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THE IMPACT OF A PRIVATE WATER ENTERPRISE
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A DISSERTATION APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

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List of Acronyms

AD	Access Development
CBM	Community-based Management
CWSA	Community Water and Sanitation Agency
GHS	Ghanaian currency (cedis)
GSS	Ghana Statistical Service
HAP	Hydrogeological Assessment of the Northern Regions of Ghana Project
IK	Indicator Kriging
JMP	Joint-Monitoring Programme
LCC	Life-Cycle Costs
ME	Mean Error
MPN	Most Probable Number
OK	Ordinary Kriging
OR	Odds Ratio
PSM	Private Service Delivery Model
RMSE	Root-mean-square Error
RMSSE	Root-mean-square Standardized Error
RWSN	Rural Water Supply Network
SDA	Service Delivery Approach
SDG	Sustainable Development Goals
SWE	Safe Water Enterprise
UCS	Uniaxial Compressive Strength
UER	Upper East Region of Ghana
USDA	United States Department of Agriculture
UNDP	United Nations Development Programme
WASH	Water, Sanitation, and Hygiene
WHO	World Health Organization
WMC	Water Management Committee

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Abstract

The goal of this dissertation is to investigate the effectiveness and sustainability of a private water service delivery model in a rural, developing context. Recent studies have found evidence for greatly increased reliability and functionality rates, faster breakdown response times, and increased revenue for water systems managed by these novel service providers (Bey, V., Magara, P., & Abisa, 2014; Kayser et al., 2014; Koehler, Thomson, & Hope, 2015). In Chapter 1, we show how other historical paradigms have claimed improved water provision in the past, but various issues prevented government, public, community, and private providers alike from providing safe, continuous water supply in developing contexts. It is imperative that the service delivery approach be carefully evaluated to guard against similar challenges while identifying potential risks. This work will investigate Access Development (AD), a private service delivery model in Ghana. Results and discussions will use institutional, technical, financial, social, and environmental perspectives to craft a holistic understanding and assessment of this approach.

In a recent assessment by the World Bank (2017), the authors called for a better understanding of water facility performance, service level received, and performance of the rural water providers. In order to address this need, Chapter 2 evaluates the overall water service of a private safe water enterprise as compared to historical management systems in the rural, developing context of the Wassa East District. A quasi-experimental design used key informant surveys, household surveys, and water quality testing to investigate the service received by households under various management schemes. Service indicators were compared using logistic regression analysis. Given the nature of private providers and the pre-payment required, it can be hypothesized that overall, the district will benefit from improved service, but the quantity of water collected, and the penetration rates, will be lower for those in poor socioeconomic classes.

The results showed that AD Users received significantly improved water service as compared to non-users for the following indicators: water quality (fecal contamination, secondary disinfection), accessibility (distance), reliability (annual uptime), and acceptability (odor, appearance). No significant difference in service provision was observed for quantity, congestion, lather, and taste. However, Users received significantly lower scores in affordability and daily availability. Further, private customers were more reliant upon multiple water sources to meet domestic needs ($p<0.05$). Although there were slightly increasing trends, penetration ($p = 0.43$), water quantity collected from AD sources ($p = 0.10$), and the Joint-Monitoring Programme (JMP) service ($p = 0.17$) from AD water sources were not significantly affected by relative wealth. This evidence shows that both poor and rich households were being served by private kiosks under the current model.

The performance of a service delivery model will inherently affect its penetration rate, or the proportion of households within a given service area that purchase its water. It can be hypothesized that Access Development, acting as a communal water provider, will be unable to reach a penetration rate approaching 100% as long as existing competition is readily available. Chapter 3 discusses this phenomenon and its relationship to financial sustainability. A cross-sectional assessment of sixty rural communities was used to evaluate the market share of the private service provider. Household survey results for motivations, willingness-to-pay, and actual spending were used to develop a customer profile. Distance, taste, appearance, and affordability were found to be the most common motivational drivers. Using this information, a Huff gravity model was developed to assess the actual and potential market share for the company in each community. While the model and actual results agreed that about 39% of respondents would be regular customers at the given price, the attractiveness of other sources would make it difficult to capture more than 58% of the sampled households, even if water was free.

The hydrogeological setting is important in understanding the resource availability and limitations of the water service provider. Chapter 4 outlines the process of producing a manual drilling feasibility map for the Upper East Region of Ghana. This coincides with potential groundwater exploitation for the Precambrian Basement in West Africa. While regional siting techniques have been developed in the past, this type of assessment had not yet been conducted in Ghana (Danert, 2015; Fussi et al., 2017; Martínez-Santos et al., 2017). Variables of interest include well yield, static water depth, laterite thickness, depth to hard rock, water quality parameters, and the degree of weathering. Indicator kriging is proposed as an interpolation method that builds upon previous efforts to identify suitable zones for manual drilling, particularly in weathered crystalline basement aquifers. This approach allows for heterogeneity within weathering profiles and provides probability mapping of success for regional planning. Indicator kriging interpolations for depth to hard rock predicted binary variables with over 90% accuracy. The model predicts that drilling into highly weathered layers will often be necessary to reach the required depths for groundwater use, emphasizing the importance of percussion techniques in the Precambrian Basement.

1. Introduction

In an effort to end poverty and fight inequality, world leaders adopted the United Nations' seventeen Sustainable Development Goals (SDGs) in 2016. SDG 6 strives to ensure the availability and sustainable management of water and sanitation for all. It has been estimated that 1.6 million deaths per year and 105 million Disability-Adjusted Life Years (DALYs) can be attributed to inadequate water, sanitation and hygiene, with about 485,000 deaths per year from diarrhea caused by inadequate water supply alone (Prüss-Ustün et al., 2019). Approximately 10% of the population, or 785 million people, still require access to basic drinking water service (UNDP, 2019). Taken a step further, 60% of the world population is exposed to health risks associated with using untreated or unimproved water sources (Bhatnagar et al., 2017).

Even when a given population gains access to an improved water supply, it can still be limited by unsafe water quality, interrupted service, or permanent failure (Fisher et al., 2015). For instance, a water source may be at risk due to poor construction quality or external contamination. There could be seasonal changes in groundwater levels, vandalism, or an uncertain supply of replacement parts that cause inconsistent service. This may lead people to return to unimproved sources and greatly reduce any health gains from safe water (Hunter, Zmirou-Navier, & Hartemann, 2009).

Development researchers have identified a multitude of hydrogeological, technical, financial, and social factors that contribute to sustainable water services (Fisher et al., 2015; Foster, 2013). Low borehole functionality rates can be caused by inadequate financing, limited training and capacity, and undefined roles of decentralized government (Mandara et al., 2013). Management needs proper institutional support, including monitoring and evaluation and specialized technical assistance over time (De Armey, 2015). All of these diverse, multidisciplinary, factors contribute to the conclusion that previous approaches to water management need to be improved or changed (Chowns, 2015; De Palencia & Pérez-Foguet, 2012; World Bank, 2017).

For these reasons, new service delivery models are taking shape in order to more effectively and consistently provide clean water to communities in developing countries (RWSN, 2019; Smits et al., 2016). This dissertation will investigate a private water company in Ghana, called Access Development, in order to better understand the service delivery approach to rural water provision in developing contexts.

1.1 - The Evolution of the Rural Water Sector

Policy and recommended practice for development in the WASH sector has evolved over time from a focus on infrastructure towards sustained access and quality service (UNICEF, 2016). There has been an emphasis on decentralization and attempts to disseminate resources (World Bank, 2017). Improved water sources are primarily built through demand driven processes rather than recommended supply (Sara & Katz, 1997). Water has been defined both as a human right and an economic good (ICWE, 1992; Salman & Mcinerney-Lankford, 2004), instigating debates around the ethics of paying for water and the role of privatization (Sultana & Loftus, 2015). A number of alternative service provider options have grown out of each of these various schools of thought, with community-based management (CBM) being the predominant form used in development (World Bank, 2017). Figure 0.1 illustrates some prevailing schools of thought that led to the service delivery approach paradigm (Lockwood & Smits, 2011; Mandara et al., 2013; World Bank, 2017).

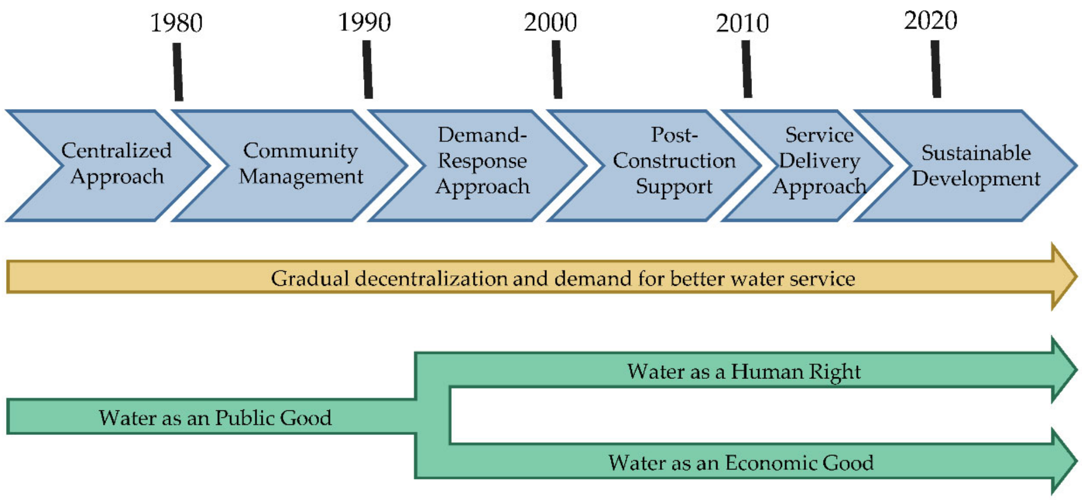

Figure 0.1 Evolution of paradigms in the rural water sector

First, let's examine the present perception of decentralization as a method to achieve sustainable development. Decentralization can be defined as "the transfer of authority and responsibility for public functions from the central government to subordinate or quasi-independent government organizations or the private sector" (Litvack & Seddon, 2002). This policy is being implemented across the world, in nations of various sizes, wealth, and history (Manor, 1999). Ideally, this concept has been designed to increase equity, local participation, economic growth, and accountability of the government to its citizens (Faguet, 2014). In water and sanitation, there is meant to be a division of power and resources between the national, service authority, and service provider levels to create and maintain appropriate infrastructure (World Bank, 2017). Yet, the success or failure of decentralization policies is very mixed, and political instability and corruption can interfere with consistent results (Faguet, 2014).

The ideals and deficiencies of decentralization can be observed in practical application for WASH in Tanzania (Mandara et al., 2013). Most commonly, this policy has led to the promotion of community involvement through water management committees (WMC) in order to increase local input and maintain the system. Yet, the authors conclude that insufficient transfer of resources or power, mixed technical capacity, and unclear stakeholder roles can interfere with the consistent functionality of their water sources. This has led to the present consensus: when the process of decentralization is incomplete or governance is limited, institutional support needs to be in place to fill voids that can negatively influence the sustainability of WASH infrastructure (Khanna & Palepu, 1997; Mair & Marti, 2009).

After decentralization policies took root, supply-driven implementation was rejected in favor of the demand-responsive approach. The supply-driven approach focused on building and implementing water and sanitation infrastructure based on top-down recommended needs, mostly from the perspective of health benefits (Sara & Katz, 1997). In contrast, the demand-responsive approach is intended to identify the quality and quantity of water, the tariff amounts, and the level of service that users want. Ideally, communities could choose an appropriate technology based on their preferences and affordability. This focus on demand correlated perfectly with the idea of increased community voice and involvement at the time. While this is still important in present day policy, the SDGs have brought a renewed focus on safely managed water as a long-term goal (UNDP, 2019).

Demand also fits with the concept of water as an economic good, established in 1992 by the Dublin Statement. At that time, the guiding principle on policy became "all human beings have a basic right to clean water and sanitation at an affordable price"(ICWE, 1992). This was a transition of thinking from the previous concept of water as a public good, with the intention of increased efficiency, shared ownership, and careful conservation of water as a resource (Rogers, De Silva, & Bhatia, 2002). Sustainability of new water infrastructure through cost recovery became a common theme in water management (Savenije & van der Zaag, 2002). Although already in practice in other industries, the statement opened up the doors to the liberalization and privatization of the water sector (Ménard & Peeroo, 2011).

Interestingly, private water provision was very common in the United States in the early 1800s, with up to 80% of urban waterworks run by private companies (Melosi, 2000). At the time, a franchise would likely benefit from long-term contracts, exclusive rights for supply, the ability to acquire property by eminent domain, tax exemptions, and other concessions. Prior to the bacteriological evolution, people were more concerned with easy access and fire protection rather than safe water quality. It wasn't until the 1890s that municipal control of waterworks became more dominant, when more modern systems with pumps, reservoirs, and treatment increased the complexity and expense of operation. This shift occurred due to increased dissatisfaction with private service, high rates, and demand outpacing capacity. In 1925, it was estimated that over 70% of American waterworks were public (Melosi, 2000). By the time the Dublin Statement was made in 1992, much of the developed world may have forgotten these early trends in its own history.

Regardless, private service providers in the water sector grew throughout the 1990s. Unfortunately, some private initiatives, such as in South Africa and Argentina, failed to provide improved water services (McDonald & Pape, 2002; Steurer, 2008). This culminated in arguments over the human right to water. Proponents of this concept insisted that since water was necessary to life, it should be free, and that state provision should preclude other sources (Bakker, 2007; Gleick, 1996). The human right to water movement argued against monopolizing water resources, prioritizing wealthier clients that could pay, unjust cutoffs to clean water sources, and the detriments to health that could occur (McDonald & Pape, 2002; Sultana & Loftus, 2015). Between General Comment No. 15 by the United Nations in 2002, and definitively in 2010 by the United Nations General Assembly, the human right to water has now been firmly established (Salman & Mcinerney-Lankford, 2004).

However, the present paradigm regarding these policies is still in debate. Unlike the consensus on decentralization and demand, water as a human right versus an economic good is still a contested subject (Sultana & Loftus, 2015). The principles are not mutually exclusive in international law and policy, since utilizing the private sector could be considered increasing access to water where the public sector has already failed. This can be demonstrated by attempts to incorporate block tariffs, or different prices based on consumption levels (Liu, Savenije, & Xu, 2003), and differentiating treated, delivered water from natural water resources (McNeill, 1998). This debate is further complicated by the "commons" perspective, where water is essential for life, non-substitutable, and should have localized, community input (Bakker, 2007)

Both private corporations and human right activists can agree that people have a right to water, but, in practice, how a community goes about affording continuous, sustainable, clean water sources can take many forms. For instance, management systems may prioritize water provision over cost recovery, especially where kinship, reciprocity, and water scarcity are involved (Anokye & Gupta, 2012; Schnegg & Bollig, 2016). Alternatively, private sector involvement could provide the entire service or work under a public-private partnership (Ménard & Peeroo, 2011). As another example, informal private vendors may sell water based on high local market prices with no assurances of safe quality, working under few formal regulations (Wutich, Beresford, & Carvajal, 2016). Yet, it can be argued that each example increases the human right to water because public utilities or the local government had not filled some market demand.

As it stands, all of these development paradigms influence the practical organizational forms that facilitate, manage, and provide water services today. At the highest level, service authorities and national entities will often determine policy and financing frameworks, as well as conduct long-term planning, monitoring, and oversight. Typically, these actors are local and national government organizations, NGOs, and international aid organizations. Ideally, the local government directs the local service providers for a given community. In practice, communities often take on the burden of risk and management of water resources, even when they are unequipped to succeed (Hope, Thomson, Koehler, & Foster, 2020).

As shown in Table 0.1, six broad categories can take on the role of service provider: public utilities, the local government, community-based managers, the private sector, NGOs, and self-supply (RWSN, 2019).

Table 0.1 - Management Model for Rural Water Supply (RWSN, 2019)

Type of Management Model	RWSN Code	Description
Community-based Management	CBM-1	Community Based Management – with minimal support.
	CBM-2	Community Based Management with external support.
	CBM-3	Community Management with delegation to private operators.
	CBM-4	Grouping of community managed organizations into large association
Local Government	LG-1	Direct management by government.
	LG-2	Local government with community operators.
	LG-3	Local government with private operators.
Public Utility	PB-1	Public water utility.
Private Service Provider	PV-1	Ministry or asset holding entity delegates service provision company.
	PV-2	Privately owned and operated scheme.
Non-Governmental Organization	NGO-1	International NGO / UN Organisation.
	NGO-2	National / Local NGO.
	NGO-3	Faith-based Organisation.
Self-Supply	SS-1	Self-Supply

Each service provider can either be independent, such as a public utility providing for a city, or work as a team, such as the community-based managers being supported by a larger professional organization. Self-supply is defined by individual households that invest their own resources to make improvements over time (Butterworth, Sutton, & Mekonta, 2013). NGOs are often supported by external donations, and can either directly or indirectly influence other water providers through cooperative endeavors. Local government providers and public utilities both work within the state to manage water resources, either by non-corporatized providers or more commercial entities, respectfully. Private providers may be informal, where local street vendors sell whatever water resources are available to them (sachets, utility water, etc.). Formal private entities may be delegated a service contract by the owners of a water source, or own and operate a water system.

The most dominant organizational form in recent years has been the ideal of community-based management (CBM) (Kyessi, 2005; Mandara et al., 2013; World Bank, 2017). CBM occurs when communities have been delegated responsibility to operate and manage their local water facilities. Internationally promoted by the New Delhi Statement in 1990 (Nicol, Mehta, & Allouche, 2012), CBM was argued to provide indigenous knowledge, local equity and voice, and a sense of ownership. Over time, the long-standing ideal of CBM has shown mixed results of success (Hutchings et al., 2015). It originally was supposed to offer improved technical performance (Chowns, 2015), improved financial sustainability (Briscoe & DeFerranti, 1988), and decentralized responsibility (Salman & Mcinerney-Lankford, 2004). However, evidence has shown that regular maintenance is unlikely, repairs are sub-standard, and there is a lack of proper supervision (Chowns, 2015; Olken & Pande, 2012). In addition, communities have difficulty collecting user tariffs, and savings are typically insufficient to cover actual operation costs (Carter, Harvey, & Casey, 2010; Chowns, 2015; Koehler et al., 2015). Should CBM be successful, regularly scheduled external support through strong local institutions seems critical (Hutchings et al., 2015).

Ultimately, concepts such as decentralization, the human right to water, and the demand-responsive approach are generally accepted. Other concepts, such as the role of privatization and the relevant success or failure of community-based management, are still contested, with differing views dependent on geographic history (Yates & Harris, 2018). Taken together, this brief history of WASH in development helps to paint a picture of the embedded assumptions, rules, and norms that shape and regulate behavior in both international policy and local practice.

1.2 - The Potential Market for the Safe Water Enterprise

The perspectives and lessons learned from the previous three decades led to the service delivery approach (SDA). Building on the definition provided by Lockwood and Smits (2011), the SDA is a conceptual set of principles and policies at the sector level for the provision of water supply services in which the entire life-cycle of the service is considered. This paradigm is defined by the "building blocks to sustainable delivery" (Lockwood & Smits, 2011). Professionalization and capacity building, rather than voluntarism and one-time training events, attempt to embed local technical and managerial expertise. Asset management and life-cycle financing aim to create transparency on the real cost of providing consistent service, and to create a plan to address those costs. Service provider regulation and monitoring of performance pushes for greater accountability and protection for the user. Coordination among different institutional levels, supporting partners, and service providers emphasizes the importance of an enabling environment. Water providers can still fit into the various categories defined in Table 0.1, but the SDA management philosophy focuses heavily on the sustainability of improved water services.

One promising sub-set of the service delivery approach is the 'safe water enterprise' (SWE) (Bhatnagar et al., 2017). A SWE is defined as a decentralized solution that expands access to safe drinking water through market-based efforts. A SWE aims to fulfill both financial and social goals, allowing it to fall under the premise of social entrepreneurship (Dacin, Dacin, & Matear, 2010; Short, Moss, & Lumpkin, 2009). It was estimated that 2.16 billion people could be served by this model with no subsidy required (Bhatnagar et al., 2017). Models can vary in source, treatment, delivery, and payment methods to provide clean water at a price. Some models have shown evidence for covering operational costs, despite low margins, low market penetration, and free competition. However, after factoring in depreciation of capital costs, few have been truly profitable (Bhatnagar et al., 2017; McNicholl et al., 2019). Greater market penetration, operational efficiency, blended financing mechanisms, and innovative business models have the potential to overcome this deficiency.

A wide range of SWE models utilizing the service delivery approach have been characterized, varying in complexity and equity of assets (RWSN, 2019; Smits et al., 2016). Different financing mechanisms aim to recover life-cycle costs and incentivize reliable water service (McNicholl et al., 2019). Service providers can assume different levels of responsibility, such as only responding to emergency breakdowns, providing regular maintenance, or guaranteeing a regular service (Lockwood, 2019). For example, Spring Health manages and delivers chlorinated water to households in India. They take responsibility for their purification system, delivery methods, and employees while charging a regular service fee (RWSN, 2019). Uduma is a private company in Burkina Faso using a build-operate-transfer model, with long-term maintenance contracts for served communities. Fundifix uses mobile tariff payments to support area mechanics in Kenya - each responsible for a cluster of pumps under their service contract. Access Development (AD) is contemporary rival to these safe water enterprises, and will be the focus of study for this dissertation in order to better understand the service delivery approach.

1.3 - Access Development in Ghana

Access Development (AD) is a private service delivery model in the Wassa East District of Ghana. In 2016, the company arranged a formal agreement with the local government to build, own, and operate solar-powered piped systems and boreholes in the area.[1] As can be seen in Figure 0.2, the company offers professional management of AD water sources, which are built in communities that agree to a contract. As of September 2019, the company served 64 of 137 communities in the district. This amounted to a population between 45,000 and 50,000 people (50-55% of the total) (Wassa East District Assembly, 2016). They have plans to ultimately provide 90% of the district with access to safe and reliable water, which is meant to benefit from economies of scale. Further information about the institutional context of AD will be discussed in Chapter 2.

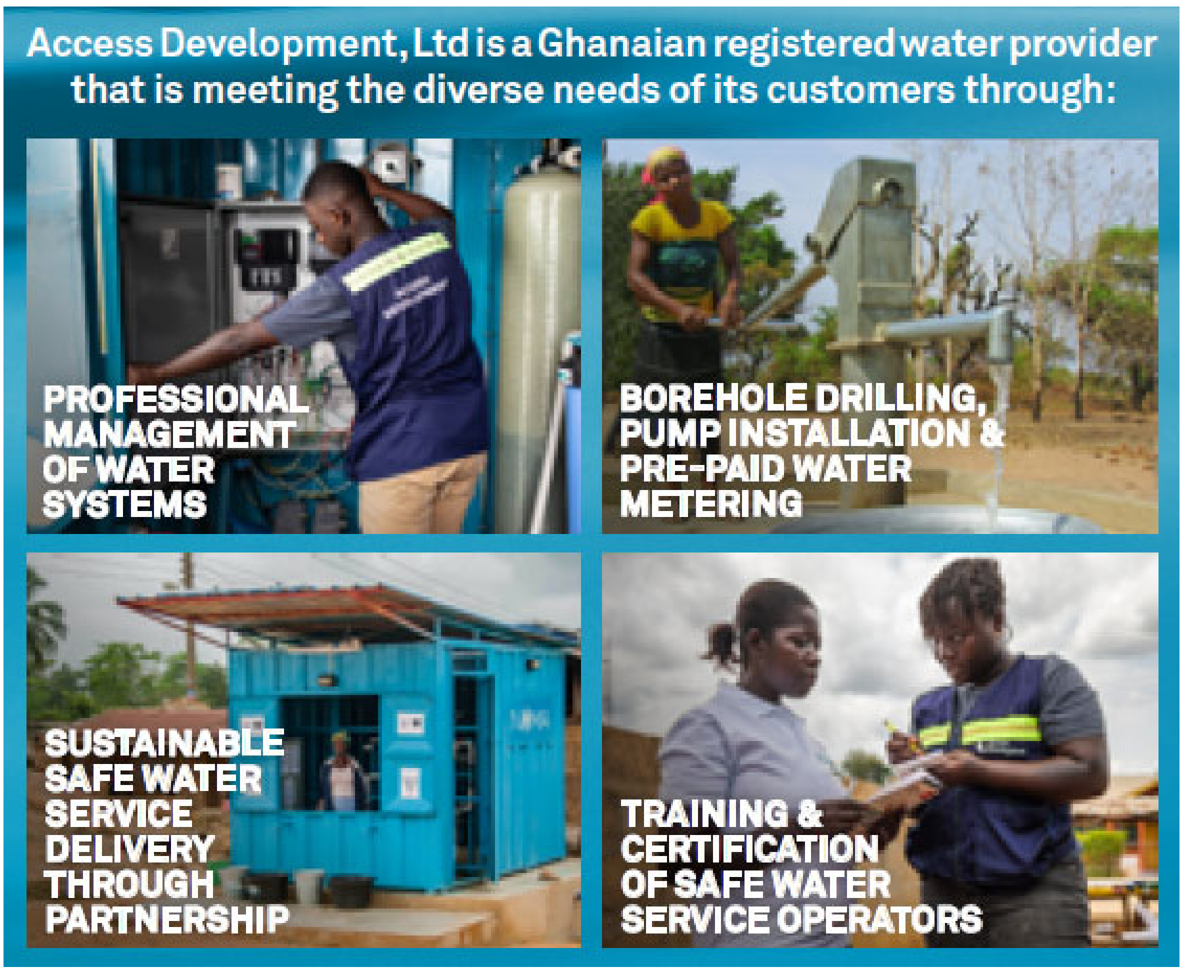

Figure 0.2 - Access Development advertisement

[1] The borehole is owned by the community, but the pump and treatment center are owned by AD.

For context, the Wassa East District is found in the Western Region of Ghana. It is predominantly rural, with only three densely populated trade communities. The total land area is about 1652 sq. km, but almost 600 sq. km is considered a forest reserve (GSS, 2015). The district capital, Daboase, has a population of about 10,000, and is about 38 km from Takoradi, the capital of the Western Region. It is within a tropical climate zone, with mean annual rainfall of 1500 mm. Subsequently, households often practice rainwater harvesting during the wet season. A map of the district is shown in Figure 0.3.

The company maintains their systems using circuit rider methods of operation (Apambire, Cuéllar, & Davis, 2016). Area mechanics are stationed at various geographic locations across the district. They regularly visit each managed water source to provide maintenance and ensure safe, continual water supply. Vendor communication and remote sensing assist in quick repairs and fast response times (Kayser, et al., 2014; Nagel, et al., 2015).

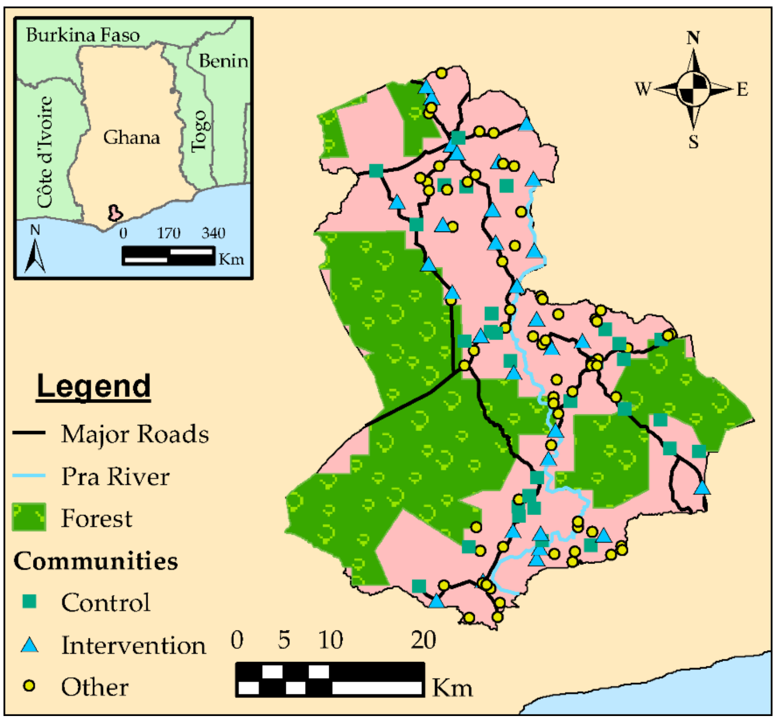

Figure 0.3 - Administrative map of the Wassa East District

Groundwater is treated at solar-powered kiosks using microfiltration, UV disinfection, and chlorination. A simple process flow diagram and photograph are shown in Figure 0.4. Iron removal has also been added to certain systems with success, and generators are available when solar power is insufficient. The treatment center provides resilience against future groundwater contamination. Periodic water quality testing is conducted by AD in the absence of government enforcement.

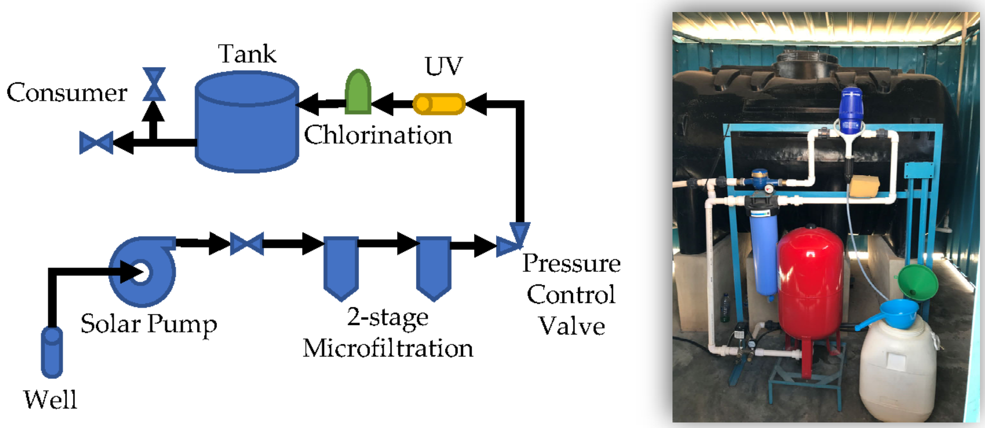

Figure 0.4 - (a) Treatment process flow diagram and (b) photo of treatment piping

The innovation of AD lies in their modular technology, which allows for a gradual expansion to decentralized sales points (Figure 0.5). Water can be sold at a central kiosk, called a Numa Nexus, or piped to other locations. Branched points can be additional kiosks (Numa Nodes) or institutional and household connections (Numa Nows). Smaller communities may also receive a borehole service contract.

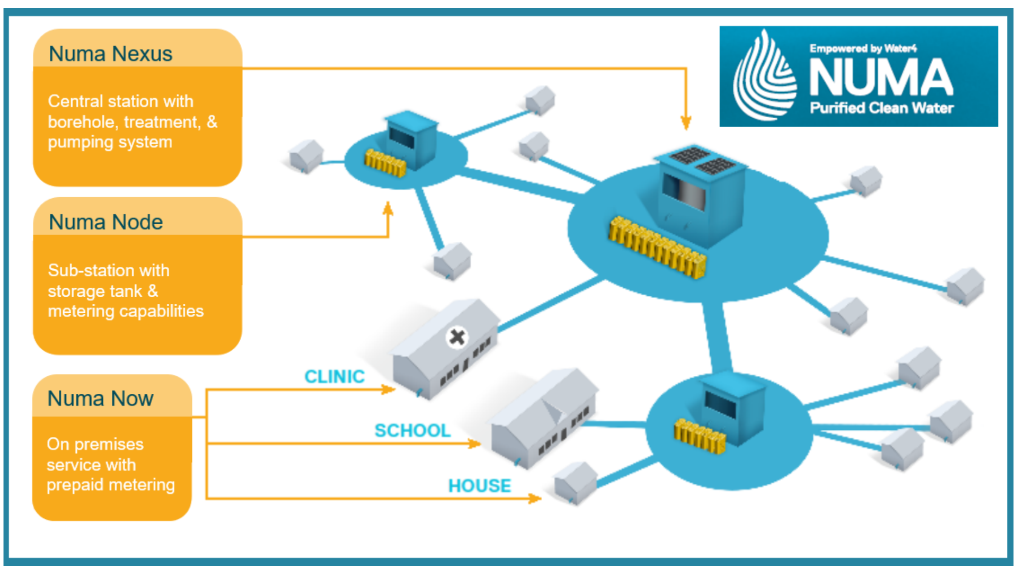

Figure 0.5 - Access Development water treatment and modular piped system (called the "Numa" brand)

Customers 'pay-to-fetch' community vendors for their water with cash (0.20 GHS per 18 L or 2.06 USD per m^3)—an established practice in the district. Cash payments are transferred to AD either by mobile money or during maintenance visits, less a percentage to the vendor. The contracted vendors submit mobile requests to AD for bulk tank fill-ups using pre-paid metering, allowing for less frequent telecom charges. Revenue is then managed by Access Development in order to maintain their assets through life-cycle planning.

Figure 0.6 - Photograph of water vendor selling to local customers

1.4 - Overview

As described in the abstract, the goal of this dissertation is to investigate the effectiveness and sustainability of a private service delivery model[2] in a rural, developing context. Access Development will be the primary case study investigated in Chapters 2 and 3, while the general, hydrogeological context of Ghana will be the focus of Chapter 4. Each chapter will build upon institutional, environmental, technical, financial, and social aspects of sustainability.

Chapter 2 will begin by conducting a service evaluation of Access Development as a private service delivery model in comparison to existing management systems in rural Ghana. The details of the multi-year quasi-experimental design will be discussed. Logistic regression will be used to compare the human right to water criteria between Users of AD water, Non-Users, and a Control group, in addition to different socioeconomic classes. The implications of the study results will be discussed with respect to policy, sustainability, and social justice.

Chapter 3 will then investigate willingness-to-pay, motivational drivers, penetration rates, and spending habits of rural households in Ghana in the presence of a safe water enterprise. Household survey results allow for the classification of water customers in intervention communities. Then, a Huff gravity model is developed to predict customer behavior and market demand in the presence of water competition. The results of these findings will inform equity and considerations for the poor in this social environment.

[2] The terms 'private service delivery model' (PSM) and 'safe water enterprise' (SWE) are synonyms used throughout the dissertation, and are both sub-groups of the 'service delivery approach' (SDA). Different terminology was used in different journals to reach a wider audience, but Access Development represents each definition.

Chapter 4 will advance manual drilling feasibility mapping for crystalline basements using indicator kriging. The northern and western areas of Ghana, including Wassa East, are underlain by the Precambrian basement. Manual drilling is known to be feasible in the weathered regions of this geological formation. However, with certain limitations of manual drilling, success can vary depending on static water depth, laterite thickness, yield, quality, and depth to hard rock. Historical feasibility techniques will be advanced using indicator kriging and weathering data, culminating in a feasibility map for the Upper East Region of Ghana.

Finally, Chapter 5 will discuss what the dissertation results illuminate regarding the sustainability of Access Development, and its representation of the service delivery approach. Results and discussions will use institutional, technical, financial, social, and environmental perspectives to craft a holistic understanding of this paradigm. Suggestions will be made for future research before concluding this work.

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2. Evaluating the Level of the Household Water Service Provided by a Private Water Enterprise in Ghana[3]

2.1 - Abstract

Innovative service delivery models are attempting to more consistently provide clean water to communities in developing countries. It is imperative that these approaches be evaluated for their performance in these contexts while understanding potential consequences. A private service delivery model in Ghana utilizing solar-powered water treatment, circuit rider principles, pre-paid metering, and a district-wide approach was assessed for three years. A quasi-experimental design used key informant surveys, household surveys, and water quality testing to investigate the service received by households under various management schemes. Service indicators were compared using logistic regression analysis. Private customers were shown to have significantly improved quality, annual reliability, and satisfaction ratings ($p < 0.05$) compared with control households, while maintaining the quantity of water collected. However, private customers were more reliant upon multiple water sources to meet domestic needs and suffered from lower affordability scores. About 38% of households used private water services, with no significant relationship with socioeconomic class. It is important for policy-makers and implementers to understand that some people will be unwilling or unable to take advantage of this model, and a transition from free improved sources to paid piped schemes will likely require a period of supporting both systems in order to reach everyone.

2.2 - Introduction

2.2.1 - Background

After decades of fighting for access to improved water sources, the Sustainable Development Goals are now aiming for universal and equitable coverage of safely managed drinking water services by 2030 (UNDP, 2015). These goals strive for continuous service, safe water quality, and sustainable management at an affordable rate. However, recent estimates suggest that 26% of handpumps in Africa are broken at any given time, with non-functionality rates of over 50% in some regions (Foster et al., 2019). Even when improved sources are available, microbiological contamination and an intermittent service can limit the benefits of both handpumps and piped systems (Bain et al., 2014; Fisher et al., 2015). This is exacerbated in rural areas, where 80% of people lack access to basic water services (WHO & UNICEF, 2017). An inadequate institutional capacity, poor financial and asset management, insufficient monitoring and

[3] Deal, P., & Sabatini, D. (2020). Evaluating the Level of the Household Water Service Provided by a Private Water Enterprise in Ghana. *Water*, 12(3), 693.

maintenance, and the unsustainable use of water resources have all been cited as causes for the enduring nature of these issues (De Armey, 2015; Foster, 2013; Kayser et al., 2014; Mandara et al., 2013; World Bank, 2017).

In response to these challenges, new service delivery models are taking shape in order to more effectively and consistently provide clean water to communities in developing countries (Smits et al., 2016). Management models of varying complexity can be structured as community-based management, local government management, public water utilities, private companies, or assorted combinations of these options (Bhatnagar et al., 2017; Lockwood, Casey, & Tillet, 2018; RWSN, 2019; Soto, Burt, & Carrasco, 2017; World Bank, 2017). Service providers can assume different levels of responsibility, such as only responding to emergency breakdowns, providing regular maintenance, or guaranteeing a regular service (Lockwood, 2019). Different financing mechanisms aim to cover various degrees of life-cycle costs in order to incentivize reliable water service provision and sustainability (Bhatnagar et al., 2017; McNicholl et al., 2019; RWSN, 2019). Recent studies have found evidence for greatly increased reliability and functionality rates, faster breakdown response times, and increased revenue for water systems managed by these novel service providers (Bey, Magara, & Abisa, 2014; Kayser et al., 2014; Koehler et al., 2015; McNicholl et al., 2019).

It is imperative that innovative service delivery models be evaluated for their viability and performance in developing contexts, and their ability to guard against potentially harmful consequences. Community-based management and private utilities have had similar hopes for an improved performance in the past. For instance, the limited ability of community-based management to achieve technical and financial targets has been highlighted in recent years, despite its prevalence in international policy (Al'Afghani, Kohlitz, & Willetts, 2019; Whaley & Cleaver, 2017; Whaley et al., 2019). Chowns (2015) found that maintenance was rarely done, repairs were delayed or sub-standard, and user committees could not save or collect sufficient funds in community-based systems. From a different perspective, informal water vendors may increase water prices based on demand or provide unsafe water quality with no regulatory oversight (Wutich et al., 2016). Large private initiatives have also failed to provide improved water services compared to public utilities (Adank & Tuffuor, 2013; McDonald & Pape, 2002; Steurer, 2008; Yates & Harris, 2018). Prepaid meters used by private companies have been known to cause diminished hygiene behavior or decreased water usage, and harsh cutoffs or increased incidences of disease at their worst (Haffeejee, Chopra, & Sanders, 2007; McDonald & Pape, 2002). These examples highlight the need to better understand new models with regards to the level of service they provide, as emphasized by the World Bank in their recent summary report (World Bank, 2017).

In this mixed-methods study, a quasi-experimental research design was used to assess the impact of a private service delivery model (PSM) on water service provision in Ghana. The study area will first be defined with regards to its geographical and institutional setting. Then, the research design and service level indicators used for evaluation (including the water quality, quantity, accessibility, reliability, affordability, and acceptability) will be described. Next, the results of this multi-year study will show the positive and negative effects of this management style. Finally, the implications of the PSM will be discussed with regards to policy, sustainability, and social justice.

2.2.2 - Site Setting

Nationally, Ghanaian service providers are regulated by the Ministry of Water Resources Works and Housing, with rural communities and small towns (typically with a population of less than 5000) falling under the jurisdiction of the Community Water and Sanitation Agency (CWSA) (Adank & Tuffuor, 2013). The national government established this arrangement in the late 1990s, when it underwent institutional reform. The most common service provider in Ghana, particularly for rural populations, is community-based management, with different tiers of external support, delegation, and ownership. Communities often own a communal source while having a committee that oversees maintenance and tariff collection. Public utilities (Ghana Water Company Ltd.) are more likely to serve large towns, such as a district capital. Religious institutions, mining companies, and self-supply are all present in varying degrees. Informal private entrepreneurs also play a role, especially those that sell sachet water (Adank & Tuffuor, 2013; RWSN, 2019; World Bank, 2017). Professional PSMs, though historically active in Ghana's urban centers, have only recently made efforts to expand into rural districts (Yates & Harris, 2018).

This study occurred in the Wassa East District in the Western Region of Ghana. In 2016, the Wassa East District had approximately 137 communities and a population of about 90,000 people (Wassa East District Assembly, 2016). The district is considered rural, with high rates of agricultural employment, lower incomes, and over 82% of communities having a population of less than 1000 people. There are three larger urban areas where significant trade occurs. Groundwater in the area is generally found to be of a good chemical quality, with the exception of aesthetic issues, such as an acidic pH and high iron, manganese, and aluminum concentrations (Addo, Boateng, & Danso, 2016; Kortatsi, 2007). Surface water, however, can often be polluted by local mining activities in the area.

A number of stakeholders have interest in the provision of water services in Wassa East: the relatively new PSM, the local government, the water management committees, the communities, and an investing NGO. The organizational structure and stakeholder exchanges can be seen in Figure 2.1. At the service authority level, the local government is responsible for planning, regulating, and maintaining water sources within their district jurisdiction (Adank & Tuffuor, 2013; Anokye & Gupta, 2012). The local government delegated this responsibility to a PSM, establishing a contract to provide water for each interested community at an agreed price point per liter. The local government has acted as a regulatory body to ensure that all obligations are met. Water management committees in each community have also assumed a regulatory role, in addition to managing existing communal water sources. Lastly, an external NGO provided the initial infrastructure capital for the intervention, and continues to provide institutional support to the PSM.

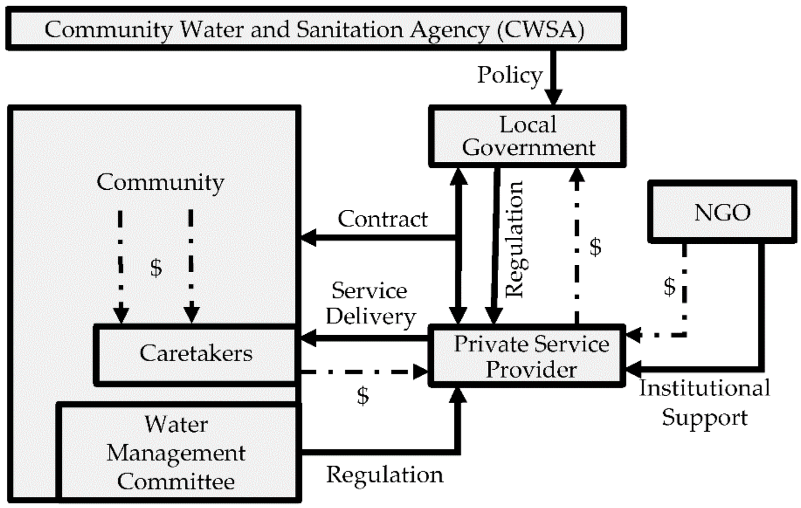


Figure 2.1 - Service provider institutional framework

The PSM under evaluation in this district is called Access Development. In 2016, the company arranged a formal agreement with the local government to build, own, and operate solar-powered piped systems and boreholes in the area. They have plans to ultimately provide 90% of the district population with access to safe and reliable water; a proportion meant to benefit from economies of scale. The focus of the business is selling water at kiosks, where it is treated by microfiltration, UV disinfection, and chlorination (see supplementary material). However, borehole service contracts are also established in the smallest communities. The company maintains their systems using circuit rider methods of operation (Apambire, Cuéllar, & Davis, 2016; Kayser et al., 2014). The innovation of the PSM lies in their modular technology, which allows a gradual expansion to decentralized sales points, institutions, and household connections. Customers 'pay-to-fetch' from vendors for their water with cash (0.20 GHS per 18 L)—an established practice in the district. The contracted vendors submit requests to the PSM for periodic tank fill-ups using mobile money accounts and pre-paid metering. Revenue is then managed by Access Development in order to maintain their assets through life-cycle planning. Similar models, each with unique approaches and payment structures, are found in Uganda (Whave and Lifeline), Kenya (Fundifix), Burkina Faso (Uduma), and Ghana (Safe Water Network) (RWSN, 2019).

Overall, this study aims to understand whether a private service delivery model, such as Access Development, can provide equivalent or improved levels of water service when compared to more traditional management systems in a rural, developing country context. Within this comparison, what risks or consequences are present within the model? When considering historical failures of private providers (Haffeejee, Chopra, & Sanders, 2007; McDonald & Pape, 2002), it is important to investigate potential disparity in access based on relative wealth. Given the institutional framework and pre-payment required, it can be hypothesized that overall, the district will benefit from an improved service, but the quantity of water collected and the penetration rates will be lower for those in poor socioeconomic classes.

2.3 - Materials and Methods

2.3.1 - Study Design

A quasi-experimental design was used to evaluate the water service provision of the PSM and compare it with existing management systems in the district. A baseline-endline assessment of an intervention group and a non-equivalent control group allowed comparisons of the overall service across time to be conducted (Campbell, 1967). The baseline surveys were conducted in 2016, prior to the PSM beginning service provision in Wassa East. The endline surveys were completed in 2019, after intervention communities had been under contract with the PSM for six months to two years. Individual cross-sectional assessments could also be completed for each temporal period (Jacobsen, 2011). Much of the initial analysis used the 2019 endline data to compare groups, after which the baseline was used to identify maturity and growth over time. A combination of key informant surveys, water quality testing, and household surveys was used to collect the required data for assessment, which all occurred within a six-week period.

The key informant survey and water quality testing used one-stage cluster sampling, in which each community was considered a cluster. Thirty intervention and thirty control communities were selected for testing. Communities selected for intervention were decided by the PSM, initiating the quasi-experimental design. The PSM prioritized communities with a poor service, little external support, and favorable political environments. As the decision-making process evolved over time, competition and the population size also factored into which communities received the service. Statistical comparisons were made between group environments from the baseline to understand potential biases at the onset of the study.

Local enumerators assessed every water point within the sixty selected communities using a key informant survey. Key informants were often representatives of previously established water management committees, but also included chiefs and other local leaders. Recorded water sources included boreholes, protected and unprotected hand-dug wells, kiosks, piped systems, springs, and surface water (such as streams), in reference to JMP classifications (WHO, 2017b). In total, 318 community water sources were identified. Privately managed water points included kiosks and boreholes. GPS coordinates, photos, and local descriptions were recorded for each water point in order for households to identify their primary source in the household survey. The ability to purchase sachet and bottled water within a community was also noted. Surveys were conducted as semi-structured interviews.

Water quality testing was primarily completed for improved water sources, with a few exceptions. Improved sources were considered to be piped systems, kiosks, boreholes, and protected hand-dug wells. Unprotected hand-dug wells and surface water were only tested periodically. They were assumed to be inferior to improved sources, susceptible to contamination by fecal coliforms, and generally unsafe for consumption (Bain et al., 2014; WHO, 2017b). Individual household sachet water samples were also not tested. Though not always the case, sachet water was assumed to be free from fecal coliforms, in reference to its positive performance in other studies (Mosi et al., 2019; Opryszko et al., 2013).

The household survey utilized a two-stage cluster sampling methodology. After the first community stage, systematic random sampling was conducted to select households in the second stage (Dillman, Smyth, & Christian, 2016). Control and intervention households were distinguished by whether their community was serviced by the PSM. Intervention households were further broken down into Users and Non-Users, with a User defined as a household which uses PSM water at least weekly.

Satellite images were used to identify and map households within a community. Two random households were chosen for enumerators to begin sampling, after which a set interval was counted before sampling again. The interval and sample size were dependent on the population estimates in census records. Enumerators received a map and GPS coordinates to identify their starting point. If the community was too large, enumeration areas were included as intermediate, randomly selected zones. Household members examined photo records of all community water sources to identify which were regularly used. Unique ID numbers could be referenced back to a database of GPS coordinates, downtime, and water quality testing results.

For the endline, a total of 1152 household samples were taken, with an average of 19.2 samples per community. A total of 24 samples were removed through a number of quality control checks placed within the survey, bringing the total number of samples analyzed to 1128. Consideration for disqualification included duplicates, age (below 18), inconsistencies, improper mental states, or poor accuracy ratings from the enumerators. Household heads, their spouse, or other adults were targeted, in order of priority. GPS tracking allowed for a verification of survey completion and accuracy.

All respondents gave their informed consent for inclusion in this research prior to participating in this study. Identifying information was removed for the protection of the subjects. After reviewing the research protocol, the University of Oklahoma Institutional Review Board deemed that approval was not required. Local enumerators collected survey data and were trained in advance to conduct ethical in-person interviews (Dillman, Smyth, & Christian, 2016). Enumerators were multilingual, allowing questions prepared in English to be translated into local dialects (Fante and Ewe) during preliminary testing of the survey instruments.

2.3.2 - Service Evaluation

Households were evaluated for the level of water service that they received based on the human right to water criteria (Baquero et al., 2016; Flores, Jiménez, & Pérez-Foguet, 2013; Moriarty et al., 2011). Indicators for the level of water service are summarized in Table 2.1, with scoring thresholds specified in Table 2.A1. They were assessed based on household responses and the traits of selected water sources (De Palencia & Pérez-Foguet, 2012; Moriarty et al., 2011; Rietveld, Haarhoff, & Jagals, 2009). Statistical comparisons of the intervention and control groups, Users and Non-Users, wealth quintiles, management styles, and technology, were considered.

Water quality was tested for fecal coliforms, pH, conductivity, turbidity, arsenic, fluoride, total chlorine, and free chlorine. Conductivity, pH, temperature, and turbidity were measured using portable, electronic meters. A Quick II Arsenic Test Kit was used to determine the arsenic concentration within 24 h of collection. A fluoride meter, in conjunction with TISAB reagent tablets, was used to test for the fluoride concentration within 24 h of collection. A Hach Chlorine Test Kit, Model CN-70, was used to test for free and total chlorine immediately using DPD and the color disc method (typically in piped systems). Conductivity was adjusted for a standard temperature of 25 °C.

Table 2.1 - Water service level indicators[1]

Service	Indicator	Type of Variable	Scoring Limits	
			Low	High
Quality	Fecal coliforms	Ordinal (4)	>10 MPN/100 mL	0 MPN/100 mL
	Geogenic contaminants	Binary	Below conc. limits	Above conc. limits
	Free Chlorine	Binary	Other	0.2–2 mg/L
Quantity	Quantity (L/person/day)	Ordinal (5)	<5 lpd	>100 lpd
	Sufficient quantity (perception)	Binary	No	Yes
Accessibility	Time spent per trip (min)	Ordinal (5)	In home	>60 min
	Distance (m)	Ordinal (5)	<10 m	>1 km
	Congestion (number of users)	Ordinal (5)	Private	Community
Reliability	Annual Reliability (days per year)	Ordinal (5)	<182 days	>345 days
	Daily Availability (hours per day)	Ordinal (5)	<4 h	24 h
	Functionality	Binary	Non-Functional	Functional
Affordability	Affordability (perception)	Ordinal (5)	Never afford	Afford domestic and agricultural needs
Acceptability	Organoleptic properties (perception)	Ordinal (5)	Poor	Excellent

[1]Adapted from Baquero et al. (Baquero et al., 2016).

Aquagenx© CBT test kits were used to test for the presence of *Escherichia coli* (*E. coli*). These kits use a growth substrate and different sized compartments to estimate the most probable number (MPN) per 100 mL sample. The MPN method produces quantitative counts of *E. coli* colonies based on discrete, presence/absence data and statistical analysis. Samples were designated as safe (0 MPN), low risk (1–3 MPN), intermediate risk (3–10 MPN), and unsafe (>10 MPN) based on Aquagenx definitions and WHO standards (Howard & Bartram, 2003). Samples were collected during daily field visits to communities and kept within an ice cooler prior to analysis. After the substrate was added and the water was transferred to the compartment bags, the sample was sealed and incubated at 34 °C for 24 h.

Questions within the household survey were used to estimate the quantity of water collected per day based on their household's responses. Volumes were converted to liters using common transport containers and terminology. These usage rates were graded based on the water quantity levels recommended by the World Health Organization (Howard & Bartram, 2003). As a secondary proxy, respondents also stated whether the collected quantity was sufficient for their domestic needs.

Accessibility was graded based on the time spent collecting water per trip, the distance from the source, and the number of users that collect from that source (congestion). These parameters were determined within the household survey. Distance was estimated using both a perceptive question and the GPS coordinates of the household compared to the coordinates of their primary source. The haversine formula was used to calculate the distance between points, as shown in Equation 1, where "d" equals distance, "r" equals the radius of the earth, "φ" is the latitude, and "λ" is the longitude (Chopde & Nichat, 2013).

$$d = 2r * \arcsin\left(\sqrt{\sin^2\frac{\varphi_2 - \varphi_1}{2} + \cos\varphi_1 \cos\varphi_2 \sin^2\frac{\lambda_2 - \lambda_1}{2}}\right) \quad (1)$$

Reliability was graded based on the number of days that a household's primary drinking water source was available throughout the year. Functionality and the hours per day that water was regularly available were also recorded. Water sources were considered functional if they were at least partially working and provided access to water during testing, but they were considered non-functional if they had been closed for more than a week or abandoned. These parameters were requested from multiple sources to guard against recall bias, including key informants, regular users, and households within the community.

Affordability was evaluated using a needs-based ordinal scale. Households specified whether they could afford water for domestic and agricultural needs, domestic needs, drinking and cooking, cooking only, or rarely afford the water. For instance, sachet water is frequently only purchased for drinking purposes, which speaks to its perceived affordability. Free sources were automatically given the highest ordinal rating. Acceptability data were collected during the customer satisfaction portion of the household survey. The purpose of this metric was to understand the subjective value people place on each source, in addition to the objective scientific value that was externally assigned. A five-point Likert scale was used to evaluate perceived taste, odor, appearance, and lather (Joshi et al., 2015).

In addition to the service level indicators outlined in Table 2.1, the JMP service levels were used to assess the overall performance within each group of communities over time. According to this universal standard, households can receive safely managed, basic, limited, unimproved, or no service (WHO & UNICEF, 2017). A safely managed service is the highest level, requiring water to be on premises, available when needed, and free from fecal contamination. Basic and limited services require access to an improved source, but differ, depending on whether it can be collected within thirty minutes. An unimproved service refers to unprotected wells or springs, while surface water is designated as no service. These service levels allow for more uniform comparisons across studies and time.

Relative wealth is the final proxy measure, separate from the service level indicators. The 2014 Ghana Wealth Index was used to compare the socioeconomic status of different households and communities (GSS, 2015). The national demographic survey can be used to identify households in five ordinal quintiles, separating those responses from a relatively poor household (1) and a relatively rich household (5). In this way, a statistical comparison of socioeconomic classes can be conducted.

2.3.3 - Data Analysis

The mWater platform was used to aggregate water inventory data with household data. Unique mWater ID's were used to match household responses to their primary drinking water sources. If a household's primary drinking source was not functional when testing occurred, their secondary source established their service level grades. Figure 2.2 shows the data aggregation process.

Finally, multinomial logistic (binary-dependent variable) or ordinal (ordinal/non-normal-dependent variable) regression was used to determine which factors had a significant effect on service level indicators. The authors conducted a statistical analysis using the software program SPSS and a cluster sampling methodology. If User scores were significantly different than both the Non-User and Control groups, there was strong evidence to support that conclusion. Predictor variables could be controlled by considering all other independent variables as covariates. Adjusted odds ratios rarely produced results that conflicted with the unadjusted values, so only the unadjusted values are reported in this paper.

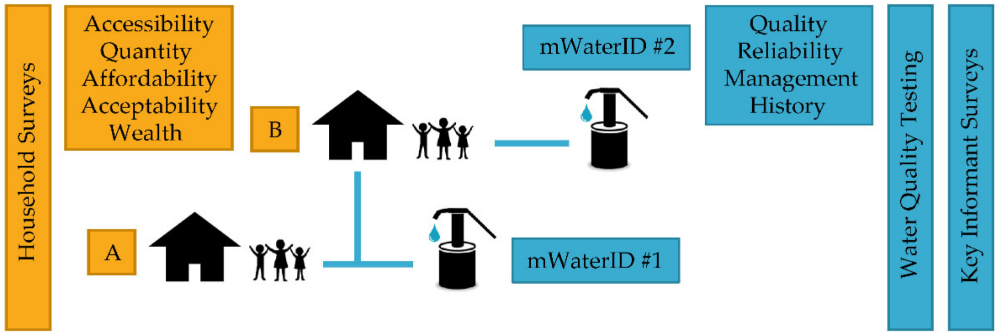


Figure 2.2 - Data aggregation diagram

2.4 - Results

2.4.1 - Descriptive Analysis

The results of the endline descriptive analysis for group demographics are summarized in Table 2.2. Comparisons of the control and intervention groups of communities were conducted. Since the start of 2016, 15 additional water sources in 11 control communities and 68 (52 by the PSM) in 30 intervention communities had been constructed. Despite this increased access over time, 98% of communities had access to improved water sources in 2016 (Table 2.2d), with statistically similar functionality rates. The proportions of surface, groundwater, and piped sources were quite similar in 2019, with the vast majority being communal in nature (Table 2.2c). Piped connections on plot or within the household were rare in the district, with only one control community having a distribution system providing water to each dwelling. Public piped systems had only been built in six larger communities at the baseline, mainly within the control group. The mean population was somewhat higher in the intervention group (Table 2.2b). This is due to the increased number of mid-sized communities (300–1000 people) within the intervention group, as compared to the control group and district as a whole. The results should be interpreted with this selection bias in mind.

Within household samples, statistically similar proportions ($p > 0.05$) of gender, household size, age range, and education were recorded. Generally, about 80% of respondents had a junior high school education or below, and about 69% of respondents that worked specified subsistence or commercial farming as their primary employment (Table 2.A2). For the national rural wealth index, both the mean score and quintile distributions were statistically similar within a given year (Table 2.2f). When using national composite scores, which also include people from urban environments, about 78% of households were considered to be among the poorest 40% in Ghana.

Table 2.2 - Temporal demographics of control and intervention groups

	Variable	Control *		Intervention *		Total *	
		2016	2019	2016	2019	2016	2019
a	Number of Communities	30		30		60	
b	Mean Population of Communities	**784**		**1017**		901	
	Range	60–3874		198–6252		60–6252	
c	Number of Water Sources	**130**	**145**	**105**	**173**	**233**	**318**
	% Surface Sources	13%	12%	16%	10%	14%	11%
	% Groundwater Sources	**56%**	57%	**82%**	61%	68%	59%
	% Piped Sources	**31%**	31%	**1.9%**	30%	18%	30%
d	Improved Source Available	97%	97%	100%	100%	98%	98%
e	Sampled Households	560	555	549	597	1108	1152
	Removed	19	11	9	13	28	24
f	Rural Quintile (Mean)	3.6	3.4	3.7	3.4	3.7	3.4
	Poorest (0%–20%)	0.5%	1.2%	0.5%	0.1%	0.5%	0.7%
	Poor (20%–40%)	8.6%	15%	11%	14%	9.7%	14%
	Average (40%–60%)	37%	43%	31%	40%	34%	42%
	Rich (60%–80%)	34%	24%	38%	36%	36%	29%
	Richest (80%–100%)	20%	17%	21%	10%	20%	14%

* Bold text denotes $p < 0.05$.

2.4.2 - Logistic Regression Analysis

Table 2.3 presents the multinomial logistic regression for communal water sources within the district in 2019. The binomial descriptive statistics for functionality, annual reliability, and water free from fecal coliforms are shown in conjunction with the odds of a positive performance, as compared to other categorical predictor variables. An odds ratio (OR) compares the odds that an outcome will occur with and without exposure to a given variable (Szumilas, 2010). An odds ratio greater than one suggests that a predictor variable produces a riskier outcome, while a value less than one deems the predictor to be more protective than the standard. Each category (management and payment method) uses a standard variable of comparison, which is assigned a null odds ratio (OR = 1). Community-based management and no tariff payment were used as the standards for their respective categories, as they were the most common historical methods of water provision and service within the district. This analysis excludes unimproved surface sources that are clearly inferior.

Generally, most variables associated with the PSM showed protective odds ratios (OR < 1) with statistical significance. Improved functionality, reliability, and quality were all observed for privately-managed water points (Table 2.3b). In addition, individually-managed water sources (Table 2.3e) showed an improved functionality, which were predominantly self-supplied unprotected wells or standpipes from a community piped system. Community-based management was common within the district (Table 2.3a), which was primarily conducted through water management committees. Elected members managed over 50% of community water sources, with less than 30% collecting regular payments. Nearly 70% had a member with a senior high school education or better, and almost 90% had a female representative. Privately-managed water sources showed an improved performance compared with community-managed sources, while other management models had a statistically similar quality and reliability (Table 2.3c–g).

Table 2.3 - Multinomial logistic regression of water source performance

	Explanatory Variables	n	Functionality *		Annual Reliability > 95% *		Free from Fecal Coliforms *	
			%	OR (95% CI)	%	OR (95% CI)	%	OR (95% CI)
	Management Scheme	252						
a	Community	141	62%	1	37%	1	35%	1
b	Private (PSM)	52	**92%**	**0.14 (0.07–0.27)**	**87%**	**0.09 (0.05–0.16)**	**90%**	**0.06 (0.03–0.13)**
c	Religious Institution	8	62%	1.0 (0.20–5.2)	51%	0.56 (0.13–2.5)	13%	3.7 (0.58–23)
d	Local Government	10	50%	1.6 (0.70–3.8)	39%	0.93 (0.40–2.1)	50%	0.54 (0.26–1.1)
e	Individual	24	**88%**	**0.22 (0.09–0.51)**	49%	0.62 (0.27–1.4)	33%	1.1 (0.55–2.2)
f	No Manager	7	52%	1.5 (0.29–7.5)	12%	4.4 (0.93–21)	20%	2.1 (0.33–13)
g	Public Utility	10	60%	1.1 (0.37–3.2)	60%	0.40 (0.13–1.2)	50%	0.54 (0.20–1.4)
	Payment Method	266						
h	Nothing	88	51%	1	31%	1	10.1%	1
i	Emergency Funds	15	54%	0.86 (0.42–1.8)	38%	0.72 (0.26–2.0)	12.7%	0.77 (0.29–2.1)
j	Monthly Tariff	17	**95%**	**0.06 (0.01–0.24)**	55%	0.36 (0.11–1.2)	**58.5%**	**0.08 (0.04–0.15)**
k	Pay-to-fetch	146	**79%**	**0.28 (0.15–0.53)**	**59%**	**0.31 (0.16–0.59)**	**68.0%**	**0.05 (0.03–0.10)**

* Bold text denotes $p < 0.05$; surface sources excluded from analysis.

Regular tariff payments, either monthly (Table 2.3j) or pay-to-fetch (Table 2.3k), also showed improved odds of a good performance in all categories. When controlling for private water sources, other pay-to-fetch sources still showed improved functionality [OR = 0.37 (0.19–0.70)], reliability [OR = 0.47 (0.24–0.89)], and biological quality [OR = 0.11 (0.06–0.21)]. For more regression analysis involving the age and type of water sources, see Table 2.A3.

Ordinal service level scores from 2019 are presented in Figure 2.3, which provides a quick summary of the logistic regression analysis of household service level indicators shown in Table 2.4. Households within the intervention communities were assigned to either the User or Non-User groups based on reported behaviors, practices, and usage rates of competing water sources within a given community. Households were also assigned to a management system based on their primary drinking source. Users (Figure 2.3a) and households managed by the PSM (Figure 2.3b) were highly correlated. These groups generally provide a better biological quality and annual reliability; equivalent quantity, collection time, and mean acceptability; and worse affordability, compared to sources managed by the community and the Control group. Non-User and Control groups were also observed to be nearly identical (Figure 2.3a), implying a null effect on Non-Users in intervention communities.

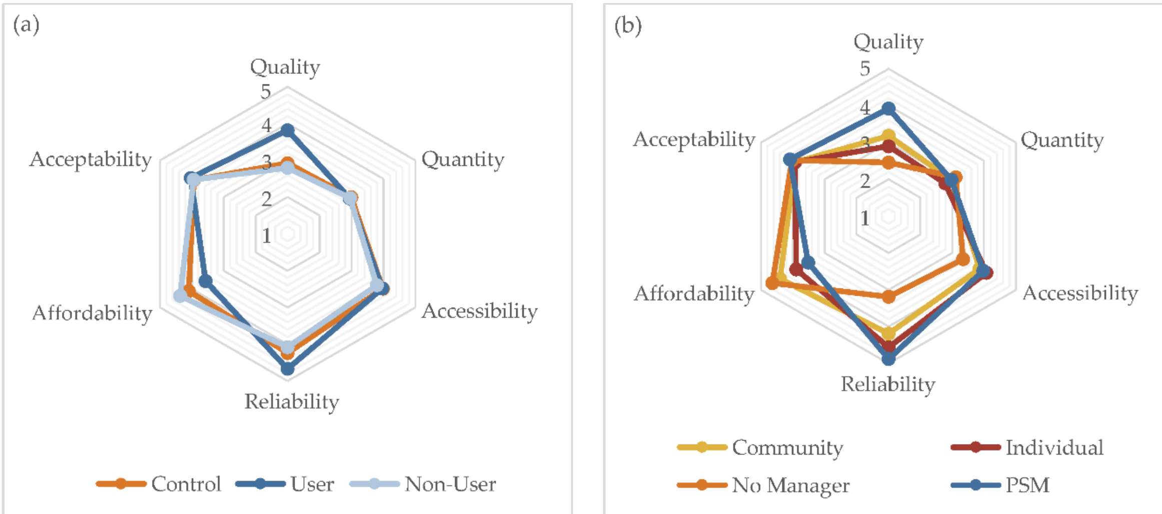


Figure 2.3 - Household service level scores by (a) Control and intervention (User vs. Non-User) groups and (b) primary source management groups

Table 2.4 - Multinomial logistic regression for service level indicators by household group

Parameter		n	Control	Control vs. User *	Non-User	Non-User vs. User *	User
			%	OR (95% CI)	%	OR (95% CI)	%
Quality							
a	Use Improved Primary Source	1128	**71%**	**3.8 (1.6–9.3)**	**71%**	**3.8 (2.0–7.2)**	90%
b	Free from fecal contamination (Prim.)	1079	**62%**	**5.7 (2.6–12)**	**54%**	**8.0 (3.7–17)**	90%
c	Free from geogenic contamination	1079	100%	1.0 (1.0–1.0)	100%	1.0 (1.0–1.0)	0.0%
d	Residual chlorine present	1076	**1.5%**	**110 (26–460)**	**2.4%**	**68 (13–370)**	63%
e	Residual chlorine above 0.2 ppm	1076	**0.4%**	**17 (1.5–190)**	0.0%	-	5.7%
Quantity							
f	Quantity collected above 20 L/p/d	1096	80%	0.86 (0.49–1.5)	76%	1.1 (0.63–1.8)	77%
g	Use of multiple water sources	1128	**41%**	**0.27 (0.14–0.50)**	**34%**	**0.20 (0.12–0.33)**	72%
h	Sufficient quantity (perception)	1128	**97%**	**0.26 (0.08–0.87)**	93%	0.66 (0.26–1.6)	89%
Accessibility							
i	Time per trip < 30 min	1114	95%	0.84 (0.35–2.0)	93%	1.1 (0.43–2.7)	94%
j	Distance to water source < 100 m	992	34%	1.9 (0.99–3.5)	**28%**	**2.5 (1.4–4.3)**	49%
k	Congestion > 20 households	1039	94%	1.7 (0.69–4.3)	98%	0.65 (0.19–2.2)	96%
Reliability							
l	Annual reliability > 345 days	963	64%	2.2 (0.93–5.2)	**48%**	**4.1 (1.9–9.0)**	79%
m	Daily availability > 12 h	1122	**84%**	**0.29 (0.15–0.58)**	**86%**	**0.26 (0.13–0.51)**	60%
Affordability							
n	Can afford to pay for domestic needs	1128	**78%**	**0.45 (0.23–0.91)**	**87%**	**0.24 (0.12–0.47)**	61%
o	Rural Quintile is above 'Average'	1128	41%	1.5 (0.73–2.9)	43%	1.3 (0.83–2.1)	50%
Acceptability							
p	'Excellent' taste ratings	1111	23%	1.5 (0.87–2.4)	22%	1.6 (0.95–2.6)	30%
q	'Excellent' odor ratings	1110	**16%**	**2.5 (1.4–4.5)**	**14%**	**2.9 (1.7–4.8)**	32%
r	'Excellent' appearance ratings	1106	**22%**	**2.5 (1.5–4.4)**	33%	1.5 (0.92–2.3)	42%
s	'Excellent' lather ratings	1097	19%	1.5 (0.81–2.7)	17%	1.7 (1.0–2.8)	25%

* Bold text denotes $p < 0.05$

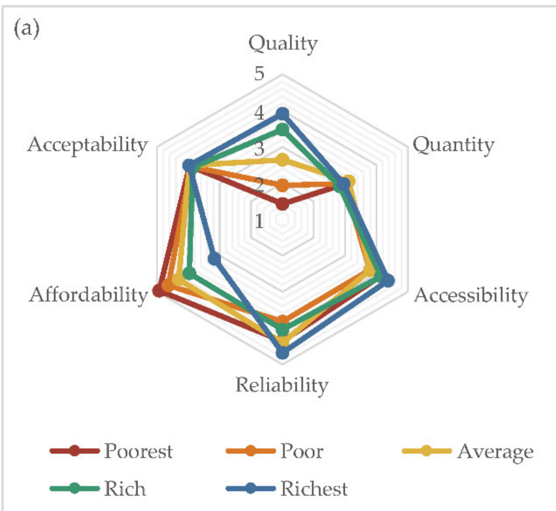
The results in Table 2.4 emphasize the generally protective or neutral effect of the intervention effort. Water quality indicators were significantly worse for Control and Non-User households in every parameter except geogenic contamination, which was not an issue in the district as a whole (Table 2.4a–e). Annual reliability indicators increased for Users (Table 2.4l) in conjunction with the increased continuity of the PSM water sources in Table 2.3. Accessibility indicators showed little change for Users with regards to the time spent fetching and household congestion (Table 2.4i–k). Although a higher proportion of Users were closer to their primary source ($p < 0.01$), this may be more indicative of customer motivations than the company's influence. Acceptability indicators showed slightly increased scores for Users (Table 2.4p–s), with a significant improvement for odor and appearance ($p < 0.05$). For all groups, ratings tended to fall in the "Good" (4) range, with each household using water sources they preferred. Individual sources tended to have defined traits, such as a poor taste or improved lather, which created a clustering effect at the community level.

However, some trends associated with risk were also observed. Despite significantly higher evidence of residual chlorine in User sources (63%), only 5.7% had concentrations higher than 0.2 ppm (Table 2.4d–e). Household water treatment was uncommon for all households (10%), and Users stored water for two to three days, on average. Considering the risk of microbial deterioration during transport to the dwelling, the low chlorine concentration was likely insufficient to maintain stored water quality under these conditions (CDC, 2019a, 2019b; Wright, Gundry, & Conroy, 2004). Additionally, daily availability scores were significantly lower for Users (Table 2.4m; $p < 0.01$). This indicator assessed the number of hours per day that water could be collected from a given source. About a third of Users claimed they could only access water between 8 and 12 h per day. While many free sources were available at any time, the PSM sources required a vendor to be present for tariff collection. This created specific opening hours for collection each day. Therefore, private water systems were more likely to be available throughout the year, but had daily restrictions on time.

Users (37 L/p/d) collected statistically similar quantities of water as Non-User (38 L/p/d) and Control (39 L/p/d) households (Table 2.4f). This amounts to about 1360 L per household per week in the dry season, on average. However, 72% of Users utilized multiple water sources to supplement 47% of their domestic needs (by volume), on average (Table 2.4g; $p < 0.01$). Households within the richest quintiles would use sachet water for drinking and PSM water for cooking and hygiene (cleaning, bathing, and laundry) needs (61% of total volume). Households within the other quintiles tended to supplement their hygiene needs with free alternatives, while using PSM water for drinking and cooking (41%–49% by volume). Further information on collection purposes and seasonal trends can be seen in Figures 2.B1 and 2.B2 (Appendix B).

With regards to affordability, 61% of Users, 87% of Non-Users, and 78% of Control households felt they could afford to pay for their domestic needs (Table 2.4n). When refined by a household's primary water source, 57% of kiosk, 88% of borehole, 93% of protected well, and 7.3% of sachet users were able to afford their domestic needs. For context, common pay-to-fetch prices for handpumps are half the kiosk price (0.10 vs. 0.20 GHS/18 L), and sachet water costs 36 times the price per liter (0.20 GHS/500 mL).

Service level indicators varied more widely between wealth quintiles in the Control group (Figure 2.4a) than for Users (Figure 2.4b). The biological quality, collection time, annual reliability, and affordability all differed significantly between Control quintiles ($p < 0.01$). Within User households, only affordability varied significantly between quintiles ($p < 0.01$). Interestingly, this was primarily related to an increase in sachet water usage by richer User households. This quintile would purchase sachet water for their drinking needs, and AD water for other domestic needs, which skews this ordinal scoring to a lower tier. Note that only one sample in the "Poorest" rural quintile was observed in the intervention communities (and sixteen samples in the Control), so they reflect a low sample size.



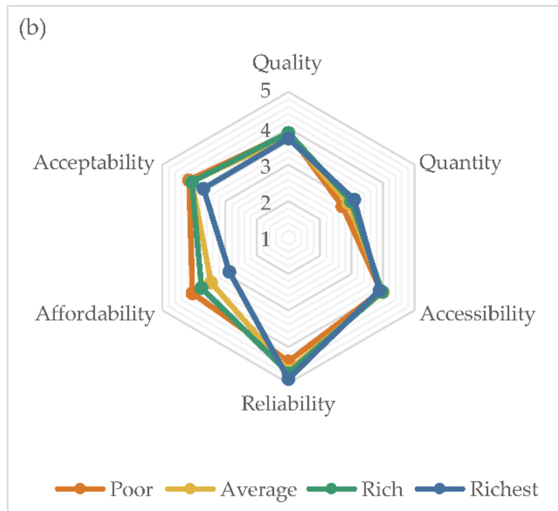


Figure 2.4 - Household service level scores by rural wealth quintile for (a) Control and (b) Users; note: Both groups have a low sample size for the Poorest quintile—16 Control and one Intervention (excluded)

All of these comparisons with Users reflect the proportion of intervention households that choose to use the PSM water at least weekly (i.e., the penetration rate). While 37% (95% CI [30,44]) of intervention households use PSM kiosks weekly, only 28% (95% CI [22,35]), use them as a primary source and 9.3% (95% CI [6.1,13.8]), exclusively. This is reflected by the same households that use multiple water sources to meet their domestic water needs (Table 2.4g). Penetration rates for PSM handpumps (56% weekly) tend to be higher than for kiosks, either due to their alternative tariff structure or reduced population. Handpumps are typically constructed in communities with less than 300 people, which is associated with less travel distance and fewer water source options. Moreover, a monthly tariff is charged per household at a rate of 2 GHS per month; estimated to be thirty times less than a kiosk per liter. Interestingly, weekly (p = 0.43), primary (p = 0.24), and exclusive (p = 0.50) penetration rates did not have a significant relationship with socioeconomic status, providing evidence against the study hypothesis.

2.4.3 - Temporal Analysis

Figure 2.5 presents the overall change in JMP water service provision between 2016 and 2019 when considering a household's primary drinking water source. In control communities, households that received at least a basic water service increased from 53% to 70% [OR = 0.50 (0.31–0.79)]. In intervention communities, households that received at least a basic water service increased from 45% to 78% [OR = 0.24 (0.14–0.42)]. Both groups had a significant decrease of households with a limited service, and the intervention group displayed a drop in the number of households with unimproved service. A statistically similar group of households with safely managed and no service prevailed over time. Control and intervention households did not exhibit a significant difference in JMP service in any given year. Figure 2.6 emphasizes these growth patterns, while showing the divergent components of Users and Non-Users. Independently, Non-Users gained an improved service at the same rate as the Control group, while Users gained statistically significant service improvements ($p < 0.05$).

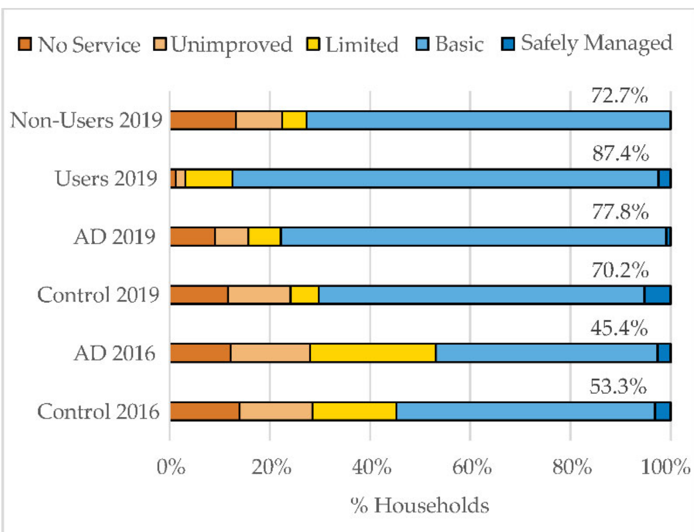


Figure 2.5 - Proportion of households with JMP service levels from 2016 to 2019

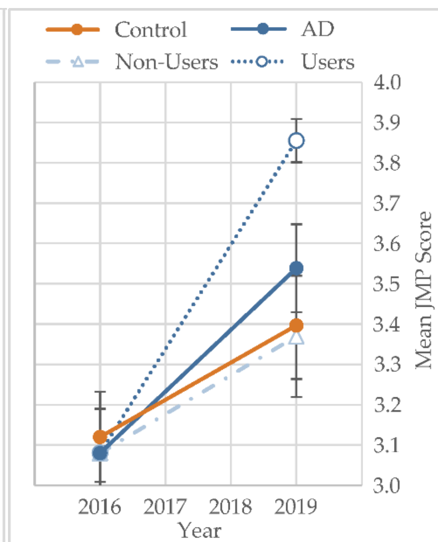


Figure 2.6 - Mean JMP service level scores from 2016 to 2019

2.5 - Discussion

Customers of the private service delivery model were associated with an improved JMP service compared to customers of historical water service providers within the district (Figure 2.6). About 90% of PSM water sources were free from fecal contamination and 87% were available more than 345 days per year. This provided User households with an improved water quality and annual reliability compared to Control and Non-User households ($p < 0.01$). Quantity and accessibility (time and congestion) scores were statistically similar between groups. However, achieving a sufficient water quantity required 72% of User households to supplement their PSM water with alternative sources. Such supplements occurred irrespective of household wealth ($p = 0.35$) and suggested a rejection of the study hypothesis. Organoleptic ratings showed higher trends of 'Excellent' scores for Users, although they were not statistically significant without isolating each component (taste, odor, appearance, and lather). PSM Users had significantly worse scores for daily reliability and affordability ($p < 0.01$).

Management traits such as regular maintenance visits and pay-to-fetch practices promoted consistent water system functionality throughout the year. This is apparent in the high reliability of PSM sources, but is emphasized by water sources not affiliated with the PSM continuing this trend (Table 2.3h–k). This supports previous literature claiming that these practices can produce a more reliable performance (Foster & Hope, 2017; Kayser et al., 2014; McNicholl et al., 2019; Truslove et al., 2019). With this in mind, the challenge for the PSM is maintaining vendor availability on a daily basis and avoiding periodic closures. Qualitative observations for vendor absence included daily farming or domestic duties, delays in waiting for a tank to be filled through remote meters, closures due to illness or moving away, and the mismanagement of collected revenue. These examples highlight the importance of human resource management and reducing associated risks for the private operator. Future research should investigate how daily opening hours and short-term closures influence customer usage and spending habits.

Services provided by the PSM were utilized by 38% (95% CI [31,45]) of households within intervention communities (kiosks and boreholes combined). This uptake rate is consistent with the 38% of households identified by Opryszko et al. (2013). For reference, self-reported penetration rates reported by Bhatnagar et al. (2017) ranged from 10% to 60%. Although there were slightly increasing trends, uptake ($p = 0.43$), water quantity collected from PSM sources ($p = 0.10$), and the JMP service ($p = 0.17$) from PSM water sources were not significantly affected by relative wealth. This evidence shows that both poor and rich households are being served by private kiosks under the current model. Only the richest quintile shows a difference in usage patterns, but this is more reflective of the disparity of sachet water. For comparison, 78% of the richest and 50% of the poorest households will purchase sachet water at least weekly.

This behavior illustrates how households will strategically use the water resources available to them in order to meet their domestic needs. Only 28% of Users collected kiosk water exclusively, supporting other literature observing the use of multiple water sources (Foster & Willetts, 2018; Vedachalam et al., 2017). Only 57% of kiosk Users claimed that they could afford to pay for all of their domestic needs using PSM water, suggesting that affordability influenced their usage patterns. Given that statistically similar rates of penetration and quantity scores were found between wealth quintiles, other motivations, such as proximity, household size, poor taste, or seasonal alternatives, must have also been impactful (Foster & Hope, 2016; Martínez-Santos, 2017). Future research on how different motivations impact water source choices in the presence of these pre-payment models could help to determine if higher penetration rates can be attained.

Regardless of why certain households do not choose to use PSM water, the continued dependence on alternative sources poses a challenging governance issue. Whether by inability or choice, not everyone was being served by the PSM. Who, then, is responsible for ensuring continued access to a basic water service for Non-Users? It is possible that the PSM could take on responsibility for maintaining alternative improved sources, but the associated costs could quickly become unsustainable. It is more likely that historical managers, such as the local government or water management committees, will be relied upon to maintain these water sources, by default.

Essentially, multiple stages of infrastructure still need to be maintained by various stakeholders at the same time. Positively, this promotes competition, and can help prevent the PSM from committing extortion. It also highlights the value of a systems approach (USAID, 2014), as both historical and professional providers are promoting access to a community water supply. However, traditional entities are likely to face the same limitations in reliability, quality, and financing as before (Chowns, 2015). If community resources are divided between different providers, it becomes even more difficult to recover life-cycle costs for either system. This challenge emphasizes a tension between equity and sustainability; providing water for all versus full cost recovery (Foster & Hope, 2017).

From 2016 to 2019, both control and intervention communities showed significant growth in basic water service provision, according to JMP indicators (Figure 2.5). For the control group, community-based managers represented the majority of traditional providers (70%) and, subsequently, portray the status quo. Without a dedicated intervention, coverage of the basic service still increased. However, households under this management system received significantly worse reliability and quality scores (Table 2.3a), often violating all three conditions of a safely managed service. Water services provided by the PSM during this time period were generally free of fecal coliforms and continuously available, but not on premises. When observing that intervention and control households overall did not have a statistically significant difference in access to the basic service or better, this is an important differentiation. However, both approaches have thus far been communal in nature, bringing risks of microbial deterioration during transport (Table 2.4d,e). It will be interesting to observe whether these trends shift as the PSM focuses on household connections in its next phase of development.

Does this mean that the private service provider had no significant impact? No selection-history events were recorded outside of water source construction for both groups. External contributors influenced both intervention and control communities, including the District Assembly, a local church, NGOs, and a few other isolated groups. Selection-maturation threats might suggest that the different groups simply matured at different rates, creating the illusion of a program effect. However, the cross-over pattern shown in Figure 2.6, along with the division of intervention households into Users and Non-Users, helps to show that the PSM did have an impact in the intervention group. The maturity rates of Non-Users and Control households are nearly identical, but Users jump up to a higher threshold ($p < 0.05$). This provides evidence that PSM Users initiate the increase of the intervention group scores, but their penetration rate prevents them from being statistically different for the sample population.

A number of limitations to this study should be considered when interpreting the results. First, selection bias could have occurred via the company in community sampling, potentially creating uncontrolled confounders. For instance, in Table 2.2, communities with a slightly higher population are observed within the intervention group, with less evidence of a piped supply at the baseline. Second, subjective bias could have influenced self-reported data (water sources, quantity, and reliability). Quality control questions were placed within surveys to identify false or incorrect information (e.g., using multiple sources for validation or asking the same question in a different manner). Third, endline cross-sectional comparisons alone cannot demonstrate causal relationships. The initial results sections should be interpreted with the later temporal comparisons in mind. Changes in quantity, accessibility, and reliability indicator scores over time reflected similar conclusions to those of the detailed endline analysis, but quality, affordability, and acceptability used different testing methods in 2016 and could not be equally compared. Households with a safely managed service in 2016 were assumed to have a good quality based on their improved status. Therefore, the safely managed proportions presented at that time are based on the best possible proportion. Likewise, JMP service indicators scores are based on a household's primary water source. When considering all drinking water sources, the results could significantly increase (e.g., all Users have at least a limited service) or decrease (e.g., some sachet water users also drink surface water). An analysis was conducted for each case, but did not influence the conclusions drawn. Finally, the variables included in the regression analysis do not represent an exhaustive list. Factors derived from previous studies provide a more comprehensive list to consider overall (Fisher et al., 2015; Foster, 2013; Foster et al., 2018; World Bank, 2017).

2.6 - Conclusions

Service delivery models across the globe have been developing and evolving with the goal of providing sustained access to safely managed water services. A district evaluation of new and traditional water services has provided a temporal perspective on the outcomes of using a private service delivery model in a rural, sub-Saharan context. The results have provided evidence for an improved household service for PSM Users of all socioeconomic classes ($p = 0.35$) compared to Non-User and Control households. In 2019, over 87% of User households benefited from at least a 'basic' service, compared to 70% of Control households. While this should be expected with a dedicated intervention effort, risks associated with a deteriorating water quality during transport, human resource management, and financial sustainability were still apparent. Furthermore, almost three out of four households still relied on existing alternatives to meet a portion of their weekly water demand.

Ultimately, this research has provided evidence that PSMs can fill an important role of increasing the standard of professional water supply, but they cannot be considered a panacea to rural water provision. Professional workers can produce superior, consistent water, but factors such as competition and affordability will limit the overall uptake. Traditional management schemes will remain relevant as long as there is a demand for both new, mechanized systems and existing improved sources, emphasizing the importance of a systems approach. While multiple providers may promote equity in improved water access, a split market share may prove challenging to financial sustainability. It is important that policy-makers and implementers account for these consequences for similar private service delivery models of rural water supply.

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2.8 - Supplementary Material

2.8.1 - Appendix A: Detailed Analysis Tables

Table 2.A1 - Service Level Indicator Scoring Criteria

Service	Indicator	Units	Variable	Range	Score
Quality	Faecal Coliforms	MPN/100mL	Ordinal	> 10	1
				3 - 10	2
				1 - 3	3
				0	4
	Geogenic Contaminants	P/A	Binary	Presence	0
				Absence	1
	pH	pH	Binary	Else	0
				6.5 - 8.5	1
	Conductivity	μS/cm	Binary	> 750	0
				< 750	1
	Turbidity	NTU	Binary	> 5	0
				< 5	1
	Residual Chlorine (Presence)	P/A	Binary	Absence	0
				Presence	1
	Residual Chlorine (Concentration)	mg/L	Binary	< 0.2	0
				0.2 - 2	1
Quantity	Liters/person/day	L/pp/day	Ordinal	< 5	1
				5 - 20	2
				20 - 50	3
				50 - 100	4
				> 100	5
	Use of Multiple Water Sources	P/A	Binary	1	0
				> 1	1
	Do you feel you can collect enough water? (Perception)	-	Binary	No	0
				Yes	1
Reliability	Annual Reliability	days/year	Ordinal	< 182	1
				182-237	2
				237-292	3
				292-347	4
				> 347	5
	Daily Availability	hours	Ordinal	0 - 4	1
				4 - 8	2
				8 - 12	3
				12 - 24	4
				24	5
	Functionality	-	Binary	Abandoned	0
				Not Functional	0
				Closed (long-term)	0
				Partially	1
				Functional	1

Table 2.A1 - Service Level Indicator Scoring Criteria (cont.)

Service	Indicator	Units	Variable	Range	Score
Accessibility	Time to collect water (round trip)	min	Ordinal	> 60	1
				30 - 60	2
				15 - 30	3
				5 - 15	4
				< 5	5
	Distance to source	m	Ordinal	> 1000	1
				500 - 1000	2
				100 - 500	3
				10 - 100	4
				On plot	5
	How many households in the community collect from this source? (Congestion)	households	Ordinal	Everyone	1
				20 - 40	2
				5 - 20	3
				2 - 5	4
				1 (Private)	5
	Do you feel safe when collecting from this source? (Security)	-	Binary	No	0
				Yes	1
Affordability	Relative Usage	min	Ordinal	Nothing	1
				Drinking	2
				Drinking / Cooking	3
				Domestic Needs	4
				All Needs	5
Acceptability	Water - Taste	Likert	Ordinal	Poor	1
	Water - Odor			Below Average	2
	Water - Appearance			Acceptable	3
	Water - Lather			Good	4
	Water - Affordability			Excellent	5
	Water - Opening Hours				
	Water - Wait Time				
	Vendor - Politeness				
	Vendor - Communication				
	Vendor - Availability				
	Vendor - Helpfulness				
	Vendor - Consider Poor				
	Manager - Professional				
	Manager - Finances				
	Manager - Responsive				
	Manager - Trustworthy				
	Manager - Engagement				

Table 2.A2 - Temporal demographics of control and intervention groups (detailed)

	Variable	Control*		Intervention*		Total*	
		2016	2019	2016	2019	2016	2019
a	Estimated Total Population	23,527		30,503		54,030	
b	Mean Population (Range)	**784**		**1,017**		901	
	Range	60 - 3,874		198 - 6,252		60 - 6,252	
c	Number of Communities	30		30		60	
d	Number of Water Sources	**130**	**145**	**105**	**173**	**233**	**318**
	% Surface Sources	13.1%	11.7%	16.2%	9.8%	13.7%	10.7%
	% Groundwater Sources	**56.2%**	57.2%	**81.9%**	60.7%	68.2%	59.1%
	% Piped Sources	**30.8%**	31.0%	**1.9%**	29.5%	18.0%	30.2%
e	Improved Source Available	96.7%	96.7%	100.0%	100.0%	98.3%	98.3%
f	Sampled Households	560	555	549	597	1108	1152
	Removed	19	11	9	13	28	24
g	Percent females	44.2%	55.2%	31.2%	60.1%	37.0%	57.3%
h	Mean Household Size	5.16	5.4	4.85	5.52	4.99	5.45
i	Mean Workers per Household	2.00	1.74	1.87	1.97	1.93	1.84
j	Median Age Range	40-49	40-49	40-49	40-49	40-49	40-49
k	Respondent Education						
	None	32.3%	37.0%	28.9%	32.2%	30.4%	34.8%
	Primary	9.2%	12.4%	7.4%	16.0%	8.2%	14.0%
	Junior High School	29.6%	32.2%	30.1%	29.8%	29.9%	31.2%
	Senior High School	19.5%	14.2%	20.2%	14.5%	19.8%	14.3%
	Post-Senior High School	9.5%	4.2%	13.5%	7.5%	11.7%	5.7%
l	Job Category						
	Unemployed	12.7%	19.1%	15.8%	15.8%	14.5%	18.8%
	Farming	55.2%	55.8%	62.4%	57.0%	59.2%	56.3%
	Retailer	12.0%	9.4%	6.0%	7.2%	8.7%	8.4%
	Food Service	5.3%	1.3%	0.7%	3.8%	2.7%	2.4%
	Mining	3.4%	1.4%	1.3%	2.4%	2.3%	1.8%
	Salaried	0.1%	4.7%	1.2%	1.3%	70.0%	3.2%
	Other	11.3%	8.4%	12.5%	12.5%	11.9%	9.0%
m	Rural Quintile (Mean)	3.64	3.40	3.67	3.42	3.66	3.41
	Poorest (0-20%)	0.5%	1.2%	0.5%	0.1%	0.5%	0.7%
	Poor (20-40%)	8.6%	14.8%	10.6%	14.0%	9.7%	14.4%
	Average (40-60%)	37.2%	43.4%	30.7%	40.3%	33.7%	42.0%
	Rich (60-80%)	33.5%	24.0%	37.5%	35.6%	35.7%	29.1%
	Richest (80-100%)	20.2%	16.6%	20.7%	10.0%	20.4%	13.8%
n	Own land	-	61.1%	-	66.3%	-	63.7%
o	Own house	-	90.1%	-	87.7%	-	88.8%

*Bolded text denotes $p < 0.05$

Table 2.A3 Multinomial logistic regression of water source performance (detailed)

	Explanatory Variables	n	Functionality*		Annual Reliability > 95%*		Free from Fecal Coliforms*	
			%	OR (95% CI)	%	OR (95% CI)	%	OR (95% CI)
System Age		270						
a	< 2 years	72	**82.2%**	**0.38 (0.19-0.75)**	**69.7%**	**0.42 (0.23-0.76)**	**77.8%**	**0.25 (0.12-0.52)**
b	3 - 4 years	37	63.5%	1	49.1%	1	46.8%	1
c	5 - 6 years	20	55.1%	1.42 (0.60-3.36)	30.8%	2.17 (0.59-7.97)	36.9%	1.51 (0.40-5.65)
d	7 - 8 years	32	51.4%	1.65 (0.64-4.23)	41.5%	1.36 (0.57-3.24)	42.0%	1.22 (0.48-3.09)
e	9 - 10 years	31	64.7%	0.95 (0.38-2.42)	27.1%	2.59 (0.97-6.97)	51.9%	0.82 (0.35-1.92)
f	> 10 years	78	68.7%	0.79 (0.39-1.63)	40.9%	1.39 (0.69-2.80)	32.5%	1.82 (0.89-3.73)
Water Source Type		283						
g	Borehole	104	63.6%	1	37.7%	1	50.9%	1
h	Unprotected Well	44	76.0%	0.55 (0.25-1.20)	54.7%	0.50 (0.25-1.01)	-	-
i	Protected Well	39	57.7%	1.27 (0.63-2.58)	30.9%	1.36 (0.69-2.68)	**7.7%**	**12.45 (4.65-33.40)**
j	Standpipe	48	54.7%	1.45 (0.81-2.59)	38.5%	0.97 (0.45-2.07)	49.4%	1.06 (0.53-2.12)
k	Kiosk	48	**91.7%**	**0.16 (0.08-0.30)**	**85.4%**	**0.10 (0.06-0.18)**	**91.5%**	**0.10 (0.04-0.23)**
Management Scheme		252						
l	Community	141	61.8%	1	37.3%	1	35.0%	1
m	Access Development	52	**92.3%**	**0.14 (0.07-0.27)**	**86.5%**	**0.09 (0.05-0.16)**	**90.2%**	**0.06 (0.03-0.13)**
n	Religious Institution	8	61.7%	1.00 (0.20-5.17)	51.4%	0.56 (0.13-2.47)	12.9%	3.65 (0.58-22.97)
o	District Assembly	10	50.0%	1.62 (0.70-3.78)	39.1%	0.93 (0.40-2.17)	50.0%	0.54 (0.26-1.14)
p	Individual	24	**88.2%**	**0.22 (0.09-0.51)**	49.1%	0.62 (0.27-1.40)	33.1%	1.09 (0.55-2.16)
q	No Manager	7	52.2%	1.48 (0.29-7.51)	11.9%	4.38 (0.93-20.54)	20.1%	2.14 (0.33-13.92)
r	Public Utility	10	60.0%	1.08 (0.37-3.19)	60.0%	0.40 (0.13-1.19)	50.0%	0.54 (0.20-1.44)
Payment Method		266						
s	Nothing	88	50.7%	1	30.8%	1	10.1%	1
t	Emergency Funds	15	54.4%	0.86 (0.42-1.77)	38.1%	0.72 (0.26-2.02)	12.7%	0.77 (0.29-2.05)
u	Monthly Tariff	17	**95.2%**	**0.06 (0.01-0.24)**	54.9%	0.36 (0.11-1.22)	**58.5%**	**0.08 (0.04-0.15)**
v	Pay-to-fetch	146	**78.8%**	**0.28 (0.15-0.53)**	**58.9%**	**0.31 (0.16-0.59)**	**68.0%**	**0.05 (0.03-0.10)**

*Bolded text denotes $p < 0.05$; surface sources excluded from analysis

Records associated with many of these variables are available within the online dataset, including whether managers were chosen, paid, or under contract, frequencies of inspections and meetings, evidence of training and written records for technical and financial purposes, and sources of external support.

Table 2.A4 Multinomial logistic regression for service level indicators by household group (detailed)

			Control	Control vs User*	Non-User	Non-User vs User*	User
	Parameter	n	%	OR (95% CI)	%	OR (95% CI)	%
Quality							
a	Use Improved Primary Source	1128	**70.9%**	**3.83 (1.58-9.26)**	**71.2%**	**3.77 (1.97-7.23)**	90.3%
b	Free from fecal contamination (Prim.)	1079	**62.3%**	**5.69 (2.61-12.43)**	**54.1%**	**7.98 (3.66-17.39)**	90.4%
c	Free from fecal contamination (All)	1070	**59.7%**	**3.41 (1.57-7.39)**	**53.1%**	**4.46 (2.33-8.57)**	83.5%
d	Free from geogenic contamination	1079	100.0%	1.00 (1.00-1.00)	100.0%	1.00 (1.00-1.00)	0.0%
e	Residual chlorine present	1076	**1.5%**	**110.1 (26.3-461.6)**	**2.4%**	**68.2 (12.6-367.4)**	62.9%
f	Residual chlorine above 0.2 ppm	1076	**0.4%**	**17.1 (1.5-188.5)**	**0.0%**	**-**	5.7%
Quantity							
g	Quantity collected above 20 L/p/d	1096	79.6%	0.86 (0.49-1.49)	75.8%	1.07 (0.63-1.80)	76.9%
h	Use of multiple water sources	1128	**41.1%**	**0.27 (0.14-0.50)**	**34.3%**	**0.20 (0.12-0.33)**	72.4%
i	Sufficient quantity (perception)	1128	**96.9%**	**0.26 (0.08-0.87)**	92.6%	0.66 (0.26-1.64)	89.1%
Accessibility							
j	Time per trip < 30 min	1114	94.8%	0.84 (0.35-2.04)	93.4%	1.07 (0.43-2.66)	93.9%
k	Distance to water source < 100 m	992	34.1%	1.85 (0.99-3.47)	**27.9%**	**2.47 (1.43-4.26)**	48.9%
l	Congestion > 20 households	1039	93.6%	1.72 (0.69-4.25)	97.5%	0.65 (0.19-2.19)	96.2%
m	Security (perception)	1124	94.9%	0.87 (0.27-2.85)	91.3%	1.54 (0.50-4.7)	94.1%
Reliability							
n	Annual reliability > 345 days	963	63.5%	2.20 (0.93-5.20)	**48.4%**	**4.10 (1.87-9.01)**	79.3%
o	Daily availability > 12 hrs	1122	**83.8%**	**0.29 (0.15-0.58)**	**85.5%**	**0.26 (0.13-0.51)**	60.2%
Affordability							
p	Can afford to pay for domestic needs	1128	**77.7%**	**0.45 (0.23-0.91)**	**86.9%**	**0.24 (0.12-0.47)**	61.2%
q	Rural Quintile is above 'Average'	1128	40.6%	1.46 (0.73-2.91)	43.0%	1.32 (0.83-2.11)	50.0%
r	'Excellent' affordability ratings	1106	17.1%	1.07 (0.54-2.13)	17.7%	1.03 (0.60-1.75)	18.1%
Acceptability							
s	Received 'Excellent' taste ratings	1111	22.9%	1.45 (0.87-2.42)	21.5%	1.58 (0.95-2.62)	30.2%
t	Received 'Excellent' odor ratings	1110	**15.9%**	**2.52 (1.41-4.51)**	**14.2%**	**2.88 (1.72-4.81)**	32.2%
u	Received 'Excellent'appearance ratings	1106	**22.1%**	**2.53 (1.46-4.40)**	33.1%	1.45 (0.92-2.29)	41.8%
v	Received 'Excellent' lather ratings	1097	18.8%	1.48 (0.81-2.71)	**17.0%**	**1.67 (1.01-2.76)**	25.4%
w	Safe to drink (perception)	1034	**89.3%**	**5.54 (2.12-14.49)**	94.7%	2.61 (0.92-7.40)	97.9%

*Bolded text denotes $p < 0.05$

2.8.2 - Appendix B: Service Provision Analysis

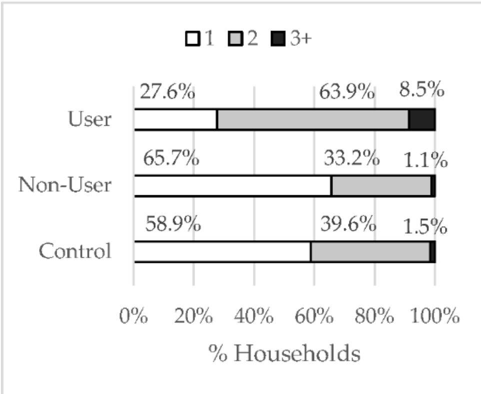


Figure 2.B1 Proportion of households using multiple water sources

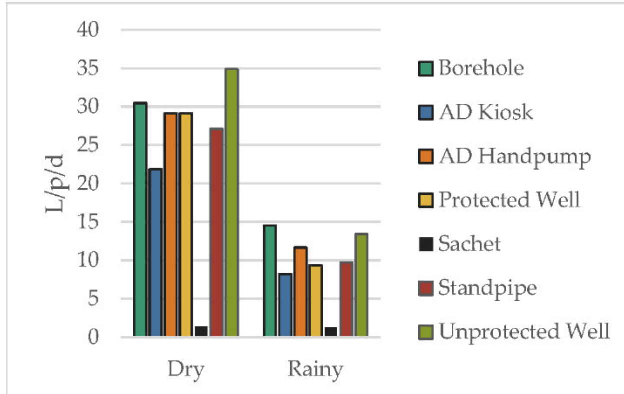
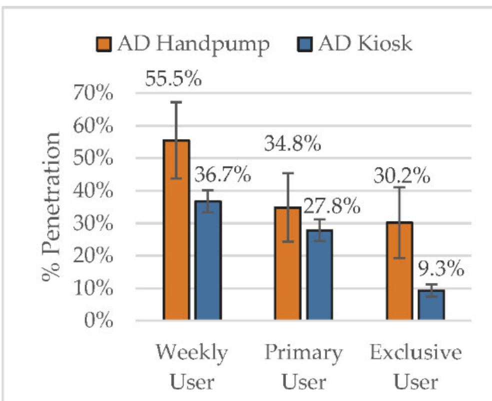
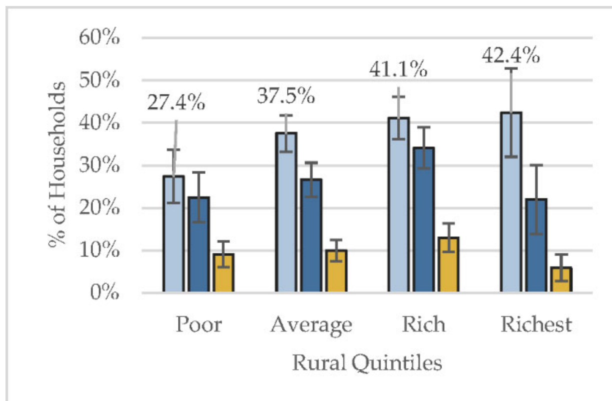


Figure 2.B2 Quantity of water collected per person per day in the dry and rainy seasons



(a)



(b)

Table 2.B3 AD penetration rates by usage frequency vs (a) water source type or (b) rural wealth quintile

Table 2.B5 Chemical measurement summary of improved water sources

Variable	Units	Median	Range		Criteria
pH	-	5.95	3.91	7.75	6.5 - 8.5 [a]
Conductivity	µS/cm	215.33	51.57	1255.40	< 750 [b]
Turbidity	NTU	0.00	0.00	52.67	<= 5 [a]
Arsenic	mg/L	0.00	0.00	0.00	< 0.01 [a]
Fluoride	mg/L	0.20	0.00	0.96	< 1.5 [a]
Free Chlorine	mg/L	0.00	0.00	0.20	0.2 – 2 [a]
Total Chlorine	P/A	17.9%	-	-	Presence

[a](WHO, 2017a); [b](EPA, 2019)

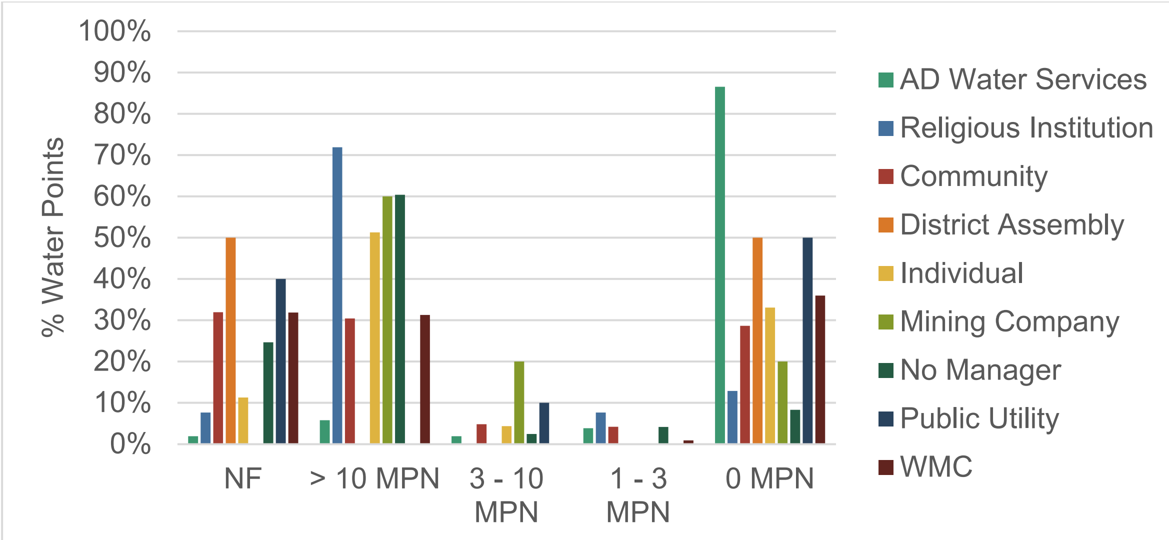


Figure 2.B4 E. coli measurements vs management entity

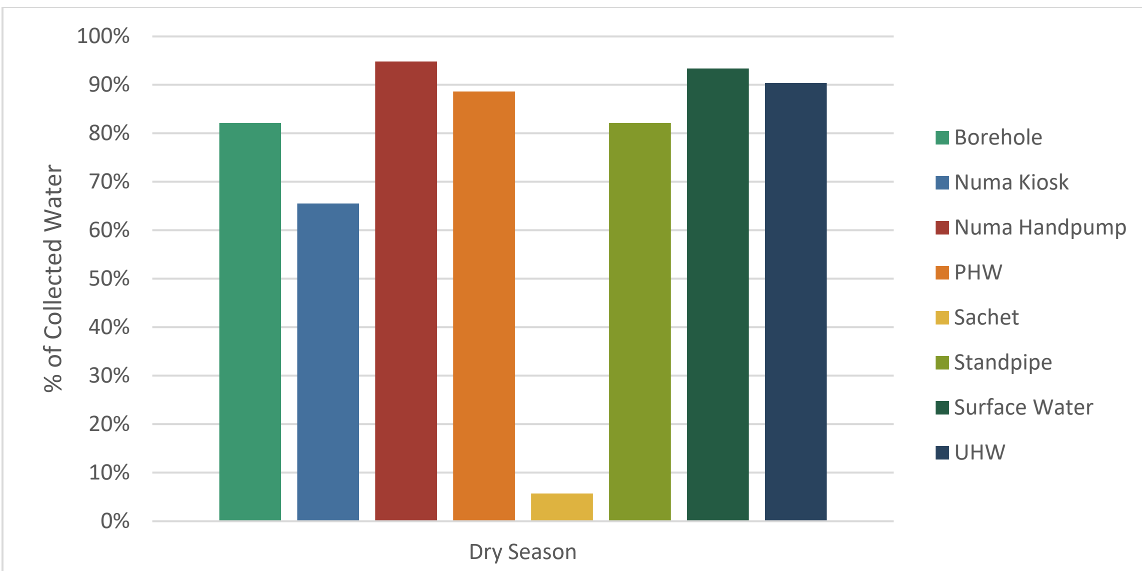


Figure 2.B5 Mean proportion of total water collected by a household for a given primary source

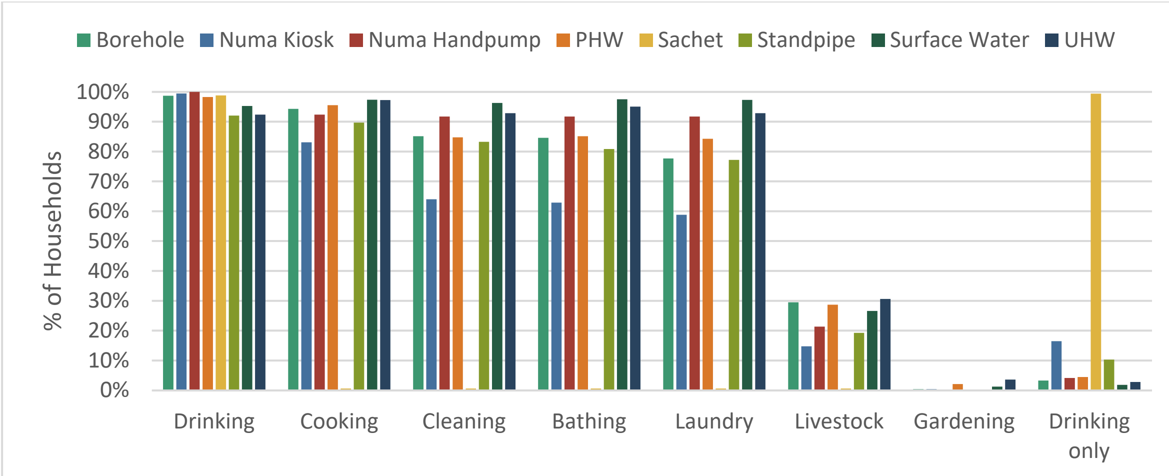


Figure 2.B6 Proportion of households that use their primary source for each category

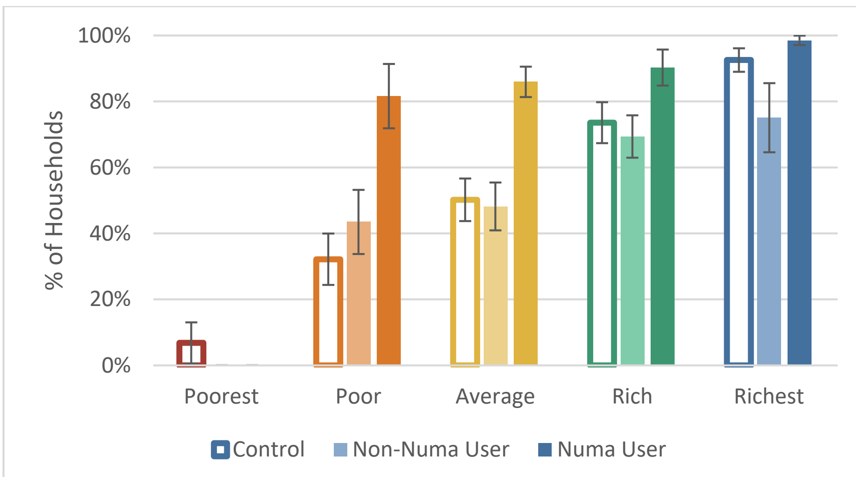


Figure 2.B7 Proportion of households that pay for their primary source vs classification and wealth index

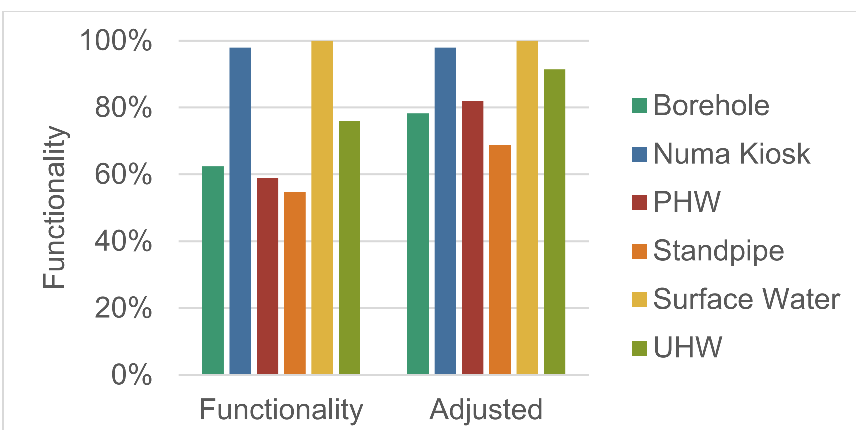


Figure 2.B8 Functionality rate vs water source type (adjusted removes those water sources determined to be abandoned)

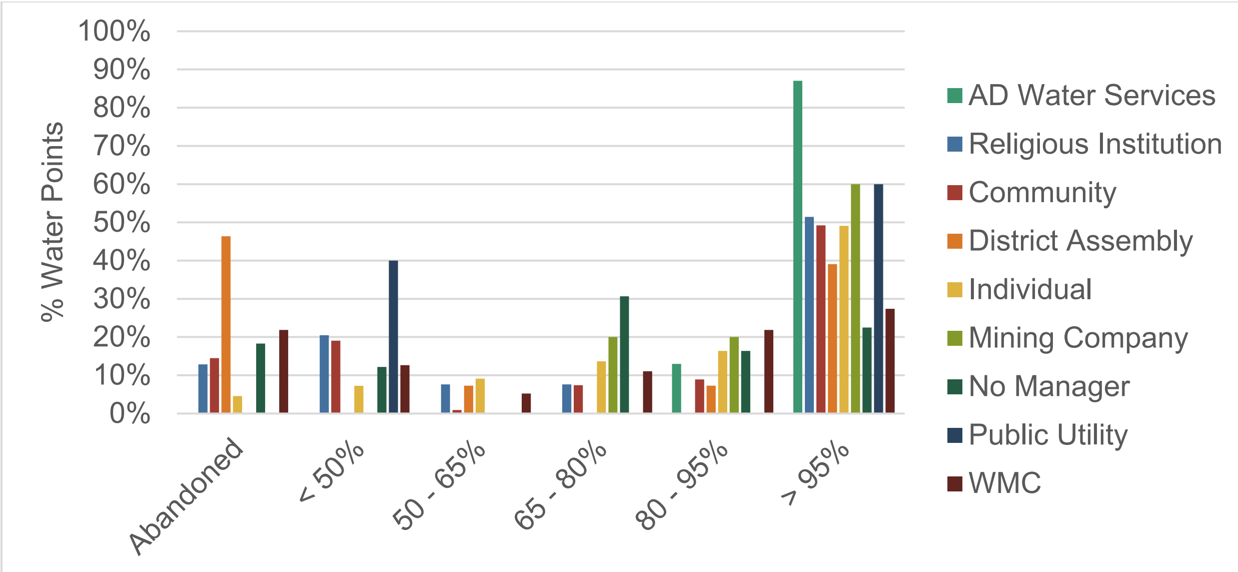


Figure 2.B9 Annual reliability in percentage of days vs management entity

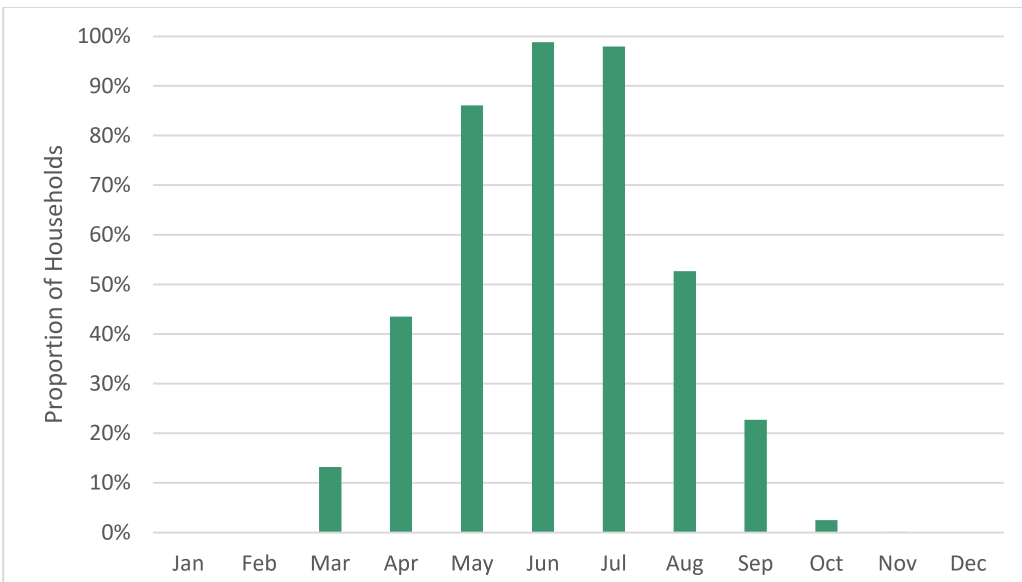


Figure 2.B10 Proportion of households that collect rainwater each month throughout the year

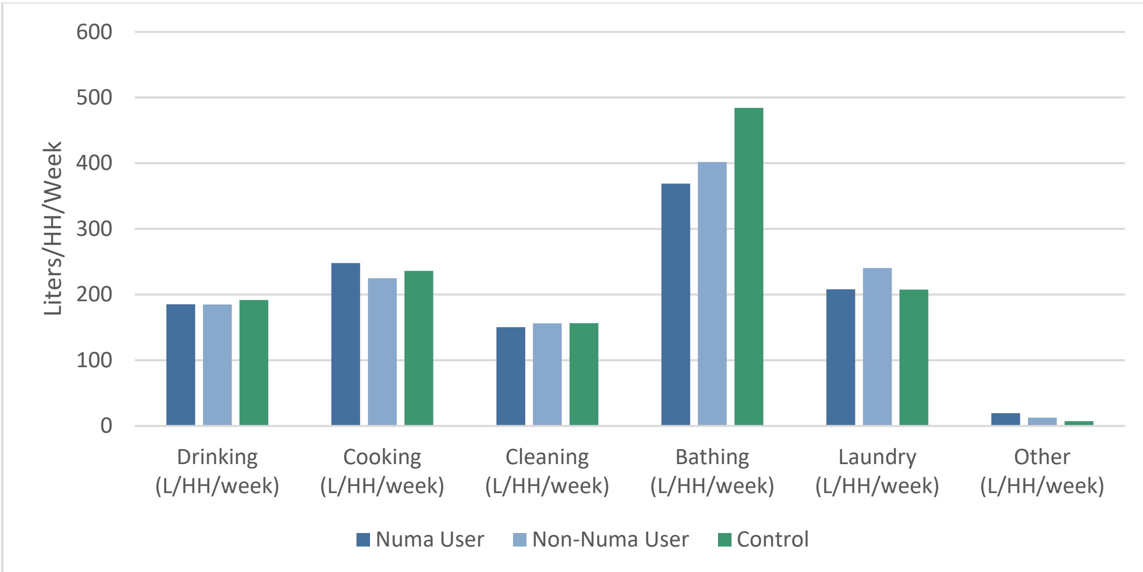


Figure 2.B11 Quantity of water collected per household per week for each purpose

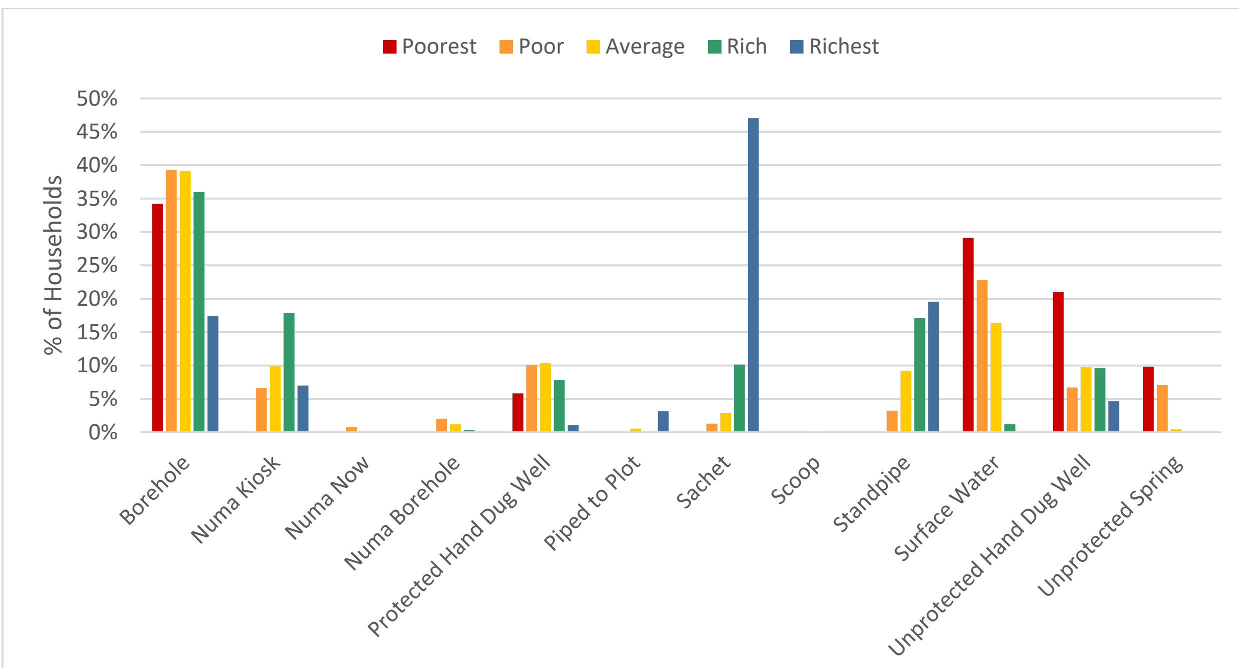


Figure 2.B12 Proportion of households using a given primary water source vs rural quintile (all samples)

Table 2.B13 Mean and median spending per household

Variable	Numa User			Non-Numa User			p-value
	Mean	SE	Median	Mean	SE	Median	
Healthcare (GHS/year)	375.31	58.23	100.00	381.09	84.64	100.00	0.698
Airtime (GHS/week)	17.40	1.78	10.00	22.19	7.69	10.00	**0.083**
Sachet – Rainy (GHS/week)	2.66	0.65	1.00	1.63	0.29	0.60	**0.001**
Sachet – Dry (GHS/week)	4.54	1.18	2.00	2.70	0.52	1.00	**0.001**
Numa – Rainy (GHS/week)	4.30	0.72	1.45	-	-	-	**-**
Numa – Dry (GHS/week)	7.09	0.64	4.20	-	-	-	**-**
Water – Rainy (GHS/week)	5.59	0.83	2.80	2.81	0.42	1.00	**0.000**
Water – Dry (GHS/week)	9.61	0.86	5.60	5.48	0.80	3.00	**0.000**

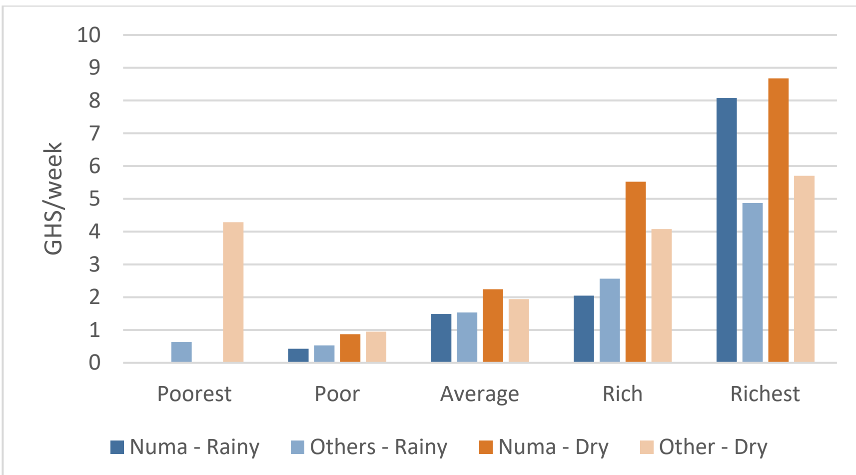


Figure 2.B14 Mean spending per household on sachet water per week vs rural quintile

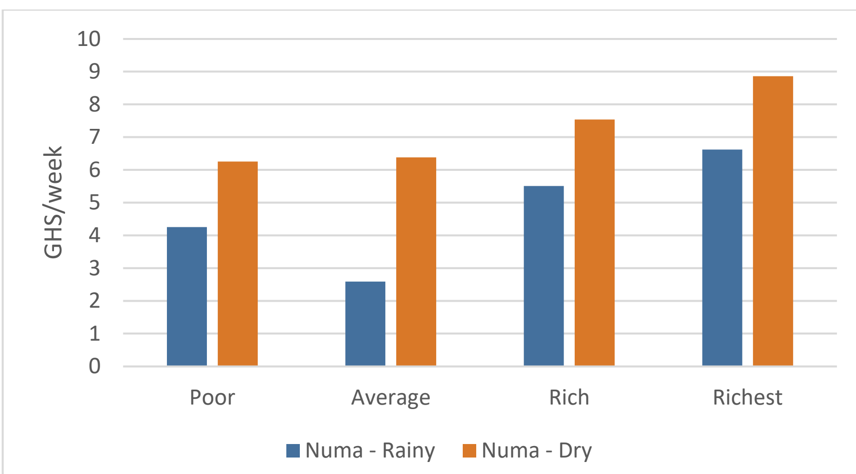


Figure 2.B15 Mean spending per household on Numa per week vs rural quintile

2.8.3 - Appendix C: Procedural Documentation

Community: Mensakrom	Community mWater ID: 16072963
	
(1) Kiosk - mWater ID: 17659910	(2) Stream - mWater ID: 17659927
	
(3) Sachet Water - mWater ID: 17705660	(4) Bottled Water - mWater ID: 17705677
(5) Piped Household Connection: mWater ID: 18103881	

Figure 2.C1 Community photo sheet for example community

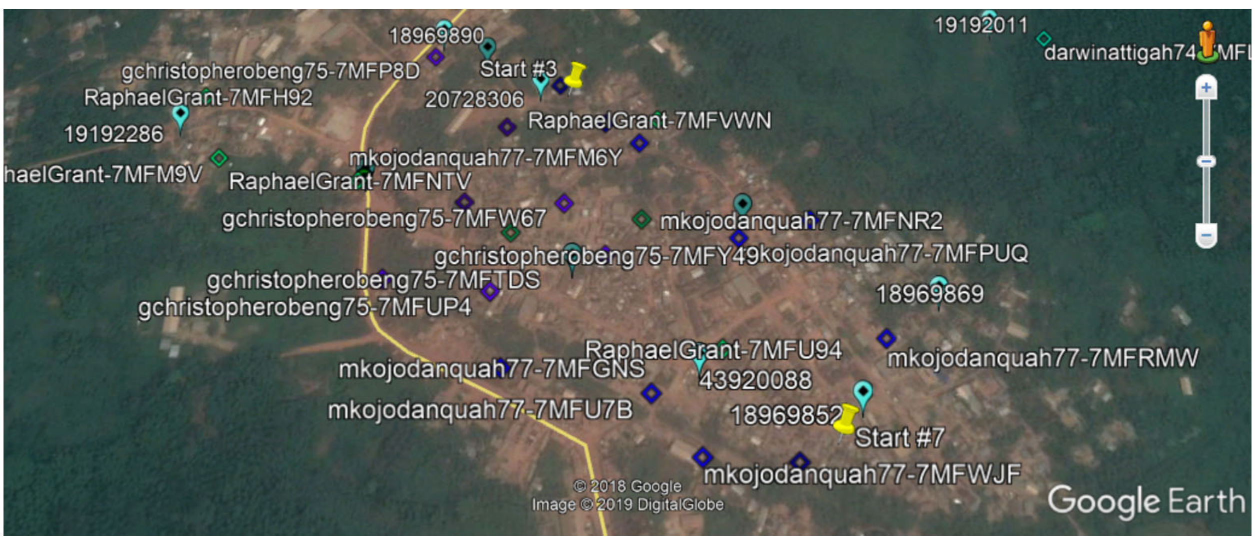


Figure 2.C1 Example of GPS quality control for household survey sampling

2.8.4 - Appendix D: Institutional Relationships

In 2014, Water4, an American non-profit organization, established Access Development as a private company in Ghana. Using a grant provided by the Netherlands Enterprise Agency, or RVO, and their own investment funds, Water4 provided the seed funding required to start-up Access Development. This included capital expenditures for land, initial staffing and training (by IDEA), and the water infrastructure. Manufacturing support by World Vision, and piped expansions by the Hilton Foundation occurred at different periods as well. By the end of the study period in 2019, Access Development had developed its own chain of command and autonomy in decision-making, but Water4 was still influential. Traditional protocol for Water4 is to develop a partner's skills through a series of steps towards complete independence. The financing necessary to reach this goal is described in greater detail in Section 3.7.2.

The University of Oklahoma partnered with Water4 in 2015 to act as the independent evaluator of Access Development. The role of the University of Oklahoma was to independently monitor the progress of the company and develop the tools necessary to track their performance. This input helped inform the focus on AD and the Wassa East District for this dissertation work. When publishing, the authors stated that funding for research was partially supported by Water4, identifying potential conflicts of interest. Furthermore, enumerators were overseen by both Access Development team members and the authors during survey interviews. However, the funders and AD had no role in the design, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

While conducting surveys, households were aware of the relationship between the University of Oklahoma, Access Development, and the District Assembly. This was stated within the consent form at the beginning of each questionnaire. As such, it is important to interpret the results with this respondent bias in mind. For instance, willingness-to-pay would have been answered knowing that current AD prices were set at 0.20 GHS per 18 liters, though this could not be changed under the contract for a set period.

3. An assessment of penetration for pay-to-fetch water kiosks in rural Ghana using the Huff Gravity Model

3.1 - Abstract

Safe water enterprises across the developing world are attempting to meet demand for a higher level of water service. Previously existing, frequently free water sources can make it difficult for these businesses to convince consumers to use a better-quality source or capture sufficient revenue for cost recovery. For this reason, it is imperative to develop a realistic understanding of penetration for small-scale water utilities. A cross-sectional assessment of sixty rural communities was used to evaluate the market share of Access Development, a private service provider in Ghana. Household survey responses were used to identify the most attractive qualities of available water sources. Distance, taste, appearance, and affordability were found to be the most common motivational drivers. Using this information, a Huff gravity model was developed to assess the actual and potential market share for the company in each community. The model and actual results agreed that about 39% of respondents would be regular customers at the given price. Even if water were free, the model predicted that the attractiveness of other sources would make it difficult to capture more than 58% of the sampled households. This illustrates the complexity of the water service ecosystem in a developing, rural context.

3.2 - Introduction

Safe water enterprises (SWE) have become increasingly pervasive in water service provision across the world. SWE are described as market-based approaches that deliver high quality drinking water through decentralized solutions (Bhatnagar et al., 2017). Businesses vary in their treatment, transportation, delivery, and payment methods; for example, home delivery of chlorinated water in India, ultrafiltration kiosks in Kenya, and private storefronts using reverse osmosis in Indonesia and Haiti (Cherunya, Janezic, & Leuchner, 2015; Patrick et al., 2017). Although often informal in the past, professionalized management systems for entire districts are becoming more common (RWSN, 2019). This has increased physical accessibility to treated water.

However, availability of treated water does not equate to usage. Market penetration rates historically range between 10 to 60% for similar SWEs (Bhatnagar et al., 2017; Deal & Sabatini, 2020; Opryszko et al., 2013). Previous studies have cited examples such as proximity, rainfall, or price as potential reasons for choosing between sources (Foster & Willetts, 2018; Martínez-Santos, 2017). This can lead to seasonal shifts in priority, periodic use of unimproved sources, or households choosing multiple sources for different domestic needs. Due to pre-existing alternatives, it may not be reasonable to assume that a SWE can achieve complete market saturation. More specifically, it can be hypothesized that a SWE, acting as a communal water provider, will be unable to reach a penetration rate approaching 100% as long as existing competition is readily available.

High penetration is critically important for both the equity and financial sustainability of SWEs. Determining ways for these businesses to reach more of the population increases true safe water coverage, which has reportedly been overestimated (Martínez-Santos, 2017). It also increases a service provider's ability to recover their life-cycle costs (Foster & Hope, 2017; World Bank, 2017). Early findings suggest that many SWEs may struggle to even cover their operational working ratio (operational expenditures and direct support costs) (McNicholl et al., 2019). Finding the right payment model and price point is an ongoing challenge for service providers, likely impacting the number of customers and revenue produced. Despite these challenges, Chapter 2 discussed how SWEs have been shown to have improved reliability and revenue generation compared to historical management models. Because of these improvements, innovative companies are working to reach profitability.

Access Development (AD) is a private, water service provider in the Wassa East District of Ghana that allowed for assessment of these challenges. The company extracts groundwater using solar-powered kiosks, which use microfiltration, UV disinfection, and chlorination for treatment. Customers collect water at the kiosk using the pay-to-fetch model. Circuit rider principles and a district approach allow AD to strive for economies of scale while working under contract for the local government (Deal & Sabatini, 2020).

A study of rural households within the Wassa East District investigated their willingness-to-pay, motivational drivers, penetration rates, and spending habits in relation to SWEs. This article will first describe the study area and methodology of the research. Then, penetration rates at the district and community levels will be analyzed in relation to key respondent motivators. Next, willingness-to-pay assessments will be compared to actual spending on water. These results will culminate in a geospatial analysis of market demand using the Huff gravity model (Huff, 1966). Finally, the implications of these results on equity, customer profiles, and consideration for the poor will be discussed.

3.3 - Study Area and Methods

3.3.1 - Description of Study Area

AD began work in the Wassa East District of Ghana in 2016. At that time, it was estimated that the district had a population of around 90,000 people in 137 communities (Wassa East District Assembly, 2016). It is predominantly rural, with only three densely populated areas. The total land area is about 1652 sq. km, but almost 600 sq. km is considered a forest reserve (GSS & GHS, 2015). The district capital, Daboase, is about 38 km from Takoradi, the capital of the Western Region. It is within a tropical climate zone, with mean annual rainfall of 1500 mm. About 69% of people claim commercial or subsistence farming as their primary employment, and nearly 80% of people do not have an education beyond Junior High School (Deal & Sabatini, 2020). A map of the district, along with sampled communities, is shown in Figure 3.1.

3.3.2 - Data Collection and Survey Techniques

A cross-sectional study design was utilized to collect quantitative data from households within the district (Jacobsen, 2011). Data collection was completed in 2019, after intervention communities had been under contract with AD for six months to two years. Two-stage cluster sampling was used to select communities and households from the district, which were split between an intervention and control group. Water sources within each community were evaluated for reliability and quality. Testing included fecal coliforms, turbidity, conductivity, chlorine, and iron (Deal & Sabatini, 2020).

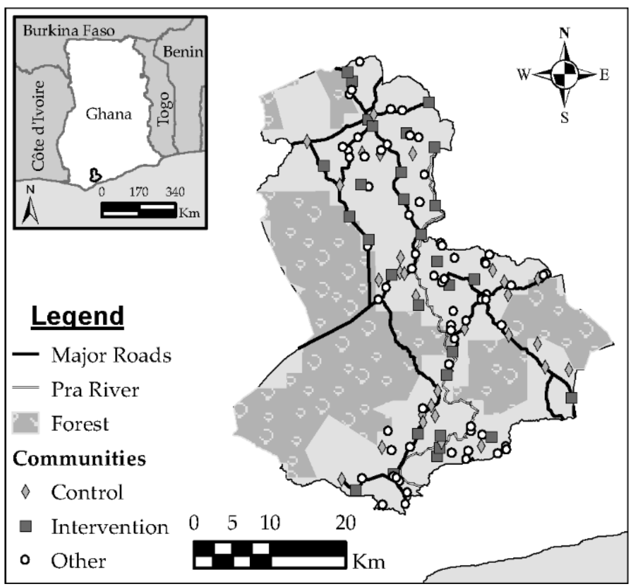


Figure 3.1 - Administrative map of the Wassa East District

Systematic random sampling of households occurred within each community. Enumerators received satellite maps, GPS coordinates, and sampling intervals to identify sampled households. Data were collected using the mWater platform. Unique mWater ID's were used to match household responses to previously identified water source characteristics and locations. Household heads or their spouse were given priority, though other adults were surveyed if necessary. GPS tracking allowed for verification of survey completion. About 1152 households were evaluated in total. Twenty-four households were removed through quality control checks of duplication, age, inconsistency, improper mental states, or poor accuracy ratings (Deal & Sabatini, 2020).

Informed consent was required prior to participating in the study. Identifying information was removed for the subjects' protection. The research protocol was cleared by the University of Oklahoma IRB. Data collection was carried out by local enumerators after completing training for ethical, in-person interviews. During preliminary survey testing, questions were asked in English, Fante, and Ewe after translation into local dialects.

Willingness-to-pay assessments were conducted using the payment card method (Cameron & Huppert, 1989). A respondent would select the maximum they would pay for a given water service from a price point list. The range was dictated from preliminary qualitative values on pay-to-fetch practices in the area. As seasonal differences were anticipated, actual spending was requested for an average week in both the dry and rainy seasons for different sources (Foster & Willetts, 2018).

Motivational options were presented from a pre-determined list derived from historical sources (Cherunya, Janezic, & Leuchner, 2015; Foster & Willetts, 2018; Martínez-Santos, 2017), both from positive and negative perspectives. Motivational categories were hypothesized to be distance, wait time, convenience, appearance, taste, quality, affordability (sometimes or never), social pressure, community pressure, opening hours, vendor attitude, belief, sense of security, and owning a private source (see Appendix A for details). An open-ended option was also allowed, though nearly all responses could be reallocated to the specified categories. Seasonal use of collected rainwater was a common addition made to this list by the respondents in the open-ended option.

3.3.3 - Data Analysis

Statistical analysis was completed using IBM SPSS Statistics 26, with complex samples used to simulate the two-stage cluster sampling. Households were assigned to various categories according to their location and preferred water sources. Table 3.1 defines the traits of each household typology. These classifications help to define penetration rate for this study. The penetration rate represents the proportion of intervention households that choose to use SWE water at least weekly, and is identified as the User (O) group. Periodic Users, who only use SWE water monthly or rarely, and Non-Users, or households within the intervention group that do not use SWE water at all, are not included. These can all be compared to the Control group, which do not have access to SWE water and reflect drinking water sources without intervention. As the results will show, Users (O) can be further broken down into different Supplemental Users (A), Primary Users (B), and Exclusive Users (C), as described in Table 3.1. These categories produce additional insight into water usage practices involving SWEs.

Lastly, a number of competitive location models were considered for assessing market demand: proximity, random utility, deterministic utility, cover-based, and gravity models (Suhara et al. , 2019). The proximity model only considers distance, and assumes that you will not be a customer of a given communal source if you are too far away. Random and deterministic utility models assume that a customer will select a location based on what is most attractive to them. Cover-based models predict customers from a radius of influence, based on attractiveness.

Table 3.1 - Household Classifications for sixty communities

Class		Samples	Description
Control		533	Control group
Non-User		307	Do not use SWE water
Periodic User		26	Use SWE water monthly or rarely
User	O	250	Use SWE water at least weekly
	A	58	Use as a supplementary source
	B	111	Use as a primary source
	C	81	Use exclusively

For this paper, the Huff gravity model was chosen to assess market demand (Huff, 1966). This competitive location model combines the variables of distance and facility attractiveness to predict the market share that a given store location can capture. It has historically been used to identify optimal locations for grocery stores, gas stations, shopping centers, or other retail outlets (Drezner & Drezner, 2004). While any environment with an extensive piped water system might not find this tool appropriate, many rural and peri-urban areas still use communal water sources where these predictions could be valuable.

In this study, Equation 1 defines the probability (P_{ij}) that a given household located at given location, *i*, would choose to collect water from source, *j*. This assumes that A_j is a measure of the attractiveness of each water source, and D_{ij} is the distance between the household and the water source. Euclidean distance was calculated using Equation 2, which is based on the radius of the earth, *r*, the latitude, φ, and the longitude, λ. The MCI model for attractiveness was used to test multiple factors, as shown in Equation 3 (Cooper & Nakanishi 1988). The variables, α and β, act as empirical model parameters, where the default α value is assumed to be 1, and β falls between -1 and -2 (Dolega, Pavlis, & Singleton, 2016). As a final step, the model (Equation 1) was transformed into a linear form using Equation 4. This allowed for linear regression analysis and optimization of the model. The variables, Π_i, Λ_j, and Δ_i, are the geometric means of P_{ij}, A_{jh}, and D_{ij}, respectfully.

$$P_{ij} = \frac{A_j^{\alpha} D_{ij}^{-\beta}}{\sum_{j=1}^{n} A_j^{\alpha} D_{ij}^{-\beta}} \tag{1}$$

$$D_{ij} = 2r * \arcsin\left(\sqrt{\sin^2 \frac{\varphi_i - \varphi_j}{2} + \cos\varphi_j \cos\varphi_i \sin^2 \frac{\lambda_i - \lambda_j}{2}}\right) \tag{2}$$

$$A_j^{\alpha} = A_{j1}^{\alpha_1} * A_{j2}^{\alpha_2} * \dots * A_{jh}^{\alpha_h} \tag{3}$$

$$\log\left(\frac{P_{ij}}{\Pi_i}\right) = \sum_{h=1}^{H} \alpha_h \log\left(\frac{A_{hj}}{\Lambda_j}\right) - \beta \log\left(\frac{D_{ij}}{\Delta_i}\right) \tag{4}$$

3.4 - Results and Discussion

3.4.1 - Descriptive Analysis

In order to derive the SWE customer classifications described in Table 3.1, household water availability, collection, and spending practices were investigated first. An endline water point inventory found that the intervention communities (30 in total) had, on average, a choice of about 6 communal water sources (range 2 to 14). Every community had a relatively new (6 months to 2 years) SWE water source available and functional, specifically 52 of the 177 identified sources. They included 48 kiosks with vendors selling water using pay-to-fetch and four boreholes under a monthly tariff scheme.

Household survey data determined which water sources were used on a regular basis, including their intended purpose and volumes collected in rainy and dry seasons. With this information, the customer classes were disseminated into groups, as shown in Figure 3.2, with Users further broken down into supplementary, primary, and exclusive categories. It can be observed that Non-Users are remarkably similar to the Control group, with the exception of standpipe availability. Although some Periodic Users claimed a SWE source as their primary source, infrequent use suggested a separate class would be more appropriate. Supplementary Users (A) cite other sources as their primary, but still use SWE sources regularly. The proportions of each class can be determined from Table 3.1.

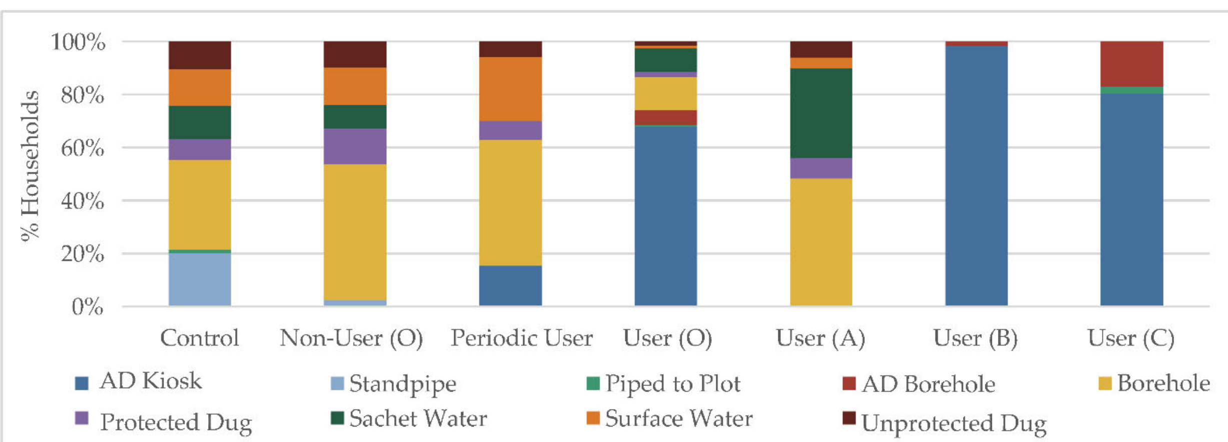


Figure 3.2 - Proportion of households using each primary drinking water source per customer classification; Households that use SWE water at least weekly – Users (O) – are sub-divided into supplementary (A), primary (B), and exclusive users (C) according to their

Given these overall customer classifications, it was important to understand any clustering effects that may have occurred. The overall SWE penetration rate within the intervention group was determined to be 36.7% for communities with kiosks and 55.5% for those with handpumps (Deal & Sabatini, 2020). However, the proportion of SWE Users had high variability from one community to another. The cumulative community penetration rates are shown in Figure 3.3. It can be observed that five of the thirty communities had a penetration rate over 80%, while seven were below 20%. The top five communities together had only two functional alternatives to SWE water, essentially requiring high uptake. The bottom seven communities had a combined 20 alternatives available throughout the year. At first glance, simply the ability to choose plays a role. This can be observed by noting the correlation between penetration and the decreasing alternatives per community (alternative ratio) in Figure 3.3.

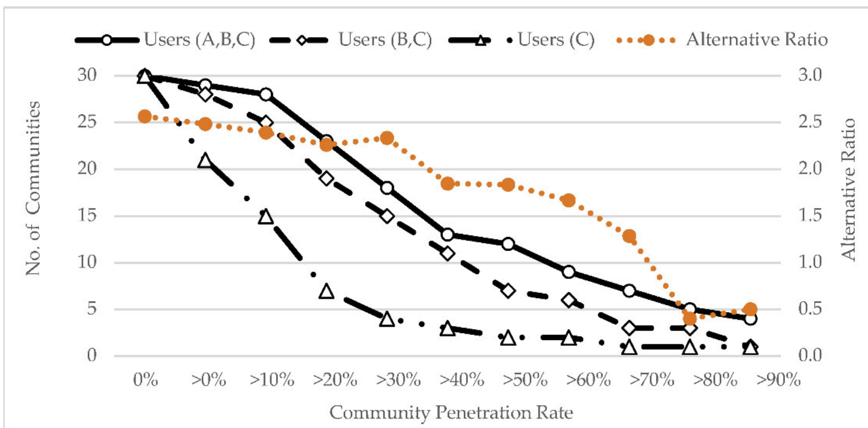


Figure 3.3 - Functional alternatives per community vs cumulative community penetration rates for all Users (A,B,C); primary and exclusive Users (B,C); exclusive Users (C)

A deeper analysis of motivation is highlighted by two questions within the household survey, which are summarized in Figure 3.4A and Figure 3.4B (descriptions of these responses can be seen in Appendix A). Respondents were asked what motivated them to choose or *not* choose a SWE water source (blue) or their primary source (orange). Non-Users and Periodic Users were the only classes to answer for both positive motivations for their primary source, and negative motivations for SWE sources. From the positive perspective in Figure 3.4A, top motivations for the Control group were close proximity (distance), appearance, and taste, while affordability was barely mentioned. While the top motivations remained the same for Non-Users, affordability saw a sharp increase for both Non-Users and Periodic Users (primary source). This might suggest an increased sensitivity to price for households within intervention communities, which are more likely to face a cost choice than the Control group. Overall, Users cited taste, quality, appearance, and distance as their greatest motivations for choosing SWE sources, following a slightly reordered priority list than other groups. However, secondary Users (A) were less likely to mention quality and taste compared to primary (B) and exclusive (C) Users.

When Control households were asked what motivated them *not* to choose an alternative drinking water source (Figure 3.4B), distance and taste were the most prevalent reasons. Other reasons, such as increased security, available hours, or affordability were rarely mentioned. All households within intervention communities were asked why they chose not to use a SWE water source. Non-Users also mentioned distance about 44.5% of the time, but never being able to afford (27.9%), only sometimes being able to afford (42.2%), taste (22.2%), and better quality (16.2%) were notable additions. Periodic Users disregarded distance, had the highest rate of affordability issues, and referenced the most diverse set of factors (though with a small sample size). This information provides evidence for a sub-section of the population that feels they cannot afford to regularly pay for water, thus limiting the market in a rural context.

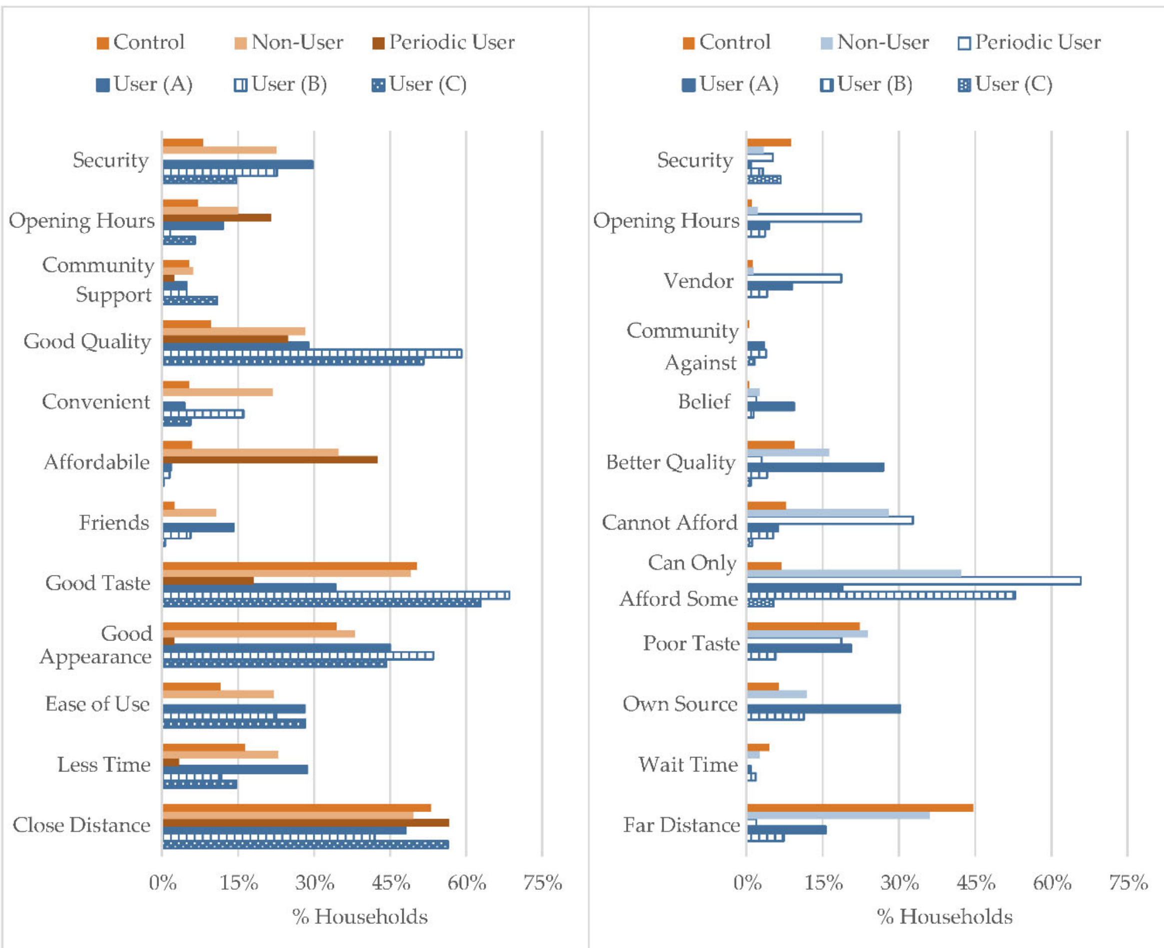


Figure 3.4 - Motivations to (A) choose or (B) NOT choose a SWE source (blue) or a given primary source (orange) for each customer class (see Table 3.1)

Figure 3.4B helps to highlight some key differences between the User classes. First, secondary Users (A) are the least likely to mention affordability as an issue, but are more likely to be motivated by a higher quality source or using their own source. While it could be assumed that supplementary Users (A) would struggle with regular water payments, only about 18.9% reference the inability to afford SWE water sometimes, as opposed to 52.8% of primary Users (B). When combining the data from Figure 3.2 and rural wealth quintiles, supplementary Users that purchase sachet water regularly are significantly more wealthy than those using communal sources ($p<0.05$). Exclusive Users (C), however, do not seem to voice any complaints. This shows the value of differentiating SWE customer classifications, as spending habits and volume demand are likely to reflect their motives.

It is also important to note that avoiding SWE water due to poor taste ($p=0.042$) and not having the ability to pay ($p=0.049$) are statistically correlated with community penetration rate. This highlights a cluster effect, where specific communities have kiosks with more complaints about payment or taste than others. For instance, four communities were observed to resist patronage of kiosks in an effort to lower pay-to-fetch costs. Of the potential chemical contaminants that can influence taste, chlorine, conductivity, and iron were tested in SWE sources (Deal & Sabatini, 2020; WHO, 2017). When isolating those communities noted for poor taste (n=14/30), a significantly lower mean penetration was observed (30.4% vs 57.0%; $p=0.013$). Quality and turbidity were also examined, but no significant tends with penetration were observed.

In order to better understand affordability, historical household income and willingness-to-pay were examined. First, median household income from a 2016 baseline was found to be 500 GHS (range 50 to 10,000 GHS) per month (Deal & Sabatini, 2020). While this is slightly dated for the 2019 endline analysis, it can be treated as a rough estimate for context. Willingness-to-pay for 18 liters of water (a standard collection bucket in the district) was requested for both handpumps and kiosk sources. These results are presented in Figure 3.5. A sharp drop-off in the proportion of households occurs after a price of 0.10 GHS per 18 liters, which is the historical price for many other pay-to-fetch handpumps in the district. Yet, the handpump curve shows that any payment requirement could lose a portion of this rural market. The slower drop-off for kiosks shows a demand for a better product, particularly mechanized or piped systems that do not require manual effort. With the current price of SWE kiosk water set to 0.20 GHS per 18 liters, these results would suggest that only 35.1% of the market would be willing to be a regular customer. This is well within the confidence interval of the actual penetration rate in the intervention group [37.8% (95%CI 31.4-44.7%)].

Finally, the partial and total volume of water collected, and the actual spending on water was requested from each household. Figure 3.6 presents these results for total water, sachet water, and SWE water per week according to each customer class (limited for simplicity to the dry season). Collected volumes from a households' primary source is compared to the total volume collected each week. The differences observed represent a portion of the sample population that uses multiple sources to meet their domestic needs (Deal & Sabatini, 2020). This highlights how supplementary sachet Users (A2) spend significantly more money on water than other classes while collecting less overall. The Control, Non-User (p=0.533, p=0.637), and supplementary communal Users (A2) (p=0.978, p=0.944) spent and collected statistically similar amounts per week, Exclusive Users (C) collected significantly less than the Control while spending more (p<0.001). These results are corroborated by the fact that only the group, Users (A2), was found to be statistically wealthier than others [OR=0.14 (0.04-0.52)], according to wealth quintile distributions, and Periodic Users were statistically poorer [OR=3.41 (1.37-8.46)].

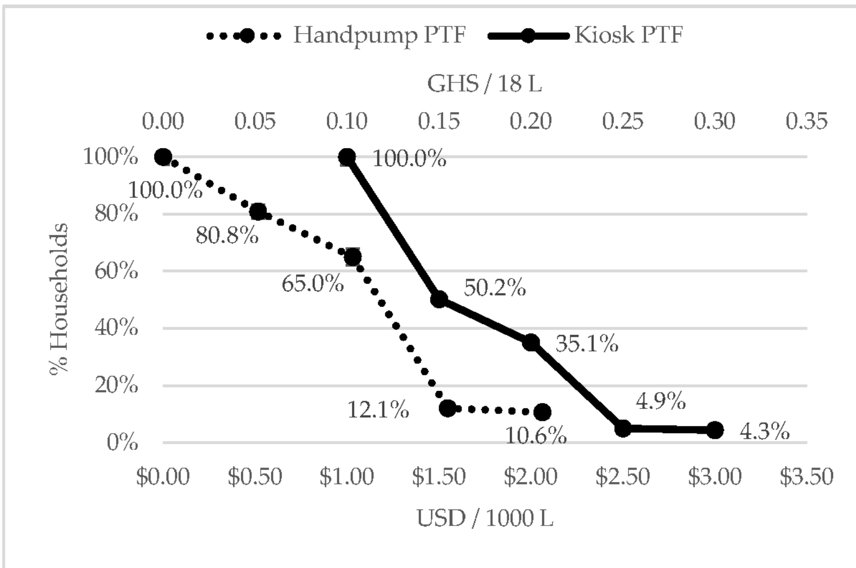


Figure 3.5 - Cumulative demand curve for households' willingness to pay-to-fetch (PTF) for 18 liters of water from a handpump and a mechanized source

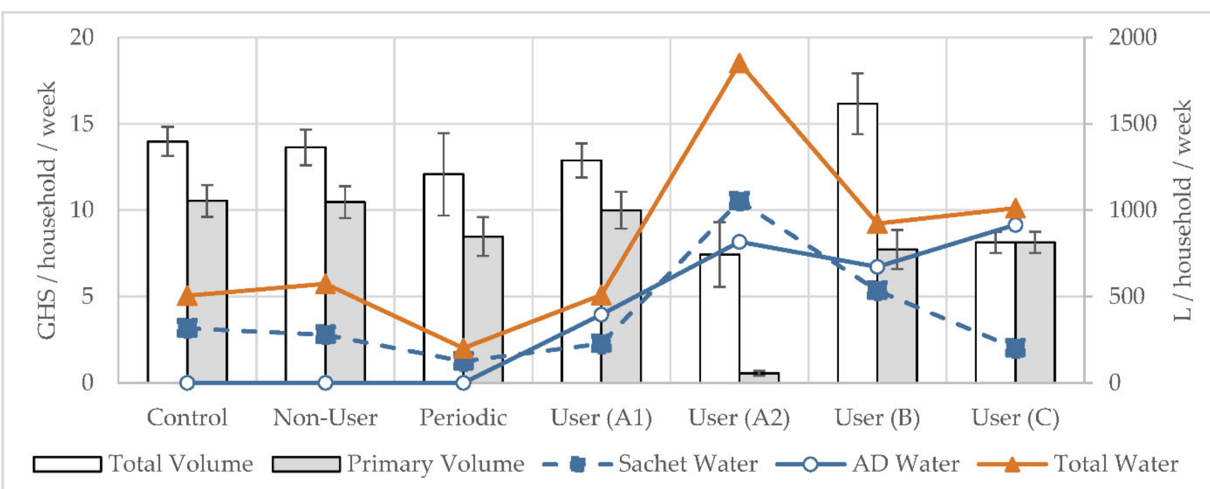


Figure 3.6 - Household water volume collected and water spending per week by customer classification

3.4.2 - Huff Gravity Model

The descriptive data analysis provided the necessary information to develop a Huff gravity model for each community in the district. The key assumption of this model is that each consumer is influenced by their distance from a given retail location and the attractiveness of the source. Table 3.2 summarizes the variables used within the model, and Figure 3.7 shows the progression of model development for an example community.

In Figure 3.7A, it can be observed that there are five water sources within the example community, each functional at the time of the survey. For reference, WP1 and WP3 are unprotected hand dug wells, WP2 is a protected hand dug well, WP4 is a SWE kiosk, and WP5 is a collection point along a stream. Randomly selected household sample locations are also noted. Figure 3.7B represents the highest probability value predicted by the model for all water sources, and a push-pull effect can be observed. This is the product of the attractiveness and distance for each water point in Equation 1. While attractiveness is static according to the model variables chosen, distance inversely reduces attraction.

Table 3.2 - Motivational variables associated with penetration and their Huff model scoring limits

			Scoring Limits	
Motivation	Variable	Type	Low	High
Availability	Functionality	Binary	Not Functional	Functional
	Annual Reliability	Ordinal	< 6 months	12 months
Taste (Chem.)	Chlorine	Binary	> 0.3 mg/L	< 0.3 mg/L
	Conductivity	Binary	> 300 µS/cm	< 300 µS/cm
	Iron	Binary	> 0.3 mg/L	< 0.3 mg/L
Appearance (Chem.)	Turbidity	Binary	> 5 NTU	< 5 NTU
Quality (Bio.)	Free coliforms	Ordinal	> 100 MPN/100 mL	0 MPN/100 mL
Organoleptic Rank	Taste, Odor, Appearance, Lather	Ordinal	Lowest rated choice	Highest rated choice
Affordability	Price	Ordinal	0.30 GHS / 18 L	Free
Social Pressure	Community resistance	Binary	Observed	Not Observed

Figure 3.7C maps out each sources' radius of influence, as well as the actual primary drinking water source for each household. The spatial influence is clearly evident, supporting the motivation of close proximity for many households. While a few households appear to be incorrectly assigned to a particular source, it is important to use both Figure 3.7B and 3.7C. Some sources far away only have around a 30% chance of using the predicted source, meaning that the others are offering considerable competition.

Attractiveness was calculated by incrementally adding the variables identified in Table 3.3. These variables were determined from the descriptive analysis and historical determinants (Martínez-Santos, 2017). They were restricted to traits of the water source independent of household traits, such as socioeconomic status or size, in order to simulate a new installation decision for a safe water enterprise. Some determinants,

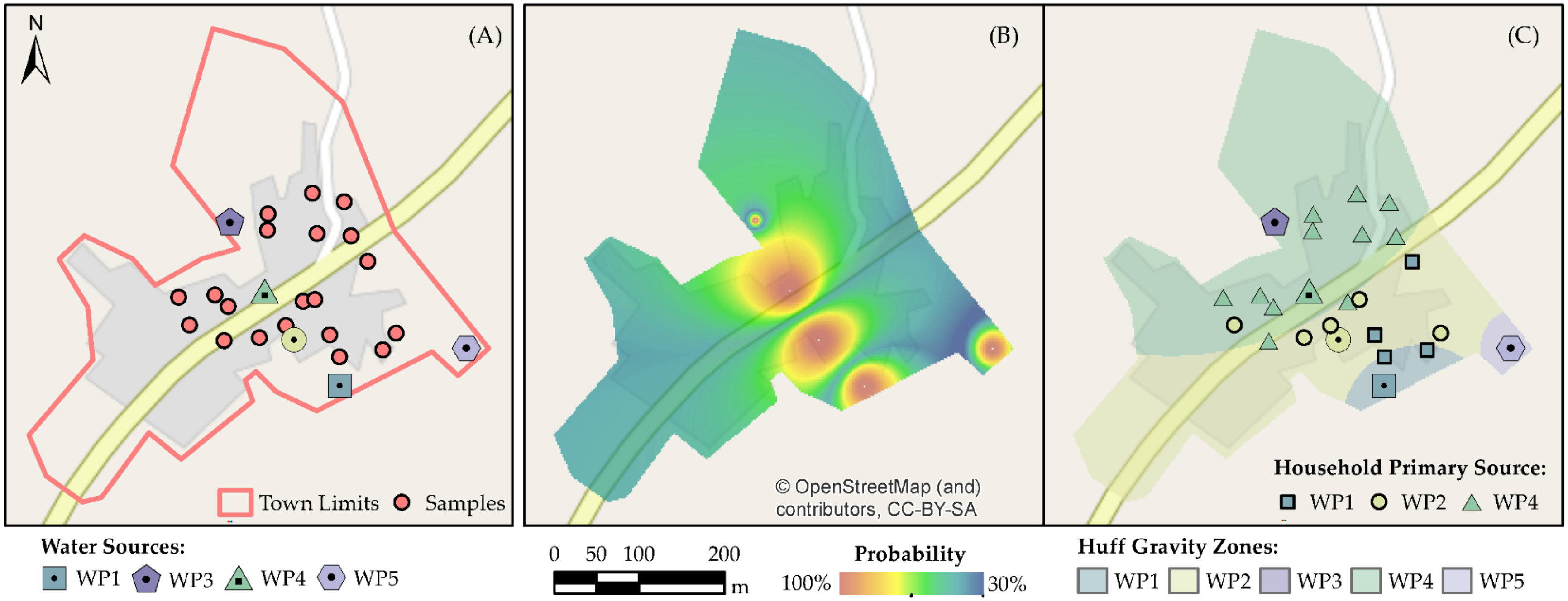


Figure 3.7 - Huff Model Analysis: (A) Sample distribution for an example community, (B) Max probability distribution for all sources (Gravity Map), (C) Highest probable water source vs respondent's primary source

Table 3.3 - Results of multiple-regression analysis for different models of probability; modeled determinants of water source usage are shown, and the subsequent penetration rates for SWE water sources are included

Model Predictions						Variable p-values [c]											
Models	Penetration [a]	Adj. R^2	Ln (Adj. R^2)	F-value	F-sig. [b]	Dist.	Func.	Reliability	Taste (Chem.)	Turbidity	Quality	Taste Rank	Odor Rank	Appear. Rank	Lather Rank	Social	Price
I	45.7%	0.279	0.018	123.9	< 0.001	0.009											
II	53.3%	0.526	0.325	354.2	< 0.001	0.001	0.140	0.001	0.260								
III	68.6%	0.468	0.343	280.8	< 0.001	0.009	0.268	0.003	0.246	0.469	0.001						
IV	57.0%	0.600	0.738	478.0	< 0.001	< 0.001	< 0.001					< 0.001					
V	58.3%	0.640	0.769	566.4	< 0.001	< 0.001	0.023	0.396	0.008				< 0.001	< 0.001	0.010		
VI	45.3%	0.740	0.776	906.7	< 0.001	< 0.001	0.017	0.356	0.020				< 0.001	0.001	0.008	0.001	
VII	38.8%	0.725	0.775	839.3	< 0.001	< 0.001	0.017	0.363	0.021				< 0.001	0.001	0.008	0.001	0.951

[a] Model prediction of % households using SWE water services; [b] Confidence level 95%; F-sig = 0.05 [c] Confidence level 95%; p = 0.05

determinants were considered binary, such as functionality and social pressure. While ordinal variables offered incremental improvements to attraction, binary variables could attribute a harsh penalty if a condition was violated (Table 3.2). Each was optimized based on the best performance of the model using multinomial linear regression in the log-normal form of the probability function (Equation 4). Table 3.3 shows the details of the model progression.

From Table 3.3, gradual improvements are observed from Model I to VII with respect to the regression fit. Distance was consistently a significant determinant. However, reliability and functionality seemed to have some redundancy due to their dependent nature. The penalty for non-functionality (A_j=0.01) serves the important role of ruling out unavailable water sources, but must be non-zero due to the log transformation.

The chemical taste determinant, which applied a penalty to sources with high conductivity or iron, was found to be more significant as other factors were applied. For this reason, it was kept instead of the Taste Rank factor. The opposite decision was used for appearance, where turbidity was generally found to be counterproductive and appearance rank performed better. The effect of the rank variables, as shown in model IV, was similar for all organoleptic properties, as they seemed to highlight the favored water sources in a given community. Quality was also found to be counterproductive, suggesting that the majority of households do not strongly consider it. This is not surprising, given that public water quality testing in the district is rather limited.

Social pressure and price proved to be rather important, but for different reasons. When a penalty was applied to sources that were observed to have negative social pressures, such as a borehole with evidence of worms or attempts to reduce kiosk prices, a significant jump in correlation occurred for Model VI. While a price factor did not have a significant effect on the linear regression (p=0.951), it dropped the penetration rate into the appropriate range. Given its good correlation with actual results, Model VII was selected as the optimal choice. The comparison between actual and predicted probability values are shown in Figure 3.8 below.

While providing useful insights, each model has the following limitations. Tested determinants are not exhaustive, with factors such as age or flow rate potentially increasing accuracy. As most communities were rural in this study, network analysis was deemed unnecessary, though the few peri-urban environments could have seen some benefit. Also, a few instances of error were observed where water sources were near schools or markets, and it is assumed respondents living far away may collect on the way home from work or school. Treating streams and other surface sources as lines or polygons rather than collection points could also impact model results. Next, recent records are important for modeling, as functionality and, subsequently, penetration can change over time. Finally, the role of seasonal rainfall could greatly impact the model.

In this region of Ghana, many households would set out large barrels to collect rain, essentially creating an onsite source of water based on rainfall patterns.

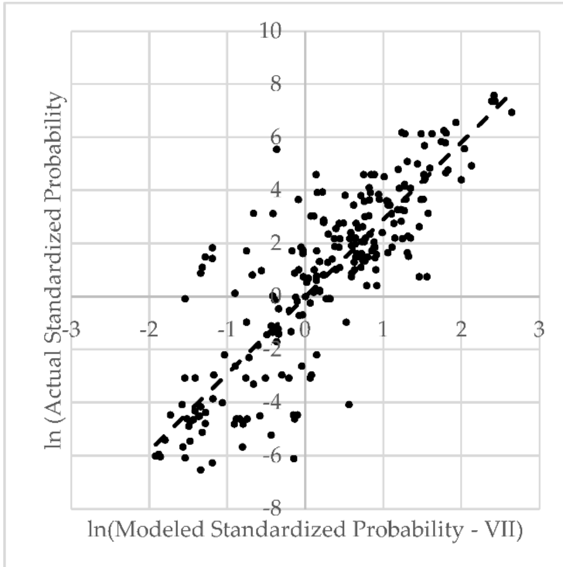


Figure 3.8 - Predicted vs actual probabilities for using a given water source using (A) the calculated probability and (B) the log-normal standardized probability

3.4.3 - Discussion

The results presented in this study provide evidence to support the hypothesis that market saturation, or approaching 100% penetration, is unrealistic for a safe water enterprise using communal water sources. First, penetration tends to increase as alternative options decrease (Figure 3.3). Second, the Huff gravity model illustrates how existing alternatives still have attractiveness, either by being closer to the home, a cheaper price, or better tasting. These effects most likely decrease as household piped connections become more prevalent, but are very applicable when central collection points exist.

For the Wassa East district, the maximum penetration observed in the various Huff models was 68.6%, which assumed that distance, reliability, and quality were the most valued traits of a water source. Understanding that taste and appearance are more valuable to the average household, it's more reasonable to assume that the maximum penetration attainable *with existing competition* is roughly 58% (model V), without considering affordability. With all factors considered, the Huff Model predicted that penetration would reach 38.8%, which falls within the confidence interval of the household survey results. The only two communities that reached 100% penetration for household samples had boreholes paid on a monthly basis, but rates above 90% were even attained for the kiosk pay-to-fetch model when little competition existed. The temporal study conducted by Opryszko et al. (2013) showed that penetration can increase over time. It would be interesting in future work to determine the role of the diffusion of innovation, where some households are early adopters while others may fall into the late majority (Moseley, 2004).

It is interesting to observe the market attempt to influence the price of water, which was captured by the 'social pressure' factor in the Huff model. Households did not strongly voice this when questioned about motivations and had to be observed externally. For communities that wanted a price drop from 0.20 GHS to 0.10 GHS per 18 liters, a 'boycott' occurred. The higher price was agreed upon in a signed agreement prior to construction. However, pressure was applied after the capital investment was made by the community to renegotiate the price. This is possible only because of the existing alternatives available. While other improved sources may take away from the financial sustainability of the SWE, they provide ongoing leverage to keep the private company accountable in both price and quality of service.

This also highlights that affordability was a critical motivator for certain households within the intervention population. While this did not play a significant role in the Control group (6-8%), Non-Users, Periodic Users, and Primary Users (B) all voiced concern about affording pre-payment of water. If the rough median household income in 2016 was 500 GHS per month, then spending on water should not exceed 25 GHS per month, or 5% (Fankhauser & Tepic, 2007). This is equivalent to the average spending on total water for Non-Users. At 0.20 GHS per 18 L at kiosks, this is only enough to afford drinking and cooking volumes of water (520 L/week). This explains why Users are spending more on water and supplementing their hygienic needs with alternative improved sources (Deal & Sabatini, 2020). Interestingly, other attractiveness factors must be influencing some Non-Users since they spend as much on water as supplementary Users (A1). However, this corroborates that a sub-set of households can only afford to pay for some of their domestic needs from the treated source. Further, 18.9% of intervention households claimed they could never afford SWE water regularly, which suggests an absolute limit for market penetration at the current price. This behavior can be observed in Figure 3.6 with the change in volume and spending between customer classifications.

3.5 - Conclusions

Overall, the willingness-to-pay assessment, the Huff gravity model (Model VII), and the household survey all agreed that the actual penetration in the Wassa East District should fall between 35-40% at the time of the study. This accounted for the attractiveness of individual water sources, the distance from each household, and the differing prices. For similar safe water enterprises, this predictive model can be used to estimate market share based on company decisions on location and price. With only a water point inventory of a given area, it can help to determine the proportion of the population actually served, rather than assuming an entire community is benefiting. It can also be used as a financial projection tool to assess cost recovery for a targeted area.

Formal safe water enterprises are looking to fill gaps in water service provision in urban and rural communities across the globe. Many examples offer treated, improved water and reliable service to their customers in an effort to provide continuous supply and protective health benefits. Their goal is to offer a better product in scenarios where existing piped, communal, and unsafe water alternatives are already providing for the population. This study has shown that SWEs will inherently face reduced penetration due to competition and differing motivations of its customer base. It is critical that implementers and funders understand these implications, allowing a realistic perspective of the role that these businesses can fill in the water provision ecosystem.

3.6 - References

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3.7 - Supplementary Material

3.7.1 - Appendix A: Motivation Descriptions

Table 3.A1 What influences your household's decision to fetch water from _______.

Motivation	Description
Close Distance	It is close to my home.
Less Time	It takes less time to fetch than other sources.
Ease of Use	It is easier to fetch than other sources.
Good Appearance	I like the appearance.
Good Taste	I like the taste.
Friends	My friends use that source.
Affordable	The water is more affordable than other sources.
Convenient	It is more convenient than other sources.
Good Quality	I trust the quality of that source.
Community Support	The community has encouraged us to use that source.
Hours	The source is open when I want to fetch water.
Security	I feel safe collecting from that source.

Table 3.A2 What influences your household's decision NOT to fetch water from _______.

Motivation	Description
Far Distance	It is too far away.
Wait Time	The wait time is too long.
Own Source	I have my own water source.
Poor Taste	I do not like the taste.
Cannot Afford	I cannot afford to pay for water sometimes.
Can Only Afford Some	I cannot afford to pay for water at all.
Better Quality	I use a better quality source.
Belief	I do not believe you should have to pay for water.
Community Against	There is social pressure in the community that discourages using the Numa systems.
Vendor	The poor attitude of the water vendor.
Opening Hours	It is closed when I want to fetch water.
Security	I do not feel safe collecting from that source.

Table 3.A3 Ordinal ranking of Huff Model variables

Motivation	Variable	Type	Scoring Limits Description	Rank
Availability	Annual Reliability	Ordinal	< 6 months	1
			6 – 8 months	2
			8 – 10 months	3
			10 – 12 months	4
			12 months	5
Quality (Bio.)	Free coliforms	Ordinal	> 100 MPN/100 mL	1
			10 – 100 MPN/100 mL	2
			1 – 10 MPN/100 mL	3
			0 MPN/100 mL	4
Organoleptic Rank	Taste, Odor, Appearance, Lather	Ordinal	Ranking	1 - 14
Affordability	Price	Ordinal	> 0.20 GHS / 18 L	1
			0.10-0.20 GHS / 18 L	2
			0.01-0.10 GHS / 18 L	3
			Free	4

3.7.2 - Appendix B: Life-cycle Cost Overview

Financing the Sustainable Development Goals for water, sanitation, and hygiene (WASH) is projected to be a daunting task. The annual global capital costs necessary to achieve universal, safely-managed water service in rural areas is estimated to cost $13.8 billion (Hutton & Varughese, 2016). In addition, operation and maintenance is estimated to cost as much as $13.0 per person per year to keep the systems running, roughly 1.6 times the capital cost in 2030. While the present rate of public and donor funding is projected to cover the initial capital investment for at least basic service, sustainable financing mechanisms for recurring costs over time remain a challenge (World Bank, 2017). For instance, Chowns (2015) found that communities either have a pitifully low savings for maintenance, only 2% of the expected value, or do not collect tariffs at all. Payments are lower than expected (Hope, 2015), and users may be reluctant to pay (Koehler et al., 2015). If improved water supply is interrupted even for a few days while money is collected for repairs, people return to unsafe sources and nearly eliminate the annual health benefits attributed to improved supply (Kumpel & Nelson, 2016). Rich community members, donors, or local governments have to step in and pay for repairs when a water point fails, rather than through careful planning and savings by the managing entity (World Bank, 2017).

For these reasons, the World Bank sustainability framework for rural service delivery models has established financial sustainability and asset management as two of their five building blocks critical to maintaining WASH infrastructure (World Bank, 2017). Ideal practices include financing mechanisms that account for the entire life-cycle of the water system, clear tariff policies affordable to all socioeconomic classes, clearly defined service authority and service provider roles for replacing and repairing assets, and scheduled capital maintenance plans in place. Funding can come from a mix of taxes, transfers, and tariffs appropriate to the environmental context (Jones, 2013). The latest strategy of 'blended finance' attempts to share the costs associated with sustainable water provision between government, donor, and users while leveraging financing from different institutional arrangements (Hope et al., 2020).

In order to allocate costs associated with water infrastructure, the true cost needs to be better understood. Attempts have been made to categorize all these expenses as life-cycle costs. Life-cycle costs (LCC) represent "the aggregate costs of ensuring delivery of adequate, equitable, and sustainable WASH services to a population in a specified area" (Fonseca et al., 2011a). This perspective can be used to better prepare for the typical cycle of WASH infrastructure – from initial construction, to maintaining the system, to repairing parts or expanding the system, to replacing major assets and restarting the cycle. Table 3.B1 provides a summary of each category.

Table 3.B1 Life-Cycle Cost Categories (Fonseca et al., 2011a)

Cost Category	Abb.	Examples	Cost range per person*
Capital Expenditures	CapEx (Hardware)	Drilling, kiosk construction, purchasing land	US $30-131
	CapEx (Software)	Community engagement, geological surveys	
Cost of Capital	CoC	Loan interest	-
Operation and Maintenance	OpEx	Overhead, labor, fuel, materials, minor repairs	US $0.5-5 per year
Capital Maintenance Expenditures	CapManEx	Asset renewal, depreciation, major repairs	US $1.5-7 per year
Direct Support Costs	ExpDS	Monitoring, evaluation, and capacity building	US $1-3 per year
Indirect Support Costs	ExpIS	Supporting government regulation, taxes	

*This range applies to small or medium water schemes serving less than 5000 people as of 2011

There are three challenges that the LCC perspective attempts to address. First, capital maintenance expenditures are often large, lump-sum costs that communities are unprepared to pay (Lockwood & Smits, 2011). Regular payments can help to prepare for this eventuality, such as monthly tariffs or pay-to-fetch models (McNicholl et al., 2019). However, there is poor evidence of communities maintaining sufficient savings for a high-cost repair every five to ten years (Chowns, 2015). This contributes to the non-functionality of existing water infrastructure.

Second, expensive post-construction support costs, such as travel, monitoring, and capacity building, are often inadequately funded or forgotten entirely (Lockwood & Smits, 2011). It is difficult to justify monetary investment for these purposes if a water system is working properly and other communities are still suffering without improved supply. This creates a tension between paying for new infrastructure, which is highly visible and builds political favor, and paying for support costs, which may seem unnecessary before failure occurs.

The third challenge that LCC has tried to address is to create a system by which different WASH models can fairly compare relative cost recovery. Different evaluations will choose to include or disregard different costs, making it difficult to compare evenly. In the study of health care facility kiosks, labor and capital expenses were disregarded when determining the cost of producing water (Huttinger et al., 2017). Hope (2015) found a local financial report neglecting 69% of incurred expenses. Others use common accounting terminology such as gross profit, depreciation, and overhead to depict the profitability of SWE under varying scenarios (Bhatnagar et al., 2017). The most recent and detailed work of McNicholl et al. (2019), separated direct costs, indirect costs, and asset depreciation in their analysis. In the midst of this confusion, efforts such as WASHCost have been made to identify an appropriate range of costs specific to the service provided (Fonseca et al., 2011b). If a system falls outside of these ranges, it is likely to be more expensive than common practice. A summary of the recommendations for small to medium water schemes, such as the ADWS kiosk, is included in Table 3.B1 for each category. It is crucial, however, that all true costs be reported for accurate comparisons such as WASHCost to be utilized.

Given these challenges, a study was conducted by Deal and Furey (RWSN, 2019) to determine how different service delivery models were tracking, delegating, and covering various life-cycle costs. Fourteen organizations were interviewed, with financial reports and estimates requested from each. Detailed accounting records were only available from a few companies, though many provided their best estimates. It was common to receive capital expenditures and some basic operational expenditures, but many capital maintenance and support costs were often predicted or incomplete, rather than firmly tracked over time.

Access Development proved to be in a similar situation. CapEx costs and OpEx wages were easily identified. However, support costs from Water4, the non-profit partner, and individual operational costs associated with each treatment facility were incomplete. Efforts were made to develop an accounting system that could break each cost down, but it has taken time for workers in the field to begin delegating expenses to specific installations and events. While this system has improved over the duration of the research study, records were insufficient for publication. Further, CapManEx costs require years to statistically determine *actual* equipment life-cycles and replacement schedules. It can be predicted through manufacturer estimates, but these can vary depending on the hydrogeological environment. Given these conditions, a rough estimate of the life-cycle costs associated with AD operations is provided in Table 3.B2, replicating the format developed in the life-cycle cost directory (RWSN, 2019).

Table 3.B2 Access Development Life-Cycle Cost Estimates

Context	Capex	Opex	CapManEx	CoC	ExpDS	ExIDS
Rural	Not responsible	Responsible but not covered presently	Responsible but not covered presently	Not responsible	Responsible but not covered presently	Responsible and required by contract
Urban	Not responsible but partially covered	Responsible and covered	Responsible and covered	Not responsible	Responsible and covered	Responsible and required by contract

Life Cycle Costs	Access Development has been working towards attaining profitability with their private water enterprise using economies of scale and cross-subsidies between rural and urban environments. Financial performance ranges widely for urban and rural contexts, with sustainability greatly dependent on the right balance of population density and market capture. In Ghana, scattered rural communities struggle to cover anything but the operation and maintenance support team, with larger communities cross-subsidizing due to increased profit. In Sierra Leone, a densely-packed, urban market has shown evidence of nearly full life-cycle cost recovery.
Capital expenditure – hardware and software (CapEx)	By the end of 2019, Access Development managed 30 Nexus, 37 Nodes, 25 Nanos, (kiosks) and 99 Nows (household connections). This infrastructure is equivalent to over 1.5 million USD in capital investments in the Wassa East District. This investment cost was supported by RVO, the Hilton Foundation, and Water4 in the form of a grant.
Operating and minor maintenance expenditure (OpEx)	Operating costs related to vendor and circuit rider wages, treatment works, minor equipment replacement, fuel, and transportation are sufficiently covered by the current revenue stream. However, overhead and salaries accounting for construction and management push costs above recoverable rates. For Wassa East, the general consensus is that supporting an O&M team could prove sustainable, but a construction team would need to continue pursuing external tenders to cover its overhead.

Capital maintenance expenditure (CapManEx)	Capital maintenance expenditures are estimated using the expected life of all equipment and replacing them over that period of time on an annual basis. Current projections are not presently covered in a purely rural environment, varying between 6 USD (Now) and 107 USD (Nexus) per month for a given installation.
Cost of capital (CoC)	CoC is not considered because CapEx has been financed through the previously mentioned grant.
Expenditure on direct support (ExpDS)	Designated AD staff members are devoted to monitoring and evaluation, as well as water quality testing of the managed infrastructure. These costs are included in OpEx. Direct support costs affiliated with grant reporting, training, and capacity building were largely covered by Water4 during the initial construction phase, but will be gradually eliminated in the following 2 years. Thus, ExpDS is split between costs within OpEx and upfront support costs from the NGO.
Expenditure on indirect support (ExpDS)	Indirect support costs are allocated to the local government (10%) and communities (5%) as a cut of the revenue. These funds are meant to be used in supporting community development and oversight by the District Assembly.
Total Expenditure (TotEx)	Investment Costs: CapEx + ExpDS (Construction Phase) Small-scale piped systems: 22 USD/person Direct Support: 14.50 USD/person Recurring Costs: OpEx, CapManEx, ExpIDS Operations: 3 to 7 USD/person/year **These figures vary depending on the size of the community*
Penetration Rates	Given the findings in Chapters 2 and 3, the estimated final coverage rates of 67,700 people in 2019 may be overstating the number of customers benefiting from this service. If about 38% of households are utilizing the small piped systems, costs per person would increase over 2.5 times. This impacts whether annual expenditures fall within the recommended WASHCost categories in Table 3.B1.
	Year: 2019

Table 3.B2 shows the mixed financial performance of AD. It can be hypothesized that population density and penetration rates are the biggest driving forces around life-cycle cost recovery for this service delivery model. If installations are closer together, less costs associated with travel and revenue collection occur. With the motivational effects discussed in Chapter 3, distance between a household and a kiosk sales point is also important. Thus, a higher population density centered around an AD kiosk is likely to produce more revenue. The societal attitude towards payment for water is another critical aspect of these predictions. People that have a longer history of payment, particularly at certain price ranges, can make or break a given installation. This creates an environment where more rural and dispersed communities decrease the likelihood of covering overall costs.[4]

Anecdotally, each individual installation may be profitable or lose-making depending on the context, penetration, and distance from a given area mechanic. The success of the business as a whole becomes dependent on the balance of the infrastructure investment. If enough profitable systems can subsidize the non-profitable systems, the business can be sustainable. This can be further helped or hindered by government costs (the 15% fee to the District Assembly and communities) or subsidies (free land, monitoring support). This is guided by preliminary evidence in Sierra Leone, where initial investment has been more focused in peri-urban environments. Future research aims to provide clear evidence for these assumptions and hypotheses.

In 2019, Access Development would have been considered at the intermediate level of financial sustainability (World Bank, 2017). Financing mechanisms are identifying all costs, but each individual system varies in its life-cycle cost recovery. Operational costs for circuit riders can be covered overall, though construction management likely needs income from new contracts to be maintained. Lumped costs for capital maintenance expenditures will require slightly increasing penetration rates (40-50%) or usage, through household connections and institutions, to be sustainable. However, peri-urban kiosks show great potential for cross-subsidization given the right balance of assets.

[4] Note that this is based on kiosk sales points, and does not yet account for household connections (Nows). Increased volumetric usage and higher revenue generation from household connections has the potential to push life-cycle cost recovery to a higher level.

3.7.3 - Appendix C: Seasonal impact on sales

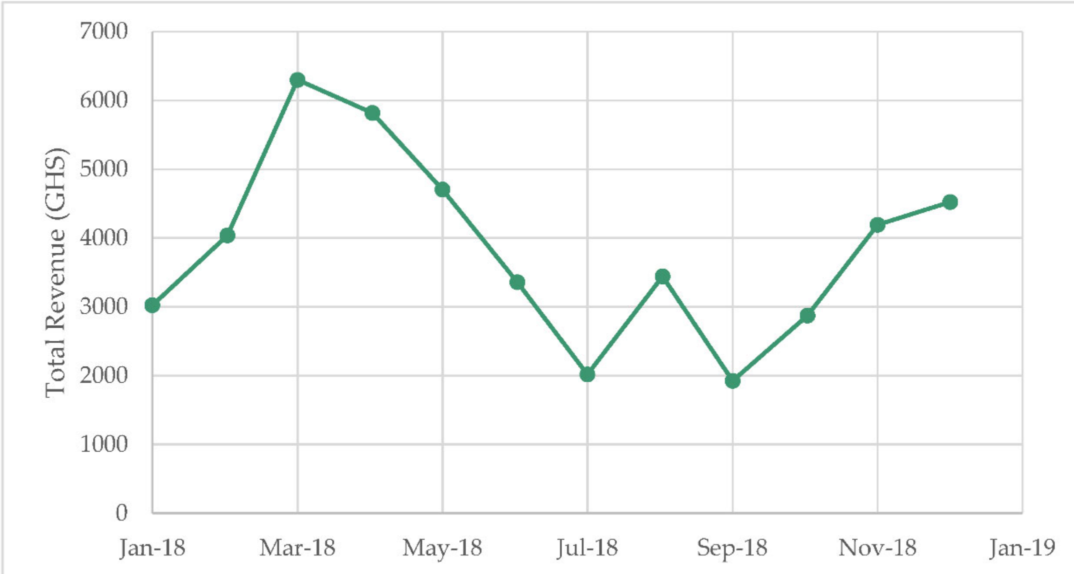

Figure 3.C1 Total revenue from 14 kiosks in 2018 showing the impact of seasonal rains on sales

4. Utilizing Indicator Kriging to Identify Suitable Zones for Manual Drilling in Weathered Crystalline Basement Aquifers[5]

4.1 - Abstract

Manual drilling offers a practical and affordable method of increasing access to groundwater supply in regions struggling with economic water scarcity. However, manual techniques are limited to specific hydrogeological contexts and must be sited appropriately. Indicator kriging is proposed as an interpolation method that builds upon previous efforts to identify suitable zones for manual drilling, particularly in weathered crystalline basement aquifers. This approach allows for heterogeneity within weathering profiles and provides probability mapping of success for regional planning. Modeling was conducted in the Upper East Region of Ghana using available borehole-log data, including: well yield, static water depth, laterite thickness, depth to hard rock, water quality parameters, and the degree of weathering. Indicator kriging interpolations for depth to hard rock predicted binary variables with over 90% accuracy. The model predicts that drilling into highly weathered layers will often be necessary to reach the required depths for groundwater use, emphasizing the importance of percussion techniques. The results suggest that suitable zones occur near Bolgatanga, Bawku, and Zebila, which coincide with historical drilling efforts in the central and eastern portions of the region.

4.2 - Introduction

Groundwater is an incredibly valuable resource in Africa, available through numerous and varied aquifers across the continent (MacDonald et al., 2012). In the rural areas of sub-Saharan Africa, roughly 100 million people are dependent on groundwater supply (Adelana & MacDonald, 2008). Groundwater can provide a reliable, resilient, and protected source of water for domestic and agricultural purposes (Lapworth et al., 2017). Further, groundwater can contribute to human development through increased food security, poverty reduction, and increased health, making it critical to the success of the Sustainable Development Goals (Conti et al., 2016; Hunter et al., 2009).

In the right context, manual drilling offers a practical and affordable method for accessing groundwater. Manual drilling replicates mechanical drilling methods, but uses human power to dig the borehole (Martínez-Santos et al., 2017). With proper construction procedures, such as sanitary seals and gravel packs, a well can effectively protect water quality. Likewise, appropriate siting, such as accounting for seasonal variations in water levels, can ensure reliable supply. Manual drilling methods include

[5] Deal, P., and Sabatini, D. (2020). Utilizing Indicator Kriging to Identify Suitable Zones for Manual Drilling in Weathered Crystalline Basement Aquifers. *Journal of Groundwater for Sustainable Development*. https://doi.org/10.1016/j.gsd.2020.100402

augering, sludging, jetting, and percussion, with each technique more effective in specific geological contexts (Labas et al., 2010). As of 2015, this practice was well established in Bangladesh, Bolivia, India, Kenya, Niger, Nigeria and Madagascar, was gaining traction in Chad, Senegal, and Zambia, and had been introduced in almost 30 other countries (Danert, 2015).

Manual drilling has its share of advantages and disadvantages. Since lighter equipment is involved, it can be moved more easily than traditional drilling rigs while still drilling faster and more safely than digging by hand (Danert, 2015). It also typically costs 4 to 10 times less than machine drilled wells. The enhanced affordability can help improve groundwater accessibility compared with the higher costs of mechanized drilling. Unfortunately, manual drilling is limited to relatively shallow aquifers found in soft, unconsolidated sediments or highly weathered crystalline rocks. The technique is also restricted by its maximum depth, with claims ranging from 25 to 50 meters (Fussi et al., 2017; Gaya, Fussi, & Van der Wal, 2005; Martínez-Santos et al., 2017; Thomas et al., 2012).

With these factors in mind, Table 4.1 summarizes the criteria that researchers have developed to identify suitable zones for manual drilling. Geological suitability and water depth are consistently the key factors associated with feasibility maps. Two recent articles brought new factors into consideration. Both Fussi et al. (2017) and Martínez-Santos et al. (2017) evaluated the minimum yield or transmissivity necessary to meet at least basic hand pump flow rates. Martínez-Santos et al. (2017) also expanded the manual drilling feasibility process by estimating drill time and cost maps in Mali. The authors used different penetration rates for alluvial and non-alluvial areas and incorporated practical field costs for drilling in the area. Fussi et al. (2017) focused on simplifying this approach with a structured, semi-quantitative process. Individual boreholes need only meet four qualifications: (1) a static water depth less than 40 m, (2) no hard rock shallower than 10 m, (3) laterite no thicker than 5 m, and yield greater than 12 L/min. Further work led to interpolations and comparisons to multivariate regression models in order to create spatial maps for manual drilling feasibility (Fussi et al., 2017).

The purpose of this study is to address two challenges discovered in the latest feasibility mapping techniques. The first challenge was encountered by Fussi (2017) while using kriging techniques to interpolate the depth to hard rock in Senegal. The data were considered to be discontinuous with little spatial correlation. The author settled for other interpolation methods such as inverse distance weighting. This raises the question - is there another way to work with discontinuous variables, such as the depth to hard rock, or non-normal data, such as fluoride contamination, for the purpose of feasibility mapping for manual drilling?

Secondly, literature that clearly defines the hard rock boundary for manual drilling is limited for weathered, crystalline aquifers. The lithological layers that are considered

Table 4.1 - Summary of Manual Drilling Suitability Criteria

Country	Variables of Interest	Criteria	Data	Citation
Chad	Geology	Unconsolidated sediment	Geology Maps	(Gaya et al., 2005)
	Depth to Static Water Level	Less than 25 m	Borehole logs	
12 Countries	Geological Suitability	Soft and permeable formations	Geology Maps	(UNICEF, 2011)
	Depth to Static Water Level	Less than 25 m	Borehole Logs	
	Morphological Suitability	Slope less than 5 degrees	DEM	
Niger	Depth to Static Water Level	Less than 35 m	Borehole logs	(Thomas et al., 2012)
	Geology Class	Various classes	Geology Maps	
	Soil Class	Various classes	Soil Maps	
	Landform Class	Flat regions	DEM algorithm	
	Topography	Low Slope	DEM	
	Dry Season Vegetation	Enhanced Vegetation Index	MODIS infrared properties	
	Surface Temperature	Low temperature	MODIS land surface temperature	
	Proximity to water channels	Less than 1000 pixels	Flow accumulation via DEM	
Senegal	Geological Suitability	Soft and permeable formations	Geology Maps	(Kane et al., 2013)
	Depth to Static Water Level	Less than 25 m	Borehole Logs	
	Presence of Laterite	Simply noted	Borehole Logs	
Ethiopia	Geological Suitability	No hard rock or boulders	Field Observations	(Huisman Foundation, 2014)
	Depth to Static Water Level	Less than 35 m	Field Observations	
Mali	Landform Proximity	Inselberg outcrops avoided	Surface Geology	(Martínez-Santos et al., 2017)
	Laterite Thickness	Less than 8 m	Borehole Logs	
	Depth to Static Water Level	Less than 25 m	Borehole Logs	
	Proximity to roads	Less than 1000 m	Google Earth	
	Well Yield	8 - 25 L/min	Pumping Tests	
	Water Quality	Less than 2000 μS/cm	Water Quality Sampling	
Senegal	Hard Rock Depth	Less than 10 m	Borehole Logs	(Fussi et al., 2017)
	Depth to Static Water Level	Less than 40 m	Borehole Logs	
	Laterite Thickness	Less than 5 m	Borehole Logs	
	Well Yield	Greater than 12 L/min	TANGAFRIC software	

drillable are often limited to unconsolidated layers above the bedrock, such as sand, clay, and silt (Fussi et al., 2017; Martínez-Santos et al., 2017). Some resources claim that soft, weathered regolith can be drilled manually using percussion methods, but no studies have shown how to integrate this information geospatially (Danert, 2015; Labas et al., 2010).

In order to address these challenges, this article will start by describing indicator kriging, and how it can be practically used to assess those variables that limit manual drilling. Next, the structure of weathered crystalline basement aquifers will be examined. This will help to describe how the degree of weathering can be used to define the limits of manual drilling in these environments. Subsequently, a historical dataset of boreholes in the Upper East Region of Ghana will be used to create a feasibility map for manual drilling. Variables of interest will include well yield, water quality, static water depth, laterite thickness, and depth to hard rock. Finally, the implications of these findings for manual drilling in basement rock formations will be discussed.

4.3 - Theory

4.3.1 - Indicator Kriging

Geostatistical methods are a useful technique for the mapping of spatially distributed data in numerous fields, including mining, engineering, hydrogeology, and soil sciences (Oliver & Webster, 2015). Interpolations can be made between individual data points to assess patterns and evaluate the associated error of predictions. One particular method, kriging, is defined as a collection of linear regression techniques that take into account the stochastic dependence among data (Olea, 1991). Essentially, the data of interest can be assessed for its spatial dependence. An unsampled location can be predicted based on its neighboring values by appropriately weighting the distance and variance of the neighboring sample points.

Kriging has the advantage of being an unbiased estimator due to its ability to calculate the range of spatial correlation and a numerical value that compares model accuracy (Eldeiry & Garcia, 2011). This is accomplished by using a semivariogram and cross-validation techniques. The semivariogram is a graph that compares the distance between points and the variance between the value at those points. The maximum distance for which there is a correlation between these variables is considered the range of spatial dependence. Various algorithms, such as spherical, exponential, and gaussian functions, can be used to match the curvature of these graphs and create a predictive model (Oliver & Webster, 2015). At this juncture, the predictive function can be used to perform cross-validation. Cross-validation uses every point in a given sample except one to predict the value at the remaining point. This value is compared to the original and an error is calculated. This process is repeated for every point in the sample, producing estimates of the mean error and other statistics for model evaluation (ESRI, 2010).

Ordinary kriging (OK) requires specific conditions and assumptions for effective modeling. Typically, data should have a normal distribution, or be transformed into one (Marinoni, 2003). Discontinuities, such as faults, should be avoided, as a smoothing effect occurs (Fussi, 2017). However, indicator kriging (IK) is a nonparametric method useful for highly variant or categorical data (Journel, 1983). It does not require normal distributions, but rather assigns data into a binary, categorical population. For instance, a sample point does (1) or does not (0) fall under a specific category, or a variable exceeds a specific threshold value (1) or falls below it (0). These values are interpolated to create a probability map, providing increased knowledge of the study area (Alli, Nowatzki, & Myers, 1990; Piccini et al., 2012). IK has been used to assess soil pollution, arsenic contamination, nitrate vulnerability, and many other conditional qualifiers (Eldeiry & Garcia, 2011; Jang, Chen, & Cheng, 2016; Liang et al., 2018; Piccini et al., 2012). Most appropriately, Marinoni (2003) used IK to improve predictions of geological layer thickness. While ordinary kriging would produce thin geological layers where they did not exist, a combined ordinary-indicator approach helped identify "zero value zones" where a particular stratigraphy was absent.

In considering how this concept could apply to factors influencing manual drilling, variables such as "depth to hard rock" could be subject to abrupt discontinuities where different formations occur. "Thickness of laterite" could be categorized into zones that exceed a given thickness. Indicator kriging could identify where these conditions are met in the form of a probability map. Potential drillers can then decide if the risk within a given region is worth investing and account for an estimated failure rate. For the purpose of feasibility mapping, this study claims that indicator kriging can offer an alternative approach for interpolating the structured process developed by Fussi et al. (2017) when non-normal data or discontinuous variables exist.

4.3.2 - Limitations in Weathered Crystalline Basements

Nearly 40 percent of land in sub-Saharan Africa is underlain by crystalline basement rock formations (Macdonald & Davies, 2000). These formations typically consist of three vertical zones: the upper weathered, the middle fractured, and the deep massive zones (Darko & Krasny, 2007). Basement aquifers develop within the weathered overburden, or regolith, and the fractured bedrock. Productivity and storativity are typically low, but sufficient to meet rural needs (Wright, 1992).

According to early assessments conducted in Sierra Leone, manual drilling feasibility in basement formations is only available in the upper weathered zone (Fussi, 2011). This definition is best summarized by the compendium developed by Danert (2015), where "highly weathered crystalline rocks (also referred to as regolith, or the overburden) above the bedrock," are considered favorable. Ideally, a quantitative measure of drillability, such as the concept of specific energy originally developed by Teale (1965), would be used to determine this limitation of manual rigs. This concept relates a rock's uniaxial compressive strength (UCS) to the required percussive and cutting forces enacted by a drill. UCS is the maximum axial compressive stress that a right-cylindrical sample can withstand before failing (Zhang, 2016). However, collecting core samples and testing this measure for an entire region can be time consuming and expensive. For the UNICEF series of country feasibility maps, only the composition of the bedrock was available to identify potentially favorable crystalline regions. Rocks with mixed mineralogical composition and coarse-grains were considered more likely to undergo the weathering process. This was the best methodology available given an insufficient distribution of borehole logs to analyze (UNICEF, 2011).

Weathering is defined as, "the physical disintegration or chemical decomposition of earth materials resulting in changes in the color, texture, composition, density, or form"(USDA, 2012). Depending on the weathering profile, a given layer can have different mineral constituents, hydraulic conductivity, and engineering properties (da Fonseca, 2003; da Fonseca et al., 2006). Fortunately, weathering tends to follow a well-defined pattern of decay, often with a significant loss in UCS (Abad et al., 2016; Dearman, Baynes, & Irfan, 1978; Kulhawy, Trautmann, & O'Rourke, 1991; Waltham, 2002). For the purposes of this study, the framework originally developed by Dearman et al. (1978) to describe a rock's weathered condition will be adopted. Table 4.2 defines the six categories used in this study, and an example of strength loss for granite (USDA, 2012). Figure 4.1 shows the profile of this framework, along with other descriptions for cross-referencing (Abad et al., 2016; Deere & Patton, 1971; Wright, 1992).

Table 4.2 - Weathering Terminology (USDA, 2012)

Category	Grade	Description	Granite UCS (MPa)
Fresh	I	No visible sign of weathering; Perhaps slight discoloration on major discontinuity surfaces.	250
Slightly Weathered	II	Discoloration indicates weathering and discontinuity surfaces. May be discolored and somewhat weakened by weathering.	150
Moderately Weathered	III	Less than half is decomposed or disintegrated to a soil material. Fresh or discolored rock is present either as a continuous framework or as corestones.	5 – 100
Highly Weathered	IV	More than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discolored rock is present either as a continuous framework or as corestones.	2 - 15
Completely Weathered	V	All rock material is decomposed and/or disintegrated to soil. The original mass structure is still largely intact.	< 1
Residual Soil	VI	All rock material is converted to soil material. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.	-

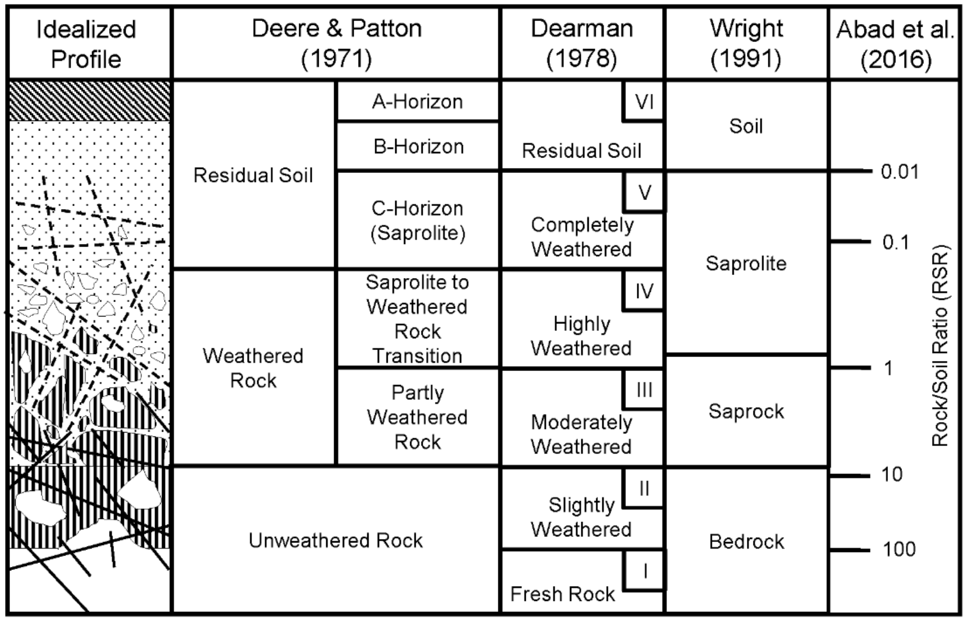

Figure 4.1 - Common Weathering Profiles

By combining the theoretical concept of UCS with the practical limits defined by Danert (2015), the degree of weathering can act as a proxy for drillability. The term 'soft, weathered rock' used by (Labas et al., 2010) is ambiguous, but could refer to a quantitative measure of uniaxial compressive strength between 1.25 – 5.0 MPa, if referencing standard hardness categories (USDA, 2012). Thick layers of laterite can also be considered difficult, with UCS examples of 824 kPa in Nigeria and 2.4 MPa in Burkina Faso (Abhilash et al., 2016; Sujeeth, 2015). This would correlate with a limit for manual drilling at the transition between highly and moderately weathered rock, depending on the formation (Waltham, 2002). This could also be considered the saprolite to saprock transition, or the point where the rock-to-soil ratio is greater than one (Abad et al., 2016; Wright, 1992). In the absence of quantitative measures of rock strength, the weathering descriptions can provide a more refined definition of hard rock limitations. More specifically, utilizing borehole records that specify the degree of weathering within a crystalline formation can refine the variable, depth to hard rock, in Fussi et al.'s approach (2017) to manual drilling feasibility assessments.

4.4 - Study Area

The study area for this research is found in the Upper East Region of Ghana, between 0° 02′ and 1° 32′ west and 10° 22′ and 11° 11′ north. It is bordered by Burkina Faso to the north, Togo to the east, and other regions of Ghana to the south and west, and has a land area of 8842 square kilometers (Agyekum & Dapaah-Siakwan, 2008). The population was projected at 1.27 million people in 2019, with around 80% being rural (GSS, 2019). Figure 4.2 shows the region's topography, major communities, and borehole record locations.

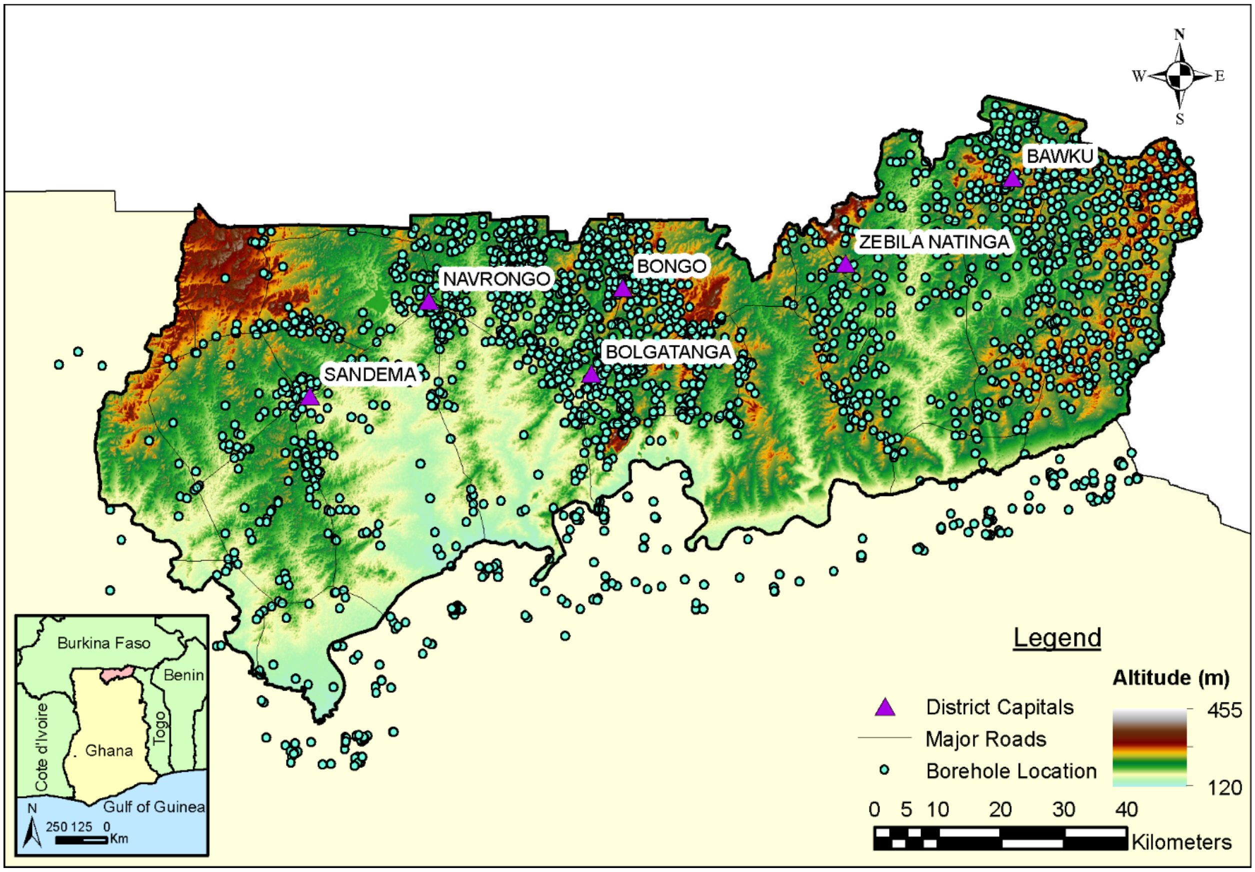

Figure 4.2 - Upper East Region (UER) of Ghana

The Upper East Region (UER) has a semi-arid climate controlled by the circulation patterns of wet, monsoonal air from the Gulf of Guinea and dry, Sahara Desert air from northern Africa (Agyekum & Dapaah-Siakwan, 2008; Lutz et al., 2007). The mean annual rainfall ranges between 800 and 1000 mm, with a unimodal season between May and October (Diabene & Gyamfi, 2013; Forkuor et al., 2013). Mean annual potential evapotranspiration typically exceeds the rainfall, leading to many surface water sources drying up periodically throughout the year (Gyau-Boakye & Schultz, 1994; Kwei, 1997; Lutz et al., 2007). For this reason, it is estimated that over 75% of domestic water use is dependent on groundwater (Gyau-Boakye & Dapaah-Siakwan, 1999).

People in the UER are dependent on aquifers that occur either in the regolith (completely and highly weathered layers) or the fractured zone of the crystalline formations (Carrier et al., 2008; Wright, 1992). The completely weathered layer's high clay content creates leaky aquifer conditions below, while the highly weathered layer provides increased hydraulic conductivity. There are also intermittent perched aquifers where coarse, permeable material overlays the completely weathered layer. For manual drilling, the perched aquifers and upper, leaky aquifers are considered attainable, but the fractured aquifers are deeper than the hard rock boundary and most likely out of reach.

Previous studies in the region have looked at the sustainability of groundwater resources (Forkuor et al., 2013; Lutz et al., 2007; Yidana et al., 2015), the potential yield and limitations of the aquifers for rural supply (Diabene & Gyamfi, 2013; Forkuor et al., 2013; Gumma & Pavelic, 2013), and hydrogeological characteristics (Acheampong, 1988; Carrier et al., 2008; Darko & Krasny, 2007; Martin & van de Giesen, 2005; Obuobie, 2008). According to Agyekum & Dapaah-Siakwan (2008), static water levels had a mean depth of 8 meters, and the average yield was 48 L/min. Transmissivity is typically in the low to intermediate magnitude in the crystalline formations. In the granites, the mean transmissivity was estimated at 6.6 m^2/d, ranging from 0.3 to 114.1 m^2/d. In the Birimian and Tarkwaian formations, the mean value was 7.4 m^2/d, ranging from 0.2 to 118.7 m^2/d (Darko & Krasny, 2007; Forkuor et al., 2013). Bannerman & Ayibotele (1984) estimated storativity to fall between 0.003 and 0.008. The mean recharge to groundwater in the White Volta River basin is estimated at 7% to 8% (Obuobie et al., 2012), while Martin & van de Giesen (2005) estimated a range in Ghana between 2% and 13%.

The majority (92%) of the UER is underlain by Precambrian crystalline igneous and metamorphic rocks, though the southern area consists of Palaeozoic consolidated sedimentary rocks (Adekile & Kwei, 2009; Agyekum & Dapaah-Siakwan, 2008). Three formations, including the Birimian, Eburnean, and Tamnean, have variations of Precambrian granitoids mixed with layers of gneiss, schist, hornblende, and biotite. Evidence of fresh granite bedrock is apparent across much of the region below other formations, and often found as the most deeply drilled layer in borehole logs. There are thin layers of sand, clay, and other sediments in the overburden. The Birimian formation also has sections of metamorphic, volcanic rock and basalt in the central area of the UER, with additional layers of shale, phyllite, schist, and greywacke. The final Precambrian formation is the Tarkwaian, which consists of immature sediments, quartzites, phyllites, and schists. Two Voltaian formations in the south consist of sandstones, arkose, and mudstones. The geological map can be seen in Figure 4.3.

Drilling programs have occurred in the UER since as early as the 1950s (Agyekum & Dapaah-Siakwan, 2008). Though NGOs are involved in drilling activities in the country, about 80% of activity is conducted by the private sector (Adekile & Kwei, 2009). Most contractors utilize light to medium drilling rigs to conduct rotary down-the-hole techniques. There have been records of manual drilling success in the Central and Upper East Regions of Ghana, specifically near Bawku East and Bolgatanga. In contrast, manual drilling has faced challenges in the Western Region in recent years, and evidence has shown those trained in the UER discontinued this practice (Adekile & Kwei, 2009; Naugle, Osei, & Ahmed, 2013; Naugle, Water4, person communication, 2018; Forson, UNICEF, personal communication, 2019).

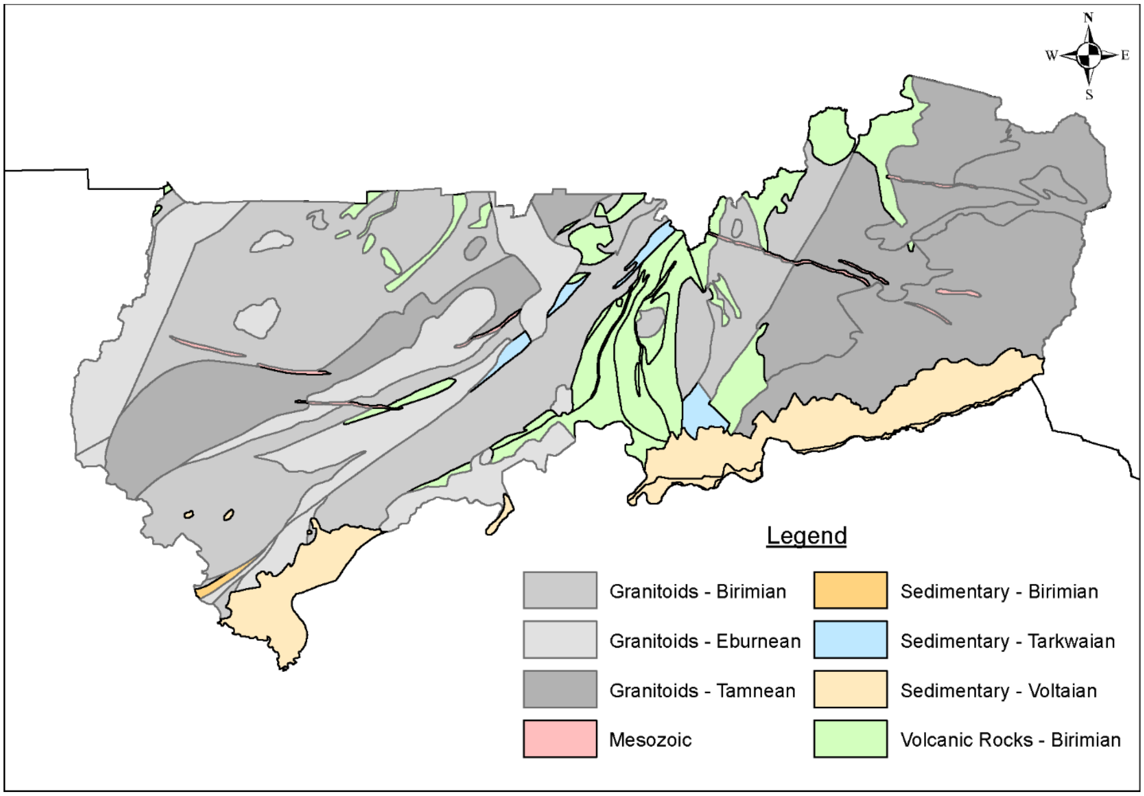

Figure 4.3 - Geological Map of the Upper East Region (Adapted from Carrier et al., 2011)

This background information shows why the Upper East region is a useful location to apply the indicator kriging technique for manual drilling feasibility. First, evidence shows that manual drilling has had mixed results in Ghana. Differences in weathering patterns and rock strength could indicate why. Second, the Precambrian crystalline formations match the characteristics for a typical weathering profile (Dearman, 1978; Wright, 1992). They have evidence of three vertical zones and interspersed semi-confined aquifers in the regolith and fractured zones (Adekile & Kwei, 2009; M. Carrier et al., 2008). Third, the degree of weathering is relatively shallow and variable, encouraging consideration of non-parametric methods (Agyekum & Dapaah-Siakwan, 2008; Marinoni, 2003).

4.5 - Materials and Methods

In order to determine the feasibility of manual drilling in the Upper East Region of Ghana, the criteria utilized by Fussi et al. (2017) will be adopted. This includes water table depth, well yield, laterite thickness, and depth to hard rock. In addition, water quality will be considered in a similar manner as Martínez-Santos et al. (2017). Each variable will be sub-divided into either “Accessibility”, “Availability”, or “Quality” categories through Fuzzy set theory to produce relative feasibility scoring (Forkuor et al., 2013; Malczewski, 2006). This process is illustrated in Figure 4.4, while the sources of the spatial databases are identified in Table 4.3.

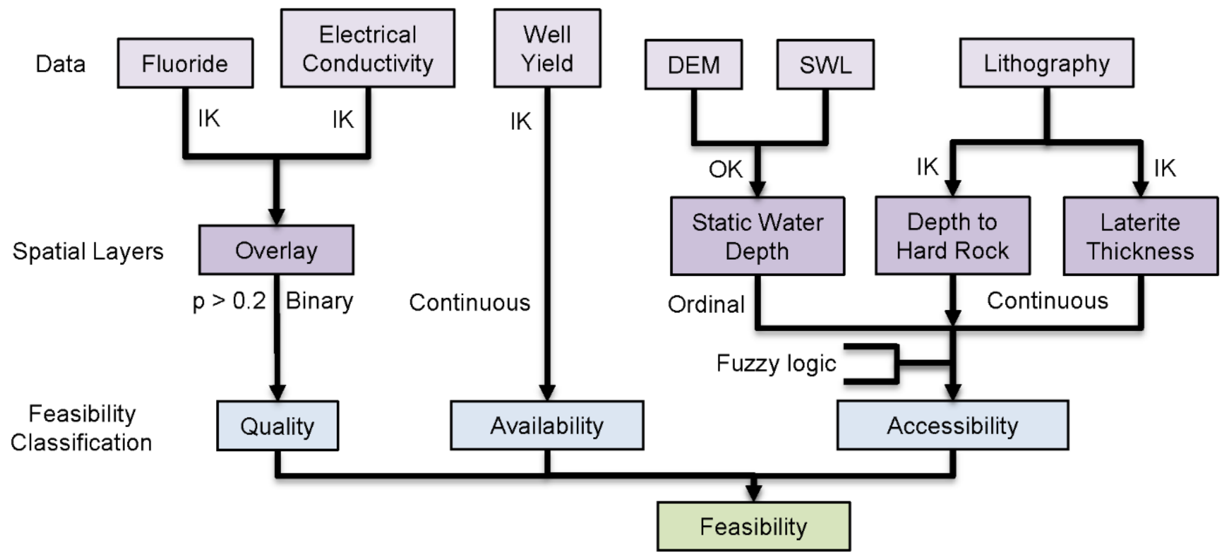

Figure 4.4 - Flowchart for Manual Drilling Feasibility Analysis
(OK: Ordinary Kriging; IK: Indicator Kriging)

Table 4.3 - Data Descriptions and Sources

Data	Source	Year	Description	Median	Range	n
Quality	HAP Database	2004 - 2008	Fluoride (mg/L) concentrations	0.4	0-5.35	274
Quality	HAP Database	2004 - 2008	Conductivity (μS/cm)	369	0.1-2040	296
Well Yield	HAP Database	2004 - 2008	Well Yield data (L/min)	22.5	1.4-540	1892
Static Water Level	HAP Database	2004 - 2008	Elevation and depth (m) data for water table readings	6.92	0.6-29.9	386
Lithography	HAP Database	2004 - 2008	Geological layer description, thickness, and weathering class	-	-	330
Roads	Humanitarian Data Exchange	2006	Major roads in the region	-	-	44
Cities	University of Ghana	2018	Major cities in the region	-	-	711
DEM	EarthExplorer	2011	90x90m resolution elevation map	-	120-455	-

The borehole data associated with water quality, lithography, static water depth, and well yield are derived from the Hydrogeological Assessment of the Northern Regions of Ghana Project (HAP) (Carrier, Lefebvre, & Asare, 2011; Carrier et al., 2008). Groundwater data from six different organizations was consolidated into one database in the Northern, Upper West, and Upper East regions of Ghana. Accuracy and depth of information varied with each data point, so a detailed review was completed to identify unique and reliable records. These data have been used in a number of regional studies since completed in 2011, including groundwater development potential, sustainability, and hydrogeological trends (Agyekum & Dapaah-Siakwan, 2008; Carrier et al., 2008; Forkuor et al., 2013; Holt, 2014; Yidana et al., 2011).

Water quality is an important factor when considering domestic water supply. Geogenic contaminants, such as fluoride or arsenic, can be correlated with specific geological contexts. For instance, fluoride contamination in the UER is often connected to Bongo Granite formations (Alfredo, Lawler, & Katz, 2014; Malago, Makoba, & Muzuka, 2017). In addition, high conductivity can act as a proxy for high levels of iron or manganese in the area. The distribution of readings collected from boreholes in the UER was non-normal, making it difficult to attain accurate interpolations through ordinary kriging (OK). For this reason, indicator kriging (IK) was used to identify areas where concentrations exceeded recommended levels, as specified in Table 4.4. A binary modifier was used to designate at risk (0) and safe (1) cells based on their probability (greater than 20%) of exceeding the concentration limits. For fluoride, the measured concentration limit was set to 1.5 mg/L, according to guidelines set by the World Health Organization (Fawell et al., 2006). The quality variable, shown by Equation 1, overlaid the manual drilling feasibility map to denote cautionary zones when using groundwater. Note that any number of binary variables signaling a risk for harmful contaminants can be applied using this methodology.

$$Qu = F \cdot E \tag{1}$$

Table 4.4 - Feasibility Classes for Manual Drilling

Layer	Unit	Probability	Range	Class
Fluoride, *F*	mg/L	0.2	> 1.5	0
			0 - 1.5	1
Electrical Conductivity, *E*	μS/cm	0.2	> 750	0
			0 - 750	1
Quality, *Qu* = *FE*	-	-	0	Caution
			1	Safe
Well Yield, *Y*	L/min	0 - 1	0 - 12	0
			> 12	1
Water Table Depth, *W*	m	0 - 1	> 40	0
			0 - 40	1
Laterite, *L*	m	0 - 1	> 5	0
			0 - 5	1
Depth to Hard Rock, *D*	m	0 - 1	0 - 10	0
			> 10	1
Manual Drilling Feasibility, *M* =*YWLD*	-	0 - 1	0	Not Feasible
			1	Highly Feasible

Various proxies were considered for availability, including well yield, specific capacity values derived from step tests and, subsequently, the empirical calculation for transmissivity (Forkuor et al., 2013). For each, OK showed poor performance due to the heterogeneous nature of this variable in hard rock formations (Darko & Krasny, 2007). As such, IK was once again an appropriate method, although it was limited to one threshold at a time. Based on the technology demand shown in Table 4.5, thresholds at 12 and 30 L/min were modeled using IK. Well yield (Y) was found to produce the best model due to its higher sample size and spatial distribution.

Table 4.5 - Modified classes of well potential (Fussi et al., 2017)

Class	Score	Well Yield Range (L/min)		Description
Low Potential	0	0	12	Wells can be equipped with hand pumps, but could become dry with intense pumping.
Moderate Potential	1	12	30	Wells can be equipped with hand pumps for reliable supply, and suitable for large groups (250 users) at max.
Good Potential	2	30	60	Wells can be equipped with hand pumps for reliable supply, and sometimes solar pumps.
Excellent Potential	3	> 60	-	Hand pumps and solar pumps can provide continuous water supply to increasingly larger populations.

The next step was to evaluate each component of the "Accessibility" score. Water table depth could be interpolated using both ordinary and indicator kriging due to its normal distribution. A maximum depth of 40 meters was chosen according to the limits set by Fussi et al. (2017). OK results were presented as the depth never exceeded 30 m in this region. However, a probabilistic map (p=1.00) was applied to the final feasibility calculation due to the highly favorable conditions.

According to Fussi et al. (2017) and Martínez-Santos et al. (2017), laterite thickness should be less than 5 meters for manual drilling to be possible. If laterite exists, percussion techniques are required to penetrate the hard, aluminum-rich layer. Further, penetrating the weathered rock layers would also require special tools (Labas et al., 2010). Laterite is commonly found in the UER, so percussion techniques were deemed necessary. However, its occurrence is discontinuous and interspersed. For this reason, indicator kriging was utilized again to identify zones with a thickness greater than 5 meters to create a binary indicator.

The final limiting condition for manual drilling is when the depth to hard rock is less than ten meters. Once again, indicator kriging was used to identify zones showing favorable conditions in the crystalline rock formations. The novelty of this approach was to incorporate the weathering profile into the assessment. Fussi et al. (2017) describes, "…when hard rock represents more than 50% of the components, the layer is assumed to be the upper limit of the basement." Spatial patterns have been successfully interpolated at this weathered gradation in previous studies for Hong Kong granite

(Dasaka & Zhang, 2012). Matching the definition in Table 4.2, the maximum limit was designated as the transition between the highly weathered and moderately weathered rock.

A number of other considerations may challenge this assumption. For instance, the weathering process can cause both gradual and sharp transitions. Wright (1992) shows that the transition from saprolite to saprock can occur within the highly weathered zone, rather than the end. Further, core stones can often be found in the lower portion of the highly weathered zone, which, if encountered, could quickly halt manual drilling progress (Carrier et al., 2008). For these reasons, a second comparison map for the depth to hard rock was created in which the transition between completely and highly weathered rock was the limiting boundary.

For each interpolation that uses IK, a probability distribution is produced for the specified condition. For instance, if the depth to hard rock distribution specifies a probability of 0.60 at a given location, this implies that a manual drill would be able to penetrate more than ten meters 60% of the time. In real world applications, this would translate to the amount of risk a company is willing to take when drilling in a new area. For this study, the feasibility of manual drilling (M) is the product of accessibility (the depth to the water table, the depth to hard rock, and the thickness of laterite) and availability (well yield) variables, forming a probability distribution through Equation 2. A score close to zero suggests a low chance of success, while a score close to one implies a high probability of success.

$$M = [P(W) \cdot P(L) \cdot P(D)] \cdot P(Y) \quad (2)$$

Validation of these results occurred in two stages. First, cross-validation techniques were used to produce geostatistics associated with each interpolation. This applied to fluoride concentration, conductivity, well yield, water table depth, laterite thickness, and depth to hard rock. In each iteration, one sample is removed from the training set and compared to its predicted value. The sum of the errors produced by these iterations are used to calculate the mean error (ME), root-mean-square error (RMSE), and root-mean-square standardized error (RMSSE). The ME should be around 0, the RMSE should be as low as possible, and the RMSSE should be close to 1 (ESRI, 2010). The second validation procedure determined whether each individual reading matched its raster classification. For instance, a well with historical yield data above 12 L/min should be designated as "Feasible" at the optimal binary classification. This methodology was also used to verify the results of each interpolation.

4.6 - Results and Discussion

The Upper East Region of Ghana was assessed for its suitability for manual drilling using the methodology described above. Groundwater quality was assessed for fluoride and conductivity to locate cautionary zones within the region. Groundwater availability was evaluated by identifying areas with sufficient well yield to support handpumps. Groundwater accessibility was evaluated by identifying areas with shallow water table depth, thin layers of laterite, and sufficient regolith thickness before encountering hard rock. The spatial distribution of these variables informs the feasibility of manual drilling in the region.

4.6.1 - Quality Maps

Water quality readings from boreholes in the UER were highlighted when high levels of fluoride or conductivity were recorded. Where high chemical measurements are observed in clusters, indicator kriging will show an increased probability of risk. According to Figure 4.5 and Figure 4.6, only a few clusters have a probability above 20% for encountering high conductivity and high fluoride from a regional level. The high fluoride readings in cluster "A" are near Bolgatanga and Bongo, which have a history of dental fluorosis (British Geological Survey, 2000; Firempong et al., 2013). This has typically been correlated with the intrusive Bongo granite, or fluorite and apatite in metamorphic formations in the area (Alfredo, Lawler, & Katz, 2014). This shows that indicator kriging can be used as a screening process for underlying geological or environmental causes. Cluster "B" is associated with just a few readings in the Voltaian sandstones, but suffer from a low sample density. Other isolated incidents maintain a relatively low probability because of the number of nearby, low concentration readings. Thus, they are more likely to be attributed to random chance.

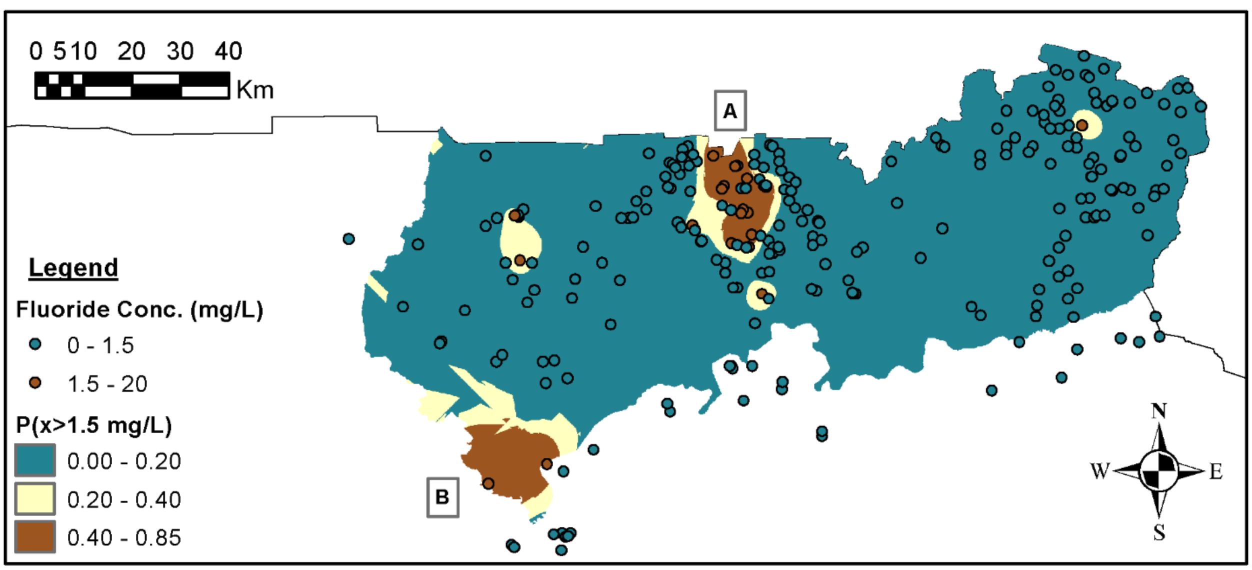

Figure 4.5 - Probability Distribution when fluoride concentration exceeds 1.5 mg/L

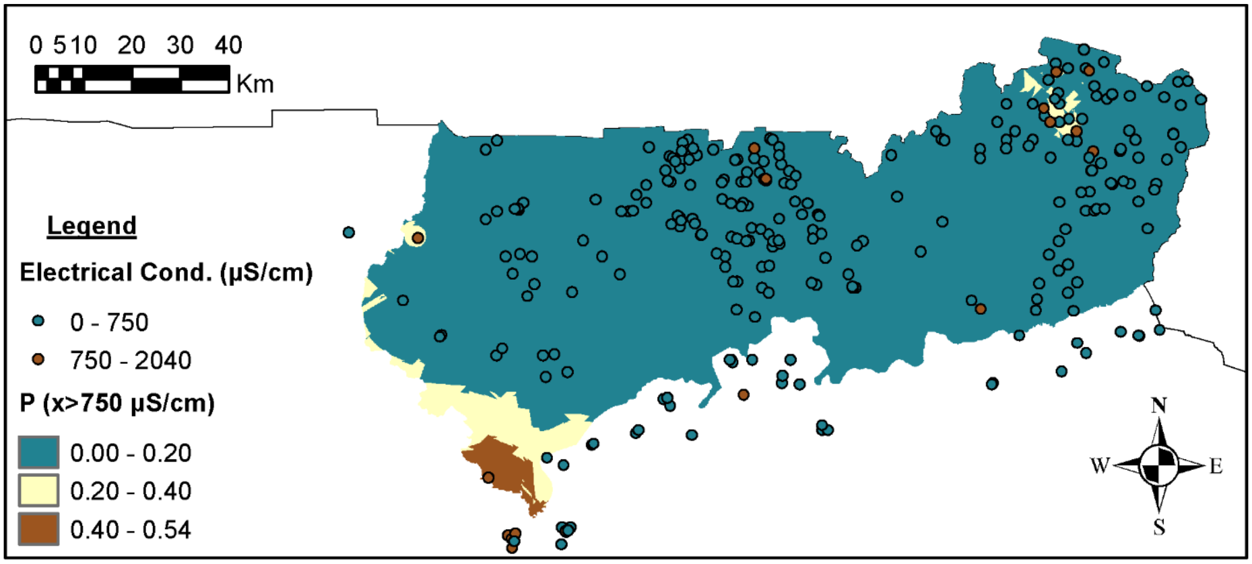

Figure 4.6 - Probability Distribution when electrical conductivity exceeds 750 µS/cm

4.6.2 - Availability Maps

Figure 4.7 and Figure 4.8 show the probabilities that well yield will exceed the recommended handpump flow rates (12 L/min) or minimum solar pump flow rates (30 L/min), respectfully. Figure 4.7 suggests that handpump requirements are highly likely to be met throughout the region. This level of production (12-30 L/min) can be attained as long as the highly weathered layer can be penetrated, which is associated with higher permeability than the completely weathered layer. The northwest cluster should be assumed to be at moderate risk of lower yield, but the central region should be interpreted with caution due to the decreased sampling density.

Figure 4.8 shows that most of the UER can expect a lower likelihood of supporting solar pumps, emphasizing the importance of using IK at different thresholds. About 25.1% of wells were above 30 L/min and about 12.0% above 60 L/min, but they were fairly sporadic. Carrier et al. (2008) found that intrusions by pegmatites or quartz-veins in the Birimian system, as well as deep fractures and fault zones, could produce sufficient yield to meet this demand. It is unlikely that manual drilling can penetrate these layers in order to take advantage of their preferential pathways, as nearly all borehole logs indicate they fall below moderately weathered levels.

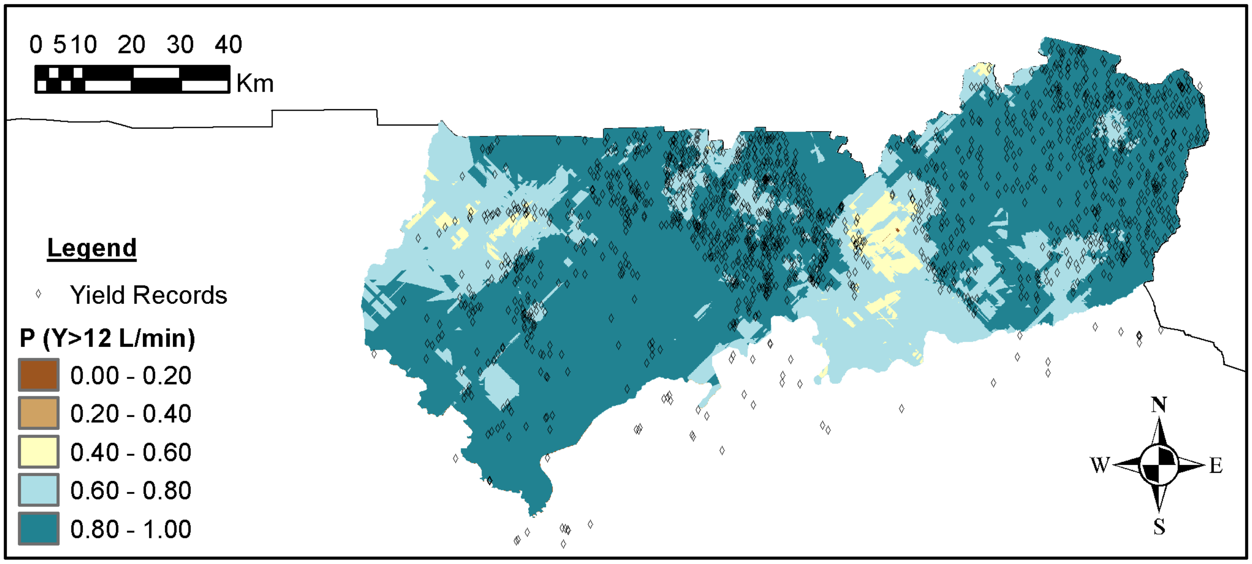

Figure 4.7 - Probability Distribution when well yield exceeds handpump levels (12 L/min)

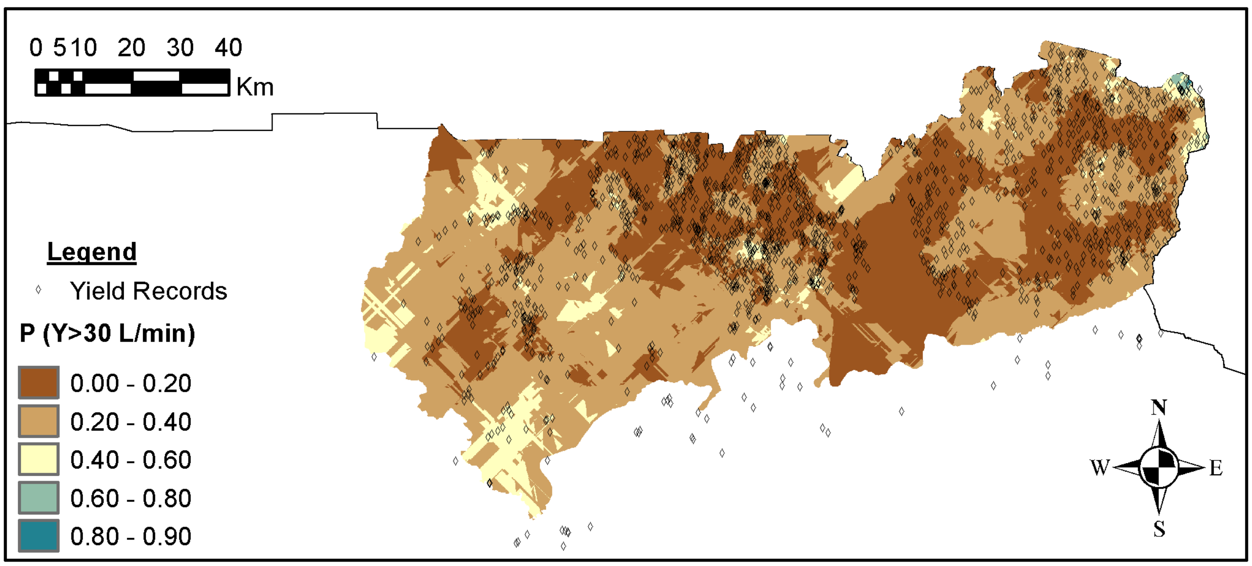

Figure 4.8 - Probability Distribution when well yield exceeds min. solar pump levels (30 L/min)

4.6.3 - Accessibility Maps

Ordinary kriging was completed for the water table depth in the UER to determine whether it exceeded the limits of manual drilling, as shown in Figure 4.9. It can be observed that the depth to the water table rarely exceeds 20 m, and never exceeds the manual limit of 40 m. Every borehole sample has favorable conditions. The crystalline bedrock likely forms an impermeable barrier that can only be penetrated by groundwater through secondary porosity at the base (Macdonald & Davies, 2000). Thus, the weathered regolith thickness largely determines the storage and depth of groundwater. For these reasons, the static water depth is not very influential for the feasibility of manual drilling in the Upper East Region of Ghana.

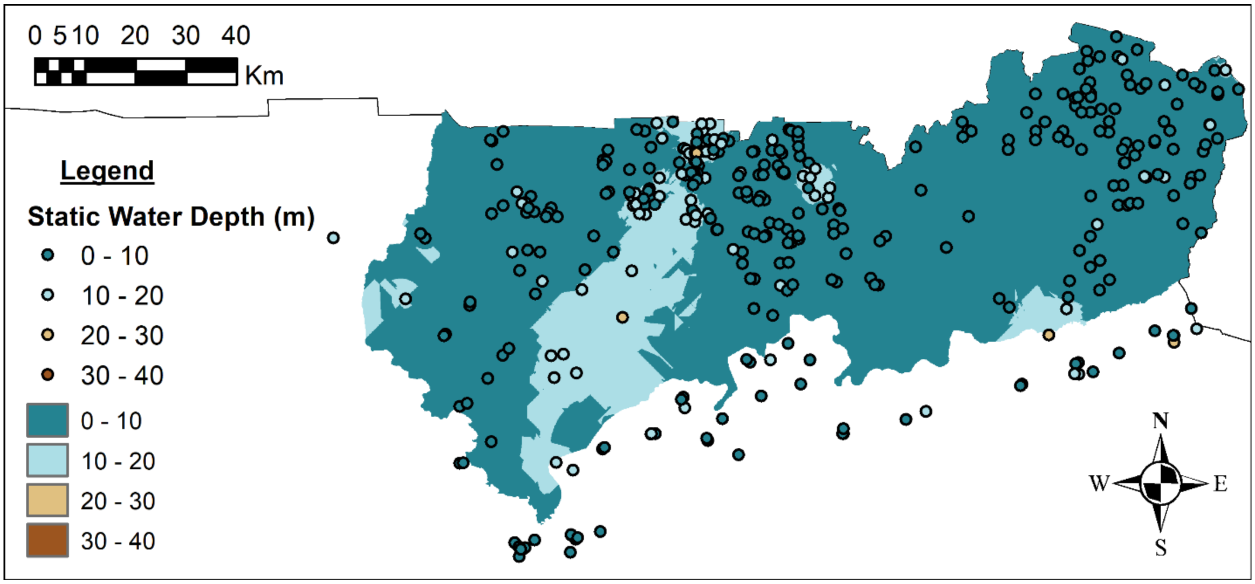

Figure 4.9 - Spatial Distribution of Static Water Depth

In a similar manner, there is rarely a layer of laterite that exceeds 5 m. When indicator kriging was used to determine the probability of exceeding this limit, only the southeast corner fell below 80% probability. This can be observed in Figure 4.10. However, it is very common to encounter some laterite when drilling in the UER, with some areas exceeding a probability of 70%. This would promote a manual drilling method that includes percussion techniques for the entire region, both for the laterite and weathered rock commonly encountered.

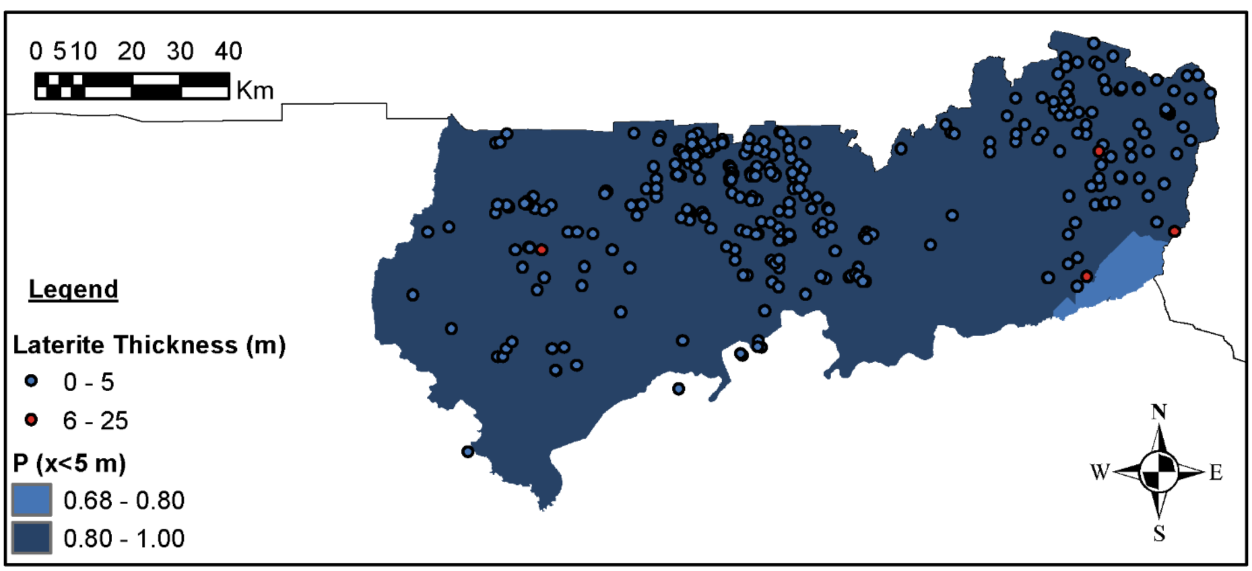

Figure 4.10 - Probability Distribution when laterite thickness is less than 5 m

Depth to hard rock is the most important limiting factor for manual drilling in the study area. Figure 4.11 shows the probability of exceeding 10 m when setting the absolute limit at the top of the moderately weathered layer, while Figure 4.12 shows the same conditions when the limit is set to the top of the highly weathered layer. When comparing these two figures, the probability of success differs significantly depending on what limits are set. If a manual drilling rig can penetrate to the moderately weathered layer, roughly two-thirds of the maps will have a success rate above 40% and east of Bolgatanga is highly favorable. If the highly weathered layer is considered too hard, then three-fourths of the study area would have a success rate less than 20%. However, they both agree that weathering tends to increase from west to east, particularly for Tamnean granitoids. These figures also depict regional clusters of depth thresholds, emphasizing the differences in geospatial weathering patterns that indicator kriging can identify.

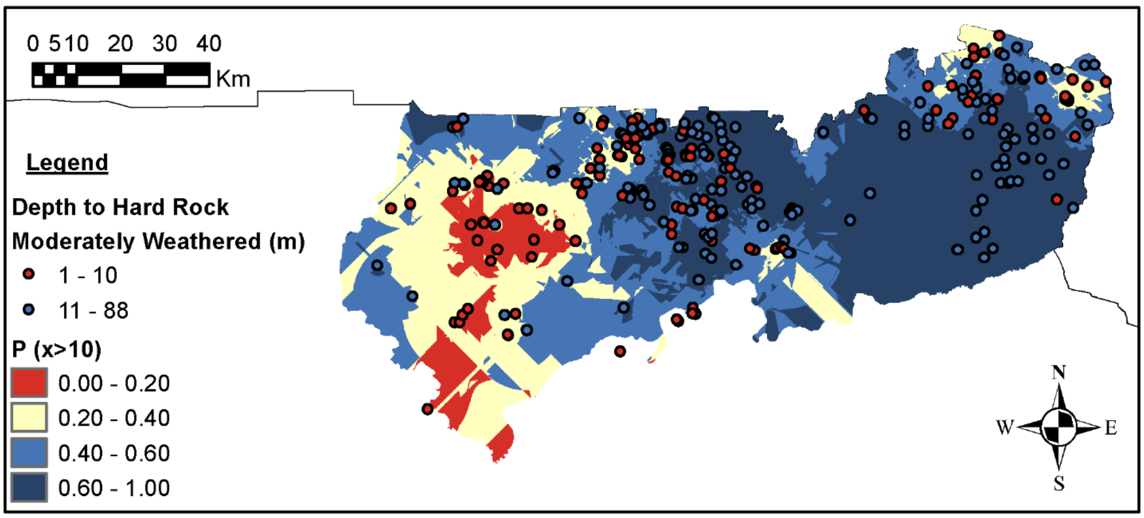

Figure 4.11 - Probability Distribution when the depth to mod. weathered rock exceeds 10 m

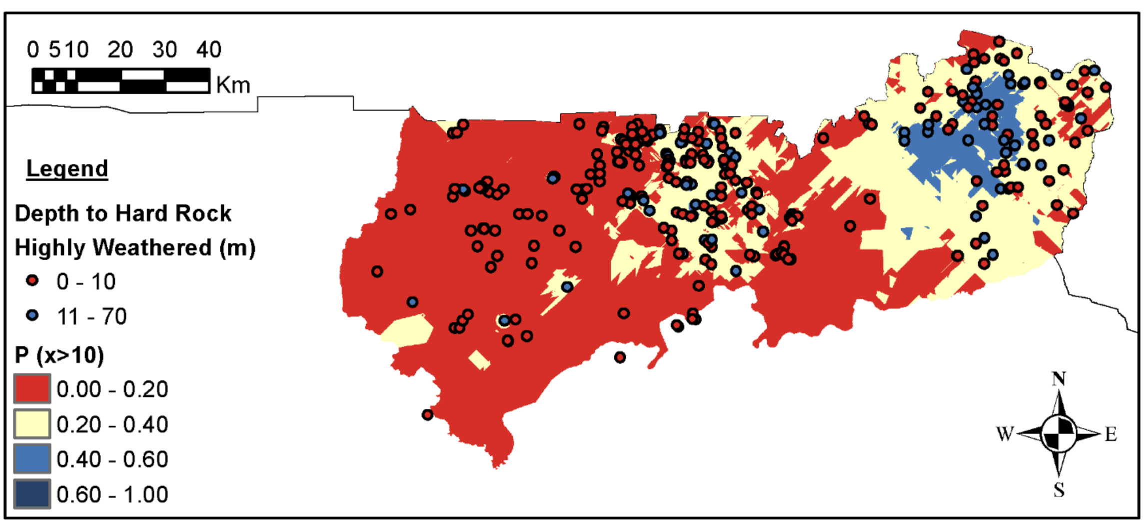

Figure 4.12 - Probability Distribution when the depth to highly weathered rock exceeds 10 m

4.6.4 - Data Interpolation and Validation Procedures

Cross-validation was conducted for each interpolation, with the summary statistics shown in Table 4.6. It can be observed that mean error (ME) is nearly zero for all included interpolations and the root-mean-square standardized error was nearly one for every variable but laterite thickness. This was due to the fact that only 4 out of 302 samples exceeded the indicator kriging limits without clustering. Root-mean-square error (RMSE) was minimized for these variables by adjusting the model, range, nugget, and sill for a given semi-variogram. Stable, spherical, circular, exponential, and gaussian models were considered, and the optimal statistics were chosen. Other geostatistical interpolation methods were tested, but produced inferior results.

Table 4.6 - Cross-validation statistics for model interpolations

Variable	Interpolation	Samples	Type	ME	RMSE	RMSSE
Fluoride	IK[a]	256	Spherical	0.0030	0.2453	0.9411
Conductivity	IK[a]	275	Spherical	0.0002	0.2443	1.0913
Well Yield - 30	IK[a]	1892	Spherical	-0.0039	0.4200	1.0172
Well Yield - 12	IK[a]	1892	Spherical	-0.0011	0.3578	0.9811
SWD	OK[b]	368	Stable	-0.0299	4.0457	0.9552
Laterite	IK[a]	302	Stable	-0.0005	0.1175	1.3705
Depth - MW	IK[a]	302	Stable	-0.0001	0.4706	0.9837
Depth - HW	IK[a]	302	Stable	0.0040	0.4131	1.0191

[a]Indicator Kriging, [b]Ordinary Kriging

Local uncertainty for these variables could be influenced by a number of conditions, including adjacency to unconsolidated sedimentary material near rivers and in valleys, seasonal changes in groundwater level, local weathering patterns, and discontinuous permeability (Fussi et al., 2017; Macdonald & Davies, 2000; Martínez-Santos et al., 2017). Professional siting and specialized techniques, such as vertical electrical sounding, should still be used to determine the most favorable drilling locations in a higher resolution area. Separately, low sample density near Zebila could skew results, and could be refined as the national borehole database increases.

Given this uncertainty, secondary validation of the feasibility map was conducted by assessing the distribution of sample points in each classification. For example, did a borehole classified independently above the fluoride threshold (> 1.5 mg/L) fall under the appropriate classification (0) after interpolation? Was a borehole historically measured at a depth between 10 and 20 meters assigned correctly (2)? As shown in Table 4.7, nearly every interpolation accurately identified over 90% of the representative sample. Well yield was the only variable that fell below this level. This interpolation tended to overcompensate for the more common designation, either below or above the cut-off threshold. Darko & Krasny (2007) attributed this to, “the heterogeneity and anisotropy of the hydraulic properties”, illustrating how statistical analysis has been the only other practical alternative for assessing crystalline rock formations at a regional scale. Yet, using OK for specific capacity (30.5%), calculated transmissivity (60.1%), or yield (42.1%) produced inferior prediction accuracy. Likewise, predictions for highly weathered (29.5%) and moderately weathered (40.0%) depth to hard rock were also poor. Thus, the use of IK was shown to offer better performance in comparison to OK, but with the cost of losing the continuous (though erroneous) spatial distributions.

Table 4.7 - Proportion of samples modeled accurately

Variable	Range	Model Class[b]	Sample Class[a] 0	1	2	3	Accuracy
Fluoride (mg/L)	> 1.5	0	9.2%	0.4%			92.1%
	0 - 1.5	1	7.5%	82.9%			
Conductivity (μS/cm)	> 750	0	2.1%	2.9%			93.8%
	0 - 750	1	3.3%	91.8%			
Well Yield (12 L/min)	0 - 12	0	2.0%	3.2%			83.7%
	> 12	1	13.2%	81.7%			
Well Yield (30 L/min)	0 - 30	0	73.1%	21.7%			76.2%
	> 30	1	2.1%	3.1%			
Water Table Depth (m)	> 30	0	0.0%	0.0%	0.0%	0.0%	94.7%
	20 - 30	1	0.0%	0.6%	0.3%	0.0%	
	10 - 20	2	0.0%	0.0%	18.9%	4.6%	
	0 - 10	3	0.0%	0.0%	0.3%	75.2%	
Laterite Thickness (m)	> 5	0	0.0%	1.4%			98.6%
	0 - 5	1	0.0%	98.6%			
Depth to Hard Rock (m) - MW	0 - 10	0	44.1%	0.0%			98.0%
	> 10	1	2.0%	53.9%			
Depth to Hard Rock (m) - HW	0 - 10	0	77.6%	0.7%			91.5%
	> 10	1	7.8%	13.9%			

[a]Actual HAP Database reading — (shaded) Accurate proportion of samples
[b]Theoretically modeled classification — (unshaded) Inaccurate proportion of samples

4.6.5 - Feasibility Map

Combining the groundwater quality, availability, and accessibility factors produced the manual drilling feasibility maps found in Figure 4.13 and Figure 4.14. The probability distribution is a product of the depth to the water table, depth to hard rock, laterite thickness, and well yield variables, as described in Equation 2. Figure 4.13 uses the moderately weathered limit, while Figure 4.14 uses the highly weathered limit. Both use the recommended handpump yield of 12 L/min. Areas with a probability greater than 0.20 for encountering high fluoride or conductivity levels are denoted by hatched caution zones.

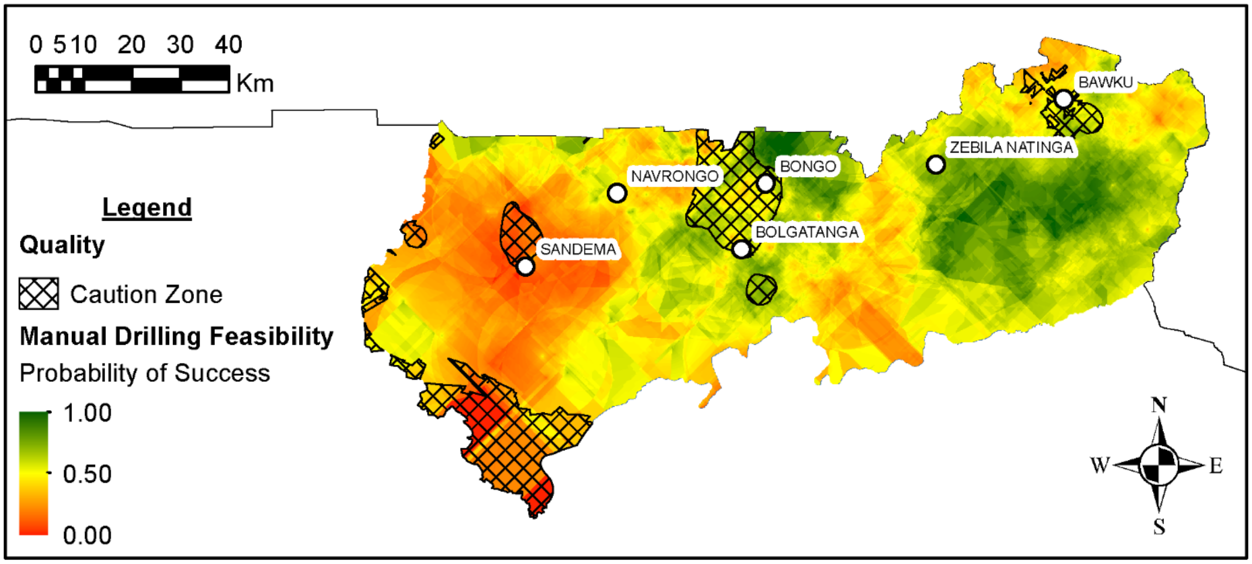

Figure 4.13 - Manual Drilling Feasibility Map (Moderately Weathered Limit)

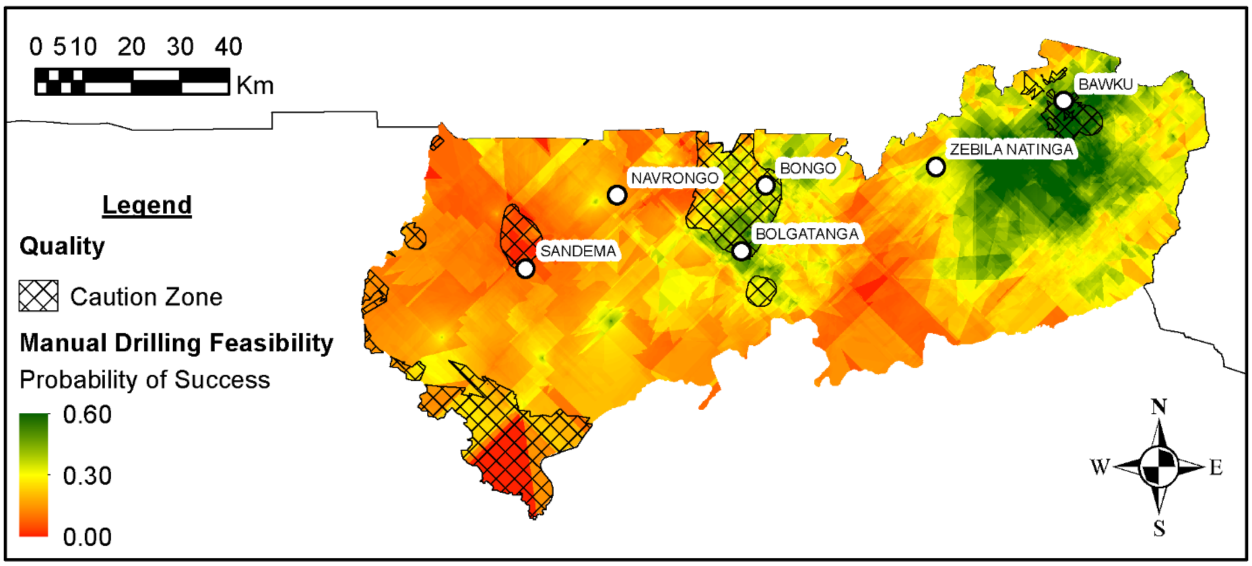

Figure 4.14 - Manual Drilling Feasibility Map (Highly Weathered Limit)

According to historical records, manual drilling was successfully completed in the Bawku East and Bolgatanga districts, with sixty boreholes completed as a pilot project (Adekile & Kwei, 2009). Forkuor et al. (2013) observed higher rates of borehole completion for machine drilling when moving from west to east. This corresponds with the increased feasibility found in the central and eastern regions in the model, with the west being hindered by shallow crystalline formations. Both limiting conditions agree on this point, but they differ in their probability of manual drilling success. The moderately weathered limit in Figure 4.13 suggests rates above 90% for certain areas, with feasibility rates above 50% spreading farther southwest. The highly weathered limit in Figure 4.14 depicts, at best, a 60% chance of success. The combined depictions form an upper (moderately weathered limit) and lower (high weathered limit) bound for success and risk.

The model suggests that the majority of the UER should have sufficient yield to meet domestic demand using handpumps. If higher volumes are required, it is recommended that mechanized alternatives be considered to take advantage of subvertical fractures, veins, or faults that are associated with increased production. With regards to quality, Bongo and the southwest Voltaian formation should exercise caution from potential contaminants in groundwater. Considerations should be taken for potential health risks or the increased cost of treatment.

Despite its initial success and efforts to increase interest, manual drilling has not been widely adopted in Ghana (Adekile & Kwei, 2009; Naugle et al., 2013). Challenging geology and regulation of drilling activities were cited as the primary reasons (Forson M, UNICEF, personal communication, 2019). Percussion drilling is necessary to penetrate both laterite and weathered rock, which may be too slow compared with mechanized rigs. Perhaps mechanized rigs were better supported by the government, or hand dug wells were more affordable to potential customers. Further studies into the politics and local opinions surrounding manual techniques in Ghana could prove enlightening.

Alternatively, high seasonal variability could render manually drilled wells periodically dry, as they are only able to exploit the aquifers found in the upper regolith (Agyekum & Dapaah-Siakwan, 2008). The highest permeability for the manually drilled aquifers would occur within the highly weathered layer, encouraging this level of penetration as a precaution. In order to consider this factor, the original HAP assessment included monitoring data for seven wells in the UER for two to five years (Carrier et al., 2011). Water table fluctuations ranged from 1 to 6.5 m annually. Although the water table never dropped below the moderately weathered limit for these monitoring wells, this change in elevation could be sufficient to cause a detrimental decrease in recovery (Bonsor et al., 2014). This feasibility map does not account for these changes, as data was recorded from different seasons, and is limited by this factor.

Another limitation to this technique is the restriction to specific cut-off thresholds when using IK. The feasibility maps in Figure 4.13 and Figure 4.14 only represent a well yield greater than 12 L/min, so other model variants, such as Figure 4.8, must be used to assess different levels of production. In contrast, OK would still be restricted by the smoothing effect of low and high peaks in the dataset.

The use of weathered rock designations as a limiting condition for manual drilling assumes that this variable is a proxy for a layer's strength and drillability. While this is true within a given rock typology, this model considered all weathered classes equal. However, highly weathered granite is generally considered to be stronger than highly weathered sandstone (Waltham, 2002). This limitation needs to be clearly understood, and could skew results towards the lower probabilities of success found in Figure 4.14.

Even within the same typology, qualities such as water absorption, roughness, fractures, and other discontinuities can all influence the strength of rock (Aydan, Ulusay, & Tokashiki, 2014; Zhang, 2016). A clear delineation using measurable qualities, such as shear strength or uniaxial compressive strength, could offer refinement to feasibility maps if available at a regional scale. Perhaps previous measures of drillability, such as specific energy (Kelessidis, 2011; Teale, 1965), could be used to further define the absolute limits of various techniques and allow comparisons between different manual rigs. Future research should investigate how the type of rock, its degree of weathering, and its resulting strength can influence manual drillability.

4.7 - Conclusion

This study investigated the feasibility of manual drilling in a crystalline basement aquifer in the Upper East Region of Ghana. The methodology developed by Fussi et al. (2017) and Martínez-Santos et al. (2017) was built upon first by incorporating indicator kriging for heterogeneous variables. Secondly, depth to hard rock, the most critical variable for this area, was more clearly defined for crystalline basements by using the degree of weathering as a proxy for manual drillability. More specifically, the highly weathered limit acts as a lower bound for success, while the moderately weathered limit defines an upper bound. The final results suggest that suitable zones occur near Bolgatanga, Bawku, and Zebila, which coincides with historical pilot projects in the region (Adekile & Kwei, 2009).

Due to the non-normal and heterogeneous nature of weathered rock and transmissivity in crystalline basements, indicator kriging was used as an alternative method of interpolation. This methodology offers a probabilistic solution for discontinuous variables, such as those encountered by Forkuor et al. (2013) and Fussi et al. (2017). Using this technique, prediction accuracy for both well yield and hard rock depth were improved compared to ordinary kriging, but at a cost of the continuous spatial distribution. The resulting probability maps produced through IK can be used to estimate the likelihood of success for future manual drilling endeavors in the UER.

It is critical that seasonal fluctuations be considered during local siting to ensure annual availability. While water table depths are well within the limits of manual drilling in this region (30 m or less), up to 6.5 m of change were observed. Further, the highest transmissivity is typically within the highly weathered layer, so penetrating as deep as possible into this zone is equally important for production. Lastly, precautions need to be taken for fluoride contamination near Bongo when utilizing groundwater. The methodology presented in this paper allows for screening of regional quality issues for regional planning.

Ultimately, the methodology developed in this research can be applied to groundwater databases as they become more refined over time. As the local manual drilling sector continues to grow and international organizations continue to promote it, future feasibility studies will help to inform new projects, encourage professionalization, and ensure funding and resources are allocated properly. In the appropriate context, manual drilling will continue to be an affordable means of accessing water in developing regions.

4.8 - References

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5. Conclusion

5.1 - Performance Assessment

Between 2016 and 2019, both control and intervention communities within the Wassa East District showed significant growth in basic water service provision (Figure 2.5). In control communities, households that received at least basic service increased from 53% to 70% [OR = 0.50 (0.31–0.79)]. In intervention communities, the proportion of households increased from 45% to 78% [OR = 0.24 (0.14–0.42)]. Though there was not a statistically significant difference between groups in 2019, Figure 2.6 provided evidence that AD Users caused the sharp rate of improvement within intervention communities. Further, households under traditional management systems received significantly worse reliability and quality scores (Table 2.3a), often violating all three conditions of a safely managed service. Water services provided by AD were generally free of fecal coliforms and continuously available, but not on premises.

With respect to service level indicators, AD Users received significantly improved water service as compared to the control for the following indicators: quality (fecal coliforms, secondary disinfection), reliability (annual uptime), and acceptability (odor, appearance). No significant difference in service provision was observed for the total quantity of water collected because households could use multiple sources to meet their domestic needs. Likewise, accessibility scores were similar between groups due to the communal nature of AD sources during the endline. However, AD Users received significantly lower scores in daily availability, due to their reliance on venders, and affordability. Risks associated with deteriorating water quality during transport, human resource management, and financial sustainability were also observed. These performance indicators highlight the positive and negative aspects of the private service delivery model, and speak to its effectiveness as a rural water provider.

5.2 - Sustainability Assessment

The sustainability of Access Development is best summarized through the environmental, institutional, technical, financial, and social factors observed throughout this dissertation. From an environmental perspective, Access Development almost exclusively relies on groundwater resources in the Western Region of Ghana. High annual rainfall combined with local recharge rates (2%-16%) in the Precambrian basement could sustainably provide for the domestic needs of the entire population of the Wassa East District. However, the crystalline basement complex often requires coarse-grained granites or fractured quarts-veins for highly productive wells, similar to the Upper East Region assessed in Chapter 4. When considering this in combination with deep boreholes and a shallow weathered zone in the Wassa East District, it is apparent that mechanized drilling is required for AD's geographical area. This was reinforced by the attempt and failure to utilize manual drilling in the district early in the construction phase. Future research should investigate if the concept of drillability and uniaxial compressive strength could more clearly define manual drilling limitations to assist in project planning.

The environmental context influences both social and financial factors for Access Development. First, the high seasonal rainfall provides free, easily collected water at the home for a number of months of the year. With respect to the Huff model in Chapter 3, the close proximity of rain barrels is highly attractive to rural households. This source has a higher risk of contamination, and it causes AD sales to drop substantially between June and October (see Chapter 3, Appendix C). Second, groundwater quality also influences water sales at AD kiosks. High iron or salt concentrations are not uncommon in groundwater in Wassa East. As discussed in Chapter 3, these chemicals are typically associated with poor taste and lather. Fortunately, iron filtration units within the kiosk treatment helps to reduce these effects. These factors illustrate how the water resources available can influence the sustainability and performance of a safe water enterprise.

From an institutional perspective, Chapter 2 highlighted the influential entities and stakeholder exchanges for water service within the Wassa East District. Access Development acts as a service provider under the jurisdiction and contract of the local government, or the District Assembly, and the national government, specifically the Community Water and Sanitation Agency. The local government facilitates a public-private partnership to provide water to each interested community. Each community is often represented by a pre-established water management committee, who may still be responsible for other existing water sources. Other institutions, such as mining companies or churches, also contribute to water provision. Together, this facilitates a competitive environment where utilities, community managers, and private companies all take a share of the water market.

Both Chapters 2 and 3 discussed how this competitive environment influenced Access Development. The penetration rate for AD users was estimated between 35-40% through household surveys, willingness-to-pay assessments, and the Huff Gravity model. From a human right to water perspective, this positively promoted increased access to 'Basic' water service through proximity, varying levels of affordability, and a form of accountability for Access Development prices. Negatively, competition potentially impacted health benefits, as only 35% of community water sources were observed to be free of fecal coliforms, and financial sustainability, as limited community resources are split. This creates a challenging transition period where both free improved sources and paid piped schemes have to be supported in order to serve the entire population.

With regards to regulation and oversight, the local government and Water4 are meant to provide support. The funds allocated to the District Assembly are supposed to be used for independent water quality testing. However, history would suggest that regulation will be weak due to limited government resources (Chowns, 2015). Instead, Water4 promotes monitoring and evaluation activities, such as mWater reporting and in-house quality testing. Further, Water4 facilitates capacity building and asset management. This represents the institutional support valued by previously mentioned authors (Lockwood and Smits, 2011; De Armey, 2015).

Overall, the performance of varying management styles was best represented by Table 2.3 in Chapter 2. Access Development, as a private service delivery model (PSM), had significantly improved functionality [OR = 0.14 (0.07–0.27)], annual reliability [OR = 0.09 (0.05–0.16)], and quality [OR = 0.06 (0.03–0.13)] as compared to community-based management, and other managers, in Wassa East. This supports the findings by McNicholl et al. (2019) of improved performance, and ties together the institutional and technical factors of sustainability.

The technical performance of Access Development was greatly influenced by its maintenance operations and the choice to implement solar-powered treatment kiosks. About 85% of kiosks were available each day throughout the entire year, though with limited hours, with downtime only affected by vendor availability rather than technical failure (Chapter 2 – Table 2.A3). By comparison, less than 40% of all other sources were consistently available throughout the year. Control water sources only performed better than AD sources in daily availability, likely because many did not require a vendor to be present [OR = 0.29 (0.15–0.58)].

Only about 50% of boreholes and standpipes were free from fecal coliforms, while over 90% of kiosks were considered safe at the source (Chapter 2 – Table 2.A3). For the remaining kiosks, corrective measures were taken to increase the chlorine dosage. Almost no existing sources in the district showed signs of chlorine application as a secondary disinfectant. However, only 5.7% of AD User households collected water with a chlorine concentration greater than 0.2 ppm (Chapter 2 – Table 2.4e). While AD treatment provides resilience to groundwater contamination and the spread of disease, recontamination during transport and storage was still a risk. Unfortunately, common social practice is to store water for many days in large open containers, with only about 10% of households claiming to treat their water. Further investigations can assess whether increased household piped connections help to minimize this risk by reducing transportation, or exacerbate the issue if insufficient chlorine dosage is applied.

The financial sustainability of the service provider could be considered at an intermediate level in 2019. Revenue was sufficient to support the local government fees and circuit rider operations. However, construction operations and, more importantly, capital maintenance expenditures were likely dependent on increasing sales or penetration rates (Chapter 3 – Appendix B). This is an important subject for future research, particularly how customer uptake varies with time, and whether this outlook changes after increasing household connections within a community. Further, identifying the right balance of urban and rural installations within a geographical cluster seems to be an important factor for cross-subsidization.

Affordability for households within the Wassa East District certainly plays a factor in sales and penetration. The Huff Gravity Model in Chapter 3 predicted that the cost of AD water would drop penetration from 58% to 39%. At least 18% of intervention households claimed they could never afford AD water regularly, suggesting an absolute limit to market capture. Yet, it was interesting to observe in Chapter 2 that both poor and rich households were served by AD kiosks. Penetration rates ($p = 0.43$), water quantity collected ($p = 0.10$), and the JMP service ($p = 0.17$) from AD water sources were not significantly affected by relative wealth. This may be reconciled by the concept that only the richest population in Wassa East (about 10%) showed significant differences in water usage behavior; specifically, more frequent sachet water purchases (Figure 3.6). The remaining social classes may share similar struggles to afford more than drinking and cooking volumes of water on a regular basis. Regardless, both User and Non-Users alike spend 25 GHS per month or more on water, suggesting that affordability is not the only factor affecting uptake.

Social factors also influenced the performance and sustainability of Access Development as a service delivery model. Motivations such as proximity, competition, taste, appearance, and social expectations influenced household behavior. Distance is incredibly important, as emphasized in Chapter 3. The benefits of a given source have to outweigh the required time investment. With other, often cheaper, alternatives available, 72% of AD customers would use multiple sources to meet their domestic needs. Positively, multiple service providers help to guard against historical pitfalls of private companies, such as harsh cut-offs or hiked tariff prices. While some installations received high appearance, taste, and lather ratings, others could have poor taste and greatly reduce sales. Even 'boycotts' were observed at a select few kiosks in an effort to reduce the price per liter to historical norms. Water quality was only valued by AD customers. Others likely failed to value water quality due to the lack of available information on the subject and a focus on appearance as a proxy. Service delivery models across the globe would find future research related to behavior change and increasing market share valuable. In spite of this, pay-to-fetch practices were already an established social norm in the district, and mechanized systems were coveted. These positive traits were likely an important factor in the acceptance of this model of revenue collection. Further, the poor historical performance of many other water sources, with respect to consistent functionality, was referenced as a strong motivation at the baseline for contracting Access Development.

More broadly, these perspectives can be applied to any safe water enterprise in similar contexts. Companies such as Whave and Uduma will likely face similar challenges with the use of multiple water sources and existing competition. Directing local people away from traditional sources has been a challenge for some time, but incorporating motivations related to proximity, taste, and affordability into community planning as new infrastructure or institutional systems are put in place could improve penetration. Governments looking to incorporate safe water enterprises into their national agendas should consider their place in a systems approach – gradually increasing household standards towards quality and reliability without the expectation that they will monopolize water provision. Existing water sources will still be relevant for the foreseeable future, but communities will need to go through a transition period. Basic water service may be the minimum international standard at present, but safely managed water is the long-term goal. Service delivery models allow for a pathway towards this goal.

5.3 - Conclusions

Evidence has been provided for more consistent, resilient, and safe water quality from a private service delivery model as compared to existing management systems in a rural context. Yet, risks of recontamination will remain as long as households must transport their water from a communal source. Service did not discriminate between different socioeconomic classes. However, community members showed that they would use both existing, free alternatives and paid, treated sources when given the opportunity. This is clear by the evidence that not everyone became regular customers, whether by choice or necessity. Household surveys, willingness-to-pay assessments, and theoretical modeling all supported this conclusion.

The sustainability of Access Development as a service delivery model showed mixed results. Groundwater supply should be more than adequate for the domestic requirements of Wassa East, although individual wells may have low to moderate yield. Other settings may struggle with different forms of water scarcity and increase extraction costs, or offer more consistent demand. Existing competition and affordable pricing are likely contributing factors in the struggle between sustainability and equity for any service delivery model. Financial sustainability will likely be dependent upon reaching higher penetration rates as time progresses. Should demand increase, the modular piped system and solar-powered treatment centers used by Access Development show potential for gradual expansion. As with any piped system, quality control checks for chlorine residual and pressure will become increasingly important for customer safety.

The service delivery approach continues to be an important trend in water and sanitation for development. The results and discussions of this study have provided a comprehensive analysis of one example, Access Development, in Ghana. Lessons learned surrounding the benefits and risks of this approach can be used by policy-makers and practitioners in the ongoing pursuit of the sustainable development goals.