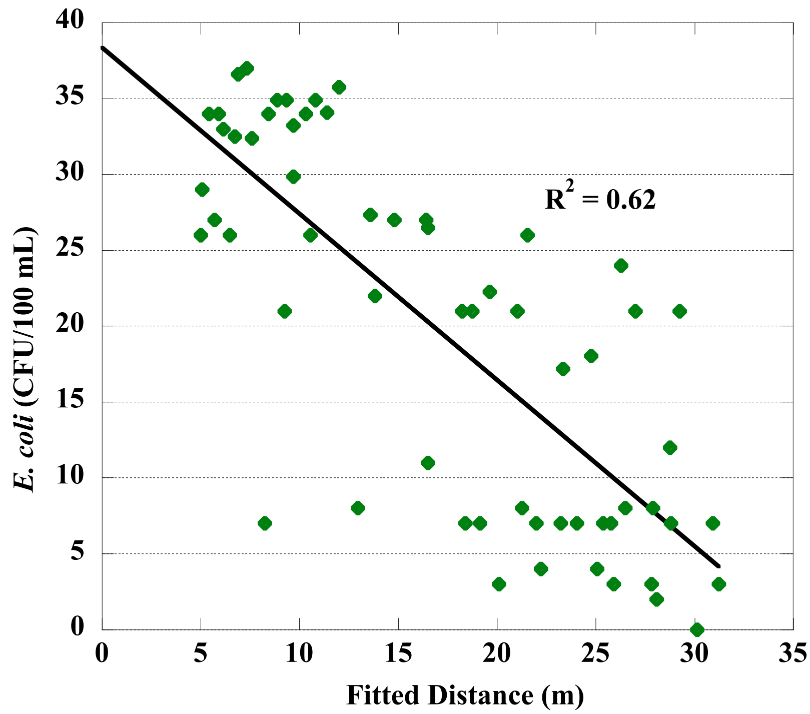


Figure A5-9. Linear regression model results of fitted distance with *E. coli* for all wells combined

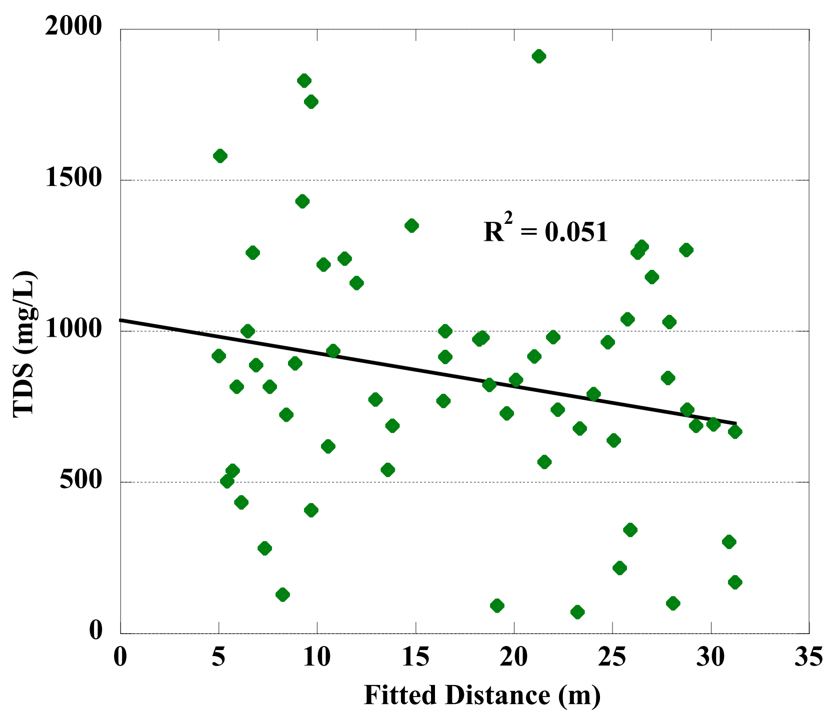


Figure A5-10. Linear regression model results of fitted distance with TDS concentration for all wells combined

Table A5-1. Different recommended well setback distances from literature

Source	Distance (m)
CDC, 2009; Sphere Project, 2011; US EPA, 2002	15
NRCS/USDA-NHS, WHO	15-30
Koralegedara & M.M.M., 2013	30
Dzwairo et. al, 2006	25
Still & Nash, 2002	20
Vinger et. al., 2012	12

Table A5-2. MODFLOW model input parameters for the groundwater flow

Model Input Parameters			
MODFLOW	**Layer 1**	**Layer 2**	**Layer 3**
Soil materials	Fine sand	Clayey sand	Sandy clay
Hydraulic Conductivities (m/day)	15.14	0.15	0.0022
Vertical Anisotropy	4	4	4
Horizontal Anisotropy	1	1	1
Starting Head (m)	60	60	60
Top Elevation (m)	60	-10	-30
Bottom Elevation (m)	-10	-30	-60
Porosity	0.3	0.3	0.3
Recharge (m/day)	0.005	0.005	0.005
Packages: Time Variant Specified Head, Drain, Recharge, Well, LPF - Layer Property Flow			

Table A5-3. MT3DMS model input parameters for the contaminant transport

MT3DMS	Layer 1	Layer 2	Layer 3
Model Parameters	Unit	Value	Value
Longitudinal dispersivity, α_L	20	20	20
Horizontal transverse dispersivity, α_H (m)	2	2	2
Vertical transverse dispersivity, α_V(m)	0.2	0.2	0.2
Initial concentration of the tracer (mg/L)	100	100	100
Packages: Advection, Dispersion, Source/sink mixing, Transport observation			

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REFERENCES

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CHAPTER 6: Conclusion

6.1 Summary

This study showed that there is an urgent need to address the public health and environmental problems related to water scarcity, sanitation, water quality, and household hygiene practices in the highly populated peri-urban areas of Dar es Salaam. The assessment of water collection and storage practices at the household level confirmed that poor water storage and mixing practices in the study area were the main cause of the contamination of the relatively clean city water at the household level. Water quality results showed that there were differences in water quality from each water source analyzed, and statistical analysis identified the predominant reasons that residents mixed water prior to and during storage. Unfortunately, the residents were largely unaware of variations in the quality of their water between sources and therefore used storage practices that led to contamination of the water of highest quality (city water). Findings also indicated that respondents made these choices because of lack of education and because of financial barriers.

The contamination of domestic wells in the study area was found to be due to the short distance from drinking water wells to pit latrines. Shallow well depth also contributed to contamination. The problem of contamination of wells is exacerbated because the wells are bored into fine to medium sand aquifer material, which is highly permeable. Site-specific distances for the separation of domestic wells from pit latrines were developed using simulations of groundwater flow and contaminant transport that considered variations in hydrogeological conditions. Based on the soil characteristics of our study area, the minimum recommended distance to locate the drinking water well from pit latrines was ~33 m, which is greater than the distance recommended by (WHO, 1992) and (CDC, 2009) and also greater than the average distance between most homes which is between 5 - 10 meters. The density of homes in the study area is about 14,250/km^2.

6.2 Recommendations

Proper management of water sources requires interdisciplinary approaches by involving community members, governmental officials, members of educational institutions, public health personnel, and other stakeholders. Programs that educate, inform, and galvanize the residents of peri-urban areas like Dar es Salaam to take actions that will protect their health are critically needed. To succeed, the community members must feel empowered. They must believe in measures that have been recommended and know that they have control over their situation in ways that will effectively protect their health. Based on the findings of this study, the following recommendations are suggested within the integrated approach that addresses education, engineering technology, and social aspects:

6.2.1 Engineering and Economic Aspects

Traditional centralized water supply systems are not feasible in peri-urban areas of Dar es Salaam due to economic and technical reasons. Decentralized systems for both water supply and wastewater management are recommended as a cost-effective engineering solution to improve water access and minimize contamination. Decentralized systems refer to the small-scale water supply or sewage management systems for communities and buildings, serving between 50 and 500 households. They can be an alternative to centralized systems due to their ease of use and maintenance, along with reduced gas or fuel consumption and cost.

Decentralized Water Supply

The existing centralized water supply system in Dar es Salaam failed to meet the demand of the community due to rapid population growth, poor infrastructure and outdated, under-sized water treatment and distribution systems. Instead, decentralized water supply systems could meet the needs of the communities due to their low capital and operating costs. In addition, they can be easily right-sized for a specific community. There are a wide range of decentralized water supply systems technologies that are inexpensive, simple to install, and cost-effective. Since surface water sources in this area are not highly reliable, groundwater (shallow or deep wells) or rainwater are recommended. Pumping costs will be significantly lower as the water does not have to be pumped great distances and the risk of recontamination in smaller networks is low.

Another advantage of decentralized water supply system is that water treatment can be tailored to the community's needs based on source water quality. The use of a decentralized water supply system can help address water quality issues because water can be treated at water source intake before it is distributed to the community. Cost-effective water treatment technologies that are available in Dar es Salaam, can be used in the decentralized system such as heat or radiation methods (e.g., boiling and solar water disinfection (SODIS)), chemical disinfection methods (e.g., chlorination (chlorine tablet, water guard etc). At the source, from the small water treatment system, physical removal processes such as sedimentation or filtration techniques or granular filter media such as bio sand filters, slow sand filtration, and rapid sand filtration can also be used.

Unlike the centralized water supply system, decentralized systems can be independent from an institutional set-up and run locally. The management at the local level is much easier and local community members can be employed for the operation and maintenance of the system. They can be in cooperated with other stakeholders such as small-scale vendors, informal market and small-scale businesses.

Decentralized Wastewater and Sewage Management

In Dar es Salaam, the traditional centralized wastewater management system (lagoons) that was in place have not worked fully for more than 15 years, treating only 8% of the population. Although the system seemed to be cost efficient at the time it was implemented, rapid population growth, poor maintenance of infrastructure and its inability to keep up with the population growth are the main reasons for system failure. Decentralized wastewater systems for sewage management are the best alternative and long-term solution in this community due to their reliability and cost effectiveness such as low capital costs, low operation and maintenance costs, and even promoting business and job opportunities. Additionally, decentralized systems allow for better local management and are simple and effective, as compared to centralized treatment system which are often expensive and challenging to operate. As Jung et al. (2018) found on their cost comparison study, the cost of operation and maintenance of the decentralized wastewater management systems is 20% - 30% less as compared to the centralized system.

Another advantage of decentralized wastewater treatment is greywater recycling. Water recycling can help solve the problem of water scarcity and reduce expenditures for purchasing water and for wastewater management and treatment in peri-urban areas of Dar es Salaam. Greywater used from laundry, bath, showers, and house cleaning can be recycled for reuse. Water produced from the recycling process can be used for cleaning toilets, house cleaning, laundry, etc. Since the system is locally operated and managed, local community members can be employed for the operation and maintenance of the system and people will feel more responsible of their treatment system may pay more attention to the issues of greywater.

Alternative Sanitation Practices

Due to poor road access to some of the homes in the study area, we recommend the use of new and improved ways of sewage management for the collection and transportation to a treatment system. One of the recommended practices is dry sanitation toilets (dehydrating and composting). Dry sanitation toilets allow for the treatment and disposal of human waste without the addition of water. The composted solids can be used as fertilizer. Dry sanitation toilets have the advantage over traditional pit latrines as they are economical, environmentally acceptable, and hygienic. These toilets are commonly used in remote areas, however, increasing environmental awareness has led to some people using them as an alternative to conventional systems even in urban areas of several developing countries (Lachapelle, 1995; Pacey et. al., 1978). The urine is usually collected separately, and the solids are collected in a separate chamber. The main advantage of dry sanitation practice in this community is to minimize the sewage overflow from pit latrines since urine will be separated from solids. As mentioned in Chapter 4, another recommendation is the use of Container Based Sanitation (CBS). These are toilets that collect human excreta in sealable, removable containers that are then transported to a treatment system. CBS could help minimize drinking water contamination in peri-urban areas such as Dar es Salaam, where it is a challenge to manage sewage due to poor road access. CBS can be used in water-scarce areas because it requires low amount of water, it is hygienically safe with proper handling, and is affordable (World Bank, 2019).

6.2.2 Social Aspects

The Tanzanian government should invest in improving access to the city water to meet the demand of this community and the population of Dar es Salaam as a whole. It is highly important to have a good water governance to ensures that water and sanitation services provided by both public and private sectors meet the needs of the people they serve. For the better management of existing water resources and environmental sustainability, proper and effective management of existing water resources and environmental sustainability requires an integrated, cross-sectoral. We recommend the implementation of Integrated Water Resources Management (IWRM) with the main responsibility of addressing the growing demands for water. As suggested by UNDP (2004), IWRM is designed to replace the traditional, sectoral approach to water resources and management that has led to poor services and unsustainable resource use. IWRM expands the development objectives to include environmental health and sustainability, human well-being, and women's empowerment. It addresses the interlinkages between these important areas and makes possible the realistic assessment of trade-offs (UNDP, 2004). Additionally, it is critical to increase the number of women working in the urban water supply management systems through operation and maintenance, water distribution, policymaking and regulations. According to World Bank, water projects that included women were about seven times more effective than those that did not.

Regulations

One of the effective ways of helping this community and others in peri-urban areas of Dar es Salaam increase access to water and sanitation is through community-based institutions, however, these institutions need good support to advocate effectively for their needs and manage resources fairly and sustainably. Enforcing regulations is critical to ensure that community-based institutions are functional and public health is protected. More importantly, regulations must be supported by adequate policies, programs, guidelines, standards and codes of practice. This includes holding responsible those who tamper with the existing systems including those who tap illegally into the city water supply.

Water Vendor Unions

Small-scale water vendors provide an important service for households in this community and in the city of Dar es Salaam as a whole, however, there are many challenges that community members and vendors themselves face, such as poor water quality, high cost and reliability of water. There is a need for more regulatory supervision through the local government to address these issues related to informal water delivery from water vendors. One of the recommendations to address these challenges is to develop mechanisms that ensure better standards of the practice. Given our findings, we believe that vendor unions or trade associations may help address these challenges. These unions should have vendor membership and community engagement to improve the quality of water delivery services. Organized water vendor unions should involve community meetings and advisory boards to improve water delivery outcomes by facilitating vendor cooperation around the establishment and enforcement of rules and norms.

The role of the unions could include:

- Discussing fair prices for water based on circumstances (e.g., availability and demand).
- Hold responsible those vendors who charge more than they should or refuse to give service to those who live far from populated areas or on rough roads.
- Be aware and participate in the development, implementation, and enforcement water quality standards

- Hold regular community meetings to discuss complaints from community members and to assess delivery and treatment
- Be available for emergencies, such as during fires or droughts

Latrines and Well Sitting

Enforcing standards and regulations for siting and proper construction of septic systems or latrine in this area will help better manage sewage and address challenges related to poor road access and lack of sewerage systems. Sanitation could also be improved through the development and enforcement of standards for the siting of domestic wells. These standards should be based on the depth of the proposed wells, the type of sanitation system, the pumping rate, and hydrogeological properties. Where latrines operate at greater than their design capacity, additional latrines should be constructed except in areas where latrines and drinking water wells are already in close proximity. In this case, other proposed sanitation practices can be implemented as mentioned earlier in this chapter. Additionally, we recommend proper training of local masons in the construction of raised, lined, and ventilated improved pit latrines as well as the use of the compositing latrines (dry sanitation and container-based sanitation practices).

Education and Capacity Building

Programs for sanitation and public health as well as capacity building for public health workers should be developed and made freely available to the community. There is evidence from literature that health education can significantly reduce water contamination at the household level (Metwally et.al., 2007). One of the ways to improve hygiene is to implement integrating hygiene promotion and environmental awareness-related interventions. Through governmental and non-governmental organizations, hygiene promotion should involve 1) interpersonal communication, such as house-to-house visits, public support meetings, as well as the development and distribution of promotional materials such as posters, flyers, and booklets; and 2) education efforts related to personal hygiene such as hand washing, especially after using the toilet, before eating, before preparing and serving food, and personal hygiene for children. Other relevant practices that can be taught to the community are proper drinking water storage and proper use and maintenance of latrines, for example, covering the latrine while not using it. In addition, it is necessary to implement a multi-barrier approach such as improving the availability of affordable and reliable water storage containers to help residents make better decisions when storing water.

At the household level, education to promote better choices of water treatment technologies will help improve drinking water quality. Basic education about household water treatment methods such as boiling, use of inexpensive water filters, chlorine tablets, and UV light disinfection, could provide a multi-barrier system to protect water quality. Additionally, community education about the quality of water sources is the key to improving water quality and human health at the household level. When residents become aware of the differences in water quality from different sources, it will change their perspective and will encourage them to pay more attention during storage. The key is to empower the community so that they feel that they are responsible for making changes in their own community. Once the community is aware of the condition of their water, education about proper water storage practices along with cost effective household drinking water treatment methods can be implemented.

6.2.3 Future Work

Based on the findings of this study, the following are suggestions for future work:

1. Future studies should focus on the larger scale surveys and controlled studies to better assess serious problems related to poor risk perception, low self-efficacy, and low response self-efficacy.
2. We acknowledge that other sources of contamination and other factors that may have impacted contamination to water sources, were not covered in this study. Future studies should focus on other factors such as the size of the well opening, means of collecting water such as using buckets, seasonal variations in rainfall patterns, and spatially variable soil and aquifer material characteristics.
3. Given the high number and frequency of pit latrine use in our study area, future studies should focus on additional contaminants beyond standard indicators, monitor temporal changes in water quality parameters, climate change, and evaluate alternative technologies that can be used for water quality analysis.
4. The groundwater model only considered point sources; however, nonpoint sources could also contribute to groundwater contamination. The future work for groundwater modeling should consider non-point sources that could be the source of groundwater contamination as well as modeling surface water sources such as river and lakes and interactions between hydrologic domains.
5. This study was done during the dry season, future work should focus on the wet season as well for the seasonal variation comparison of water quality.

It is hoped that based on the work done so far, some insight has been provided about the way forward in addressing some of the enduring and endemic public health and environmental conditions.

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