Sustainable Management of Piped Water Supply Infrastructure in Developing Communities

A Doctoral Thesis

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Supervised by

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Acknowledgments

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Where ever you go, whatever you do; always start with the heart.

In memory of

Dean Gary Gabriele

and

Erwin Taleno

ABSTRACT

As the international development community continues to identify the sustainability of water infrastructure as an important development goal, the need for technical performance-monitoring is significant. A number of research initiatives have identified limitations with respect to current strategies for monitoring sustainability. These studies suggest that progress monitoring and proxy indicators used to evaluate the Millennium Development Goals, are not sufficient for measuring the Sustainable Development Goals. Whereas, progress can be viewed as a discrete and linear variable, sustainability is complex and continuous in nature. As a result, water development goals that call for "ensuring availability and sustainable management of water", require research initiatives that use more objective and continuous monitoring to move the sector beyond progress monitoring. In addition, there is a need for research that employs performance monitoring methods that are intended to improve local management and inform utility operations.

The research associated with this study addresses issues related to the sustainable management of piped water supply infrastructure in low-income developing communities. Projects site locations included seven water systems in Madagascar that used a public-private-partnership model, and twelve water systems in Nicaragua that employed a community management model. To explore relationships between system performance and water management, analytical methods were used to measure water quantity and water quality characteristics and surveys were used to measure strength of management. Water quantity performance included the continuous monitoring of water levels in storage tanks which were used to evaluate reliability and availability of water. Water quality performance was analyzed based on percent compliance with international standards and field methods for measuring microbial, chemical and physical constituents. Strength of management (SoM) was based on surveys and interviews that were used to evaluate human resources, system administration, operation and maintenance, asset management and financial management. The results were triangulated using household customer-satisfaction surveys, and an exploratory analysis was conducted using univariate and multivariate linear regression.

The results from this study have identified links between system performance and SoM, and key findings suggest that strong management is essential to preventing failure but not

necessarily related to ensuring success. In terms of water quantity, the results show significant evidence that good management results in higher reliability and availability of water services when compared with poor management. Despite this, no evidence was found that strong management guarantees higher levels of water quantity performance. Further investigation into the relationship between SoM and water availability revealed that strong management is essential to providing minimum basic needs of water and that the strong community managed systems in Nicaragua, provide higher volumes of water as compared to the strong privately managed systems in Madagascar. In addition, SoM showed a positive relationship with the percentage of days that the systems provided 20 liters per person per day. In terms of water quality the results suggest that there is no evidence of a relationship between SoM and overall water quality compliance within the system. However, there was significant evidence of a strong relationship between SoM and changes in water quality within the system. In this regards water quality improved from the source to the distribution system as the strength of management increased between systems.

The conclusions from this study have raised some important questions with respect to monitoring progress and measuring performance. Given the unique nature of each system and the non-discrete nature of sustainability, a shift is needed to more objective and continuous monitoring techniques. Furthermore, the need to measure the "availability and sustainable management" of water, justifies developing new tools to empower local operators to improve water services. Also, a shift in the focus from progress to performance, should coincide with a change in the dialog from beneficiaries to customers in that, customer satisfaction is essential for long-term sustainability and can be an effective way to monitor both progress and performance. Recommendations associated with this study include using customer satisfaction tools as a strategy for monitoring water development goals and developing smart technologies to enable local management teams to improve operation and maintenance. In addition, a shift to performance-monitoring would coincide with the needs of development organizations to show evidence of long-term sustainability of water infrastructure.

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CHAPTER 1

INTRODUCTION

1.0 Introduction

As the international development community continues to identify the sustainability of water supply infrastructure as an important development goal, there is a need for research initiatives that focus on the technical performance of water supply infrastructure. In September of 2015, the United nations General Assembly adopted the 2030 Agenda for Sustainable Development which calls for, ensuring the availability and sustainable management of water and sanitation for all, through Goal 6 (SDG 6). SDG 6 includes eight targets that highlight sustainable development challenges related to water, including; affordability, pollution, water-use efficiency, natural resources management, environmental protection, capacity building, technology and local stakeholder engagement (UN, 2015 and UN, 2018).

The research associated with this study proposes that the methods used to monitor progress on water development targets associated with the Millennium Development Goals (MDG, 2003 and UN, 2006), are not sufficient for monitoring sustainability. Whereas, progress towards a particular development objective can be viewed as linear and discrete, sustainability is more complex and continuous in nature. As a result, research initiatives are needed that explore more objective and continuous monitoring, in order to move the sector from progress monitoring to performance monitoring. In addition, a concerted effort is needed, to develop practical tools that are intended to inform water system operations. Furthermore, establishing links between sustainable management and technical performance is essential to ensuring that, progress towards water development goals are sustained in the long-term.

This research included seven site-locations in Madagascar and twelve site locations in Nicaragua. The systems investigated in Madagascar were implemented using public-private-partnership (PPP) model and were located throughout the country, primarily along the eastern coast. The systems investigated in Nicaragua were implemented using a community management model and were located within the North Atlantic region within the Rio Grande de Matagalpa basin.

1.1 Research Framework

The research framework for this study includes an investigation into the sustainable management of piped water supply infrastructure in developing communities. Relationships between the strength of management and technical performance were investigated with the goal of exploring links between strong management and long-term sustainability of services. The boundary conditions for this study delineate between internal and external sustainability factors.

Internal factors, the focus of this study, are considered as having a direct influence on the technical performance of the systems. Internal factors included measurements of water quantity, water quality and strength of management. Water quantity parameters included the continuous monitoring of reliability and availability of water. Water quality parameters included compliance characteristics for microbial, physical and chemical parameters. Strength of management characteristics included human resources, administration, operation and maintenance, asset management and financial management. External or surrounding factors that describe the enabling environment were considered in the overall research design but were not investigated. External factors were categorized as social, technical, environmental, economic and political factors.

1.2 Research Problem

The research problem being addressed in this study includes an exploration of relationships between strength of management and the technical performance of piped water supply infrastructure in low-income developing communities. In order to accurately measure the performance of water supply systems, objective analytical tools were needed to evaluate technical performance in terms of water quantity and water quality. In addition to this, strength of management characteristics were explored for private and community managed systems in Madagascar and Nicaragua.

The research question being investigated in this study is; how does the strength of water management influence the performance of piped water supply infrastructure in low-income developing communities? Figure 1.1 shows the general approach taken to address this question with performance characteristics associated with technical aspects of the systems and management characteristics associated with local water utility teams. In addition, the study employs measurements of customer satisfaction for the purposes of triangulating and validating the results.

Figure 1.1: Research Question and Performance Characteristics

<table>
<tr><td colspan="4">How does the strength of water management influence the performance of piped water supply infrastructure in low-income developing communities?</td></tr>
<tr><td colspan="2">Strength of Water Management</td><td colspan="2">Performance of Water Supply Infrastructure</td></tr>
<tr><td>Human Resources
System Admin</td><td>O&M
Assets Financial</td><td>Water Quantity</td><td>Water Quality</td></tr>
<tr><td colspan="4">Customer Satisfaction</td></tr>
</table>

1.2.1 Research Aim, Objectives and Knowledge Areas

The aim of this research is to contribute to the sustainable management of piped water supply infrastructure by investigating objective tools and establishing clear metrics for monitoring the performance of water services. The intention of this study is to improve the ability of local management teams to provide reliable services, anticipate system failure and mitigate threats to long-term sustainability. A key aspect of delivering reliable water services includes understanding the role that local utility management has with respect to mitigating external threats to sustainability. As a result, this research is entirely exploratory in that new methods for evaluating management and performance are introduced and relationships between strength of management scores and technical performance characteristics are explored. In addition, this research is comparative wherein the results of different systems investigated are discussed.

Objective 1: To develop objective measurements for monitoring the technical performance of piped water supply infrastructure in developing communities.

Knowledge Area 1: Monitoring, Evaluation and Water System Performance

Objective 1.1 – Identify water quantity parameters which can be used to continuously monitor the performance of piped water supply infrastructure.

Objective 1.2 – Identify water quality parameters which most closely reflect the performance of the system in terms of user's acceptability of the water supply.

Objective 1.3 – Identify criteria to compare strength of management for water utility operations.

Objective 2: To investigate the relationship between the performance of water infrastructure and the strength of local water utility management.

Knowledge Area 2: Strength of Water Management

Objective 2.1 – Categorize system performance to better anticipate system failure.

Objective 2.2 – Identify criteria to compare system performance characteristics.

Objective 2.3 – Explore relationships between system performance and strength of management.

1.2.2 Measuring Performance: Water Quantity and Water Quality

To address the research question and the aim of this study, objective measurements of the technical performance of water supply infrastructure are needed. This study considers both water quantity and water quality parameters when evaluating system performance. Water quantity analysis includes source supply flowrates, per-capita availability of water in the system, peak consumption and water system reliability in terms of continuity of the water service. Water quality analysis includes compliance characteristics of microbial, chemical and physical parameters base on World Health Organization guidelines for drinking water quality (WHO, 2011) with further delineation between source, tank and distributed water quality. A system performance score was employed for comparison purposes that evaluates water quantity and water quality characteristics with associated detailed provided Chapter 3: Research Methodology, Chapter 4: Water Quantity Performance and Chapter 5: Water Quality Performance.

1.2.3 Water Management and System Performance

New methods to evaluate Strength of Management (SoM), not derived from theory or hypothesis, are explored in this study for the purposes of investigating relationships between management and technical performance characteristics. SoM categories include Human Resources, Operation and Maintenance, System Administration, Asset Management, and Financial Management. In Madagascar, SoM analysis included a presence/absence test for various indicators within each category and included evidence of community involvement, system expansion, accounting, planning, office space, watershed management and billing. In Nicaragua, the analysis included per-capita investments into various SoM categories including a monetized assessment of time and money spent managing the system. Further details on the data collection and analysis is described in Chapter 3: Research Methods with results and analysis provided in Chapter 6: Strength of Water Management.

1.3 Research Project - Site Background

This section provides contextual information on the development of water supply systems in Madagascar and Nicaragua with some important contextual differences with respect to the sector in each country. In Nicaragua the primary model used for the management of piped water systems in rural communities is community management. In this regards, the water policy and regulations at the national and local government levels have been structured to support this approach. In Madagascar however, community management has had a difficult past and a significant percentage of community managed piped water systems have completely failed. As a result, the national and local governments are utilizing Public Private Partnerships as a model for managing water delivery services (CRS, 2014). In addition to this, some differences with respect to each project partner should be highlighted. In Nicaragua, the program partners include local

NGOs and local government offices that focus their efforts within a single municipality. In Madagascar, the program partner is an International NGO aimed at improving access to water throughout the country including efforts to improve governance through comprehensive integrated development programs.

1.3.1 Project Background: Madagascar - Partners and Site Locations

The water sector in Madagascar can generally be described as centralized with the National Government operating out of the capital city of Antananarivo. In 2008, the Ministry of Water, Sanitation and Hygiene (MWASH) was established and tasked with managing water resources in the country. A five-year political crisis in 2009 had a significant impact on the WASH sector, effecting foreign aid and local economies throughout the country (World Bank, 2013).

As a result, the national water sector has made moderate progress towards meeting MDG water targets (Table 1.1). Nationally, the population being served by an improved water source has increased from 29.4% in 1990 to 53.3% in 2015. The difference between urban and rural areas is significant in that 86.1% of the population in urban areas and 35.5% in rural areas, have access to improved services (JMP, 2017). Even more significant is the limited access to piped water supply in the country. In rural areas slow progress has been made since 2000 with an increase from 11.5% to 15.4% in access to piped water (JMP, 2017). The issue of sustainability with respect to pipe water supply infrastructure is further highlighted by JMP figures which show a total increase from 24.4% to 34.0% in coverage representing a 2.4% exponential growth in a country that has a population growth rate of close to 3% annually (World Bank, 2017). More promising however is the rate at which access to improved water (2.4%) and pipe water (6.9%) has increased since 1990, with the awareness that data before 2000 may have limitations.

Prior to 2010, piped water supply infrastructure in rural areas, failed at an alarming rate and several systems serving small towns were completely abandoned (CRS et al., 2010). The United States Agency for International Development (USAID) implemented two initiatives from 2009 to 2013 (Rano HP and Ranonala) through a consortium of international NGOs. These projects were aimed at increasing sustainable access to water and sanitation in 43 communes in twelve districts throughout the country while also introducing innovations using information communication technologies (ICT) for information dissemination and, monitoring and evaluation (USAID, 2014). At this time, it was largely recognized that community management of water supply in the country had failed and that innovations in water management were needed to improve access for the country's 20 million people, of which over 70% live in rural communes (Annis, 2012). As a result, USAID funded programs that employed a Public-Private Partnership approach to project implementation and water utility management through a competitive bidding process where, private companies would invest in water infrastructure while obtaining a contract to manage and charge for water services for a 20 year period (CRS, 2014).

Table 1.1: Percent Access to Improved Water Source, Madagascar[1] (JMP, 2017)

	Percent Access to Improved Water Supply								
	Urban			Rural			Total		
	Total	Piped	Other	Total	Piped	Other	Total	Piped	Other
Madagascar									
1990	71.4	21.9	49.5	16.6	1.7	14.9	29.4	6.4	23
2000	72.6	59.0	13.6	26.0	11.5	14.5	38.6	24.4	14.3
2015	86.1	68.3	17.8	35.5	15.4	20.1	53.3	34.0	19.3

1. JMP workshops and consultations in Madagascar led to changes in coverage as compared to 2015 reporting.

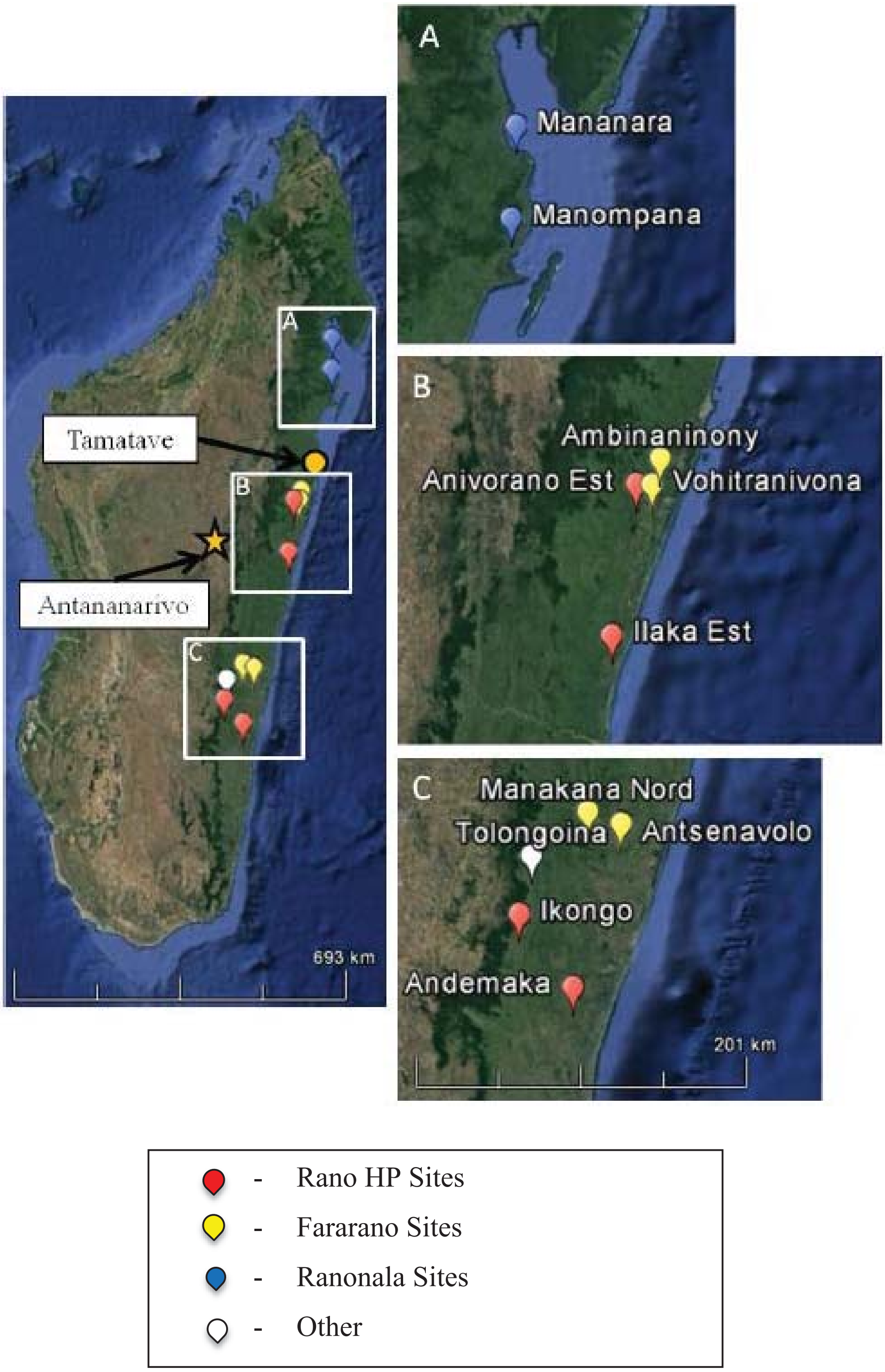
The sites studied in Madagascar were a part of a national initiative to address the sustainability of water infrastructure through the Rano HP and Ranonala projects. These projects focused on small rural towns along the eastern coast of Madagascar, each with unique project partners and municipal offices. The site locations were selected based on being in a similar rural context, the presence of a gravity-driven water network and prior experience with Catholic Relief Services (CRS), the partner organization for this study. During a visit to Madagascar in May of 2014, a research collaboration was established along with other technical areas related to a university partnership. CRS has a well-established program in Madagascar and has been working with marginalized communities there since 1959. In 2012, they were invited to participate in a grant from USAID as member of a consortium of organizations working to improve water infrastructure.

Table 1.2 shows the systems studied during this research and Figure 1.2 shows the sites locations. Projects included in this study were all implemented by CRS during the Rano HP, Ranonala and more recently, the Fararano programs. Some important distinguishing characteristics of the sites in Madagascar are that the systems studied here were rehabilitated using a Public-Private-Partnership (PPP) model for improving the management structure. In addition to this, the sites are spread throughout the country and some significant political and cultural differences could exist between site locations. Furthermore, the average service area population for these projects is larger than the sites studied in Nicaragua.

Table 1.2: System Specifications in Madagascar

Municipality	No. Connections	No. Users	Implementing Organization
Tolongoina	197	2,497	CRS, Bushproof
Mananara	1,158	13,433	CRS, EGC3S
Andemaka	141	4,344	CRS, SEROM
Ikongo	155	2,567	CRS, SERTRano
Anivorano Est	164	1,920	CRS, Velo
Manompana	41	3,000	CRS, Fandriaka
Imorona	215	2,921	CRS

Figure 1.2: Site Locations on the Easter coast of Madagascar (Bogardus, 2015).



1.3.2 Project Background: Nicaragua - Partners and Site Locations

In Nicaragua, progress towards meeting MDG water targets has been significant with actual progress (83.2%) just below pace for the national target of 86.3 percent (JMP, 2017). Whereas, the national MDG water target has been met, this increase is significantly different between urban and rural areas. Table 1.3 shows the progress for Nicaragua and delineates between urban and rural areas where, access in 2015 is reported to be 97.6% and 62.7% respectively. This table also shows where these gains have been made with respect to piped water and other improved water sources including public water taps, boreholes, protected hand-dug wells, protected springs and rainwater collection (JMP, 2017). From this data, it can be seen that a large contribution to meeting these targets can be attributed to the construction of piped water supply infrastructure in both urban and rural areas. In fact, the increase in rural areas is significant where an annual growth rate of 0.51% has been realized since 1990 as compared to 0.38% in urban areas. Whereas, this growth is consistent with global rates for improved access to piped water supply, they are lower than regional growth within Latin America and the Caribbean where annual growth in access to piped water for rural areas was 1.22 percent (JMP, 2015).

Table 1.3: Percent Access to Improved Water Sources, Nicaragua[1] (JMP, 2017).

	Percent Access to Improved Water Supply								
	Urban			Rural			Total		
	Total	Piped	Other	Total	Piped	Other	Total	Piped	Other
Nicaragua									
1990	90.6	82.0	8.6	53.0	17.9	35.1	72.6	51.4	21.2
2000	95.9	90.8	5.1	64.4	38.2	26.2	81.7	67.0	14.7
2015	97.6	95.3	2.3	62.7	33.0	29.7	83.2	69.6	13.6

1. JMP workshops and consultations in Nicaragua led to changes in coverage as compared to 2015 reporting.

Conceptually, development practitioners point to decentralization as one of the ways to improve service delivery to poor and marginalized communities. However, within the academic community, debate continues as to the actual impact of decentralization (Robinson, 2007). In Nicaragua, the National Water Authority is responsible for overseeing the management of water resources in the country (ANA, 2010). In 2010, the Comunidad Agua Potable Saneamiento (CAPS) Law was passed (Law 722), which delegates the legal authority of managing water and sanitation in rural areas, to local authorities at the community level (INAA, 2010). Under this law, rural water committees are required to register as legal entities and are given the authority to manage various aspects of water service delivery including; operation and maintenance, source protection, system rehabilitation, charge water fees, manage accounts and contract services (Hunt, 2015). In order to become legally recognized, local water committees must register with the local municipal authority who is tasked with providing technical support and ensuring that the committee has adopted a constitution and bylaws. In addition to this, water committees have the option of becoming a recognized non-profit organization which gives them the right to title land and open bank accounts (Hunt, 2015).

The sites studied in Nicaragua are all in the Rio Grande watershed within the North Atlantic Region of the Cordillera Mountains, north of the capital city of Managua. Three municipalities were selected for the study based on being in a similar rural context, the presence of a gravity-driven water network and prior experience in the region. Figure 1.3 shows the region that was studied in this research and includes an outline of the municipalities included. Table 1.4 shows a list of the sites studied along with an overview of each system.

In Matagalpa, four sites were investigated that ranged from 540 to 975 people in terms of service population. These projects were implemented under the "Water for Everyone and Forever" initiative by CARE and Agua Para La Vida and were closely coordinated with the Municipal Government of Matagalpa. In Waslala, eight sites were included in the study and service populations ranged from 425 to 2,950 people. Project partners for this study included the local municipal government as well as a local non-profit called the Associacion Deserollo Integral Sustenible (ADIS) which means the Associated for Integrated Sustainable Development. This organization was previously administered through the local church and was transitioned into an independent entity in 2014. Recently, ADIS was absorbed by a national NGO, El Porvenir (The Future) and the research project, along with other university engineering outreach efforts, have been transitioned to the new implementing partner.

Figure 1.3: Site Locations within the Rio Grande de Matagalpa Basin.

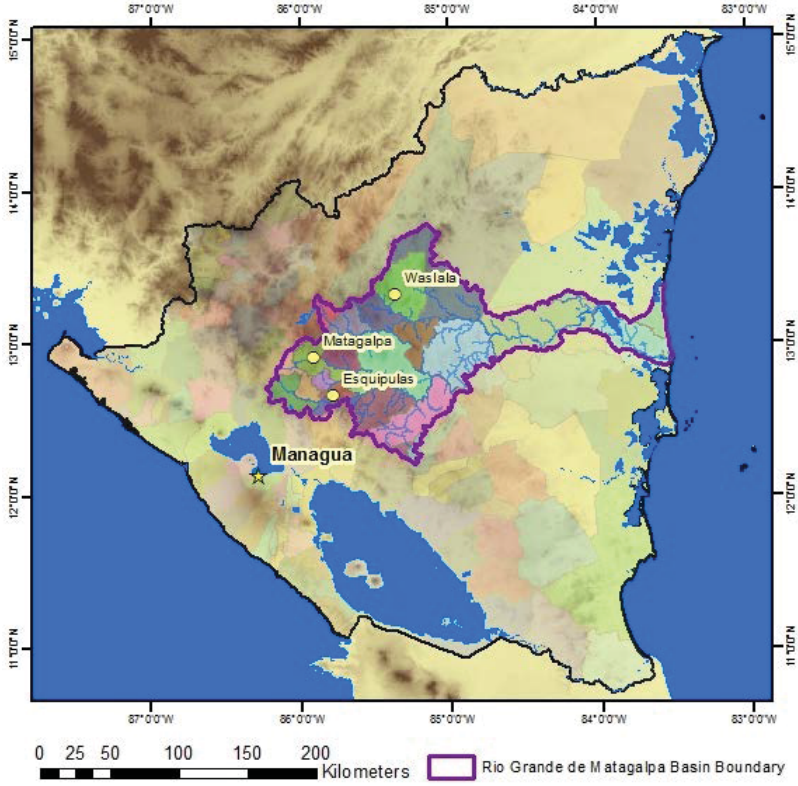


Table 1.4: System Specifications in Nicaragua

Municipality	Community	No. Connections	No. Users	Implementing Organization
Matagalpa	Los Lipes	68	540	CARE
Matagalpa	Molino Norte	155	975	CARE
Matagalpa	San Jose	108	740	CARE, APLV
Matagalpa	San Francisco	78	590	CARE, APLV
Waslala	Dipina Esperanza	81	605	WfW, ADIS
Waslala	Ausberto Paladino	204	1220	Alcaldia, FISE
Waslala	Naranjo Central	550	2950	Save the Children, FISE
Waslala	Puerto Viejo	220	1300	COSUDE, FISE
Waslala	Dipina Central	75	575	Save the Children
Waslala	Yaro Central	51	455	ADIS, El Porvenir
Waslala	El Guabo Jicaral	45	425	ADIS, El Porvenir
Waslala	Santa Maria Kubali	79	595	ADIS, El Porvenir

1.4 Thesis Overview

This research is intended to assist professionals involved with planning, design and management of water supply infrastructure aimed at improving the lives of people in developing communities. Engineering professionals and water utility managers involved in the provision of water services with an interest in understanding sustainability from a holistic point of view, will be interested in this study. Development practitioners who plan and implement programs as well as funding agencies will also be interested in this study, as it relates to long-term sustainability and impact. Whereas, each of these audiences is primarily interested in different aspects of implementing international projects, everyone would agree that improving the capacity of local managers who operate water systems is essential to ensuring the reliability and long-term sustainability of services.

This thesis is primarily written for an academic audience with an understanding that monitoring and evaluation tools are needed to improve management of water infrastructure. Chapter 1 introduces the research initiative, provides background about the projects and presents the logical framework for the study. Chapter 2 provides detailed review of literature with a critique of existing research in order to position the current study. The literature review follows the research framework which has been created to establish boundary conditions for this study. Chapter 3 provides details on methodology including data collection and analysis, along with a discussion on research ethics. This chapter also links research methods to the research framework for this study.

Chapters 4, 5 and 6 focus on analysis and results. Chapter 4 gives results on the performance characteristics with respect to water quantity; reliability and availability. Chapter 5 provides results on water quality and compliance with respect to microbial, chemical and physical parameters. Chapter 6 provides results on the strength of management in terms of human resources, system administration, operation and maintenance, asset management and financial management. Chapter 7 synthesizes results by exploring univariate and multivariate relationships between the different performance characteristics. Chapter 8 concludes the study and provides a summary of key findings within the context of the research objectives, discusses limitations, and gives recommendations for development practitioners and researchers.

CHAPTER 2

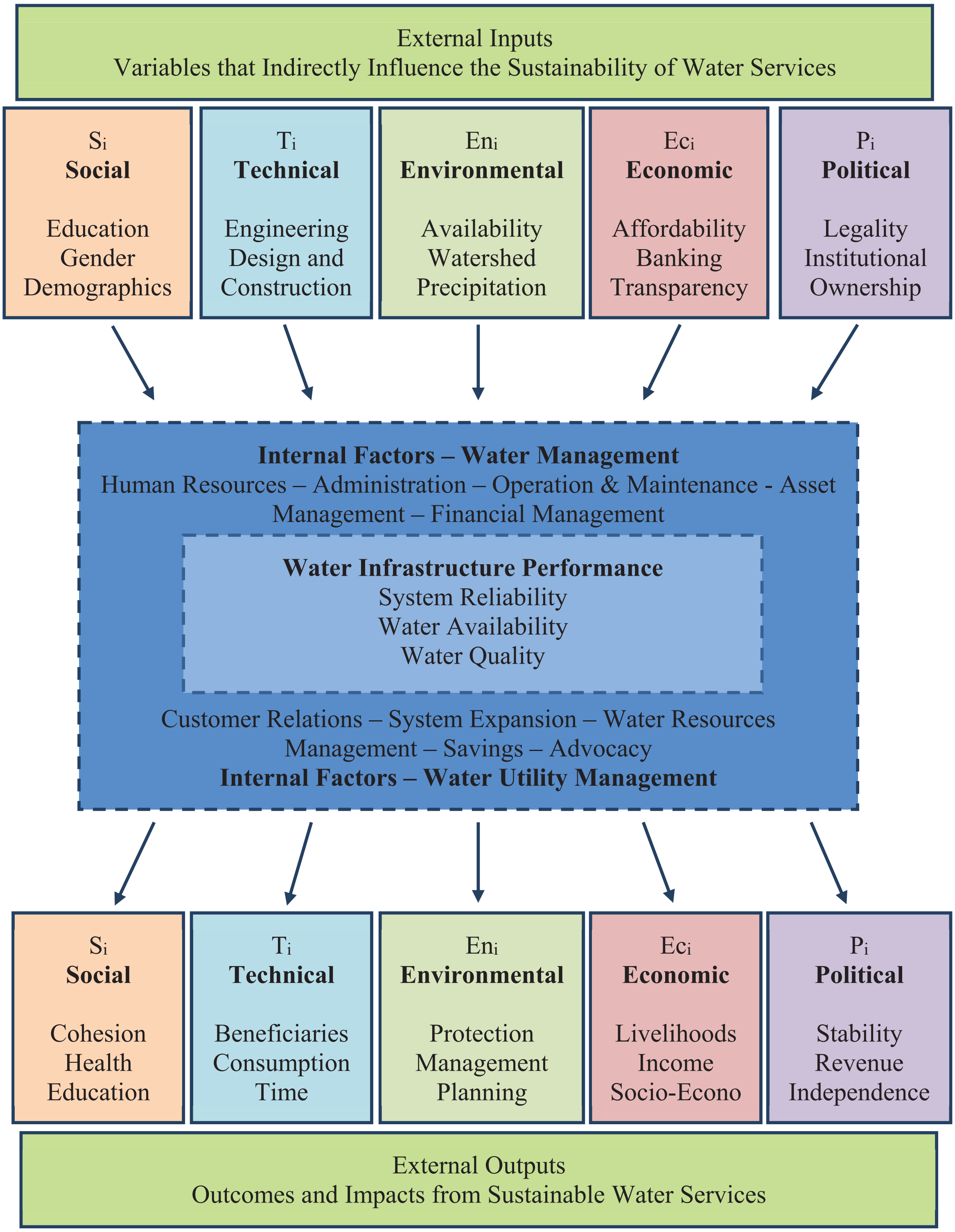
LITERATURE REVIEW

2.0 Sustainability of Water Supply Infrastructure

This chapter provides a critical review of existing literature and an overview of issues related to the sustainable management of water supply infrastructure in developing communities. Sustainability is defined within the framework of this study, and limitations with respect to monitoring water development goals are presented. Previous research on water sustainability is also presented with an emphasis on the need to understand the difference between external-factors that have an in-direct influence, and internal- factors that have a direct influence on system performance at the operator level. Figure 2.1 provides the framework for the research associated with this study and is the basis for the critical review of literature presented in this chapter. It is argued that existing monitoring tools and research related to water sustainability emphasizes project related best-practices, sector sustainability and governance and that future research needs to focus on system performance and capacity at the water operator level. Whereas, external factors, shown in Figure 2.1 can be viewed as necessary considerations at the project and program level, research on the sustainable delivery of water services must consider internal factors.

This chapter also presents, a holistic system view of sustainable management in order to position this study within the context of emerging research on system dynamic modeling, classified as fundamental, theoretical research which needs empirical evidence and practical applications at the local operator level. A critical review of literature on the sustainability of water supply infrastructure suggests a) there is a need for objective tools for monitoring the performance of water infrastructure, b) that there is a need to better understand the influence that management has on system performance, and c) that the monitoring of global water development goals should emphasize the needs of local water operators.

Figure 2.1: Research Framework; Sustainable Management of Water Infrastructure (modified from Ermilio, et. al. (2014).



2.1 Defining Sustainability

In this study, sustainability refers to factors, both internal and external, that influence the performance of water delivery services. External factors have an indirect influence on the technical performance of the system and can be described as surrounding or existing conditions that could reinforce or threaten the long-term sustainability. External sustainability factors for this study are defined using the STEEP framework (Leubkeman, 2006), which identifies Social, Technical, Environmental, Economic and Political variables. Within the WASH sector, the STEEP framework follows closely with models established by researchers who have identified factors that influence water system sustainability including Technical, Financial, Community and Institutional variables (Parry-Jones et al.,2001; Lockwood et. al., 2002; Moriarty et. al.; 2013).

Internal sustainability factors are defined as variables that have a direct influence on technical performance and represent the boundary conditions of this research study. Internal factors have been identified based on discussion groups with local operators, interviews with water professionals, literature and experience. Internal factors include management characteristics categorized in terms of Human Resources, System Administration, Operation and Maintenance, Asset Management and Financial Management. Technical performance characteristics include water quantity in terms of reliability and availability, and water quality in terms of compliance with microbial, physical and chemical parameters.

2.1.1 Historical Context

Sustainability is a broad subject area that is complex, interdisciplinary in nature and has as many as 300 definitions (Dobson, 2000). Historically, the first reference to sustainability was in the 11th Century when Anglo-Norman authorities legally required landowners to practice forestry management by harvesting no more timber than what could be replenished (Wilson, 2004). This practice was called “sustainable yield” and has evolved into what is known today as sustainability (Held, 2000). In the field of international development, the use of the term “sustainable development” emerged in the

1970s and has been interpreted widely with different meanings (Olson, 1995). Throughout the 1980s and 1990s, sustainable development has been viewed as a compromise between economic growth and environmental protection (Brundtland, 1987). Since this time, the concept of sustainability evolved from being a catchall phrase for environmental protection to a cultural movement that exemplifies the significant importance of sustainable development (Lorenz, 2014). Organizations from all parts of the world are discussing sustainability and believe that sustainability helps define their identity and, is an important part of their work (Lockwood, 2002; Gabriele, 2018).

2.1.2 Sustainable Development

A common reference to sustainable development entails a framework known as the triple bottom line (Elkington, 1994). In this model, organizations measure environmental impact as it relates to financial gains through the adoption of the Triple Bottom Line, sometimes referred to as the three Ps; Profit, People and Planet. This framework introduced the idea that an environmental bottom line could ultimately impact long-term financial growth and is sometimes referenced as Social, Economic and Environmental Sustainability. This concept includes the notion that, only organizations who consider social, economic and environmental factors, can holistically understand the true cost of development. Within the private sector this concept has evolved into a business ethics know as corporate social responsibility (Schmidt, 2014, 2016).

Another commonly accepted definition of sustainable development is, "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations General Assembly, 1987). Whereas, this definition has a lot of merit and is a holistic way to approach sustainability, it still has limitations. The context of the problem in 1987 was significantly different and, it is important to realize that this definition was created for the purposes of highlighting the need for environmental protection. At the present time, protecting the environment is widely accepted and the interconnectedness between the health of the environment and the development of society is largely un-contested. In addition, this definition is not universally applicable to all sectors and, it is very difficult to anticipate the needs of future generations. The ability of future generations will certainly include advancements in technology and innovation and their needs are likely to change. A modification of this definition includes the need for a circular economy that considers the lifecycle of products and services and adopts the terminology; "enough, for all, forever" (Lorenz, 2018).

2.1.3 Sustainability in the Water Sector

Within the water supply sector, the concept of environmental sustainability has long been an important aspect of delivering reliable services. This coupled with a strong regulatory framework has required water utilities in developed countries to focus equally on all aspects of the triple bottom line. At the present time, the water sector in many developed countries are employing lifecycle methodologies to assess the potential for wastewater utilization to meet future demands for water supply (Flynn, 2011). Within the international development – water and sanitation sector (WASH), regulatory issues, long-term institutional support, integrated water resource management and lifecycle cost have been key elements of the sustainability discussion (Sohail, 2001; Warner, 2010; Lockwood, 2011; Moriarty, 2013; Ayala, 2013).

Many organizations implementing WASH programs in developing communities, define sustainability as the continual delivery of long-term benefits associated with improved access to water; such as health, economic impact and educational attainment (Carter, 1999). Leubkeman (2006) defines sustainability using the STEEP framework, which identifies Social, Technical, Environmental, Economic and Political indicators. This framework was established to highlight the importance of technical and political aspects within the sustainability discussion. Previous research on the sustainability of water infrastructure has identified several factors that influence sustainability of rural water supply that closely relates to the STEEP framework (WELL 1998, Abrams 1998, Mukherjee 1999, Parry-Jones 2001, Lockwood et. al. 2002). Sustainability indicators include; Technical, Financial, Community/Social, Institutional/Policy and Environmental, and two factors identified as being of critical importance to water supply are tariff collections and external support. Additional factors identified relate specifically to piped water supply in rural areas include; social cohesion, management capacity, parts availability and training (Lockwood et. al., 2002).

The WASH Sustainability Forum of 2010 saw the emergence of three general themes; the need to collaborate with in-country government agencies, the challenges associated with long-term monitoring and evaluation, and the importance of changing the focus from service coverage via project implementation to service delivery and reliability (JMP, 2012). Since that time, a common theoretical framework has been established amongst development organizations known as the WASH Sustainability Charter (WASH, 2014). In this charter, organizations agree to a set of strategic initiatives on sustainability including; participatory planning, coordination with government agencies, accountability, financial management, and reporting and knowledge sharing. Within these initiatives include actionable items related to performance monitoring and establishing metrics for measuring sustainability using a water service delivery approach (Verhoeven et al., 2011). Whereas the existing discussion on sustainability provides direction for future initiatives, not enough is being done to ensure that objective measurements of performance are rooted in evidence-based research and that monitoring considers the needs of local operators.

2.2 Monitoring of Water Development Goals

Thomson and Koehler (2016) describe complex relationships that create tension with respect to achieving universal and affordable access to water services, and the importance of research that moves beyond collecting data for the sake of measuring progress to monitoring that informs decision making. In addition, current approaches to monitoring have been criticized by researchers (Shaheed, 2014) who propose that monitoring and evaluation should inform action rather than measure progress (Bartram, 2014).

The monitoring of global targets on water supply began with the League of Nations Health Organization in the 1930s and continued with the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) through several global development initiatives, including the International Drinking-water Supply and Sanitation Decade in the 1980s. The Joint Monitoring Program for Water Supply and Sanitation (JMP) was created in 1990 when WHO and UNICEF combined their efforts. During this period, monitoring of water development goals was primarily based on reports from national ministries with inconsistent data and limited verification (Bartram et al., 2014).

In 1996, after leading three global monitoring initiatives, the Joint Monitoring Program recognized the need for better national monitoring to improve consistency within and between countries (JMP, 1996). In March of 2000 at the Second World Water Forum, the Water Supply and Sanitation Collaborative Council presented a "shared vision" for water, sanitation and hygiene which was later adopted by the United Nations at the Millennium Summit as Target 7.C of the Millennium Development Goals. As a part of the overall strategy the JMP addressed several limitations with respect to monitoring progress, initiated household surveys to supplement government provided data (JMP, 2000), and later abandoned the use of information from national authorities (Bartram et al, 2014). Subsequent to this, the JMP began reporting progress towards Target 7.C every two years using census data, household surveys and questionnaires based on proxy indicators.

Limitations with respect to progress monitoring have been recognized by the JMP who explicitly highlights the need for further attention towards, "measuring the actual sustainability of water and sanitation facilities" (JMP, 2012). Whereas, it was reported that Goal 7, Target 7.C of the Millennium Development Goals (MDG), to "halve the proportion of people without sustainable access to safe drinking water by 2015", was met five years ahead of schedule (JMP, 2010), this declaration was criticized by water development professionals (Warner, 2010). Among the limitations identified was the use of proxy indicators that allowed for monitoring the "use of an improved water source" based on technology type (JMP, 2000), rather than monitoring "sustainable access to safe drinking water". In addition to limitations with the use of proxy indicators, additional criticism is justified based on research findings which suggest system failure rates of 30 to 40 percent for water supply infrastructure in developing countries (RWSN, 2009).

As a result, there is a need for improved methods to monitoring water development goals. Two types of monitoring have been established since initial monitoring began with a third and fourth type currently emerging. Initial development programs focused on impact monitoring wherein, poverty alleviation and outcomes related to health and economic development have been linked to water services (Bartram et. al., 2010; Ibrahim, 2017). Carter et. al. (1999) suggests that ensuring impact is a requirement for long-term sustainability. During the last 30 years, development organizations have shifted towards progress monitoring, resulting from the need for reliable data aimed at increasing access to improved services (Bartram et. al., 2014; Schwemlein, et. al., 2016).

Recent trends, established in response to terminology associated with the MDGs that called for "sustainable access to safe water", have focused on tools to monitor sustainability. Schweitzer, Grayson and Lockwood (2014) assessed sustainability tools and identified 25 tools for sustainability monitoring of water initiatives. In response to a need to evaluate sustainability, some studies have proposed that new metrics are needed. Koestler et al. (2010) suggest that existing tools to monitor progress only provide a discrete measurement of access and that monitoring sustainability should include a time dependent variable called water-person-years. More recently, a shift towards performance monitoring that measures functionality has emerged with the rational that research should provide local operators with the tools for better operation and maintenance (Lockwood et al., 2011, Ermilio et. al, 2014, Thomson et al., 2016).

Several studies have evaluated monitoring tools within the field of international development with an emphasis on water related development (Kusek and Rist, 2004; Schwemlein et. al., 2016) and others highlight the needs of local water management (Kayaga et. al., 2013, Schouten and Smits, 2015). When synthesizing the efforts of previous studies, it is apparent that the perspective and motivation of researchers needs to be considered when evaluating existing tools. A critical engagement of concepts and ideas related to previous studies suggests that regardless of monitoring type (impact, progress etc.) there are three classifications of monitoring tools which are closely related to the objectives of an investigation. Monitoring tools can be intended to meet the needs of program managers at the development agency or donor level, further classified as Program Monitoring Tools sometimes call institutional monitoring (Schouten and Smits, 2015). Kusek and Rist's (World Bank, 2004) work on results-based monitoring primarily focusses on policy, governance and programs in their guidance document for development practitioners. Other monitoring tools focus on efforts at the project level and are intended to establish best practices for field practitioners, defines as Project Monitoring Tools by Schouten and Smits (2015). A similar guidance document (WELL, 1998) on water supply and sanitation emphasizes project related activities such as assessment and implementation of programs. Some researcher propose however that existing tools are insufficient in that, they do not address monitoring needs at the local operator level where true sustainability is achieved (Lockwood et. al., 2002; Howard and Bartram, 2005; Kayaga et. al, 2013). These studies introduce a third classification of monitoring which is further referenced in this study as Performance Monitoring with further reference to technical performance implying applications at the local water operator level. A critical engagement of concepts and ideas concerned with this thesis would suggest that performance monitoring is consistent with the "service delivery approach", as defined by Lockwood and Smits (2011) and Moriarty et. al. (2013).

Further synthesis of previous research with sector-needs, to increase access to piped water, suggests that there is a real opportunity to influence sustainability through research intended to inform local management and operations of water services. There is a consensus within the WASH sector, that significant work needs to be done with respect to providing higher service levels and ensuring sustainable access to safe drinking water (Warner, 2010). In addition to this, it is recognized that there is a need for improvements in monitoring and evaluation particularly given the lack of attention that has been given to measuring sustainability (WASH, 2014). A significant challenge with respect to monitoring sustainability is a lack of universally accepted definitions (Parry-Jones, et al, 2001). The challenges associated with monitoring sustainability are further complicated by the interrelated nature of sustainability factors (Parry-Jones et al., 2001) as well as the impact that improved access has on other development objectives, making sustainability a complex, nonlinear system (Mukherjee, 1999).

At the present time, the international development community is discussing new challenges including; obtaining one hundred percent coverage for improved access to water, increasing the level of service to include private household connections and improving monitoring and evaluation techniques for measuring performance (JMP, 2012). International Development Organizations are transitioning to meeting targets associated with the Sustainable Development Goals; 17 goals that support development initiatives ranging from "ending poverty" to "establishing development partnerships". Specific to the WASH Sector, Goal 6 seeks to "Ensure available and sustainable management of water and sanitation for all". As a result, establishing a single universally accepted definition of sustainability with clear metrics for monitoring and evaluation is essential. To this extent, the JMP, as the official organization in charge of monitoring SDG-6, has created a five-year strategy that includes creating "indicators and methods for enhanced monitoring of WASH" (JMP, 2016).

2.3 External Influences

When considering the complex nature of sustainability, it is useful to delineate between external and internal factors that influence the system. External factors are often described as the enabling environment (Smits & Schouten, 2015) and can either reinforce or threaten sustainability. Figure 2.1 above, shows the research framework for this study and describes how external factors, ranging from social factors like education and gender, to political factors like legal frameworks and policies, can influence the overall performance of water infrastructure. This figure is intended to provide the basis for a critical engagement of concepts and ideas with which this thesis is concerned.

A critical review of existing tools to monitoring sustainability has revealed that, methods to investigate sustainability do not consider endogenous factors that directly influence technical performance of water infrastructure. In this sense, research on sustainability and M&E initiatives efforts are mostly donor-driven and are intended to inform program and sector wide decisions. This theoretical gap is particularly striking, given finding from previous case-study analysis on sustainability which calls for community-driven development. In addition, previous research in the area of sustainability which includes monitoring and evaluation efforts, often investigates discrete scenarios which are useful for identifying best-practices and reporting existing conditions. Kayaga et. al (2013) describe the nature of external and internal factors in their study on tools for evaluating institutional capacity and the need for non-discrete tools for utility management in an urban setting. Whereas, the scope of this thesis includes rural towns and communities, it is consistent with other researchers who call for continuous and objective measurements of performance.

2.3.1 Social Factors

Social factors that influence the performance of water infrastructure are important considerations when investigating sustainability and can help to highlight the interconnected nature of sustainability. Social sustainability factors include community cohesion, needs and priorities, social acceptance of technology, gender, management structure and ownership (Parry-Jones et. al. 2001). Ultimately, the need to maintain a water service is influenced by the demand for the service and several studies have identified access to secondary water sources and willingness to pay as being key constraints to social sustainability (Davis, 2014; Bakalian et. al., 2009) which further highlights the complex nature of sustainability in that STEEP factors influence each other in addition to the performance of the system.

In many cases, a lack of social acceptance is an indication that community participation and thus ownership was not integrated in the initial phases of a project. Very often a lack of understanding of the health benefits of a water supply system is an indication that educational activities need to be included in the project cycle (Skinner, 2000). Thus, awareness of the benefits is another social indicator for the sustainability of the long-term impact of water supply infrastructure. At the same time, if the community's awareness of the full benefits of improved access to water exists, there are other social constraints that still need to be overcome. For example, if social cohesion influences the management of services, then slippage can occur in the sector ultimately leading to system failure on a wide scale (Reddy, 2010, Davis, 2014, Jimenez, 2017).

The interrelated nature of sustainability is further highlighted by the social aspects of a community's sense of ownership and the technical aspects of service levels provided by the system. Marks and Davis (2012) investigated the how different types of participation influenced the user's sense of ownership of a water supply system and developed tools to evaluate different types of community participation in a water project. Of the many finding from this study, it was determined that there is a strong association between a sense of ownership and private household water connections (Marks et. al., 2012).

The subject of social sustainability highlights the complex nature of sustainability and the need for holistic thinking. Whereas, social acceptance of a technology is important, a lack of acceptance ultimately leads to financial problems because of the lack of willingness to pay for services. Gender issues and woman participation can be viewed as indicators that community participation was integrated into the planning stages of a project. In this regard, the planning process would typically include a technology selections stage (Bouabid, 2004) that requires buy-in from the end-users. Wherein women are frequently tasked with water collection in rural communities, their participation in planning is essential to sustaining both impact and functionality (Fischer, 2017).

Debate continues however, in that certain types of community participation lead to a more significant sense of ownership, with ownership being an essential component of long-term sustainability (Marks, 2012). A sustainable livelihoods approach that views sustainable development in terms of assets, processes and outcomes, helps to better understand sustainability dynamics and links between factors. In this regards, policy and processes influence social capital and social capital is the basis for sustainable development (Sohail et. al., 2001). A critical review of literature on social sustainability and water system failure however offers little in terms of empirical evidence that is needed for comparative analysis. Whereas previous studies provide insights into best practices on a project level, there is a theoretical gap in knowledge with the evaluation of systems being relatively subjective and discrete in nature.

2.3.2 Technical Factors

The idea that technology and sustainable development are interrelated began with the establishment of the Intermediate Technology Development Group (ITDG) in 1962 with an initiative that is currently described as appropriate technology (Hazeltine & Bull, 1999). The economist, E.F. Schumacher (1965) is recognized as the founder of the appropriate technology movement which is based on the limitations of development initiatives that uses large-scale technologies without the availability of resources locally to sustain them. The use of appropriate technology in the water sector is rooted in the concept that the choice of technology needs to consider socio-economic, political and environmental factors within a community, in order to have a lasting impact (Akubue, 2000). As a result, during the International Water Supply and Sanitation Decade (IWSSD) handpump technologies were developed, appropriate for use in rural areas (Reynolds, 1992). From this work, a number of low-cost technologies emerged with the design constraint of being easily maintained at the village level, defined as Village Level Operation and Maintenance, VLOM-pumps. (Haysom, 2006).

Despite these concerted efforts, the sustainability of water systems utilizing appropriate technologies, continues to be a problem (Murphy et. al., 2009), particularly with respect to rural areas in Africa (Parry-Jones, 2001). These sustainability issues are largely attributed to a misinterpretation that even VLOM technologies are universally appropriate without consideration of the local context (Harvey & Reed, 2006). Commonly recognized technical constraints to sustainability of handpumps include; availability of spare parts (Breslin, 2000; WELL, 2001), preventative maintenance (ODA, 1995), durability and appropriate use of technology (Parry-Jones, 2001), quality control during manufacturing (Obiols, 1998), training for pump mechanics (Fonseka et. al., 1994), and design and construction (Curtis et al., 1993; UNCDF, 1996).

Whereas, the technical aspects of the sustainability of handpumps has been well studied, the challenges associated with delivering piped water to communities is significantly different (Jones, 2010). Despite this, several lessons learned from research on the sustainability of handpump technologies should be employed when considering the local management of piped water supply. With estimations that approximately 30 to 40% of water points are nonfunctional at any given time (RWSN, 2009), close to $1.5 billion USD of investments potentially wasted in the last two decades because of handpump failure alone (Baumann, 2009), and the need to increase service levels (JMP, 2012); understanding the technical sustainability factors associated with piped water is of critical importance.

Whereas, approximately 1.2 billion people gained access to piped water between 2000 and 2015, close to 3.3 billion people, or 35.6% based on a global population of 7.3 billion, still do not have access (JMP, 2017). Of importance is the geographic inequity with respect to access to piped water with close to 70 percent of people living in sub-Saharan Africa, Oceania, Southern Asia and Southeast Asia who do not have piped water within their property (JMP, 2010). In order to monitor progress towards the SDGs, the JMP has created an indicator measuring access to “safely managed” water. With benchmark data from

2015, this data reveals that approximately 2.12 billion people (28.8%) lacked access to safely managed water (JMP, 2017). When water development data is combined with development goals that call for increasing service levels (JMP, 2012) research that links water management and technical performance of piped water systems is of critical importance. In addition, research findings that call for monitoring that informs decisions (Shaheed, 2014; Bartram, 2014) further supports the need for performance monitoring in the area of water management and technical performance.

A critical engagement of literature on technical sustainability of piped water supply infrastructure in rural communities offers little in terms of continuous monitoring of technical performance and relationships between performance and water management. To date, the most comprehensive comparative analysis on piped water system performance which, collected information from 400 rural communities in Bolivia, Ghana and Peru; was conducted to evaluate the effectiveness of post construction support (Bakalian and Wakeman 2009). A critical engagement of this research suggests that that more resolution in terms of the technical performance of the system is needed.

In this regard, the researcher's assumption that reasonable variation in the dependent variable of functionality would exist between systems may have been correct but their ability to measure performance was not resolute. It is being contested in this thesis that, Bakalian and Wakeman's claim that "in reality, the great majority of systems were being sustained" is not true and that the methods that they used to measure performance were too subjective. To further the concepts and ideas presented in this thesis, it is being proposed here that, sustainability is not binary and that more objective and continuous monitoring of technical performance is needed to further ongoing research.

2.3.3 Environmental Factors

Environmental factors have long been the focus of sustainable development initiatives intended to increase access to water for low-income developing communities (Skinner, 2000; Hertz, 2017). Whereas, it could be argued that environmental factors including precipitation, watershed conditions and the physical terrain are direct influences on sustainability (US EPA, 2013), it is being proposed here that these factors influence performance characteristics in terms of water quantity and water quality. In this sense, the performance characteristics directly influence functionality which ultimately influences sustainability in a nonlinear way as, other sustainability factors are also involved. Several studies have established links between environmental factors and sustainability (Lockwood & Smits, 2011) and have investigated access to secondary water sources (Harvey & Reed, 2006; Parry-Jones et al., 2001). In this way, access to secondary water resources is influenced by local and regional hydrology but, it influences end-user acceptability and willingness to pay for improved water services, further demonstrating the complex nature of sustainability.

Parry-Jones, Reed and Skinner (2001) conducted a review of water projects in Africa and concluded that sustainability is influenced by the presence of secondary sources of water. In Zimbabwe, where 480 systems were studied, it was observed that areas with the most significant dependence on technology were still performing and that maintenance was being performed in the more arid communities (Cleaver, 1991). These conclusions were further verified in Mozambique where secondary water sources were impacting the community's interest in maintaining the systems because the perceived benefits were not enough to warrant community contributions in terms of time and money (Breslin, 2001). The use of secondary sources of water during the dry season was also studied in 50 rural villages in Kenya. Findings from this research suggest that the availability of secondary water sources is inversely correlated to the user's sense of ownership of a water system (Marks, 2012). A study of 200 villages with access to residential piped water in Volta and Brong Ahafo region of Ghana showed that 38 percent of the households were still using unprotected sources of water for drinking purposes. In Peru and Bolivia, the same study showed that 21 percent and 23 percent of users were using secondary sources of water for domestic consumption (Bakalian, 2009).

Recent trends in the water sector, have shifted the discussion towards monitoring climate change influences with a focus on resilience and water resources vulnerability. The need for monitoring precipitation within water catchment basins is amplified by the vulnerability of water resources to influences resulting from climate change (Roshan et al., 2014; Nematchoua, 2017). A number of climate models predict significant variability in precipitation patterns resulting in potential increases or decreases in precipitation volume depending on the site location and a likely increase in intensity for all areas (Bates, et al., 2008). Whereas, in some cases annual precipitation within a country or region may not change in total volume, the distribution frequency may change within regions and throughout the year (Nematchoua, 2017). The research associated with this study is proposing that, when climate change influences become a more significant issue, the need for strong local water utility management to mitigate environmental threats will be even more important. As a result, research that focuses on water management needs to be prioritized. This is further discussed in Section 2.4.1 Water Management.

Other environmental constraints to sustainability include protected areas and land-use restrictions within the watershed. Watershed basins can be evaluated based on the existence or absence of a protected area, the total drainage area supplying the intake to a system, and the percentage of a land cover (forest, grass, farmland etc.). These examples clearly demonstrate the unique nature of sustainable development in that they highlight the relationship between environmental, economic and social constraints. Whereas some researchers view the availability of secondary water resources as a social constraint, this research proposes to categorize it as an environmental factor since water resource availability is ultimately influenced by hydrology.

2.3.4 Economic Factors

Economic constraints to sustainability are important considerations in that a number of research studies have concluded that failed water infrastructure are associated with weak payment schemes (Parry-Jones et al., 2001; Harvey & Reed, 2004; Harvey, 2007; RWSN, 2009; Marks & Davis, 2012; Foster, 2013). Economic factors however do not directly influence the performance of the system in that payment schemes, affordability and willingness to pay by themselves, do not ensure reliable water services. In many cases, other external factors such as corruption, social conflict or seasonal variability in supply could still prevent economic factors from ensuring reliable services.

As a result, several studies prefer to reference socioeconomics with a more explicit reference to the connectivity between economics and social factors. In this sense, community participation in the form of labor and time during project implementation could be viewed as a capital investment and would better reflect a community's contribution to a project (Skinner, 2000). More recently, community development projects are requiring monetary contributions during the initial stages of a project as a "demand filter" for identifying communities where water supply is a high priority (Bakalian, 2009). Marks and Davis (2012) suggest that there is a threshold for capital contribution and that households who contributed one months of annual income to the initial project cost are two to four times more likely to express a moderate to high sense of ownership of the system. Households that contributed smaller "token" contributions were not likely to express a sense of ownership (Marks and Davis, 2012).

Another financial constraint that influences the reliability of a water supply system is the extent to which households pay for water consumption. In 2009 the World Bank via the Netherlands Water Partnership completed a five-year study on the provision of post-construction support (PCS) of water supply infrastructure in 400 rural communities in Bolivia, Peru and Ghana (Bakalian, 2009). In most cases, it is reported that flat monthly fees are too low to achieve real financial sustainability for the system. After considering; depreciation, operational expenses, short and long-term maintenance needs, it is reported that users are paying anywhere between 3 and 7 times lower fees than are needed. The cost recovery objective as designed in the initial projects studied was to simply cover the expenses for system operation and maintenance. Conclusions from this research show that financial sustainability is a serious concern in that very few communities were achieving this objective (Bakalian, 2009).

In Tanzania, a national policy stipulates that full cost recovery of water supply infrastructure, which includes capital and operational expenses, is the responsibility of the community. This policy includes community cash contributions at 5 percent of the initial capital cost. Key findings from a WaterAid study of 38 villages in Tanzania showed that financial management was the primary correlate with system functionality. This study concluded that a lack of revenue collection and low-price setting, were the primary reasons for system failure (Haysom, 2006).

A critical engagement of literature related to financial sustainability includes the nature of financial issues having the prerequisite assumption that water services are functional in terms of availability, reliability and overall water quality. As a result, any investigation of financial willingness to pay, affordability and community contributions needs to consider the history of development in a community which may negatively influence opinions about water services. This knowledge gap however can be filled with more technical monitoring of water infrastructure performance wherein, the reliability and quality of services is likely a major contributor to financial sustainability.

2.3.5 Political Factors

Political factors are often described as institutional sustainability and make specific reference to policies and external support needed to ensure reliable water services. Parry-Jones, Reed and Skinner (2001) identify policy context as an essential element to providing sustainable water services. Howard and Bartram (2010) describe the need for policy to ensure long-term sustainability of water services, particularly as it relates to climate change. In addition to this, they describe the influence that policy has on technology selection and the need for policies to support access to higher service levels. Political and institutional factors also influence sustainability in that policy choices determine how infrastructure projects are planned, implemented and managed.

Kayaga et al. (2014) describe the concept of institutional sustainability as being a primary factor in how programs are implemented. Furthermore, they describe a scenario which suggests that failure may be a result of how development agencies have defined sustainability. In this sense, projects that were implemented before 1990, defined success within the framework of the project cycle and, ultimately organizations described sustainability as being the continuation of benefits without external support (Honadle & Sant, 1985; Brown, 1998; LaFond, 1995). The political framework within which organizations operate have an influence on the overall sustainability of water infrastructure. Policy factors include decisions made with respect to the provision of water infrastructure projects as well as the type of management used for the provision of services with community, government and private management being feasible options. Other factors include opportunities for private sector investment, the legal framework and enforcement of local regulations as well as presence of external support in the form of national or international assistance (UN Water, 2013; UN Water, 2016).

Kayaga et. al. (2013) completed an extensive review of metrics used to evaluate institutional sustainability with a focus on urban water utilities. Findings from this study revealed that existing tools for measuring institutional sustainability do not track progress within a project or program over time and, do not define sustainability in operational terms. This study further describes existing tools as abstract and having limited practical applications for monitoring progress towards sustainability. Furthermore, they propose that institutional sustainability is essentially a function of capacity over time and that a more effective approach would be evaluating institutional sustainability using modern management concepts, further discussed below in Section 2.4: Internal Influences.

Other institutional factors that influenced sustainability include the approach taken by the implementing agency when defining the scope of the project. Whereas, participatory planning is a commonly referenced best-practice within the WASH sector, organizations involved with water supply projects may take different approaches to integrating this practice into their programs. Ultimately, community participation in the form of time and money, influences the community's sense of ownership of a project, with ownership being an important aspect of delivering sustainable water services (Marks, 2012).

2.4 Internal Influences

Further reference to Figure 2.1 is useful when discussing the boundary conditions of this study which address limitations identified from previous research. Whereas, previous research has investigated sustainability at the sector level, this study is unique in its focus on direct influences which are objective and continuous. Internal factors in this study include two types; local water management and technical performance. It is being proposed in this thesis, that previous research on water sustainability and functionality has a causality dilemma. As a result, this thesis adopts the concept that sustainability is "whether or not something continues to work over time" (Abrams et. al. 1998) and delineates between internal and external factors (Lockwood et. al, 2002).

External factors are defined using the STEEP framework, and internal factors include management and technical performance which directly influence the delivery of services. In this sense, reliability of services is the desired outcome and is viewed as a pre-requisite for long-term sustainability. Lockwood and Smits (2011) define sustainability as "the indefinite provision of a water service with certain agreed characteristics over time". The research associated with this study accepts this definition and proposes that the "agreed characteristics" should be defined in terms of water quantity and water quality. Furthermore, it is also proposed that management has a direct influence on these characteristics, and that strong management mitigates external threats to sustainability in what is described by Walters et. al (2017) as dynamic, systemic interaction of technical, social, financial, institutional and environmental factors.

2.4.1 Water Management

The importance of water management is explicitly stated in SDG-6 which calls for ensuring the sustainable management of water. In this regard, water experts are advocating for professionalizing water management (Moriarty et. al., 2010) in low-income developing communities to ensuring the sustainability and reliability of services (Smits and Lockwood, 2011; World Bank, 2017). The challenge with standardizing water management is that utilities vary significantly within developing communities (Samson, 2013). There are several water management models employed with unlimited variations when these models are adapted to the local context. Among the various options are three basic models which are common within rural communities and small towns; public or government management, private management and community management (Well, 1998). Whereas, the sustainability of water infrastructure is influenced by management (Hurdey, 2003), there is tension between the need for highly skilled personnel and the need to understand the local context of water sustainability (Loyd and Bartram, 1991).

As rural communities and town continue to expand water services, lessons learned from urban water utilities can be useful (Samson, 2013). Kayaga et. al. (2013) suggest that a common understanding of institutional sustainability and indicators are needed to evaluate performance at the operational level. Their study delineates between tools to evaluate institutional sustainability that support the needs of donor agencies and those that support the operational needs of urban water utility managers. They propose the use of a water utility maturity model using five key attributes representing aggregated characteristics that adds resolution and continuity over time. The WUM tool can be used to measure what Cooke and Davis (2005) describe as capacity maturity as it measures and documents continuous improvement. Furthermore, the WUM tool is diverse in that it can be used as a discrete tool to describe current status of an organization, a diagnostic tool to identify weaknesses and prescribe solutions, or a benchmarking tool to compare the capacity of different utilities. Whereas, investigating urban water utilities is outside the scope of this study, many of the institutional capacity principles apply within the rural context. Of interests to this study, are findings that leadership and human resources are important dimensions of water service delivery where local human resources and capacity translate into improvements in performance (Kayaga et. al., 2013).

Franceys (1997, Well, 1998) showed that institutional and human resource development of the National Water Supply and Drainage Board resulted in significant improvements in performance indicators related to water availability and financial sustainability of water utilities in Sri Lanka. Gender and water management is another dimension of human resources which has been researched extensively with women's participation in planning and management of resources being a key aspect of sustainability (Fischer, 2008, Bartram, 2010). Women's participation in water management has been linked to improvements in performance with women in key management positions being an important factor (Momen, 2017).

Other dimensions of human resources which have been linked to increased performance is mentoring (Bell, 1996) and technical support. Contrary to prior studies that defined sustainability as the continuation of benefits without external support (Honadle & Sant, 1985; Brown, 1998; LaFond, 1995), the service delivery approach (Moriarty et. al, 2013) entails ongoing technical support. In 2004, the World Bank commissioned a study on the effects of supply driven – post construction support for water supply infrastructure via its Bank-Netherlands Water Project program. This project included 400 rural communities in Peru, Bolivia and Ghana. Reports of user satisfaction suggest that the current schemes were relatively successful, and that the sustainability of community managed water supply infrastructure is in fact a possibility. In Bolivia, 83 percent of the beneficiaries surveyed, reported being "satisfied" or "very satisfied" with the system. In Peru and Ghana, satisfaction was reported as being 61 percent and 88 percent respectively (Bakalian et al., 2009). Whereas, these finding support the need to consider customer satisfaction when monitoring water infrastructure, the conclusions implicitly reveal the low standards that are being used to measure success.

Sansom and Coates (2011) investigated water utilities in Africa and South Asia to identify factors that contribute to improvements in performance. The links between human resources and the overall administration of water delivery services are highlighted by this study, where capacity and competency of staff were linked to successful water management. Among the these identified were; performance management, financial management, infrastructure services, customer services, managing change programs, human resources management and services for the poor. Key competencies included strategic planning, reporting, project management, asset management and office management. Ultimately these themes and related competencies were shown to improve accountability, customer satisfaction, communications, organizational performance and operation and maintenance.

Whereas, sustainability is seen as having environmental, institutional, technical, financial and social dimensions; fundamentally operation and maintenance is seen as having a direct impact on long-term performance of water services (Well, 1998). In this sense, the differences between urban and rural water supply, including small towns, is significant. The isolated nature of many rural water schemes is referenced when studying sustainability issues related to water supply. The availability of spare parts and skill levels of local maintenance personal are considerations when investigating factors that influence sustainability (Oyo, 2002). As a result, development organizations have been exploring the role of the private sector and are encouraging small and medium size enterprises to fill the demand for parts and services needed to operate and maintain water services (WSP, 2002). Whereas, regular operation and maintenance, the use of preventative maintenance techniques and, the availability of skilled labor are often referenced as technical constraints, this study proposes that these are challenges that can be addressed by effective management.

The link between O&M and managing assets is clearly established through water tariffs that include setting charges at levels that will cover capital maintenance (Well, 1998, Moriarty et. al., 2010). This further entails equipping local operators with the needed tools to manage water systems. Traditionally, this has included actual tools to carry out O&M as well as capital maintenance of physical infrastructure but, it has been shown (Schouten and Moriarty, 2003l Harvey and Reed, 2006; Bakalian and Wakeman, 2009) that communities can effectively manage basic services but that they struggle with long-term sustainability and asset management.

More recently, managing assets has included better understanding watershed issues through integrated water resource management with the understanding that water resources are the ultimate asset. Watershed assets and environmental constraints have an direct influence on water quantity and water quality. Seasonal fluxes in precipitation impact water quantity and, it is common for communities to experience water scarcity during the dry season. During heavy periods of rain, it is also common that outbreaks of diarrhea and other gastrointestinal diseases are more prevalent. Increased precipitation results in flooding and an increase in pathogen loading, suspended solids and chemical pollution from agricultural runoff. Extended periods of low precipitation can result in increased concentrated loads of existing pollutants and lead to saltwater intrusion for coastal communities (Howard & Bartram, 2010).

Uncertainty with respect to climate change and the need for more resilient infrastructure supports the need for strong local management of water resources. This uncertainty has a large impact on the performance of rural water supply infrastructure. For piped water systems, the supply and demand differential is directly related to regional hydrology in terms of both precipitation volume and intensity. The variability of climate patterns from one area to another will increase the need for a complete environmental assessment for each water delivery system in that the total storage capacity requirement will ultimately depend on site specific hydrology and, assumptions made about regional similarities may no longer apply. The resilience of piped water supply and distribution systems is also a concern where networks are vulnerable to the environmental effects of climate change such as an increase in landslides on steep terrain and flooding in low laying areas (Howard & Bartram, 2010). As a result, several organizations and research initiatives are exploring technologies to better monitor physical infrastructure assets, discussed below in Section 2.4.2: Water Infrastructure Performance.

Financial management and the collection of water fees have been linked to sustainability in several studies (Schouten and Moriarty, 2003; Reed and Havery, 2006) but there is limited evidence of how these factors influence actual performance (Bakalian and Wakeman, 2009). Franceys' (1997) research on institutional and human resource development, further highlights the interconnected nature of sustainable water management with human resources further influencing financial sustainability. A parallel to Haysom's research on the functionality of water infrastructure in Tanzania (2006), explored the causality of system failure. This study investigated the root cause of failure in 38 villages in 6 different districts and highlighted the importance of revenue collection and management structure. (RWSN, 2010).

2.4.2 Water Infrastructure Performance

Several organizations have investigated sustainability from the perspective of functionality, defined in this study as system performance or reliability. A study in Tanzania showed that the functionality of water supply infrastructure as measured by flow at the extraction point (pump or standpipe) was as low as 45 percent for all districts studied. This study was conducted to evaluate the implementation of community managed water supply projects and revealed that 67 percent of the projects implemented were still performing effectively (Haysom, 2006).

Other studies on sustainability suggest that limitation in monitoring could prevent the evaluation of functionality in that poor data can be a limiting factor (Welle, 2001). Welle, Williams and Pearce (2015) suggest that cellular technologies can be an effective tool for monitoring functionality with tools for crowdsourcing customer feedback using mobile phones. The development of smart handpumps (Oxford, 2016) was specifically designed for the purpose of improving functionality and employed a management model that was intended to reduce system downtime (Welle, 2001). In addition, system performance or functionality has been the driving factor in several innovative initiatives aimed at improving sustainability. One such example, piloted the use of mobile technologies in eight districts in Uganda with the assumption that increased accountability would lead to higher functionality through text message reporting of handpump performance sent to area mechanics and local officials (Williams et. al., 2016). Ultimately, this pilot failed at improving functionality as the initiative did not properly consider the local context and buy-in from the local or national government officials.

Adank et al. (2016) revealed that, despite progress indicators showing high levels of access to improved water services in small towns in Ethiopia, a different picture emerges after considering performance characteristics including reliability, quantity and quality of water. When considering performance characteristics related to water quality, it has been shown that global figures reporting progress towards access to improved water sources would have to be significantly reduced if measurements of safe water were included in the analysis (Bain et al., 2012; Onda et al., 2012). As a result, the international WASH sector is currently discussing terminology with respect to water system performance including functionality, reliability and sustainability with the intension of better defining metrics related to meeting SDG water targets (Bartram, 2018).

Despite an awareness of the importance of monitoring performance, there is a need to investigate and better understand the continuous nature of system performance in that water quantity, water quality and service reliability change over time, and functionality is not binary in nature. In addition, user generated data is subjective in that the acceptable levels of performance are unique within the local context which make it difficult to compare systems. Furthermore, the exploration of objective measurements of water infrastructure performance will better inform local management teams, will provide comparative tools to evaluate performance and will provide needed information to anticipate and mitigate system failure. Finally, measurements of functionality rarely include the need to monitor water management as an internal factor and often view management characteristic in terms of maintenance of technology without considering operational characteristics with respect to human resources, system administration, asset and financial management.

Development practitioners and researchers are currently considering low-cost computing platforms for the sustainable development of water infrastructure (Pearce et al., 2014; Welle et al., 2015; Williams et al., 2016; Thomson & Koehler, 2016). Particularly, when low cost technologies are combined with the penetration of mobile communication systems, there is a paradigm-shift opportunity to improve the monitoring of water system performance (Pearce et al., 2014). Thomson and Koehler (2016) suggest that performance-oriented monitoring needs to include data to improve water management and, to re-engineer systems with the assumption that information is affordable and continuously available. As a result, several organizations are working to develop smart technologies so that the WASH sector can participate in the data revolution (Stuart et al., 2015) and so that monitoring can better inform decision making (UNDP, 2017). Current initiatives that employ information communication technologies in the WASH sector however are limited to islands of success (Pearce et al., 2014), with the majority of these innovations aimed at improving the sustainability of handpumps utilizing smart pump technologies (Tomson et al., 2012; Nagel et al., 2015; Oxford, 2016).

2.5 Systems Approach

The factors shown in Figure 2.1 are further delineated between Inputs and Outputs, to highlight the complex non-linear nature of sustainability and the importance of establishing clear metrics to evaluate sustainable management (Schweitzer et al., 2012; Neely et. al, 2016). In recent years, research in the field of sustainable development has seen the emergence of system-dynamics modeling that is intended to identify causal loops with positive and negative influences on system functionality. Amadei (2015) describes communities as being a "system of systems" with interconnections between human, economic, natural and engineered systems interacting in a time-dependent, dynamic way. A critical engagement with research related to sustainable development using a systems-approach would include limitations of models that are used to assess and plan community development projects. In this regard, system modeling can be used to optimize inputs and outputs in terms of impact or long-term benefits. At the same time, concepts, ideas and phenomena with which this thesis is concerned are more consistent with monitoring and evaluating sustainability or what Lockwood and Bartram describe as being the necessary condition of functionality.

Walters (2016) conducted a comprehensive review of literature on the sustainability of rural water infrastructure along with surveys that included WASH experts and revealed 8 factors that closely resemble the STEEP framework. Figure 2.2 shows these factors along with a causal loop diagram that identifies the dominant feedback mechanisms, shown in color, that influence water system functionality. Walters is contending that systems modeling presents dynamic links between inputs that can ultimately describe either destructive or beneficial feedback mechanisms that influence functionality over time. A critical engagement with these concepts and limitations therein include methodology that did not consider issues at the local operator level. In this regard, the limited practical experience of the WASH experts who did not have expertise in water system management led to the scenario where Management (as shown in Figure 2.2) is not included as a part of Water System Functionality. In this regard, local water operators understand the local context and issues surround sustainability better than anyone and input from water operators would have likely led to an appreciation for how water management mitigates potential destructive mechanisms.

Additional critique related to the systems approach to modeling water sustainability includes the theoretical nature of this work in that it has little practical value to daily water utility operations. Whereas, these models are useful in terms of highlighting the complex relationship between sustainability factors and functionality of water infrastructure, there is still a need for empirical evidence and quantitative measurements of performance to further develop and validate these models (Walters, 2016). In addition, the endogenous relationship between management and system functionality is not represented in this model and current research in the area of sustainability and system dynamics is generally more theoretical rather than applied.

To ensure that development initiatives consider long-term sustainability several organizations are considering systems-modeling to improve implementation. In this regards, international development organizations are implementing MEAL (Monitoring, Evaluation, Accountability and Learning) into their programs and are defining sustainability more explicitly. As a result, the water sector is seeing a shift from improving access to water, to demonstrating evidence of sustainability in response to the Sustainable Development Goals. WaterAid's sustainability snapshot tool and the work of IRC with respect to aid effectiveness via its Triple S program are excellent examples of clearly defined sustainability benchmarks. Existing research in WASH Sustainability has identified the importance of the institutional culture that exists around various initiatives in water infrastructure. Furthermore, the need for community participation and financial mechanisms for continuous support via internal and external entities has also been highlighted. Whereas current research has successfully identified several sustainability indicators, a significant limitation to past and present efforts exists with respect to how sustainability is defined and measured. Furthermore, there is a need to validate sustainability models using a systems-approach and to link the efforts with actionable efforts to ensure accountability at the local operations level (Schweitzer, 2014).

Figure 2.2: Causal Loop Diagram with dominant feedback mechanism (Walters, 2016)

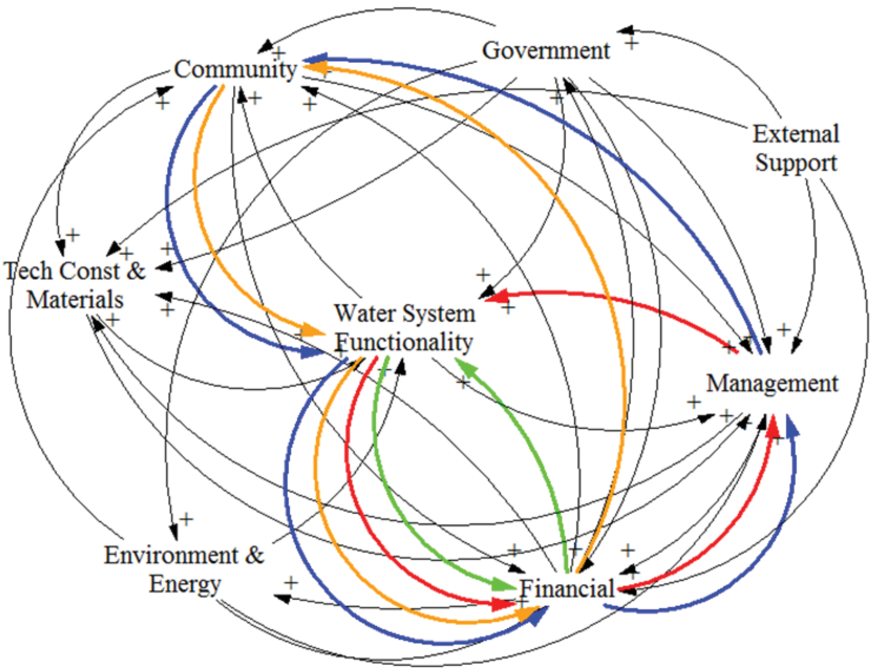
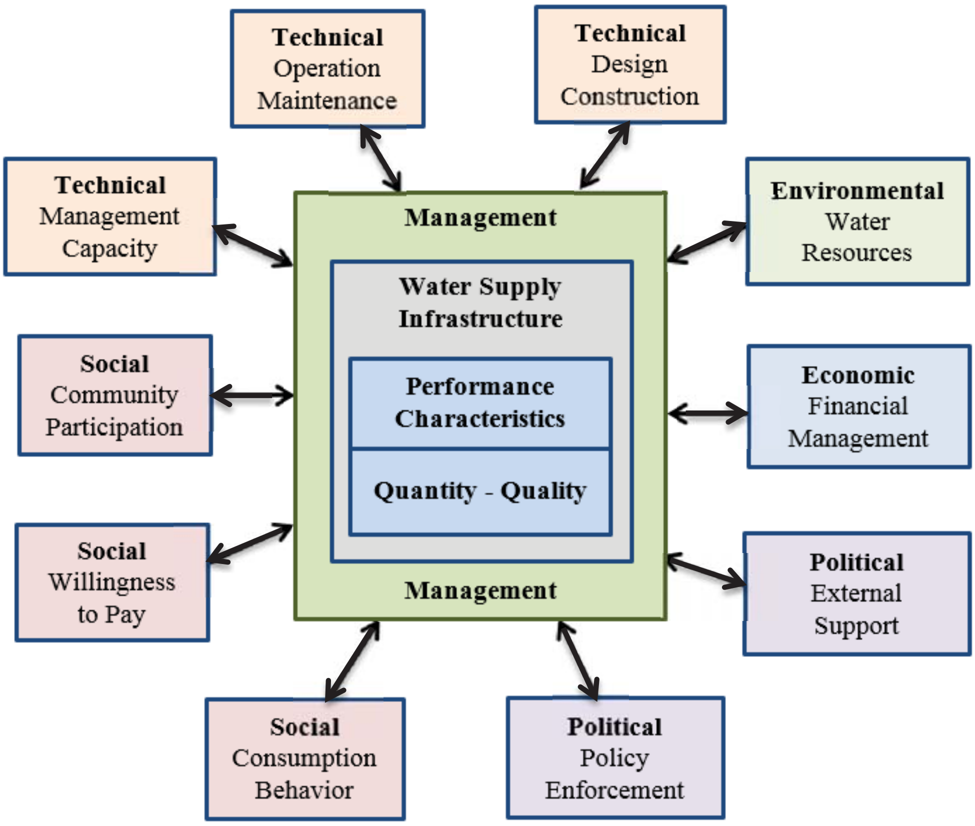


Figure 2.3 shows the conceptual diagram being used in this study to highlight the how external threats to long-term sustainability are mitigated by water management (Ermilio, et. al 2014, 2015). In this sense, performance monitoring is delineated at the local operational level in terms of technical characteristics of the infrastructure. These characteristics are defined in this study as water quantity and water quality performance which are further intended to inform and improve local management. In this sense, external threats are managed by local water utility personnel. Strong management can

mitigate these influences and protect the performance of the system and poor management could exacerbate these influences and compromise the system.

Figure 2.3: Mitigating Effect of Management on External Sustainability Threats



In Figure 2.3, external sustainability factors are identified that can positively or negatively influence the overall performance of water services. These external factors are shown here as multiple variables that influence system performance in a linear fashion with the understanding that strong management is needed to mitigate external threats to long-term sustainability. Previous research on water infrastructure sustainability has recognized that these influences are not linear, and some researchers are calling for a more systems-approach to monitoring sustainability (Amedie, 2014; Walters, 2015; Moriarty, 2017; Lockwood, 2018). In this sense, external factors influence the technical performance of water supply infrastructure and they influence each other. Furthermore, reliable water services and strong management can also influence external factors, which ultimately creates the conditions of a complex, non-linear system of systems.

As a result of these complex relationships, monitoring sustainability often focuses on the needs of researchers rather than the needs of development professionals that are involved in the planning and design of programs. Furthermore, research that meets the needs of local operators who manage and maintain water systems is often neglected entirely. Technical performance monitoring at the operator level however, has the potential to fill this gap. Performance monitoring can provide technical rigor and empirical evidence to support the needs of researchers while also supporting the needs of development professionals who need to demonstrate evidence of sustainability. Most importantly, performance monitoring can also support the needs of local water operators to make informed decisions for daily operational purposes, to better anticipate sustainability challenges, and to mitigate system failure.

2.6 Summary of Knowledge Gaps and Limitations

Several knowledge gaps and limitations of previous research should be highlighted, which have been used to better inform the research question and the objectives for this study. To address the research question, two objectives with associated knowledge gaps were identified. These knowledge gaps can be categorized into two areas: establishing objective measurements of performance in terms of water quantity, water quality and water management; and linking performance characteristics to sustainable management. The research associated with this thesis intends to fill these gaps and demonstrate the need for objective measurements of sustainable development.

In terms of monitoring performance, there is a need for higher resolutions of technical characterization when investigating system sustainability. Several researchers are advocating for performance monitoring (Bartram, Howard, Moriarty, Lockwood) because water supply systems are dynamic in nature and require research that goes beyond discrete measurements. In addition, previous investigations to monitor performance have had validity problems, in that, they employ a presence/absence test, based on technology type, when defining sustainable access to safe drinking water. The research associated with this study fills this gap by defining system performance in terms of water quantity and water quality; characteristics which, are essential to the overall sustainability of any water supply system. The performance of the system in terms of water quantity is defined in terms of the reliability (%) and the availability (l/p/d) of the service. System performance in terms of water quality is based on compliance (%) with respect to pre-defined criteria for microbial, chemical and physical parameters.

In terms of measuring sustainability, previous research has several limitations. There is a need to better appreciate the difference between external and internal influences and to delineated boundary conditions for research initiatives that investigate sustainability. Whereas, the framework for this study recognizes and includes external factors, the primary research objectives focus on internal factors, defined as those that directly influence the performance of water services. Another limitation of existing research includes the need for more objective measurements that can be used for comparative purposes and which move beyond case-study methods intended to identify best-practices. Whereas, case studies have shown that social, technical, environmental, economic and political factors all influence the functionality of water supply infrastructure (Thomas, Koehler, 2016; Bartram et al., 2014; Moriarty et al., 2013; Lockwood et al,, 2002; Harvey, Reed, 2003), recent investigations in sustainability modeling have explored the accumulated affect that they have on functionality (Walters et. al, 2017; Walters, 2015; Amadei, 2015). Despite these efforts, case-study methods and sustainability modeling still need more objective tools to demonstrate empirical evidence (Walters, 2016).

An additional gap, identified during the literature review, demonstrates the need for research to explore links between water system performance and sustainable management. In this study, water management is viewed as being at the interface between external sustainability influences and the performance characteristics of the water system. In this sense, external threats to sustainability can be mitigated by local management, to ensure effective performance of the system. The research associated with this study proposes that performance monitoring is the key to ensuring sustainability and that, it also supports the need for impact monitoring and progress monitoring. In this sense, performance monitoring is essential to the sustainable management of services given the notion that "you cannot management what you cannot measure" (Drucker, 2013). As a result, this study proposes that a shift towards objective measurements is needed to show conclusive evidence of links between technical performance and water management.

As a result, the research framework associated with this study intends to contribute to SDG-6 by investigating objective tools and establishing clear metrics for monitoring the performance of piped water infrastructure. The challenges associated with meeting SDG 6 are significant and trends in technological innovation will be important factors in meeting these targets. In addition to this, measuring progress towards the SDGs will require innovations in monitoring so that high quality information can be used for decision making (UNDP, 2017). Most importantly, as the WASH sector begins to participate in the data revolution (Stuart et al., 2015), research on technical performance of water supply services is critically important, to ensure that monitoring and evaluation efforts includes the needs of local operators.

2.7 Chapter Summary

With the creation of the Sustainable Development Goals which seeks to ensure available and sustainable management of water, an exploration of terminology with respect to the sustainable management of water infrastructure is important. This chapter provides the framework for this study and justifies the need for research that explores relationships between technical performance and management characteristics of water supply infrastructure. Given the emphasis on sustainable management and recent trends in the development sector towards systems-thinking, it is important to better understand performance characteristics so that objective metrics can be used to monitor performance and to accurately evaluate progress towards sustainable management. Furthermore, development terminology that explicitly identifies the "sustainable management of water" implies a direct relationship between sustainability and management of water services.

CHAPTER 3

RESEARCH METHODOLOGY

3.0 Research Methodology

Redman and Mory (1923), define research as being a "systematized effort to gain new knowledge". Sekaran (2007) expands on this definition to include an "organized effort to investigate specific problems". Research is often categorized as being applied or fundamental. Applied Research is practical and has real world applications that focus on solving specific and more immediate problems (Gray, 2009). Fundamental Research is theoretical and is often referred to as Basic Research with a focus on developing, refining or validating existing or new theories. In both cases, research usually focuses on solving problems or answering questions about the nature of things, both social and physical.

Participatory Research is an approach that builds on local knowledge and enhances effectiveness when conducting research in low-income developing communities (World Bank, 1994). Callon (1999) describes this model as a co-production of knowledge, where local stakeholders and researchers collaborate closely to define a problem, and to produce and disseminate knowledge.

The research associated with this investigation would be classified as an applied, participatory study. This study included a mixed methodology, where qualitative data was used to inform the research design and to validate the results of a largely quantitative analytical study. Quantitative methods emphasized objective measurements of the technical performance of piped water supply systems with noted limitations of prior research in the sustainable development of water infrastructure. Data collected for this research included a review of technical reports, continuous monitoring of water levels in storage tanks, discrete water sampling and analysis, interviews with local water operators, workshop discussion groups and household surveys. Analytical methods included calculations of the reliability and availability of water services, compliance with water quality standards, strength of management, and statistical analysis using univariate and multivariate linear regression.

This chapter includes details of the research methods associated with data collection and analysis as well as an overview of the research design. Section 3.1 described field methods employed for data collection and includes details of site inspections, instrumentation of water infrastructure, sampling and analysis of water quality, semi-structured interviews, and household customer satisfaction surveys. Section 3.2 provides details on the analytical methods used to evaluate system performance including water quantity, water quality and strength of management characteristics. This section also provides details on the classifications used for comparative analysis and the univariate and multivariate analysis used to explore relationships between management and performance characteristics. Section 3.3 describes the triangulation of the results and how data reliability and construct validity were ensured during the study. Section 3.4 discusses some of the limitation of the results, Section 3.5 discusses the how ethical issues were addressed during the investigation, and Section 3.6 provides a chapter summary.

3.1 Data Collection and Instrumentation

Several methodological options are available for evaluating water management and the technical performance of water infrastructure. Table 3.1 provides a summary of the various options along with the strengths and weaknesses associated with each. In addition, the rationale for the selected data collection methods are also provided. In terms of water quantity monitoring, several options related to overall per-capita water consumption were considered. Two types of water meters were considered with further consideration for the location of the meter being at the household or within the water main. The traditional turbine water meter using a mechanical register was considered for installation within the water mains of the system but was later determined to be not feasible because of the invasive nature, cost and potential complications during the installation. The OVR meter is a turbine meter that provides for data logging. This meter was considered not feasible because of the cost. Ultrasonic sensors were considered an option and were explored in a parallel study. This option installed sensors within the storage tank to measure water levels based on sound. This option was determined to be not feasible because the sensors were sensitive to tampering and needed re-calibration. The pressure transducer option was selected because of its low cost, ease of installation and precision. One of the challenges with this method was that on-site extraction of data was needed and information provided was not instantaneous. For this reason, another parallel study investigated options for remote monitoring which would employ SMS text messaging and data transmission via the local cellular network. This option was not considered for this study because the technology has not been proven and there was the potential for data reliability issues.

Data collection for water quality considered two general methods; field methods and laboratory methods. Whereas, laboratory methods would have provided certified results, these results would have to be further explained in that the holding time for the water parameters being studied, would have rendered the results questionable. In addition, the added transportation cost, laboratory fees and limited availability of data at the water operator level made this option not feasible for this study. In terms of field methods, several proven QA/QC techniques were available to ensure that the results were within a reasonable level of accuracy. In addition, the low-cost nature of field methods and through consultations with water sector professionals made this option the most feasible. Water quality sampling and analysis field methods are further discussed below.

In terms of water management, several existing tools were considered. Given the limited number of tools for evaluating water management in the context of rural water supply and the limitations of existing tools previously discussed, the option of creating a new tool was considered. Whereas, the SoM tool is not well-established and has not been derived from management theory, the exploratory nature of the study justified its use. In addition, the literature review, Delphi technique and consultations with water sector professions provided a basis for determining SoM indicators. Most importantly, this approach utilized input from local operators using participatory methods discussed below. The Customer Satisfaction tool, also discussed below, was used to validate the water quantity, water quality and water management tools and employed a Likert scale for analyzing the results. Whereas, it was apparent that household water users would be able to evaluate water quantity and water quality as a consumer, household level evaluation of water management is more nuanced. In this sense, households would have an opinion about the billing process, maintenance calls and general water services but individual user interpretations of water operations and management may differ. For this reason, the customer satisfaction survey also provided an open-ended question to qualitatively assess customer's perspective on water management.

Table 3.1: Methodological Options for Data Collection

Topic / Options	Strengths	Weaknesses	Notes
Water Quantity			
Turbine Meters	Accurate at both low and high volumes	Invasive to the system, No data logging, Requires manual reading	Household meters were already installed and used for validation purposes.
OVR Meters	Accurate at low and high volumes, includes time delineated data logging	Invasive to the system, Cost prohibitive	Not considered feasible for this study because of cost.
Ultrasonic Sensors	Includes data logging, low-cost, non- invasive,	Requires manual data extraction, single point monitoring, difficult to install, requires temp correction, requires analytical methods to process	Method was field tested and determined to be unfeasible because of installation difficulties.
Pressure Transducers	Includes data logging, Low-cost, Non-invasive, Easy Installation, Precise	Requires manual data extraction, requires atm pressure correction, requires analytical methods to process	Chosen for this study because of listed strengths.
Remote Sensing	Includes data logging, access to data via email and SMS,	Unproved technology, difficult to install, cost prohibitive, requires temp. or atm pressure correction	Field tested during the study with low-cost Arduino and SMS platforms. Determined not feasible because of reliability problems.

Table 3.1: Methodological Options for Data Collection (continued)

Topic / Options	Strengths	Weaknesses	Notes
Water Quality			
Laboratory Analysis	Reliability of results, certified, third-party QA/QC protocol, objective analysis	Cost, sample holding time, information not available locally, potential cross contamination during transport.	Not considered feasible because of weaknesses which would prevent transparency of limitations.
Field Methods	Low-cost, within sample holding time, information locally available	Potential for microbial cross contamination during sample transport, subjective results vulnerable to interpretation of field team	Chosen methods because of limited need to handle samples and ability to test on site. Options to analyze microbial samples using low-cost incubation made this option more feasible.
Water Management			
Existing Tools	Established, rooted in theory, able to synthesize with other studies	Intended to inform donors and project managers, limited applications at the water operator level	The participatory methods used for this study prevented the use of existing tools.
SoM	Relevant in the rural context, includes input from local water operators,	Requires calibration, not rooted in management theory, no previous work to support findings	Modifications to SIT and STEEP using the Delphi method, literature and water sector professionals was employed.

3.1.1 Project Reports and Site Inspections

Information about the existing water infrastructure was collected during this study through a review of project reports that included design specifications as well as through on-site field inspections of the systems. Project reports and system design specifications were often available within various local offices. In some cases, electronic copies of reports were available from the government office and in other cases, reports were available from the local implementing NGO or from regional or national level agencies. Information about the water supply infrastructure was also available in some cases at the local water management level wherein, some of the site locations had small offices with diagrams of the systems available.

The primary purpose of reviewing project reports was to determine the technical constraints of the systems being investigated prior to site visits. Field visits and site inspections were conducted to verify information available in project reports, collect GPS coordinates of critical nodes in the systems being studied, and establish relationships with the local management team prior to collecting data on strength of management. Where information was not available in technical reports, additional field visits were used to collect missing information. Information consolidated during the initial review included; pipe diameters, distances, intake and storage specifications, elevations and number of household connections. In addition to this, information about the local management structure was collected to better inform the semi-structured interviews.

In most cases, the project reports included technical details based on transit and GPS surveys that were conducted during the assessment phase of the project. Project reports also included details about the design specifications of intake structure, water treatment facilities and storage tanks in the system. At all sites, an independent verification of the inside dimensions of the storage tank facilities was conducted using a tape measure, during field visits. Technical specifications about the systems were imported into Google Earth™ and system diagrams were created to better understand technical constraints for each project area studied, as shown in Appendix A.

3.1.2 Water Quantity Monitoring and Instrumentation

Water quantity data was collected through the installation of In-Situ® Rugged Troll 100 pressure transducers on the bottom of water storage tanks. These titanium devices measure and record absolute pressure at a pre-determined time interval and are designed for environmental monitoring in difficult conditions. The devices come pre-calibrated to NIST certification standards and are accurate to ±0.1% at 9.0 meters of water pressure (In-situ, 2013). Absolute pressure data was collected on fifteen-minute intervals, and water level data was extracted using a Rugged Troll Docking Station. Barometric pressure transducers were installed regionally to monitor changes in atmospheric pressure in order to investigate the accuracy of analytical methods that used absolute pressure instead of gauge pressure, further discussed in Section 3.2.

The installation process involved consultation with project partners to identify storage tank locations within each system. Additional consultation and coordination with the local water management team was required to explain the purpose of the device and to demonstrate the value of monitoring water levels in the system. Figures 3.1 and 3.2 show the consultation process and the system installation diagram respectively. Upon completion of a site consultation, pressure transducers were installed within the storage tanks of the system. Access to the water tank was provided by the local operator and Winsitu® software was used to zero the devices prior to installation. The onsite calibration of the device was an important part of the installation as, atmospheric pressure differences that resulted from elevation changes from site to site were apparent and thus eliminated by during installation. As a result, having a laptop computer on-site was necessary in that, the device was plugged into the computer, the current pressure reading was noted, and then the device was zeroed at the tank location during installation.

To ensure that the instrumentation was measuring and recording data properly, the research team remained at the tank for a 1-hour period and extracted the device to upload test data. Photos and GPS coordinates were taken to document the site location and further consultation with the local operators was conducted to verify system specifications. After the test period, the transducer was removed from the tank and the test data was uploaded onto a laptop using a Rugged Troll Docking Station. Upon verification of the test data, the device was reinstalled in the tank where it remained throughout the duration of the study.

Figure 3.1: Onsite consultation with water operators in Mananara, Madagascar

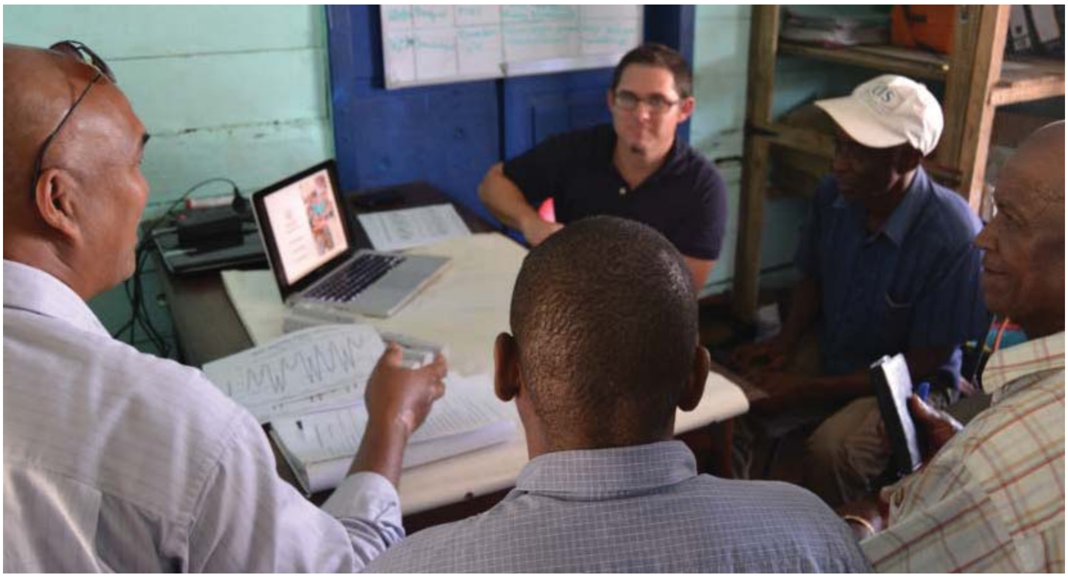
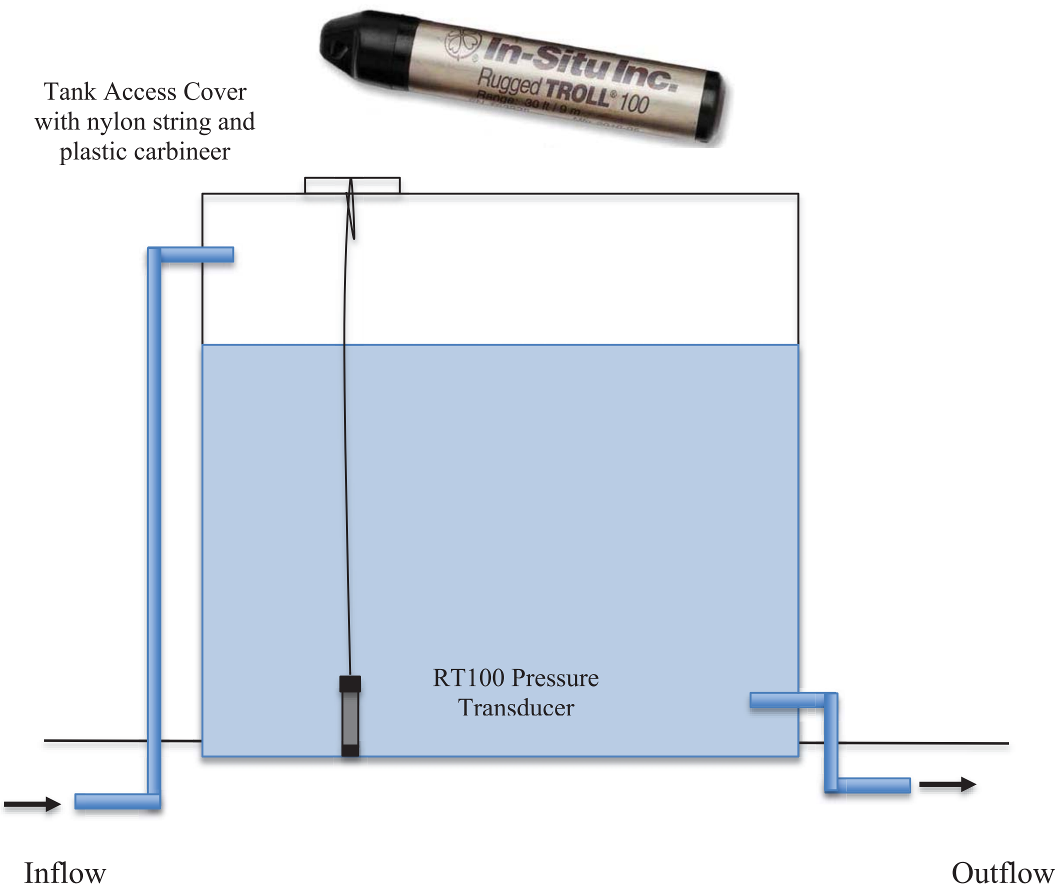


Figure 3.2: In-Situ Rugged Troll 100, Installation Diagram



Periodically throughout the study period, data was extracted from the device which required additional site visits. During these additional visits, the water levels in the storage tank were reviewed with the local water operators and unusual readings were discussed to identify potential sources of error which would have resulted from someone tampering with the device or tank maintenance during the study period. In addition to this, site visits for downloading data provided another opportunity to consult with the local operators and collect data relevant to the water quantity monitoring such as maintenance frequency and water meter readings.

3.1.3 Water Quality Sampling and Analysis

During the initial site consultation described above, water quality sampling plans were created with the local operators. Using sketches and diagrams of the system, sample locations were identified with criteria established by WHO Guidelines, which recommends a minimum of 12 samples annually for piped water systems serving up to 5000 people (WHO, 2012). Based on consultations with local operators, water quality monitoring included household locations within the distribution system, and strategic locations within the system including source, storage tank and pre/post treatment where applicable.

Figure 3.3 shows an example of a site diagram that includes sampling locations identified during this process. Diagrams like this, were used at each site location to create a water sampling plan. In this example, the source, storage tanks and household connections are shown. More specifically, the site diagrams were used to determine sample locations within the distribution systems (circled) so that the water quality analysis was representative of the entire system. A minimum of one sample was collected at each branch of the distribution system with additional samples being collected proportionally, based on the number of connections at each location with a minimum of 12 samples collected annually. In the example shown here a minimum of six samples along with two duplicates would have been collected at the household level, representing water quality within the distribution system. In addition to this, one sample from the source and two samples from the tanks, would have been collected along with one duplicate from this set. This process was repeated twice during each year of the study and a minimum of 16 household samples and 8 system samples would have been collected.

To facilitate sampling and analysis, research assistants that included local partner staff members, engineering student interns and graduate students were trained on quality assurance and quality control (QA/QC) protocols prior to implementation. During the training, field methods were discussed that included; identifying sample locations, the use of common nomenclature, sampling frequency, analysis and interpretation as well as methods for preventing cross-contamination such as the use of field blanks and duplicate samples. Table 3.1 shows the nomenclature used for this study along with an example of the site location and sample identifiers used during data collection.

Water samples were analyzed for physical, chemical and microbial constituents. Physical constituents used commercially available test strips for measuring Total Dissolved Solids (TDS), Total Hardness and pH, and hand-held meters for measuring Conductivity and Turbidity where feasible. Chemical constituents also use commercially available test strips to measure Nitrate, Nitrite, Residual Chlorine and Total Metals. Microbial testing employed a combination of Petrifilm^{TM}, Pathoscreen^{TM}, and a Compartment Bag Test^{TM} (CBT) to measure Total Coliform and Escherichia Coliform.

Figure 3.3: Example Water Sampling Plan

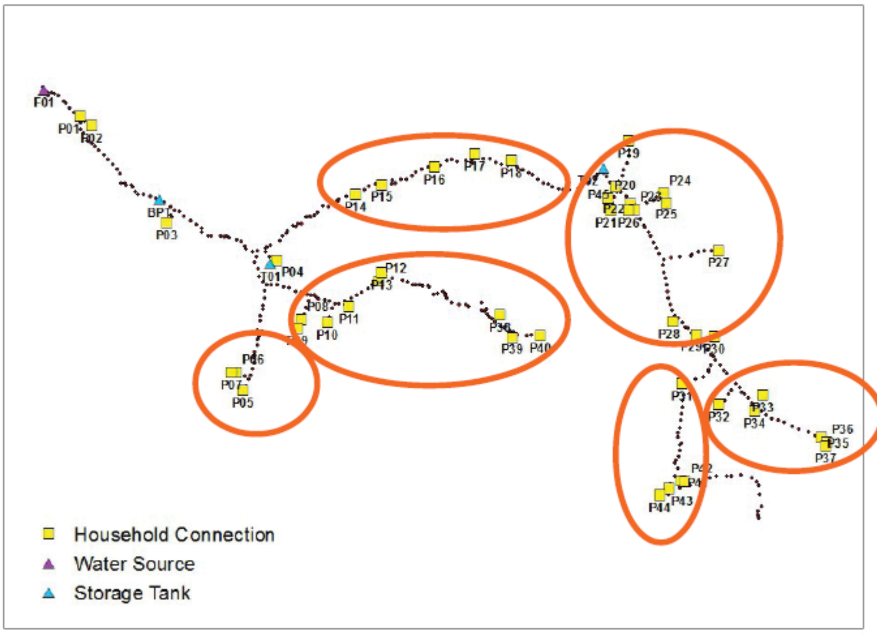


Table 3.2: Water Quality Sampling - Data Collection and Nomenclature

Sample ID	Sample Location	Latitude	Longitude	Comments
EG-1-S-1	Source	13.343430	-85.342793	Protected Spring
Abbreviations and Identifiers - Nicaragua				
EG – El Guabo DP – Dipina PV – Puerto Viejo EN – El Naranjo AP – Ausberto Paladino LC – La Cieba ER – El Rodeo SJF – San Jose Francisco MN – Malino Norte LL – Los Lipes		F – Fuente (Source) T – Tanque (Tank) P – Pipe (Household) BC – Blanco de Campo (Field Blank) BL – Blanco de Laboratorio (Lab Blank) D – Duplicar (Duplicate)		
Abbreviations and Identifiers – Madagascar				
MN – Mananara MP – Manompana TG – Tolongoina IK – Ikongo AV – Anivorano IK – Ilaka AD – Andemaka AB – Ambaninaninony VH – Vohitranivona AT – Antsenavolo MK – Manakana		S – Source F – Filter C – Chlorinator T – Tank D – Distribution B – Field Blank		

All sampling and analysis followed quality assurance and quality control procedures using the following guideline;

- Sample Collection – Physical and Chemical constituents were analyzed on-site using the instructions provided for each test. When the instructions called for a specific sample volume, the provided container was rinsed three times using the sample water prior to collection. Microbial samples required laboratory analysis and were collected in a sterile 100 ml Wirlpak™ Thio-bag which contains sodium thio-sulfate to neutralize chlorine and were stored in a sterilized, clean cooler at room temperature during transportation. Sample bags were opened on-site just prior to collection and were placed without contact under a stream of water from a spigot for household distribution samples. Samples collected from the source and storage tanks used the Wirlpak™ bag to scoop water from the surface while preventing direct contact with the water from the field assistant.

- Sample Analysis – Physical and Chemical parameters were analyzed instantaneously on-site using the procedures described below. Microbial testing required laboratory procedures and is also described below. Samples tested for coliform and e-coli were processed and put into incubation within 8 hours of sampling. An incubation period of 24 and 48 hours was used for total coliform and e-coli respectively.
- Field Blanks – The primary purpose of using field blanks was to ensure that the sample collection process did not introduce microbial contamination. As a result, bottled water was used following the same sample collection process described above for all water quality constituents. One field blank was collected and analyzed at each site during each sampling event.
- Laboratory Blanks – The primary purpose of using laboratory blanks is to ensure that the water testing process does not introduce contamination. Laboratory blanks also used bottled water using the microbial testing procedures described herein. One laboratory blank was collected and analyzed for each sampling event.

Total Dissolved Solids (TDS) and Conductivity were tested using an HM Digital COM-100, hand-held multi-meter with an accuracy of ±2.0% (full-scale). This method provided three significant figures of resolution with a range of 0 to 8560 mg/L (ppm) and reports TDS using a KCl coefficient with automatic temperature correction (HM, 2014). Electrical Conductivity ranged from 0.0 to 9990 (μS) with a resolution of 3 significant figures. Total Hardness and (pH) were tested using WaterWorks™ test strips with a pH range of 6.0–9.0 at a 0.5 interval and Hardness range of 0.0-500 ppm at a 10.0 interval.

Chemical constituents also used commercially available test strips to measure Nitrate, Nitrite, Residual Chlorine and Total Metals. Nitrates (NO_2 and NO_3) used a two-in-one WaterWorks™ test strip to measure both constituents. Nitrite (NO_2) was measured with a range of 0.15 to 10 ppm and had a variable interval of 0.15-0.30, 0.30-1.0, 1.0-1.5, 1.5-3.0

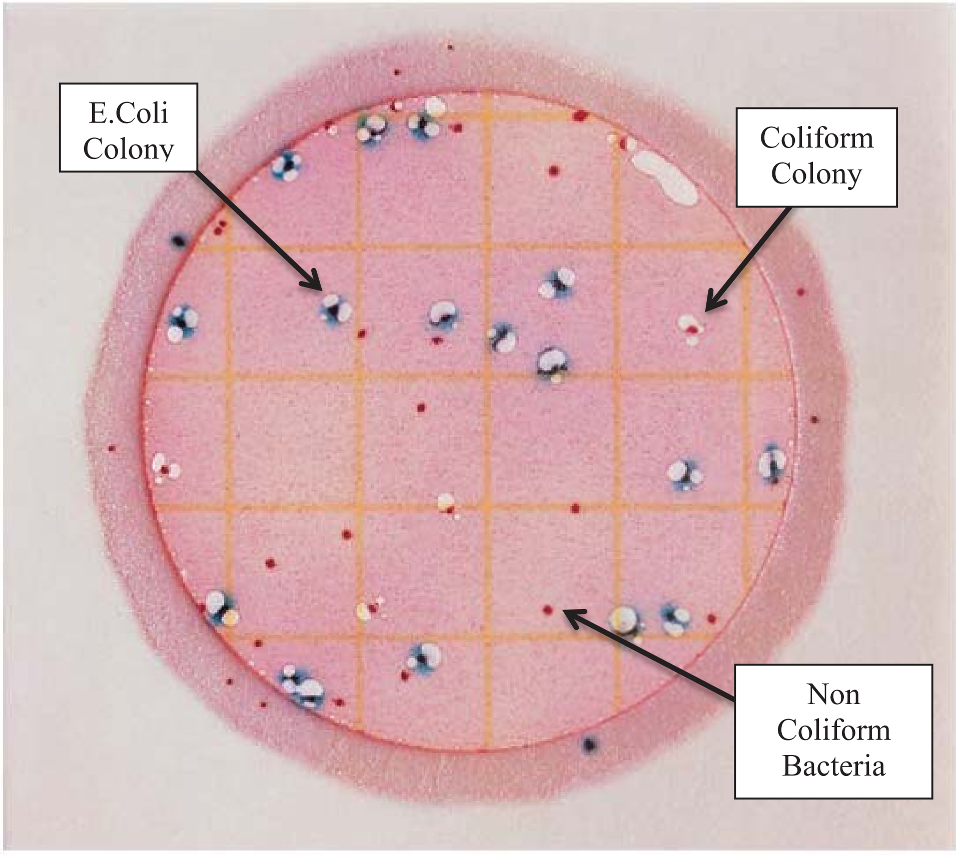
and 3.0-10 ppm. Nitrate (NO_3) was measured with a range of 0 to 50 ppm and had a variable interval of 0-0.5, 0.5-2.0, 2.0-5.0, 5.0-10, 10-20 and 20-50 ppm. Free Chlorine was measured in water systems that used chlorination for treatment using Sensafe™ test-strips with a range of 0.0 to 6.0 ppm and a variable interval of 0.0-0.05, 0.05-0.1, 0.1-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.2, 1.2-1.5, 1.5-2.0, 2.0-2.5, 2.5-4.0 and 4.0-6.0 ppm. Total Metals testing included Sensafe™ test-strips that detect trace levels of heavy metals in water. This test included Copper, Lead, Cobalt, Nickel, Zinc, Cadmium and Mercury. Detection levels ranged from 0 to 1000 micrograms per milliliter (ppb) with an interval of 0-10, 10-20, 20-50, 50-100, 100-200, 200-400 and 400-1000 ppb.

Wherein, the results of any water quality testing are below the detection limits of the analytical method, Non-Detect (ND) values are reported in the field notes. Ongoing debate within the environmental water resources community exists with respect to the analysis and reporting of water quality results which is below the detection limit of a test method (Hertz, 2017). Wherein a particular analytical result is below the detection limit, environmental scientists are forced to report the results in one of three ways. Reporting Non-Detect or "ND" values is the most common way to communicate results below a particular limit, however this prevents the ability to report averages and compare results within a particular scenario. Another option is to use the Substitution Method which entails substituting the detection limit itself or a zero value for the result. Using this approach however, has the potential to incorrectly report results where zero-values would lower averages and detection-values would raise averages (Cohen and Ryan, 1989). Within the water supply regulatory community, a modified substitution method has emerged where one-half of the detection limit is substituted for ND values (Hertz, 2017). This option provides scientists with the needed resolution of data for comparing while simultaneously avoiding over or underestimating the results. This study employs the modified substitution method when reporting ND values and uses one-half of the detection limit value for each analytical test with the understanding that raw data with a one-half ND value is actually a non-detect result.

Microbial testing employed a combination of Petrifilm™, Pathoscreen™, and a Compartment Bag Test™ (CBT) to measure Total Coliform and Escherichia Coliform. All microbial tests required transporting the samples from the field to a central location where a temporary field laboratory with incubation was set up for processing samples and analyzing results. The field lab depended on site specific conditions and was commonly located in a local municipal office, the local water-sanitation committee or the implementing NGO partner’s office. Preparation of the field lab included identifying a dedicated place to store samples and maintain notes, cleaning any work surfaces with soap and water and setting up the incubator.

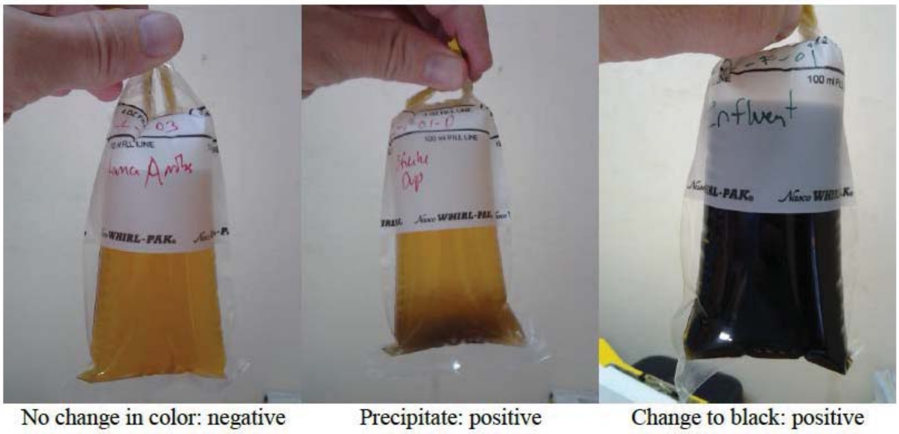
Petrifilm™ tests were conducted using the manufacturers recommended procedures. A dedicated pipette was used to remove 1ml of water from the sample bag and was spread onto a petrifilm plate that was labeled with the sample location details. The petrifilm plate was then placed in the incubator which was pre-heated to 37 degrees Celcius (ºC) for 24 hours and 48 hours for Total Coliform and E.coli respectively. After 24 hours, the film was removed from incubation and the Total Coliforms was determined by counting the number of colonies that were established within the plate area. Only red colonies associated with gaseous bubbles were counted as coliform forming units (CFU) and the results were recorded in terms of the volume of water applied (1 ml), resulting in a unit of CFU/ml, rather than the WHO criteria which requires 100 ml of sample. A total coliform count of up to 100 CFU/ml was possible using the direct count method and an approximation for up to 1000 CFU/ml was possible using the total inoculated area of the plate. When high numbers of colonies are present, the plate area and media cannot support the growth of colonies and petrifilm turns purple-blue with gaseous elements that consume the entire plate area. These incidents are considered to be too numerous to count (TNTC) and are recorded as such. After 48 hours, a sub-set of the red coliform colonies will change to a blue color indicating that these coliforms are Escherichia (E.coli) which is further indication of the potential for pathogenic contamination. Figure 3.4 shows an example of the CFU count for both Total Coliforms and E.coli.

Figure 3.4: Petrifilm™ plate count for Total and Escherichia Coliforms
Total Coliform Count: 25 CFU/ml, E.coli Count: 17 CFU/ml



Pathoscreen™ tests utilized a presence-absence (P/A) test for H_2S producing bacteria as an indicator of coliform contamination. Where pathoscreen tests were conducted, a dedicated sample bag was used to prevent cross contamination during processing. The dedicated Whirlpak sample bag was opened and the sample was collected using the above-mentioned methods. In order to facilitate the analysis process immediately, the P/A media was added to the sample during collection and the sample was transported at ambient temperature (approximately 27 ºC). The sample were then stored in the field lab for 48 hours where ambient temperatures were used to incubate the samples, prior to analysis. In order to ensure that the samples were incubated within the designated range of temperatures (25 to 30 ºC, as defined by DOC316.53.01197, Method 8506), ambient temperatures were measured using a barometric pressure transducer located within the vicinity of the sample storage area. With a detection limit of 1 CFU/100ml, the presence of coliform contamination was determined based on a change of color in the sample from a yellow to black within a 48 hour period. A blackish-brown precipitate in the sample was another indication of H_2S producing bacteria which was also used to determine the presence of coliform. Figure 3.5 shows an example of Pathoscreen samples using this method.

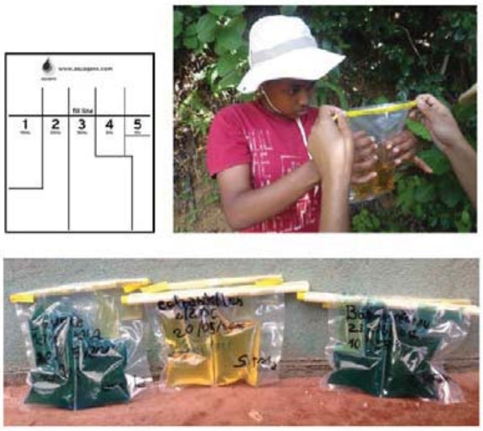
Figure 3.5: Presence-Absence of H_2S Producing Bacteria (Photos by Hunt, 2015)



The CBT uses the Most Probably Number (MPN) method to determine the amount of Escherichia Coliform in a 100 ml sample. This test allows for incubation in ambient air, if temperatures are above 25 ºC for longer than 25 hours during the testing period. Incubation periods for the test range from 24 hours at 35 ºC to 48 hours at 25 ºC and are dependent on ambient air temperatures (AquaGenX, 2015). During the sampling process, 100 ml of water was collected in a Wirlpak™ bag as previously described and a chromogenic growth media was added and dissolved in the sample. The sample was then poured into the compartment bag which separates the water into five compartments of different volumes (1 ml, 3 ml, 10 ml, 30 ml and 56 ml). The CBT bag was sealed and incubated in ambient air for 24 to 48 hours and the results were recorded based on the manufacturer's provided chart for measuring E.coli. Figure 3.6 shows the chart used to determine the MPN of E.coli and also includes some examples to clarify the process. From this Figure, it can be seen that two colors are present for each compartment, Yellow or Blue. Yellow indicates the absence of E.coli in that sample volume and Blue indicates the presence of E.coli in that sample volume. In addition to this, the 95% confidence interval is also shown along with a Risk

Category that is based on WHO Guidelines for Drinking Water Quality for Safe, Probably Safe, Possibly Safe, Possibly Unsafe, Probably Unsafe and Unsafe.

Figure 3.6: Aqua GenX CBT Analysis Guideline for MPN of E.Coli per 100 ml of water (Photo by Bogardus, 2016)



Compartment #					MPN/100mL	Upper 95% Confidence Interval/100mL	Health Risk Category Based on MPN and Confidence Interval
1 10mL	2 30mL	3 56mL	4 3mL	5 1mL			
					0.0	2.87	Low Risk/Safe
					1.0	5.14	Intermediate Risk/ Probably Safe
					1.0	4.74	
					1.1	5.16	
					1.2	5.64	
					1.5	7.81	
					2.0	6.32	
					2.1	6.85	
					2.1	6.64	
					2.4	7.81	
					2.4	8.12	
					2.6	8.51	
					3.2	8.38	
					3.7	9.70	
					3.1	11.36	Intermediate Risk/ Possibly Safe
					3.2	11.82	
					3.4	12.53	
					3.9	10.43	
					4.0	10.94	
					4.7	22.75	
					5.2	14.73	
					5.4	12.93	
					5.6	17.14	
					5.8	16.87	
					8.4	21.19	
					9.1	37.04	
					9.6	37.68	
					13.6	83.06	High Risk/Possibly Unsafe
					17.1	56.35	
					32.6	145.55	High Risk/Probably Unsafe
					48.3	351.91	
					>100	9435.10	Unsafe

3.1.4 Sustainability Indicators and Participatory Methods

This research used a series of meetings and workshops to inform the research plan and include local knowledge in the data collection and analysis process. Initial meetings with local officials included the project partners in both Nicaragua and Madagascar and were conducted to coordinate field activities, present preliminary research plans and discuss project site locations. Workshops were then conducted to bring together local leaders involved in the management of water supply services.

In Nicaragua the initial workshop brought together local leaders involved in community-managed water systems. This workshop included a two-day training to introduce the research project, provide an overview of pressure transducers and water testing procedures, create diagrams of the water system, discuss technical issues, and plan site visits for installation and water testing. In Madagascar, where the systems are privately managed, the initial workshop brought together company owners who employ local staff that are involved in water utility management. This workshop occurred over a one-day period and was intended to introduce the research project and provide an overview of the use of pressure transducers and water testing procedures, as well as discuss technical challenges and plan site visits.

After the planning session, site visits were conducted where further discussion included some of the same information from the workshop but, with an audience at the community level. Initial community meetings in both Nicaragua and Madagascar, included local water operators, community leaders, the research partner organization, and in some cases, municipal officials. These initial meetings were also used to finalize the plan and further discuss technical issues related to the water system including discussions about the local management structure for the system. In addition to workshops and meetings, follow up site visits for data collection and water sampling provided opportunities to discuss available data and preliminary results with the local management team to ensure that any anomalies were identified and explained. These follow up visits also included semi-structured interviews as described in Section 3.2.5, below.

During the implementation phase of the research, a second workshop was conducted to discuss sustainability issues related to the management of water resources. This workshop used a modified Delphi method, which is a tool created to establish consensus amongst a group of experts on complex issues (Brown et. al, 1969; Linstone & Turoff, 1975). Key elements of successfully utilizing the Delphi method include; participation of qualified experts, a common question or questions, iterative discussions to share opinions, confirmation and validation of opinions, an opportunity to change opinions, and individual anonymity (Pill, 1975; Rowe & Wright, 1999; Robson, 2011). In cases where this method is used to measure consensus, a ranking process is employed using the mean rank, to prioritize and score opinions about the issue being discussed (Schmidt, 1997; Pare et al., 2013). In this study, the information collected during these workshops was used to inform the direction of the research and to provide the participants with an opportunity to share and exchange ideas.

In Nicaragua, a total of 40 participants attended the second workshop representing experts on local water management issues based on the criteria that experts mush possess specialized knowledge in the subject area (Glaser & Laudel, 2009). In this case, the workshop included water committee presidents, treasurers, secretaries, community coordinators and committee members. The members were divided into 6 different groups representing their individual roles in the committee in order to establish relative anonymity. In Madagascar, 48 participants attended the Delphi workshop and included owners of private companies involved in utility management, government officials at the national level and local NGO representation from organizations working in the water sector. The following schedule of activities was used to facilitate group discussions using a common question and iterative discussion techniques.

- Introduction: At the beginning of the workshop, a general introduction was given along with an overview of the objective for the workshop, which was to discuss and prioritize sustainability challenges related to water supply infrastructure. In addition to this, the workshop participants introduced themselves and briefly presented their motivation for participating in the workshop.
- Initial Discussion: A generic diagram of the STEEP framework was used to introduce the different categories of sustainability and to facilitate an open discussion about technical challenges related to managing water infrastructure.

- Identifying Sustainability Indicators: After the initial discussion, the participants were asked to create a list of factors that influence the sustainability of their water systems. The question that was presented was: What are the most important elements to having a sustainable water supply system? The participants were instructed to discuss the question and make a list of their group's response to the question. A representative from the group presented their group's response to the general audience.
- Consolidation: After the group presentations, the responses were reviewed, common themes were identified, and the group's responses were consolidated into a single list representing the entire workshop. The final list of responses was then presented to the participants at the beginning of Day 2 and included a total of 11 sustainability factors from the workshop in Nicaragua and 15 factors for the workshop in Madagascar.
- Verification: At the beginning of the second day, the final list of factors was presented to the audience to verify that each group's opinion was represented. A short discussion followed to allow for the participants to identify their opinions within the consolidated list and to confirm that no other factors needed to be added to the final list.
- Prioritizing Sustainability Indicators: After the sustainability indicators were finalized, each group was asked to independently rank the factors in order of most important to least important. After the ranking, each group presented their independent assessment to synthesize the information with the entire workshop.
- Ranking: Based on each group's prioritized assessment, the mean ranking was determined using a spreadsheet and the list was sorted from highest to lowest.
- Reporting and Verification: The final step in the process was to report the results to the participants and allow for any discussion that would warrant a change in the ranking with the option of moving any item up or down one rank. This step was only used to foster further discussion and to ensure that the participants could to clarify and/or justify any opinions (Robson, 2011). In both cases, no changes were made to the final evaluation of sustainability indicators but a rich discussion was had and consensus was established.

Some important differences between the workshops in Nicaragua and Madagascar should be noted. Whereas, both workshops followed the same general process described above, the audience and the purpose for bringing the participants together was different. In Nicaragua, the purpose was primarily to share results and to facilitate the Delphi technique with water committee members at a local level. In Madagascar, the workshop was initially organized by the implementing partner and ultimately, the national government saw it as an opportunity to discuss water issues on a national level. As a result, the audience was less grassroots and water operators were not present. Nonetheless, the workshop presented a unique opportunity to facilitate discussion and the results were equally as valuable in terms of better understanding water sustainability issues and informing the overall research study.

Finally, a third Delphi activity was facilitated during the 39th WEDC International Conference as capacity building workshop. This workshop was composed of 12 participants from an NGO and academic audience and was conducted primarily for the purposes of demonstrating the Delphi Technique as a tool for facilitating community development. An additional activity was included in this workshop to initiate discussions on how sustainability factors influence each other as well as how they influence the performance of water supply infrastructure. This activity became the basis for understanding non-linear relationships between sustainability factors and how system dynamics can be used as a tool for analysis of sustainability influences.

Whereas, the results of these discussions were not directly integrated into the analysis of either the performance characterization or the strength of management study, they were useful in understanding the overall sustainability issues related to management of water infrastructure. In this sense, these methods are being included here to help further the long-term objectives of the study and to better facilitate synthesis of results and next steps presented in the conclusions. In addition to discussing sustainability issues, these workshops were used to present data that was collected during site visits and share preliminary results on the system performance. Site specific system performance characteristics were distributed to each water management team and preliminary results from the first round of data collection on water quantity and water quality were presented to the entire audience.

3.1.5 Semi-structure Interviews and Surveys

As a result of the participatory nature of the study, the research plan evolved differently with each partner in Nicaragua and Madagascar. In Nicaragua a questionnaire was developed, based on prior experience in the project area that included input from the local partner, local municipal officials and other water sector professionals. Appendix D shows the surveys used for assessing the strength of management in Nicaragua. Survey data was collected on the structure of the water committee, the legal status, coordination of meetings and financial management. In addition to this, other information was collected about the water supply system itself, including service availability, operation and maintenance and availability of parts.

In Madagascar, the interviews and surveys considered issues at both the national and local level and, as a result, the methods included bilateral perspectives from a number of different stakeholders. The surveys used, combined two models; the Sustainable Index Tool (USAID, 2013) and STEEP (Ermilio, 2014; Hunt, 2015; Bogardus, 2016). Appendix D shows the survey that was developed for the study in Madagascar. These questions were broken into categories based on the following; Social, Technical, Environmental, Economic and Political factors. In addition, background information regarding the technical aspects of the system was collected using the surveys.

In both Nicaragua and Madagascar, data collection included local staff members who were recruited and trained to implement the surveys. During site visits, the research team arranged a meeting with the local management, further explained the research study and received consent prior to data collection. The survey was implemented over a one-hour period in either the local water office or in the individual's homes depending on the nature of the site. Technical details were also reviewed and, in most cases,, the survey concluded with an open-ended discussion about technical issues related to the performance of the system. These discussions continued in a semi-structured manner during an inspection of the water system wherein, the local management would elaborate on technical issues related to the system in what would commonly be called a sanitary inspection.

3.1.6 Customer Satisfaction Surveys

Discrete customer satisfaction (CS) surveys were conducted at the household level and were used to triangulate and validate the results of the strength of management and technical performance characteristics. These surveys were implemented at the household level where customer satisfaction surveys were evaluated with respect to water quantity, water quality and water management. These surveys used a technique for measuring attitudes employing a 1 to 5 (strongly disagree – strongly agree) scale commonly referred to as a Likert scale (Likert, 1932; Wuensch, 2015). In Nicaragua the surveys were implemented at 5 locations: El Guabo, El Naranjo, Puerto Viejo, Dipinia Esperanza and Ausberto Paladino; and in Madagascar the surveys were implemented in 4 locations: Ikongo, Manompana, Tolongoina and Mananara.

In both countries, a stratified random sampling approach was taken by mapping the water systems and identifying sectors, or neighborhoods. In order to ensure that the information was representative of the entire system, the research team randomly selected at least two households in each sector prior to completing the customer satisfaction survey. The research team approached the identified home and asked permission to include their household in a study on the water supply infrastructure in the community. Prior to conducting the survey, the participant gave consent and were informed that the information provided would be confidential. Households were very receptive to the survey with a response rate of 99.0% total of in Nicaragua where 70 surveys were completed and a response rate of 93.6% in Madagascar where 141 surveys were completed.

Figure 3.7 shows an example of how the customer satisfaction surveys were implemented which included using a site map to identify sectors within the water system and a survey questionnaire. In order to determine the total sample size (n) for each location, an iterative approach was employed, taking an initial sample of 5 households and calculating a sample standard deviation (S). Based on an acceptable margin of error (MOE) of 10%, the sample size was calculated using a student t-value of 1.96 allowing for a 95% Confidence Level. After the initial round of sampling, additional surveys were completed with new estimations of the population standard deviation of customer satisfaction, until the actual MOE in the overall survey results was below 10 percent. Equation 3.1 shows the calculation for the MOE. Where, the results of the surveys (1 to 5 scale) equates to a 4-point numerical system for customer satisfaction, the MOE analysis was converted to a percent score by dividing the results by four, the total available points.

Equation 3.1: $$MOE = t \times \frac{S}{4 \times \sqrt{n}}$$

In the example shown here for the El Naranjo system, 550 connections existed during the time of the investigation and initial household surveys showed a sample standard deviation of 0.82 for the three survey questions on water quantity, water quality and water management. Using the above equation, an estimated sample size (n) was calculated and the iterative process began with multiple rounds of customer satisfaction survey sampling until the margin of error was within 10%. Table 3.2 shows the results of the calculated sample size values, along with the actual number of CS surveys completed during the study. It is important to consideration the purpose of the survey when determining the overall acceptable error within the study. In this regard, it was decided that a 10% error was sufficient (Bernhart, 2015), in that the purpose of the survey was to validate analytical metrics for monitoring system performance and not as a primary means of measuring performance. Where the actual sample size (n) is less than the calculated value, the iterations of E occurred more quickly and where actual is greater than calculated, E values converged more slowly. In some cases, additional sampling of CS was collected at the request of the local water operators and were included in the study.

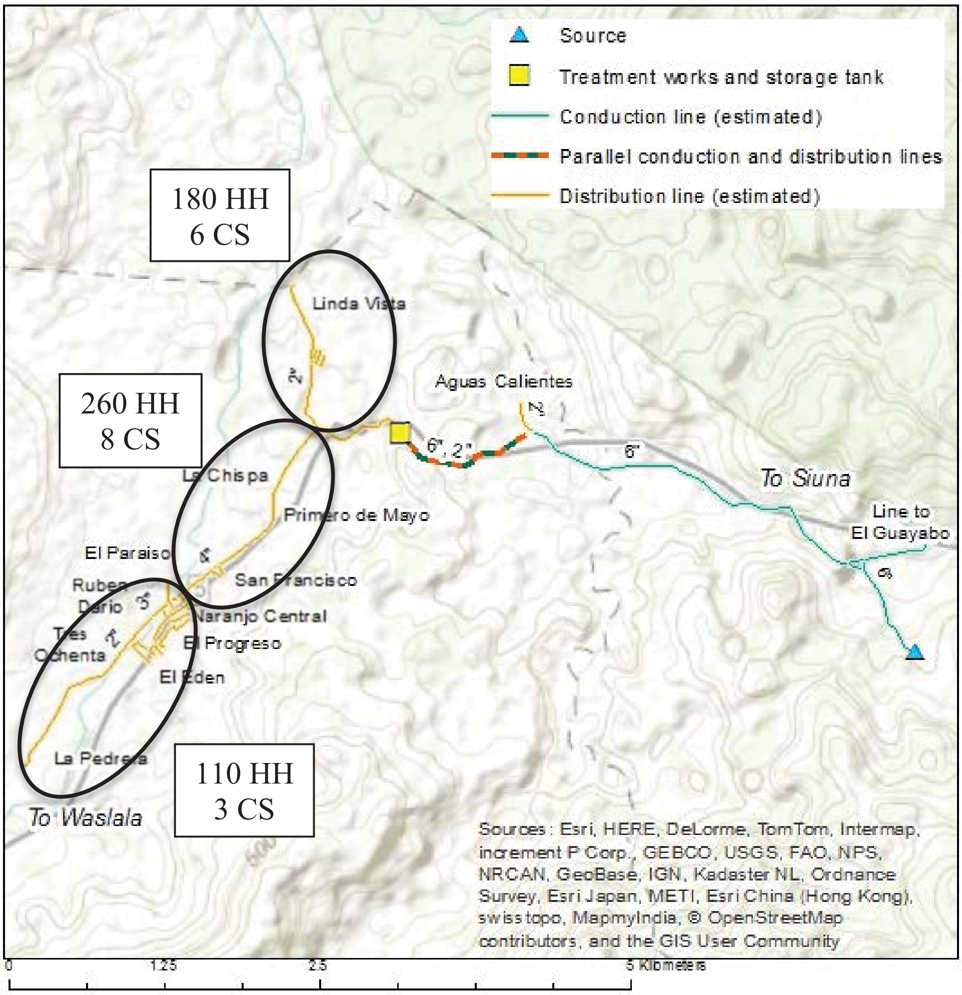
Whereas, the mechanism for household customers to evaluate the reliability, availability and quality of the water is clear, customer satisfaction in terms of the overall water management is not. In order to address potential discrepancies, an open-ended question about how to improve the management of the system was included as a qualitative assessment of management. At the same time, customer awareness of water management is rural schemes is generally higher than in urban systems because of the communal nature of rural towns and a history of failed water systems. Nonetheless, the Customer Satisfaction Tool has subjective limitations and the reliability of the data might prevent its use as a primary measure of performance without other mechanisms to ensure data validity. Further exploration of variance between the CS categories suggests that on average, the results of water management varied more (S=0.72) than quality (S=0.69) and quantity (S=0.69).

Table 3.3: Sample Size Approximation for Customer Satisfaction Surveys

Community	Standard Deviation	Calculated n	Actual n
El Naranjo	0.82	16.1	17
Puerto Viejo	0.73	12.7	19
El Guabo	0.72	12.3	10
Dipina Esp.	0.33	2.6	10
Anivorano Est.	0.30	2.1	12
Ikongo*	0.75	13.3	38
Mananara	0.58	8.0	24
Tolongoina*	0.61	8.9	38

Note: "*" identifies sites where additional CS surveys were completed at the request of the local operators.

Figure 3.7: Household Customer Satisfaction Survey in Nicaragua



The following questions were asked during the household CS survey.

In your opinion, how would you classify the quantity and reliability of the water in your house?

1 ☹☹	2 ☹	3 😐	4 ☺	5 ☺☺
Very Bad	Bad	Okay	Good	Very Good

In your opinion, how would you classify the quality and taste of the water in your house?

1 ☹☹	2 ☹	3 😐	4 ☺	5 ☺☺
Very Bad	Bad	Okay	Good	Very Good

In your opinion, how would you classify the management of the water system in the community?

1 ☹☹	2 ☹	3 😐	4 ☺	5 ☺☺
Very Bad	Bad	Okay	Good	Very Good

In your opinion, how can the management of the water system be improved?

3.2 Data Analysis and Evaluation Criteria

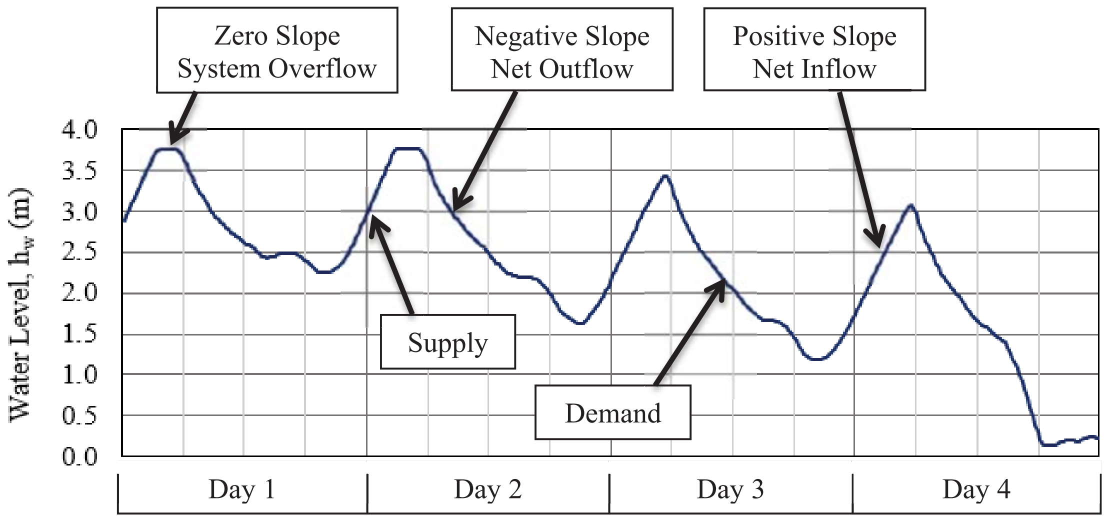
This section provides details about the evaluation criteria used for analyzing and interpreting the results of the study. The methods used to analyze Water Quantity are described in Section 3.2.1 with results in Chapter 4 and employed a number of different criteria including investigations of supply and demand, system reliability and per-capita availability of water. The analysis of Water Quality is detailed in Section 3.2.2 with results provided in Chapter 5, and included compliance with WHO guidelines for microbial, physical and chemical constituents. Strength of Management (Section 3.2.3 and Chapter 6) was evaluated by creating composite scores for different variables and ranking the systems to compare performance characteristics for sites in Nicaragua. In Madagascar, the Strength of Management was evaluated using a series of presence/absence tests of different management indicators.

3.2.1 Water Quantity Performance – Reliability and Availability

The continuous monitoring of water levels in storage tanks provided a unique opportunity to evaluate several different conditions within the water supply system. The storage capacity of the system was monitored given the geometry of the tank and the water level (height) at any given time. Water supply through the intake system was measured based on the rate that the tank filled during periods of low or zero demand, and the water demand was evaluated based on the rate of water leaving the tank at certain times. In addition to this, the system reliability was evaluated based on tank empty conditions where water levels fell below a predefined threshold of the 25% full condition. In this sense, it is being hypothesized that access to water within the distribution system is not sufficient during tank empty conditions.

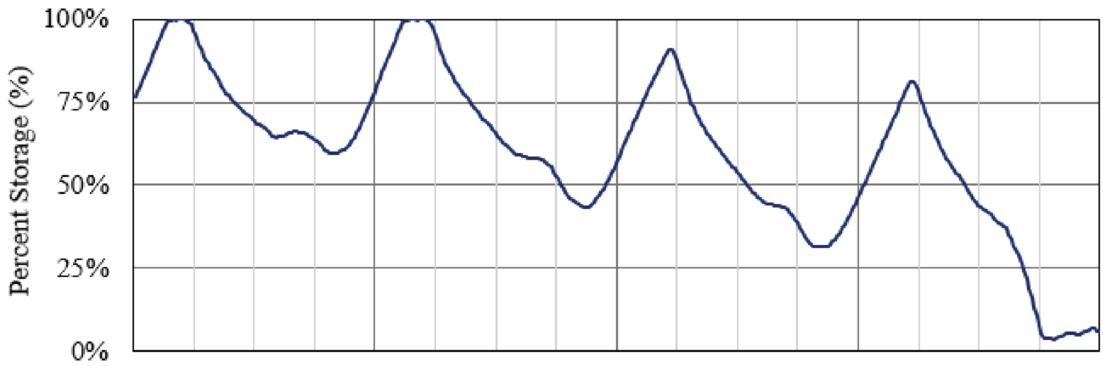
Figure 3.8 shows an example of the data used to measure the system capacity, based on a four-day period for the Mananara system in Madagascar. The first step in this process was to upload the data into a spreadsheet program and isolate the period being investigated. Data for this study was consolidated monthly in order to better identify seasonal trends and the results were reported as monthly averages to better inform local management of performance characteristics. The next step was to plot the water level data and conduct a cursory review to ensure that there are no anomalies that would require correction. In some cases, if the transducer was removed during the data collection, unusual spikes in the data would warrant removing sections of the data prior to analysis.

Figure 3.8: Example Water Depth - Mananara, Madagascar



An analysis of reliability was completed to provide daily resolution on system performance characteristics with the justification that performance monitoring is needed to better inform local water management and ensure long-term sustainability. In order to complete the analysis of system reliability, the data was converted from water levels into a percent storage volume, by calculating the ratio of the current water level for each time step by the maximum water level in the dataset. Figure 3.9 shows example water level data for the system in Mananara after it was converted to percent storage volume. The percent-storage data was then used to determine the system reliability by identifying the periods of time when the water levels were below 25% full, defined here as tank-empty conditions (PE25). Table 3.3 shows a partial data set and demonstrates the PE25 method used to calculate system reliability. The first data point in this table has a water depth of 1.083 meters which is 28.7% of the maximum water depth of 3.767 meters. Since this value is greater than 25%, the system is given a 100% reliability score for this time step as the analysis assumes that the customers have access to water within the distribution system when the tank is not empty. When the water level gets to 0.914 meters, the percent available storage is less than 25% and the system gets a 0% reliability score. By averaging all of the scores for the 24-hour period the daily system reliability is determined which was 68% in this example which equates to the percentage of time that the system was not empty.

Figure 3.9: Example Percent Storage - Mananara, Madagascar



Another measurement of water quantity performance was the overall per-capita availability of water in the system in terms of liters per person per day (L/p/d). Two factors accumulate to determine the overall water availability; system storage and system supply flowrate. The per-capita available storage was determined by converting the percent volume into liters and dividing by the total number of people being served by the system. The average available storage shown in Table 3.3, is the volume of water per person per day in the storage tank during the 24 hour period. In this example, 1.803 meters of water in storage equates to 50,430 liters (tank area of 46.6 m^2) which served a total of 10,835 people or, 4.65 liters per person at that moment. The average available storage shows the total average for that entire day which equates to 6.5 liters per person per day.

Table 3.4: Example - Determining System Reliability and Availability in Storage

	Raw Data			PE-25 Method		Storage Availability	
		Sensor Pres(A) 30ft SN#: 386356	Percent Available Storage		Average Daily	Per Capita Availability Storage	Average Availability Storage
Day	Date and Time	Depth (m)	(%)	1-PE25	1-PE25	(L/p/d)	(L/p/d)
19	11/19/2015 15:58	1.083	28.7%	100%	68%	4.65	6.5
19	11/19/2015 16:13	1.005	26.7%	100%	68%	4.32	6.5
19	11/19/2015 16:28	0.914	24.3%	0%	68%	3.93	6.5
19	11/19/2015 16:43	0.823	21.8%	0%	68%	3.54	6.5

To determine the total water available in the system, the volume available in storage was added to the amount of water entering the system, in the form of inflow. Inflow or supply flow rate was measured by converting the water levels into net flowrates by multiplying the change in water depth by the footprint area of the storage tank and dividing by the time step. Table 3.4 shows an example of how the water levels are converted into a calculated system inflow. To identify inflow and outflow, positive and negative values are isolated numerically using an "if" function. Positive values are identified as net "IN" flow and negative values are identified as net "OUT" flows. Calculated System Inflow was determined by averaging two flowrate calculations during the 24-hour period for each day. The maximum daily inflow is the largest change in water level during a single time step, and the minimum inflow is defined as the average of all positive flowrates for the entire day. The calculated daily inflow, supply flowrate into the tank was defined as the average between the maximum and minimum potential inflow for that period. This is further demonstrated in Table 3.4 where, the net flow changes from positive to negative at approximately 5:30AM when peak demand would be expected on the system. The maximum inflow during this day was 3.518 liters/sec and the average inflow was 2.179 liters/sec. As a result, the Calculated System Inflow in this example was approximated as 2.849 liters/sec for this day. It is important to note that this analysis assumes that there is at least one 15-minute period when the outflow or demand on the system is equal to zero.

Table 3.5: Example - Determining Daily System Inflow

	Raw Data		Instantanious Flowrate Calculations				Daily Flowrate Calculations		
Day	Date and Time	Sensor Pres(A) 30ft SN#: 386356 Depth (m)	delta h (m)	15-min Flowrate (liters/sec)	15-min Flowrate (IN) (liters/sec)	15-min Flowrate (OUT) (liters/sec)	Maximum Daily Inflow (L/s)	Average Daily Inflow (L/s)	Calculated System Inflow (L/s)
19	11/19/2015 4:58	3.013	0.062	3.208	3.208		3.518	2.179	2.849
19	11/19/2015 5:13	3.057	0.044	2.277	2.277		3.518	2.179	2.849
19	11/19/2015 5:28	3.065	0.008	0.414	0.414		3.518	2.179	2.849
19	11/19/2015 5:43	3.035	-0.03	-1.552		-1.552	3.518	2.179	2.849
19	11/19/2015 5:58	2.964	-0.071	-3.673		-3.673	3.518	2.179	2.849
19	11/19/2015 6:13	2.87	-0.094	-4.863		-4.863	3.518	2.179	2.849

Maximum of all Positive Flow (IN) = Maximum Daily Inflow

Table 3.5 shows an example of the analysis which includes water availability in terms of storage and inflow. The total available water in the system is equal to the Average

Availability in Storage and the Calculated System Inflow converted to liters per person per day. An important variable to account for when determining the total availability of water in the system is periods of time when the storage tank is overflowing. In order to account for these periods of time when inflow to the system is overflowing the tank and not actually available for consumption, a threshold of 95% full was used to turn off the Calculated System Inflow analysis, which has not been highlighted through this example.

Table 3.6: Example – Determining Total Water Availability

	Raw Data		Performance Characteristics			Total Water Availability	
		Sensor		Average	Calculated	Instantanious	Average
		Pres(A) 30ft	Average	Availability	System	Availability	Availability
		SN#: 386356	Daily	Storage	Inflow	Storage & Inflow	Storage & Inflow
Day	Date and Time	Depth (m)	1-PE25	(L/p/d)	(L/s)	(L/p/d)	(L/p/d)
19	11/19/2015 4:58	3.013	68%	6.5	2.85	35.7	29.2
19	11/19/2015 5:13	3.057	68%	6.5	2.85	35.9	29.2
19	11/19/2015 5:28	3.065	68%	6.5	2.85	35.9	29.2
19	11/19/2015 5:43	3.035	68%	6.5	2.85	35.8	29.2
19	11/19/2015 5:58	2.964	68%	6.5	2.85	35.5	29.2
19	11/19/2015 6:13	2.87	68%	6.5	2.85	35.0	29.2

In the example shown here at 4:58 AM on 11/19/15, the average instantaneous water available was 35.7 liters per person and the average water available for the entire day was 29.2 liters per person. To interpret these results in general terms, daily and monthly summaries are calculated. In this sense, the daily results from the above example would suggest that there was an average of 29.2 L/p/d available in the system and that the reliability of the system for that day was 68 percent. To compare system performance characteristics, sustainable access is defined as the system reliability multiplied by the total availability. This meaning that the sustainable access to water on 11/19/15 day was 68% of 29.2 L/p/d, or 19.9 liters per person.

Table 3.6 shows an example of analysis for peak demand on the system. The same procedures were followed for calculating inflow with one exception. Since the decline in water level represents a measurement of rate of change in volume at the tank, conservation of mass needs to be included to determine the actual flowrate exiting the system. Equation 3.2 shows this relationship and thus the flowrate exiting the tank must include flow into the system during that period. Whereas, this principal would also apply for determining flow into the system, the inflow calculations assume that there is a period of time when flow existing the tank is equal to zero and thus the measurement of change in volume is an actual measurement of inflow. In the example shown here, the Calculated System Inflow was 2.85 liters/sec and the Calculated Peak Demand (System Outflow) was -7.37 liters/sec. The Peak Factor was then calculated by taking the absolute value of the ratio of these two values.

Equation 3.2: $$Qout = Qin - \left(\frac{\Delta V}{\Delta t}\right)$$

Note: Where $Q_{out} = 0$ liters/sec, $Q_{in} = \Delta V / \Delta t$.

Table 3.7: Example Data set for determining System Outflow and Peak Demand

	Raw Data		Performance Characteristics			Daily Flowrate Calculations			
		Sensor			Calculated	Maximum	Average	Calculated	
		Pres(A) 30ft	15-min	15-min	System	Daily	Daily	System	Peak Factor
		SN#: 386356	Flowrate	Flowrate (OUT)	Inflow	Outflow	Outflow	Outflow	(Qout/Qin)
Day	Date and Time	Depth (m)	(liters/sec)	(liters/sec)	(L/s)	(L/s)	(L/s)	(L/s)	(--)
19	11/19/2015 4:58	3.013	3.208		2.849	-6.467	-2.577	-7.371	2.59
19	11/19/2015 5:13	3.057	2.277		2.849	-6.467	-2.577	-7.371	2.59
19	11/19/2015 5:28	3.065	0.414		2.849	-6.467	-2.577	-7.371	2.59
19	11/19/2015 5:43	3.035	-1.552	-1.552	2.849	-6.467	-2.577	-7.371	2.59
19	11/19/2015 5:58	2.964	-3.673	-3.673	2.849	-6.467	-2.577	-7.371	2.59
19	11/19/2015 6:13	2.87	-4.863	-4.863	2.849	-6.467	-2.577	-7.371	2.59

The final step in the analysis is to summarize the data into a monthly performance evaluation score. To evaluate each system, daily plots of per-capita water availability (Storage and Inflow) were summarized monthly. Figure 3.10 shows an example of a monthly per-capita water availability highlighting the example on November 19th. In addition to this, summary tables showing statistical results for monthly performance characteristics were created to simplify a comparative analysis of systems. Table 3.7 shows an example of a monthly summary where Water Level Data, System Reliability, Inflow and Outflow Data as well as Water Availability and Sustainable Access Scores are characterized.

Figure 3.10: Example – Monthly Summary of Per-capita Water Availability

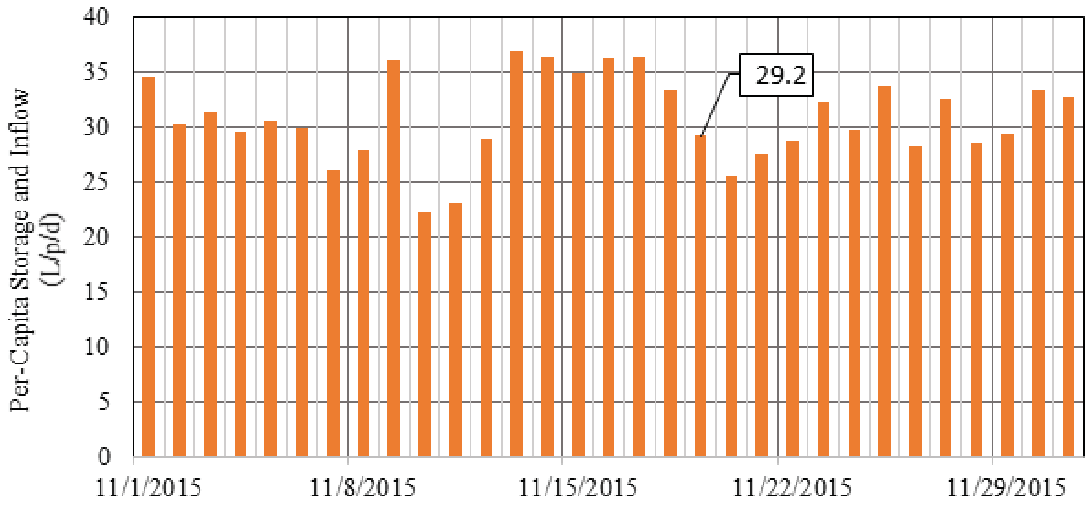


Table 3.8: Example – Monthly System Performance Characteristics

Monthly Summary

Water Level Data		
Average	2.14	m
Maximum	3.79	m
Minimum	0.13	m
Median	2.20	m
StDEV	0.99	m

System Reliability	
Average	86.3%
Maximum	100.0%
Minimum	42.7%
Median	100.0%
StDEV	19.6%

Inflow Data		
Average	2.70	L/sec
Maximum	3.42	L/sec
Minimum	0.76	L/sec
Median	2.78	L/sec
StDEV	0.61	L/sec

Outflow Data		
Average	-5.74	L/sec
Maximum	-1.35	L/sec
Minimum	-7.37	L/sec
Median	-6.07	L/sec
StDEV	1.34	L/sec

Water Availability		
Average	30.7	L/p/d
Maximum	42.0	L/p/d
Minimum	20.83	L/p/d
Median	31.0	L/p/d
StDEV	5.0	L/p/d

Performance Evaluation		
Water Level	2.14	m
Inflow	2.70	L/sec
Outflow	-5.74	L/sec
Availability	30.72	L/p/d
Reliability	86.3%	

Sustainable Access		
Score	26.5	L/p/d

The overall system performance was determined by creating a composite score that averaged the overall reliability and the percentage of days that per-capita availability thresholds were met. Using per-capita thresholds of 20, 50 and 80 liters/person/day, the percentage of days that each system provided the prescribed amounts was determined. Percent duration curves were created to show these results graphically. The various performance characteristics were then plotted against customer satisfaction scores of water quantity performance to explore the different relationships and to validate the results.

In addition to customer satisfaction surveys, further validation was conducted by investigating the theoretical capacity of the systems and by comparing the per-capita availability with daily consumption measured from household water meter readings. In terms of the theoretical capacity of the system, the energy equation, along with system specific site parameters was used to determine the theoretical flowrate capacity of the intake system. Equation 3.2 was used to calculated theoretical capacity of the intake system and compare the theoretical results with the measured inflow data using the water level data. This equation is based on the Bernoulli Equation and pressure loss using the Darcy-Weisbach Equation. All systems used plastic pipe, either High Density Polyethylene (HDPE) or Poly Vinyl Chloride (PVC) and the analysis assumed a constant pipe roughness coefficient of 1.52×10^{-6} (m) and a constant temperature of 25 degrees Celsius with a kinematic viscosity of 1.00×10^{-6} (m^2/s). Text Box 3.1 shows an example of how this analysis was used to determine the theoretical capacity of the system. Table 3.8 provides a summary of the variables used to evaluate the system performance in terms of water quantity and includes the nomenclature and units used in the analysis.

Equation 3.2: $$Qc = \left(\frac{\pi^2 * g * \Delta z * D^5}{8 * f * L}\right)^{\frac{1}{2}}$$

The investigation of per-capita consumption at the household level was completed to further validate the results of water availability. Where customer satisfaction surveys were completed, water meter readings provided approximations of per-capita daily consumption. The theoretical results were then compared with actual results of per-capita availability of water to ensure that system performance monitoring using pressure transducers is an accurate tool for measuring the actual performance of the system.

Text Box 3.1: Determining the theoretical capacity of the intake system

Site Location: Mananara, Madagascar

Intake System: Source to Treatment Tank
Length: L = 1072 meters
Change in Elevation: Δz = 64 meters
Pipe Diameter: D = 2 ½ -in HDPE, (Inside Diameter, ID = 0.0814 m)

$$Qc = \left(\frac{\pi^2 * g * \Delta z * D^5}{8 * f * L}\right)^{\frac{1}{2}} \qquad Qc = \left(\frac{\pi^2 * g * 64 * (0.0814)^5}{8 * 0.0157 * 1072}\right)^{\frac{1}{2}}$$

$Qc = 0.0013$ m^3/s $\qquad$ $Qc = 12.9$ l/s

Intake System: Treatment to Storage

In many systems, different pipe diameters were used for the intake pipe. In these cases, a composite pipe diameter (Dc) was calculated using the below equation (Jones, 2010):

L = 1230 meters of 125 DN Pipe (ID = 0.116 m)
L = 5150 meters of 80 DN Pipe (ID = 0.0814 m)
L = 1580 meters of 60 DN Pipe (ID = 0.0678 m)

$$Dc = \left(\frac{La}{L} * \left(Da^{-\frac{19}{4}} - Db^{-\frac{19}{4}}\right) + Db^{-\frac{19}{4}}\right)^{-\frac{4}{19}}$$

$$Dc = 0.0791\ m$$

$$Qc = \left(\frac{\pi^2 * g * \Delta z * D^5}{8 * f * L}\right)^{\frac{1}{2}} \qquad Qc = \left(\frac{\pi^2 * g * 103 * (0.0791)^5}{8 * 0.0186 * 7960}\right)^{\frac{1}{2}}$$

$Qc = 0.0052$ m^3/s $\qquad$ $Qc = 5.22$ l/s

System Capacity: $\qquad$ $Qc = 5.22$ l/s

Note: This analysis is only intended to evaluate the theoretical capacity of the intake system itself and not the capacity of the source flowrate. Wherein the source flowrate is greater than the intake system capacity, the intake system will determine the supply flowrate for the entire system. Where the source flowrate is less than the intake capacity, the source flowrate defines the overall system capacity. Where multiple atmospheric nodes exist within the intake (break pressure tanks or treatment facilities) the intake capacity is defined by the minimum. In the above example, the 5.22 l/s would define the overall intake capacity and the difference would overflow at the treatment facility. This would be an example of a poorly designed system but is not uncommon. Validation of inflows to the storage tank would only be relevant with respect to the 5.22 l/s in this case. Referencing the example from Table 3.4 shows that the measured flow rates of 2.70 and 3.42 are within the theoretical capacity of the system shown in this text box example.

Table 3.9: Variables used for the Performance Evaluation of Water Quantity

Variable	Nomenclature	Units	Notes
Watershed			Measured using Google
Basin Area	A_b	m^2	Earth™
Source Supply			
Supply Flowrate	Q_s	l/s	Measured at tank
Intake Capacity	Q_c	l/s	Theoretical
Change in Elevation	Δz	m	Transit, GPS and GE™
Pipe Diameter	D	m	Converted from inches
Intake Length	L_i	m	Transit, GPS and GE™
friction	f	--	
System Storage			
Storage Volume	V_s	m^3	Water level incline
Tank Area	A_T	m^2	Intake capacity
Tank Height	h_T	m	Measured on site
Water Level, depth	h_w	m	Pressure Transducer
Change in Water Level	Δh	m	Pressure Transducer
Time Interval	Δt	s	Pressure Transducer
Water Demand			
Peak Flow	Q_p	l/s	Maximum Outflow
Peak Factor	PF	--	Q_p / Q_s
Number of People	P	people	Reported
Per-capita Demand	Q_d	l/p/d	Measured at tank
Per-capita Consumed	Q_m	l/p/d	Metered customer
Water Level Variables			
Percent Storage	PS	%	
Daily Water Level	h_{avg}	m	
Per-capita Storage	V_{pcs}	l/p/d	
Per-capita Availability	V_{pca}	l/p/d	
System Reliability	η_{del}	%	Delivery Efficiency
Overflow	Q_{over}	l/d	
Net Inflow	Q_i	l/s	
Max Daily Inflow	Q_{imax}	l/s	
Average Daily Inflow	Q_{iavg}	l/s	
Calculated Inflow	Q_{in}	l/s	$Q_{in} = Q_s$ (supply)
Net Outflow	Q_o	l/s	
Max Daily Outflow	Q_{omax}	l/s	
Average Daily Outflow	Q_{oavg}	l/s	
Calculated Outflow	Q_{out}	l/s	$Q_{out} = Q_d$ (demand)
Monthly Summary			
Average Water Level	$h_{\underline{avg}}$	m	
Average Reliability	$\eta_{\underline{del}}$	%	Delivery Efficiency
Average Inflow	$Q_{\underline{in}}$	l/s	
Average Outflow	$Q_{\underline{out}}$	l/s	
Per-capita Availability	$V_{\underline{pca}}$	l/p/d	
Performance Evaluation	--	--	
Sustainable Access	$V_{\underline{sus}}$	l/p/d	

Note: Nomenclature is most commonly used in appendices and variable name is used in written document.

3.2.2 Water Quality Performance – Compliance Criteria

Water quality was evaluated throughout the system including household level sampling as well as source and storage tank sampling. Water quality analysis included a composite evaluation of compliance with respect to microbial, physical and chemical parameters investigated during the study. In order to be consistent with recent trends in the sector (Bartram, 2018) and WHO guidelines described in its Rapid Assessment of Drinking Water Quality Guidelines (WHO, 2012), all water quality constituents were given equal weights regardless of their classification as being primary or secondary concerns in terms of impact on health. Three different percentages are reported that include a compliance scores with microbial, physical and chemical criteria. The system performance for water quality (η_{WQ}) was determined by analyzing percent compliance with all constituents.

Table 3.9 shows the criteria used to evaluate system performance in terms of water quality characteristics. Water Quality performance was defined in terms of compliance with microbial, physical and chemical water quality and an overall water quality performance efficiency (η_{WQ}) was defined using a composite score that averaged each category. Table 3.10 shows an example of a system performance evaluation for water quality. In this example, 35 samples were taken from a system with 8 water quality parameters investigated for a total of 280 tests. From the 280 tests, 63 failed to meet one of the WHO standards for water quality and thus 76.8% of the tests passed. Whereas, it may appear that this simplistic approach can provide a reasonable approximation of system performance for water quality, the distribution of parameters investigated was not proportional and thus artificially creates a weighted average during the analysis. In other words, 25% of the samples tested were microbial, 50% were physical and 25% were chemical. This essentially means that physical parameters were given twice the weight in the overall compliance as compared to microbial and chemical factors for this example.

Since each of the sites investigated during this study had different water testing plans, it was not possible to ensure that this distribution of testing within each category was proportional. As a result, the methods used to evaluate water quality performance delineated the results for each category and then averaged the compliance score to establish an overall performance efficiency. In the example shown in Table 3.10, 72.9% would represent the overall water quality compliance characteristics for the system.

Table 3.10: Water Quality Compliance Criteria

	Parameter	Criteria	Units
Microbial	Total Coliforms	< 10	CFU/100ml
	Escherichia Coliform (E.Coli)	< 1	CFU/100ml
Physical	Total Dissolved Solids (TDS)	< 500	mg/l
	Conductivity	< 200	uS/cm
	Total Hardness	< 3	mg/L
	pH	6.0 to 8.0	--
Chemical	Nitrate	< 50	mg/L
	Nitrite	< 3	mg/L
	Total Metals	< 8.0	µg/L
	Residual Chlorine	1.5 to 5.0	mg/L

Note: 1 mg/L = 1 ppm and 1 µg/L = 1 ppb.

Table 3.11: Example – Water Quality Compliance Evaluation, η_{WQ}

	Microbial	Physical	Chemical	Total
n	70	140	70	280
Pass	21	124	70	215
Fail	47	16	0	63
% Compliance	30.0%	88.6%	100%	76.8%

Water Quality Compliance	
η_{WQ}	72.9%

3.2.3 Strength of Management Analysis

Initial surveys identified Sustainability Indicators using the STEEP framework. From these indicators, direct influences, within the control of the local water utility management team, were isolated for the purposes of analyzing Strength of Management (SoM). Since the process of data collection included input from the local partners, the interviews and surveys were unique for each country. Whereas, the variables and indicators were based on literature, workshops and discussions with water professionals, SoM is not based on management theory and the use of this tool is entirely exploratory. Five SoM variables were identified with sub-indicators for each; Human Resources, System Administration, Operation and Maintenance, Asset Management and Financial Management.

In Madagascar, the survey design was based on the Sustainable Index Tool (SIT, USAID, 2015) and questions evaluated the presence/absence of sub-indicators. Table 3.11 shows the variables, indicators and sub-indicators used to evaluate SoM for the systems in Madagascar. The analysis of SoM included a percent SoM score that was based on an average of each SoM category as shown in Equation 3.3. Indicator scores were determined using a percentage, based on the presence of sub-indicators.

Eq. 3.3: $$SoM = \frac{1}{5} \times \left(\frac{\sum HR}{n} + \frac{\sum OM}{n} + \frac{\sum SA}{n} + \frac{\sum AM}{n} + \frac{\sum FM}{n}\right)$$

Human Resources included sub-indicators for external support, community involvement and water management personnel. Operation and Maintenance included sub-indicators for the frequency of maintenance activities associated with the source intake, storage tank and treatment systems, as well as capital maintenance, system expansion and operational communications with customers. System Administration was evaluated based evidence of reporting and record keeping in terms of customer accounts, complaints, maintenance activities, water consumption and as well as having a business plan.

Asset Management was evaluated based on initial investments into the infrastructure, office space, tools and equipment as well as watershed management initiatives. Financial Management was evaluated based on evidence of monthly income, total income, annual expenses, tax payments and overall savings. In order to prevent artificially weighing any one variable or sub-indicator, an average of the sub-indicators for each variable was used. The overall SoM score used an average of the five variables shown.

Table 3.12: Summary of SoM Categories, Indicators and Sub-indicators; Madagascar

Strength of Management Variable	Indicators	Description of sub-indicators (P/A-indicators)	Reference[1]
HR: Human Resources	Technical Support	Technical Receptions, Municipal and National Government Involvement	Moriarty, 2013; Bakalian, 2009
	Community Involvement	Local employment and participation during initial construction	Kayaga, 2013; Franceys, 1997; Delphi, 2015
	Water Utility Personnel	Management staffing, gender equity and staff training	Kayaga 2013; Franceys, 1997; Fisher, 2008;
SA: System Administration	Accounting and Reporting	Available local banking, bookkeeping, reporting to local authorities	VU, 2014; SIT, 2015
	Strategic Planning	Contracts and records, business planning	Sansom & Coates, 2011; SIT, 2015
	Billing and Records	O&M records, billing and receipts, water consumption records	Baietti et. al., 2006; VU, 2014; SIT, 2015
OM: Operations and Maintenance	Source, Storage and Treatment	Maintenance frequency, water treatment stages and water testing	SIT, 2015; Sansom & Coates, 2011; WELL, 1998; SIT, 2015
	Capital Maintenance and System Expansion	Initial capital investments, growth rate, programs to support new connections	WELL, 1998; Moriarty, 2010 SIT, 2015
	Customer Communications	Customer survey on complaints, information sharing about maintenance	Sansom and Coates, 2011; Delphi, 2015
AM: Asset Management	Capital Investments and Infrastructure	Records of initial construction, PPP contributions, growth	Sansom & Coates, 2011; Harvey and Reed, 2006
	Office, Supplies, Tools and Equipment	Office equipment, electronic records, warehousing of parts	Oyo, 2002; Iyer, 2006; SIT, 2015
	Watershed Management	Stakeholder engagement, livestock and agricultural activity, regulations	Delphi, 2015; Howard & Bartram, 2010
FM: Financial Management	Monthly Income	Evidence of monthly income and records	Schouten, 2003; RWSN, 2010
	Total Income	Evidence of annual income and records	Bakalian & Wakeman, 2009
	Savings	Records of tax payment, expenses and savings	SIT, 2015

1. Delphi, 2015 and VU, 2014 – See Section 3.1.4 for details on methodology.

In Nicaragua, the SoM analysis was based on the same five variables, however the results were monetized with respect to per-capita investments into the water supply infrastructure. Table 3.12 shows indicators used within each SoM variable, along with a description of the monetized per-capita analysis. Each variable was monetized by calculating time and money spent managing the system and was normalized using the range of results to establish a percent value. Figures are reported in US$ using an exchange rate of 26.6 Cordoba per US$ (Hunt, 2014) and volunteer time was monetized based on opportunity cost using 2013 per-capita GDP which equates to approximately $5.00 USD daily (World Bank, 2017).

Investments in Human Resources were determined based on the number of committee members, the number of committee meetings annually, the number of assembly meetings and the election frequency of committee members. Investments in Operation and Maintenance were monetized using the cleaning frequency of the source intake, storage tank and treatment system as well as capital investments for large repairs. System Administration was monetized using the actual operational expenses associated with managing the system including payment of administrative staff, payment to local operators and plumbers, as well as repairs and other overhead expenses.

Asset Management investments were evaluated based on the presence/absence of an office space, storage space for supplies, tools and equipment, land ownership and watershed management. These assets were monetized equally across all sites within the area wherein partner organizations were aware of the typical value for office space and land. Financial Management was evaluated based on records of actual savings with or without interest depending on banking in the area. The total available savings was adjusted for the age of the system and an annual savings was determined. For all the SoM variables in Nicaragua, the total monetized values were adjusted for per-capita values by dividing the investments by the total number of customers being served by the system.

Table 3.13: Summary of SoM Variables; Nicaragua

SoM Variable	Indicators	Description (Monetized Per-capita)	Reference[1]
HR: Human Resources	Committee Members (n)	Number of volunteer members	Mukherjee, 2003; VU, 2014; Delphi, 2015
	Days Annually (d)	Time spent in committee meetings, assemblies and other community engagement.	VU, 2014; Delphi, 2015
	HR Investment Annual: A Per-capita: B_{HR}	Monetized Investments in HR $A = (n \times d) \times (\$5/p/d)$ $B_{HR} = A / (\text{No. Customers})$	VU, 2014; Delphi, 2015
SA: System Administration	Annual Staff Salary: S	Payments to water management staff	VU, 2014; Delphi, 2015; WEDC, 2016; WELL, 1998
	Annual Expenses: E_{SA}	Administrative expenses for office and system management.	VU, 2014; Delphi, 2015
	SA Investment Per-capita: B_{SA}	Monetized Investment in SA Per-capita Amount $B_{SA} = S + E$	Baietti et. al., 2006; VU, 2014
OM: Operations and Maintenance	Annual Person – Days (p x d)	Maintenance frequency, sources, tanks and water treatment and testing	Sansom & Coates, 2011; WELL, 1998; Delphi, 2015
	Annual Expenses: E_{OM}	O&M Expenses; supplies, parts etc.	VU, 2014; WEDC, 2016; Delphi, 2015
	OM Investments: B_{OM}	Monetized Investments in OM Per-capita Amount $B_{OM} = (p \times d \times \$5/p/d) + E_{OM}$	Sansom and Coates, 2011; Delphi, 2015
AM: Asset Management	Office and Storage: O+S	Estimated value - rated at equivalent cost of renting space: $50 monthly.	Lockwood, 2002; SIT; 2015
	Supplies, Tools and Equipment: T+E	Estimated value - rated at equivalent cost of renting equipment: $5 monthly.	Oyo, 2002; Iyer, 2006; Sugden, 2013; SIT, 2015
	Land Ownership: Mz	Source and Watershed – estimated value rated at $50 per Mz[1] and prorated for 20 years.	Delphi, 2015;
	AM Investments: B_{AM}	Monetized Investments in AM Per-capita Amount $B_{AM} = \$50(O+S) + \$5(T+E) + \$50(Mz)$	VU, 2014
FM: Financial Management	Savings: S	Amount in Savings	Schouten, 2003; RWSN, 2010; Sugden, 2003

	Bank Accounts	Presence of accounts with 4% applied interest.	VU, 2014; Delphi; 2015
	FM Investments: B_{FM}	Monetized Investments in FM Per-capita Amount $B_{FM} = S+0.4(S)$	VU, 2014

1. Delphi, 2015 and VU, 2014 – See Section 3.1.4 for details on methodology.

In both Nicaragua and Madagascar, a second measurement was employed to evaluate SoM as compared to the Income Potential (IP) of the systems investigated. In this sense, identifying highly functioning management with little resources in terms of income or revenue from water fees could delineate optimal SoM characteristics when compared with those with larger revenue streams. In addition, systems that had poorly functioning management with higher revenue were important to identify, in that these systems could be wasting resources. In Nicaragua, Income Potential was based on the number of connections and the minimum monthly fees charged to customers. In Madagascar, Income Potential was measured based on the type of revenue stream for the water utility in that different connection types had different payment structures, and the reported annual income from the most recent year on record. In both cases, the Income Potential used the total number of customers on the system to analyze the results on an annual per-capita basis. The results were normalized to a percent score based on the maximum Income Potential value within each country, prior to any comparative analysis.

3.2.4 System Performance Classification and Comparative Analysis

To compare the different systems and identify trends in performance, two classification metrics were used. Within each of the three system performance variables; water quantity, water quality and strength of management, initial classification used percent thresholds to delineate performance characteristics using a numeric type (1 through 5). In addition to this, within each performance variable, quadrant plots were used to further classify system to delineate achievement using an alphabetic classification (A through D).

The percent threshold classifications used a difference of 10%, to be consistent with common thresholds used to evaluate performance. Table 3.13 shows these classifications with associated qualitative assessments. High performance systems (Type-1) are those that scored 90.0% and above which are also described as being very good or excellent. Systems that performed less than 60% (Type-5) are classified as being Low or very poor performance with a range of performance in between using the 10% threshold as shown, with performance scores were rounded to the nearest tenth.

Table 3.14: System Performance Classification Thresholds

Percent Performance Threshold	Classification Type	Qualitative Assessment
90.0 – 100 %	Type – 1	High Performance Very Good
80.0 – 89.9 %	Type – 2	Good Performance
70.0 – 79.9 %	Type – 3	Okay Performance
60.0 – 69.9 %	Type – 4	Poor Performance
< 60.0 %	Type – 5	Low Performance Very Poor

Quadrant plots were used to evaluate and compare systems based on achievement. In this regard, each performance variable had unique criteria. Table 3.14 shows the system performance classifications using the alphabetic quadrant evaluation. In terms of water quantity, systems were classified based on achieving percent reliability and water availability thresholds. In terms of water quality, systems were classified based on percent compliance with source and distributed water quality. In terms of water management, systems were classified based on the percent thresholds for strength of management (SoM) and the income potential (IP) of the system.

Table 3.15: Quadrant Plot - System Performance Classification Thresholds

System Performance Variable	Classification	Threshold	Qualitative Assessment
Water Quantity	Class A	> 50 l/p/d and > 80%	System is providing a reliable supply of sufficient volumes
	Class B	< 50 l/p/d and > 80%	System is providing a reliable supply of minimum basic needs
	Class C	> 50 l/p/d and < 80%	System is providing un-reliable supply of sufficient volumes
	Class D	< 50 l/p/d and < 80%	System is providing un-reliable supply of low volumes
Water Quality	Class A	Source < 80% Distribution > 80%	Poor source water quality is improving as it moves through the system
	Class B	Source > 80% Distribution > 80%	Good source water quality is being maintained as it moves through the system
	Class C	Source < 80% Distribution < 80%	Poor source water quality is not improving as it moves through the system
	Class D	Source > 80% Distribution < 80%	Good source water quality is declining as it moves through the system
Water Management	Class A	SoM > 80% IP < 80%	High management capacity is beyond the income potential capacity of the system
	Class B	SoM > 80% IP > 80%	High management capacity is equivalent to income potential of the system
	Class C	SoM < 80% IP < 80%	Low management capacity and low income potential.
	Class D	SoM < 80% IP > 80%	Low management capacity and high income potential.

Prior to completing a comparative analysis that included an exploration of relationships between performance variables, a common unit of analysis was needed. Whereas, the performance metrics used for water quantity and water quality were common for all the systems investigated in Madagascar and Nicaragua; the SoM analysis within each country was unique. As a result, the different tests had to be normalized to a percent score and then calibrated to each other, using a common point of analysis. Since, each of the SoM variables (HR, SA, OM, AM, and FM) in Madagascar were evaluated on a percent basis, the most direct means of creating a common point of analysis was to normalize the results in both Madagascar and Nicaragua to represent a percent score based on the maximum value within the data set for each category. After normalizing the results within each SoM category, the total SoM score was calculated using an average of the individually normalized indicators values.

Upon completion of a normalization process, content validity for the different SoM tests was investigated. To address the difference in content for each test, the results needed to be calibrated with each other, through data transformation prior to any additional comparative analyses. The data transformation process included a graphical approach where the SoM results for both sites were plotted against a common point of analysis, where Customer Satisfaction surveys, maintained content validity. Wherein the test of SoM showed significantly different results for both countries, the average difference was used to calibrate the tests to each other while maintaining variability in the results. After transforming the SoM results through this calibration process, the SoM test used in Nicaragua was used for a single site in Madagascar to investigate the accuracy of the overall transformation. This process is further discussed in Chapter 6.3.3: Validation and Transformation of SoM Results.

3.2.5 Exploratory Analysis: Univariate and Multivariate Relationships

An exploration of the relationships between the different performance characteristics and the strength of management variables was completed using univariate and multivariate statistical analysis. Statistical analysis was completed using Microsoft™ Excel, Data Analysis Toolpak. SoM variables were isolated as independent variables against water quantity and water quality performance characteristics. Univariate linear regression used a graphical approach to investigate Pearson Correlation Coefficients between overall SoM, reliability of services, water availability and distributed water quality compliance.

Multivariate linear regression investigated each SoM variable against the different water quantity and water quality performance characteristics. Multivariate models were then created to predict various performance characteristics to further explore the potential for SoM to categorize water infrastructure performance.

Further exploration of results included an investigation into the probability that similarity existed between SoM, Water Quantity and Water Quality characteristics based on the quadrant categories was investigated. Various threshold SoM values were used to further explore these relationships and to identify management influences on water quantity and water quality performance. Throughout the statistical analysis, student-t values were used to validate the results in terms of probability that the null-hypothesis was true.

3.3 Reliability and Validity

Reliability and validity of system performance was ensured through triangulation. The reliability of the results with respect to water quantity was ensured using high precision instrumentation[1] that was calibrated onsite during installation. Water quantity results were validated using customer satisfaction surveys as well as through triangulation between consumption records from the water utility management team and theoretical analysis of system capacity. Reliability with respect to water quality was ensured through duplicate sampling and standard laboratory QA/AC protocol. The results were validated through customer satisfaction surveys and physical site inspections.

Reliability and validity with respect to the semi-structured interviews with the water utility management teams was more challenging to confirm because of inter-cultural communication issues as well as subjectivity during data collection and analysis. To ensure the reliability of data, local research assistants who were familiar with the local context were trained and oriented prior to data collection. Surveys were translated into Spanish, French and Malagasy to ensure that information and data collection was communicated clearly. Finally, the results were validated through customer satisfaction surveys and by reviewing preliminary results with the local water management teams during workshops and site visits.

1. In-situ Rugged Troll™ pressure transducer calibration reports are available upon request.

3.4 Research Ethics

This study uses an integrated approach to implement and report ethical issues related to the research study. Whereas, local stakeholders (customers and managers) were involved in the data collection, the subject of the research study was the management of water infrastructure. As a result, it was determined that this research does not fit into the definition of Human Subject Research, which is regulated by Title 45 Public Welfare, Part 46 Protection of Human Subjects criteria (VU IRB, 2016). Despite this, several precautions were taken in order to protect the confidentiality of the participants and ultimately ensure the ethical integrity of the research.

The research partners voluntarily participated in the study. In order to ensure that the research study had applications that were relevant to the local partners as well as the local water utility management teams, a participatory approach was used during the planning and design phase. As a result, the research initiative included input from the local project partner throughout the process except for data analysis and interpretation of results. Prior to data collection at workshops, semi-structured interviews and household surveys, the participants were informed about the research and were given an opportunity to decline participation. Informed consent was either collected in writing or verbally and the anonymity of the participants has been protected entirely throughout the reporting and documentation of the study. An interesting observation about the informed consent process was that some household voluntarily participated but preferred to withhold signing an informed consent and the official nature of signing a waiver appeared to be culturally inappropriate in some situations.

Whereas, this study has included a five-year collaboration with project partners, students, volunteers and faculty from both Villanova University and Loughborough University, the author of this study has been the principal investigator throughout this process. Being that one of the long-term objectives of this study is to better understand sustainability from a whole systems perspective, an important part of this work has been including input from academic experts as well as field practitioners and research assistants. In this sense, this study synthesizes data from different sources however being that the author has been the principal investigator, all data can be considered primary data, collected specifically for the purposes of implementing this study. All data that has been collected has been retained in a raw data format without any corrections for outliers or anomalies. Wherein any data had to be corrected or removed from the analysis, the results are reported with a technical note to the nature of the corrections. Also, where any field notes during the study suggested that an error had occurred during the data collection process, the results were reported with notes on field observations. References throughout this thesis have been used to identify observations and input from individual contributors to this work.

3.5 Chapter Summary

This applied research study investigates the performance characteristics of piped water supply in rural communities using a mixed methodology that emphasized quantitative metrics that are continuous and objective. The research design included a participatory approach by incorporating local knowledge during the planning phase and presenting results to local stakeholders throughout the implementation of the study. Data collection included three primary measurements of system performance; water quantity, water quality and water management. Water quality data was collected through the installation of pressure transducers in water storage tanks to monitor the availability and reliability of water services. Water quality data was collected via water sampling and analysis throughout the system and isolated microbial, physical and chemical parameters. Water management data was collected using semi-structured interviews and a series of presence/absence tests to determine strength of management. Triangulation and validation of results employed additional data collection through project reports, site inspections and household level customer satisfaction surveys on water quantity, quality and management. Workshops were facilitated to discuss water sustainability issues with local stakeholders and to inform the planning and implementation phases of the study.

Data analysis for water quantity included per-capita availability of water, based on storage and flowrates into the system, and the reliability of services based on incidences of tank empty conditions. Data analysis for water quality included a composite compliance score based on microbial, chemical and physical parameters. Sample results were isolated based on the location of the sample in terms of source, tank or distributed water quality.

Strength of water management was analyzed using five variables; human resources, system administration, operation and maintenance, assets and financial management. In Madagascar, SoM was evaluated using a series of presence/absence tests and in Nicaragua SoM was evaluated by ranking monetized per-capita investments into managing each system. The two different SoM tests were normalized to each other using linear transformation with customer satisfaction being the common point of analysis.

Exploratory analysis of the results included univariate and multivariate linear regression using Pearson Correlation Coefficients and scenario-based probability analysis. Data reliability and validation of the results used triangulation with respect to Quantity, Quality and Management factors with household level Customer Satisfaction results. Water quantity results were also triangulated with theoretical analysis of the capacity of the water supply systems as well as per-capita consumption based on household level water meter readings. Further validation for water quality results included an analysis of field blank and duplicate samples collected during the study. In addition to this, further validation included reviewing the results with local stakeholders. Limitations with respect to the overall methods used in this study includes subjectivity with respect to the analysis and interpretation of results. Further limitations would include making discrete and binary conclusions based on a comparative analysis, which do not consider site specific context at each location.

CHAPTER 4

RESULTS AND ANALYSIS
WATER QUANTITY

4.0 Results and Analysis: Water Quantity Performance

This chapter includes an investigation intended to address knowledge gaps related to Objective 1, with the specific purpose of identify water quantity parameters which can be used to continuously monitor the performance of piped water supply infrastructure. In addition, this chapter begins to explore knowledge gaps identified in terms of identify technical criteria to compare system performance and to better anticipate system failure, as defined in Objective 2. Furthermore, this chapter is essential to meeting the overall goal of the study, which is to explore how strength of management influences the technical performance of water supply infrastructure. In this regards, technical performance has been delineated in terms of water quantity characteristics to explore objective measurements of performance.

The results are based on the continuous monitoring of water levels within storage tanks located at seven sites in Madagascar and twelve sites in Nicaragua. The results are summarized in terms of their country location and are delineated into supply, demand and overall system performance characteristics. Contextual details are provided for three selected site location in each country and a summary of results is provided for all sites investigated. Table 4.1 shows the range of data available for each sites investigated along with notes about any missing data during the respective periods. Being that the implementation of this study has occurred over several years and included different project partners in different countries, the data collected has unique time periods for each site location. Table 4.1 also identifies the sites (*) where a context analysis has been included to provide contextual information at selected locations.

The analytical approach for evaluating water quantity performance included the continuous monitoring of storage tank water levels and delineating for positive slopes where inflow exceeds outflow, defined by net-flow into the storage tank. Figure 4.1 shows an example calculation of the methods used for analyzing inflow. In this figure, the water levels associated with inflow have been highlighted and the average and maximum slopes are shown. The average slope represents the minimum inflow, Q_{in} (min) for the day and the maximum slope represents the maximum inflow Q_{in} (max). The calculated inflow or supply (Q_s), is the average of the maximum and minimum inflows and is being used as a more conservative measurement of per-capita daily availability of water. Figure 4.2 shows an example of the analytical approach for determining the delivery efficiency or system reliability. In this example two days of data are shown where the reliability changes significantly, to highlight the importance of continuous monitoring in that reliability of services changes on a daily basis.

Table 4.1: Available Water Quantity Data – Transducer Installation Timeframe

Site Location	Start Date	Finish Date	Notes *NA – Data Not Available*
Madagascar			
Ikongo*	6/11/14	11/3/15	10/6/14 thru 11/7/14 ; NA
Tolongoina*	12/14/14	6/9/16	3/27/15 thru 4/9/16; NA
Mananara*	10/15/14	3/13/16	8/27/15 to 9/5/15; NA
Anivorano	4/1/15	5/5/16	
Andemaka	7/16/14	11/3/15	
Manompana	4/15/16	5/31/16	
Imorona	9/15/15	1/1/16	
Nicaragua			
El Guabo*	10/18/13	1/6/17	5/28/14 to 10/13/16; NA
El Naranjo*	10/30/14	1/4/17	3/1/15 to 10/10/16; NA
Puerto Viejo*	11/1/14	1/5/17	3/2/15 to 10/21/16; NA
Dipina Esp.	10/15/13	7/19/17	11/24/14 to 10/19/16; NA
Dipina Central	10/29/14	7/19/17	3/17/15 to 11/3/16; NA
Ausberto Paladino	10/15/14	7/12/17	3/3/15 to 10/21/16; NA
Los Lipes	10/24/14	2/27/16	6/23/15 to 8/23/15; NA
Molino Norte	10/24/14	2/27/16	6/23/15 to 8/23/15; NA
San Jose	11/10/14	6/22/15	
San Francisco	11/10/14	6/1/15	
El Rodeo	10/22/14	3/9/15	
La Ceiba	11/6/14	6/12/15	

Figure 4.1: Example of analytical methods used for measuring inflow

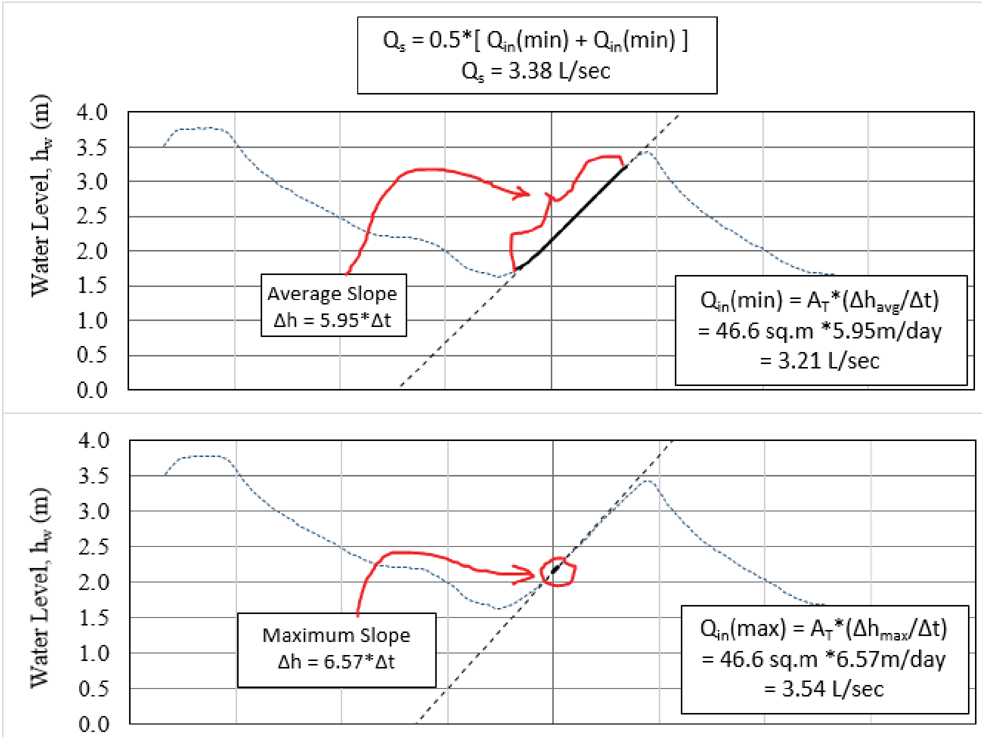
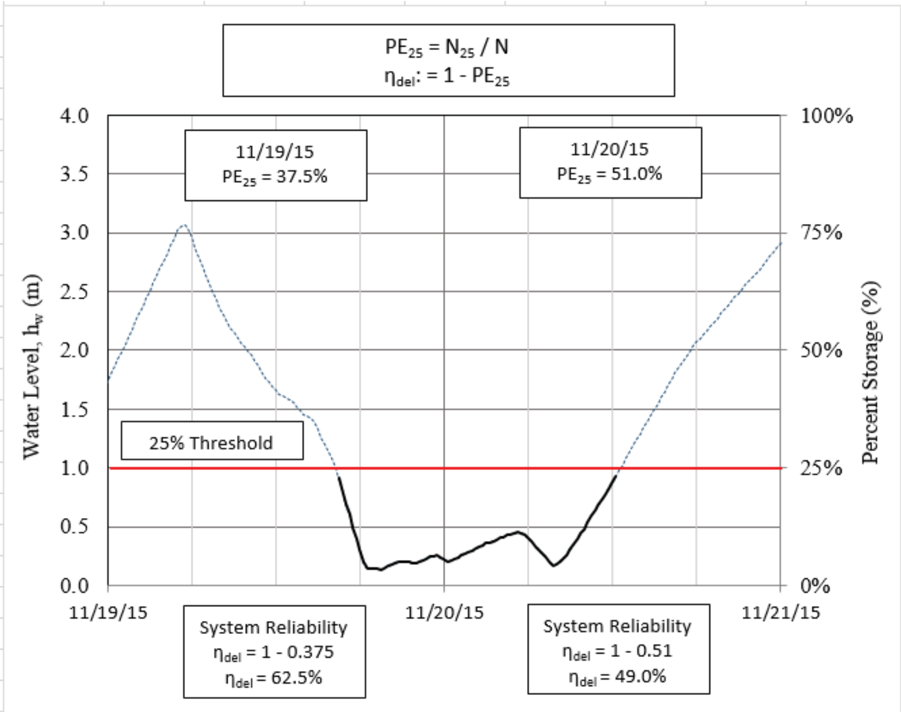


Figure 4.2: Example of analytical method to determine system reliability (PE25)



Note: N_{25} – The number of time steps where the water level was below the 25% threshold, N – the total time steps during the day or month depending on the analytical period

4.1 Context Analysis of Water Quantity Performance: Madagascar

This section provides system performance characteristics of water quantity for three selected sites in Madagascar in order to highlight the contextual details which are unique to each water system investigated. The Tolongoina evaluation demonstrates the importance of utility management wherein the results from this case study show a significant difference between the performance of the system prior to and after the initiation of a public-private partnership (PPP) management model. With 18-months of continuous monitoring, the case study in Ikongo demonstrates the seasonal variability of system performance and provides unique insight into system performance over time. The Mananara case study demonstrates the limits of system functionality wherein the growth of this system doubled during the period of the investigation.

4.1.1 Water Quantity Characteristics, Tolongoina

The continuous monitoring of water levels in Tolongoina, Madagascar has provided a unique perspective on system performance, in particularly as it relates to pre and post PPP management. The water supply and distribution system in Tolongoina was rehabilitation in September, 2014 with 157 connections serving an estimated 2000 people. System monitoring and data collection began in December of 2014 and the private management of the system began in May of 2015. As of June, 2016, the water system in Tolongoina served 2497 people with 197 connections, including both social and private connections.

Figure 4.3 shows system performance characteristics during the implementation phase of the project where the system was cycled on and off for several days. On December 14th, 2014 the 46 cubic meter storage tank was filled over night while the distribution system was closed. In the morning the distribution system was opened at 12:00PM and the tank emptied continuously until 11:00PM. During this time, the rate of water level decline allowed for an approximation of system outflow and the peak demand on the system was 4.60 liters/sec and the system provided a calculated 58.6 liters/person/day. The system remained empty for about 8 hours and on December 15th at approximately 10:00AM, the distribution system was closed again and the tank was allowed to fill. The distribution system was turned on twice during this day, once at 12:00PM for one hour, and again at 5:00PM. During this period, the system supply flowrate was determined to be 1.8 liters/sec, the peak demand on the system was 5.0 liters/sec and the total water availability was 110 liters/person/day.

The large difference in water availability from the 14th to the 15th is due to the distribution system being open for most of the day which results in no overflow in the storage tank wherein, faucets likely remained open for the entire time at the household level (as referenced in field notes). On December 16th the system was cycled on and off again and the tank filled to about 80% of its capacity before being turned back on. Without overflow, the available supply of 3.0 liters/sec resulted in 110 liters/person/day with a peak demand of 4.7 liters/sec. On December 17th, the system remained closed and the tank overflowed for most the day with the exception of a one hour period from 10:30AM to 11:30AM when the system was turned on. On December 18th the tank was overflowing from 12:00AM to 7:00AM, after which time, the system was turned on and was left open for several weeks. During the period from December 17th and beyond, the per-capita availability of water was low, in the order of 20 to 30 liters/person/day, because the tank was either overflowing or empty.

Table 4.2 shows a summary of the system performance characteristics along with the number of days included for each period of the analysis. Appendix B shows the complete monthly summaries along with descriptive statistics for the period analyzed for this system. It can be seen from this table that the reliability of the service significantly changes in April of 2016 when the system began to be managed using the Public-Private Partnership (PPP) model. Whereas, it appears that the per-capita water availability does not change significantly during this transition, it is important to note that the system supply flowrate analysis during the April, May and June 2016 period was not possible because of the water levels never fell below the 95% tank full conditions and thus by definition, the tank was overflowing throughout this three month period. A closer inspection of Appendix B.1 reveals that the unaccounted supply flowrate entering the tank (an ultimately never getting into the distribution system because of overflow) ranged from 1.5 to 4.0 liters/sec and, as a result the average daily availability during the PPP managed period should be considered minimum availability as, it is likely that some of this inflow supply was available in the distribution system.

Figure 4.3: System Performance Characteristics, Tolongoina Project Implementation

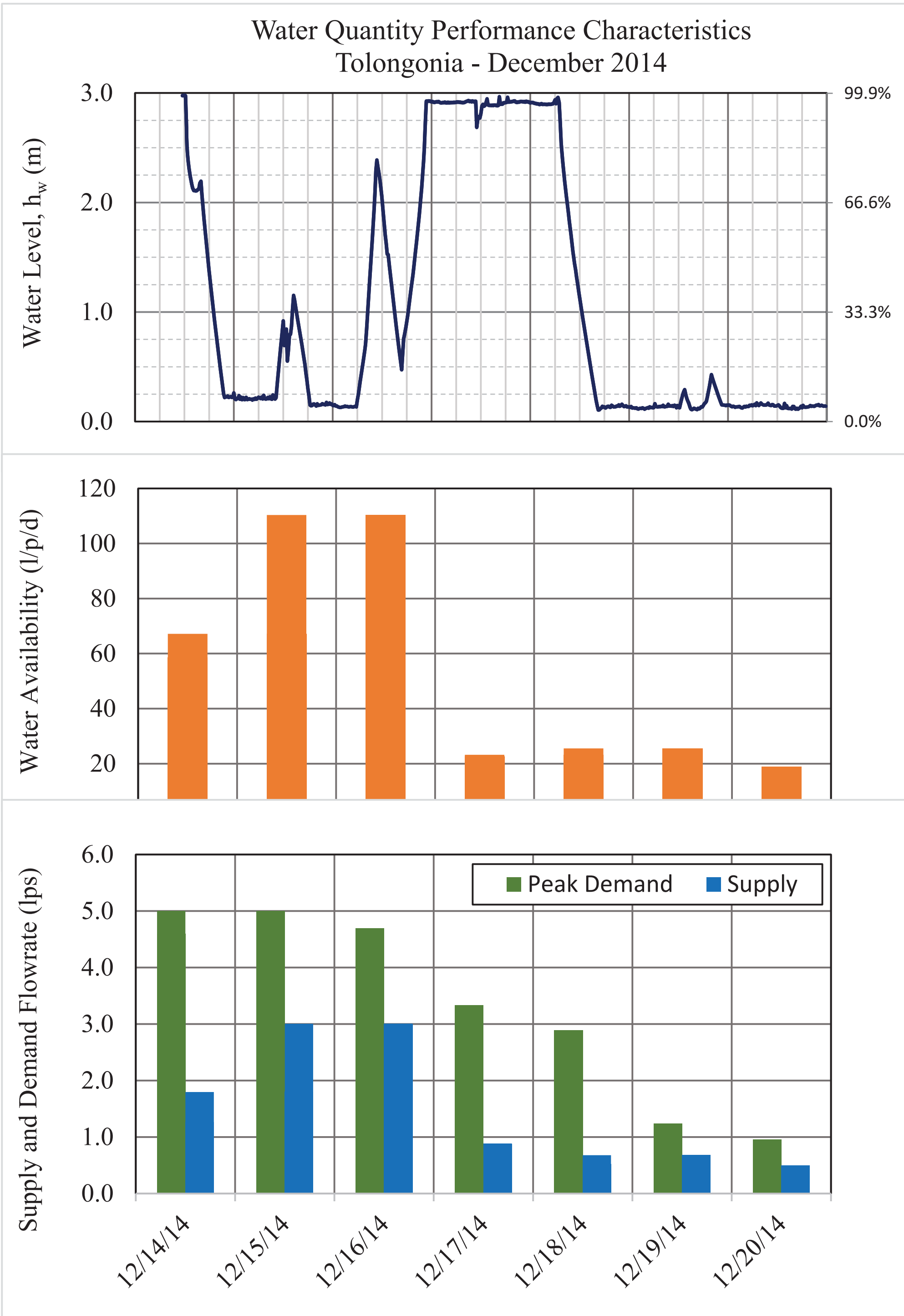


Table 4.2: Water Quantity Performance, Tolongoina, Madagascar

Month	Number of Days	System Reliability η_{del}	Average Daily Availability (L/p/d)	Sustainable Access (L/p/d)	Project Status
December 2014	18	14.4 %	29.6	4.26	System Testing Implementation
January 2015	31	0.0 %	21.9	0.0	Un-managed
February 2015	28	31.9 %	44.8	14.3	Un-managed
March 2015	27	14.4 %	40.8	5.89	Un-managed
April 2016	21	100 %	20.9	20.9	PPP Managed
May 2016	31	100 %	21.0	21.0	PPP Managed
June 2016	11	99.9 %	22.3	22.3	PPP Managed

In fact, it appears from this analysis, that the supply is always exceeding demand in the system, and that the capacity of the overall system is significantly larger than the current 2497 customers. Sustainable access, as defined by the system reliability multiplied by the availability shows an increase of 71.4% as a result of the PPP management which suggests that an essential factor with respect to the potential capacity of the system is ensuring that the utility is well managed.

Table 4.3 shows the monthly summary for supply (Q_s) and peak demand (Q_p) flowrates for this system, along with the Peak Factor (PF = Q_s/Q_p). The results from this analysis when combined with the data in Table 4.1 clearly identify the reasons that the reliability of the system has increased once the PPP management started. Whereas, the supply flowrate analysis does not change significantly during the 7 months of data collection, the peak demand on the system changes dramatically after PPP management began. This particular analysis sheds light on a conflict that exists between improving access to water and improving sustainable access to water. Whereas, prior to the system being managed, access to water on average was higher, with 34.3 L/p/d as compared to 21.4 L/p/d; the reliability of the system was substantially higher after management with 15.2% as compared to 100%. Ultimately, this increase in reliability can be attributed to the peak demand on the system decreasing after management as shown in Table 4.3 where the Peak Factor averaged 2.2 prior to PPP management and averaged 1.2 after PPP management. This increase in reliability when combined with the decrease in Peak Demand suggests that consumers began to manage their consumption, which is likely a result of the payment structure that was implemented where households were being charge based on volume of water consumed (field notes).

Table 4.3: Supply and Demand Characteristics, Tolongoina, Madagascar

Month	Supply Flowrate (lps)	Peak Demand (lps)	Peak Factor	Range of calculated daily supply and demand (lps)
December 2014	0.67	1.55	2.54	Q(in): 0.21 – 3.0 Q(out): 0.15 – 5.0
January 2015	0.50	1.12	2.24	Q(in): 0.21 – 0.79 Q(out): 0.44 – 1.91
February 2015	1.14	2.29	2.01	Q(in): 0.15 – 5.05 Q(out): 0.16 – 10.1
March 2015	0.96	1.92	2.0	Q(in): 0.48 – 5.09 Q(out): 0.92 – 9.68
April 2016	0.68	0.63	0.93	Q(in): 0.20 – 0.92 Q(out): 0.13 – 1.00
May 2016	0.80	0.78	0.98	Q(in): 0.59 – 1.10 Q(out): 0.43 – 1.09
June 2016	0.91	1.53	1.68	Q(in): 0.07 – 2.29 Q(out): 0.09 – 9.73

4.1.2 Water Quantity Characteristics, Ikongo

The continuous monitoring of water levels in Ikongo, Madagascar has provided an interesting perspective on system performance as it relates to seasonal variations in water supply, availability and reliability. This project site is unique for several reasons. Ikongo is a small rural town of approximately 7500 people and is relatively isolated. It is located in the foot hills of the Andringitra Mountain range, 90 kilometers south of the regional capital and is only accessible by a dirt road. The water supply system was rehabilitated in 2013 and provided three levels of service connections; private, social and public; with 2442 customers at that time. Since the initial system rehabilitation, the number of connections has grown by an estimated 1.8% annually and as of June 2016, the system served 2567 customers. This site is also unique as the data available includes close to 18 months of continuous information about the system performance and rain gauge data in the region align with system performance data.

Table 4.4 shows a summary of the results for the system performance characteristics during the 18 month study period. This table includes a statistical summary of the entire date set along with delineated results for rainy and dry season performance. An initial inspection of these results shows that, despite a 77.4% deviation in monthly precipitation and a 24.5% deviation in the average monthly inflow; water levels in the system (4.9% deviation), the reliability of the system (2.5% deviation) and the availability of water (12.3% deviation) show less variability within the 18 month period. In order to investigate the potential influence from seasonal variation further, the results shown in Table 4.4 were isolated by identifying performance characteristics associated with months where the precipitation was great than, and less than 15 cm. An inspection of the difference between rainy (Precip. > 15 cm) and dry (Precip. < 15 cm) season performance characteristics confirms that the environmental influences in terms of precipitation are not significantly impacting the performance characteristics of the water supply system where, a significant difference in monthly precipitation of 15.8 cm ($p=0.002$) does not correspond with a change in water levels (difference = 0.11 m, $p = 0.038$) or a change in reliability (difference = 2.23%, $p = 0.059$).

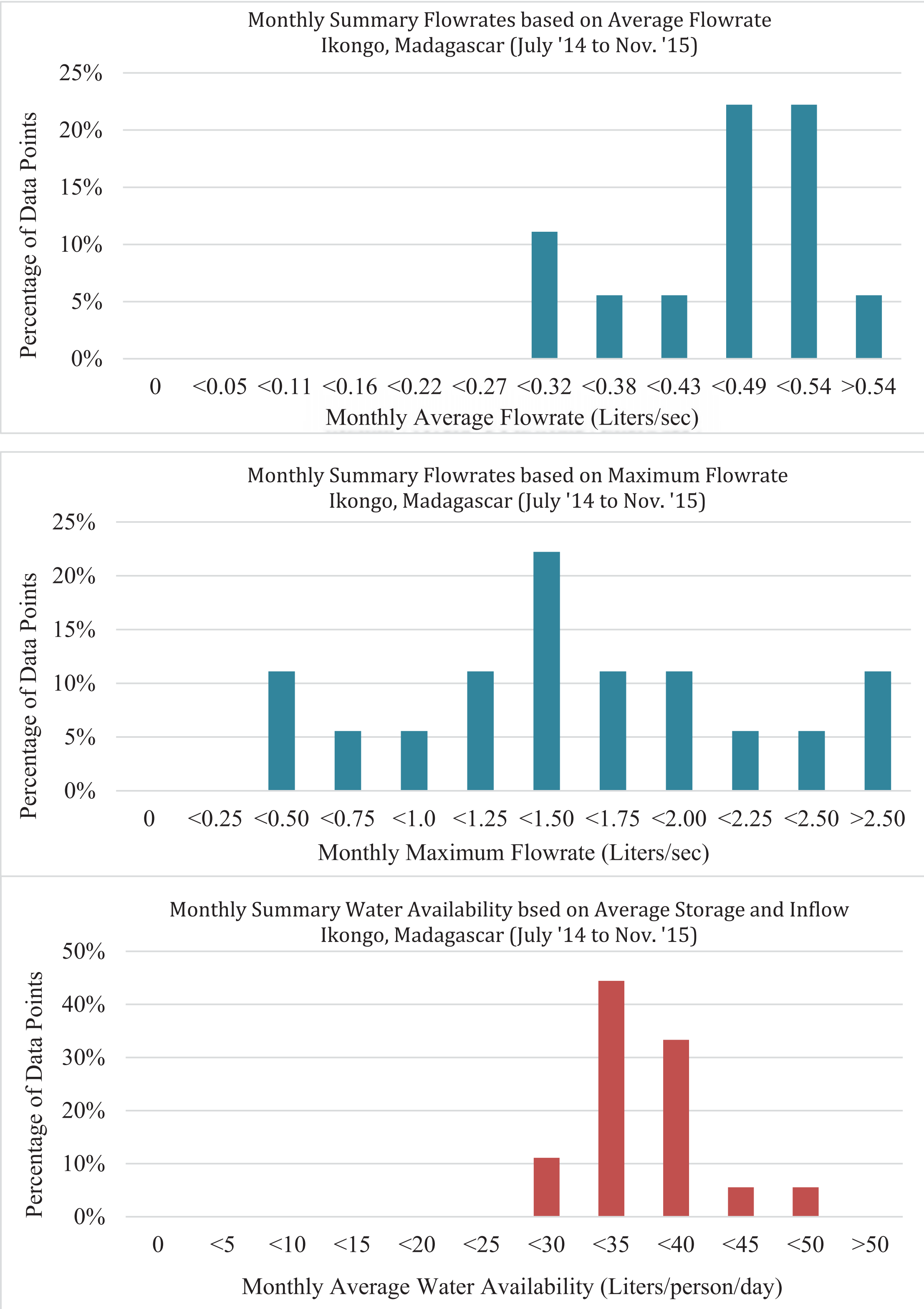
Figure 4.4 further demonstrates this by showing the data distribution for the average monthly flowrates, along with the maximum monthly flowrates and the average per-capita water availability. A review of these data, shows normal distribution for water availability wherein both the maximum and average daily flowrates do not show normal distribution. The results from the data distribution further suggests that the availability of water is not impacted by variations in supply flowrate, possibly a result of the effective management of water storage in the system.

Table 4.4: Water Quantity Performance, Ikongo, Madagascar

Month	Precip (cm)	Performance Characteristics				
		Average Daily Water Level (m)	Average Supply Flowrate (lps)	Average Peak Demand (lps)	Average Daily Availability (L/p/d)	Average System Reliability η_{del}
Jun-14	3.8	2.45	0.51	0.63	33.3	100%
Jul-14	10.3	2.22	0.75	2.03	39.4	99%
Aug-14	7.3	2.38	0.52	1.03	36.0	100%
Sep-14	5.8	2.43	0.49	1.06	46.6	100%
Oct-14	9.1	2.36	0.48	1.04	33.9	100%
Nov-14	15.5	2.27	0.62	1.15	36.6	98%
Dec-14	18.5	2.28	0.64	1.23	37.4	99%
Jan-15	51.4	2.21	0.65	1.32	38.2	95%
Feb-15	38.2	2.35	0.48	0.94	32.4	100%
Mar-15	16.1	2.33	0.51	0.97	36.5	100%
Apr-15	10.2	2.41	0.28	0.56	28.9	100%
May-15	19.0	2.44	0.42	0.87	31.5	100%
Jun-15	12.5	2.23	0.66	1.31	40.8	97%
Jul-15	11.8	2.48	0.45	0.91	32.9	100%
Aug-15	6.5	2.50	0.37	0.71	31.8	100%
Sep-15	11.7	2.51	0.29	0.58	30.0	100%
Oct-15	15.3	2.09	0.54	1.34	33.8	90%
Nov-15	11.0	2.38	0.47	0.99	32.3	100%

Comparing System Performance Characteristics – Rainy and Dry Season Results (Prec. > 15 cm) and Dry Season (Prec. < 15 cm)						
	Precip (cm)	Average Daily Water Level (m)	Average Supply Flowrate (lps)	Average Peak Demand (lps)	Average Daily Availability (L/p/d)	Average System Reliability η_{del}
Total Average	15.2	2.35	0.51	1.04	35.1	99%
Percent Deviation	77.4%	4.9%	24.5%	-33.5%	12.3%	2.5%
Rainy Season Average	9.1	2.39	0.48	-0.99	35.1	99.7%
Dry Season Average	24.8	2.28	0.55	-1.12	35.2	97.4%
Difference	-15.8	0.11	-0.07	0.13	-0.13	2.23%
P-value	0.002	0.038	0.247	0.444	0.953	0.059

Figure 4.4: Data Distribution for Monthly Flowrates and Per-Capita Availability



4.1.3 Water Quantity Characteristics, Mananara

In Mananara, the data collected for this study has been able to quantify the impact of high growth in the region wherein, the number of customers has more than doubled during the two year study period. Mananara is a district capital of approximately 16,500 people located in the northeastern coastal region of Analanjirofo. It is several days travel from the capital city of Antananarivo along a road that has been described as, the worst in the country. Despite the remote nature of the region, the town of Mananara has experienced significant economic growth resulting from global demand for vanilla which is the primary cash crop in the area. This increase in standard of living has created some complex migration patterns where the town's population can change with the agricultural calendar which has ultimately influences water demand.

The water supply infrastructure for this town was rehabilitated in 2012 during the Ranon'ala project and initially included 286 connections serving approximately 5,032 customers. System monitoring began in October, 2014 with an estimated 602 connections and 6,984 customers at that time. In May of 2016 an inspection of the water management records indicated that there were 1,158 connections with approximately 13,433 customers which equates to a 33% annual growth rate since the initial construction. As a result, Mananara is the largest system investigated in this study in terms of the total number of people being served as well as the rate of growth. In addition to this, it is the most complex system being investigated with a total of 230 cubic meters of water storage and approximately 24,000 meters of piping which includes a 10,000 meter intake and a looped distribution system.

Table 4.5 shows the system performance characteristics using the average daily results for each month. Unfortunately, two full years of data were not available at the time of the analysis and a detailed comparative analysis using annual results was not possible. Nonetheless, a quarterly summary provides enough information to complete a partial analysis using five common months, which provides some insight into the system performance over time. An initial inspection comparing the performance between the first quarter of 2015 and the first quarter of 2016, suggests that the system performance did not change significantly in terms of per-capita availability of water (42.2 l/p/d to 42.0 l/p/d) and reliability (89.8% to 86.2%). It does however appear that changes in the peak demand on the system are consistent with the increase in customers during this period and that the supply flowrate also increased to meet this additional demand. An investigation into the common monitoring periods during the study (11/1/14 to 4/1/15 and 11/1/15 to 4/1/16) shows that there has been a reduction in system delivery efficiency where the average reliability was 91.8% for the first five month period and was 76.1% during the following year. This reduction in system reliability has, however been accompanied by an increase in availability (38.4 l/p/d to 41.5 l/p/d) and thus the overall sustainable access has not decreased (34.9 l/p/d to 31.6 l/p/d).

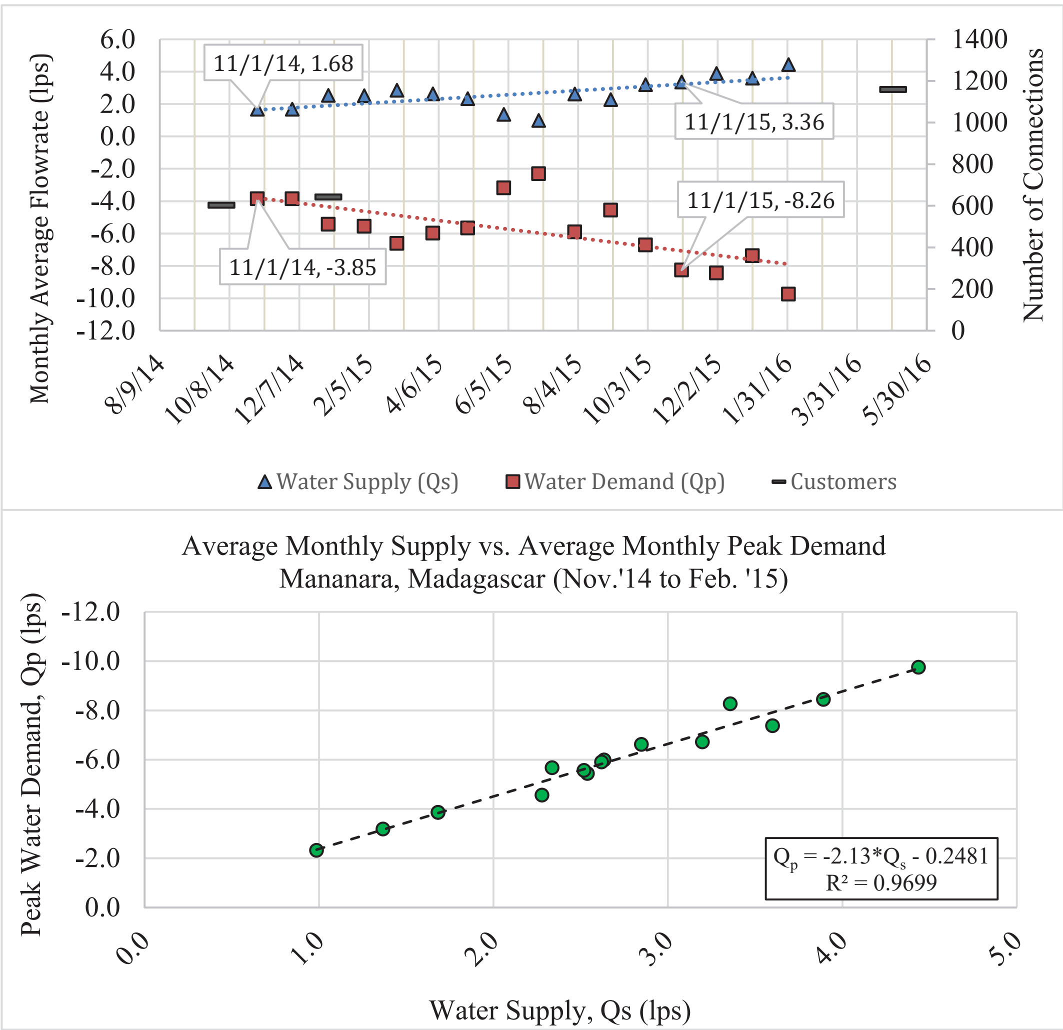
Table 4.5: Water Quantity Performance, Mananara, Madagascar

Quarter	Month	Performance Evaluation					
		Average Daily Water Level m	Average Supply Flowrate (lps)	Average Peak Demand (lps)	Average Daily Availability (L/p/d)	Average System Reliability η_{del}	Average Sustainable Access (L/p/d)
	11/1/14	**3.38**	**1.68**	**3.85**	**32.8**	**95.0%**	**31.2**
	12/1/14	**3.38**	**1.68**	**3.85**	**32.8**	**95.0%**	**29.9**
Q1	**1/1/15**	**2.73**	**2.54**	**5.43**	**42.6**	**94.4%**	**40.3**
	2/1/15	**2.17**	**2.52**	**5.56**	**40.5**	**86.2%**	**34.9**
	3/1/15	**2.37**	**2.85**	**6.62**	**43.3**	**88.6%**	**38.4**
Q2	4/1/15	2.74	2.63	5.98	41.1	97.7%	40.1
	5/1/15	2.49	2.34	5.67	36.8	89.2%	32.8
	6/1/15	3.65	1.37	3.18	26.7	100%	26.7
Q3	7/1/15	3.78	0.99	2.31	23.1	100%	23.1
	8/1/15	0.95	2.62	5.90	38.9	85.3%	33.2
	9/5/15	3.39	2.28	4.55	32.8	100%	32.8
Q4	10/1/15	2.26	3.20	6.71	40.1	82.2%	32.9
	11/1/15	**1.19**	**3.36**	**8.26**	**38.3**	**52.4%**	**20.1**
	12/1/15	**1.70**	**3.89**	**8.44**	**43.3**	**69.6%**	**30.2**
Q1	**1/1/16**	**2.61**	**3.60**	**7.37**	**40.7**	**93.2%**	**38.0**
	2/1/16	**1.18**	**4.44**	**9.75**	**47.2**	**76.5%**	**36.1**
	3/1/16	**1.30**	**3.55**	**6.66**	**38.0**	**88.9%**	**33.8**

11/14 - 4/15	2.80	2.25	5.06	38.4	91.8%	34.9
11/15 - 4/16	1.60	3.77	8.09	41.5	76.1%	31.6

Figure 4.5 shows the monthly average for water supply and demand flowrates, along with the number of system connections shown on the secondary axis, during the study period. Also included in Figure 4.5, is a plot of the water supply versus the water demand to demonstrate evidence of sustained growth in Mananara. Highlighted in this figure is the supply and demand values for the month of November in 2014 and 2015. An investigation into the ratio of Qs (2014/2015) and Qp (2014/2015) suggests that increases in demand are outpacing supply by approximately 7 percent wherein the supply in 2015 was 2 times the supply in 2014 and demand in 2015 was 2.14 times the demand in 2014.

Figure 4.5: Water Supply and Peak Demand Characteristics, Mananara, Madagascar



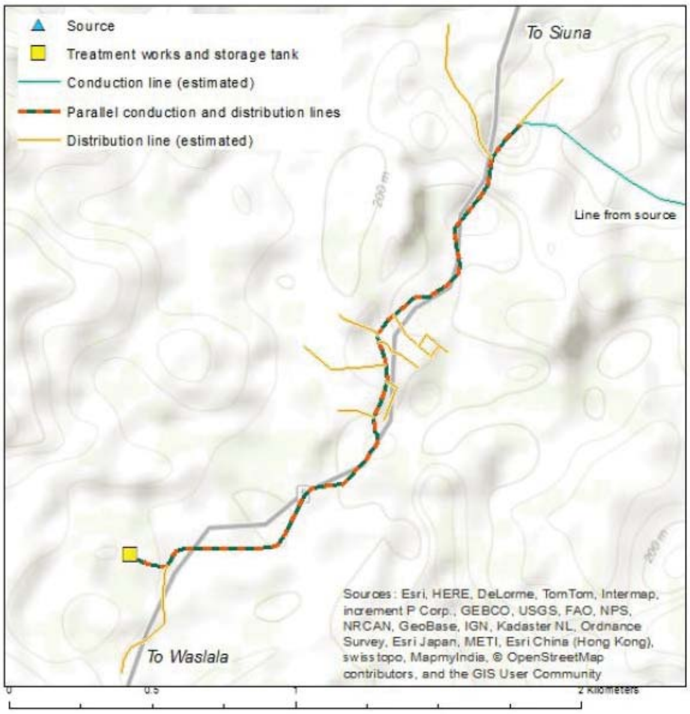
4.2 Context Analysis of Water Quantity Performance: Nicaragua

This section provides system performance characteristics of water quantity for three selected sites in Nicaragua where continuous monitoring of water levels in storage tanks began in 2014. The case in Puerto Viejo included 8-months of continuous monitoring and shows significant variability in system performance. The case study in El Naranjo demonstrates the importance of continuous monitoring wherein the system is operating at the threshold of functionality. The case study in El Guabo demonstrates the impact of good management wherein the local community expanded the system to include additional water resources into the system during the study period.

4.2.1 Water Quantity Characteristics, Puerto Viejo

A context analysis of system performance in Puerto Viejo has provided some unique insights into the potential complexities involved with delivering reliable water services. Puerto Viejo is a rural community outside of the municipality of Waslala that acts as a commercial and transportation hub for agricultural activities throughout the region. Located on the main road between Waslala, a town of approximately 8,000 people and Siuna a town of 10,000 people, this rural community of 1,200 people acts as a commercial outpost for agricultural activities for a number of more isolated communities in the area. The water system (Figure 4.6) in Puerto Viejo was originally constructed in 2004 and was later rehabilitated in 2010 to include a new intake line, a water treatment plant and the expansion of an existing distribution system. The source of water supply for this system is located on a 52 acre plot of land that is owned by the Rio Bravo – Puerto Viejo S.A. Hydroelectric Company, which maintains a 180 kW facility, providing electricity to the area. The intake system includes a surface water intake, 6.6 kilometers of 3-inch diameter piping, a slow sand filter, a drip chlorinator and a 45,000 liter storage tank.

Figure 4.6: Water Supply and Distribution System, Puerto Viejo



Whereas the system in Puerto Viejo is less reliable on average than other systems studied (61.6% as compared to an average for all sites studied of 65.9%), the amount of water available per-capita (88.7 l/p/d), is on average higher than the other systems investigated (51.5 l/p/d), and is sufficient to meet the needs of the customers. A visual inspection of the water levels (Figure 4.7 and Appendix B) reveals that the system experiences empty conditions for periods ranging from one to two days and then operates normally for several days. A cursory comparison with the water system performance characteristics in Table 4.3 (Ikongo) would suggest that the percent deviation in water levels in Puerto Viejo are over six times that of a similar system investigated during this study, 31.1% deviation as compared to 4.9% deviation for the Ikongo system. Table 4.6 shows the system performance characteristics for Puerto Viejo. The results suggest that the system is providing between 34.6 and 94.5 L/p/d of sustainable access to water with an average sustainable supply of 54.7 L/p/d. Section 4.2 of this study provides more information about the comparative analysis.

Figure 4.7: Water Quantity Performance - Water Levels and Storage

Puerto Viejo (December, 2014)

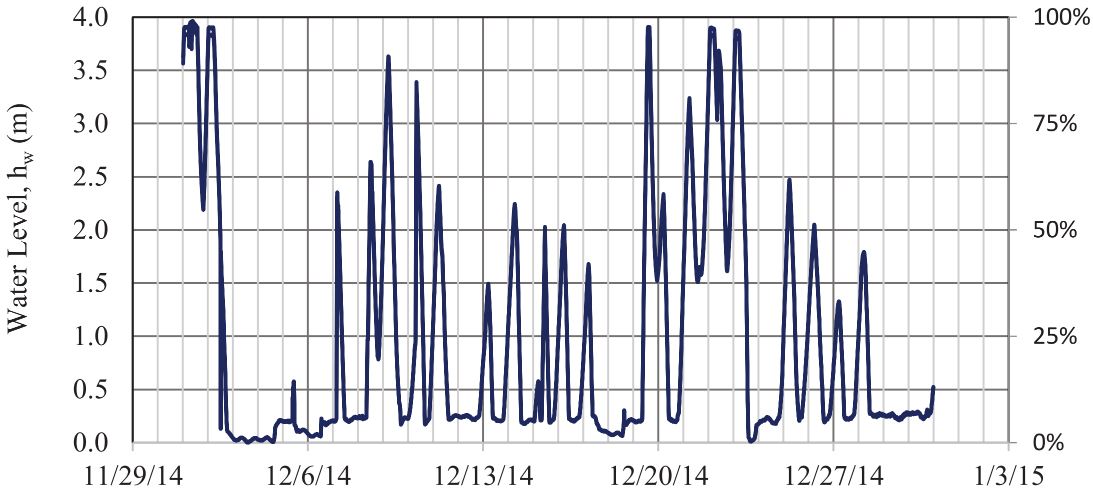


Table 4.6: Water Quantity Performance, Puerto Viejo, Nicaragua

Month	Performance Evaluation					
	Average Daily Water Level (m)	Average Daily Supply Flowrate (lps)	Average Daily Peak Demand (lps)	Average Daily Availability (L/p/d)	Average Daily System Reliability η_{del} %	Average Daily Sustainable Access (L/p/d)
11/1/14	2.31	0.87	2.01	75.0	84.8%	63.5
12/1/14	0.85	1.10	2.15	88.1	39.3%	34.6
1/1/15	1.27	0.87	1.97	74.0	57.2%	42.3
2/1/15	1.58	0.96	2.08	83.7	68.1%	57.0
10/20/16	1.23	1.34	2.39	101.8	44.8%	45.6
11/1/16	1.38	0.95	2.16	76.9	63.0%	48.4
12/1/16	1.14	1.20	2.54	94.8	54.1%	51.3
1/1/17	1.27	1.46	3.55	115.6	81.8%	94.5

Average	1.38	1.09	2.36	88.7	61.6%	54.7
Maximum	2.31	1.46	1.97	115.6	84.8%	94.5
Minimum	0.85	0.87	3.55	74.0	39.3%	34.6
StDEV	0.43	0.22	0.52	14.6	16.2%	18.4
Percent Deviation	31.1%	20.4%	22.0%	16.5%	26.3%	33.6%

4.2.2 Water Quantity Characteristics, El Naranjo

The town of El Naranjo is located on the boundary of Siuna and is the largest rural community within the municipality of Waslala with a population of 2,760 people (Jan. 2015). Similar to Puerto Viejo, this community acts as an economic hub for several isolated communities in the region that do not have road access to Waslala or Siuna. The water supply system in this community is composed of a surface water intake, a 4.5 kilometer intake pipe (6-in diameter), water treatment facility that includes a sand filter and chlorination, a 60,000 liter storage tank and 6.5 kilometers of distribution lines (4-in, 3-in and 2-in) that provide water to 12 neighborhoods (Figure 4.8). The system was originally constructed in 1990 with 200 household connections and was later rehabilitated in 2011 with 400 connections. During site visits (Jan. 2015) it was reported that the system served 552 households and that the service was intermittent with the neighborhoods furthest from the storage tank, only receiving water for a portion of the day.

The investigation in El Naranjo has provided an opportunity to observe a water supply system that has declined in all areas of system performance. A comparison of the 3 month period from November 2014 thru January of 2015 and November 2016 thru January 2017 shows a 26.2 % decrease in water levels, a 31.9% decrease in supply flowrate, a 40.9% decrease in availability and an 82.8% decrease in reliability. As a result, the per-capita availability has decreased from 48.8 L/p/d to 20.6 L/p/d, the sustainable access has declined from 5.39 L/p/d to 0.58 L/p/d and the overall sustainability of the system is being compromised significantly. Figure 4.9 shows the performance characteristics for the period between November 2014 and January 2017. The converging nature of the supply and demand trends suggests that this system is approaching full system failure as, it appears that the water supply is reducing at a rate of 24% annually using linear decay. This decline in water supply is also being matched by a decrease in peak water demand where customers are likely adapting their consumption based on available supply. In addition to this, the Figure 4.9 shows the per-capita availability along with the system reliability and Appendix B.5 shows the monthly summary data for the entire study period.

Figure 4.8: Water Supply and Distribution System, El Naranjo, Nicaragua

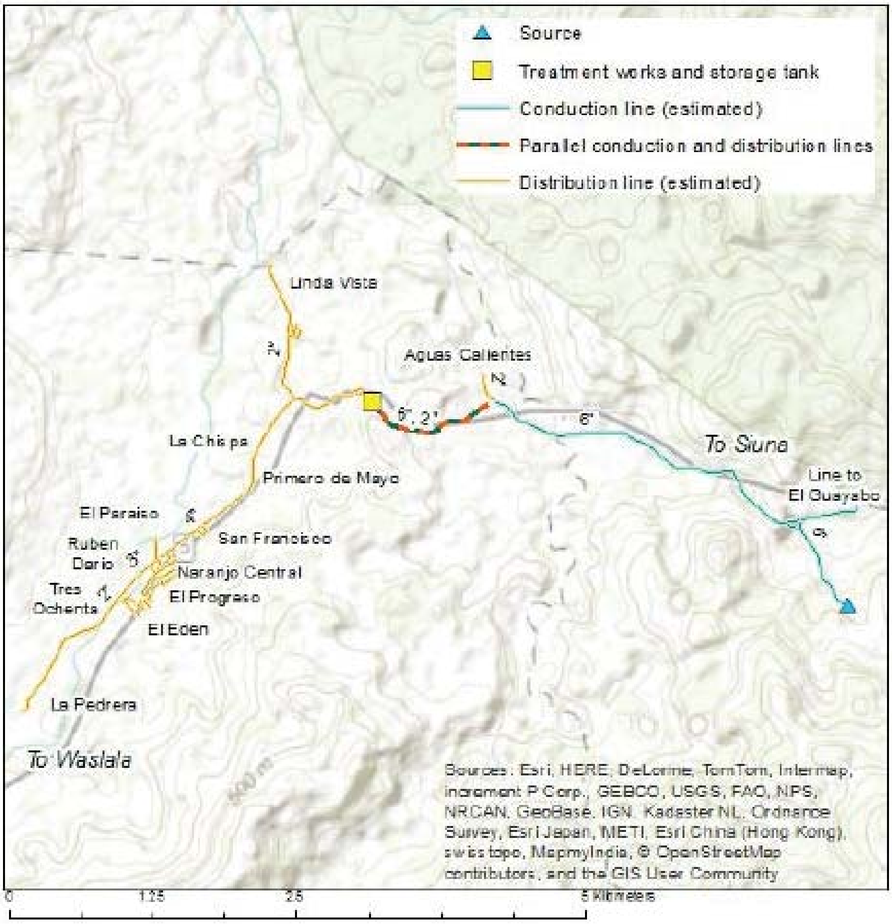
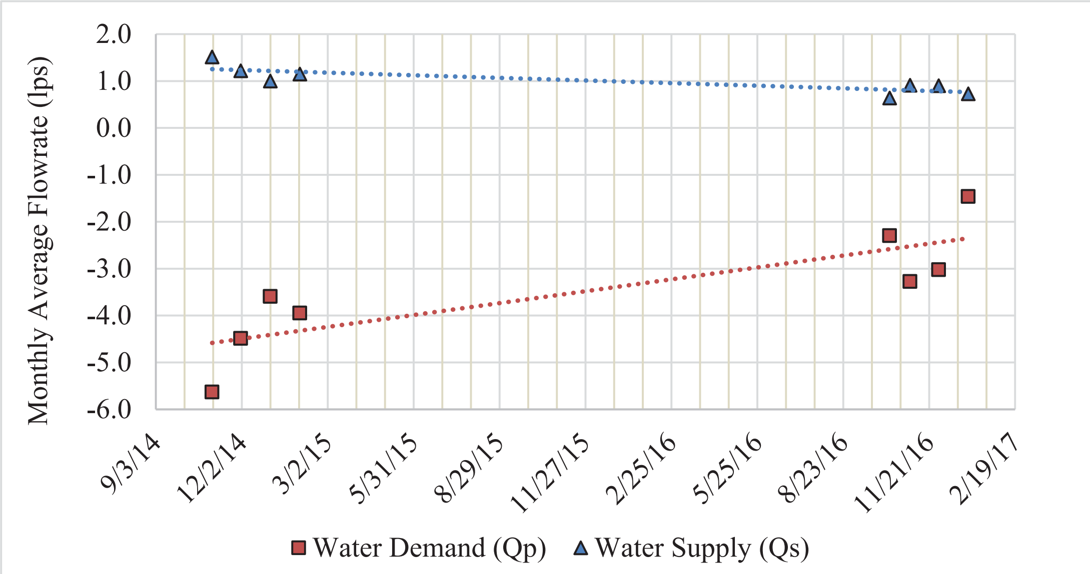
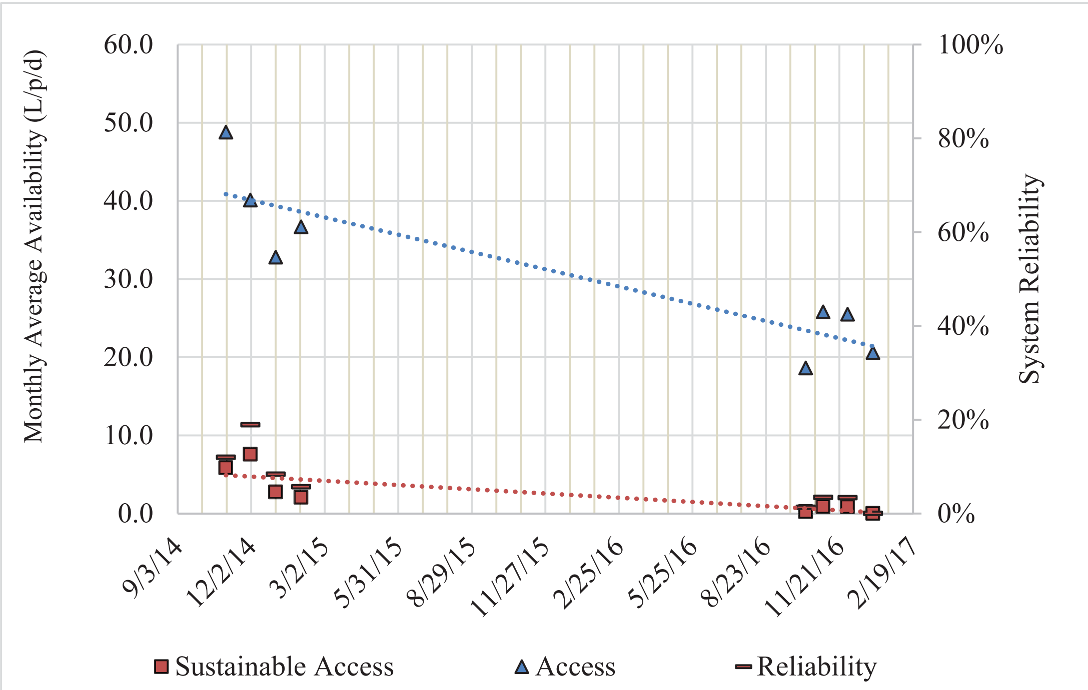


Figure 4.9: Water Supply and Demand Characteristics, El Naranjo, Nicaragua



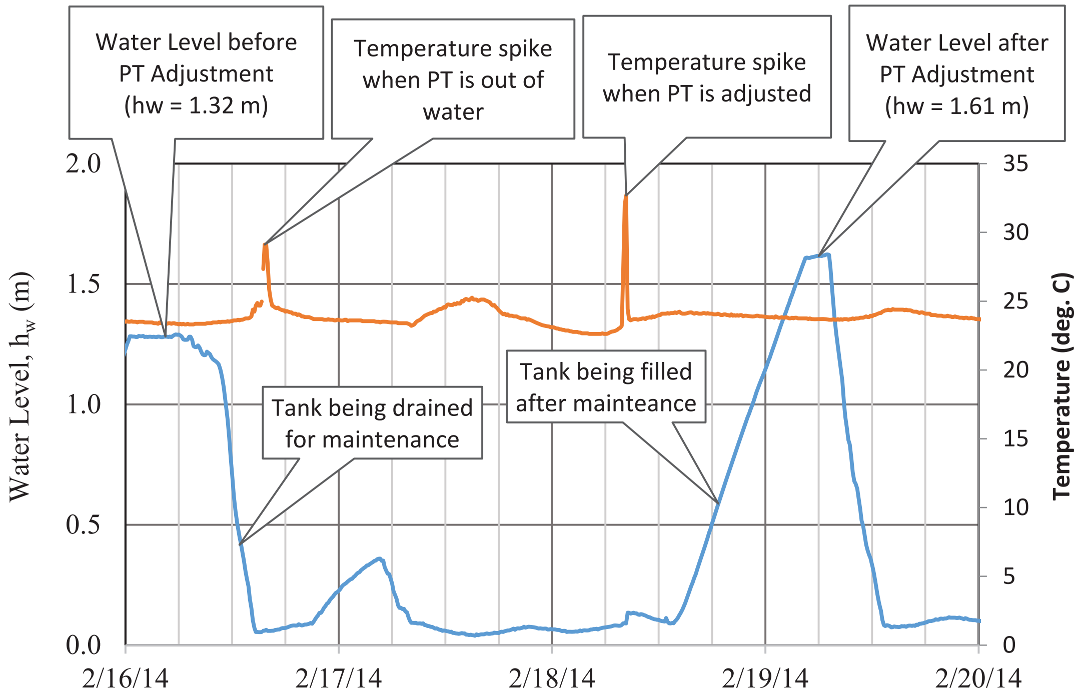


4.2.3 Water Quantity Characteristics, El Guabo

The community of El Guabo Jicaral (El Guabo) is located approximately 4.5 kilometers outside the town of Waslala, or roughly 30 minutes driving on an unpaved road along the main corridor between Waslala and Siuna. The water infrastructure in El Guabo was originally constructed in 2011 and included a spring intake located in the surrounding mountains and a 1,000 meter intake pipe (1 ½ - inch) that delivers water to a 18,000 liter storage tank. The distribution system in El Guabo includes an additional 4 kilometers of piping that combines 2-in, 1 ½ -in and 1-in PVC piping serving 45 customers at the time of the original construction. Since this time, a number of system upgrades have been made that included the development of another source in January of 2014 and the connection of additional customers. During the most recent field visit in October of 2016, the system had 54 customers which represents a 3.2% growth rate.

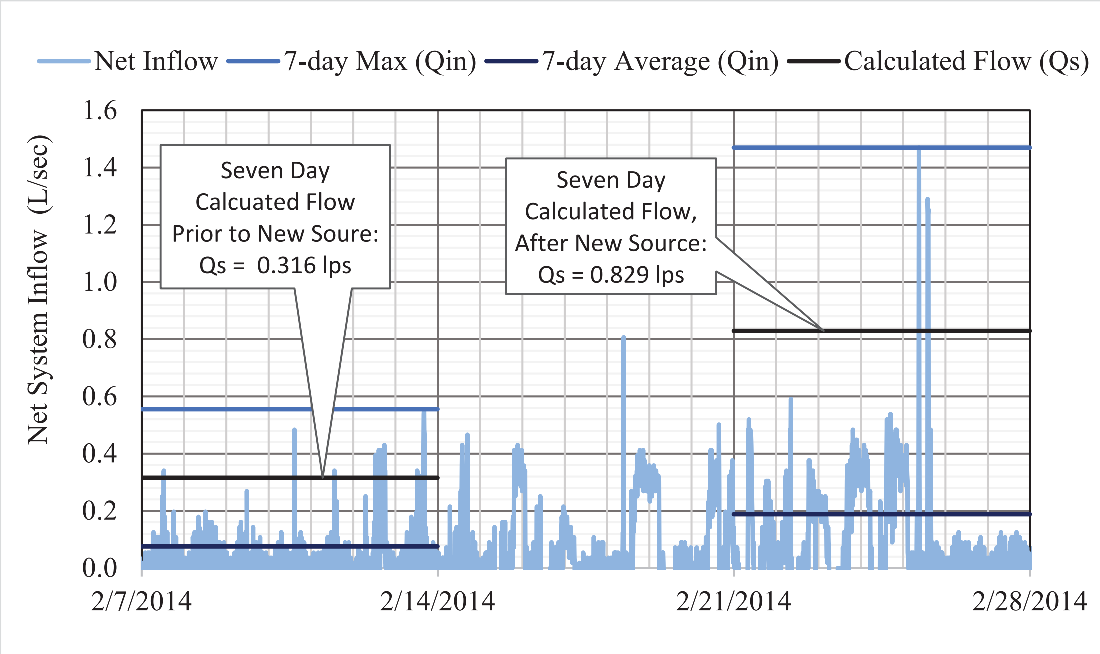
System monitoring of the El Guabo water supply began in October of 2013 and included the installation of a pressure transducer in the storage tank. The pressure transducer was removed and reinstalled in February of 2014 when the new source was included into the intake system. A review of the February 2014 monthly data (Appendix B.6) reveals that the transducer was installed at a different depth after the second source was brought online. As a result, the analysis of water levels for this site have been calibrated separately for the period prior to, and after February 2014 so that the performance evaluation would reflect actual availability of water rather than the difference in depth that resulted from the reinstallation of the pressure transducer. This particular system brings to light the importance of understanding the storage tank specifications as it relates to the water distribution outlet height. In this case, the transducer was originally installed at the height of the outlet, 0.29 meters off of the tank floor and was later reinstalled (2/18/14) on the bottom of the tank as was originally specified in the research plan for all sites studied. Figure 4.10 shows the details of the second source coming online along with evidence of the pressure transducer being reinstalled at a new depth.

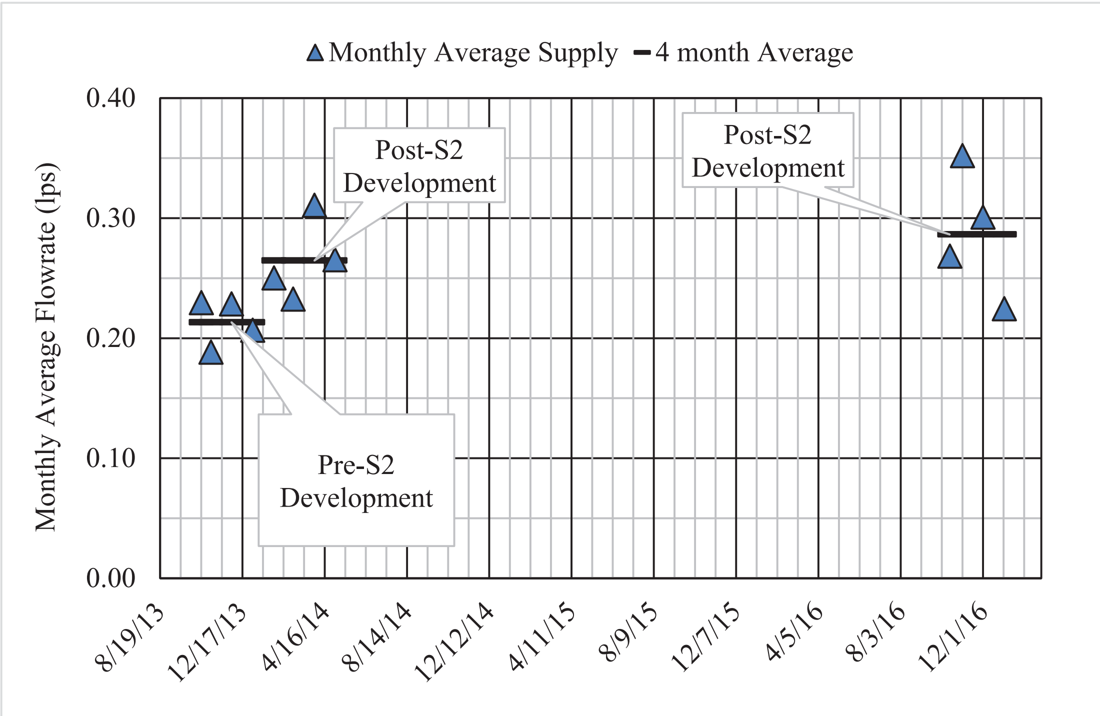
Figure 4.10: Pressure Transducer Adjustment during Spring #2 development, El Guabo, Nicaragua (2/16/14 thru 2/20/14)



Whereas, the development of a new source during the research study presented some challenges with respect to ensuring accurate data collection, it also presented an opportunity to evaluate the source supply and per-capita availability prior to and after the source development. Figure 4.11 shows the calculated flowrates of the system for a seven-day period prior to and after the development of the second water supply for the El Guabo system. From this figure, it can be seen that the development of a new source had a impact on the source supply flowrate entering the storage tank. The net flowrates, the maximum flowrate, the average flowrate and the calculated flow rate all increased after the second source (S2) was brought online. Figure 4.11 also shows the monthly summary data for four months prior to the development of S2, four months immediately after the development of S2, and another four months of more recent data. The additional data shown in Figure 4.11 shows conclusive evidence that the supply flowrate increased after the February 2014 timeframe, when the second source was development.

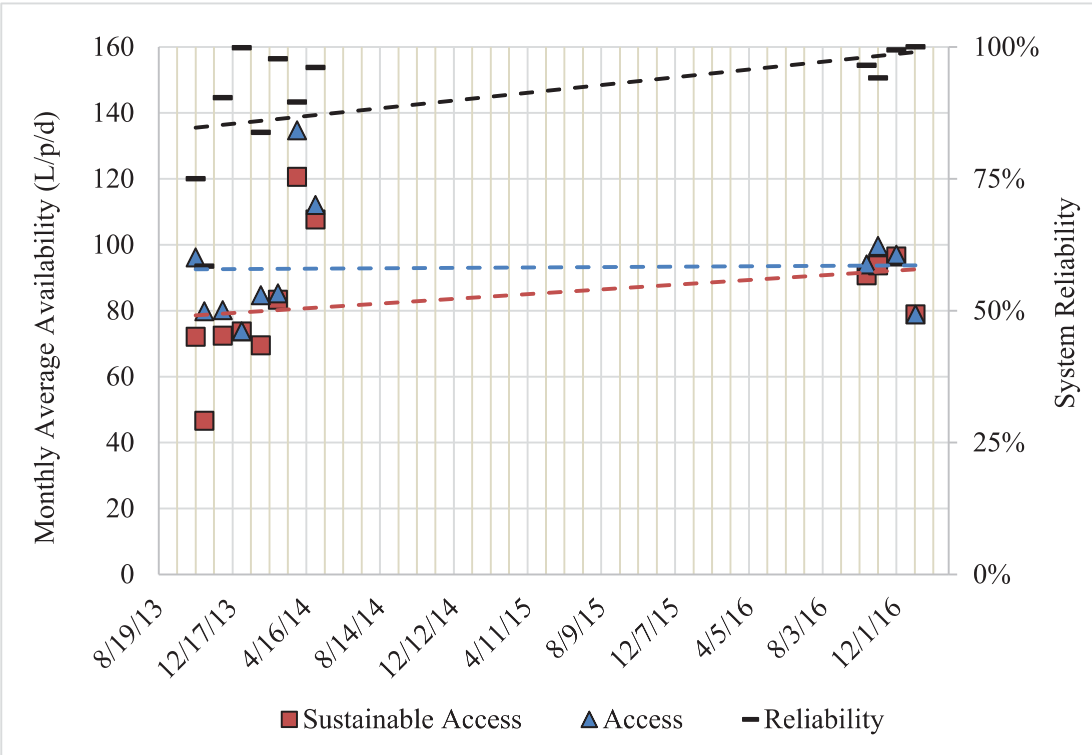
Figure 4.11: Flowrate Analysis Pre & Post Spring-2, El Guabo, Nicaragua





Finally, the analysis of water quantity results for the El Guabo water supply suggests that the system was providing sustainable access to 66.2 L/p/d before the addition of the second source and is now providing sustainable access to 95.9 L/p/d after. Figure 4.12 shows the system reliability along with the per-capita availability and sustainable access scores. Whereas it appears that the availability of water is steady throughout the two-years of system monitoring, this result is matched with an increase in reliability and thus also an increase in sustainable access to water. Whereas this trend is unique to this site, it is possible that the smaller rural nature of this particular system was more conducive to adopting water conservation and behavior change, which could explain this particular characteristic. In other words, as the system is becoming more reliable and the customers are establishing confidence in the availability of water, consumers are establishing more regular water demand patterns and the reliability is approaching 100%, resulting in the proportion of available water being equal to the proportion of sustainable water. Appendix B.7 provides additional details about the monthly performance characteristics.

Figure 4.12: Availability, Reliability and Sustainable Access, El Guabo, Nicaragua



4.3 Comparative Analysis of Water Quantity System Performance

This section provides a comparative analysis of seven sites investigated in Madagascar and twelve sites investigated in Nicaragua. The project sites are introduced for the purposes of providing some context and the system performance is compared within each country location using flow duration curves to show to proportion of time, in days, that the system provided selected thresholds of per-capita water availability. Finally the systems are presented together to categorize system performance based on threshold characteristics.

4.3.1 Comparative Analysis of System Performance – Madagascar

The seven sites included in this comparative analysis are shown in Table 4.7. All of the project sites include private and shared (social) connections to a gravity-fed piped water system that are metered, with the exception of Manompana which has un-metered connections. All of the systems investigated were rehabilitated using United Stated Agency for International Development (USAID) funding, during the RanoHP, Ranon'ala and Fararano development programs where the use of Public Private Partnerships was established as a national initiative to improve the sustainability of water services. The areas served were located on the eastern coast of Madagascar, where annual precipitation is on the order of 125 centimeters with rain gauge data from the town of Toamasina showing annual precipitation of 263 centimeters in 2013 (World Bank, 2015).

The water systems investigated during this study had similar features with respect to technologies being used however, they ranged significantly with respect to the number of customers served as well as the annual growth rate in terms of the number of new customers since the initial construction. Table 4.6 shows the system specifications for the sites studied and reveals that the number of customers per water point connection is relatively high, ranging from 12.6 customers per connection in Tolongoina to 31.9 customers per connection in Manompana. This characteristics represents a significant difference from the systems studied in Nicaragua where the average number of customers per connection is slightly higher than five (5.13 customers/connection). This difference is attributed to the different types of water connections provided during the project implementation in Madagascar, where households could purchase a private connection providing water directly to the home, or a social connection where household clusters could cooperate to purchase a single connections for multiple families. The service connection options implemented in Madagascar also creates some differences among the sites studied in that the number of social and private connections differs from site to site. For example, the system in Tolongoina started with 53 private and 81 social connections and the system in Manompana started with 23 private and 20 social connections. In order to bring further attention to the unique nature of each site location, project briefs and system diagrams are provided in Appendix A. Complete project reports are provided as a supplemental appendix to this study and are available electronically upon request.

Table 4.7: System Specifications for Comparative Analysis, Madagascar

Site	System Specifications				
	Initial Number of Connections	Initial Number of Customers[2]	Annual Growth Rate (%)	System Storage Capacity (Liters)	Estimated Intake and Distribution Length (km)
Tolongoina	157	1990	14.2	50,000	6.0
Ikongo	148	2,442	1.70	74,000	5.6
Anivorano	134	1,796	4.12	78,000	6.2
Andemaka	132	1,769	4.12[1]	68,000	4.8
Mananara	602	6984	26.6	170,000	24.7
Manompana	43	1,374	4.12[1]	54,000	16.8
Imorona	215	2,921	4.12[1]	67,000	6.7

1. Approximated using Anivorano data which is regionally and contextually similar.
2. Total town population data (2-5 times the number of customers) is available in Appendix A.

Table 4.8 shows the summary of results for selected sites in Madagascar including the system reliability score, the per-capita water availability and the per-capita sustainable access to water analysis. The results presented were analyzed on a daily basis and summarized as monthly averages prior to consolidating the performance evaluation of the entire system. Outliers were identified graphically by visually inspecting the supply and demand flowrates, along with the water level and temperature data to determine if the outlier was associated with maintenance or instrumentation error. Appendix B shows the system performance summary data for all of the sites and includes graphical results of per-capita system performance on a daily basis as well as water level and supply and demand flow rates. The system in Tolongoina is being presented twice in Table 4.7 in order to delineate the system performance before and after PPP management where 164 days of data collection included three months of data prior to management and two months of data after PPP management began.

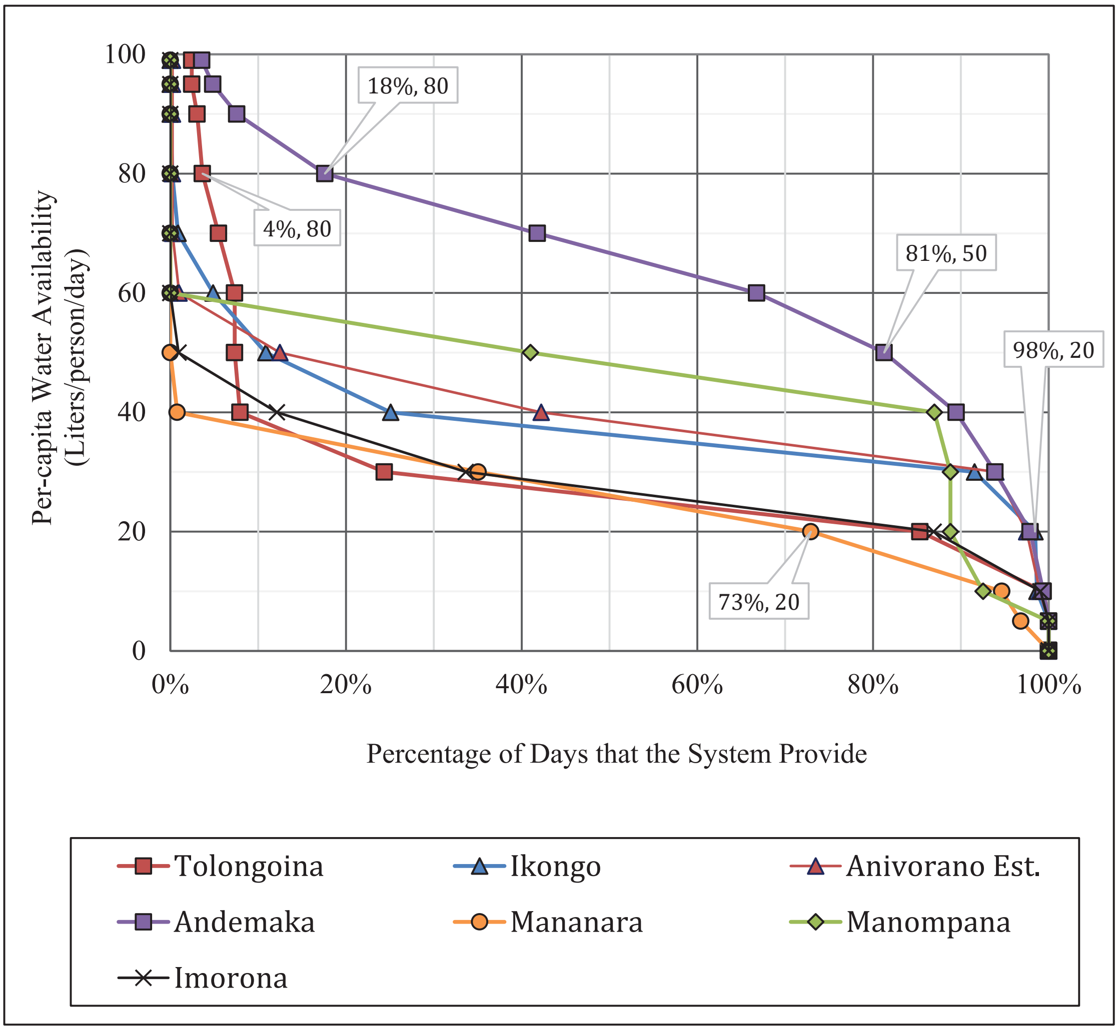
Table 4.8: System Performance Characteristics, Madagascar

Site Location	N (days)	System Reliability η_{del}	Availability (L/p/d)	Sustainable Access (L/p/d)
Tolongoina	61	99.9%	21.1	21.1
Ikongo	452	99.2%	37.8	37.7
Anivorano	400	96.0%	40.5	39.5
Andemaka	476	94.5%	65.1	63.1
Mananara	508	84.1%	25.3	22.1
Manompana	47	74.4%	41.0	36.4
Imorona	108	78.8%	26.2	24.3
Tolongoina[1]	164	49.3%	28.8	14.1

1. Data presented twice. N = 164 includes all data both pre and post PPP management and N = 61 includes only post PPP management data.

Another question that emerges when reviewing the results is, how often the above systems provide certain thresholds of per-capita water availability. In order to answer this question, a performance duration curve was developed to identify the proportion of time that the systems operated within various per-capita availability thresholds. Figure 4.13 shows the results of this analysis. Of particular interest is how often the water systems studied, provided the minimum basic needs of 20 liters/person/day of water. In addition to this, economic thresholds of 50 L/p/d and 80 L/p/d are identified where the systems could provide higher levels of domestic water as well as some commercial water needs. Highlighted on this figure are the systems that provided the highest level of minimum basic needs where Anivorano, Ikongo and Andemaka all provided the minimum basic needs of 20 L/p/d for 98% of the days investigated. Also highlighted is the Mananara system which provided the lowest level of minimum basic needs with 20 L/p/d for 73% of the days while noting that this system does provide a relatively reliable service with a system delivery efficiency of 90.7 percent. Furthermore, the Andemaka system also provided the highest level of 50 L/p/d water where 81% of the days met this threshold. None of the systems appear to have provided economic or commercial demands for water where only two systems met the 80 L/p/d threshold, Andemaka at 18% and Tolongoina at 4%, with the remaining systems having never met this threshold.

Figure 4.13: Performance Duration Curves; Water Availability, Madagascar



4.3.2 Comparative Analysis of System Performance – Nicaragua

The twelve sites investigated for the comparative analysis are shown in Table 4.8. All of the project sites included private connections to a gravity-fed piped water system with the majority of the systems being metered and with un-metered system being noted. The systems investigated in Matagalpa and Esquipulas were implemented between 2009 and 2011 by CARE during the Agua para Todo para Siempre, national initiative to improve access to water. The systems studied in the Waslala region were implemented in the 2009 to 2011 timeframe by a number of different organizations including collaborative efforts between the local government, Save the Children, Water for Waslala and the local NGO, Asociacion de Desarrollo Integral y Sostenible. Only one of the systems was implemented prior to the other systems, wherein the El Rodeo system was constructed in 1994, reported by CARE International. Additional context specific information about the systems studied is provided in Appendix A, along with system diagrams and full project reports are available in the supplemental electronic appendix, upon request.

Table 4.9 shows the system specifications for the sites studied and reveals some significant differences between the sites in Nicaragua and Madagascar. Wherein, the technical constraints in terms of the piped intake and distribution systems are similar, the number of customers served on average, 629 customers/system in Nicaragua is lower than the system studied in Madagascar (2,753 customers/system). This difference is largely attributed to the rural nature of the sites studied in Nicaragua where the local economy and culture are largely dependent on coffee and cattle plantations. The annual growth rate of the systems are also more consistent with engineering design standards that typically assume a growth rate of between 2 and 4 percent. The average growth rate of 3.5% for the systems in Nicaragua as compared to 8.4% for the systems in Madagascar.

Table 4.9: System Specifications for Comparative Analysis, Nicaragua

Site	System Specifications				
	Initial Number of Connections	Initial Number of Customers	Annual Growth Rate (%)	System Storage Capacity (Liters)	Estimated Intake and Distribution Length (km)
El Guabo	45	225	3.88	17,300	5.0
El Naranjo	400	2,000	8.39	47,900	16.3
Puerto Viejo	220	1,100	1.76	46,500	11.6
Dipina Esp	56	280	4.4	24,900	16.7
Dipina Central[1]	60	300	3.28	14,500	6.1
Ausberto Paladino	204	1020	1.63	52,000	9.7
Los Lipes	68	340	1.79	21,600	6.4
Molino Norte	150	750	3.93	51,500	7.8
San Jose[1]	108	648	4.48	24,900	1.6
San Francisco	70	420	2.19	22,800	6.4
El Rodeo[1]	50	300	2.17	26,300	4.7
La Ceiba[1]	35	175	3.94	7,700	2.4

1. Un-metered system.

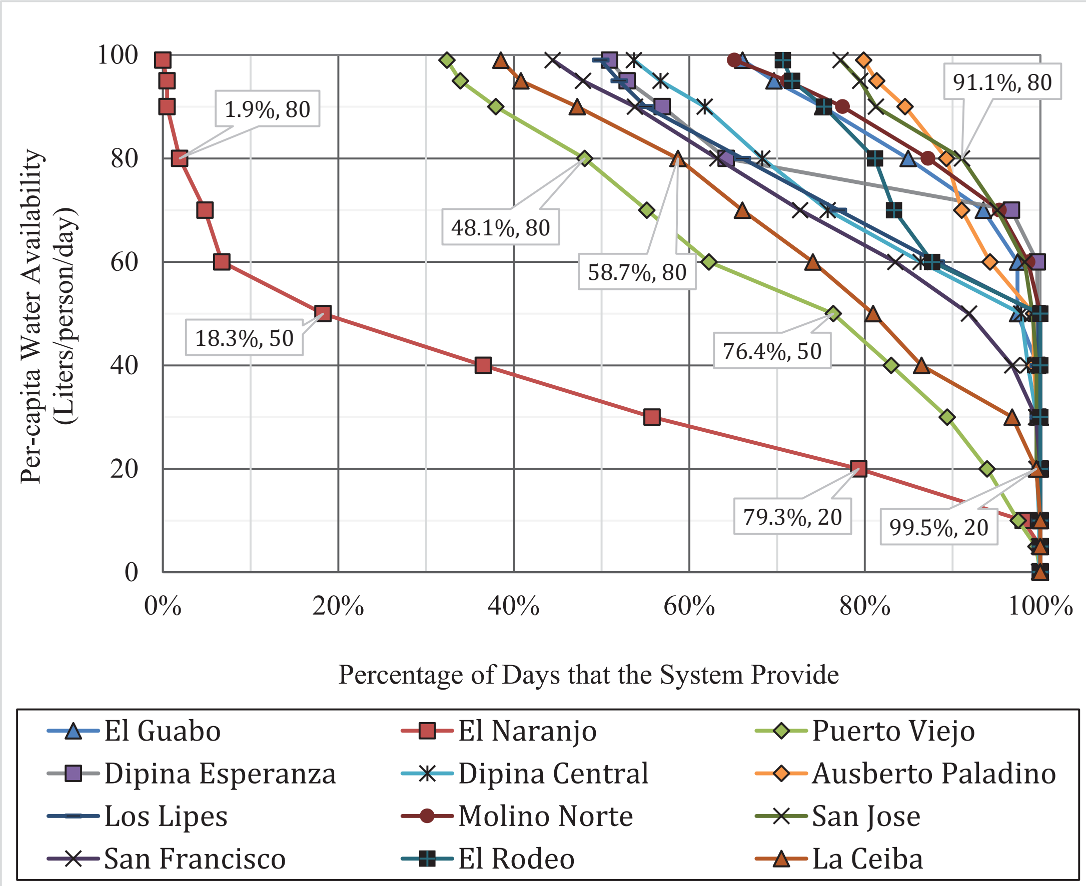
Table 4.10 shows the results of the system performance characteristics for the systems studied in Nicaragua. The analytical methods for the systems in Nicaragua was the same as those studied in Madagascar wherein the system delivery efficiency (or reliability), per-capita availability and per-capita sustainable access to water were calculated using the same technical approach. The lowest system performance score for any of the sites studied was in El Naranjo, Waslala where, approximately 2,000 people only have access to 35.1 liters/person/day with service reliability score of 8.6%, ultimately only providing 4.2 liters/person/day of sustainable access to water. Two of the three systems that are providing the highest per-capita availability of water are un-metered wherein San Jose, Ausberto Paladino and El Rodeo are all providing more than 130 L/p/d of water availability. At the same time, three of the un-metered systems are providing less than 90% service delivery efficiency with two, La Ceiba and San Jose scoring less than 70% in terms of system reliability. All of the systems with the exception of El Naranjo provided high levels of water availability, being greater than 80 L/p/d and high levels of sustainable access being greater than 50 L/p/d.

Table 4.10: System Performance Characteristics, Nicaragua

Site Location	N (days)	System Reliability η_{del}	Average Availability (L/p/d)	Sustainable Access (L/p/d)
El Guabo	308	90.4%	121.3	110.6
El Naranjo	208	8.6%	35.1	4.2
Puerto Viejo	199	54.5%	88.0	55.9
Dipina Esp	658	95.6%	102.7	97.6
Dipina Central[1]	398	90.9%	108.9	101.7
Ausberto Paladino	403	96.7%	137.7	132.7
Los Lipes	432	96.4%	107.1	100.9
Molino Norte	431	98.8%	113.2	111.4
San Jose[1]	224	60.5%	138.7	87.7
San Francisco	203	87.1%	121.0	101.2
El Rodeo[1]	138	86.7%	131.2	108.9
La Ceiba[1]	218	69.1%	88.4	59.4

Figure 4.14 shows the performance duration curves of water availability for the systems studied in Nicaragua. Using an 80% duration and 20 L/p/d threshold shows that El Naranjo is the only system that is failing to meet the minimum basic needs of the customers in the service area, where the remaining sites provide this level of service greater than 99% of the time. Using the economic threshold of 50 L/p/d and an 80% duration criteria shows that both El Naranjo and Puerto Viejo are the only systems not meeting this threshold. Furthermore, using the 80 L/p/d and 80% duration criteria shows that all of the systems with the exception of El Naranjo, Puerto Viejo and La Ceiba are providing water consumption levels that are consistent with commercial needs for water consumption.

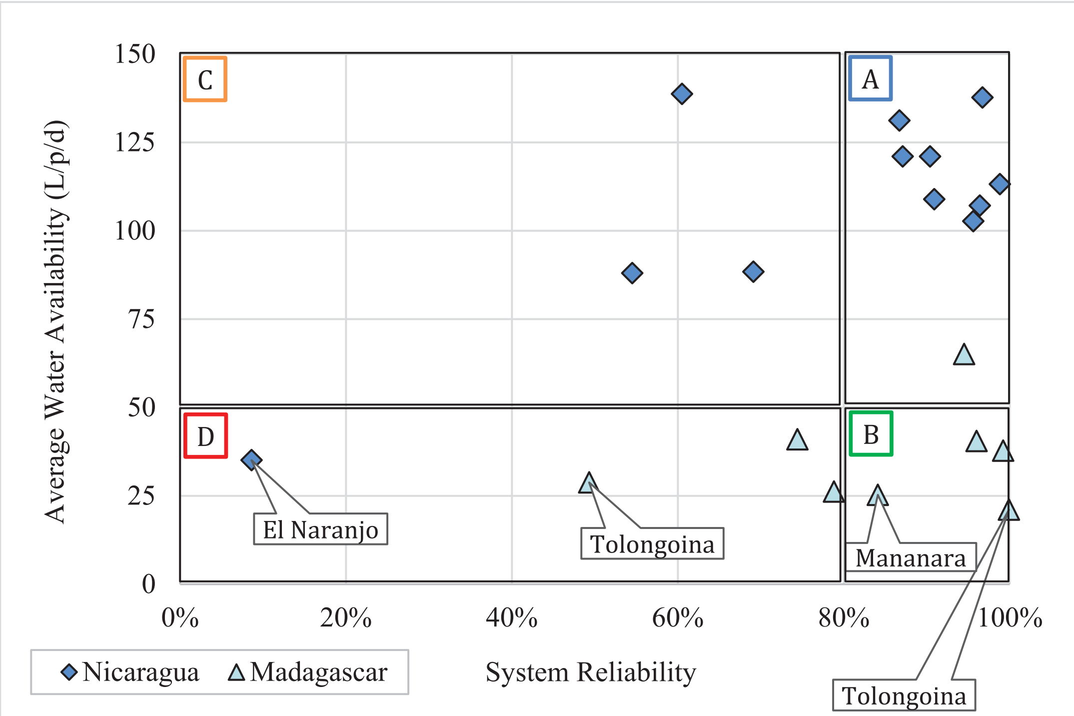
Figure 4.14: Performance Duration Curves; Water Availability, Nicaragua



4.3.3 Characterization of System Performance

A comparative analysis of the results from Nicaragua and Madagascar reveals a range in system performance and suggests that continuous monitoring of water supply infrastructure can improve sustainability by identifying failing systems. Reviewing the results of the water quantity performance and using the 80% system reliability and the 50 L/p/d threshold, different categories, or types of system performance start to emerge, see Figure 4.15. Type-A systems are those that are providing reliable access to larger volumes of water in which, consumption is beyond basic household demand. Type-B systems are providing a reliable service but are only providing volumes which are typical of household consumption, or what might be classified as basic needs. Type-C systems are providing larger volumes of water but are not reliable and thus the sustainability of the system is vulnerable. Type-D systems are not providing a reliable supply of sufficient water and the sustainability of the systems are compromised.

Figure 4.15: Quadrant Analysis of Availability and Reliability of Water Services



From this analysis, it can be seen that Type-D systems identified from this study include one system in Nicaragua and three systems in Madagascar. The lowest performing system in terms of reliability is in El Naranjo which provided 35.1 L/p/d with an 8.6% reliability score. The system in Tolongoina was providing 28.8 L/p/d with a 49.3% reliability score prior to the commencement of PPP management and 21.1 L/p/d with a 99.9% reliability score after management. Two boarder-line sustainable systems identified here are Manompana and Imorona which are providing 41 L/p/d and 26.2 L/p/d respectively.

Table 4.11 shows the System Capacity Duration, SDC scores, for the 20, 50 and 80 L/p/d thresholds, along with the system reliability and a composite performance evaluation score. The SDC Score represents an average of the three threshold values and the Composite Score takes an average of the SCD and the Reliability scores. In this table, Class-1 systems are reliably providing a high volume of water based on the composite score that takes into account the reliability and system capacity duration. The Molino Norte system is performing at the highest level followed closely by the Ausberto Paladino system, both in Nicaragua. Class-2 systems have potential, in that they are either providing a generally reliable supply with sufficient water for medium levels of consumption, or are providing a really reliable supply of basic levels of consumption. For example, San Fransisco, a Class-2 system with a Reliability Score of 87.1% has an SCD Score of 85%, is reliably providing medium levels of consumption and, Andemaka, also a Class-2 system, with a Reliability Score of 94.5% and an SDC Score of 65.6% is providing a very reliable supply of minimum basic needs of water

Class-3 systems are providing either a reliable supply of basic needs for water or they are providing an un-reliable supply of higher amounts of water. For example, the La Ceiba system in Nicaragua has a 69.1% Reliability Score but it provided greater than 50 L/p/d during 80.9% of the days investigated. Class-4 and Class-5 systems are underperforming in terms of water quantity performance being on the verge of failure or being a failed system. Class-4 are essentially underperforming on one, and Class-5 systems are underperforming on both water quantity performance scores. For example Ikongo, a Class-4 system, is providing a reliable service (99.2%) for a lower amount of water wherein, the capacity of the system only provided more than 50 L/p/d during 10.9% of the days. The system in El Naranjo, a Class-5 system is underperforming on both reliability (8.6%) and in availability (SDC-50 = 18.3%).

An interesting point of comparison with respect to the two analytical methods presented here is the Mananara system in Madagascar. Whereas, Figure 4.15 has this system identified as a Type - B system, in that it provides a reliable supply of water, the composite analysis used in Table 4.9 identifies this site as a Class-5 system because is never meets the 50 L/p/d or the 80 L/p/d criteria. In both comparative analysis, the El Naranjo system (Type-D, Class-5) is underperforming significantly and long-term sustainability is not likely.

Table 4.11: Comparative Analysis: Reliability and System Capacity Duration (SCD)

	Site Location	Reliability η_{del}	SCD Criteria 20	SCD Criteria 50	SCD Criteria 80	SCD Score	Composite Score
Class-1	Molino Norte	98.8%	100.0%	100.0%	87.2%	95.7%	97.3%
Class-1	Ausberto Paladino	96.7%	100.0%	99.2%	89.3%	96.2%	96.4%
Class-1	Los Lipes	96.4%	100.0%	99.8%	66.1%	88.6%	92.5%
Class-1	El Guabo	90.4%	100.0%	97.4%	84.9%	94.1%	92.3%
Class-1	Dipina Esp.	95.6%	100.0%	99.6%	64.2%	87.9%	91.8%
Class-1	El Rodeo	86.7%	100.0%	100.0%	81.1%	93.7%	90.2%
Class-2	Dipina Cen.	90.9%	99.6%	97.8%	68.3%	88.6%	89.7%
Class-2	San Francisco	87.1%	100.0%	91.9%	63.2%	85.0%	86.1%
Class-2	Andemaka	94.5%	97.9%	81.3%	17.6%	65.6%	80.1%
Class-3	San Jose	60.5%	99.6%	99.1%	91.1%	96.6%	78.6%
Class-3	La Ceiba	69.1%	99.5%	80.9%	58.7%	79.7%	74.4%
Class-4	Ikongo	99.2%	98.4%	10.9%	0.2%	36.5%	67.9%
Class-4	Tolongoina	99.9%	100.0%	0.3%	0.2%	33.5%	66.7%
Class-4	Anivorano Est	96.0%	97.5%	12.5%	0.3%	36.7%	66.4%
Class-4	Puerto Viejo	54.5%	93.9%	76.4%	48.1%	72.8%	63.7%
Class-5	Manompana	74.4%	88.8%	41.0%	0.0%	43.3%	58.8%
Class-5	Mananara	84.1%	72.9%	0.0%	0.0%	24.3%	54.2%
Class-5	Imorona	78.8%	86.9%	0.9%	0.0%	29.3%	54.0%
Class-5	Tolongoina	49.3%	85.4%	7.3%	3.7%	32.1%	42.8%
Class-5	El Naranjo	8.6%	79.3%	18.3%	1.9%	33.2%	20.9%

4.4 Validation of Results

This section provides details on three types of data analysis that were used to triangulate the results of water quantity performance. Validation of the supply flowrate entering the storage facility included calculations of the theoretical capacity of the intake system based on pipe-flow hydraulics and the gravitational potential energy available in the system. Validation of the per-capita consumption was conducted on selected sites where management records and visual inspection of household water meters was possible. Finally, customer satisfaction surveys with respect to water quantity were used to validate the overall analysis of system performance.

4.4.1 Theoretical Capacity and Supply Flowrate Analysis

The review of technical design documentation for two systems in Madagascar and two systems in Nicaragua was used to create hydraulic models of the intake systems where, the capacity of the intake pipe was calculated to validate the supply flowrate analysis using net-flow into the storage tanks. In addition to this, more detailed analysis of selected days where the supply flowrate into the storage tank can be isolated for a period of time was conducted to provide higher resolution analysis of net-flow into the storage tanks.

Table 4.12 shows the results of the hydraulic models for the selected sites where detailed information was available on the system specifications. Whereas, the theoretical capacity for all of the systems is higher than the net-flowrates measured at the storage tanks, this is fundamentally consistent with expected results. For several reason, the measured flowrate into the storage tank, based on pressure transducer data, should be lower than the theoretical flowrate, based on the system constraints. With respect to the local hydrology, the capacity of the watershed and ultimately the source itself could be lower than the hydraulic capacity of the intake piping. A simple investigation into the El Guabo watershed shows that there is an estimated 70,000 square meters of heavily forested land above the intake structure of the water system. With an estimated 2000 millimeters of annual rainfall (Hunt, 2014), this would suggest that the hydro-potential in the area is roughly 140,000 cubic meters annually, which translates into 4.43 liters/sec assuming an equal distribution of precipitation. Wherein, it has been estimated that up to 85% of rainfall in tropical climates can be lost from evapotranspiration, runoff and deep infiltration (Windsor, 1990), this would equate to approximately 0.66 liters/sec being available at the spring intake. Thus, it is conceptually feasible that the source supply flowrates for the selected sites could be lower than the intake pipe's capacity to move water. In addition to this, leaks in the intake system could prevent the available supply from the source from reaching the storage facility.

Finally, since the theoretical capacity calculations include data from engineering feasibility studies, the final as-built system could differ because of changes during implementation and/or changes in pipe roughness since installation. At the same time, the design specifications were verified with local water operators during the investigation so any changes have been noted and, the theoretical analysis used the most accurate information available. The theoretical analysis did however ignore minor losses in the system and, as a result the values reported in Table 4.12 are theoretical maximum flow rates.

Table 4.12: Intake System Hydraulic Model: Selected Sites, Madagascar and Nicaragua

Site Location	**Elevation Change (m)**	**Intake System Length (m)**	**System Inside Diameter (mm)** [1]	**Theoretical Capacity Q_t (L/s)** [2]	**Calculated Daily Net-Flow Q_s (L/s)**	**Max Daily Net-Flow Q_{max} (L/s)**
El Guabo[3]	55.6	797.7	32.0	1.05	0.24	0.84
Dipina Esperanza	59.0	679	32.0	1.26	0.34	0.91
Ikongo	19.2	2,490	84.3	4.37	0.47	1.83
Tolongoina	93.0	615.7	42.6	3.63	0.78	3.20

1. Composite pipe diameter used where appropriate
2. Theoretical Capacity is based on the potential flow in the system. Where multiple break pressure tanks or a treatment system is a part of the intake system, the minimum capacity of each leg would define the limits of the theoretical capacity.
3. Analysis only includes data prior to 2/16/14, when a second source was developed at the site.

Text Box 4.1: Example theoretical capacity calculation, intake system.

Site Location: El Guabo, Nicaragua

Intake System: Source to Treatment Tank
Length: L = 1760 meters
Change in Elevation: Δz = 55.6 meters
Pipe Diameter: D = 1 -in SDR26, PVC (Inside Diameter, ID = 0.032 m)

$$Qc = \left(\frac{\pi^2 * g * \Delta z * D^5}{8 * f * L}\right)^{\frac{1}{2}} \qquad Qc = \left(\frac{\pi^2 * g * 55.6 * (0.032)^5}{8 * 0.02544 * 797.9}\right)^{\frac{1}{2}}$$

$Qc = 0.00105$ m^3/s $\qquad Qc = 1.05$ l/s

4.4.2 Per-capita Consumption using Water Meter Data

Table 4.13 below shows the results of the average per-capita consumption based on water meter readings along with the average water availability as measured by the pressure transducers within the storage tanks at selected site locations. Also noted is the precent difference between the readings for each location. Whereas, the results help to validate that, the availability analysis is within an order of magnitude of the meter readings, the percent accuracy for sites in Ikongo, Anivorano and Tolongoina suggests that there are limitations with respect to the accuracy of the pressure transducer measurements at the lower end of water consumption levels. At the same time, wherein the availability analysis reports higher consumption values, the analysis of performance would be more conservative in terms of reporting higher performance scores. In addition, reports of inaccurate meters was not uncommon with leaks and broken meters observed during field work. As a result, further analysis of these results is justified and an important note is that the average per-capita availability measurement does not align with the actual time period of the water meter reading.

Table 4.13: Per-capita Consumption using Water Meter Data

Site Location	Months (n)	Average Per-capita Consumption Meter Reading (L/p/d)	Average Per-capita Availability Inflow and Storage (L/p/d)	Percent Accuracy (%)
Ikongo	27	19.7	37.8	52.1%
Anivorano Est.	24	19.9	40.5	49.1%
Tolongoina	12	14.5	28.8	50.3%
Mananara	15	26.9	24.7	91.8%
Los Lipes	4	107.2	107.1	99.9%
Molino Norte	4	114.5	113.2	98.8%

4.4.3 Customer Satisfaction of Water Quantity

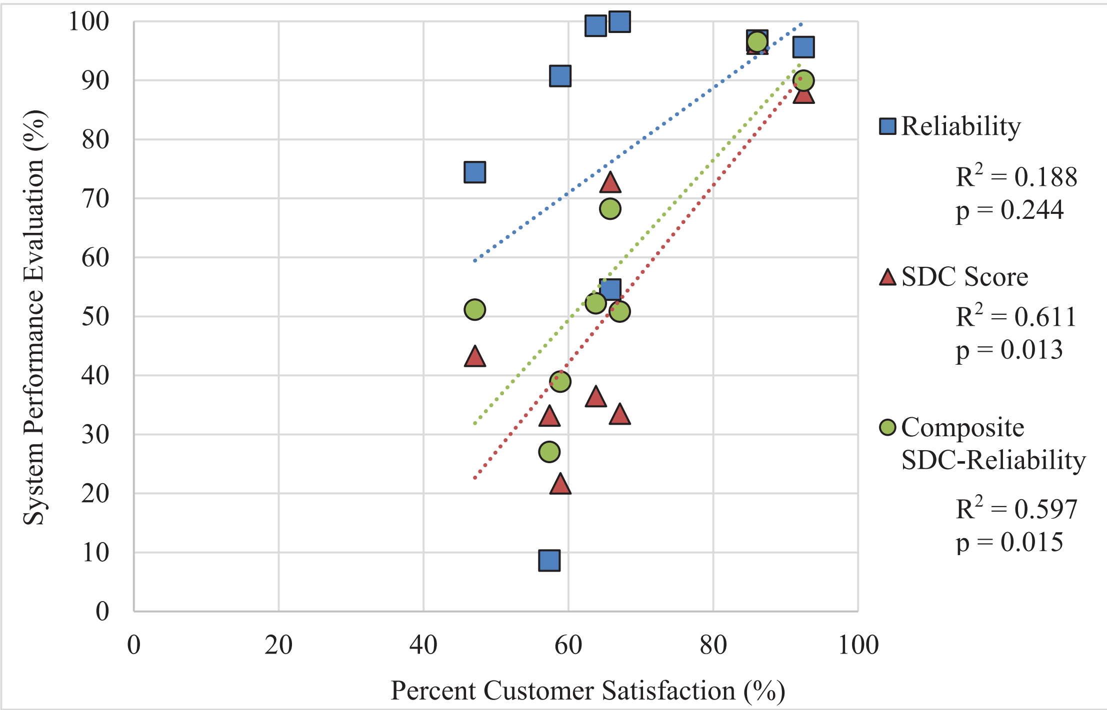
Customer satisfaction surveys at the household level were conducted to triangulate the water quantity performance evaluation. Table 4.14 shows the results of the customer satisfaction surveys along with sample size and the margin of error for each survey and Appendix E shows the surveys used in Nicaragua and Madagascar. The performance efficiency, or system reliability are shown along with the system capacity duration score and the composite SDC-Reliability score which takes into account both the reliability and the availability of water. In terms of customer satisfaction, the highest ranking systems were in the communities of Dipina Esperanza which was constructed in 2009 with 56 connections and the community of Ausberto Paladino which was constructed in 2014 with 204 connections. The lowest ranking systems in terms of customer satisfaction were in El Naranjo, constructed in 2011 with 400 connections and Mananara, constructed in 2014 with 602 connections. In terms of the composite SDC-Reliability scores, the Ausberto Paladino, El Guabo and Dipina Esperanza systems all score among the highest and the Mananara and El Naranjo systems score among the lowest.

Figure 4.16 shows the relationship between customer satisfaction and reliability, SCD and the composite evaluation scores. Also shown in this figure are the linear correlations along with Person R-Square correlation coefficients for the different evaluation criteria used during the analysis. Whereas, a positive relations exists between these independent variables, it is clear from this analysis that the SDC Score shows the most evidence of a significant relationship (R^2=0.61, p=0.013) and that the composite score which considers both reliability and availability of water also shows significant (p=0.015) evidence of a strong relationship (R^2=0.597) with customer satisfaction.

Table 4.14: Customer Satisfaction and System Performance Characteristics

Site Location	Sample Size HH (n)	Percent Customer Satisfaction (%)	Margin of Error (%)	System Performance Efficiency Reliability (%)	SCD Score (%)	Composite SCD-Reliability Score (%)
Aus. Paladino	9	86.1	9.93	96.7	96.2	96.4
El Guabo	15	75.0	7.80	90.4	94.1	92.3
Dipina Esp.	10	92.5	8.64	95.6	87.9	91.8
Ikongo	38	63.8	4.41	99.2	36.5	67.9
Tolongoina	38	67.1	4.57	99.9	33.5	66.7
Puerto Viejo	19	65.8	12.4	54.5	72.8	63.7
Manompana	34	47.1	6.46	74.4	43.3	58.8
Mananara	31	58.9	7.02	90.7	21.7	54.2
El Naranjo	17	57.4	11.6	8.60	33.2	20.9

Figure 4.16: Customer Satisfaction vs. Performance Criteria with R^2 Correlations



4.5 Chapter Summary: Water Quantity

This chapter includes water quantity analysis based on the continuous monitoring of water levels within storage tanks located at seven sites in Madagascar and twelve sites in Nicaragua. The analytical approach for evaluating water quantity performance included the continuous monitoring of storage tank water levels and delineating for positive slopes where inflow exceeds outflow, defined as net-flow into the storage tank. Section 4.1 provides system performance characteristics of water quantity for three selected sites in Madagascar in order to highlight the contextual details which are specific to each system investigated. The continuous monitoring of water levels in Tolongoina provided a unique perspective on system performance, in particularly as it relates to pre and post PPP management. The continuous monitoring of water levels in Ikongo provided perspective on system performance as it relates to seasonal variations in water supply, availability and reliability. In Mananara, the data collected for this study quantified the impact of high growth in the region wherein, the number of customers has more than doubled during the two year study period.

Section 4.2 provides system performance characteristics for three selected sites in Nicaragua where continuous monitoring of water levels in storage tanks began in 2014. The collection of system performance data in Puerto Viejo provided unique insights into the potential complexities involved with delivering reliable water services. The investigation in El Naranjo provided an opportunity to observe a water supply system that has declined in all areas of system performance. Continuous monitoring in El Guabo provided an opportunity to evaluate system performance prior to and after the addition of a new intake which increased source water supply.

Section 4.3 provided a comparative analysis of seven sites in Madagascar and twelve sites in Nicaragua. In Madagascar the systems included private and shared connections to a metered gravity-fed piped water system and were all funded by USAID funding using a Public-Private Partnership model for utility management. In Nicaragua, the systems investigated included metered and un-metered piped water supply that used a community management model for operation and maintenance. All of the systems investigated during this study were implemented in the 2009 – 2015 timeframe, the majority of which included the rehabilitation of existing water infrastructure. The monitoring period for data collection in Madagascar ranged from 47 days of continuous monitoring in Manompana to 508 days of monitoring in Mananara. The monitoring period in Nicaragua ranged from 138 days in El Rodeo to 658 days in Dipina Esperanza.

The results from this investigation delineated system performance characteristics in terms of system reliability and per-capita availability of water. Performance Duration Curves were used to evaluate the proportion of time, in days that the water infrastructure provided different thresholds of per-capita availability of water, and a comparative analysis used a composite criteria taking into account both reliability and availability of water services. The results of this analysis suggest that water delivery services fall into four categories and five classifications. Categories include, Type A systems that provide reliable delivery of large amounts of water, Type B systems that provide a reliable delivery of low volume water, Type C systems that provide an un-reliable supply of higher volumes and Type D systems that provide low reliability of low volumes of water. Classifications include systems that are identified based on a composite of the reliability and availability scores and are delineated as Class-1 (> 90%), Class-2 (80%-90%), Class-3 (70%-80%), Class-4 (60%-70%), and Class-5 (< 60%).

Finally, Section 4.4 provides details of three types of analysis that were used to validate the results. Validation of the supply flowrate entering the storage facility included calculations of the theoretical capacity of the intake system based on the gravitational potential energy available in the system and fundamentals of pipe flow hydraulics. Validation of the per-capita consumption was conducted on selected sites where management records and visual inspection of household water meters was possible. Finally, customer satisfaction surveys with respect to water quantity were used to validate the overall analysis of system performance.

CHAPTER 5

RESULTS AND ANALYSIS
WATER QUALITY

5.0 Results and Analysis: Water Quality Compliance

The results presented in this chapter are intended to address research objectives identified in Section 1.2, and knowledge gaps described in Section 2.6. More specifically, this chapter explores water quality parameters which reflect the performance of the system as described in Objective 1.2, with results that are essential to addressing knowledge gaps related to identifying technical criteria to compare system performance and better anticipate system failure, described in Objective 2.2. Water quality analysis was based on discrete sampling events taken over a three-year period, from within the water supply and distribution systems at seven sites in Madagascar and twelve sites in Nicaragua. The results are summarized in terms of percent compliance with water quality criteria and categorized with respect to microbial, chemical and physical parameters. This chapter starts by presenting the results for three sites in Madagascar and Nicaragua, to further highlight contextual details specific to each system, and then discusses the results for all the systems investigated, for comparative purposes.

Table 5.1 shows a summary of the sampling and analysis schedule and includes information about sample locations and the number of samples from each location. The analytical approach for evaluating water quality performance included a minimum of two sampling events for each site location. Sample locations were determined on-site and included input from the local water operators to ensure that the results were representative of the entire system. Water Quality for each system investigated was analyzed for each individual constituent and was reported in terms of a percent compliance and an average concentration. A composite evaluation of water quality compliance was also calculated, delineating the results for microbial, chemical and physical parameters. Finally, an overall water quality performance score was calculated, giving equal weight to each categorical parameter. The analytical approach did not consider primary or secondary classification for water quality so that results could be used to explore relationships objectively in terms of customer satisfaction with respect to water quality. Table 5.2 shows the water quality criteria used to determine compliance efficiency and Text Box 5.1 shows an example calculation for evaluating system performance in terms of water quality.

In the example shown, fifteen samples were taken from within the supply and distribution system. Two samples were collected from the supply-intake, three samples were collected from the storage tank and ten samples were collected from the distribution system, at the household level. In terms of microbial analysis, of the 45 tests that were completed, 18 samples passed with a compliance score of 40.0%. Of the 60 tests conducted for physical parameters, 50 passed at 83.3% and 93.3% of the chemical tests passed; 138 of 180 tests conducted. The water quality compliance score (η_{WQ} = 72.7%) averages the compliance score for each analytical category in order to present an un-weighted evaluation of water quality. In this example, the total number of tests with an artificially weighted result of 76.7% is also shown, to demonstrate the importance of analyzing the results separately with respect to each categorical parameter.

Text Box 5.1: Example Water Quality Compliance Calculation, η_{WQ}.

Number of Water Samples: 15

Sample Locations: 2 – Source, 3 – Tank, 10 – Distributoin

Summary of Analytical Parameters and Number of Analysis Performed

Microbial - Pathoscreen: 15 Total Coliform: 15 E.Coli: 15

Physical - pH: 15 TDS: 15 Conductivity: 15 Hardness: 15

Chemical – NO_3: 15 NO_2: 15 Cl_2: 15 Metals: 15 Fe: 15

	Microbial	Physical	Chemical	Total
n	45	60	75	180
Pass	18	50	70	138
Fail	27	10	5	42
% Compliance	40.0%	83.3%	93.3%	76.7%

Water Quality Compliance	
η_{WQ}	72.2%

Table 5.1: Available Water Quality Data – Sampling and Analysis Timeframe

Site Location	Sampling Dates	Number of Samples *S: Source, T: Tank D: Distribution, HH: Household*
Madagascar		
Ikongo*	4/1/16, 5/19/16	S2, T4, D19
Tolongoina*	4/5/16, 6/5/16	S2, T2, D12
Mananara*	7/22/15, 3/19/16, 5/20/16	S1, T2, D10
Anivorano Est.	2/12/16, 5/3/16	S5, T4, D8
Andemaka	2/13 - 4/12, 2/15 - 3/15	
Manompana	3/19/16, 6/5/16	S2, T2, D6
Imorona	7/5/13, 7/22/15, 3/15/16	
Nicaragua		
El Guabo*	10/13 – 12/13, 1/14 – 3/14, 10/14, 7/17	S6, T6, D40
El Naranjo*	12/2/14, 3/2/15, 10/10/16, 7/10/17	S3, T4, D50, HH2
Puerto Viejo*	12/2/14, 3/2/15, 10/11/16, 7/11/17	S2, T4, D38, HH35
Dipina Esp.	10/14/14, 3/13/15	S3, T4, D11
Dipina Central	10/29/14, 11/24/14, 3/17/15	S2, T2, D12
Ausberto Paladino	10/30/14, 3/10/15, 7/12/17	S2, T3, D21, HH1
Los Lipes	11/4/14, 2/24/16	S2, T4, D9, HH2
Molino Norte	11/3/14, 2/24/15	S2, T3, D12
San Jose	11/4/14, 2/25/15	S2, T3, D5
San Francisco	11/4/14, 2/25/15	S2, T3, D7
El Rodeo	3/9/15	D5
La Ceiba	11/6/14, 3/9/15	S1, T2, D7

Table 5.2: Water Quality Compliance Criteria

	Parameter	Criteria	Units	Detection Limits
Microbial	Total Coliforms	< 10	CFU/100ml	0
	Escherichia Coliform (E.Coli)	< 1	CFU/100ml	0
Physical	Total Dissolved Solids (TDS)	< 500	mg/L	50
	Conductivity	< 1000	uS/cm	0.1
	Total Hardness	< 300	mg/L	40
	pH	6.5 to 8.5	--	6.0
Chemical	Nitrate	< 50	mg/L-NO_3	2.2
	Nitrite	< 3	mg/L-NO_2	0.5
	Residual Chlorine	0.05 to 1.5	mg/L	0.05
	Total Metals	< 300	µg/L	10
	Iron	< 300	ug/L	20

5.1 Context Analysis of Water Quality Performance: Madagascar

This section provides system performance characteristics of water quality for three sites in Madagascar to highlight the importance of the unique local context for each water system investigated. The analysis of water quality in Tolongoina highlights the importance of understanding how different parameters vary throughout the water supply system. Water Quality analysis in Ikongo further reinforces issues related to variations amongst different water quality parameters and also demonstrates the impact of system disinfection and watershed management. The analysis of water quality in Manaranara further demonstrates the need for watershed management when it comes to protecting water quality wherein a large portion of the watershed is developed and introduces issues related to secondary un-improved water sources within the municipality.

5.1.1 Water Quality Characteristics, Tolongoina

The sampling and analysis of water quality in Tolongoina included twelve samples from within the water distribution system, two samples from the surface water source intake and two samples from the storage tank. From the sixteen samples collected, a total of eleven microbial tests were completed using the CBT MPN method for coliform. The results from this investigation show that 100% of the samples showed the presence of coliform with source samples that ranged from 4.7 to 100 CFC/100ml and distribution samples ranging from 4.7 to 13.6 CFC/100ml. All of the physical parameters tested fell within recommended guidelines for water quality with the exception of pH which was below the prescribed 6.5 criteria. Total Dissolved Solids were analyzed using test-strips and a multi meter and the results ranged from non-detect (ND) for the strip-tests to 21.9 mg/L for the meter test. All of the chemical parameters measured also fell within the recommended criteria. Nitrates and Nitrites were ND for all of the samples and have been reported using the substitution method which allows for a value of one-half the detection limit of the analytical method. All of the samples tested for Total Metals and Iron were within the recommended guidelines for safe drinking water.

Table 5.3 shows the average concentration of each water quality parameter, along with the range and standard deviation of the results for all of the parameters investigated in Tolongoina. This table shows the number of tests included in the analysis (n) for each constituent and the percent compliance with prescribed criteria. Wherein, the results suggest that coliform contamination is the primary concern with respect to the water system's ability to deliver safe drinking water, it also appears that the remainder of the parameters are within recommended standards. A review of the range and standard deviation results is used to better identify how the results vary with respect to different constituents. This data reveals that the range and standard deviation of E.coli (coliform) within the system is an order of magnitude larger than any other samples, with a standard deviation that shows 122.3% deviation from the average. This particular case, highlights the variation in results for microbial contamination as compared to physical and chemical contamination.

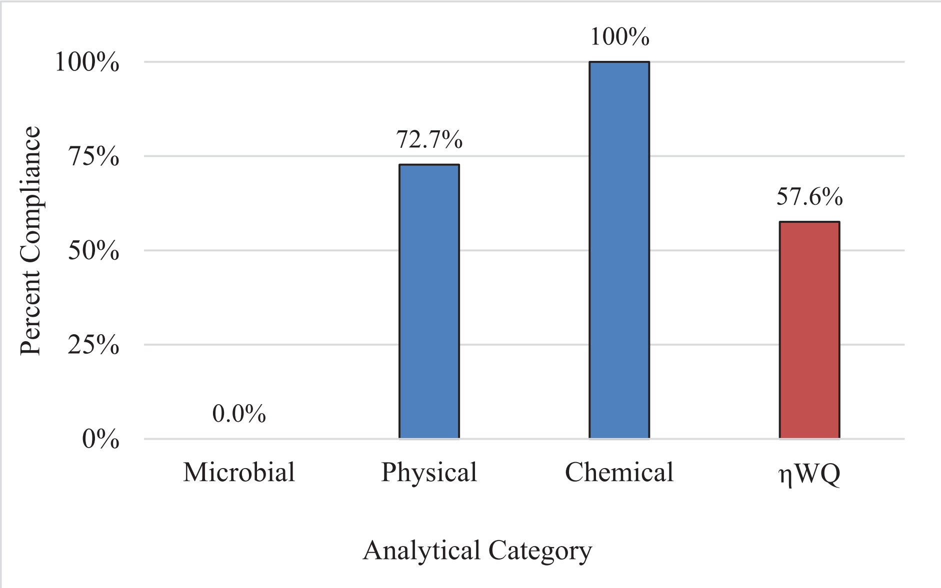
Table 5.3: Water Quality Performance; Tolongoina, Madagascar

Analytical Parameter	n	Percent Compliance	Average Concentration	Range	Standard Deviation
E.Coli (CFC/100ml)	11	0%	24.6	4.7 – 100	30.1
pH (--)	12	0.0%	5.9	5.9 – 6.0	0.0
TDS (mg/L)	13	100%	14.2	10.4 – 18.4	1.9
Conductivity (uS/cm)	13	100%	21.6	16.5 - 27.2	2.4
Hardness (mg/L)	6	100%	20.0	20 - 20	0.0
Nitrate (mg/L-NO3)	6	100%	1.1	1.1 - 1.1	0.0
Nitrite (mg/L-NO2)	6	100%	0.2	0.2 - 0.2	0.0
Free Chlorine (mg/L)	NT	NT	NT	NT	NT
Total Metals (ug/L)	9	100%	16.7	5 - 20	6.6
Iron (ug/L)	8	100%	10.0	10 - 10	0.0

NT: Not tested.

Figure 5.1 shows the consolidated, composite-results of the system's compliance for microbial, physical and chemical parameters. In addition to this, an overall composite water quality score is shown, wherein the system in Tolongoina can be described as providing safe drinking water 57.6% of the time. Appendix C shows additional details about the sampling and analysis of water for the Tolongoina system.

Figure 5.1: Water Quality Compliance; Tolongoina, Madagascar



5.1.2 Water Quality Characteristics, Ikongo

Despite its mountainous location and relative remoteness, the community of Ikongo is classified as an urban commune by the national government. The water system for this town of approximately 7500 people, includes private household connections, shared social connections and a public water kiosk that sells water near the market area. The water system was rehabilitated in 2013 and includes a surface water intake, a slow-sand filter, 2 kilometers of intake piping, a 74,000 liter water storage tank, a solar powered chlorine disinfection system and approximately 3 kilometers of piped distribution. The intake is located in a plateaued watershed that has ongoing agricultural activities and the storage tank is located within an elevated compound adjacent to the town center.

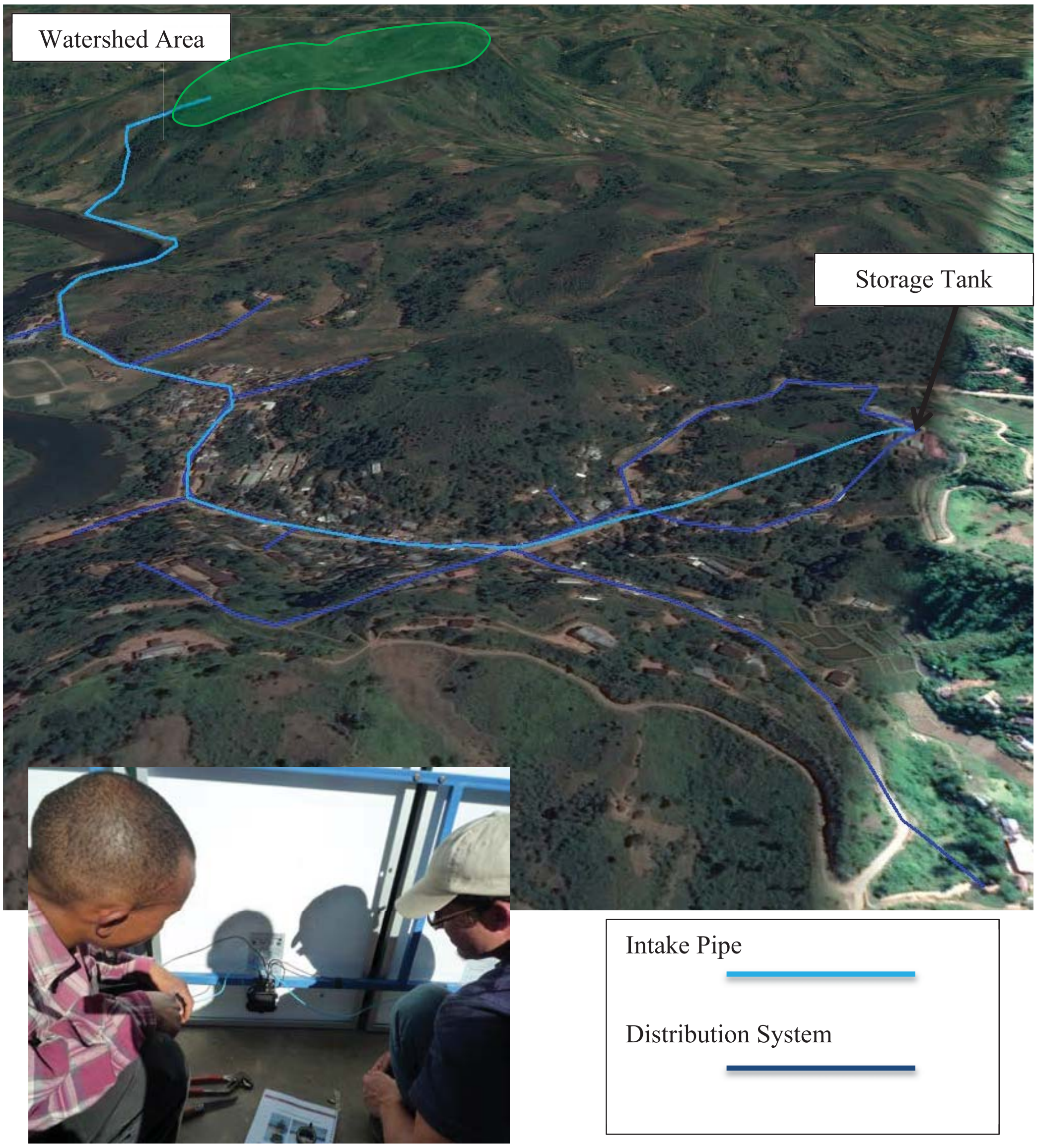
Figure 5.2 shows an overview of the water supply infrastructure along with a photo of the solar powered chlorine generator that uses electrolysis to convert salt to chlorine for disinfection purposes. Whereas, the intake of this system is un-protected, the local management has taken measures to ensure that the water supply is safe for drinking including bypassing the intake system during certain times of the year to prevent agricultural runoff from entering the system as well as chlorinating the system regularly.

In Figure 5.2, the intake and distribution systems are highlighted separately and the bowl shaped plateaued watershed that is supplying the system is also shown. Arial images of the intake watershed (Appendix A) along with discussions with the local water management teams, reveals that there is significant agricultural activity within the watershed, with approximately 35% (8 hectares) of the land-use being rice and coffee farming and very little, if any virgin forest. In addition to this, discussions with local management has confirmed that a number of families reside within the watershed.

The results of the water quality analysis confirm that the system is being disinfected with chlorine however, it appears that the dosing is too low. Both the presence of microbial contamination in the distribution system along with low concentrations of residual chlorine suggest that the chlorine demand is potentially three to five time higher than what is currently being applied. In fact, measurements of batch chlorine being applied to the storage tank suggests that the generally recommended dosing of 2.0 to 5.0 mg/L of chlorine is not being applied wherein, batch concentrations of chlorine solution were entering into the system prior to mixing with raw water at a concentration of 0.5 to 0.8 mg/L. Of the fifteen samples that were analyzed for free chlorine, only seven showed evidence of residual chlorine above the detection limits of the analytical method and only two were within the targeted residual chlorine concentration of 0.5 to 1.5 mg/L. During the study, eight samples were analyzed for E.coli using the CBT MPN method and five samples showed the presence of contamination with a range of 0 to 100 CFC/100ml.

Despite the intake system's vulnerability to contamination from agricultural runoff, water quality results for total dissolved solids, conductivity, nitrate and nitrite suggests that local management has been able to mitigate threats to water contamination with a note that pesticides were not tested during this study. Samples were taken from the source prior to any treatment, after treatment works, from within the storage tank and throughout the

Figure 5.2: System Diagram; Ikongo, Madagascar



distribution system. Two rounds of water testing included sampling and analysis of water just after the rainy season, during the first week of April of 2016 and during the dry season, the last week of May in 2016. In both rounds, 100% of samples taken for TDS (n=15), Conductivity (n=16), NO_3 (n=10) and NO_2 (n=9) passed the prescribed criteria. Other physical parameters studied included pH and it appears that acidity is an issue within the water supply in that the average pH was 6.1 (SD=0.3, n=13) with a note that the testing methods used low-resolution test strips. As a result, the physical water quality compliance was influenced by the pH results where only 77.8% of the physical parameters passed the compliance criteria. In addition to this, the low chlorine residual levels have ultimately influenced the compliance score for chemical constituents where 83.0% of the 53 tests, passed the prescribed criteria. Ultimately however, the microbial results were the lowest among the categories where only 37.5% of the samples met the prescribed criteria. These results combine into a total water quality compliance score of 66.1%. Appendix C provides details of this analysis and Table 5.4 and Figure 5.3 shows a summary of the results. In addition to this, Figure 5.4 is being included in the results to bring attention to the need for further studies with respect to the vulnerability of this particular watershed when it comes to agricultural runoff during the rainy season. Whereas, all of the conductivity measurements passed the prescribed criteria, the difference between conductivity from the rainy to the dry season (15%) suggests that more continuous monitoring of water quality would better inform the impact of human activity within the watershed with a particular vulnerability to agricultural runoff.

Table 5.4: Water Quality Performance; Ikongo, Madagascar

Analytical Parameter	n	Percent Compliance	Average Concentration	Range	Standard Deviation
E.Coli (CFC/100ml)	8	37.5%	30.4	0 – 100	44.1
pH (--)	13	7.7%	6.1	6 – 7	0.3
TDS (mg/L)	15	100%	17.6	13.4 – 23.4	3.2
Conductivity (uS/cm)	16	100%	26.7	19.8 – 36.4	5.0
Hardness (mg/L)	10	100%	24.0	20 - 40	8.4
Nitrate (mg/L-NO3)	10	100%	1.1[1]	1.1 - 1.1	0.0
Nitrite (mg/L-NO2)	9	100%	0.3[1]	0.3 – 0.3	0.0
Free Chlorine (mg/L)	15	40.0%	0.15	0.02 - 0.64	0.21
Total Metals (ug/L)	11	100%	21.4	5 – 100	28.8
Iron (ug/L)	8	100%	36.3	10 - 200	0.1

1. *All samples were below detection limits (ND) and one-half the Detection Limit was reported.*

Figure 5.3: Water Quality Compliance; Ikongo, Madagascar

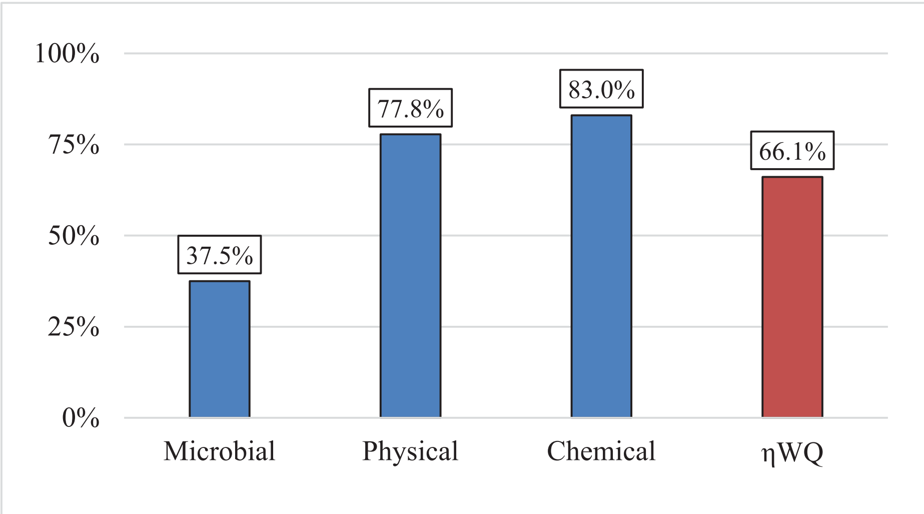
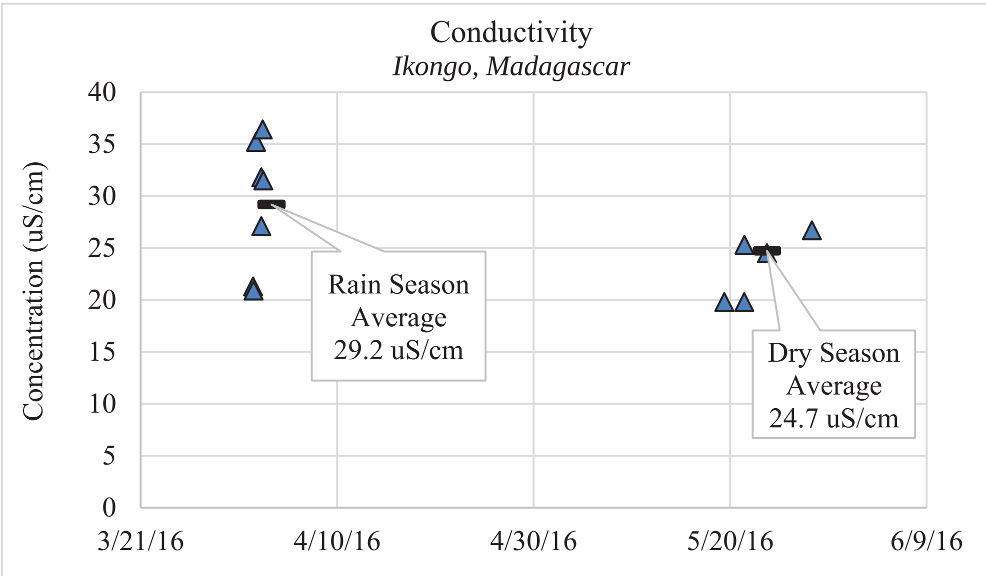


Figure 5.4: Comparison of Rainy and Dry Season Conductivity; Ikongo, Madagascar



5.1.3 Water Quality Characteristics, Mananara

Mananara, the district capital of Analanjirofo, is town of approximately 16,500 people, located in the north eastern coast of Madagascar. The water supply system in Mananara was rehabilitated in 2012 and includes a surface water intake, a gravel intake filter, an electro-chlorinator providing daily batch disinfection, a 200 cubic meter storage facility and approximately 24 kilometers of distribution pipes. A sanitary inspection of the source and information provided by the local management has confirmed that the watershed has significant human activity that includes agricultural as well as residential land use. In fact, a portion of the community of Anasibe, with an estimated 500 people, lives directly in the source watershed wherein the 65.9 hectare basin-area includes approximately 29% virgin forest, 57% farm land and 14% residential land-use types (see text box 5.2).

Water quality analysis of the Mananara water supply system comprised 13 samples collected from throughout the water supply system including source samples collected from the intake system, tank samples collected at the storage facility and distribution samples collected at the household level. An additional 3 samples were collected from secondary water sources where households reported using un-improved shallow wells, and these results are being included here for comparison purposes. Water quality compliance analysis reveals that the Mananara water supply is vulnerable to microbial contamination throughout the water supply and distribution system. With eight water samples analyzed for E.coli contamination, the results averaged 50.5 CFC/100 ml, and none of the samples analyzed pass the compliance criterial. When compared with secondary sources of water, the results are similar wherein three samples collected from shallow concrete lined wells, averaged 52.5 CFC/100ml and no samples passed the compliance criteria for microbial contamination.

Figure 5.5 shows the location of known secondary sources of water within Mananara with photos of different types of water sources, available at the household level. Also shown in this figure is the piped distribution system in the town center wherein household connections include shared and private water points. Whereas, the focus of this research study is to investigate the performance of piped water infrastructure, a relevant surrounding issue with respect to the overall sustainability of improved water supply, is the availability of secondary water resources. In addition to this, the rationale for improving water supply infrastructure often references improvements in community health as related to water quality. As a result, perceived or actual improvements in water quality from un-improved to improved water supply will likely influence the customer's willing to pay for services and ultimately the financial sustainability and long-term reliability of piped water infrastructure.

Table 5.5 shows the composite results for water quality based on location within the water supply distribution system, including the results for samples collected from un-improved sources. Whereas the results would require additional sampling for validation due to the low sample size (n) at each location, it does appear that water quality is not influenced by the type of water source or the location within the water distribution system. Wherein, three samples were collected from an un-improved shallow well and a total of thirteen were collected from different locations within the distribution system, the water quality compliance in terms of percentage of total analytical parameters investigated shows that the un-improved sources are only slightly less compliant than the piped water system. In addition to this, all of the samples that were analyzed for microbial contamination (n=11) failed the E.coli criteria (see Appendix C).

In terms of the overall water quality performance in Mananara, the results reveal that microbial contamination is the primary water quality concern within the system. Figure 5.6 shows the results for the water quality compliance analysis using a composite score, delineated for microbial, physical, chemical constituents and overall water quality compliance. Physical parameters largely complied with the prescribed criteria with the exception of pH which, when taken into consideration with the results from other sites studied in Madagascar, begins to identify the need for higher resolution analytical methods for pH measurements of water quality. In addition to this, the majority of the chemical parameters investigated complied with the prescribed criteria with the exception of free chlorine. Despite the system being treated with chlorine, none of the samples show the presence of free chlorine above the detection limits of the testing methods which further verifies the need for higher resolution when measuring residual chlorine in the distribution system. Appendix C shows additional details on the water quality results base on each parameter investigated.

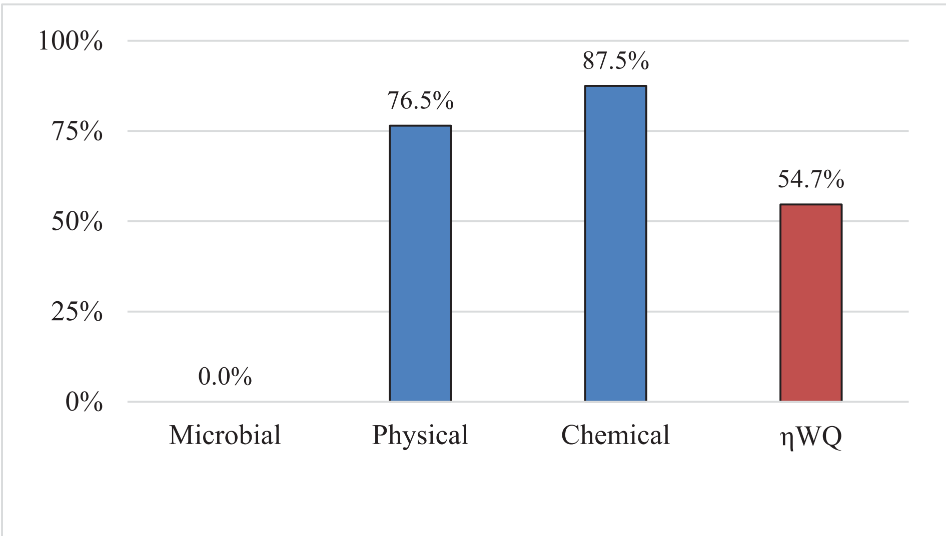
Figure 5.5: Available Water Points, Mananara, Madagascar

Shallow Well　　Private Connection　　Water Kiosk

Table 5.5: Composite Water Quality Results base on Type; Mananara, Madagascar

	Source Intake (n=3)	Storage Tank (n=2)	Distribution System (n=8)	Un-improved Sources (n=3)
No. of Water Quality Tests Analyzed	22	14	38	25
No. of Tests that Passed Prescribed Criteria	16	11	27	17
No. of Tests that Failed Prescribed Criteria	6	3	11	8
Percent Compliance	72.7%	78.6%	71.1%	68.0%

Figure 5.6: Water Quality Compliance; Mananara, Madagascar



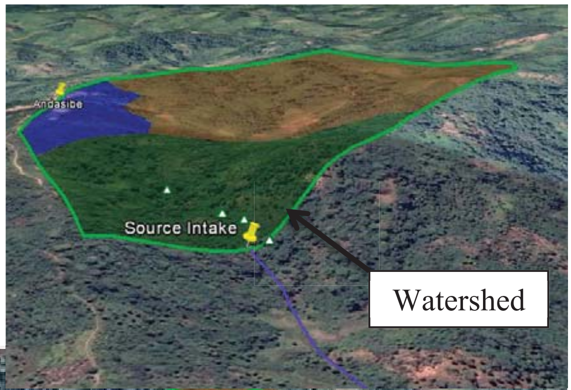
Text Box 5.2: Approximation of Land-use using Arial Images

Watershed Basin Area: 65.9 Hectares

Virgin Forest: 19.4 Hectares

Farm Land: 37.8 Hectares

Residential: 8.1 km^2



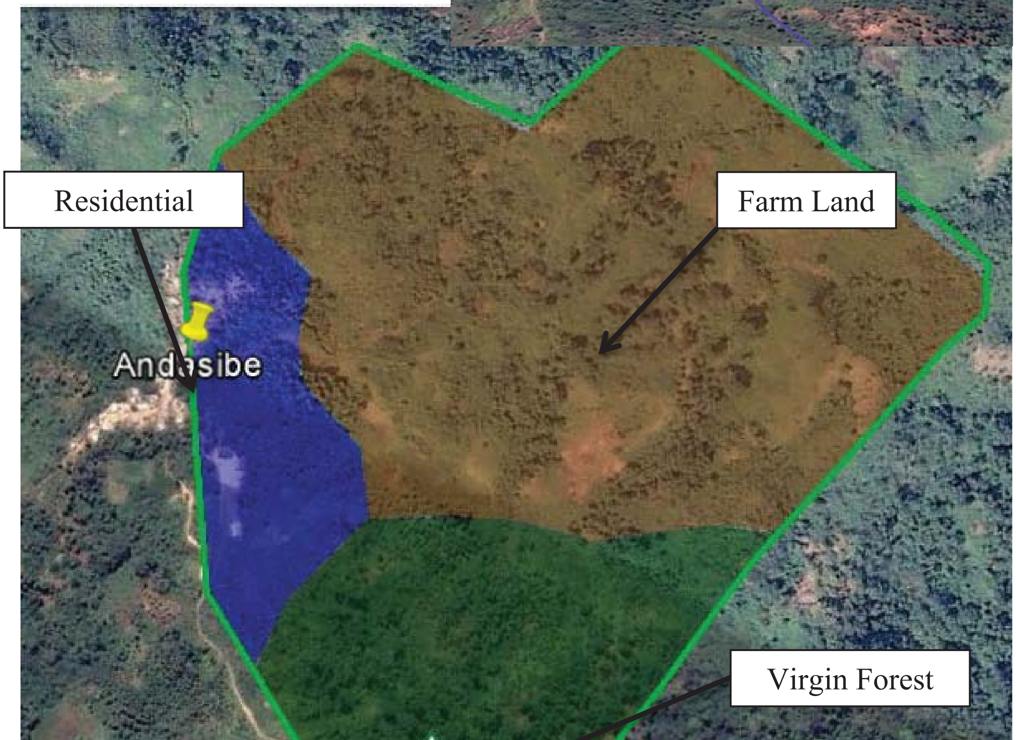


Photo above intake

5.2 Context Analysis of Water Quality Performance: Nicaragua

This section includes water quality results for three site locations in Nicaragua and is being presented here to highlight the contextual details that are essential to understanding system performance characteristics in terms of water quality. Water quality monitoring in Puerto Viejo, El Naranjo and El Guabo involved a number of discrete sampling events spanning a three year period where teams of local researchers and volunteers collected and analyzed water samples using the prescribed field methods. Microbial analysis was completed using Pathoscreen (presence/absence) tests as well as semi-quantitative petrifilm tests for total coliform and e.coli. Physical water quality parameters were analyzed for pH, Total Dissolved Solids, Conductivity and Hardness. Chemical parameters investigated included Nitrate, Nitrite, Free Chlorine, Total Metals and Iron.

The results from this analysis suggests that in Puerto Viejo, secondary household storage is introducing microbial contamination wherein samples collected included system level analysis, household level analysis and household filtration technologies. In El Naranjo, the results indicate that a well-managed watershed and community scale water treatment facility can improve water quality. At the same time, further investigation into the watershed has revealed that the system is vulnerable to illegal connections because of the nature of the intake piping system. In El Guabo, the results introduce the need for innovation in water quality monitoring, in that customer satisfaction aligns closely with water quality results despite the absence of water treatment within the system.

5.2.1 Water Quality Characteristics, Puerto Viejo

The analysis of water quality in Puerto Viejo included four rounds of discrete sampling events spanning a period of three years and totaling 79 samples from throughout the water distribution system as well as from within secondary storage at the household level. As a result, a total of 12 analytical parameters with 401 analytical results have been included in the summary of water quality results for this system. Figure 5.6 shows a summary of the number of samples collected in terms of the location type, within the community of Puerto Viejo. In order to isolate the performance of the water supply infrastructure, samples collected at the household level have been eliminated from the system performance evaluation. At the same time, the data available presents a unique opportunity to compare between household and system level water quality characteristics.

Table 5.6: Water Quality Sampling Summary, Puerto Viejo, Nicaragua

Sample Type	Sample Location	Number of Samples
System	Source	2
	Storage	4
	Piped	38
Household	Bucket	26
	Filter	9

In terms of overall system performance, a composite analysis of 2 samples collected from the source, 4 samples collected from within the storage tank and 38 water samples collected directly from the tap, reveals that the overall water quality compliance was 68.5% for the entire system. At the household level, water samples that were collected from secondary storage that did not include any form of household filtration (n=26), resulted in 66.6% of the analytical parameters being within the targeted compliance criteria. Water samples at the household level that included filtration (n=9) resulted in 71.9% of the parameters complying with the targeted criteria. Table 5.7 shows the results of water quality compliance delineated in terms of analytical category and sample location. In terms of microbial contamination, the results from this analysis reveal that there is microbial contamination within the water distribution system with on 17.9% of samples being compliant. This analysis also reveals that households utilizing secondary storage have lower water quality in terms of microbial contamination wherein only 7.1% of the samples pass the compliance criteria. Furthermore, this analysis reveals that household level water filters only provides modest improvements in water quality, where only 22.2% of the samples passed the compliance criteria. Further investigation of the relationship between water quality and the use of household filtration technology would be needed prior to making conclusions, and; the use of household filtration did show some improvements in overall water quality.

Table 5.7: System and Household Water Quality; Puerto Viejo, Nicaragua

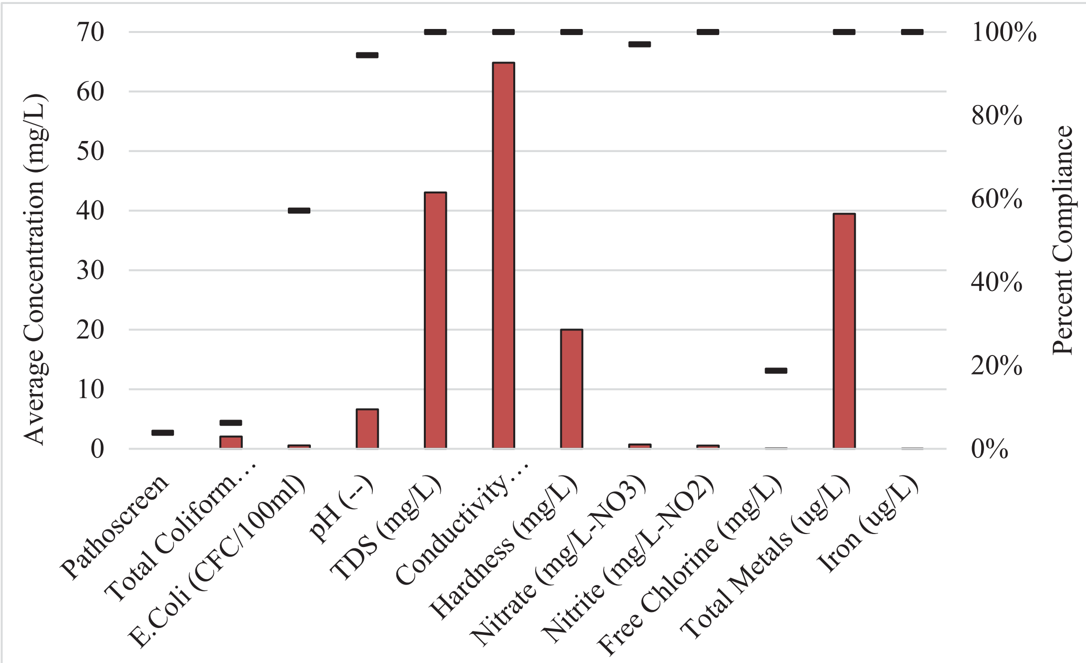
Sample Location	Microbial	Physical	Chemical	Compliance η_{WQ}
System Water Quality	17.9%	99.1%	88.5%	68.5%
N	56	116	122	
Household Water Quality	7.1%	92.6%	100.0%	66.6%
N	56	116	122	
HH Filtered Water Quality	22.2%	93.3%	100.0%	71.9%
N	15	21	2	

Figure 5.7 shows the average concentration for all of the samples collected from within the water supply and distribution system, delineated for each parameter investigated. In order to provide a point of comparison, this figure includes the percent compliance characteristics since each constituent has unique compliance criteria. Percent compliance (shown on the secondary axis) varies significantly for each parameter. Microbial samples ranged from 3.8% to 57.1% in terms of compliance, physical samples ranged from 94.4% (pH) to 100% and chemical constituents ranged from 18.8% (residual chlorine) to 100% for NO_2, metals and iron. An important trend being highlighted here is the relationship between low levels of residual chlorine and the presence of microbial contamination.

Whereas, this trend is to be expected, it is important to note that the water supply systems that included chlorine disinfection also included measurements of chlorine residual and thus, the overall water quality results in terms of percent compliance will be skewed if residual chlorine levels are below the detection limit of the analytical methods. For example, in Tolongoina, Madagascar, the water system is not being chlorinated and thus, this investigation did not include residual chlorine analysis. As a result the water quality compliance for chemical constituents was 100% (see Table 5.1 and Figure 5.1). In this regards, the Puerto Viejo system that does include chlorine disinfection may have equal or better water quality but, thirteen of the sixteen samples fell below the detection limits of the analytical method which results in a lower water quality compliance, 88.5%

for chemical parameters and 67.7% overall. This particular issue is explored further in the comparative analysis as well as in the validation section of this chapter. Additional details on water quality data is provided in Appendix C including information about sample locations and individual sample results.

Figure 5.7: Unconsolidated Water Quality Results, Puerto Viejo, Nicaragua



5.2.2 Water Quality Characteristics, El Naranjo

The community of El Naranjo is located several hours on an unpaved road that connects the municipality of Waslala and Siuna. The water supply for this community includes a surface water intake system that delivers water to a treatment plant consisting of a sedimentation tank, slow-sand filter and chlorination system. The water supply infrastructure includes 4.5 kilometers of intake supply piping as well as 6.5 kilometers of distribution lines that serve 552 connections (January, 2015). The analysis of water system reliability (Chapter 4) suggests that the water infrastructure in El Naranjo is not meeting the minimum basic needs in terms of per-capita availability of water and that, the system is on the verge of failing entirely. Despite this, a qualitative assessment of the community in El Naranjo suggests that there is good demand for water services and that the capacity of the local water management team is relatively high in that they have been operating a water treatment plant and issuing monthly water bills regularly.

Water testing in El Naranjo began in December of 2014 and included a total of four rounds of sampling over a two and a half year period. A total of 59 samples were taken from within the water supply system including 3 samples from the source intake, 4 samples from the storage facility, 50 samples from throughout the distribution system and 2 samples from within secondary storage at the household level. The overall water quality in El Naranjo is consistent with other systems investigated in this study, in that water quality compliance with respect to microbial contamination is lower than the compliance for chemical and physical parameters. The overall composite water quality compliance for the El Naranjo system was 72.4% which included a total of 85 microbial tests, 177 physical tests and 189 chemical tests. The composite compliance analysis averages each water quality category in order to determine an un-weighted water quality performance score, with a microbial compliance score of 38.8%, a physical compliance score of 98.9% and a 79.4% chemical compliance score. Given the water treatment process that involves chlorine disinfection, measurements of chlorine residual were also included in the study. A total of 40 chlorine tests were completed throughout the system with 14 samples showing presence of free chlorine and a 35% compliance score for chlorine residual.

Whereas, the goal of any water treatment initiative is to ensure 100% delivery of safe water, the treatment of water in El Naranjo appears to have a positive influence on the overall water quality of the system as compared to the other systems included in the investigation. In terms of microbial parameters, the El Naranjo water supply is providing higher quality water than any of the other sites referenced thus far in this study, wherein the microbial compliance efficiency was 38.8% as compared to 27.4% (El Guabo), 17.9% (Puerto Viejo), 37.5% (Ikongo), 0% (Mananara) and 0% (Tolongoina). In terms of overall water quality performance, the El Naranjo system also performs okay, which suggests that local management has the capacity to sustain water service delivery. When the relatively good water quality performance is combined with the low water quantity score, it appears that other factors may be playing a role in terms of their ability to provide sustainable access to safe drinking water. The comparative results of water quality is further discussed in Section 5.3 of this study and management capacity is discussed in Chapter 6.

Figure 5.8 shows the unconsolidated water quality results for the El Naranjo system and Figure 5.9 shows an overview schematic of the water supply system. An investigation of both of these figures introduces a logical explanation for the higher water quality performance despite a low water quantity performance. Whereas, the source intake is well forested and the treatment system appears to be well managed, several communities reside along the intake pipeline, making the system vulnerable to illegal or unmanaged connections prior to the treatment and storage facility. More specifically, the community of Aguas Calientes (approximately 300 people) is along the pathway of the intake pipeline serving the El Naranjo system. Whereas, this situation would not create a direct threat to the water quality within the system, it would potentially threaten the quantity of water available in the system. Meanwhile, the well forested watershed above the source intake and the well managed water treatment facility explains the good water quality being provided by the system. Further verification of the nature of water quality is provided in Section 5.4 where customer satisfaction in terms of water quality is discussed. Appendix C shows water quality results with sample dates and location for the El Naranjo system.

Figure 5.8: Unconsolidated Water Quality Results, El Naranjo, Nicaragua

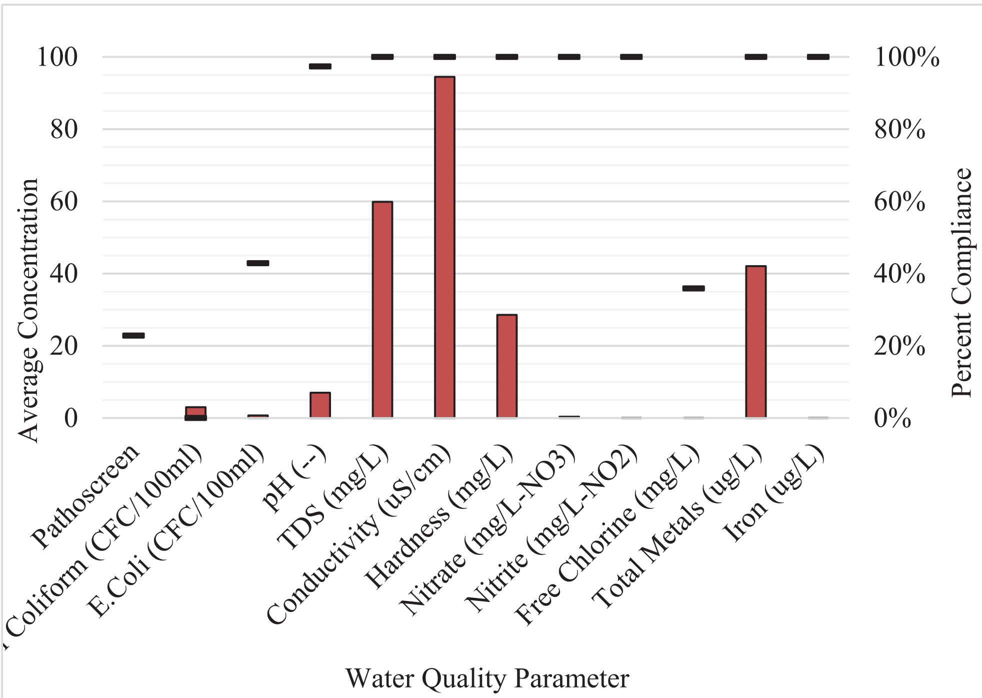


Figure 5.9: System Diagram; El Naranjo, Nicaragua

5.2.3 Water Quality Characteristics, El Guabo

El Guabo is a rural community located approximately 30 minutes from the town of Waslala. Originally constructed in 2011, the water supply infrastructure has included a number of capital improvements and has acquired new customers at a steady rate. The system includes two protected spring intakes that supplies an 18,000 liter storage tank and delivers water to 54 households without water treatment. Rather than having a centralized community water treatment system, the community of El Guabo has elected to use household level water treatment through the use of ceramic filters that have been impregnated with silver nitrate for disinfection. Whereas, ceramic filters have become an available option for household level treatment within the region, this study does not include detailed analysis of post household water treatment wherein the scope is focused solely on the performance of water infrastructure.

Water quality sampling and analysis of the El Guabo system began in October of 2013 and included eight rounds of sampling over a period of almost four years. A total of 52 samples were collected during the study period including 6 source samples, 6 storage tank samples and 40 household level water samples. Samples were tested for microbial contamination using Hach Pathoscreen© tests and 3M Petrifil© tests for Total Coliform and E.Coli. Physical water quality was characterized using a composite analysis of pH, Total Dissolved Solids, Conductivity and Hardness and, chemical water quality included Nitrate, Nitrite, Total Metals and Iron using methods described in Chapter 3. Sampling and analysis of residual chlorine was not conducted because the system was not being disinfected with chlorine at any time during the study period.

Table 5.8 shows the composite analysis of water quality for the El Guabo System, along with the number of analysis for each category (n) and the number of sampling passing and failing the previously described criteria. In terms of Microbial contamination, the system in El Guabo failed all of the Pathoscreen tests for a 0% compliance score (n=17), failed 15 of 38 Total Coliform tests for a 39.5% compliance score and failed 11 of 40 E.Coli tests for a 27.5% compliance score. When combined into a composite score, with the total of 95 tests completed for microbial contamination, only 26 tests passed the criteria resulting in a 27.4% compliance efficiency. Similarly, a total of 195 tests were completed to characterize Physical water quality contamination and 182 or 93.3% of the tests passed the prescribed criteria with only 1 sample failing the TDS test and an unusual number of pH sampling failing the criteria, 12 out of 51 tests. Being that the Chemical compliance analysis did not include residual chlorine, the composite compliance efficiency is relatively high for chemical constituents with 100% of the 135 tests passing the criteria for NO_3, NO_2, Total Metals and Iron. When combined into an overall Water Quality Compliance Score (η_{WQ}) a total of 425 tests were conducted and 343 samples passed the criteria for a 73.6% composite compliance score. Worthy of mention is the nature of customer satisfaction with respect to water quality in El Guabo where, 15 households were surveyed and 80% reported being satisfied or very satisfied with the water quality being delivered to their household, with a MOE of 8% using a 95% confidence interval. Additional information about customer satisfaction is provided in Section 5.4 of this study however, the results from this analysis suggest that the water supply system in El Guabo is providing safe drinking water 73.6% of the time. Appendix C shows additional details for water quality date collected in El Guabo.

Table 5.8: Composite Analysis of Water Quality; El Guabo, Nicaragua

	Microbial	Physical	Chemical
N	95	195	135
Pass	26	182	135
Fail	69	13	0
% Compliance	27.4%	93.3%	100%

Water Quality Compliance	
η_{WQ}	73.6%

5.3 Comparative Analysis of Water Quality Performance

This section provides a comparative analysis of water quality results for seven sites investigated in Madagascar and twelve sites investigated in Nicaragua. In order to compare water quality performance characteristics, the results are presented in terms of water quality from the source, water quality from within the storage tanks and water quality throughout the distribution system.

A composite water quality score, representing samples taken throughout the entire system is also presented for each site location that does not include residual chlorine. Finally, the results are summarized in terms of individual constituents and are presented for each site to further highlight issues related to microbial contamination.

5.3.1 Comparative Analysis of Water Quality – Madagascar

Within the seven sites investigated in Madagascar, a total of 71 microbial tests, 292 physical tests and 272 chemical tests were completed. In order to provide a true comparison, the results for residual chlorine have been eliminated from the analysis which ultimately yields a total of 244 chemical tests included in the comparative analysis. In addition to this, household level samples were analyzed from improved and un-improved water points where users reported having access to secondary water points within the study area. These results were consolidated for all sites investigated and were delineated between improved and un-improved in order to provide additional points of comparison. Issues related to the difference between improved and un-improved were outside the scope of this research study but have been included in text box discussions to introduce additional context with respect to the relationship between sustainable water infrastructure and access to secondary water sources within the project area.

Table 5.9 shows the average overall water quality performance for all of the systems investigated in Madagascar delineated by sample location within the study area and water quality category. Included in this table are the average results for all systems studied showing details for source samples, samples collected from within the storage tanks and samples collected from within the distribution system. The overall performance is also shown, wherein the average of the individual water quality categories is determined in order to provide an un-weighted analysis that is independent of the number of analysis (n) performed for each water quality category. The analytical results for the improved and un-improved where households reported using secondary water sources are also included in this table.

Table 5.9: Sample Location Delineated Water Quality, Madagascar

Sample Location	Microbial		Physical		Chemical		Performance	
	Compliance	n	Compliance	n	Compliance	n	Compliance η_{WQ}	n
Source	14.3%	14	78.7%	47	95.5%	44	62.8%	105
Tank	15.4%	13	82.4%	68	98.0%	54	65.3%	135
Distribution	12.5%	24	79.5%	88	100%	72	64.0%	184
Improved	0%	3	78.6%	28	81.0%	21	53.2%	52
Un-improved	0%	7	78.0%	50	100%	36	59.3%	93

Average Water Quality Compliance	
η_{WQ}	62.5%

The results shown in Table 5.9 clearly show evidence that microbial contamination is a major concern throughout the systems investigated, including un-improved and improved water points. Physical water quality constituents for the sites investigated was also low, wherein only the results from within water storage tanks scored higher than 80% with an 82.4% compliance score. An investigation into the details for physical constituents (Appendix C) reveals that the results for pH were generally lower than the 6.5 value recommended by the World Health Organization which was the criteria used for this study. The results for chemical constituents investigated show that the water supply improved within the distribution system where source and tank water scored 95.5% and 98% respectively and distribution water scored 100%, where samples were collected from faucets at the household level. An investigation into the details for chemical analysis (Appendix C) shows that seven of the 61 samples analyzed for total metals failed to meet the threshold criteria of 300 ppb which would warrant further investigation at these locations. Finally, these results show only a marginal difference in water quality between the piped system and improved (handpumps) and un-improved (shallow wells) water sources, see Text Box 5.3 for further discussion.

Wherein, the water quality issues related to microbial contamination have been clearly identified, the comparative analysis can focus entirely on the overall system compliance (η_{WQ}) in order to investigate differences in water quality between systems as well as within the system itself. An analysis of the difference between source quality and distribution quality reveals four potential scenarios of interest. Systems with poor water quality at the source that improve in quality as it is delivered to the community, would be increasing quality within the system. Systems with poor source-water quality that remain low in water quality would be maintaining low water quality. Systems with good source-water quality that decline in water quality within the distribution system would be decreasing and system with good source-water quality that remain good would be maintaining good water quality. Figure 5.10 shows a plot of the source water quality compliance versus distribution water quality compliance. In order to highlight increasing quality within the system, the source water compliance (y-axis) is shown using a reverse axis so that the upper right quadrant of the graph can be used to identify high performing systems. A criteria of less than 80% compliance has been used to define poor water quality and greater than 80% compliance to define good water quality. The systems identified within Quadrant A are those that had poor source-water quality but good distribution-water quality. Quadrant B would be systems with good source-water and good distribution-water quality and Quadrant C would be systems with both poor source-water and poor distribution-water quality. Quadrant D would be systems that are failing wherein, good source-water quality is being contaminated within the system and is providing poor distribution-water quality.

Text Box 5.3: Comparing Improved and Un-improved Secondary Water Points

All of the project site locations investigated in Madagascar had evidence and reports of secondary access to water points at the household level. This combined with the low per-capita water use from the piped water system, suggests that the majority of households are using secondary water points for domestic purposes. Secondary water-use was also confirmed by the local field research team who reported that households use both improved (hand-pumps) and un-improved (surface water or shallow wells) water points.

Average Concentrations of Water Quality Samples from Un-improved Sources:

Description	E.coli	pH	TDS	Conductivity	Hardness
Average Concentration	50.3	6.0	92.0	304.0	68.0
Percent Compliance	0.0%	15.4%	100.0%	100%	100%
No. Samples	7	13	10	17	10

Description	Nitrate	Nitrite	Total Metals	Iron
Average Concentration	3.3	0.4	40.0	0.30
Percent Compliance	100%	100%	100.0%	100%
No. Samples	10	10	10	6

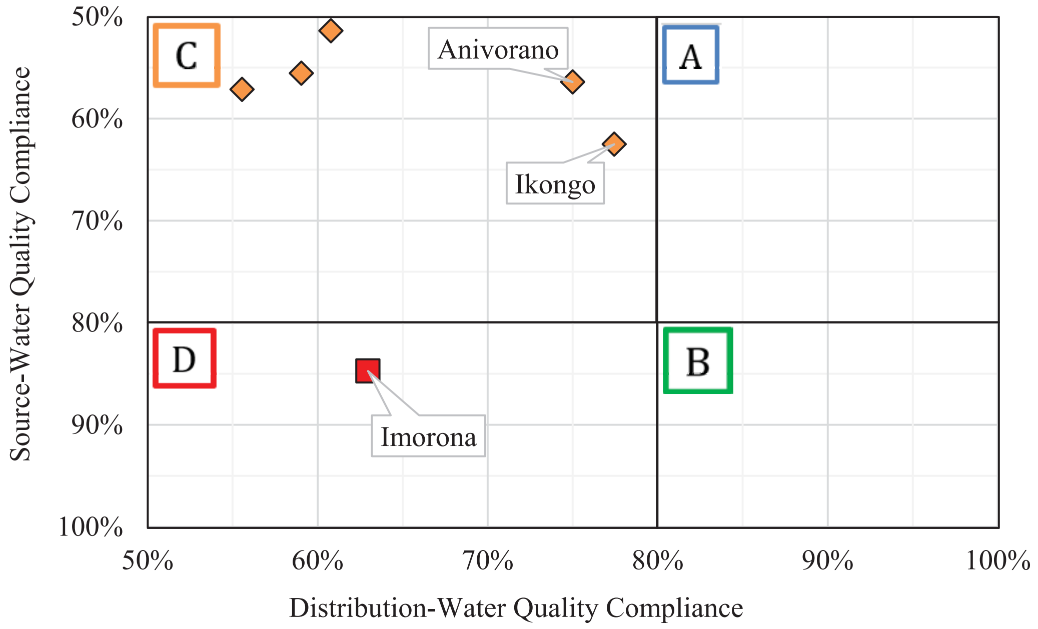
Average Concentrations of Water Quality Samples from Improved Sources:

Description	E.coli	pH	TDS	Conductivity	Hardness
Average Concentration	8.90	6.05	68.4	175.9	33.4
Percent Compliance	0.0%	25.0%	100.0%	100%	100%
No. Samples	3	8	6	8	6

Description	Nitrate[3]	Nitrite[4]	Total Metals[5]	Iron
Average Concentration	1.28	0.25	476.6	0.17
Percent Compliance	100%	100%	33.3%	100%
No. Samples	5	5	6	5

The results for all of the water quality parameters investigated show an increase in water quality between un-improved and improved water sources, with the exception of total metals where four of the six improved source samples failed. Nonetheless, the increase in water quality is evident with the important note to the fact that the improved sources still did not pass the prescribed water quality criteria for microbial contamination.

Figure 5.10: Comparative Water Quality Analysis using Quadrants; Madagascar



System Identification (Highest to Lowest Distribution Quality)
Quadrant A - None
Quadrant B – None
Quadrant C – Ikongo, Anivorano Est., Mananara, Tolongoina, Manompana
Quadrant D – Imorona

In Figure 5.10, it can be seen that no systems investigated in Madagascar exhibit increasing water quality within the system (Quadrant A) with only two of the sites, Ikongo and Anivorano approaching the 80% compliance threshold established for this analysis. In addition to this, no site locations investigated started with and maintained good initial source water quality (Quadrant B). The system in Imorano (Quadrant D) exhibits good initial water quality and that decreases in compliance at the household level where the initial source-water compliance of 84.7% declines to 63.0% within the system. The remaining systems investigated started with very poor water quality with an initial source-water compliance of less than 60% and the water quality remained poor within the system as it was distributed to the household customers.

Regardless of initial source water quality, an important consideration when investigating system performance is simply comparing water quality at the household customer level. In this regards, any system with a compliance score of greater than a 90%

compliance score within the distribution system, would be identified as providing very good or high quality water. Similarly, using a 10% interval, water systems with compliance scores of 80-90%, 70-80%, 60-70% and less than 60% would be defined as good, okay, poor and very poor respectively. Table 5.10 shows the results for all of the systems investigated and has been ranked with respect to the final household level water quality with the above described criteria identified. In Table 5.10 it can be seen that none of the water distribution systems investigated provided very good or good water quality and only two (Ikongo and Anivorano) provided okay water quality. The remaining system provided either poor or very poor water quality with further emphasis that Imorona initially had good water quality (84.7%) but that the water quality declined to 63.0% within the system prior to reaching the household customers. Both the un-improved and improved water sources in the area provided very poor water quality in terms of compliance with the prescribed criteria.

Table 5.10: Comparative Water Analysis using Compliance Thresholds; Madagascar

		Water Quality Compliance					
		Source		*Tank*		**Distribution**	
	Site Location	*Compliance*	*n*	*Compliance*	*n*	**Compliance**	**n**
Very Good	None	--	--	--	--	**--**	**--**
Good	None	--	--	--	--	**--**	**--**
Okay	Ikongo	*62.5%*	*17*	*70.0%*	*55*	**77.5%**	**32**
	Anivorano Est.	*56.4%*	*29*	*64.1%*	*29*	**75.0%**	**15**
Poor	Imorona	*84.7%*	*15*	*63.0%*	*21*	**63.0%**	**21**
	Mananara	*51.4%*	*16*	*61.9%*	*15*	**60.8%**	**36**
Very Poor	Tolongoina	*55.6%*	*7*	*61.9%*	*13*	**59.0%**	**65**
	Un-improved	*NA*	--	*NA*	--	**59.3%**	**93**
	Manompana	*57.1%*	*15*	*55.6%*	*15*	**55.6%**	**15**
	Improved	*NA*	--	*NA*	--	**53.2%**	**52**

5.3.2 Comparative Analysis of Water Quality Performance – Nicaragua

Within the twelve sites investigated in Nicaragua, a total of 714 microbial tests, 848 physical tests and 913 chemical tests were completed. In order to provide a true comparison of results, all of the water quality results for residual chlorine were eliminated from the analysis which ultimately yields a total of 788 chemical tests being included in the results presented here. In addition to this, household level samples where water quality was analyzed within secondary storage and post-household treatment have been eliminated from the analysis in order to isolate system performance specific to the infrastructure itself. Issues related to secondary storage and household treatment are included in text box discussions to introduce these results for discussion purposes.

Table 5.11 shows the average overall performance for all of the systems investigated in Nicaragua in terms of sample location and is presented here as a point of comparison for the individual systems. Included in this table is the number of samples analyzed for each water quality category which introduces some limitations when considering the limited sample size for the individual systems. For example, the total microbial analysis performed on source samples for the entire study is 71 however the number for each individual site ranges from 4 at Ausberto Paladino to 17 at El Guabo. The results from Table 5.11 suggests that water quality is improving as it moves through the system wherein, the overall performance in terms of water quality (η_{WQ}) has improved by 5.5% between source and tank samples and by 5.0% from the source to the end users within the distribution system. Whereas, the overall water quality goal of any water delivery system is to provide water that is 100% compliant, these results are encouraging in that there is clear evidence that microbial contamination is the primary water quality constituent of concern. Furthermore, these results introduce an excellent source of comparison when interpreting the results for each site and identifies systems that are performing better, on average.

Table 5.11: Sample Location Delineated Water Quality, Nicaragua

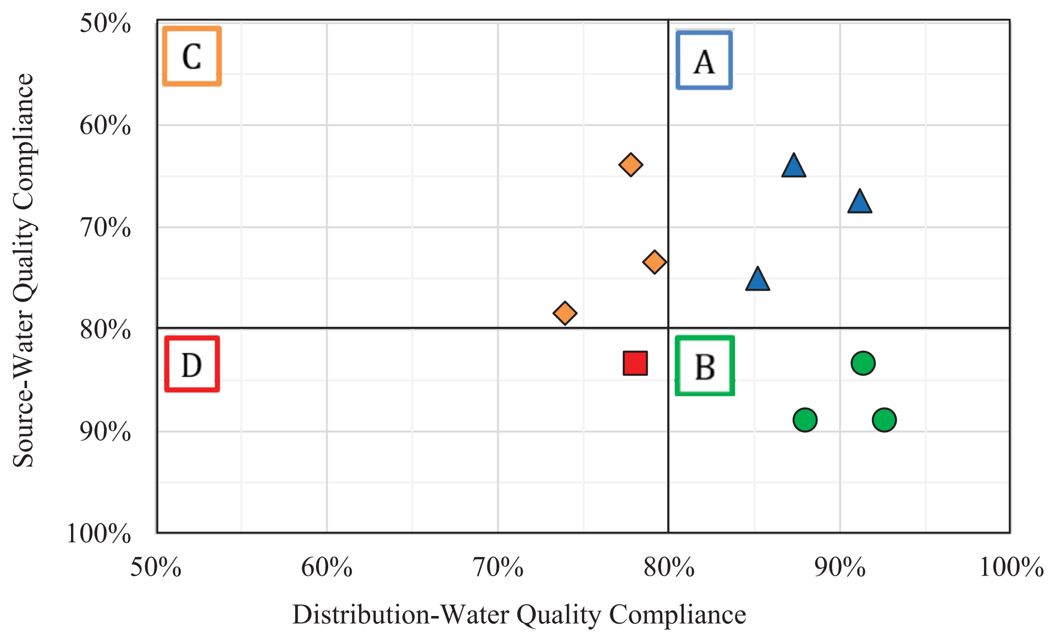
Sample Location	Microbial		Physical		Chemical		Performance	
	Compliance	n	Compliance	N	Compliance	n	Compliance η_{WQ}	n
Source	36.6%	71	95.4%	109	98.8%	83	76.9%	263
Tank	48.2%	83	99.0%	102	100%	93	82.4%	278
Distribution	46.8%	500	98.8%	646	100%	603	81.9%	1749

Average Water Quality Compliance	
η_{WQ}	81.3%

Wherein, the water quality issues related to microbial contamination have been clearly identified, a comparative analysis can focus entirely on the overall system compliance (η_{WQ}) in order to identify differences in water quality between systems as well as within the system. An analysis of the difference between source quality and distribution quality reveals four potential scenarios of interest. Systems with poor water quality at the source that improve in quality as it is delivered to the community, would be increasing quality within the system. Systems with poor source-water quality that remain low in water quality would be maintaining low water quality. Systems with good source-water quality that decline in water quality within the distribution system would be decreasing and system with good source-water quality that remain good would be maintaining good water quality. Figure 5.11 shows a plot of the source water quality compliance versus distribution water quality compliance. In order to highlight increasing quality within the system, the source water compliance (y-axis) is shown using a reverse axis so that the upper right quadrant of the graph can be used to identify high performing systems. A criteria of less than 80% compliance has been used to define poor water quality and greater than 80% compliance to define good water quality. The systems identified within Quadrant A are those that had poor source-water quality but good distribution-water quality. Quadrant B would be systems with good source-water and good distribution-water quality and Quadrant C would be systems with both poor source-water and poor distribution-water quality. Quadrant D would be systems that are failing wherein, good source-water quality is being contaminated within the system and is providing poor distribution-water quality.

An important consideration when investigating water quality performance is the final water quality delivered in the system regardless of the initial water quality. In this regards, any system providing water quality at a greater than 90% compliance should also be identified as high performance. Table 5.12 shows the water quality results using distribution compliance thresholds wherein the system performance is evaluated only on the water quality delivered to the household customer. Using the 90% compliance threshold, four sites have been identified as providing very good, or high quality water to the end-users. Using the 80% compliance threshold, three sites have been identified as providing good quality water and four sites have been identified as providing okay water quality to the customers. Also shown in Table 5.12 are the results for Source and Tank water quality which are being presented for discussion purposes and to highlight systems that are increasing in water quality from source to distribution, see Figure 5.11.

Figure 5.11: Comparative Water Quality Analysis using Quadrants; Nicaragua



System Identification (Highest to Lowest Distribution Quality)
Quadrant A - Dipina Esperanza, San Francisco, Ausberto Paladino
Quadrant B – Molino Norte, Los Lipes, Dipina Central
Quadrant C – El Naranjo, San Jose, El Guabo
Quadrant D – Puerto Viejo

Table 5.12: Comparative Water Analysis using Compliance Thresholds; Nicaragua

	Site Location	*Source*		*Tank*		**Distribution**	
		Compliance	*n*	*Compliance*	*n*	**Compliance**	**n**
Very Good	El Rodeo	*NT*	--	*NT*	--	**97.2%**	**27**
	Molino Norte	*NT*	--	*88.9%*	*25*	**92.6%**	**54**
	Los Lipes	*83.3%*	*14*	*93.3%*	*21*	**91.4%**	**39**
	Dipina Esperanza*	*67.4%*	*28*	*94.4%*	*10*	**91.2%**	**70**
Good	Dipina Central	*88.9%*	*19*	*83.3%*	*14*	**88.0%**	**66**
	San Francisco*	*63.9%*	*14*	*74.1%*	*21*	**87.3%**	**33**
	Ausberto Paladino*	*75.0%*	*17*	*85.7%*	*19*	**85.2%**	**118**
Okay	El Naranjo	*73.4%*	*31*	*77.8%*	*38*	**79.2%**	**347**
	Puerto Viejo	*83.3%*	*17*	*85.7%*	*25*	**78.0%**	**320**
	San Jose	*63.9%*	*14*	*74.1%*	*21*	**77.8%**	**18**
	El Guabo	*78.4%*	*97*	*75.3%*	*74*	**73.9%**	**600**
Poor	None	--	--	--	--	**--**	**--**
Very Poor	None	--	--	--	--	**--**	**--**

**: High Performing Systems using the Quadrant Analysis,*
NT: Not tested, Note: Molino Norte used Tank Compliance in Quadrant Analysis.

5.3.3 Characterization of System Performance

Within the twelve sites investigated in Nicaragua and the seven sites investigated in Madagascar, there is a wide range in water quality system performance. Whereas, there is consistency for all site investigated in that all of the systems performed very poorly with respect to microbial water quality criteria, the overall performance ranged from very good to very poor in terms of overall system performances. The highest composite water quality source, taking into account all of the samples collected from throughout the supply and distribution system was located at the Dipina Central system in Nicaragua with an 88.9% compliance score that includes a 66.7% microbial score and 100% for both physical and chemical parameters. The lowest overall water quality compliance was located in Mananara, Madagascar with a 51.4% compliance score that included a 0% score for microbial quality (n=2), 66.7% physical quality (n=6), and 87.5% chemical quality score (n=8). The average source water compliance score for all of the systems studied was 69.7%, with a 12.2% standard deviation.

Figure 5.12 shows the overall water quality compliance results delineated with respect to the sample location for each site. The results in this figure are ordered in terms of highest to lowest distribution water quality. The highest water quality delivered to household customers is located in El Rodeo wherein 97.2% of the samples collected from within the distribution system passed the water quality compliance criteria. This system however only included five water samples and a total of 27 analytical tests with 12 microbial, 3 physical and 12 chemical analysis completed. Molino Norte, Los Lipes and Dipina Esperanza, all located in Nicaragua, had distribution water quality scores above the 90% threshold used to define very good water quality. Three sites, Dipina Central, San Francisco and Auberto Paladino (also located in Nicaragua) provided good water quality using the greater than 80% criteria. The four lowest performing systems were all located in Madagascar with poor or very poor water quality; Imorona, Mananara, Tolongoina and Manompana. In addition to this, Figure 5.12 provides a simple means of identifying water systems that are increasing or decreasing in water quality by showing the results of the source, tank and distribution water separately.

Figure 5.12: Water Quality Performance Summary; Nicaragua and Madagascar

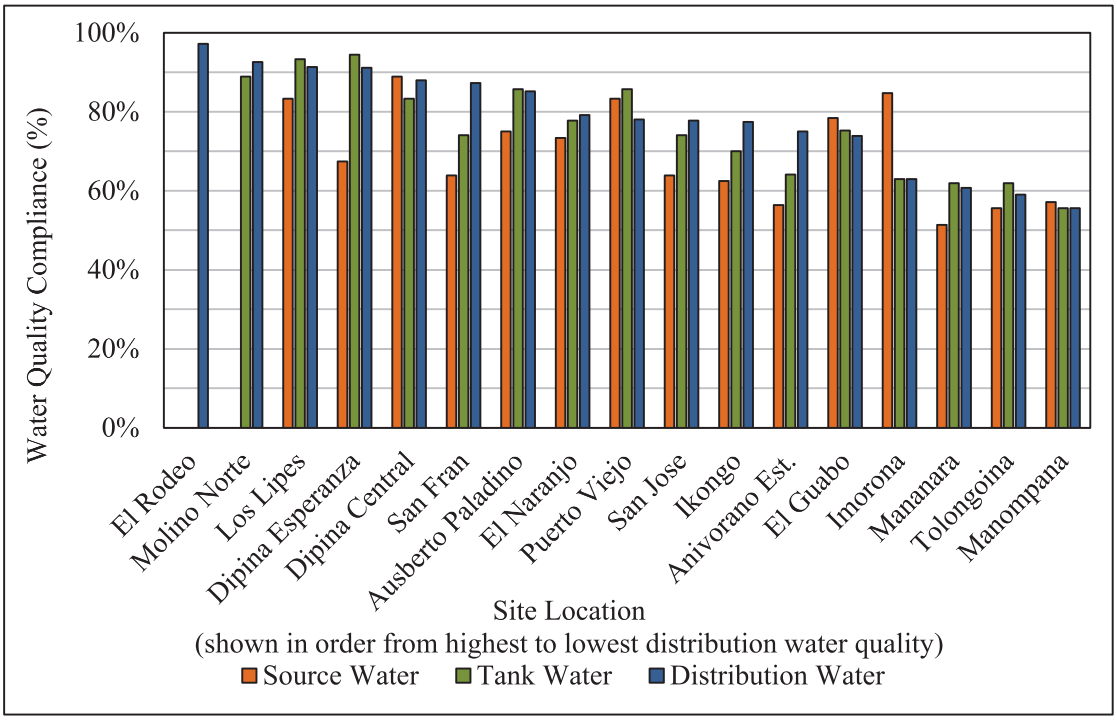
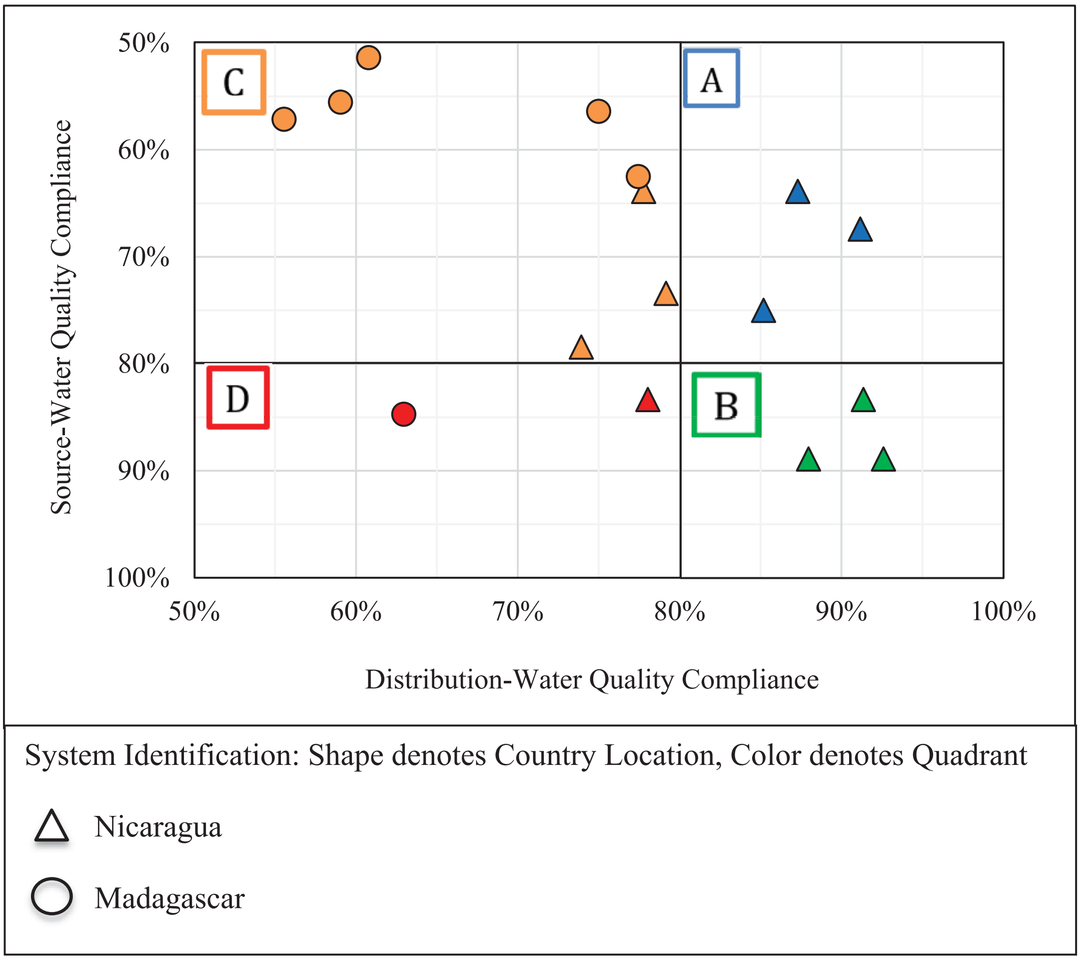


Figure 5.13 shows the results using the quadrants for all of the sites studied including Nicaragua and Madagascar. From this figure, it can be seen that the majority of the sites investigated in Nicaragua are outperforming the systems in Madagascar in terms of initial source water quality as well as distribution water quality. Recommended follow up studies should investigate the type of intake and watershed characteristics to determine if these factors play a role in the overall water quality performance of the systems.

Figure 5.13: Comparative Water Quality using Quadrants; Nicaragua and Madagascar



5.4 Validation of Results

This section provides a summary of the data used to confirm the validity of the results for water quality performance characteristics. Quality assurance and quality controls were used to ensure that the analytical methods did not introduce contamination during the sampling and analysis process. Furthermore, customer satisfaction data at the household level was used to ensure that the results were reasonable and to provide qualitative information about the system performance.

5.4.1 Quality Assurance and Quality Control

Two types of QA/QC were used to test the reliability of the water quality data. Field and laboratory blank samples were analyzed and processed using the same sampling and analytical methods used to evaluate system performance of water quality, and were compared against the expected results of being 100% compliant with the established criteria. Field blank samples were collected onsite during the field investigation for specific communities and were handled using the same sampling methods previously described in Chapter 3. Laboratory blank samples were used to ensure that the laboratory procedures for analyzing and incubating water samples did not introduce contamination. In addition to this, duplicate samples were collected during the field investigation wherein, every sampling round collected a minimum of one duplicate per system. The analytical approach to testing the reliability of the data, isolated all duplicate samples for the entire study and evaluated the results using the compliance criteria with and without the duplicate samples.

Table 5.13 shows a summary of results for field blank samples collected during this study. Included in this table is the percent compliance with the prescribed criteria along with the average concentration, range and standard deviation of the results. Also shown is the number of analysis performed for each parameter with a particular emphasis on the limited number of analysis performed on physical and chemical parameters. Also noted in this table is the pH compliance wherein, the one blank sample collected failed the criteria resulting in a 0% compliance for this parameter.

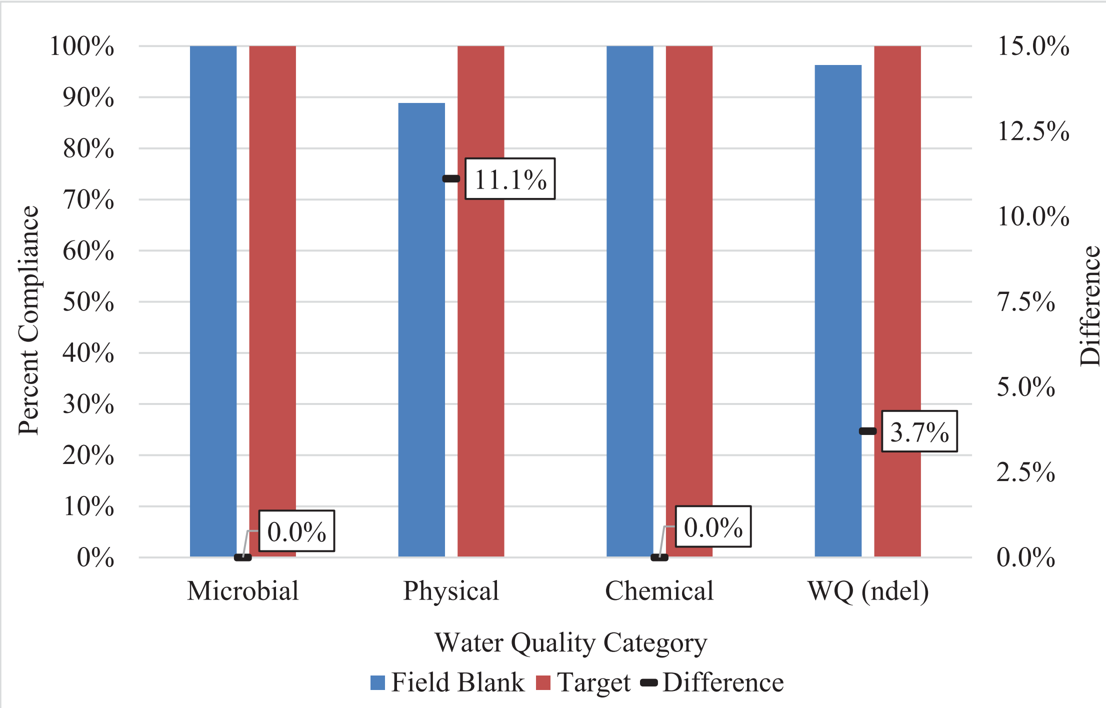
Table 5.13: Water Quality Performance; Field Blanks, Nicaragua and Madagascar

Analytical Parameter	n	Percent Compliance	Average Concentration	Range	Standard Deviation
Pathoscreen (P/A)	26	100%	NA	NA	NA
Total Coli (CFC/100ml)	13	100%	0	0.0 - 0.0	0.0
E.Coli (CFC/100ml)	23	100%	0	0.0 - 0.0	0.0
pH (--)	1	0%	5.9	5.9 - 5.9	NA
TDS (mg/L)	3	100%	7.0	5.0 - 9.9	2.59
Conductivity (uS/cm)	3	100%	12.2	10.0 - 15.6	2.99
Hardness (mg/L)	2	100%	20.1	0.1 - 40	28.2
Nitrate (mg/L-NO3)	2	100%	0.8	0.5 - 1.1	0.42
Nitrite (mg/L-NO2)	2	100%	0.25	0.25 - 0.25	0.0
Free Chlorine (mg/L)	0	NT	NT	NT	NT
Total Metals (ug/L)	2	100%	10.0	9.9 - 10	0.07
Iron (ug/L)	0	NT	NT	NT	NT

NT: Not tested.

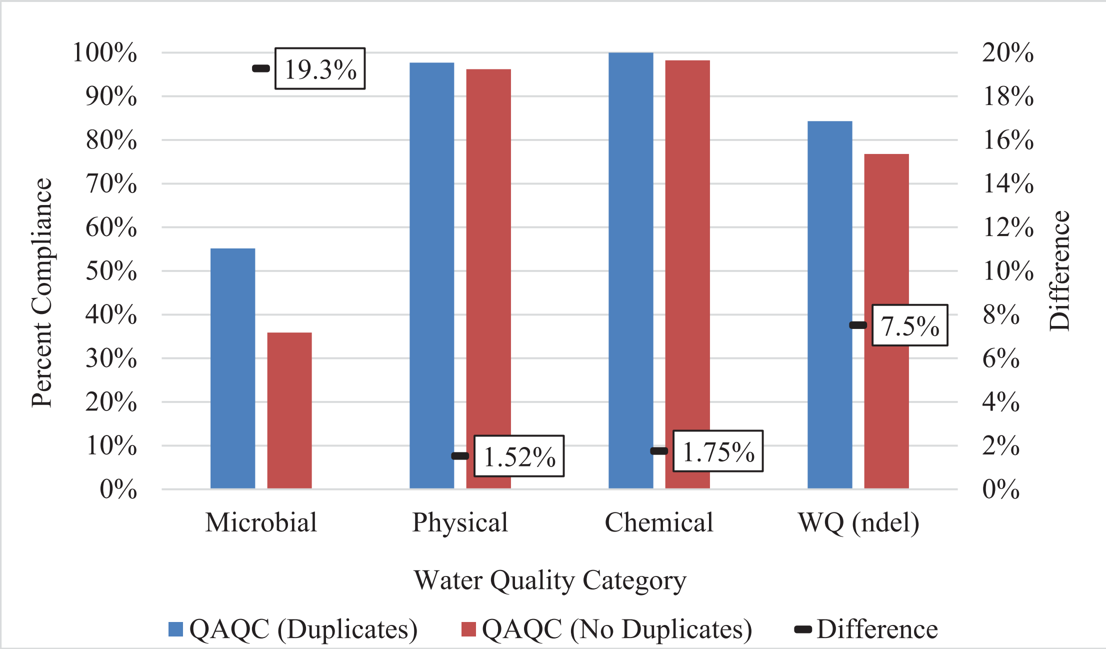
Figure 5.14 shows the overall performance characteristics for all field and laboratory blank samples collected as a part of the QAQC protocol for the study. This figure shows the percent compliance for blank samples categorized in terms of microbial, physical, chemical and overall composite water quality. Shown on the secondary axis is the difference between the compliance results for the blank samples and the expected result of 100% compliance wherein, bottled water would be compliant with the criteria unless the field and laboratory methods introduced contamination. In terms of microbial parameters, of the 62 tests performed on blank samples, 100% of the results complied with the prescribed criteria, confirming that field and laboratory methods did not introduce microbial contamination. In terms of physical parameters, 9 tests were conducted and all but one of the pH results complied resulting in an 88.9% compliance. In terms of chemical parameters, 6 tests were conducted with 100% compliance. The analytical methods for evaluating overall system performance took an average of each water quality category and thus, the overall performance of blank samples was 96.3%, primarily resulting from the single pH sample which did not pass the criteria. As a result, this means that the field, laboratory and analytical methods have introduced an error of 3.7% during the water quality analysis, or the field methods used were 96.3% reliable.

Figure 5.14: Data Reliability Testing using Field and Laboratory Blanks



Duplicate samples were collected throughout the study to further test the reliability of the sampling and analysis of water quality during this study. In order to evaluate the reliability of the data collected, a total of 27 samples were duplicated and a compliance analysis was conducted with and without duplicates, regardless of site location. As a result, a total of 181 tests were conducted that included live samples and a total of 106 tests were conducted using only duplicate samples. The water quality performance analysis was performed for both sets of data with and without duplicate samples and the results were compared to determine test the reliability of the data. Figure 5.15 shows the results of the data reliability-test where the target value uses the data without duplicate samples. After establishing a target value, the difference between the results of live and duplicate samples was used to calculate the data reliability. From this analysis, it can be determined that the overall analytical methods for collecting and analyzing the results introduced a 7.5% error and that the overall reliability of the analytical method for evaluating system performance was 92.5% reliable.

Figure 5.15: Data Reliability Test using Duplicate Samples

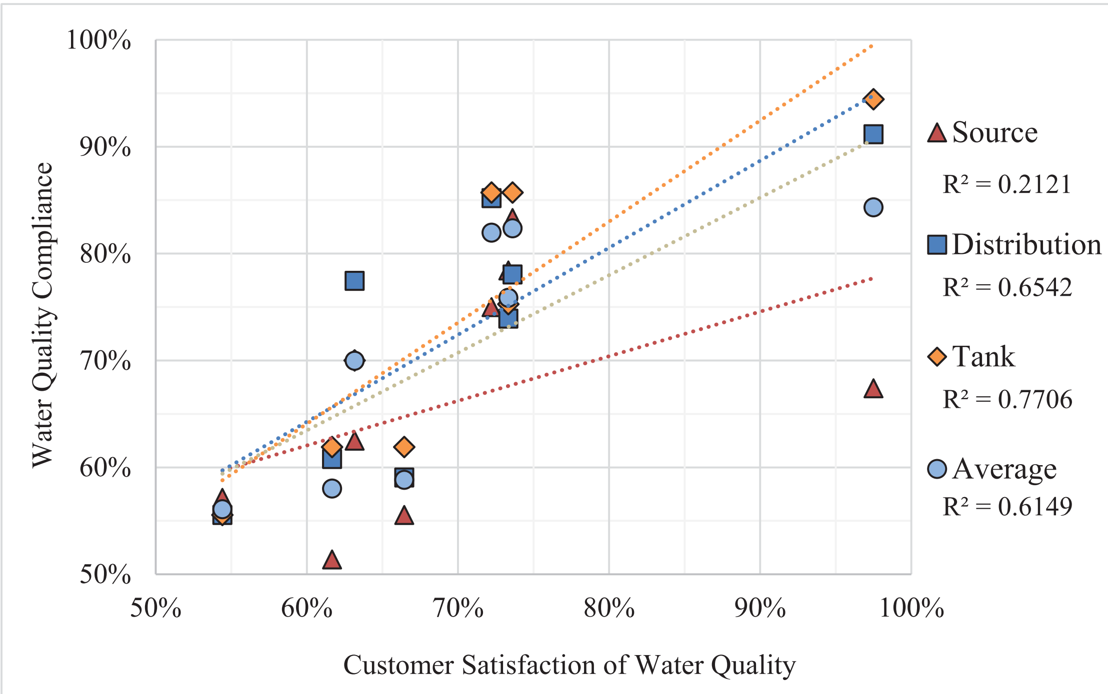


When combining the two data reliability tests, you would not accumulate error because the tests are parallel test. As a result, the reliability of the water quality analysis for this study would be 92.5 to 96.9% reliable in terms of the overall system performance.

5.4.2 Customer Satisfaction of Water Quality

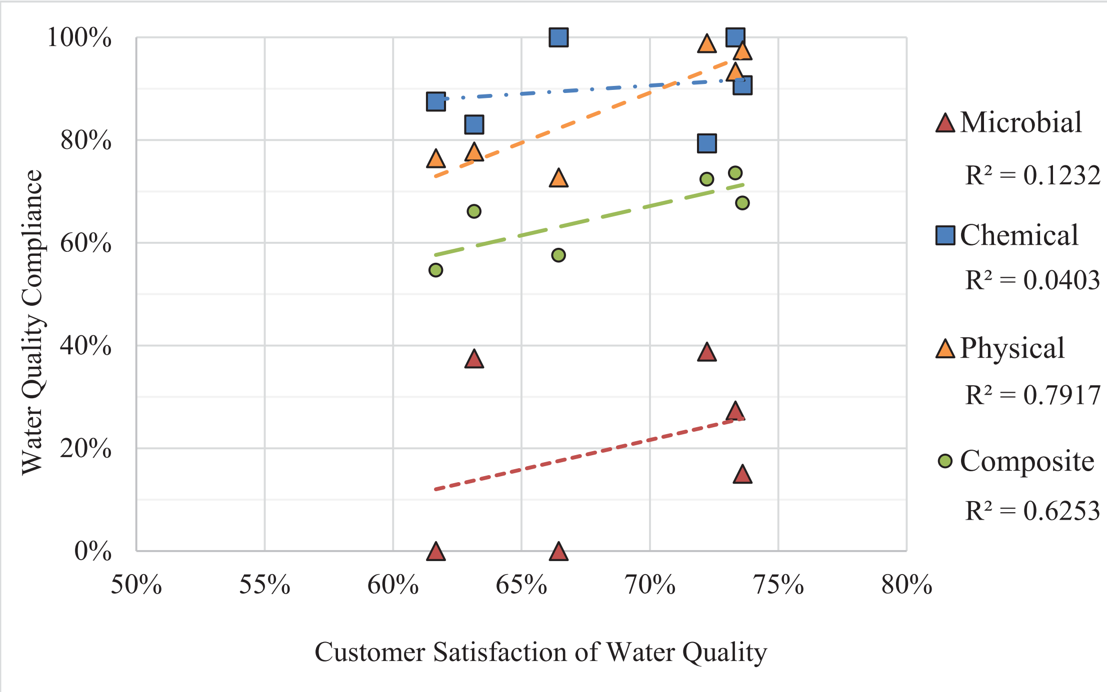
Customer satisfaction data was collected at the household-customer level to evaluate the end-user's perception of water quality and to further validate the data collected during the study. The first validation identified the location within the water supply infrastructure that most closely represents user-satisfaction with respect to water quality. Figure 5.16 shows the linear relationship between Customer Satisfaction and Water Quality Compliance for different sample locations considering source, tank and distributed water samples. Also shown is the composite analysis of water quality that includes all of the samples collected. It can be seen from this analysis that the water quality from within the distribution system at the household level most strongly correlates with customer satisfaction with a Persons Coefficient (R^2) of 0.65, as compared to 0.21 and 0.62 for source and composite samples respectively. This analysis further validates the use of distribution water quality as a measure of system performance and also confirms the need for quadrant analysis of system performance wherein source and distribution water samples are analyzed separately. Of particular interest is the relatively strong correlation between water samples collected from the storage tanks, and the overall customer satisfaction. For several reason however, it was decided to use distribution water quality compliance when evaluating the overall system performance with the primary reason being that the samples collected from the tank had roughly half the sample size as those collected from within the distribution system, and generally excepted guidelines require water quality sampling at the household level.

Figure 5.16: Customer Satisfaction and Sample Location Water Quality Compliance



Further validation included and investigation of water quality parameters used to measure system performance in that microbial, physical and chemical parameters were combined into a composite water quality score. An investigation into customer satisfaction versus different water quality categories reveals that physical water quality parameters correlate most closely to end-user's perception of water quality. This result is not surprising since physical parameters would typically have a direct impact on taste and odor which is the most common means of evaluating water quality at the household level. At the same time, a positive Person's Correlation Coefficient for all of the water quality categories suggests that a composite score that combines various parameters is the most effective means of evaluating water quality. In addition to the Persons Coefficient (R^2) of 0.625 suggests that the composite analysis sufficiently represents water quality within the system and validates the analytical methods used to calculate system performance.

Figure 5.17: Customer Satisfaction and Parameter Specific Water Quality



5.5 Chapter Summary

This chapter explores the characterization of water quality performance with the objective of addressing knowledge gaps related to identifying criteria to compare system performance and better anticipate system failure. This chapter includes water quality results based on multiple discrete sampling events for seven piped water systems in Madagascar and twelve piped water systems in Nicaragua. The analytical approach included sampling and analysis of microbial, chemical and physical water quality parameters.

Section 5.1 provides water quality characteristics for three selected sites in Madagascar to highlight important contextual details which are unique to each site investigated. Water quality analysis for the water supply and distribution system in Tolongoina reveals that the system is complying with WHO standards 57.6% of the time with 0% of samples meeting water quality targets for microbial parameters. The investigation of water quality in Ikongo introduces the importance of watershed management and the relationship between land-use and water quality wherein, local management actively works with watershed stakeholders to divert source water during certain periods of the year. The results from Ikongo shows that 66.1% of the water samples collected complied with the water quality targets. In Mananara, the water quality investigation introduces contextual issues related to the use of secondary water resources within the area. More specifically, differences between water quality compliance with respect to sampling location are highlighted.

Section 5.2 provides context specific details for sites investigated in Nicaragua and highlights issues related to storage of water at the household level, as well as watershed management and community based water treatment systems. In Puerto Viejo, household and system level samples were delineated to introduce issues related to behavior in that it appears that the poor reliability of water services in terms of water quantity has resulted in secondary storage of water within households. Despite this, water quality results between system level, household level and household filtered water shows only marginal differences in water quality. In El Naranjo, water treatment at the community level has shown some improvements in water quality with the most significant difference being microbial water samples with 38.8% of samples being compliant with microbial targets. Finally, the investigation of water quality in El Guabo introduces the need to consider customer satisfaction when investigating water quality compliance characteristics.

A comparative analysis of water quality in Sections 5.2 and 5.3 introduces the need to eliminate certain water quality parameters in order to equally compare system performance as well as the need to better understand source versus distribution water quality. Section 5.4 provides results using QA/QC protocol and customer satisfaction surveys to validate the water quality performance characteristics used to compare system performance.

CHAPTER 6

RESULTS AND ANALYSIS
STRENGTH OF MANAGEMENT

6.0 Results and Analysis: Strength of Water Management

Objective 1.3 of this study (see Section 1.2) is to identify strength of management criteria that can be used to compare water utility operations. In addition, Objective 2.1 is to explore internal influences which are within the control of local water management. When combined with the results from Chapters 4 and 5, this chapter is an essential aspect of meeting the overall goals of the study which is to contribute to the sustainable management of piped water supply infrastructure and to explore relationships between strength of management and technical performance.

This chapter includes an analysis of water utility management characteristics based on semi-structured interviews with local water management teams, a review of documentation, physical site inspections and surveys with local household customers. Sustainability indicators were categorized using the STEEP Framework in Nicaragua and the SIT Framework in Madagascar, to identify external factors that could influence water system performance. These factors were further explored to delineate internal management characteristics that would be essential to mitigating external threats to water system performance and overall sustainability of services.

Five Strength of Management (SoM) indicators were identified; Human Resources, System Administration, Operation and Maintenance, Asset Management and Financial Management. In Madagascar, a Public-Private Partnership (PPP) management model was used and the SoM analysis entailed a series of presence/absence tests for various sub-indicators. In Nicaragua, a community management model was used for water service delivery and the SoM analysis monetized per-capita investments in terms of direct and indirect contributions by the community.

In order to introduce context specific information, relevant to managing water service delivery, three cases are presented for Madagascar (Section 6.1) and three cases are presented for Nicaragua (Section 6.2) with country specific comparisons provided within each section. Section 6.3 of this chapter discusses validation wherein, the results were triangulated and then synthesized using customer satisfaction through a data calibration process. In this sense, it is important to emphasize that findings related to SoM need to consider the local context and the specific needs of each individual community. As a result, generalizing findings in terms of a composite SoM is a limitation of this study. More specifically the mechanisms with which each individual indicator influences specific sites may be entirely unique to that location. Chapter 7 of this study provides a detailed discussion of results, including an exploratory analysis between SoM Indicators and Water Quantity and Water Quality performance characteristics.

6.1 Context Analysis of Strength of Management: Madagascar

This section provides performance characteristics of water management for three sites in Madagascar in order to highlight contextual details that are unique to each system investigated. The analysis of water utility management in Madagascar included semi-structured interviews with local water management teams, household surveys, direct observation of operational procedures and a review of documentation and records available at both the community and national levels. The survey design was based on the Sustainable Index Tool (SIT) and, the Strength of Management (SoM) analysis utilized a presence/absence test of indicators consolidated into five categories of water utility management; Human Resources, System Administration, Operations and Maintenance, Asset Management, and Financial Management. Appendix D shows raw data from the survey with results that were further delineated into a series presence/absence tests.

6.1.1 Water Utility Management, Tolongoina

Tolongoina is a town of approximately 9,000 people in the Ikongo District of Madagascar's Fitovinany region. The water supply infrastructure in the town center was originally constructed in 1996 and was rehabilitated in 2014 with the installation of a 50 cubic meter storage tank and 197 connections serving an estimated 2,497 people through private and shared taps. The delivery of water services uses a PPP model wherein a private company headquartered in Antananarivo was contracted to rehabilitate and manage the water system. Prior to the rehabilitation of the water infrastructure, households had un-metered connections that were managed by the local municipality with limited payment for services. The system was generally unreliable and only a few locations in the town reported having access to water from the previous system. Figure 6.1 shows photos of the system prior to rehabilitation. Relevant to the management of the current system is surrounding social issues that existed prior to rehabilitation with reported issues related to customers being accustomed to poor services and low willingness to pay for services. In this regard, upon completion of the rehabilitation project, the PPP allowed for a three month grace period prior to instituting water bills in order to build confidence with household customers (Ranaivojaona, 2018).

A number of additional external factors could influence the overall sustainability of the water supply system in the area. Surrounding STEEP factors would include technical issues related to high pressure within the distribution system and economic factors related to affordability. With respect to pressure, the system in Tologoina has the largest elevation difference (131 meters) between the storage tank and the center of distribution and the largest reported incidences of leaks (32%) at the household level. Economic factors would include the cost of service connections, in that a new connection ($96) ranks amongst the highest connection fees for all of the system studied. Environmental factors include a well-protected watershed of 0.54 km^2 that is entirely (100%) composed of old-growth forest. Political factors that could influence the sustainability of the system include a three-year political crisis that ended in 2013 impacting international donors and external support for water infrastructure during the planning stages of the rehabilitation. Additional political factors would include changes to the local municipal leadership with the election of a new mayor, a year after the project was completed and a legal framework that supports the institutionalization of public-private partnerships at the national level.

Figure 6.1: Water Supply Services; Tolongoina, Madagascar in June 2014

Table 6.1 shows a summary of results for Strength of Management analysis in Tolongoina with an overall SoM score of 78.6 percent. The category for financial management scored highest at 100% with the water utility having evidence of records of monthly, annual and total income, as well as evidence of tax payments and annual expenses. The SoM category of asset management scored 72.8% with records of initial construction, evidence of counterpart contributions and evidence of office management. The utility was also able to demonstrate evidence of watershed management however, improvements in this regard would entail meetings with watershed stakeholders, better management of supplies and spare parts. The SoM analysis of Human Resources scored 68.4% which suggests that training of water utility personnel and introducing programs to ensure community participation would improve management significantly. In terms of Operations and Maintenance, limited evidence of water treatment and water testing, along with issues related to system expansion could influence long-term sustainability. System Administration could improve if the water utility had access to banking and financial services. The overall SoM for the system was 78.6% and, it appears that there is significant opportunity to improve services by strengthening water utility management.

Table 6.1: Strength of Management Analysis; Tolongoina, Madagascar

Strength of Management Categories and Indicators	Tolongoina	Notes
Human Resources	**68.4%**	
External Support	85.7%	Partial evidence of technical reception.
Community Involvement	66.7%	No initial community contribution to project.
Water Utility Personnel	52.7%	No gender balance and limited experience at local level.
Operations and Maintenance	**73.5%**	
Source, Storage and Treatment	60.0%	No evidence of water testing, no chlorination.
Capital Maintenance and Expansion	66.7%	Limited capital investment since initial construction.
Customer Communications	93.8%	Customer survey on utility communication (Appendix D).
System Administration	**78.2%**	
Accounting and Reporting	50.0%	No evidence of a local bank account, no regulatory reporting.
Strategic Planning	88.9%	No record of PPP contract within the Municipality.
Billing and Records	95.7%	No record keeping for customer complaints at water utility.
Asset Management	**72.8%**	
Capital Investments and Infrastructure	75.0%	Limited annual growth since initial construction.
Office, Supplies, Tools and Equipment	60.0%	Limited evidence of managing spare parts and available tools.
Watershed Management	83.3%	No evidence of meetings with watershed stakeholders.
Financial Management	**100.0%**	
Monthly Income	100.0%	Records of monthly income available.
Total Income	100.0%	Records of annual income available.
Savings	100.0%	Records of tax and total savings available.
Total SOM	**78.6%**	

6.1.2 Water Utility Management, Ikongo

The water supply and distribution system in the town of Ikongo provides water services to approximately 7,500 people and includes private household connections, shared social connections and a public water kiosk. The water system was rehabilitated in June of 2013 and includes a surface water intake, a slow-sand filter, 2 kilometers of intake piping, a 74,000 liter water storage tank, a solar powered chlorine disinfection system and approximately 3 kilometers of piped distribution. The management of the water utility began in September of 2013, using a public-private partnership that was based on a 20-year invest/operate contract giving the private utility, rights to charge local customers for water services. As a part of the initial contract, the PPP invested approximately $25,000 USD into the rehabilitation of the water supply infrastructure and employed a team of three local staff to operate and maintain the system providing water to 2,567 customers.

Several external factors could influence the long-term sustainability of the water-supply infrastructure. The most significant threat to sustainability is ongoing agricultural activity within the watershed of the water supply intake wherein, 35% of the watershed is being used for coffee and rice farming with very little old-growth forests. In addition to this, reports of financial losses in terms of recovering the initial investment may threaten the long-term sustainability of the system if the PPP management were to go out of business. In this regard, it appears that new customer acquisition is difficult because of initial connection fees that average $67.00 per connection that are limiting growth and ultimately profitability of the system. Finally, some external factors may influence the long-term sustainability in that, there are discrepancies between the PPP management team and the contractor who rehabilitated the system. In this regard, discussions with the local management team and field observations have noted leaks in the filter and storage tanks which are reportedly due to poor construction.

Table 6.2 shows a summary of results for Strength of Management analysis in Ikongo with an overall SoM score of 78.7 percent. The category for Financial Management scored highest at 100% wherein, the water utility showed evidence of records of monthly, annual and total income, as well as evidence of tax payments and annual expenses. The SoM category that scored the lowest was Operation and Maintenance at 70.2% primarily resulting from limited expansion of the system since the beginning of PPP management and reported problems wherein, 46% of customers reported breaks in the system within a one-week period (n=28).

Table 6.2: Strength of Management Analysis; Ikongo, Madagascar

Strength of Management Categories and Indicators	Ikongo	Notes
Human Resources	**74.8%**	
External Support	71.4%	No evidence of technical reception with national water ministry.
Community Involvement	66.7%	No initial community contribution to project.
Water Utility Personnel	86.4%	No gender balance, 50 percentile on total number of staff.
Operations and Maintenance	**70.2%**	
Source, Storage and Treatment	90.0%	Water testing not specified in contract.
Capital Maintenance and Expansion	50.0%	Limited capital investment since initial construction.
Customer Communications	70.7%	Customer reported breaks in the system (Appendix D).
System Administration	**78.2%**	
Accounting and Reporting	50.0%	No evidence of a local bank account, no regulatory reporting.
Strategic Planning	88.9%	No record of contract with PPP office.
Billing and Records	95.7%	No record of total monthly consumption.
Asset Management	**70.3%**	
Capital Investments and Infrastructure	100.0%	
Office, Supplies, Tools and Equipment	60.0%	No evidence of system map or information for new connections.
Watershed Management	50.9%	Livestock in watershed, little old-growth forest.
Financial Management	**100.0%**	
Monthly Income	100.0%	Records of monthly income available.
Total Income	100.0%	Records of annual income available.
Savings	100.0%	Records of tax and total savings available.
Total SoM	**78.7%**	

The remaining categories in Table 6.2; Human Resources, System Administration and Asset Management scored 74.8%, 78.2% and 70.3% respectively with sub-indicators on accounting and reporting (50%) as well as watershed management (50.9%) being areas for improvement. In terms of accounting and reporting, limited access to local banking and no regulatory reporting was evident in Ikongo. Whereas, the local management team has regular communications and meeting with local stakeholders within the watershed, the overall watershed management indicator was low because of ongoing agricultural activity, little old-growth forest and no regulatory enforcement.

6.1.3 Water Utility Management, Mananara

Mananara, the district capital of Analanjirofo, is town of approximately 16,500 people, located in the north eastern coast of Madagascar. The water supply system in Mananara was rehabilitated in 2012 and includes a surface water intake, a gravel intake filter, an electro-chlorinator providing daily batch disinfection, a 200 cubic meter storage facility and approximately 24 kilometers of distribution pipes. Whereas, the town of Mananara is located several days travel from the capital city of Antananarivo and is relatively isolated, the town is experiencing significant growth as a result of global demand for vanilla which is a cash crop in the region. In fact, of all of the systems investigated in this research study, Mananara is the largest in terms of number of customers and in terms of annual growth. When the system was rehabilitated in 2012, the system served an estimated 5,032 customers and in 2016 it served approximately 13,433 customers, equating to a 26.6% annual growth rate. In addition to this, the infrastructure includes 24,000 meters of piping making the Mananara system the largest system studied in terms of overall size. Table 6.3 shows the size of the Mananara system along with the average specifications for all other systems studied and is being shown here for comparison purposes. In terms of water utility management, the system in Mananara is unique in that the total customers served is 9 times the study average and the annual growth rate is 6.5 times the study average.

Table 6.3: Mananara Water System Specifications versus Study Average

System Specification	Mananara	Study Average	Ratio
Total Customers	13,433	1,488	9.0
Annual Growth Rate (%)	26.6	4.1	6.5
Storage Capacity (liters)	170,000	41,606	4.1
Length of Piping (m)	24.7	7.8	3.2

Note: Average includes 18 site locations in Nicaragua and Madagascar and excludes Mananara

Despite having success in terms of customer acquisition, the management of water services in Mananara struggles in some key SoM indicators. In some regards, the analysis of the system in Mananara may present some limitations with respect to the study-methods, as some of the SoM categories may be indirectly influenced by the size of the system and the total number of customers. For example, in terms of Human Resources, the three areas of measurement are external support, community involvement and water utility personnel. Two of these indicators, community involvement and utility personnel have sub-indicators that might artificially be weighted towards smaller system. Community involvement is measured based on the local management and technicians being from the town, as well as the presence/absence of community contribution to the project implementation. In larger system, the need for highly skilled managers and technicians may result in these individuals being recruited from outside the immediate area of the system.

In addition to this, larger systems may need to contract out services rather than rely on community contributions during implementation. In terms of water utility personnel, this directly influences the SoM score in that, the number of full-time staff has been used as one of the sub-indicators for determining human resource investments into the system. In Mananara however, a group of several technicians have been employed on a part-time basis for conducting system repairs and installing new connections. Whereas this may be an effective and efficient way of maintaining the system, optimization is not considered in the overall score, given the presence/absence nature of the SoM analysis.

Table 6.4 shows a summary of the SoM analysis for the system in Mananara with external support, watershed management and financial savings being the lowest sub-indicators. In terms of financial savings, limited evidence of monthly and annual expenses as well as payments to the local government in taxes were available. Other factors that have influenced the overall SoM score in Mananara are limited records in terms of system operations, maintenance, water consumption, delinquencies, and customer complaints. Whereas, these factors have directly influenced the System Administration score through the sub-indicator for billing and records, they have also influenced management's ability to account and report on system performance. In addition to this, the asset management score has been influenced by issues related to activity within the watershed of the water supply intake. In this regard, watershed management issues may be one of the largest threats to long-term sustainability of the Mananara water supply in that 45% of the watershed is being used for agricultural and residential purposes. Text Box 6.1 below provides exerts from technical briefs which were used to communicate preliminary results and facilitate discussions with the local PPP management. Full technical briefs on all of the system investigated in Madagascar are available in the supplemental appendix.

Table 6.4: Strength of Management Analysis; Mananara, Madagascar

Strength of Management Categories and Indicators	Mananara	Notes
Human Resources	**41.9%**	
External Support	28.6%	No evidence of technical reception with national water ministry.
Community Involvement	33.3%	Utility management team is not from the town.
Water Utility Personnel	63.7%	Part-time technicians used, PPP does not conduct design studies.
Operations and Maintenance	**62.4%**	
Source, Storage and Treatment	50.0%	No O&M records, no water testing records, no link with decisions.
Capital Maintenance and Expansion	66.7%	Limited capital investment since initial construction.
Customer Communications	70.4%	Limited communication on repairs (Appendix D.1).
System Administration	**41.6%**	
Accounting and Reporting	50.0%	No regulatory reporting, limited government coordination.
Strategic Planning	44.4%	Partially complete contract in terms of official signatories.
Billing and Records	30.4%	No records of O&M, consumption, delinquencies, complaints.
Asset Management	**60.3%**	
Capital Investments and Infrastructure	75.0%	
Office, Supplies, Tools and Equipment	80.0%	No evidence of system map or information for new connections.
Watershed Management	25.8%	Livestock in watershed, little old-growth forest.
Financial Management	**75.0%**	
Monthly Income	100.0%	Records of monthly income available.
Total Income	100.0%	Records of annual income available.
Savings	25.0%	No records of tax payments.
Total SoM	**56.2%**	

Text Box 6.1: Exert from Technical Brief Provided to PPP Management

Water Delivery: There is a need in Mananara to improve water delivery in the dry season and water quality in the rainy season. While the number of connections is rapidly increasing, the system experiences water shortages particularly from Sep. - Nov. This may be aggravated by several factors. First, average consumption grew to ~300m^3/day in the first half of 2016 as estimated using transducer data and noted by the enterprise director. While this is less than the 634m^3/day predicted in the design study, it is greater than all other sites included in this research study. Leaks in the distribution piping could be causing water loss. A representative household survey (all n=31, system n=25) conducted in May 2016 showed that secondary piping was exposed at 16% of connections, the highest for all sites studied. Issues related to low-quality materials for the piping and meter connected were reportedly used to bring down the cost of connecting, and are often not well protected. Primary distribution pipes are reportedly exposed throughout the town. Staff are incentivized with a 10.000 Ar (~$3) reward for each new connection installed, which may lead to an emphasis on the number of connections installed rather than quality. Staff are also required to provide their own tools for installation, potentially limiting the quality of their work. Incidents of vandalism also impact water delivery. On Dec. 19, 2015 a rock was found to have been inserted in the supply pipe at the source. The storage tank repeatedly went empty at this time and after the rock was removed water levels and flow increased.

Water Quality: The 0.83km^2 watershed had low sanitary inspection scores and included human habitation, farm animals, and crop production. While there is a filter below the intake, the water changes color and grows turbid when there are heavy rains. The filter is reportedly only cleaned once per month, while for many other systems they are cleaned at least every 1-2 weeks and more often if the rains are bad. A functioning electrochlorinator is present on-site and water is reportedly batch chlorinated at the primary storage tank between 7:00 and 8:00h each morning. However, no total or residual chlorine was ever detected in the distribution system during field work. Microbial water quality was consistently at a high or unsafe risk level in the distribution system. Turbidity levels may be influencing the ability to chlorinate effectively.

Sustainability Assessment: As of May 2016, there was no evidence of a public-private partnership (PPP) and no contract had yet been signed. The local management has reportedly never paid taxes to the local municipality. There are reported disagreements with the local/regional government as to whether or not the town should be classification as an urban area, which would mean higher taxes. System construction and the beginning of management took place during the political crisis from 2010-2013, potentially disrupting the PPP process, and Ministry approval of any decision can also take a long time due to Mananara's isolation. The director of the water utility management team also ran for mayor in 2015 using his involvement in water system implementation as a platform, potentially increasing tensions with the current mayor. Some evidence of internal issues also exists with the local management with complaints of a lack of personnel and no official work contracts.

Future Work: Mananara is the largest and most profitable system studied, and might be even more profitable with longer-term investments in infrastructure and relationships. Given the potential for income from this system, the local management could likely support long-term investments into the infrastructure. The use of higher quality materials in connections and better protection for currently exposed pipes could reduce non-revenue water and improve water quality. While filter maintenance may be difficult since the source is so far away, chlorination is not effective if the filter is not properly removing suspended solids and if contamination occurs through leaks in the supply/distribution lines. Management should prioritize finding a solution to clean the filter more often. Close collaboration between the management and the local municipality has yielded benefits at the other sites studied in terms of reducing social and political tensions including improved watershed practices and increased ability to resolve disagreements with clients. A formal contract and improved relationship with the local government could discourage vandalism via regulation enforcement. With improvements to the strength of management, the local team could even expand to manage other system in the region.

6.1.4 Comparative Analysis of Strength of Management, Madagascar

Several approaches were taken to evaluate and compare strength of water utility management in Madagascar. A composite score using a presence/absence (P/A) test for various indicators was used to evaluate the SoM based on different categories. Human Resources was measured based on the P/A of external support, community involvement and water utility personnel. Operation and Maintenance was evaluated based on the frequency of maintenance at locations within the water system, expansion of the infrastructure and customer communications. System Administration was evaluated based on a P/A test for accounting and reporting, business planning, and billing and record keeping. Asset Management was evaluated using indicators for capital investment, warehousing supplies and equipment as well as watershed management. Financial Management was evaluated based on records of monthly and annual income as well as annual savings. A composite score was determined using the mean of all the indicator categories to determine the overall strength of management.

Figure 6.2 shows the results for the different indicator categories along with the overall SoM for the systems investigated in Madagascar. In terms of individual categories, all of the systems scored greater than 70% for financial management indicators, with the exception of Imorona and Manompana. The Asset Management and the System Administration scores show the largest deviation within the results, with 68.2% and 62.2% deviation from the mean respectively. Whereas, all of the management categories showed a percent deviation within the results of greater than 50 percent, highlighting the largest deviations would potentially identify differentiators within the management categories. Table 6.5 shows the average, standard deviations and percent deviations for the SoM categories and is being shown here, to supplement the results in Figure 6.2. With respect to the overall composite SoM analysis, none of the systems scored higher than 90%, or what would be considered highly functional and no systems scored higher than 80%, or simply functional. Two systems, Tolongoina and Ikongo, scored 78.6% and 78.8% respectively which could use improvement. Anivorano and Mananara scored 60.5% and 56.7% respectively which suggests that external support may be needed to improve the strength of management and prevent system failure. The remainder of the systems

Manompana, Imorona and Andemaka scored below 50% which could be designated as failed or failing management systems. The need to calibrate the SoM analysis between sites in Nicaragua and Madagascar is discussed further in Section 6.3: Validation and Transformation of Results. Relationships between SoM and technical performance are discussed in Chapter 7: Synthesis of Results.

Figure 6.2: Summary of Strength of Management, Madagascar (n=7)

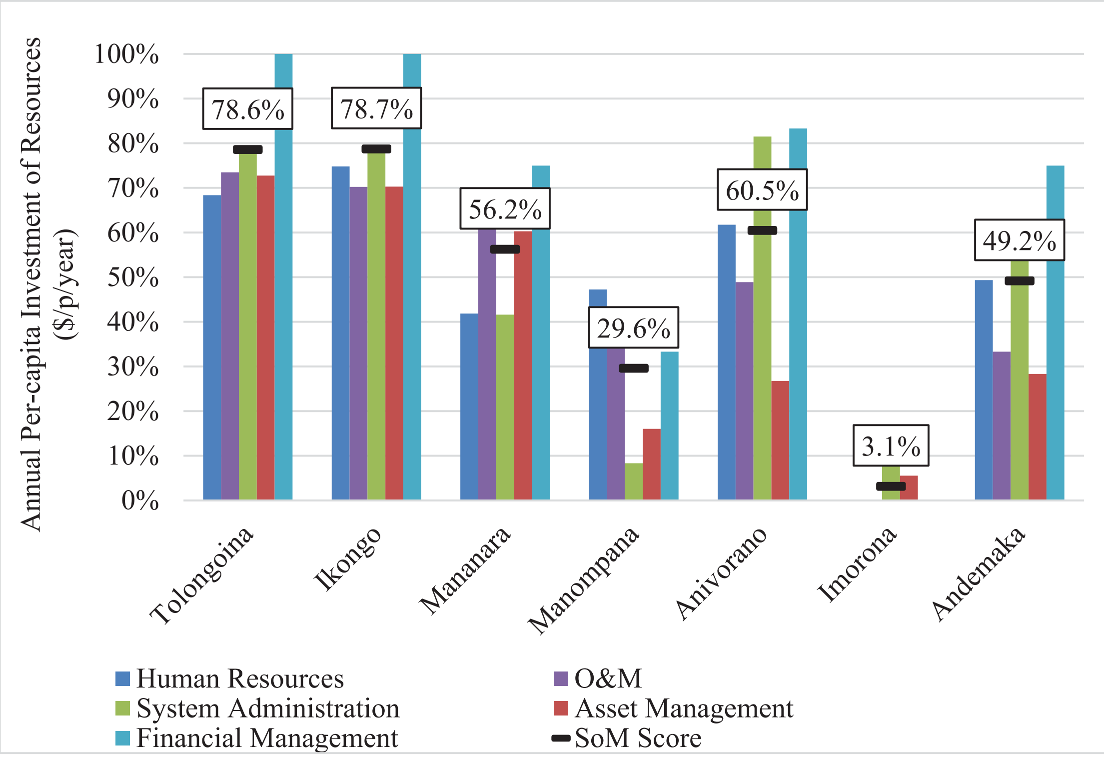
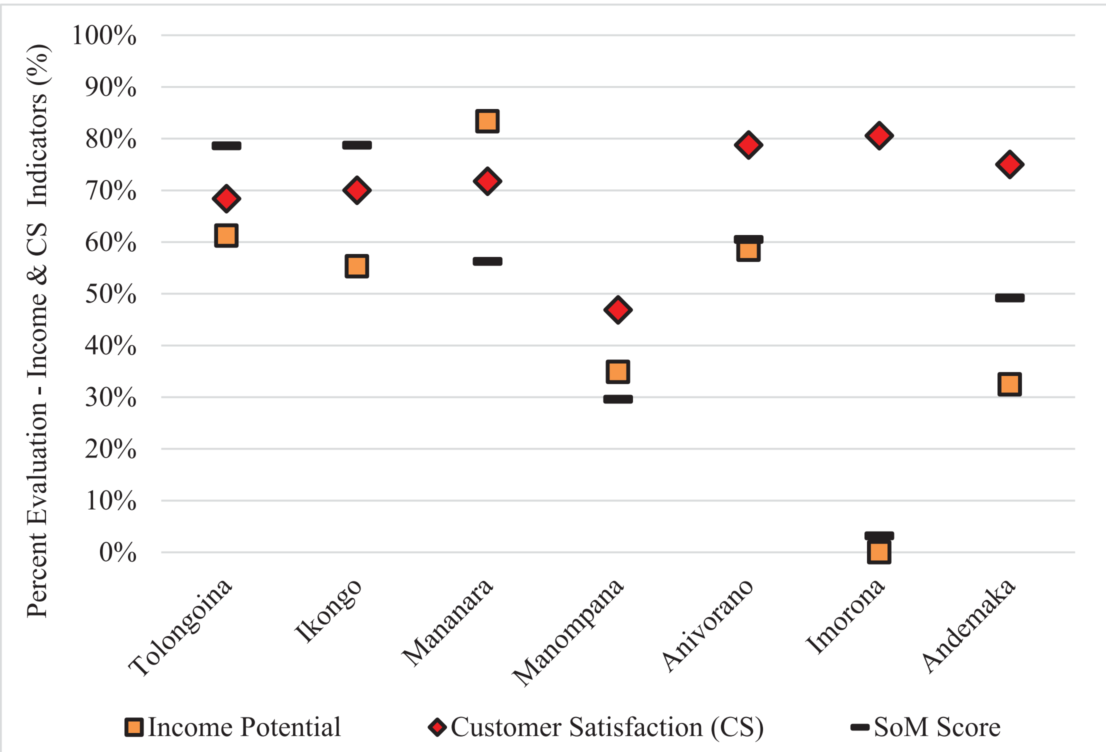


Table 6.5: Statistical Summary for SoM Categories, Madagascar (n=7)

Management Indicators	Average	Standard Deviation	Percent Deviation
Human Resources	49.1%	24.7%	50.3%
Operations and Maintenance	47.3%	25.5%	53.8%
System Administration	51.1%	31.8%	62.2%
Asset Management	40.0%	27.3%	68.2%
Financial Management	66.7%	37.0%	55.4%
Total SOM	50.8%	27.1%	53.3%

Another approach used to evaluate the strength of management included analyzing the income potential of the water utility in terms of per-capita income generated from the water and the presence/absence of different payment schemes available to customers. In addition to this, household level interviews and discussions with water customers were used to evaluate the overall management of the system. Figure 6.3 shows the results of income potential, along with customer satisfaction surveys and includes the composite SoM Analysis for comparison purposes. A qualitative review of the results shown in Figure 6.3 would suggest that Customer Satisfaction (CS) Surveys could be a more reliable method of evaluating Strength of Management as compared to the Sustainable Index Tool used through water utility management surveys. In this regards, two categories emerge from the results shown here. Where CS values are bracketed by Income and SoM results and where CS values are higher than Income and SoM results. In the second case, it appears that the SoM results, based on the SIT could justify further investigation wherein, it is unlikely that customer satisfaction with respect to water utility management would exceed the actual SoM.

Figure 6.3: Income Potential and Customer Satisfaction; Madagascar (n=7)



6.2 Context Analysis of Strength of Management: Nicaragua

The analysis of water utility management in Nicaragua included semi-structured interviews with local water management teams, direct observation of operational processes and a review of documentation available at the community level. This section includes the results for the Strength of Management (SoM) analysis for three site locations in Nicaragua. The information presented is intended to provide a contextual framework for the use of STEEP as a qualitative tool for understanding sustainability issues and, SoM to quantify the sustainable management of water services.

Several key indicators were isolated during the investigation to determine Strength of Management. Management factors were delineated in terms of investments made by the local water management team into the water infrastructure and in terms of the income potential of the water infrastructure. Investments were categorized as Human Resources, System Administration, Operations and Maintenance, physical Asset Management and Financial Management. Each variable was monetized by calculating time and money spent managing the system and was normalized using the per-capita value and the range of results to establish a percent value. Monetizing contributions to managing the water supply is a new concept however, it is rooted in practice where communities provide counterpart contributions to a development project. In this regard, the two inputs are time and money and, monetizing time is the most direct means of establishing a common unit of analysis. In this sense, monetizing investments into the community water system was needed to establish a common unit of measurement for comparing SoM between systems. In addition, wherein communities provide input in the form of time and money, they also have access to monetary resources through the process of billing customers. For this reason, an Income Potential variable was created to gauge management with potential resources. The Income Potential was based on the number of connections and the minimum monthly fees charged to customers. Figures are reported in US$ using an exchange rate of 26.6 Cordoba per US$ (Hunt, 2014).

In terms of Human Resources, investments into the water utility were analyzed by approximating the annual time spent organizing the water committee based on the total number of water committee members, the total number of committee meetings and the total number of assembly meetings. Investments in the form of Physical Assets were analyzed based on availability of office/warehouse space, ownership of land within the watershed, and equipment. Investments in the form of system Administration, combined paid employees and expenses for administration. Investments into the infrastructure in the form of O&M were determined based on the amount of funding spend on repairs as well as regular maintenance activities throughout the year. Financial Indicators included annual savings and interest if savings were kept in a bank. Investments back into the water system were then compared to the potential annual gross income resulting from water charges to existing customers and the overall analysis of management was determined by comparing investments and income potential from the system.

6.2.1 Nicaragua, Puerto Viejo

In Puerto Viejo, the water supply and distribution system was managed by six active committee members that included a president, vice president, secretary, treasurer, auditor, a vocal and, seven neighborhood-customer representatives. Being that the area is a hub for agriculture products in the region, the community also includes a satellite office for the local municipality, a high school and a medical clinic. Unique to the system in Puerto Viejo is the presence of a privately operated micro-hydro electrification facility that includes a water fee in the electricity bill for local customers. As a result of this arrangement, local water management team operates out of the office of the electric utility to manage customer accounts.

The water supply project was initially constructed in 2004 and was rehabilitated in 2010 wherein, a community counterpart contribution of 20 days of labor per household was negotiated into the project. The community water committee is composed of 50% women with one of them being in a leadership position as the president of the organization and includes private, metered connections that are both indoor and outdoor, as well as several public connections at local schools and clinics. Environmental considerations include no reported seasonal variations in water supply services, an area of land that surrounds the source that is owned and managed by the local hydro-electric facility and several coffee farms within the supply watershed. Economic considerations would include having a tiered payment structure where customers pay a minimum flat rate for water with an additional fee for every cubic meter above 20 cubic meters which is the highest flat rate volume amongst the systems studied. Political aspects of the system include the recognition of the water committee within the community with the noted absence of legal recognition of the organization within the municipality.

Table 6.6 shows a summary of the monetized SoM indicators for Puerto Viejo. With six water committee members and seven neighborhood volunteers, the community ranks third amongst sites studied in Nicaragua in terms of annual investments ($227.50) managing the system but ranks seventh in terms of per-capita Human Resource expenditures ($0.19) because of the larger number of customers on the system. Similarly, investments in the form of System Administration ranks third amongst all of the sites studied in terms of annual investments ($3,022.56) which includes salaries for two employees as well as supplies and a small fee to landowners for use of the source intake. Interestingly, the per-capita System Administration ranks fifth wherein, $2.52 is spent per customer annually on administrative activities. Investments into the system in the form of O&M includes time spent cleaning the source intake (once a month), filter cleaning (3 times monthly) and chlorination (3 times monthly) which, totals to $420.00 in annual investments or $0.35 per customer. Physical Assets in Puerto Viejo include an office and land ownership within the watershed which equate to $603.80 of annual investments and $0.50 per customer. In addition to investments in the form of time and money, Financial Indicators in the form of existing savings were identified to gauge the capacity to managed future expenses wherein, the water committee has saved $97.74 annually for ten years, since its initial construction. The total annual investment of the community in terms of volunteers, staff and expenses in Puerto Viejo is $4,371.60 which ranks third amongst all of the sites (n=10) studied in Nicaragua. After consideration for the number of connections on the system (240) and the number of customers being served (1200 people), the final annual per-capita investment made by the community to manage the water supply infrastructure was $3.64 per person which ranks seventh.

In Puerto Viejo, the community managed water utility charges a flat monthly rate of $2.00 for up to 20 cubic meters of water with an additional charge of $0.25 for every cubic meter consumed above the flat rate amount. The annual income potential of the water system in Puerto Viejo is $4,330.83 (ranked second) which equates to an annual per-capita income potential of $3.61 per person (ranked third). When considering the ratio of annual investments into the water infrastructure to the annual income potential, it becomes apparent that there are additional resources within the community of Puerto Viejo that could be used to manage the system. It is important to note however that an Investment-Income ratio of greater than 1.0, implies that the community is investing time and resources beyond that which is generated by the water supply. Where the ratio is less than 1.0, the community is not investing time and resources beyond its economic means and improvement can be made to better manage the system. The investment-income ratio (see Table 6.6 where A is Investments and C is Income) for the system in Puerto Viejo is 1.01 (ranked ninth) which suggests that some improvements could be made in terms of water utility management and community participation. As a result of the A/C ratio, it appears that the water utility management in Puerto Viejo more closely aligns with a privately management as compared to a community managed system.

Table 6.6: Monetized Strength of Management Indicators; Puerto Viejo, Nicaragua

Management Indicators	Puerto Viejo, Waslala	Units
Investments		
Human Resources	$ 227.50	$/year
- Per-capita Human Resources	$ 0.19	$/p/year
Administration	$ 3,022.56	$/year
- Per-capita Admin	$ 2.52	$/p/year
Operation and Maintenance	$ 420.00	$/year
- Per-capita O&M	$ 0.35	$/p/year
Physical Assets	$ 603.80	$/year
- Per-capita Physical Assets	$ 0.50	$/p/year
Financial Savings	$ 97.74	$/year
- Per-capita Savings	$ 0.08	$/p/year
Annual Investments		
Total Invested (A)	$ 4,371.60	$/year
- Per-capita Invested (B)	$ 3.64	$/p/year
Income		
Annual Income Potential (C)	$ 4,330.83	$/year
- Per-capita Income Potential (D)	$ 3.61	$/p/year
Investments - Income		
Income/Investment Ratio	1.01	A/C
Net Difference	$ 40.78	A - C
- Per-capita Difference	$ 0.03	B - D

6.2.2 Water Utility Management, El Naranjo

The water supply system in El Naranjo is managed by a local water committee that is composed of 5 active members. The system supplies water to 12 different neighborhoods with intermittent services wherein, water operators open and close valves throughout the day to provide water to different areas. Three of the areas have access to 24 hour water supply and the remaining areas are provided access to water for a few hours in the morning or in the afternoon based on a schedule. Three neighborhoods at the exterior of the system reported only having water for during non-peak periods. Despite close to 3000 customers and local resources for managing the water system, the El Naranjo water committee does not have legal certification with the local municipality.

Social and political challenges associated with managing the water supply in El Naranjo include legal rights to the water source resulting from the water supply intake being located on the boundary of two municipalities. As a result, a separate connection within the intake supply line between the source and the El Naranjo water storage facility exists that supplies water to the community of El Guayabo with approximately 127 customers that are not managed by the El Naranjo water committee. Additional political factors that could indirectly influence the management of water is activism in the area that has been advocating for the community of El Naranjo to become a new municipality independent of the local government authority in Waslala. External economic factors that could indirectly influence the management of the water supply in the area include the community's growth, as the area has become an economic hub for agricultural activities between the town of Waslala and Siuna. Technical factors that should be considered include the nature of the intake system that includes un-managed connections that could interfere with the water supply. An additional factor would include customer connects that are mostly private and metered at the household level.

The water management in El Naranjo includes a team of 5 elected water committee members that meet twice annually for board meetings and twice annually for assembly meetings. Water bills are issued to customers monthly and are based on a flat rate of 37 Cordoba (US$ 1.85) for water consumption up to 10 cubic meters and 3.25 Cordoba (US$ 0.16) per meter above 10 cubic meters. The water committee employs one full-time plumber and one full-time administration person to manage repairs and the collection of water fees. Regular operation and maintenance includes twice annual cleaning of the source intake, twice monthly cleaning of water filters and weekly applications of chlorine.

Table 6.7 shows the monetized SoM score for the system in El Naranjo. Included in this analysis are Human Resources in terms of community involvement, System Administration, O&M, Physical Assets associated with the water system and Financial Management from the collection of water fees. Unique to El Naranjo is the nature of investments in the form of Physical Assets wherein, the management includes an office space for the water committee, tools, equipment and 10 acres of land within the source watershed that is titled to the community. In terms of participation in the form of Human Resources, it has been estimated that the community is contributing $125.00 annually to the management of the water utility. Administrative activities that are being re-invested into the water system account for $3,624.06 annually which is primarily in the form of two paid staff members of the water management team. Operation and Maintenance activities that include water treatment, accounts for $550.00 of annual investments into the system and Physical Assets primarily in the form of land within the watershed, account for $900.00 of annual investment into the system.

The overall Investment-Income Ratio for this system is 0.58 which suggests that there is potential to improve the Strength of Management in that the income potential of $9,213.83 from the system is close to two-times the resources being put into management. In particularly, professionalizing the water utility management in El Naranjo for the purposes of improving the system's performance should consider the existing nature of water management. With an A/C ratio of less than 1.0, it appears that the system in El Naranjo is not being managed using a tradition community management model where volunteerism and community participation would provide investments beyond the income potential of the system. Like Puerto Viejo, it appears that the system in El Naranjo is being managed like a private entity and thus additional regulations and oversight would be an effective way to improve management.

Table 6.7: Monetized Strength of Management Indicators; El Naranjo, Nicaragua

Management Indicators	El Naranjo	Units
Investments		
Human Resources	$ 125.00	$/year
- Per-capita Human Resources	$ 0.045	$/p/year
Administration	$ 3,624.06	$/year
- Per-capita Admin	$ 1.31	$/p/year
Operation and Maintenance	$ 550.00	$/year
- Per-capita O&M	$ 0.20	$/p/year
Physical Assets	$ 900.00	$/year
- Per-capita Physical Assets	$ 0.33	$/p/year
Financial Savings	$ 185.20	$/year
- Per-capita Savings	$ 0.07	$/p/year
Total Annual Investments		
Total Invested (A)	$ 5,384.26	$/year
- Per-capita Invested (B)	$ 1.95	$/p/year
Income Potential		
Total Annual Income (C)	$ 9,213.83	$/year
- Per-capita Income (D)	$ 3.34	$/p/year
Income - Investment		
Income/Investment Ratio	0.58	A/C
Net Difference	$ (3,829.57)	A - C
- Per-capita Difference	$ (1.39)	B - D

6.2.3 Water Utility Management, Los Lipes

Los Lipes is located about 20 minutes from the regional capital city of Matagalpa, Nicaragua and is a transportation hub within the La Isabella coffee growing region. The water supply system in Los Lipes was constructed in 2009 as a part of a regional development initiatives called Aqua Para Todos – Para Siempre and includes 68 connections being supplied by a spring intake, located 3.1 kilometers from the storage tank (CARE, 2009, Hunt, 2014). Water supply services are managed by a local water committee with 6 members including a president, vice president, treasurer, secretary, an auditor and a vocal. Two full-time employees manage the system including a plumber for maintenance and a secretary for billing and communications.

Social factors that could influence the management of water services include gender balance (50% Female) on the water committee as well as generally high levels of literacy

(86.8% according to INIDE, 2008). Technical factors that could influence the system include private connections with water meters, a number of connections above the tank, chlorination treatment and a spring intake system. Environmental factors would include reported farming within the watershed despite the water committee having a land title for 0.89 acres at the source intake.

Economic factors include a minimum monthly water rate of $2.63 plus an additional $0.34 for every cubic meter above 10 cubic meters, which is the highest rate charged amongst the systems studied in Nicaragua. Other factors that could influence the system but that would be considered external to system operations are, the local economy which is influenced by tourism and coffee farming in the region. Access to the regional capital of Matagalpa also influences the local economy where many of the residence of Los Lipes work in the capital city. Political factors that could influence water system sustainability would include having a fully certified water committee that has legal recognition within the local municipality to operate and charge customers as a registered non-profit association with tax identification.

Table 6.8 shows the monetized SoM score for the community water supply system in Los Lipes. Of interest from this analysis is the Investment/ Income Ratio and the Net Difference between resources invested into the infrastructure as compared to income from the infrastructure. Being that the Investment/Income Ratio is greater than one at 1.70 (unit-less), it appears that the local community is investing resources in terms of time and funding into the infrastructure beyond the resources being generated by the infrastructure itself. Based on the net difference, it appears that the community is investing $5.00 per person into the infrastructure itself which is equivalent to one day of volunteering for each customer. In terms of administrative expenses, the Los Lipes system is spending an estimated $5.73 per customer to keep the system functioning and an additional $1.25 per customer in operation and maintenance. With additional resources in the form of an office space (Figure 6.4) along with a place to store supplies, tools and equipment, the Los Lipes system is ranked amongst the highest of all the site studied in terms of Physical Asset investments at $3.71 per customer. When combining all the financial inputs, a total of $12.13 per customer of direct and indirect expenses has been invested into managing the system.

Table 6.8: Monetized Strength of Management Indicators; Los Lipes Nicaragua

Management Indicators	Los Lipes	Units
Investments		
Human Resources	$ 450.00	$/year
- Per-capita Human Resources	$ 1.25	$/p/year
Administration	$ 2,063.99	$/year
- Per-capita Admin	$ 5.73	$/p/year
Operation and Maintenance	$ 450.38	$/year
- Per-capita O&M	$ 1.25	$/p/year
Physical Assets	$ 1,335.00	$/year
- Per-capita Physical Assets	$ 3.71	$/p/year
Financial Savings	$ 67.02	$/year
- Per-capita Savings	$ 0.19	$/p/year
Total Annual Investments		
Total Invested (A)	$ 4,366.40	$/year
- Per-capita Invested (B)	$ 12.13	$/p/year
Income Potential		
Total Annual Income (C)	$ 2,566.02	$/year
- Per-capita Income (D)	$ 7.13	$/p/year
Income - Investment		
Income/Investment Ratio	1.70	A/C
Net Difference	$ 1,800.38	A - C
- Per-capita Difference	$ 5.00	B - D

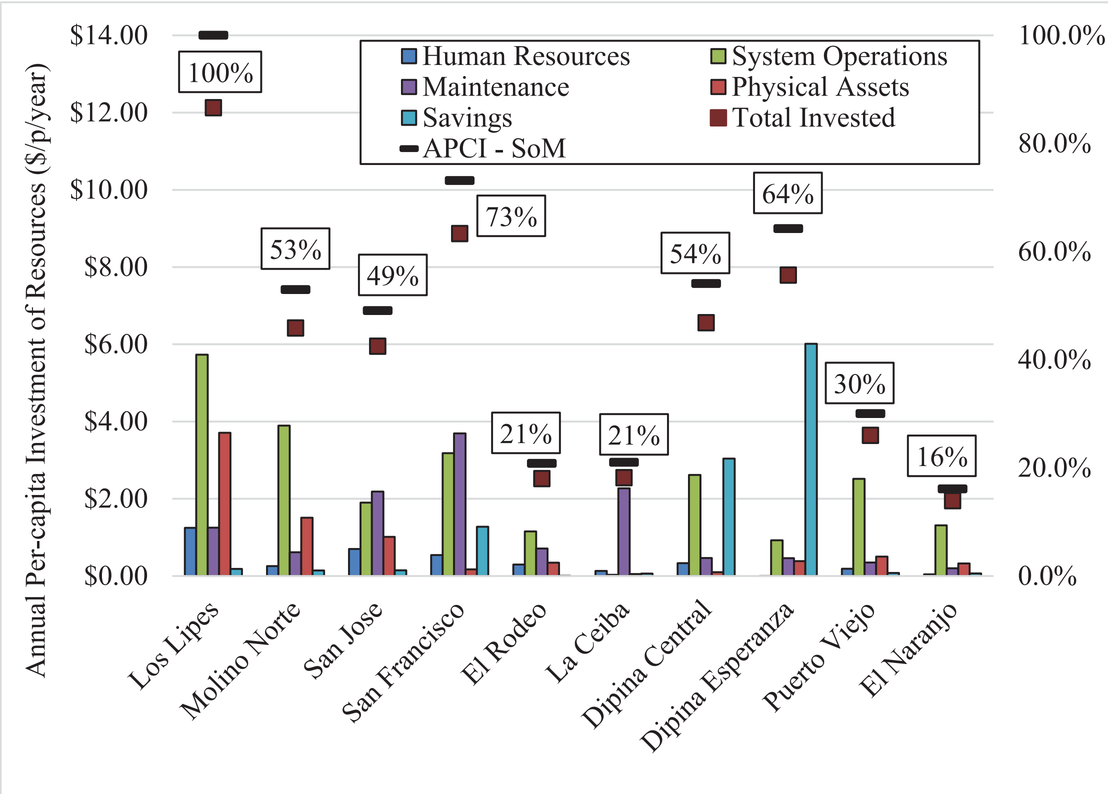
Figure 6.4: Water Committee Office, Los Lipes, Nicaragua (Photo Hunt, 2014)

6.2.4 Comparative Analysis of Strength of Management, Nicaragua

Several approaches were taken to evaluate and compare Strength of Management. The first approach simply determines the total annual per-capita resources ($/p/yr) invested back into the water supply infrastructure. Figure 6.5 shows the results from this analysis with Human Resources, System Administration, O&M, Physical Assets and Financial Management are all delineated in clustered columns for each site location. Also shown in this figure is the total annual per-capita investments into the system on a line diagram, which is the summation of all the management indicators discussed. Finally, this figure presents an SoM score that has converted the per-capita investment value into a percent value by dividing all the results by the highest value in the set. From this figure, the Los Lipes system is clearly investing the most in terms of community resources, with $12.13 per customer being invested into managing the water supply system. In addition, since Los Lipes was the highest per-capita value, it scored 100% in terms of the SOM (APCI) score. The only other two systems that are even close to this, are San Francisco and Dipina Esperanze which invest $8.87 per customer and $7.79 per customer back into the system, respectively. In this regard, $8.87 per customer would equate to an Annual Per-Capita Investment (APCI) score of 73.1% where, the community of San Francisco invested 73.1% as much as the community of Los Lipes. On the lower end of this scale are those system that are not investing as much resources into the water infrastructure. On the lower end; El Naranjo is investing $1.95 per customer, El Rodeo is investing $2.52 per customer, and La Ceiba is investing $2.55 per customer, which represents 16.1%, 20.8% and 21.0% of the Los Lipes investments respectively.

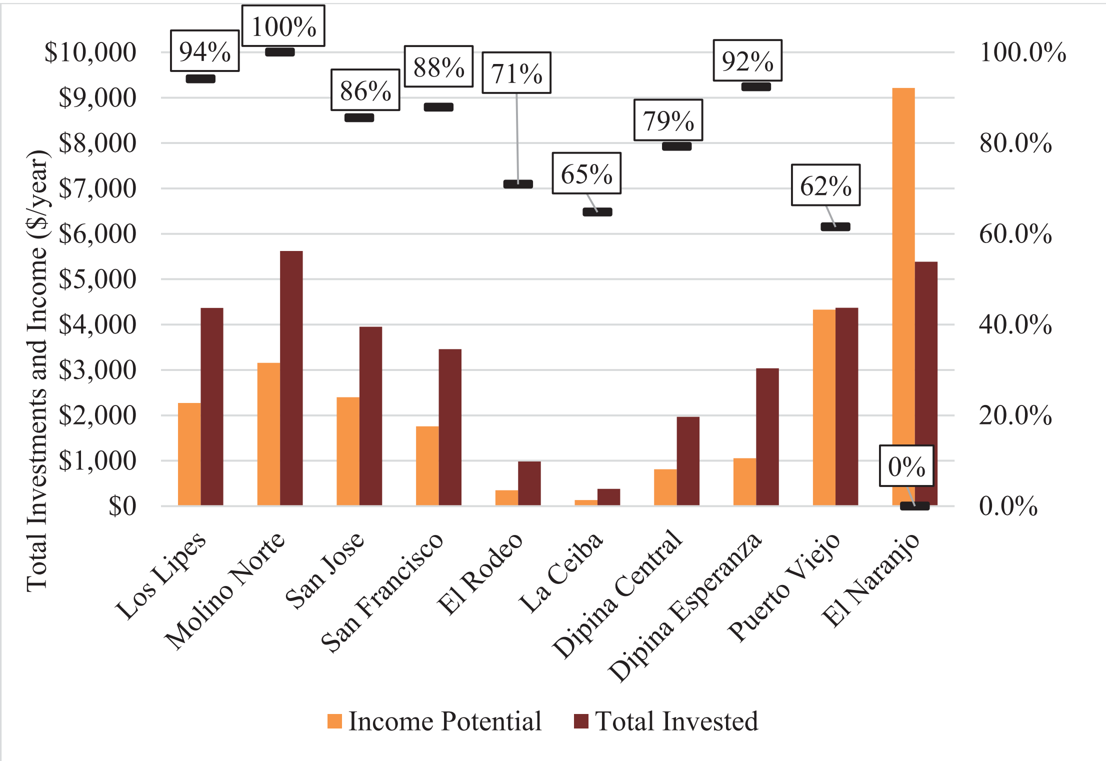
The second approach to evaluating strength of management considers the potential income generated by the infrastructure and the net difference between income from and investments into the water supply system. An initial inspection of the investment – income differential suggests that Income that is greater than investments is desirable from the point of view of business analytics. It is important however to understand that the Investments into the water system includes both revenue and non-revenue resources in the community in the form of time and other community assets as well as deposits into the water committee bank or community fund. As a result, the investment/income differential would ultimately represent potentially lost revenue that is no longer available for water management activities. Therefore, a positive difference or an investment/income ratio of greater than one, would represent investments greater than income and would equate to additional resources being available for management. A negative difference, where investments are lower than income or that have an investment/income ratio of less than one, would equate to a deficit in resources available for management.

Figure 6.5: Strength of Management using Per-capita Investments (n=10)



Wherein the potential for deficit exists, there is a need to convert the data so that the results range from 0 to 100 percent. As a result, the analysis of SoM using the investment/income differential employs a sliding scale where the highest performing system equates to 100% and the lowest performing system equates to a 0% score for SoM. An interpretation of the results shown in Figure 6.6 reveals five categories of systems. Those that perform greater than 90% would be considered highly functional management systems. SoM scores of between 80 and 90% would be functional management and system between 70 and 80% would be systems that need improvement. Systems below 70% is failing management and systems below 60% would be failed management.

Figure 6.6: Strength of Management using Investment/Income Differential (n=10)



To summarize, the SoM analysis can be used to delineate between communities that are successfully and those that are unsuccessfully managing their water utility. In terms of successfully managed systems, both metric types have identified Los Lipes and Dipina Esperanza as having well managed systems. In terms of failing systems, both metric types have identified Puerto Viejo and El Naranjo as have poorly managed systems. Whereas, San Francisco was identified as a well-managed system using the per-capita investment measurement, ranking third with a 73% score, it only ranked seventh (71%) using the investment/income differential score. Monlino Norte on the other hand ranked third using the investment/income differential but ranked fifth using the per-capita investment score. The remaining systems ranked in the middle in for both metrics.

6.3 Validation and Calibration of SoM Results

Unique tests were used to evaluate the Strength of Management (SoM) of water infrastructure in Madagascar and Nicaragua. In Madagascar, SoM data was primarily based on the Sustainable Index Tool (SIT) which was developed by international agencies for the purposes of evaluating post-construction sustainability of water supply systems. In Nicaragua, SoM data was based on the STEEP Framework, in collaboration with local municipal agencies and the project partner for this study. In both cases, the results were consolidated into SoM Categories that included Human Resources, System Administration, Operation and Maintenance, Asset Management, and Financial Management. An important difference between the two tests should be noted. In Madagascar, the available data from the SIT survey was delineated into a Presence/Absence test (%) of various sub-indicators and the results are presented in terms of a percent value. In Nicaragua, the available data was consolidated into monetized per-capita investments ($/p/yr) into the water infrastructure.

In order to synthesize the results, the data was first converted using the maximum value within each category and was then calibrated using a common customer satisfaction survey that was implemented in each country. Table 6.9 shows the converted results of each SoM category for the systems investigated in Madagascar and Nicaragua. An investigation of these results reveals an external validity issue where the SoM tests used in Nicaragua and Madagascar are not generalizable to each other. The difference in the averages between the SoM results in Madagascar and Nicaragua would suggest that the per-capita monetized SoM test used in Nicaragua was more difficult test than the presence/absence SoM test used in Madagascar. Therefore, calibration of the results would be needed prior to conducting further analysis. In order to calibrate the results for the different SoM tests, customer satisfaction was used as a common point of analysis.

Table 6.9: Normalized SoM Results; Madagascar and Nicaragua

	Site Location	Human Resources	System Admin	O&M	Asset Management	Financial Management
Madagascar	Tolongoina	*91.4%*	*95.9%*	100.0%	100.0%	100.0%
	Ikongo	100.0%	*95.9%*	95.6%	96.6%	100.0%
	Mananara	*55.9%*	*51.1%*	84.9%	82.8%	75.0%
	Manompana	63.1%	*10.2%*	58.3%	*22.1%*	33.3%
	Anivorano	82.5%	100.0%	*66.5%*	*36.8%*	83.3%
	Imorona	*0.0%*	12.4%	*0.0%*	7.6%	0.0%
	Andemaka	65.9%	73.4%	*45.4%*	38.9%	75.0%
	Average	76%	71%	75%	63%	78%
Nicaragua	Los Lipes	100.0%	100.0%	*33.9%*	100.0%	*3.1%*
	Molino Norte	20.6%	68.0%	*16.7%*	40.7%	*2.4%*
	San Jose	56.1%	*33.1%*	59.3%	27.4%	*2.3%*
	San Francisco	43.6%	55.5%	100.0%	*4.7%*	*21.3%*
	El Rodeo	23.9%	20.2%	19.3%	*9.4%*	*0.2%*
	La Ceiba	10.7%	*0.5%*	61.5%	1.3%	*1.0%*
	Dipina Central	26.7%	45.7%	*12.6%*	*2.7%*	50.6%
	Dipina Esp.	*0.3%*	16.1%	12.5%	*10.4%*	100.0%
	Puerto Viejo	15.2%	43.9%	*9.5%*	13.6%	*1.4%*
	El Naranjo	*3.6%*	22.9%	5.4%	8.8%	*1.1%*
	Aus. Paladino	*12.3%*	65.6%	*9.6%*	31.7%	17.2%
	Average	28%	43%	31%	23%	18%

Note: Final SoM results are discussed below and shown in Table 6.10

Figure 6.7 shows a plot of the SoM scores for Madagascar and Nicaragua against the Customer Satisfaction (CS) surveys to further demonstrate issues related to external validity where the two SoM surveys are not generalizable to each other. Figure 6.8 shows the distribution of the CS surveys which suggests that these results are generalizable given the normal distribution for both locations. The results shown in Table 6.9 combined with Figure 6.7 and Figure 6.8, demonstrate that the average SoM Indicator scores in Nicaragua should be higher, given the CS Scores and, that the data between the two sites can be calibrated through statistical methods. Text Box 6.2 shows the data calibration process used for this study.

Figure 6.7: Customer Satisfaction versus SoM; Madagascar and Nicaragua (n=10)

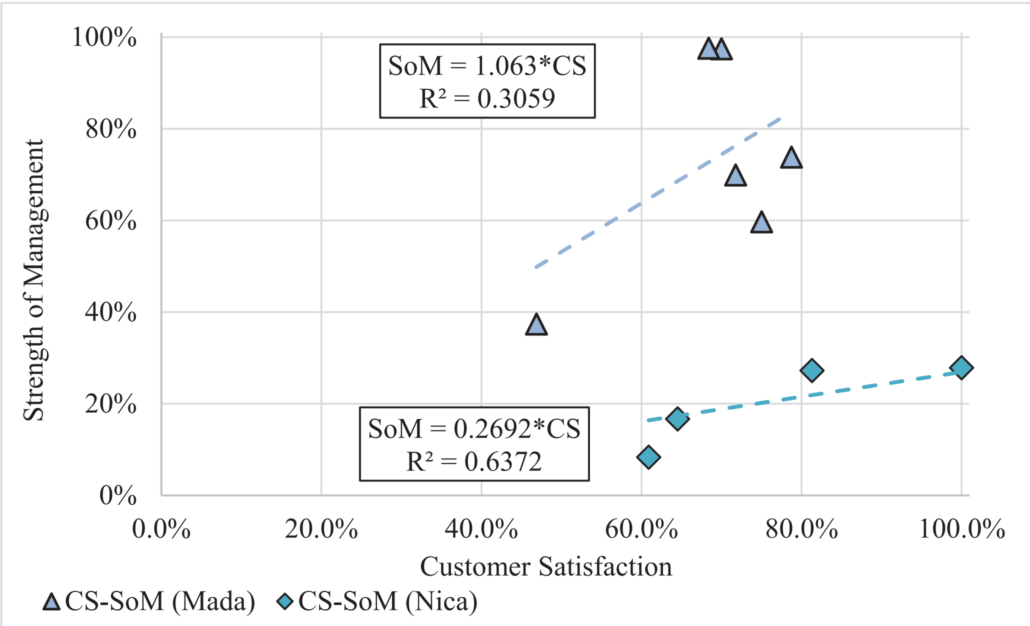


Figure 6.8: Distribution of Customer Satisfaction; Nicaragua and Madagascar (n=10)

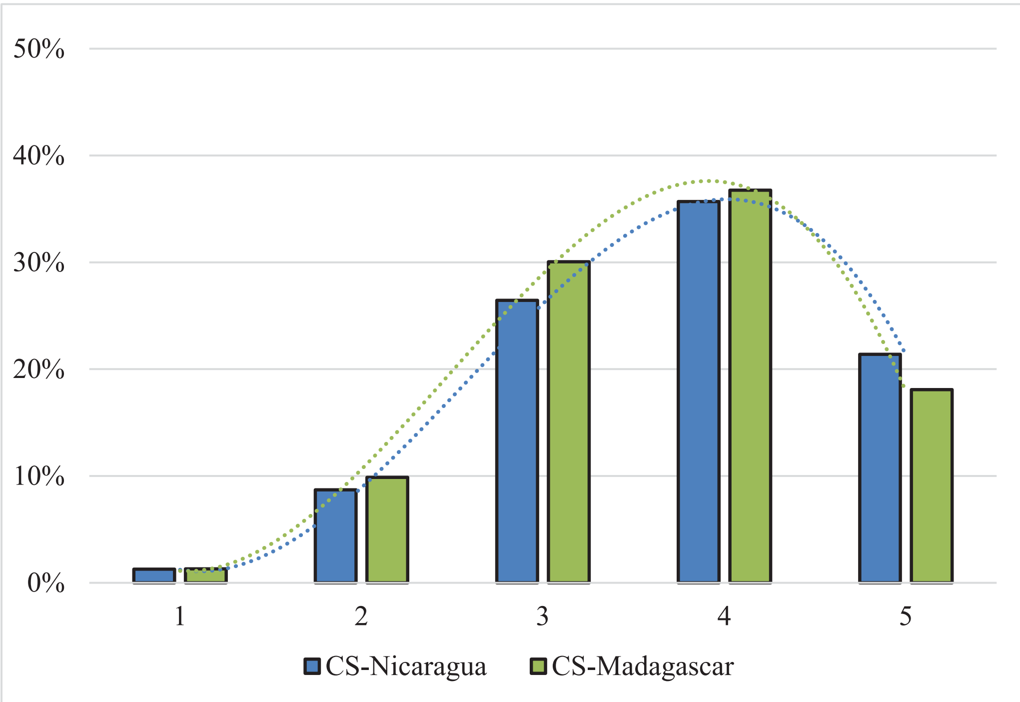


Table 6.10 shows the calibrated SoM scores for the systems in Madagascar and Nicaragua along with the customer satisfaction results and the original SoM Scores. The synthesized results of the SoM analysis suggest that there are five types of SoM categories. Type 1 systems (scoring greater than 90%) are very good management, Type 2 systems (scoring between 80% and 90%) are good management, Type 3 (70-80%) are okay management, Type 4 (60-70%) are poorly managed and below 60%, Type 5, are very poorly managed. In addition to this, the quadrant values are shown (A through D) to identify the systems classifications that consider both income and management.

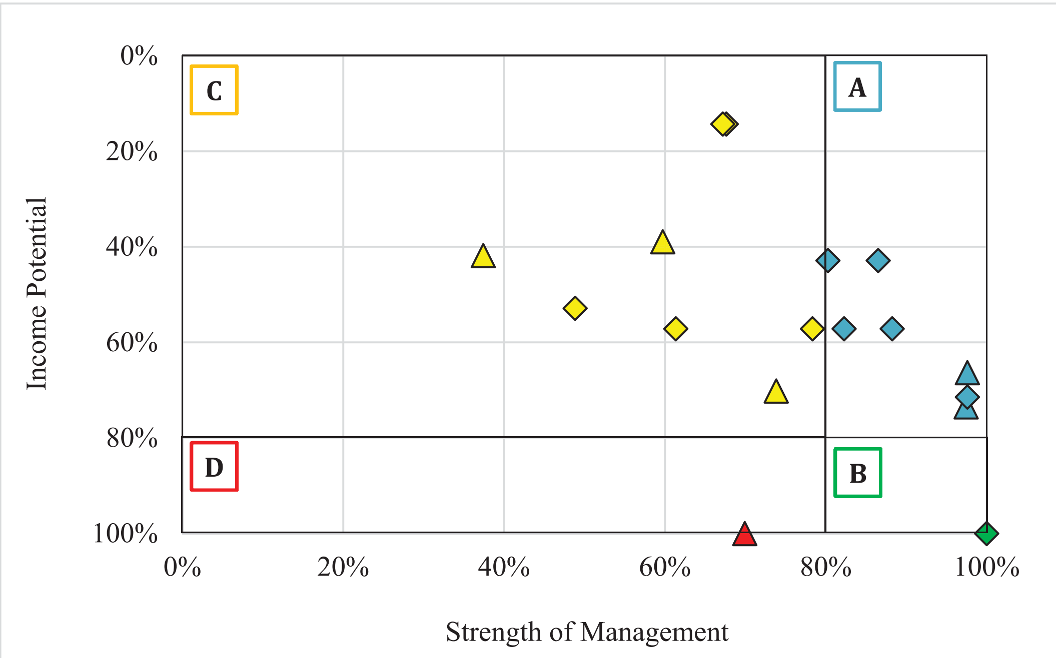
Table 6.10: Transformed SoM and Customer Satisfaction; Madagascar and Nicaragua

Site Location		Average Converted SoM[1]	Calibrated SoM based on average difference	SoM Classification	Customer Satisfaction[2]
Madagascar	Tolongoina	97.5%	97.5%	Type 1 – A	70.0%
	Ikongo	97.6%	97.6%	Type 1 – A	68.4%
	Mananara	69.9%	69.9%	Type 4 – D	71.8%
	Manompana	37.4%	37.4%	Type 5 – C	46.9%
	Anivorano	73.8%	73.8%	Type 3 – C	78.8%
	Andemaka	59.7%	59.7%	Type 5 – C	75.0%
Nicaragua	Los Lipes	67.4%	100.0%	Type 1 – B	*100%*
	Molino Norte	29.7%	82.3%	Type 2 – A	*82.4%*
	San Jose	35.7%	88.3%	Type 2 – A	*88.4%*
	San Francisco	45.0%	97.6%	Type 1 – A	*97.7%*
	El Rodeo	14.6%	67.2%	Type 4 – C	*67.3%*
	La Ceiba	15.0%	67.6%	Type 4 – C	*67.7%*
	Dipina Central	27.7%	80.3%	Type 2 – A	*80.4%*
	Dipina Esp.	27.9%	80.5%	Type 2 – A	100%
	Puerto Viejo	16.7%	69.3%	Type 4 – C	64.5%
	El Naranjo	8.4%	61.0%	Type 4 – C	60.9%
	Ausberto Paladino	27.3%	79.9%	Type 3 – C	81.3%

Note: 1. Un-calibrated SoM is based on the average results shown in Table 6.9
2. Italicized CS Values were calculated using linear regression.

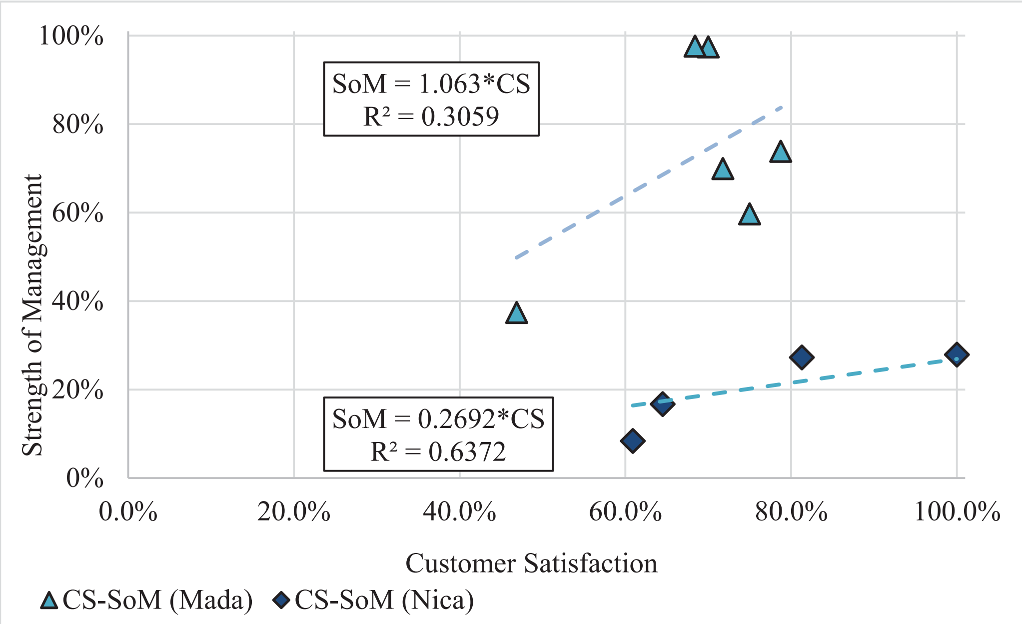
Using the same normalization process for converting Income Potential to a percentage of the maximum value in the study provides an opportunity to identify management that is exceeding expectations. When SoM is combined with the Income Potential for the sites, a quadrant analysis reveals systems that are out-performing their potential. Figure 6.9 shows the quadrant analysis used to compare SoM using quadrants. Category A systems are those that are exceeding expectations in terms of SoM and income potential. Category B systems have high SoM with high IP and are thus meeting expectations. Category C systems have low SoM and low IP and are systems that could be improved with capacity building and improved management. Category D systems are under performing in that they have low SoM with high IP which could be described as having the most potential for improvement as financial resources are likely available locally for better management. The results shown previously in Table 6.10 also included the quadrant classification.

Figure 6.9: Comparative SoM using Quadrants; Madagascar and Nicaragua (n=17)

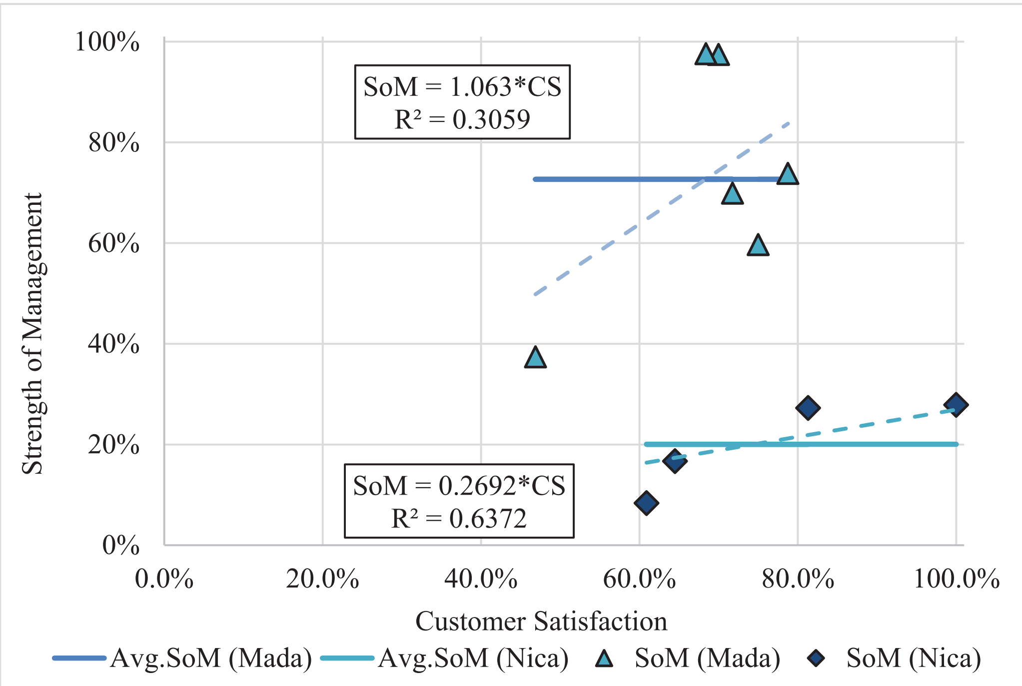


Text Box 6.2: Calibrating the Results of Strength of Management for External Validity

Step 1: Determine the linear relationship between Strength of Management and Customer Satisfaction

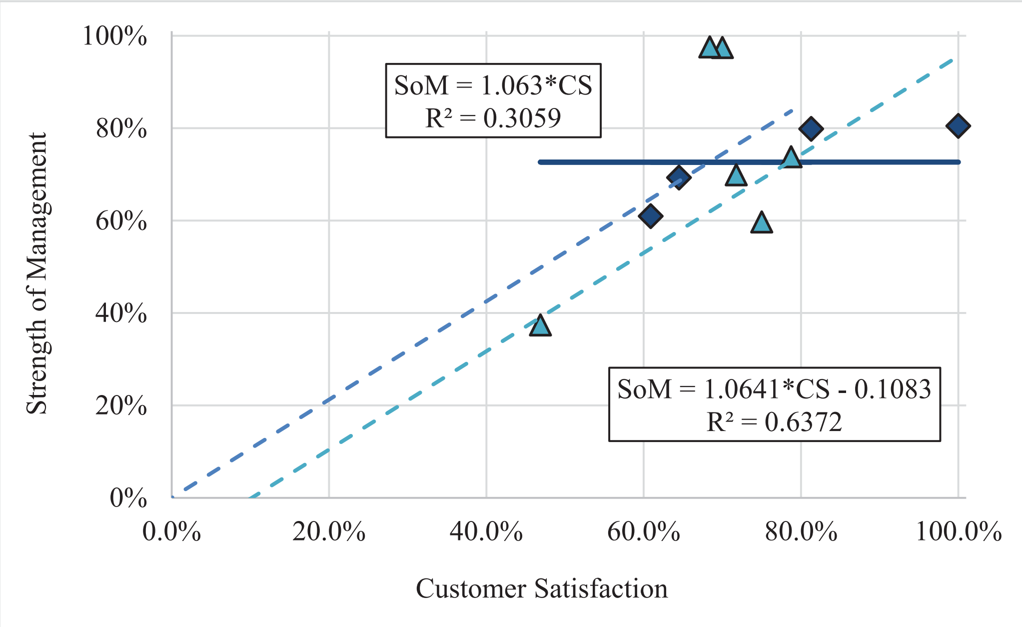


Step 2: Determine the average SoM score for all sites delineated by country



Text Box 6.2 (cont): Calibrating the Results of Strength of Management for External Validity

<u>Step 3</u>: Transform the average SoM (Nica) score to align with the average SoM (Mada) score.



<u>Note</u>: A separate validation calculation was conducted wherein, the SoM test completed in Nicaragua was implemented for the Tolongoina system in Madagascar. The results for SoM'(Tolongoina) shows that when using the same SoM test, the data transforms back to 1.5% of the original SoM Tolongoina score. SoM'(TLG) = 23.3% and SoM(TLG) = 97.5% and SoM(TLG-Calibrated) = 96.0%.

Site Location (test)	Original Composite SoM	Transformed SoM based on average difference	SoM Classification	Customer Satisfaction
Tolongoina (Presence/Absence SoM)	97.5%	97.5%	Type 1 – A	70.0%
Tolongoina (Monetized SoM)	23.3%	96.0%	Type 1 – A	70.0%

Finally, prior to any further analysis, outliers were identified to eliminate sites where the results between the three methods; SoM, IP and CS were inconsistent. Table 6.11 shows the results of the three methods along with the percent deviation between the different methods. Six sites were identified; Andemaka, Imorona, El Rodeo, La Cieba, Dipina Central and Dipina Esperanza, where the results were inconsistent enough to be reconsidered for further analysis. Imorona shows a 161.1% deviation and Andemaka shows a 31.3% deviation. In both cases, the CS values, 80.6% and 75.0% respectively, suggests that there was an error during the implementation of the SoM and IP surveys. In the four site locations in Nicaragua, the percent deviation would also suggest that there is an error with respect to the approach taken to measure SoM, where the percent deviations was greater than 30 percent. These sites however are similar in that they could be classified as extremely remote communities. This has ultimately caused the percent IP values to be artificially low because the results were normalized with the maximum value in the data set. For example, in Dipina Esperanza, the combined SoM scores has a 39.0% deviation which is ultimately a result of the 42.9% IP score as compared to the 100% CS score and the 80.5% SoM score. In this case, the per-capita IP score of 2.71 $/p/yr may be artificially low in that two of the Nicaragua site locations, Los Lipes (6.32 $/p/yr) and San Franscisco (4.51 $/p/yr) have higher socio-economic conditions, with easier access to the regional capital of Matagalpa and thus the cost of living is also higher. In this regard, the sites with inconsistent IP score were not considered outliers.

Table 6.11: Validation of SoM Analysis, Madagascar and Nicaragua

Site Location	Calibrated SoM	Income Potential	Customer Satisfaction	Percent Deviation
Tolongoina	97.5%	73.5%	70.0%	19.5%
Ikongo	97.6%	66.3%	68.4%	21.9%
Mananara	69.9%	100%	71.8%	20.9%
Manompana	37.4%	41.8%	46.9%	11.3%
Anivorano	73.8%	70.2%	78.8%	5.8%
Andemaka	**59.7%**	**38.9%**	**75.0%**	**31.3%**
Imorona	**4.00%**	**0.00%**	**80.6%**	**161.1%**
Los Lipes	100%	100%	*100%*	0.0%
Molino Norte	82.3%	57.1%	*82.4%*	19.7%
San Jose	88.3%	57.1%	*88.4%*	23.1%
San Francisco	97.6%	71.4%	*97.7%*	17.0%
El Rodeo	67.2%	14.3%	*67.3%*	61.7%
La Ceiba	67.6%	14.3%	*67.7%*	61.8%
Dipina Central	80.3%	42.9%	*80.4%*	31.9%
Dipina Esp.	80.5%	42.9%	100%	39.0%
Puerto Viejo	69.3%	57.1%	64.5%	9.6%
El Naranjo	61.0%	52.9%	60.9%	8.0%
Barrio Aus.	79.9%	57.1%	81.3%	18.6%

6.4 Chapter Summary – Strength of Management

This chapter explores knowledge gaps associated with characterizing strength of management for the purposes of comparing water utility management and identifying internal factors that directly influence water system performance. The analysis of strength of water utility management for piped water supply systems in Nicaragua and Madagascar included management capacity in the form of Human Resources, System Administration, Operation and Maintenance, Asset Management and Financial Management. The SoM analysis in Madagascar was primarily based on the Sustainable Index Tool, developed by USAID in conjunction with Rotary International and Lockwood (2013) and used a presence/absence test of various sub-indicators. The SoM analysis in Nicaragua was based on the STEEP framework and used per-capita investments into the water supply infrastructure.

All the systems investigated in Madagascar used a PPP management model for water service delivery. The monitoring and evaluation of water management in Tolongoina is unique in that the water infrastructure was rehabilitated in July of 2014, but the PPP management of these services began roughly six months later. The overall SoM in Tolongoina was given a 78.6% score with the highest indicator being Financial Management (100%) and the lowest indicator being Human Resources (68.4%). In Ikongo, the system serves an area of 7,500 people with approximately 2,500 customers. This system is unique in that the cost of a private connection may be limiting customer acquisition. The overall SoM score was 78.7% with a Financial Management score of 100% and an Operation and Maintenance score of 70.2%. The system in Mananara is unique with respect to the overall size of the system, wherein the water supply serves an area of 16,500 people with roughly 13,500 customers and an annual growth rate in terms of customer acquisition that is 6.5 times the study average. The overall SoM for this system was 56.2%, with the highest indicator being Financial Management (75%) and the lowest indicator being System Administration (41.6%).

A comparative analysis for Strength of Management of all the system in Madagascar reveals that SoM in Imorona, Manompanana and Andemaka are amongst the lowest SoM scores evaluated with 3.1%, 29.6% and 49.2%, respectively. Some evidence of quality assurance and quality control issues with respect to the data collection in Imorona have been noted from a qualitative point of view during the study which has been verified with Customer Satisfaction results. Some evidence that Customer Satisfaction Survey results could be a better measurement of SoM was also discussed.

In Nicaragua, the systems being investigated were generally smaller in size and used a community management model wherein some of the systems had elements of contracting out operation and maintenance or administrative activities. In Puerto Viejo, the community invests \$3.64 per customer annually (approximately 1,300 customers) to manage the system and utilizes a local electric company to issue water bills. In El Naranjo the community provides services for close to 3000 customers and invests \$1.95 per person annually with little evidence of community participation in managing the system beyond the existing water committee. In Los Lipes, the strength of management is amongst the highest of all the systems with investments of \$12.13 per person annually because of significant community participation in managing the system.

In order to compare the two different SoM tests conducted for systems in Madagascar and Nicaragua, the final analysis included a data calibration process which used the Customer Satisfaction results as a common point of analysis. Chapter 7 of this study provides a holistic summary of the results and explores univariate and multivariate relationships between different SoM Indicators and the water system performance characteristics in terms of water quantity and water quality.

CHAPTER 7

SYNTHESIS OF RESULT EXPLORATORY ANALYSIS

7.0 Synthesis of Results and Exploratory Analysis

This chapter addresses knowledge gaps related to investigating relationships between strength of management and performance characteristics of water supply infrastructure, as described in Section 1.2. Whereas, Chapter 4 has identified objective measurements of water quantity that can be used for comparison purposes and Chapters 5 and 6 identify criteria for water quality and strength of management respectively; this chapter intends to complete the process by exploring links between these relationships.

The chapter starts by synthesizing the results of Strength of Management (SoM) and Performance Characteristics in terms of Water Quantity and Water Quality. A summary of the results is provided to introduce a holistic perspective of the different performance characteristics with the noted limitation that any generalization of the results would be out of context with respect to specific site conditions. In this sense, it is possible that individual SoM indicators could outweigh other factors in a unique fashion, creating the mechanisms for success or failure. A univariate linear regression analysis was completed to explore correlations between different parameters and key factors within the performance characteristics. The key factors were then used in a multivariate analysis to explore relationships between individual SoM parameters as independent variables, and system performance characteristics as dependent variables.

Independent variables with respect to SoM included Human Resources (HR), System Administration (SA), Operation and Maintenance (O&M), Asset Management (AM) and, Financial Management (FM). Dependent variables in terms of Water Quantity included system Reliability (η_{del}) water Availability (defined as the system duration capacity, SDC) and composite performance scores. Independent variable in terms of Water Quality included Source (S.WQ), Tank (T.WQ) and Distributed water quality (D.WQ) as well as Microbial (M.WQ), Physical and Chemical water quality parameters. This chapter summarizes an exploration of univariate and multivariate relationships and Appendix E provides additional details on the results of the statistical analysis.

7.1 Strength of Management and Performance Characteristics

Table 7.1 shows a summary of results for the overall SoM and composite analysis of Water Quantity and Water Quality. The individual classifications for each variable are also shown to better identify and compare the overall performance characteristics. In addition to this, the results are sorted by SoM to identify higher and lower performance characteristics in each category. An important difference between the composite scores and the performance classification should be noted. The composite score for water quantity (η_{del}-SDC) represents an average between the reliability score and the availability score and the composite water quality score combines all of the samples taken for each location into a single compliance score (S.WQ-T.WQ-D.WQ).

The classifications shown, includes two aspects of the overall performance characteristics within each category. The numerical classification, uses a threshold value for each category and the alphabetic classification, identifies the quadrant values for each category as described in the results section of this study. Most importantly, the composite score of water quality combines the results of all water samples taken throughout the system and the numeric classification for water quality only considers the distributed water quality results. As a result, some discrepancies can be identified between the composite and the numeric classification of water quality. For example, the water quality results reported here for Los Lipes show that 89.3% of all of the samples taken throughout the water system complied with the various criteria. In this regards, a Class-2 numeric value would be given to the system since the result was less than 90 percent. The classification given however, is Class-1 because the actual classification only considered water quality results within the distribution (D.WQ) system which resulted in a 91.4% compliance score (not shown).

A review of the results in Table 7.1 does not reveal obvious trends between the performance characteristics and strength of management. An initial inspection of the highest performing systems in terms of SoM (Los Lipes and San Francisco) reveals potential trends however, these initial trends are offset by the remaining systems that show little or no trends amongst higher SoM performing systems. For example, two of the five highest SoM systems (Ikongo and Tolongoina) ranked within the lower third with respect to water quality compliance. At the same time, a review of the poor performing SoM systems would suggest that strong management is essential for preventing system failure. In this regard, four of five sites within the lowest SoM systems scored in the lower third for water quantity performance characteristics and two were in the lower third for water quality. More specifically, a cursory review of the systems that scored below 70% SoM reveals that only one of the sites (El Rodeo) was classified as high performing (1A and 1B) in terms of water quantity and water quality. This site justifies further investigation into the mechanisms by which management influences performance and would be a candidate for a case-study analysis.

Table 7.1: Summary of Results – SoM, Water Quantity and Water Quality

			Composite Score		Classification					
Site Location	Country	Strength of Management	Water Quantity	Water Quality	SoM		Quan		Qual	
Los Lipes	Nicaragua	100.0 %	[1] 92.5%	[1] 89.3%	1	B	1	A	1	B
San Francisco	Nicaragua	97.6%	86.1%	75.1%	1	A	2	B	2	A
Ikongo	Madagascar	97.6%	67.9%	[2] 70.0%	1	A	4	C	3	C
Tolongoina	Madagascar	97.5%	66.7%	[2] 58.8%	1	A	4	C	5	C
San Jose	Nicaragua	88.3%	78.6%	71.9%	2	A	3	B	3	C
Molino Norte	Nicaragua	82.3%	[1] 97.3%	[1] 90.8%	2	A	1	A	1	B
Dipina Esp.	Nicaragua	80.5%	[1] 91.8%	[1] 84.3%	2	A	1	A	1	A
Dipina Cen.	Nicaragua	80.3%	89.7%	[1] 86.7%	2	A	2	A	2	B
Aus. Paladino	Nicaragua	79.9%	[1] 96.4%	82.0%	3	C	1	A	2	A
Anivorano Est	Madagascar	73.8%	66.4%	[2] 65.2%	3	C	4	C	3	C
Mananara	Madagascar	69.9%	[2] 54.2%	[2] 58.0%	4	D	5	D	4	C
Puerto Viejo	Nicaragua	69.3%	[2] 63.7%	82.3%	4	C	4	C	3	D
La Ceiba	*Nicaragua*	*67.6%*	*74.4%*	*NT*	*4*	*C*	*3*	*B*	*N*	*T*
El Rodeo	Nicaragua	67.2%	[1] 90.2%	[1] 97.2%	4	C	1	A	1	B
El Naranjo	Nicaragua	61.0%	[2] 20.9%	76.8%	4	C	5	D	3	C
Manompana	Madagascar	37.4%	[2] 58.8%	[2] 56.1%	5	C	5	C	5	C
Andemaka	*Madagascar*	*59.7%*	*80.1%*	*NT*	*5*	*C*	*2*	*B*	*N*	*T*
El Guabo	*Nicaragua*	*NT*	*92.3%*	*75.9%*	*N*	*T*	*1*	*A*	*3*	*C*
Imorona	*Madagascar*	*NT*	*54.0%*	*70.2%*	*N*	*T*	*5*	*D*	*4*	*D*

1 – Top third; 2 – Bottom Third; NT – Not Tested; Italicized – Incomplete data

In order to investigate this further, the results were delineated between different SoM classifications to explore if SoM scores of greater than 90%, 80% and 70% performed better, on average with respect to water quantity and water quality. The results in Table 7.2 show the SoM delineations, along with the change in average water quantity performance. These results suggest that there is very significant evidence (p=0.017) that poor management of water services results in lower water quantity performance with a 25.8% difference between systems that were poorly managed (SoM less than 70%) and those that were not poorly managed (SoM greater than 70%). The results also suggest that an SoM threshold of 80% is a good indicator of potential success in that this value also resulted in an average water quantity performance of greater than 80% with reasonable confidence (p=0.069). Note that rounding up the Ausberto Paladino system from SoM 79.9% to SoM 80% would results in an average water quantity score of 85.2% with very significant evidence of SoM influence (p=0.011). In this sense, it can be concluded that, if a system is poorly managed, then it is highly likely that the availability of water and reliability of services will be compromised. At the same time, two of the higher performing SoM systems (Ikongo and Tolongoina) were classified as 4C systems in Table 7.1. This reveals that delineating SoM characteristics at above 90% (Table 7.2) does not necessarily reflect higher reliability and availability of services.

Table 7.2: Student's t-test for Water Quantity System Performance

SoM Delineation	Average Water Quantity (greater than)	Average Water Quantity (less than)	Difference in Average Water Quantity Performance	Student's t (2T)	p-value
Class 1 (> 90)	78.3%	73.4%	4.8%	0.459	0.706
Class 2 (> 80)	83.8%	64.4%	19.4%	0.430	0.069
Class 3 (> 70)	83.3%	57.6%	25.8%	0.432	0.017

The results for SoM and Water Quality (Table 7.3) suggest that there is little or no evidence that strength of management influences water quality performance characteristics. Whereas, these results could be described as "disappointing" in that one of the objectives of the study was to establish links between management and performance characteristics, a lack of evidence, or evidence against any relationships is a finding worth referencing. In this regard, it could be said that there is no evidence of a relationship between strong management and the overall composite water quality performance throughout the system. In addition to this, these results further verify the challenges associated with delivering safe water in low-income developing communities and, that the complex nature of doing so should not be underestimated. Further explanation of these results is warranted. In this regard, it is important to understand that the composite water quality analysis includes samples throughout the system including source, tank and distributed water. This is being highlighted here to demonstrate the importance of understanding the mechanisms with which management should influence water quality in that composite compliance that includes poor source water quality would offset the improvements realized from strong management on average. For this reason, an exploration of changes in water quality is provided below in Section 7.2.2.

Table 7.3: Student's t-test for Water Quality System Performance

SoM Delineation	Average Water Quality (greater than)	Average Water Quality (less than)	Difference in Average Water Quality Performance	Student's t (2T)	p-value
Class 1 (> 90)	73.3%	77.4%	-4.1%	0.487	0.604
Class 2 (> 80)	78.4%	73.9%	4.4%	0.459	0.523
Class 3 (> 70)	77.4%	74.1%	3.3%	0.464	0.653

7.2 Exploratory Analysis of Univariate Relationship

7.2.1 Strength of Management and Water Quantity

This section explores linear relationships between the various Water Quantity performance characteristics and Strength of Management. In terms of Water Quantity, the relationships between Reliability and Availability have been isolated to identify how individual SoM indicators influence performance. In order to compare individual SoM indicators a data transformation, as described in Chapter 6, was completed at the indicator level to align the SoM indicator-results for Madagascar and Nicaragua. Strength of

Management indicators included Human Resources, System Administration, O&M, Asset Management and Financial Management. The exploratory analysis used for this investigation included univariate analysis between individual performance criteria as dependent variables and SoM indicators as independent variables.

Figure 7.1 shows a plot of the overall SoM score versus the overall Reliability (η_{del}) of the system delineated for systems in Madagascar and Nicaragua separately. Both of the relationships show a positive correlation between SoM and η_{del} and, the linear regression model for Madagascar represents a better fit ($R^2 = 0.729$, $p = 0.031$, $n = 6$) as compared to the variability of the linear regression model for Nicaragua ($R^2 = 0.340$, $p = 0.090$, $n = 10$). When combining both of the data sets, the linear regression model shows a positive but relatively weak fit with respect to r-squared correlation ($R^2 = 0.175$, $p = 0.094$, $n = 17$). An interpretation of these results suggests that there is some evidence that SoM influences the reliability of water services.

Figure 7.1: Strength of Management versus System Reliability

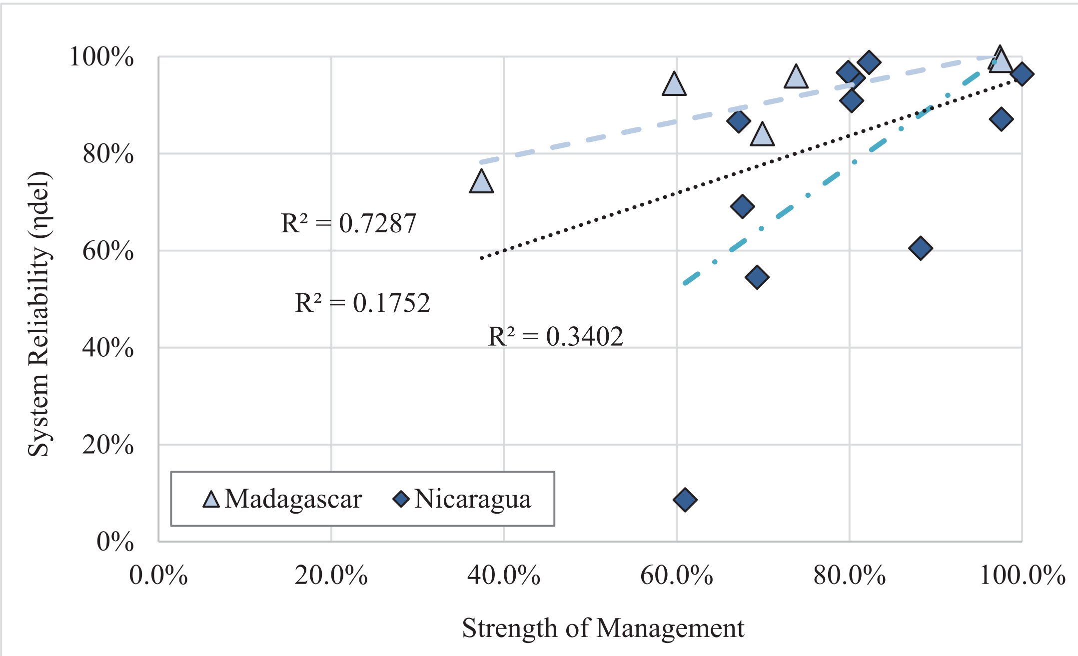


Figure 7.2 shows the relationships between Strength of Management and the composite SDC-Water Availability score, based on the percentage of days that the systems provided 20, 50 and 80 liters per person. The Pearson r-squared correlation coefficient for

systems investigated in Nicaragua (R^2 = 0.301, p = 0.081, n = 11) is consistent with the relationship shown between Reliability and SoM. At the same time, the univariate linear regression analysis for the systems investigated in Madagascar shows a negative relationship (R^2 = 0.166, p = 0.422, n = 6) between SoM and SDC which would suggest that better water management provides less water to the local community. Whereas, initially this may appear to render the results non-conclusive, it is important to recognize the differences in management models between Nicaragua and Madagascar. In Nicaragua, the systems are community managed and thus water fees are structured to provide the most access for the lowest cost. In Madagascar, the systems are privately managed and the water fees are structured to provide a reasonable income to the water utility and ensure long-term financial sustainability. It is therefore logical that stronger water management would have more efficient billing and can better manage non-revenue water and leaks in the system. Furthermore, as concluded by Bakalian and Wakeman (2009), economic differences between affordability and access to secondary water resources are likely influencing the overall water consumption in Madagascar. Finally, the regression analysis of the combined systems shows no real correlation (R^2 = 0.059, p = 0.347, n = 17) because of the offsetting nature of the positive and negative relationships between SoM and Availability in Nicaragua and Madagascar respectively.

Figure 7.3 shows the relationship between overall SoM and water Availability using the SDC value for 20 liters per person per day (SDC-20). In this case, the univariate linear regression models for Madagascar, Nicaragua and the combine data, have positive relationships and the slopes of the regression lines are relatively equal. In addition to this, the r-square values (R^2=0.32, p=0.069, n=11) for Nicaragua are again consistent with the other linear models shown in this analysis. These results when combined with the analysis of the composite SDC Availability score (Figure 7.2) would suggest that SoM is essential to providing minimum basic needs of water (20 l/p/d), regardless of management type and that strong community managed system are more likely to provide higher volumes of water as compared to strong privately management systems. In fact, on average, the community managed systems in Nicaragua provided 69.9 l/p/d more than the privately managed systems in Madagascar (p = 0.0001) with very significant evidence that the results were statistically valid.

Figure 7.2: Strength of Management versus Composite SDC Availability

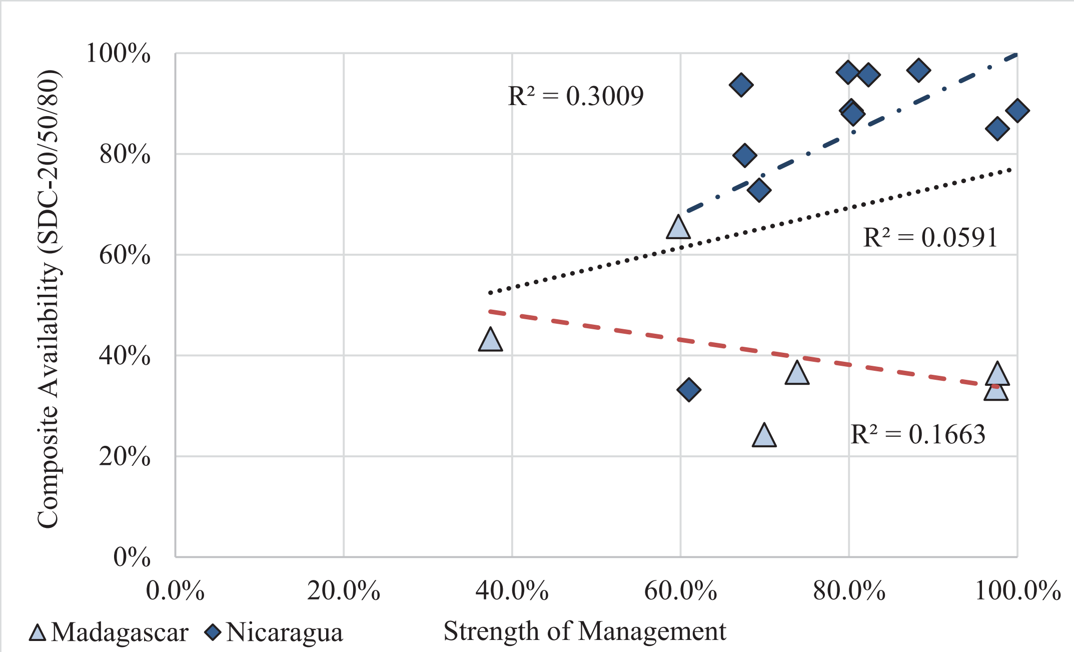
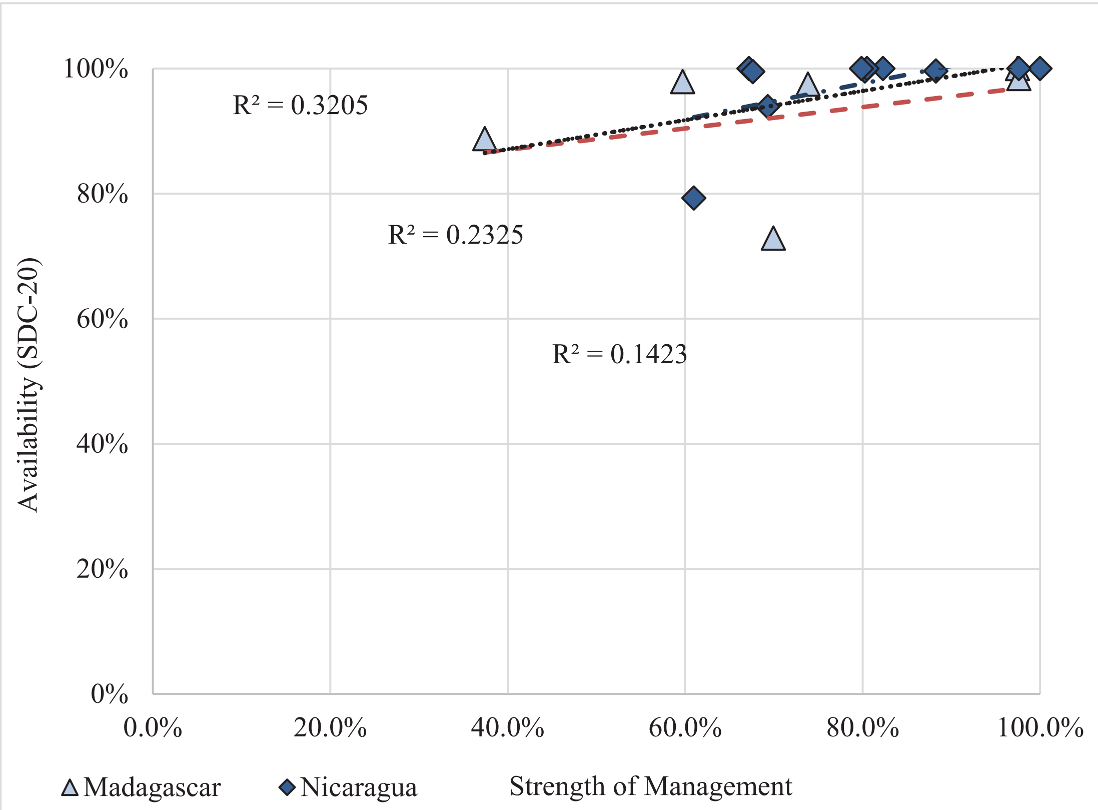


Figure 7.3: Strength of Management versus SDC-20 Water Availability (20 l/p/d)



In order to further investigate relationships between SoM and performance characteristics, a correlation matrix of the Reliability and Availability results, and the individual SoM indicators was created. Table 7.4 shows the results of this analysis using the Pearson Correlation Coefficients for the linear regression model used to identify relationships between Reliability and Availability of water and individual SoM indicators as well as the overall Strength of Management scores. Highlighted in this table are the maximum correlation coefficients for each water quantity performance characteristic. The largest linear correlation ($R=0.61$, $p=0.009$) is between the Availability of greater than 20 l/p/d and the SoM indicator for Human Resources Management; followed closely by the linear correlation ($R=0.57$, $p=0.018$) between Reliability and Financial Management.

The relationship between the overall Reliability and the overall Availability of water services with respect to the average Strength of Management was also investigated to determine the extent to which, one can be used to predict the other. In this regard, the largest linear correlation ($R=0.48$, $p=0.05$), is between the Availability (>20 l/p/d) of water and the average SoM. In addition to this, the overall Reliability of services and the combined composite water quantity score (ηdel-SDC) show a positive linear correlation ($R=0.42$, $p=0.093$) with respect to average SoM. Setting an artificial value for linear correlation ($R=0.5$ and $p=0.05$) helps to identify relationships that are more significant than others. In this regards, only Availability of water greater than 20 l/p/d and Human Resources, as well as Reliability and Financial Management correlations are above this criteria. Of additional interest is the relationship between System Administration and water Availability wherein, three of the six criteria had their highest individual correlations in this category, with the water Availability greater than 80 l/p/d ($R=0.390$, $p=0.122$) being the largest of these.

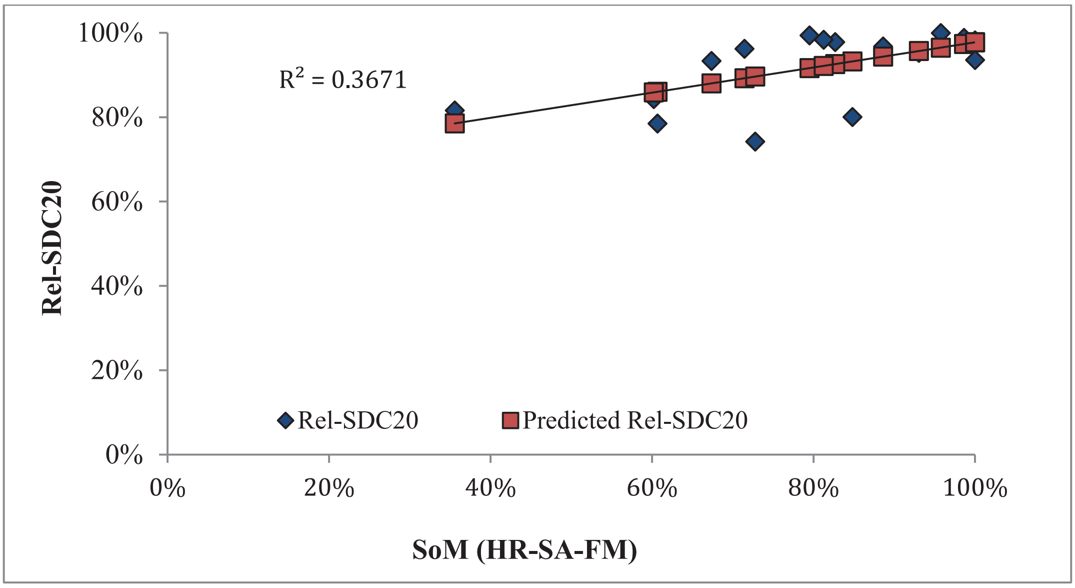
Table 7.4: Correlation Coefficients; Reliability and Availability versus SoM Indicators

Strength of Management Indicator Nicaragua and Madagascar (n=17)	Pearson Correlation Coefficients Linear Regression					
		SDC Availability of Water (Percentage of Days)				
	Reliability η_{del}	> 20 (l/p/d)	> 50 (l/p/d)	> 80 (l/p/d)	Average Availability Score	Composite Score η_{del}-SCD
Human Resources	0.392	**0.612**	0.143	0.242	0.243	**0.404**
System Administration	0.252	**0.533**	**0.252**	**0.390**	**0.357**	0.398
Operation & Maintenance	0.220	0.260	-0.015	0.192	0.106	0.206
Asset Management	0.251	0.202	0.099	0.345	0.227	0.307
Financial Management	**0.566**	0.357	-0.034	-0.011	0.013	0.350
Average - SoM	***0.419***	***0.482***	*0.118*	*0.300*	*0.244*	***0.420***

Further exploration of these relationships consolidated certain indicators prior to the investigation of key factors. In terms of water quantity performance characteristics, two composite scores were created and analyzed with respect to strength of management. The first regression analysis explored the relationship between overall SoM as an independent variable and the SDC-Reliability composite score as a dependent variable. The results of this analysis show that 12.7% of the variability (R^2 = 0.13) of the Water Quantity Performance (as measured by a composite of η_{del} and SCD) can be explained by the Strength of Management of the system. Furthermore, the results suggest that there is a 17.5% chance (p = 0.18) that the relationship between SoM and a composite score of η_{del}-SCD is completely random, using the F-statistic test to determine the p-value of the null hypothesis. The second regression analysis shows that 23.5% of the variability with the η_{del}-SCD20 Water Quantity Performance results can be explained by the linear relationship with SoM (R^2 = 0.235). This analysis isolated the 20 liters/person/day availability and used an overall composite score of η_{del} and SCD20. A test of the null-hypothesis reveals that there is evidence of a real effect with increasing SoM resulting in an increase in availability of 20 liter/person/day with the F-statistic test showing a 5.69% chance (p = 0.057) that the relationship was random.

Further investigation of the results discussed in Table 7.4 reveals relationships between individual SoM indicators and various Water Quantity Performance variables with Human Resources (HR) and SDC-20, System Administration (SA) and SDC-20 and, Financial Management (FM) and Reliability (η_{del}) all having Pearson Correlation Coefficients of greater than 0.5 ($r > 0.5$). In order to explore these relationships further, a composite SoM score was created by averaging the scores for the above mentioned indicators. A linear regression analysis was then performed on SoM (HR, SA, FM) as an independent variable and with the composite η_{del} and SDC-20 score as a dependent variable. Figure 7.4 shows a plot of the composite SoM using HR, SA and FM indicators and the η_{del}-SCD20 water quantity performance score. The results of this analysis show that 36.7% of the variability ($R^2 = 0.37$) of the Quantity Performance (as a function of η_{del} and SCD-20) can be explained by the Strength of Management of the system as measured by Human Resources, System Administration and Financial Management. Furthermore, the results suggest that there is a 1.3% chance ($p = 0.013$) that the relationship between SoM (HR-SA-FM) and a composite score of η_{del}-SCD20 is completely random.

Figure 7.4: SoM (HR, SA, FM) versus η_{del}-SDC20 System Performance (n=16)



Whereas, this study explores relationships using statistical tools for analysis, a brief discussion on the mechanisms by which the SoM indicators may influence performance is important. In this regard, the SoM variable of Human Resources used three indicators in its evaluation; technical support, community involvement and water utility staffing.

These indicators have additional sub-indicators ranging from visits from technical teams to the project site and local counterpart contributions during construction to gender balance on the water committee and capacity building. As a result, the composite score employed to evaluate SoM does not isolate individual sub-indicators. This analysis does provide insight into potential mechanisms which could be explored further through additional research and contributes to the body of knowledge wherein previous studies have also identified influential indicators of reliable water services. More specifically, whereas the results from this analysis suggest that Human Resources is an influential indicator in terms of providing a reliable supply of 20 l/p/d, it supports the findings of Bakalian and Wakeman (2009) who conclude that external support is a factor, Kayaga (2013) and Franceys (1997) who conclude that community participation is a factor and Fischer (2008) who concludes that gender play a role in sustainability. Furthermore, the analysis shown in Table 7.4 also supports the works of Sansom and Coates (2011) and Baietti et al. (2006) where sub-indicators related to System Administration include planning and record keeping.

7.2.2 Strength of Management and Water Quality

In terms of Water Quality, relationships between water quality compliance and individual SoM indicators were explored, with the objective of identifying SoM indicators which have the potential to influence water quality performance. Appendix E shows the results of the linear regression analysis between the composite SoM and Water Quality throughout the system (Source, Tank and Distributed). The linear regression for SoM and Source Water Quality showed a negative correlation with little evidence that the relationship was not random ($R^2 = 0.040$, $p = 0.493$, $n = 14$). The linear regression for SoM and Tank Water Quality showed a more positive correlation with better evidence that the relationship was not random ($R^2 = 0.18$, $p = 0.120$, $n = 15$). The linear regression for SoM and Distributed Water Quality showed a more positive correlation with still-better evidence that the relationship was not random ($R^2 = 0.21$, $p = 0.076$, $n = 16$). In general, the results of the linear regression analysis show that there is very little relationship between composite Strength of Management and Water Quality performance characteristics with an increasing relationship from the source to the tank and from the tank to the distribution system.

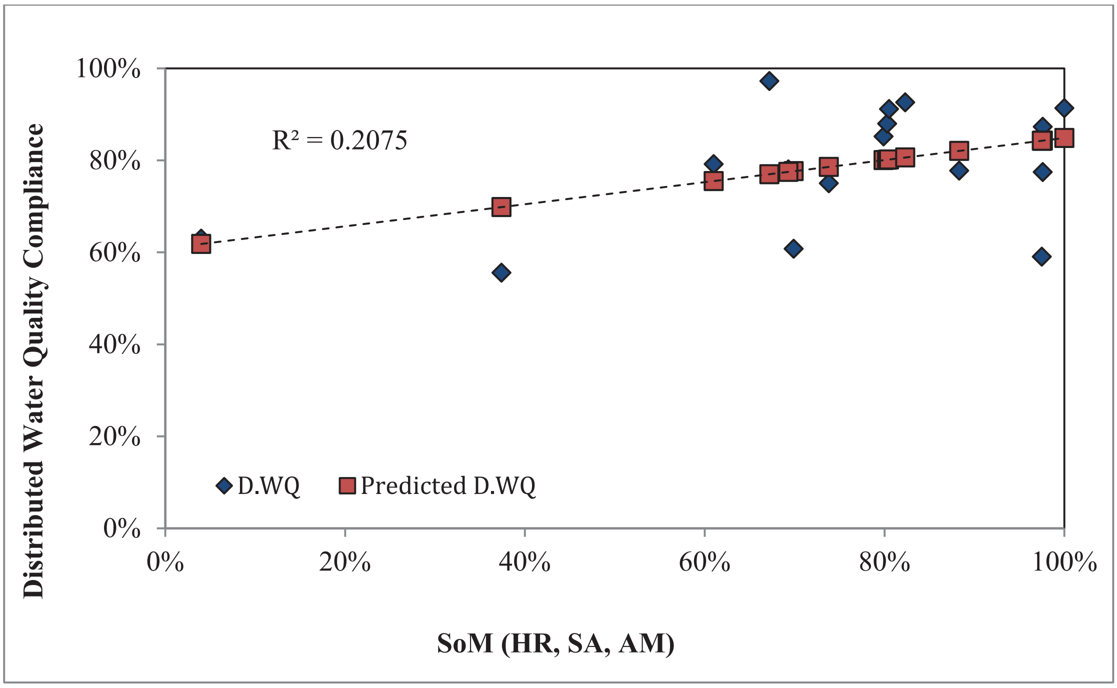
Table 7.5 shows the linear regression coefficients between the individual SoM indicators and the compliance characteristics for source, tank and distributed water quality. This analysis further demonstrates that the distributed water quality more closely aligns with management indicators with the System Administration indicator showing the largest Pearson Coefficient (R=0.62, p=0.01). Of interest is the relationship between changes in water quality between the source and distribution system when evaluating the influence that strength of management has on water quality performance characteristics. In this regard, an analysis of ΔWQ(D-S) could potentially reflect a causal relationship in that poor initial source water quality likely requires more management to bring water quality to a minimally accepted standard. Table 7.5 also shows these relationships with the strongest Pearson Correlation Coefficient being between change in water quality and O&M (R=0.74, p=0.0025). The results of this analysis have the potential to influence research on sustainable water management as all of the Pearson Correlation Coefficients are positive and all show significant evidence of a real relationship (see Appendix E). Additionally, the overall SoM (R=0.73, p=0.003) shows significant evidence of a real influence on change in water quality.

Table 7.5: Correlation Coefficients; Water Quality versus SoM Indicators

Strength of Management Indicator	Pearson Correlation Coefficients Linear Regression			
	Source	Tank	Distribution	ΔWQ (D-S)
Human Resources	-0.271	0.241	0.384	0.690
System Administration	**0.106**	**0.587**	**0.619**	0.584
Operation & Maintenance	-0.435	0.192	0.252	**0.739**
Asset Management	-0.170	0.463	0.394	0.585
Financial Management	-0.188	0.348	0.359	0.733
Average - SoM	-0.200	0.419	0.455	0.733

Figure 7.5 shows the regression analysis of the composite SoM score using the three most influential indicators (Human Resources, System Administration and Asset Management) and the results for Distributed Water Quality. The linear regression model between SoM (as a function of HR, SA and AM) and D.WQ that reveals some evidence ($p=0.08$) of a relationship ($R^2 = 0.21$) between strength of management and distributed water quality. Further discussion on the mechanisms by which these factors should relate to overall distributed water quality is justified. Whereas, obvious relationships between human resource and system administration indicators are not clear, it is implicit that general organization of the water utility should influence distributed water quality. The mechanisms by which asset management indicators would influence water quality is clearer in that, availability of supplies and equipment as well as watershed stakeholder engagement should related to water quality.

Figure 7.5: SoM (HR, SA, AM) versus Distributed Water Quality (n=16)



Given the results in Table 7.5, further exploration of relationships between strength of management and changes in water quality is justified. Of initial interest is the negative relationship between the SoM indicators and source water quality. In this regard, it is important to recognize the indicators and sub-indicators used for the analysis and the potential for an inverse causal relationship with initial source water quality. For example, in terms of operation and maintenance, which showed the strongest negative relationship (R = -0.435), it is logical that high quality source water would not require extensive operation and maintenance. In addition, poor source water quality would require higher maintenance frequency, water testing and potentially better customer communications in terms of public health announcements or addressing complaints. In order to explore this further, a linear regression analysis between changes in water quality and strength of management was completed. Figure 7.6 shows the linear regression wherein; it can be said that there is very significant evidence ($p = 0.003$) of a strong relationship ($R^2 = 0.54$) between SoM and delta water quality. Further discussion on these results is provided in Chapter 8: Conclusions and Recommendations.

Figure 7.6: SoM versus ΔWQ (D-S) (n=14)

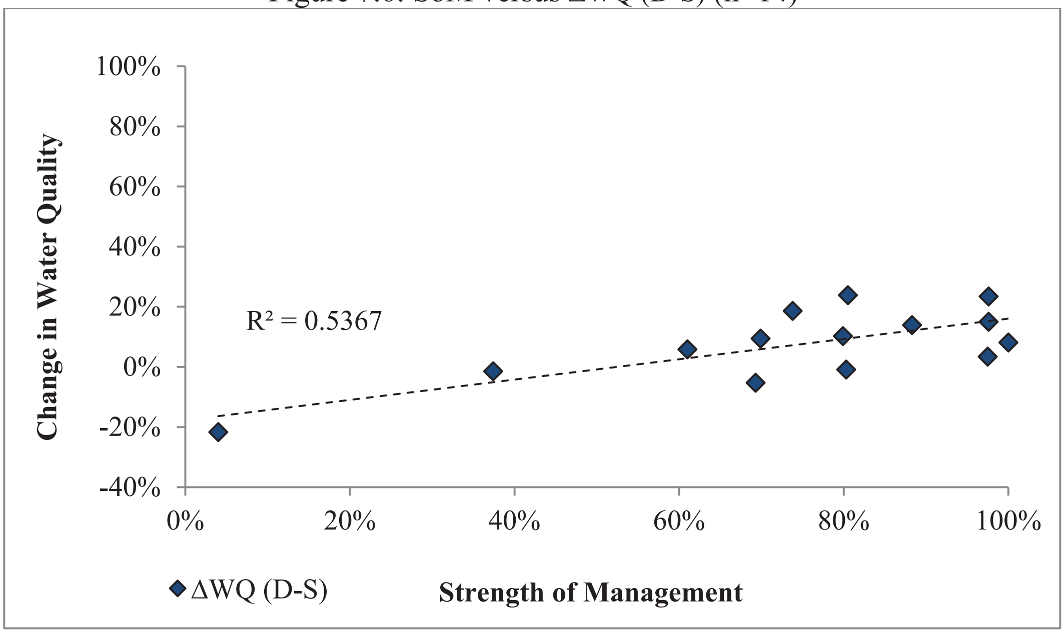


Table 7.6 shows the linear regression coefficients between the individual SoM indicators and the compliance characteristics for distributed water quality delineated for Microbial, Physical and Chemical constituents. The strongest relationship within the delineated results is between Microbial Water Quality and System Administration and the strongest relationship within the entire set is between the Composite Water Quality Score and System Administration. This analysis clearly demonstrates a link between the management characteristic and microbial water quality as well as distributed water quality. More specifically, Distributed Water Quality and System Administration ($R=0.62$, $p=0.01$) and Microbial Water Quality and System administration showed significant evidence of a relationship ($R=0.61$, $p=0.01$). Wherein, overall SoM and D.WQ did not show a strong correlation (defined as $R>0.5$), the results shown here do show enough evidence of a positive relationship ($R=0.46$, $p=0.076$) to warrant further investigation. An important note with respect to Chemical Water Quality (Appendix E.4) is that all of the samples resulted in 100% compliance, rendering the analysis of variance meaningless in this regards.

Table 7.6: Correlation Coefficients; Distributed Water Quality, Water Quality Categories versus SoM Indicators

Strength of Management Indicator	Pearson Correlation Coefficients Linear Regression			
	Microbial	Physical	Chemical	Composite D. WQ
Human Resources	0.436	0.128	0.000	0.384
System Administration	**0.606**	0.478	0.000	**0.620**
Operation & Maintenance	0.288	0.080	0.000	0.252
Asset Management	0.361	0.373	0.000	0.395
Financial Management	0.422	0.080	0.000	0.359
Average - SoM	0.477	0.263	0.000	0.456

7.3 Exploratory Analysis of Multivariate Relationships

A multivariate linear regression analysis was completed to further explore the influence of individual SoM indicators on Water Quantity and Water Quality performance characteristics. Water Quantity was isolated to composite reliability (η_{del}) and system duration capacity (SDC-20) for 20 liters per person per day. Water Quality performance was isolated to the compliance of distributed water quality (D.WQ) using the composite of Microbial, Physical and Chemical parameters.

7.3.1 Strength of Management and Water Quantity

Table 7.7 shows the results of the multivariate analysis that included five SoM indicators ($R^2 = 0.86$, $p=0.007$, $n=13$). From this analysis, it can be seen that, the only individual indicator that passed the null hypothesis test ($p>0.05$) was Financial Management and that, there is significant evidence ($p=0.000$) that no management (SoM = 0.0%) would result in a system with some functionality, where the Y-Intercept would equate to 58.2 percent. In addition to this, it appears that System Administration, O&M and Asset Management have a negative effect on the combined η_{del}-SDC20 performance criteria which would initially raise some concerns about the validity of the results. Upon further inspection, it can be seen that the p-value for O&M is too high to render the results of this relationship to be significant. In terms of SA and AM results, the Margin of Error and the p-value would suggest that these indicators have little influence on the overall system performance in terms of the η_{del}-SDC20 water quantity characteristics.

Table 7.7: Results of Multivariate Analysis; SoM Indicators and η_{del}-SDC20

$R^2 = 0.86$, p=0.007, n=13

Symbol and Number	*SoM Indicator* X_i	*Linear Coefficients* C_i	*Standard Error*	*Student t-test statistic*	*p-value*	*Margin of Error*
Intercept	Y-Intercept	0.582	0.078	7.464	0.000	0.184
HR	Human Resources	0.224	0.135	1.657	0.142	0.319
SA	System Administration	-0.115	0.088	-1.316	0.230	0.207
OM	Operation & Maintenance	-0.014	0.139	-0.104	0.920	0.329
AM	Asset Management	-0.185	0.110	-1.687	0.136	0.259
FM	Financial Management	0.472	0.089	5.330	0.001	0.210

In order to investigate the influences of HR and FM further, these indicators were isolated, and another iteration of the multivariate linear regression was completed using two SoM indicators. Table 7.8 shows the results of this analysis which further validates the claim that no management (SoM = 0.00%) would result in some functionality (59.6%). In addition to this, Financial Management again shows the most significant evidence (p=0.004) of an influence on the overall Water Quantity performance in terms of the system's ability to reliably supply 20 liters per person per day.

Table 7.8: Results of Multivariate Analysis; SoM (SA,FM) and η_{del}-SDC20

$R^2 = 0.72$, p=0.003, n=12

Symbol and Number	*SoM Indicator* X_i	*Linear Coefficients* C_i	*Standard Error*	*Student t-test statistic*	*p-value*	*Margin of Error*
Intercept	Y-Intercept	0.596	0.083	7.181	0.000	0.376
HR	Human Resources	0.064	0.116	0.551	0.595	0.526
FM	Financial Management	0.312	0.083	3.783	0.004	0.373

7.3.2 Strength of Management and Water Quality

Table 7.9 shows the statistical results of the multivariate linear regression for SoM Indicators and the composite Distributed Water Quality (D.WQ). From this analysis, it can be seen that none of the SoM Indicators passed the null hypothesis test (p>0.05) but that two of the indicators shows some evidence of a significant relationship. In this regards, O&M (p=0.077) showed a negative relationship with water quality performance which initially suggests that there may be construct validity problem with regards to the analysis. At the same time, a causal relationship between O&M and D.WQ could logically suggest that systems with larger water quality issues require more O&M and thus, a negative trend could be possible in this regards. Asset Management (p=0.072) however, shows a positive relationship with respect to D.WQ which would also be logical in that better watershed management should result in improvements in water quality. Furthermore, Human Resources (p=0.158) shows the strongest positive influence on D.WQ. Finally, from this analysis it can be determined that there is significant evidence that no management (SoM=0.0%) would results in a system with some functionality, where the intercept of the distributed water quality score is 57.3 percent.

Table 7.9: Results of Multivariate Analysis; SoM Indicators and D.WQ

$R^2 = 0.86$, p=0.007, n=13

Symbol and Number	*SoM Indicator* X_i	*Linear Coefficients* C_i	*Standard Error*	*Student t-test statistic*	*p-value*	*Margin of Error*
Intercept	Y-Intercept	0.573	0.050	11.4	0.000	0.238
HR	Human Resources	0.416	0.263	1.58	0.158	1.244
SA	System Administration	0.126	0.135	0.934	0.382	0.637
OM	Operation & Maintenance	-0.652	0.315	-2.07	0.077	1.488
AM	Asset Management	0.325	0.153	2.12	0.072	0.725
FM	Financial Management	0.065	0.121	0.538	0.607	0.571

In order to investigate the influence of HR, O&M and AM further, these indicators were isolated, and another iteration of the multivariate linear regression was completed. Table 7.10 shows the results of this analysis which further suggests that no management would result in some functionality (56.8%) and that O&M is negatively linked to distributed water quality. In addition to this, Human Resources has the largest positive influence and all of the results and shows significant evidence of a statistically valid relationship with distributed water quality.

Table 7.10: Results of Multivariate Analysis; SoM (HR,O&M,FM) and D.WQ

$R^2 = 0.89$, p=0.0003, n=12

Symbol and Number	*SoM Indicator* X_i	*Linear Coefficients* C_i	*Standard Error*	*Student t-test statistic*	*p-value*	*Margin of Error*
Intercept	Y-Intercept	0.568	0.040	14.273	0.0000	0.183
HR	Human Resources	0.735	0.135	5.457	0.0006	0.621
OM	Operation & Maintenance	-0.905	0.169	-5.360	0.0007	0.779
AM	Asset Management	0.481	0.082	5.889	0.0004	0.376

7.4 Chapter Summary – Synthesis of Results and Exploratory Analysis

This chapter provided a holistic summary of the results and explores univariate and multivariate relationships between different SoM Indicators and system performance characteristics in terms of water quantity and water quality. The initial investigation delineated the SoM results to determine if threshold values yielded a significant difference in performance characteristics in terms of water quantity and water quality. The results from this investigation suggests that SoM threshold-values of greater than 80% and greater than 70%, corresponded to a 19.4% (p=0.069) increase and to a 25.8% (p=0.017) increase, respectively in water quantity performance. No significant difference in water quality performance was identified with respect to different SoM threshold values.

An exploratory analysis of univariate relationships between SoM and system performance has provided insights into different relationships between SoM and performance characteristics. In terms of water quantity, 23.5% of the variability (R^2 = 0.235, p = 0.05) of the composite system reliability and 20 L/p/d availability can be explained by Strength of Management. In terms of individual SoM indicators, Human Resources accounts for 37.4% (R^2 = 0.374, p = 0.01) of the variability of the independent variable of 20 L/p/d availability. Finally, a composite of SoM using HR, SA and FM indicators was created to further explore univariate relationships wherein, 36.7% of the variability in the composite reliability and 20 L/p/d availability score (R^2 = 0.367, p=0.013) could be explained by Strength of Management as a function of Human Resources, System Administration and Financial Management.

The exploration of univariate linear relationships between SoM and Water Quality revealed that Distributed Water Quality is most influenced by strength of management (R^2 = 0.207, p = 0.076). In addition to this, a regression analysis of individual SoM indicators revealed that 38.3% of the variability in distributed water quality (R^2 = 0.383, p = 0.01) could be explained by System Administration. In order to further explore SoM indicators, a composite of HR, SA and AM was created which together can account for 52.0% of the variability of D.WQ (R^2 = 0.520, p = 0.008). Further exploration of water quality included delineating the results of the D.WQ into microbial, physical and chemical parameters and comparing individual SoM indicators. In this regards, System Administration was shown to account for 37% of the variability with respect to Microbial water quality (R^2 = 0.370, p = 0.01). An exploration between SoM and changes in water quality between the source and the distribution system revealed very significant evidence (p = 0.003) of a strong relationship (R^2 = 0.54).

Finally, a multivariate linear regression analysis was conducted to explore SoM and system performance characteristics with respect to η_{del}-SDC20 and D.WQ. Through an investigation of the linear coefficients positive relationships were identified and an additional multivariate analysis was completed with selected SoM Indicators. The results show that Human Resources and Financial Management have a positive influence on overall Water Quantity performance and that Human Resources, O&M and Asset Management have a positive influence on Water Quality performance. At the same time any conclusions from these results should caution that the sample size (n) was not sufficient. In this regards, it is important to note that, with any multivariate analysis, as the degrees of freedom (n-1) approaches the number of independent variables (in this case five SoM categories were identified), the Pearson r-squared correlation approaches one. Further investigation into the relationship between the sample size and the confidence interval suggests that approximately 50 sites would be needed for a comprehensive investigation into multivariate relationships between SoM and System Performance Characteristics.

The results from these analyses contribute to the body of knowledge on sustainable management of water services. In addition, a review of the mechanisms for which indicators influence overall performance further supports previous studies on sustainable development of water infrastructure. The connection between human resources in the form of technical receptions, supports the finding of Bakalian and Wakeman (2009) who investigated relationships between post-construction support and sustainable community-managed water supply. The connection between gender and sustainability established by Fischer (2008) is also supported through this analysis. In addition, connections between strategic planning, leadership and O&M established by Sansom and Coates (2011, 2015) is supported by this study. Whereas, this analysis uses a composite SoM score, links to previous research through individual indicators is also established. At the same time, further investigation into individual sub-indicators would be needed whereas, this research primarily explored connections between overall SoM and technical performance characteristics.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.0 Conclusions and Recommendations

This chapter provides conclusions by presenting a summary of results in terms of the research objectives and the research question investigated during this study. The chapter is organized into sections which specifically address the research objectives. These objectives are described in Section 1.2 and were created to ensure that the overall study directly addresses the research question being investigated.

- Section 8.1: Addresses objective metrics which can be used to evaluate the management and performance of piped water systems.
  - Objective 1: to develop objective measurements for monitoring the performance of piped water supply infrastructure in developing communities.
- Section 8.2: Addresses the overall research question; how does the strength of water management influence the performance of rural water supply infrastructure?
  - Objective 2: To investigate the relationship between strength of management and the performance of water infrastructure.
- Section 8.3: Addresses the long-term goal of the study by identifying management characteristics that can be used to forecast long-term sustainability.
  - Research Aim: to contribute to the sustainable management of piped water supply infrastructure and improve the ability of local management to provide reliable services, anticipate system failure and mitigate external threats to sustainability.

This research investigated the performance characteristics of piped water supply infrastructure in low-income developing communities and is intended to address knowledge gaps related to the sustainable management of water systems (Lockwood and Smits, 2011; Moriarty et. al, 2013). Relationships between the strength of management and technical performance of water supply systems in terms of water quantity and water quality were explored with the goal of establishing links between strong management and long-term sustainability of services. In order to accurately measure performance, objective analytical methods were developed for the continuous monitoring of water systems.

Project site locations for this study included twelve community managed systems in Nicaragua and seven privately managed system in Madagascar. In Nicaragua progress towards water development goals has exceeded national targets, however large differences exists between access in urban areas (99.3%) as compared to rural areas (69.4%). The sites investigated in Nicaragua ranged in size from 45 to 550 connections serving between 425 and 2950 customers with an average of 914 customers (SD = 703) and, all of the sites were located in rural communities within the Rio Grande de Matagalpa watershed. In Madagascar, national water development goals have not been met, with 82% of urban areas and 35% of rural areas having improved access (JMP, 2015). The research site locations in Madagascar included rural towns throughout the eastern portion of the country, ranging in size from 41 to 1158 connections serving between 1,920 to 13,433 customers with an average of 4627 customers (SD = 4390).

8.1 Objective Metrics to Evaluate Management and Performance

The aim of this research was to contribute to the sustainable development of piped water supply infrastructure in low-income communities, with the goal of developing objective measurements for the continuous monitoring and evaluation of system performance. In this regards, three sub-objectives were identified that included establishing metrics on water quantity, water quality and water management. Water Quantity measurements included the analysis of system reliability and water availability. Water Quality measurements included investigating compliance throughout the supply and distribution systems and delineating parameters for microbial, physical and chemical characteristics. Water Management measurements included investigating strength of management in terms of Human Resources, System Administration, Operation and Maintenance, Asset Management and Financial Management. Objective measurements in these terms were validated through household customer satisfaction surveys at selected project site locations.

8.1.1 Objective Measurements to Evaluate Water Quantity

Measurements of water quantity performance included continuous monitoring of system reliability and availability of water. Reliability was defined using the PE25 criteria (Ermilio et. al, 2014) which measures the amount of time that water levels within the storage tank drop below the 25% threshold, defined as tank empty conditions. Availability of water was measured by determining the amount of water within the system at any given time and calculating per-capita water availability on a daily basis. System Duration Capacity (SDC) was defined as the percentage of time that the water system provided threshold values of 20, 50 and 80 liters per person per day. Table 8.1 shows a summary of these results which are also presented in more detail in Chapter 4: Results and Analysis of Water Quantity Performance.

Conclusions associated with this analysis suggest that monitoring water levels within storage facilities is an effective means of evaluating system performance in terms of water quantity, and that a composite of reliability and availability best reflects end-user customer satisfaction. In this regards, reliability alone does not show a strong correlation with customer satisfaction (R^2 = 0.188, p = 0.244) and availability of greater than 80 liters/person/day shows significant evidence of a relationship (R^2 = 0.644, p = 0.0092). At the same time, the composite of system reliability and availability of water greater than 80 liters/person/day shows the most significant evidence of a strong relationship (R^2 = 0.654, p = 0.0083).

In terms of meeting the research objectives; Objective 1.1 was to identify water quantity parameters which can be used to continuously monitor the performance of piped water supply infrastructure. In this regard, this objective was met in that, a composite of reliability and availability of water is the most appropriate criteria for measuring system performance in terms of water quantity. This conclusion further supports previous research which identified the need for empirical evidence of system performance (Walters, 2016) as well as studies which advocate for research that goes beyond discrete measurements (Howard, 2005; Bartram, 2014; Thompson and Koehler, 2016). It also supports the needs of professionals who advocate for design standards related to the engineering design of water infrastructure (Jordan, 1998; Mihelcic, 2009; Jones, 2010).

Table 8.1: Measuring Water Quantity Characteristics – Summary of Results

Site Location	Reliability	SDC Criteria			Customer Satisfaction
	η_{del}	20	50	80	
Molino Norte	98.8%	100.0%	100.0%	87.2%	*NT*
Aus. Paladino	96.7%	100.0%	99.2%	89.3%	86.1%
El Guabo	90.4%	100.0%	97.4%	84.9%	75.0%
El Rodeo	86.7%	100.0%	100.0%	81.1%	*NT*
Los Lipes	96.4%	100.0%	99.8%	66.1%	*NT*
Dipina Esp.	95.6%	100.0%	99.6%	64.2%	92.5%
Dipina Cen.	90.9%	99.6%	97.8%	68.3%	*NT*
San Jose	60.5%	99.6%	99.1%	91.1%	*NT*
San Francisco	87.1%	100.0%	91.9%	63.2%	*NT*
La Ceiba	69.1%	99.5%	80.9%	58.7%	*NT*
Andemaka	94.5%	97.9%	81.3%	17.6%	*NT*
Puerto Viejo	54.5%	93.9%	76.4%	48.1%	65.8%
Ikongo	99.2%	98.4%	10.9%	0.2%	63.8%
Anivorano Est	96.0%	97.5%	12.5%	0.3%	*NT*
Manompana	74.4%	88.8%	41.0%	0.0%	47.1%
Tolongoina	99.9%	100.0%	0.3%	0.2%	*NT*
Imorona	78.8%	86.9%	0.9%	0.0%	*NT*
Mananara	84.1%	72.9%	0.0%	0.0%	58.9%
Tolongoina	49.3%	85.4%	7.3%	3.7%	67.1%
El Naranjo	8.6%	79.3%	18.3%	1.9%	57.4%

8.1.2 Objective Measurements to Evaluate Water Quality

Measurements of water quality performance included; multiple discrete sampling events throughout the water system and an analysis of compliance for microbial, physical and chemical water quality against international standards (WHO, 2011). The results were delineated in terms of sample location and the type of water quality contamination and were compared with household level customer satisfaction results. In this regards, tank water quality ($R^2 = 0.77$, $p = 0.004$) and distributed water quality ($R^2 = 0.65$, $p = 0.015$) correlated closely with customer satisfaction as did the overall compliance score ($R^2 = 0.612$, $p = 0.021$) which includes all samples from the supply and distribution system. Source water compliance showed a positive relationship with less significance ($R^2 = 0.21$, $p = 0.25$). In terms of the type of contamination, Physical Water Quality results correlated most closes with Customer Satisfaction ($R^2 = 0.79$, $p = 0.018$) with results from Microbial

(R^2 = 0.123, p = 0.495) and Chemical (R^2 = 0.04, p = 0.703) water quality showing a relationship with no significance. The composite of water quality parameters within the distribution system, showed evidence of a positive relationship (R^2 = 0.625, p = 0.061).

Table 8.2: Measuring Water Quality Characteristics – Summary of Results

Water Quality Compliance				
Site Location	Source Compliance	Tank Compliance	Distribution Compliance	Customer Satisfaction
El Rodeo	NT	NT	97.2%	NT
Molino Norte	NT	88.9%	92.6%	NT
Los Lipes	83.3%	93.3%	91.4%	NT
Dipina Esperanza	67.4%	94.4%	91.2%	97.5%
Dipina Central	88.9%	83.3%	88.0%	NT
San Fran	63.9%	74.1%	87.3%	NT
Ausberto Paladino	75.0%	85.7%	85.2%	72.2%
El Naranjo	73.4%	77.8%	79.2%	66.2%
Puerto Viejo	83.3%	85.7%	78.0%	73.6%
San Jose	63.9%	74.1%	77.8%	NT
Ikongo	62.5%	70.0%	77.5%	63.2%
Anivorano Est.	56.4%	64.1%	75.0%	NT
El Guabo	78.4%	75.3%	73.9%	73.3%
Imorona	84.7%	63.0%	63.0%	NT
Mananara	51.4%	61.9%	60.8%	61.7%
Tolongoina	55.6%	61.9%	59.0%	66.4%
Manompana	57.1%	55.6%	55.6%	54.4%

Table 8.2 shows the results used to measure water quality performance characteristics delineated based on sample location. Conclusions associated with this analysis suggest that continuous evaluation of water quality should focus on monitoring physical characteristics of water located within the storage tanks. Despite this, for several reasons explained in the Chapter 5, a composite score of water quality from the distribution system was used to evaluate the system performance in this study. Additional conclusions from this analysis include the need for low-cost tools that provide local water operators with information needed to manage water quality in the system. In this regard, the international water development community should explicitly delineate between water quality monitoring for compliance-regulatory purposes and monitoring for daily operations, with unique guidelines for sampling and analysis that consider the needs of local operators.

In terms of meeting the research objectives; Objective 1.2 was to identify water quality parameters which most closely reflect the performance of the system in terms of user's acceptability of the water supply. In this regard, this objective was met in that, relationships between customer satisfaction and water quality which has been delineated based on type of contamination and location within the system was established. These conclusions further support research that advocated for global monitoring which considers water quality (Moriarty et. al, 2010; Thomson and Koehler, 2016).

8.1.3 Objective Measurements to Evaluate Water Management

Measurements of water management included a Strength of Management score based on semi-structured interviews, a review of documents, physical site inspections, and surveys. Five strength of management indicators were identified; Human Resources, System Administration, Operation and Maintenance, Asset Management, and Financial Management. In Madagascar, a PPP Model is being used for water management, and the SoM score was based on the Sustainable Index Tool utilizing a series of presence/absence tests. In Nicaragua, a community management model is used, and the SoM score was based on per-capita investments of local resources into managing the systems. In order to compare the two different models, the SoM data for each country was normalized to a percent score, and then calibrated using the average of each country location.

Conclusions associated with this investigation suggest that the overall composite SoM score does not reflect customer satisfaction ($R^2 = 0.262$) however, these results did not show statistically significant evidence ($p = 0.131$) with a 13.1% chance that the null hypothesis is true, or that results are random. Further exploration into statistical relationships within each SoM indicator revealed that Financial Management shows significant evidence of a strong relationship with Customer Satisfaction ($R^2 = 0.52$, $p = 0.018$). Table 8.3 shows the results of SoM delineated for each indicator. One apparent conclusion from this investigation would suggest that SoM surveys should consider simplified methods of data collection. In particularly, data which would be relevant to the local operators might include monitoring of Financial Management and Customer Satisfaction as a tool for decision making at the local level. In addition, capacity building on financial management would have an optimal impact on water system performance. Another important conclusion from this investigation includes the need to investigate individual indicators within the context of each site location.

In terms of meeting the research objectives; Objective 1.3 was to identify criteria to compare strength of management for water utility operations. This objective was not entirely met because of the unique nature of data collection for each country location. Despite this, data calibration was employed to create a common unit of analysis which would provide the means of comparing strength of management. In this regard, however recommendations associated with the investigation into strength of management include simplified tools to analyzing management characteristics and common institutional frameworks to support the sustainable management of water resources (Ayala, 2013).

Table 8.3: Measuring Strength of Management – Summary of Results

	Strength of Management					
Site	Average SoM	Human Resources	System Admin.	O&M	Asset Man.	Financial Man.
Tolongoina	97.5%	91.4%	95.9%	100%	100%	100%
Ikongo	97.6%	100%	95.9%	95.6%	96.6%	100%
Imorona	4.0%	0.0%	12.4%	0.0%	7.6%	0.0%
Mananara	69.9%	55.9%	51.1%	84.9%	82.8%	75.0%
Manompana	37.4%	63.1%	10.2%	58.3%	22.1%	33.3%
Anivorano	73.8%	82.5%	100.0%	66.5%	36.8%	83.3%
Andemaka	59.7%	65.9%	73.4%	45.4%	38.9%	75.0%
Los Lipes	100.0%	100%	100.0%	100%	100%	100%
Molino Norte	82.3%	78.3%	100.0%	74.5%	98.5%	60.1%
San Jose	88.3%	100%	92.6%	100%	86.9%	61.8%
San Francisco	97.6%	100%	100.0%	100%	88.2%	100%
El Rodeo	67.2%	76.5%	72.8%	71.9%	62.0%	52.8%
La Ceiba	67.6%	66.8%	56.7%	100%	57.5%	57.2%
Dipina Central	80.3%	80.1%	99.1%	66.0%	56.1%	100%
Dipina Esp.	80.5%	66.1%	81.9%	78.3%	76.1%	100%
Puerto Viejo	69.3%	67.8%	96.5%	62.1%	66.2%	54.0%
El Guabo	*NT*	*NT*	*NT*	*NT*	*NT*	*NT*
El Naranjo	61.0%	56.2%	75.5%	58.0%	61.4%	53.7%
Aus. Paladino	79.9%	69.4%	100.0%	66.7%	88.9%	74.3%

8.2 Strength of Management and Influences on System Performance

An additional goal of the study was to investigate relationships between the strength of water management and system performance characteristics by exploring links and comparing systems. In order to explore how management-characteristics influence the overall performance in terms of water quantity and water quality, a univariate linear regression analysis was completed with strength of management as an independent variable and water quantity characteristics as dependent variables. To compare systems, a quadrant analysis was created along with performance thresholds within each performance criteria; management, water quantity and water quality.

In terms of meeting the research objectives; Objective 2 of the study was to investigate relationships between strength of management and water system performance. In this regard, three additional objectives were identified; Objective 2.1 was to categorize performance characteristics, Objective 2.2 was to identify criteria to use for a comparative analysis and Objective 2.3 was to explore relationships between system performance and strength of management. This section summarizes how these objectives were met by presenting an overview along with conclusions based on results and analysis. A noted limitation with this investigation includes the need for additional research on how individual indicators influence the overall performance of water services.

8.2.1 Strength of Management Influences on Water Quantity

An initial investigation of SoM and Water Quantity included delineating the results for systems that scored greater than 90%, greater than 80% and greater than 70% in terms of overall SoM. Using these delineated results provided an opportunity to see if different threshold SoM scores resulted in a difference in composite water quantity performance as defined by reliability (η_{del}) and availability of water (SDC). On average, this analysis revealed that SoM is essential to preventing system failure but that other factors are likely influencing system success. In this regard, there was a 4.8% difference in the average water quantity performance where SoM was delineated using a 90% threshold. These results, however, showed no evidence of a statistically significant relationship (t=0.459, p=0.706). Using the SoM threshold value of 80% showed a 19.4% difference in water quantity performance (t=0.430, p=0.069) and using the threshold value of 70% showed a 25.8% difference (t=0.432, p=0.017), both with statistically significant evidence. The conclusion from this analysis being that there is statistical evidence that strong management is essential for preventing system failure, but that there is no statistical evidence that strong management will ensure system success.

Further investigation into how SoM influences water quantity performance included a series of univariate analysis between SoM and delineated water quantity performance characteristics. Overall, SoM and System Reliability (η_{del}) showed some evidence of a relationship (R^2=0.175, p=0.094, n=17) and SDC Availability showed no evidence of a relationship (R^2=0.059, p=0.347, n=17). In terms of overall availability (SDC) the results were delineated into performance characteristics that define the percentage of days that the systems provided minimum thresholds of 20, 50, and 80 liters per person per day. Whereas, the overall availability did not show a significant relationship with SoM, the regression analysis between SDC-20 and SoM does show significant evidence of a relationship (R^2=0.233, p=0.057, n=16). Conclusions associated with these results would suggest that SoM is essential to providing minimum basic needs of water (20 l/p/d), regardless of management type and that strong community managed system are more likely to provide higher volumes of water as compared to strong privately management systems. In fact, on average, the community managed systems in Nicaragua provided 69.9 l/p/d more than the privately managed systems in Madagascar (p=0.0001) with very significant evidence that the results were statistically valid.

8.2.2 Strength of Management Influences on Water Quality

In order to explore the influence that SoM has on Water Quality, the results were delineated for systems that scored greater than 90%, greater than 80% and greater than 70% with respect to SoM. In this regard, it was concluded that on average, the systems with greater than 90% SoM showed no significant difference in average Water Quality Compliance. In addition to this, the delineated scores using the 80% and 70% thresholds also showed no significant difference in average Water Quality. From this, it can be concluded that in general, Strength of Management has little influence on overall Water Quality in the system. At the same time, it should be noted that there would logically be an inverse causal relationship between SoM and Water Quality in that where water quality issues are the most difficult, because of environmental factors, there is a need for strong management. Therefore, it would make sense that measurements of SoM would not necessarily correlated with overall Water Quality within the system.

In order to explore SoM influences on Water Quality further, the water quality results were delineated by location and the type of water quality constituent. Source water quality showed a negative correlation with SoM which validates the potential for environmental influences with respect to an inverse causal relationship between SoM and Water Quality. Tank water samples showed a positive relationship with SoM (R^2=0.175, p=0.120, n=15) and distributed water samples showed a positive relationship with SoM (R^2=0.207, p=0.076, n=16). These results were further investigate by comparing SoM and the difference between the Distributed Water Quality (D.WQ) and the Source Water Quality (S.WQ). This investigation revealed that there is very significant evidence that strong management influences changes in water quality from the source to the distribution system ΔWQ(D-S). In this regard, the 70% SoM threshold showed a 15.5% difference in Water Quality (t=0.929, p=0.016). In addition, linear regression analysis of SoM and ΔWQ(D-S) shows very significant evidence of a strong relationship (R^2=0.537, p=0.003, n=14).

In terms of water quality constituent, the results showed that microbial quality correlated most with overall SoM (R^2=0.228, p=0.062, n=16) and that physical quality showed a positive but weak correlation (R^2=0.069, p=0.324, n=16). Taking into account potential outliers from within the data set, provided an opportunity to explore SoM influences on Microbial and Distributed water quality more closely. With noted limitations in terms of sample size, this analysis revealed a more significant influence, with microbial quality showing the strongest relationship (R^2 = 0.663, p=0.008, n=9), and distributed water quality also showing a strong relationship (R^2 = 0.456, p=0.023, n=11). When these results are taken together, conclusions from this would suggest that Strength of Management is most likely to influence Microbial Water Quality within the distribution system but that these influences should be verified with further investigation.

8.3 Management Characteristics to Forecast Sustainability

In order to investigate management characteristics which can be used to forecast the conditions for long-term sustainability, different SoM composite scores were created to explore univariate and multivariate linear relationships. In terms of SoM and Water Quantity, a correlation analysis revealed that Human Resources, System Administration and Financial Management were primary influences ($R>0.5$). As a result, an SoM composite that included these indicators was created, and a univariate regression analysis was complete using a composite, Reliability and 20 l/p/d Availability score. The results of this analysis showed evidence of a relationship between SoM as a function of HR, SA, and FM, and performance as a function of η_{del} and SDC-20 ($R^2 = 0.425$, $p=0.092$).

An investigation of multivariate relationships using five SoM Indicators (Human Resources, System Administration, O&M, Asset Management and Financial Management) revealed that Human Resources showed some evidence of a positive influence ($C_{HR}=0.224$, $p=0.142$) and Financial Management showed significant evidence of a positive influence ($C_{FM}=0.472$, $p=0.001$). Of particular interest is the intercept of the multivariate regression analysis which suggests that no management would result in some functionality (58.2%) which could provide insight into the threshold for defining a failed system. This classification would be consistent with Category 5 systems as defined in Chapter 4, and would identify; Mananara, El Naranjo, Manompana, and Imorona, as communities that are at risk for having a failed water systems.

In terms of SoM and Water Quality a correlation analysis identified three SoM indicators (HR, SA and AM) as potential influences on overall distributed water quality (D.WQ) and a composite of SoM(HR,SA,AM) showed significant evidence ($p=0.008$) of a relationship ($R^2 = 0.520$). After delineating the results for water quality type, three SoM indicators (HR, SA and FM) showed significant evidence ($p=0.008$) of a strong relationship ($R^2=0.663$) with Microbial Water Quality (M.WQ). The multivariate regression analysis between SoM indicators as independent variables and distributed water quality, shows Human Resources ($C_{HR}=0.416$, $p=0.158$) and Asset Management ($C_{AM}=0.325$, $p=0.072$) as having a positive influence with only AM showing some evidence of a relationship.

Of particular interest is the multivariate linear coefficient for Operation and Maintenance (C_{OM} = -0.652, p=0.077) which shows some evidence of a negative influence, further demonstrating an inverse relationship between water quality and management characteristics. In this regards, it is logical that challenging water quality issues resulting from environmental influences, would require more O&M, in particularly given that one third of the sub-indicators used to evaluate O&M included maintenance frequency, water treatment and maintenance cost. In addition to this, the intercept of the multivariate analysis would suggest that no management would result in some functionality (56.8%) with respect to water quality performance. In terms of water quality threshold classifications, this would suggest that the 60% threshold for identifying failed systems is appropriate and that Category 5 systems (Tolongoina and Manompana) would be at risk for having failed water systems in terms of water quality performance.

Conclusions from this analysis would suggest that additional research is needed to verify how management characteristics can be used to forecast long-term sustainability in that the sample size for this study presents limitations with respect to a multivariate analysis. In this regards, computational models for estimating the sample size as well as best practices within the field of statistics would suggest, that in order to evaluate five independent variables, a sample size of between 50 and 75 systems would be needed (Bernhardt, 2018). With the limitations of the current analysis being said, some preliminary conclusions can be made with respect to what SoM indicators most influence long-term sustainability. From this analysis, it appears that Financial Management most influences Water Quantity in terms of reliability and availability and that Asset Management most influences Water Quality within the distribution system. These conclusions would also be logical in that Financial Management is most likely to also influence other indicators needed to ensure system reliability and Asset Management, having sub-indicators related to watershed management, supplies and parts could have a more direct influence on water quality.

8.4 Discussion of Performance Characteristics

A review of the overall system performance classifications is an appropriate way to discuss conclusions in terms of both objective and subjective observations during the study. Table 8.4 shows the system performance classifications for Strength of Management, Water Quantity and Water Quality characteristics. A qualitative review of field notes along with the results shown in this table would suggest that several of the systems are in danger of failing and that the long-term sustainability of services is not likely without post-construction external support (Bakalian and Wakeman, 2009).

The community of Mananara, Madagascar (4D, 5D, 4C) is one of the largest systems investigated in this study and is vulnerable to near-term failure. The primary cause of system failure in Mananara is un-regulated growth in that the number of new connections into the existing distribution system suggested an annual growth rate of close to 30 percent, without the needed human resources or the necessary watershed management to support this growth (Perez, 2003). In a recent site visit to Mananara (January, 2018) 43% of the customers surveyed said that they have poor or very poor access to reliable water and only 15% said that they were very satisfied with the water quantity. It should be noted however, that 31% said they were very satisfied with the management of the service.

A field visit to Manompana, Madagascar (January, 2018) revealed that this system has completely failed due to a lack of capital maintenance that was needed after a cyclone (March, 2017) washed out the intake pipeline. This example brings attention to the need for resiliency in the design of water supply infrastructure and the need to plan for capital maintenance that often result from catastrophic events (Howard et. al., 2010). Prior to the failure of the Manompana system, field visits and surveys (June, 2016) suggested that the water supply infrastructure was vulnerable to potential failure where the results in Table 8.4 reveal that the system was a category 5C system in all aspects of performance. Field notes also suggest that watershed management is needed with observations of deforestation in the region. In addition to this, field observations during this study suggest that customers were not paying for water services in the area prior to system failure.

Table 8.4: System Performance Classifications

Site Location	Country	System Performance Classification					
		Strength of Management		Water Quantity Performance		Water Quality Performance	
Los Lipes	Nicaragua	1	B	1	A	1	B
San Francisco	Nicaragua	1	A	2	B	2	A
Ikongo	Madagascar	1	A	4	C	3	C
Tolongoina	Madagascar	1	A	4	C	5	C
San Jose	Nicaragua	2	A	3	B	3	C
Molino Norte	Nicaragua	2	A	1	A	1	B
Dipina Esp.	Nicaragua	2	A	1	A	1	A
Dipina Central	Nicaragua	2	A	2	A	2	B
Aus. Paladino	Nicaragua	3	C	1	A	2	A
Anivorano	Madagascar	3	C	4	C	3	C
Mananara	Madagascar	4	D	5	D	4	C
Puerto Viejo	Nicaragua	4	C	4	C	3	D
La Ceiba	*Nicaragua*	*4*	*C*	*3*	*B*	*N*	*T*
El Rodeo	*Nicaragua*	*4*	*C*	*1*	*A*	*1*	*B*
El Naranjo	Nicaragua	4	C	5	D	3	C
Manompana	Madagascar	5	C	5	C	5	C
Andemaka	*Madagascar*	*5*	*C*	*2*	*B*	*NT*	*NT*
El Guabo	*Nicaragua*	*NT*	*NT*	*1*	*A*	*3*	*C*
Imorona	*Madagascar*	*NT*	*NT*	*5*	*D*	*4*	*D*

Regarding the long-term sustainability, follow up studies could include monitoring sites where the technical performance of the system is over performing as compared to SoM, to see if technical performance decrease over time. In this regard, El Rodeo (5C, 1A, 1B) and Ausberto Paladino (3C, 1A, 2A) could potentially see a decline in system performance if there is truly a causal relationship between management and performance. Alternatively, if there are other environmental or political factors that are contributing to the success of these systems, these sites would provide an opportunity to engage in a case-study research initiative to explore external influences. For example, El Rodeo is one of the oldest systems investigated (constructed in 1994) and ranked in the lower 20 percentile amongst the systems studied in Nicaragua in all SoM categories. In addition to this, the customers in El Rodeo pay the lowest monthly rate amongst the systems studied in Nicaragua despite having reliable access (η_{del} = 86.7%) to over 80 l/p/d (SDC-80 = 100%) of safe drinking water (D.WQ = 97.2%).

In addition, systems where management capacity is exceeding the technical performance of water service delivery, additional research could provide an opportunity to explore if water quantity and water quality performance increases over time. In this regards, two systems in Madagascar; Ikongo and Tolongoina, and one system in Nicaragua; San Jose, would provide opportunities for case-study investigations. In particularly, Ikongo (1A, 4C, 3C) and Tolongoina (1A, 4C, 5C) both have management capacity that is largely exceeding the performance characteristics. In both of these cases, it is likely that there are other factors; technical, environmental or socio-economic (Thomas, Koehler, 2016; Bartram et al., 2014; Moriarty et al., 2013; Lockwood et al,, 2002; Harvey, Reed, 2003) that are influencing the overall performance of the systems.

Finally, the mechanisms by which individual indicators influence the overall technical performance of water services should be investigated further. In this sense, it is possible that individual SoM indicators could influence water services in a unique fashion and on a case-by case scenario thus, creating unique mechanisms for success or failure. For example, findings from multiple studies (RWSN, 2010; Kayaga et. al., 2013; Lockwood et. al, 2017; Schouten and Smits, 2015,) suggests that leadership within a community, or what is also references as a “local champion” can have a direct influence on overall sustainability of water services. In this sense, identifying lower SoM systems that performed better than average on water quantity and water quality performance would be good candidates for case-study analysis. Future studies employing case-study analysis would transition this research from being exploratory to being explanatory wherein an analysis of individual SoM components would be more credible than composite SoM analysis.

8.5 Summary of Conclusions

The research question being investigated in this study was; how does the strength of water management influence the performance of piped water supply infrastructure in low-income developing communities? To address this question, two objectives were identified (as described in Section 2.1). Objective 1, focused on the need for objective measurements of performance and, Objective 2 addressed the need for an exploratory analysis of relationships between performance and management characteristics. To explicitly address the research question, the following conclusions are being presented:

- In terms of water quantity performance, strong water management is essential to preventing system failure but is not necessarily a guarantee of success.
    - None of the systems that had very strong (Class 1) or strong (Class 2) management, were within the lower third of composite score for water quantity performance.
    - All the failing systems in terms of water quantity performance were in the lower SoM (Class 4) category.
    - At the same time, some of the poorly managed system still performed adequately in terms of water quantity and, some of the well management system performance at a moderate level.
- In terms of water quality performance, strong water management does not categorically ensure higher end-user water quality within the system; but, there is significant evidence of a relationship between strength of management and changes in water quality between the source to the households.
    - Significant evidence was found that strong management influences the overall water quality within the distribution system and that strong water management prevents poor water from being delivered to the households.
    - Categorically, two of the four higher performing SoM systems (Class 1) were within the lower third in terms of water quality.
    - Evidence of a causal relationship between poor source water quality and the need for strong management was evident.

8.5 Limitations

Several limitations with respect to the research being presented in this thesis should be highlighted for the purposes of clarity and transparency. Whereas, the need for continuous objective metrics for evaluating water supply infrastructure have been discussed, subjectivity with respect to interpretation of results is a possibility in any research initiative. In terms of water quantity, during the cursory review of graphical results, anomalies had to be identified and addressed accordingly. Whereas, the ideal scenario would include confirming anomalies with local management teams, this was not always possible because of the remote nature of many of the systems being studied. In some cases, data was either corrected or removed from the analysis depending on the nature of the anomaly. For example, when the pressure transducers were removed from the tank, the data would suggest that the water level in the tank drained within a fifteen-minute time step. As a result, if the transducer was removed for some reason (data collection, tank cleaning, etc.) then the data would reflect this and would have to be corrected. In one case, the transducer was not re-installed correctly after being extracted for data-transfer and the water levels appeared to change artificially after being reinstalled. This limitation was not realized until the data was extracted later, when the local research assistant returned to the site for an inspection, and it was realized that the transducer cable got caught on the storage tank cover. In this case, the data was corrected manually, and the results were not impacted because the variability in tank water levels was not significant enough to impact the result. Nonetheless, this event highlights a limitation of the methodology used to evaluate system performance in terms of water quantity.

Subjectivity with respect to interpreting water quality results is also a limitation with respect to this study. In particularly, water testing strips provided limited resolutions with respect to the concentration of the constituent of concern wherein, color charts used a large range of values. With respect to water quality analysis, the results and analysis used to evaluate performance used the upper limits of water testing strips so that compliance characteristics reported were more conservative. In this regard, the binary pass/fail nature of the final analysis provided the highest confidence possible in terms of whether water samples met the respective criteria.

Subjectivity with respect to water management and household interviews was addressed through random sampling and error analysis to ensure accuracy of the results and have been reported accordingly. Another limitation with respect to this study entails the participatory nature of the data collection process with unique surveys being employed for the evaluation of water management. Whereas, determining the SoM indicators included a review of literature, workshops with local operators and water sector professionals; SoM as a composite is not derived from management theory. In addition, the local partners and the local research assistants used for data collection had different backgrounds which could introduce human error during data collection.

In Nicaragua the local field assistants included a male and female resident of the local municipality who had previous part-time experience because of family members that worked with the partner organization. They understood the local context and challenges of sustainability because of personal experience but they did not study formally at the university level. In Madagascar, the local field assistants included two males and two females who did not have previous experience in the water sector and were not residents of the local areas being investigated. These individuals however were formally trained in engineering at a national university in the capital city and were highly motivated to learn about water development issues.

Another limitation with respect to this study is the tendency of the analysis to make discrete and binary conclusions rather than reporting the dynamic, time sensitive nature of water and sustainability. Wherein the resolution of data which is provided through continuous monitoring of water system performance is one of the advantages of this approach, taking continuous data and making discrete conclusions reverts to methods that have been criticized in this study. In addition to this, taking the results and comparing systems outside of the local context should be cautioned because the culture, history and the political context are unique to each site location. In Madagascar, the systems investigated were significantly more complex than those in Nicaragua in that the population being served was larger and the system operations had service levels that included private, social and public connection options. The dynamic nature of population in each service areas was also unique and could vary from month to month as well as from year to year because of culture and seasonal migration.

Finally, assumptions that were made during this research initiative should be noted. This study assumed that there was no social or political interference with respect to the research initiative and that the objective nature of the methodology itself was not impacted by exogenous factors. It was also assumed that any consultations with the local water management teams did not impact the study with the understanding that it may impact the water systems but that this impact would be measured and reflected accordingly. Finally, it was also assumed that records from both the water management teams and from the project partner were accurate and that survey respondents shared information honestly.

8.6 Recommendations

Recommendations associated with this research study are summarized in two terms; those associated with the sustainable management of water supply services and those associated with ongoing research on Sustainable WASH. In terms of sustainable management of water services, it is important to recognize that management of services requires designing monitoring systems that are intended to inform local operators on performance characteristics so that management can be preventative rather than reactive to technical issues. In addition to this, development organizations and government agencies would also benefit from operator-informed monitoring systems wherein donors and funding agencies are looking for evidence-based development that demonstrates long-term sustainability.

As a result, M&E systems should be designed and installed on existing and future water supply systems as a part of the overall strategy of the 2030 Agenda for Sustainable Development which calls for "ensuring the availability and sustainable management of water and sanitation for all". More specifically, monitoring systems should include both low-cost tools for remote monitoring via SMS platforms so that operators can have instantaneous access to information and, low level technical solutions that require visual inspections such as pressure gauges, flow meters and handheld water testing devices. Finally, early alert systems should be included in the design of any monitoring system so that operators, local governments and development organizations can better anticipate problems with respect to technical performance and mitigate threats to long-term sustainability more proactively.

Next steps associated with Sustainable WASH Research initiatives should include a number of follow up studies to; further validate the research conducting during this study, explore new areas that would relate to external threats to sustainability, and develop new technologies for the low-cost monitoring needs of the WASH sector. Further validation of this work would include expanding the project site locations to a minimum of 60 site locations to fully address research questions associated with forecasting sustainability. Exploring new areas related to external threats would include developing a case-study research initiative at selected sites to further study the root cause of system success and failure. Employing case-study methodology would also support the need to better understand specific mechanisms by which water systems are successful. In addition to this, research in the area of watershed management as it relates to sustainable growth and hydrological limits of water supply services should be further investigated. In terms of technology development, participatory research that includes local operators in the planning process as well as during the study should be conducted to ensure that technological solutions truly address the needs of water utility operators in addition to government and development agencies.

Final recommendations for this study would include the need for capacity building initiatives to ensure that local operators have the skills to sustainably management water services. Training programs that include certifications for local operators which are recognized by national governments is essential to empowering local communities to sustainably manage local resources. These programs should utilize a combination of workshops and distant learning materials so that operators can take advantage of international expertise while simultaneously being given the opportunity to learn material at their own pace and apply new skills within the local context.

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