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WATER USE AND SYSTEM RELIABILITY UNDER DIESELGENERATOR AND SOLAR PHOTOVOLTAIC POWERED PUMPING SYSTEMS: A CASE STUDY OF SOLLA TOGO

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WATER USE AND SYSTEM RELIABILITY UNDER DIESEL-GENERATOR AND SOLAR PHOTOVOLTAIC POWERED PUMPING SYSTEMS:
A CASE STUDY OF SOLLA TOGO

By
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A REPORT

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This report has been approved in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Environmental Engineering.

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Abstract

Access to improved potable water sources is recognized as one of the key factors in improving health and alleviating global poverty. In recently years, substantial investments have been made internationally in potable water infrastructure projects, allowing 2.3 billion people to gain access to potable water from 1990-2012. One such project was planned and installed in Solla, Togo, a rural village in the northern part of the country, from 2010-2012. Ethnographic studies revealed that, while the community has access to potable water, an estimated 45% of the village's 1500 residents still rely on unprotected sources for drinking and cooking. Additionally, inequality in system use based on income-level was revealed, with the higher income groups accessing the system more regularly than lower income groups. Cost, as well as the availability of cheaper sources, was identified as the main deterrent from using the new water distribution system. A new water-pricing scheme is investigated here with the intention of making the system accessible to a greater percentage of the population.

Since 2012, a village-level water committee has been responsible for operations and maintenance (O&M), fulfilling the community management model that is recommended by many development theorists in order to create sustainable projects. The water committee received post-construction support, mostly in the form of technical support during system breakdowns, from the Togolese Ministry of Water and Sanitation (MWSVH). While this support has been valuable in maintaining a functional water supply system in Solla, the water committee still has managerial challenges, particularly with billing and fee collection. As a result, the water committee has only received 2% - 25% of the fees owed at each private connection and public tap stand, making their finances vulnerable when future repairs and capital replacements are necessary. A new management structure is proposed by the MWSVH that will pay utilities workers a wage and will hire an accountant in order to improve the local management and increase revenue. This proposal is analyzed under the new water pricing schemes that are presented.

Initially, the rural water supply system was powered by a diesel-generator, but in 2013, a solar photovoltaic power supply was installed. The new system proved a fiscal improvement for the village water committee, since it drastically reduced their annual O&M costs. However, the new system pumps a smaller volume of water on a daily basis and did not meet the community's water needs during the dry season of 2014. A hydraulic network model was developed to investigate the system's reliability under diesel-generator (DGPS) and solar photovoltaic (PVPS) power supplies. Additionally, a new system layout is proposed for the PVPS that allows pumping directly into the distribution line, circumventing the high head associated with pumping solely to the storage tank. It was determined that this new layout would allow for a greater volume of water to be provided to the demand points over the course of a day, meeting a greater fraction of the demand than with the current layout.

1 Introduction

The World Health Organization (2014) estimated that from 1990-2012, 2.3 billion people gained access to improved drinking water. This is an encouraging statistic in the fight against global poverty, and in fact the world met the Millennium Development Goal for access to improved drinking water in 2010 (UNICEF 2014). But it is important to critically analyze these statistics and to look at the inequality that still exists in drinking water access and the challenges to achieving sustainable access. Of the people who are now counted as having access to improved drinking water sources, how many are actually using them? How functional are the systems providing this clean drinking water and can their prolonged use be assured so that these populations are not vulnerable to system breakdowns? A study conducted across 11 countries in sub-Saharan Africa showed that between 20-65% of water systems in rural areas are not functional (Sutton 2004). This prevents the target population from accessing the clean water the system is meant to provide, thus negating any potential health benefits. There could be several causes for the poor sustainability of many rural water systems, from a poorly established local management structure, to systems built without the involvement or training of a local workforce, to lack of a financial structure to pay for repairs. This has lead researchers to develop frameworks to analyze the sustainability of rural water supply systems, highlighting community demand, local financing, operation and maintenance as essential components (Whittington et al. 2009, McConville and Mihelcic 2007, Montgomery et al 2009).

To investigate the questions posed above, this study analyzes the physical and managerial structures associated with an improved drinking water distribution system (WDS) in Solla village in northeastern Togo. Solla is a rural village located in the Kara region on the border with Benin. The population was estimated to be roughly 1500 in 2014, and the residents are served by a water distribution system that was installed in 2012. The first

objective of this study is to identify how residents use this system and other water sources, including what inequalities may exist across the population. The second objective is to investigate the challenges the water committee members are facing during the nascent stages of this system's life cycle. These include how to train and motivate effective water salespeople, how to price water so that it may be accessible to the target population but can also provide the funds needed for functionality, how to manage these funds, and how to reduce the potential for water shortages. The third objective is to quantify the effectiveness of two different pumping strategies that have been used over the short lifetime of this WDS- pumping using power from a diesel-generator and from solar photovoltaic.

To achieve this, ethnographic methods including participatory observations, surveys and key-informant interviews were conducted. Additionally, a hydraulic model of the system was developed in EPANET, a hydraulic modeling tool developed by the U.S. Environmental Protection Agency to analyze water distribution systems (Rossman 2000). This model was used to determine the reliability of the system under these two pumping schemes. The economic, social and environmental aspects of these two technologies were also evaluated to compare their appropriateness for use in the Solla WDS. This work showed that there is significant inequality across the population of Solla and that while over 80% of the high-income group use the WDS throughout the year, only 13% of the low-income residents and 27% of the middle-income group use this water source consistently. Additionally, despite the availability of potable water from both the WDS and protected boreholes, over 45% of the population still uses water from unprotected sources for their drinking and cooking needs.

One major inhibitor towards universal use of the WDS is the cost and the availability of other sources, namely unprotected hand-dug wells. When these sources are unavailable, a greater percentage of the population uses the WDS. It was found that the cost of water could be decreased from 20CFA (0.04USD) to 15CFA (0.03USD) for a 40L basin. Additionally, internal subsidies that charge private connection holders a higher rate would allow for

a reduced rate at the public taps, permitting a greater percentage of the population to use to the system.

Furthermore, it was revealed that while the Solla water committee (AUSEPA) has access to some post-construction support (PCS) from the Togolese Ministry of Water, Sanitation and Village Hydraulics (MWSVH), they still faced problems with billing, fee recovery, and general bookkeeping. A new management structure is proposed to provide greater PCS to AUSEPA in these managerial aspects. Additionally, in 2013 when the pumping system shifted from a diesel-generator to a solar photovoltaic power supply, the available supply declined and the residents noted significant problems with the system's reliability. This was especially a problem in March/April 2014, which is not only the driest time of year but was also the time of the biannual Oudjombi festival, when the population of Solla increased to over 5 times the normal size. However, under this system AUSEPA has fewer financial difficulties and is able to recover enough from water sales to cover some of the operations and maintenance costs, which had been a significant problem under the DGPS.

This report is divided into five chapters. In Chapter 2, some background information on Togo is provided, including its demography, political history, and water access statistics. Additionally, background on the study area is provided in Section 2.3. In Chapter 3, the methods used in this study are described, including both the ethnographic methods and the hydraulic modeling methods. In Chapter 4, the results of this study are presented and discussed. Household water use and existing inequalities are presented in Section 4.1. System reliability under these two systems and the appropriateness of the two technologies are investigated in Section 4.2. The management of the Solla WDS and the PCS provided to AUSEPA are investigated in Section 4.3, and different water pricing strategies are investigated in Section 4.4. Finally, the conclusions of this study and possibilities for future work are presented in Chapter 5.

2 Background

2.1 Background on Togo

2.1.1 Geography and Climate

The Republic of Togo is a small country located on the western portion of the African continent. Its area of 56,785 sq. km, roughly the size of West Virginia, expands longitudinally between 6°10' and 11°10'N and is centered around 1°10'E. It shares borders with the countries of Ghana, Burkina Faso and Benin to the west, north, and east, respectively (Figure 2.1). The country is bordered to the south by 56 km of coastline along the Atlantic Ocean at the Bight of Benin. Togo is divided into five political regions, which are subdivided into a total of 30 prefectures (Figure 2.2). The Atakora mountain chain runs diagonally through the country, from the western part of the Maritime region to the eastern part of the Kara region, where the study area is located. In the Savannes region, north of the Atakora Mountains, the terrain is characterized by a rolling savannah. The southern regions consist of a large plateau and a low relief coastal plain (CIA 2014).

Figure 2.1 Map of Africa showing Togo highlighted in green (CIA 2014)

Figure 2.2 Map of Togo showing the five regions. The red star denotes the study area in Solla Village, Binah Prefecture, Kara Region. (CIA 2007)

Rainfall and climate patterns differ significantly across the country, especially moving from south to north, and are heavily influenced by the West African Monsoon. The southern regions are characterized by two rainy seasons- a heavy rainy season in May/June and a light rainy season in July-October- followed by a dry season running from October to March/April. The northern regions, however, witness only one rainy season from April/May through October. The rainy/dry season cycle is important to the local farming patterns and affects many parts of life in the country, including access to water. As the dry season progresses, some water sources, such as rivers and shallow hand dug wells, run dry. Identifying accessible water sources then becomes a high priority for some citizens, particularly those in rural areas.

During the winter months (Dec-Feb), the temperature drops as cool, dry, dusty winds, known as the Harmattan, blow off the Sahara Desert, transporting large quantities of dust. The annual rainfall varies from 800mm-1700 mm/yr, with the lowest rainfall occurring in the far north and at the coast, and the highest rainfall occurring in the Plateaux region. Countrywide, the average temperature ranges from 18°C to 35°C, with the highest seasonal temperature changes occurring in the north (World Bank 2015). Figure 2.3 shows the average monthly temperatures and rainfall for the Kara region.

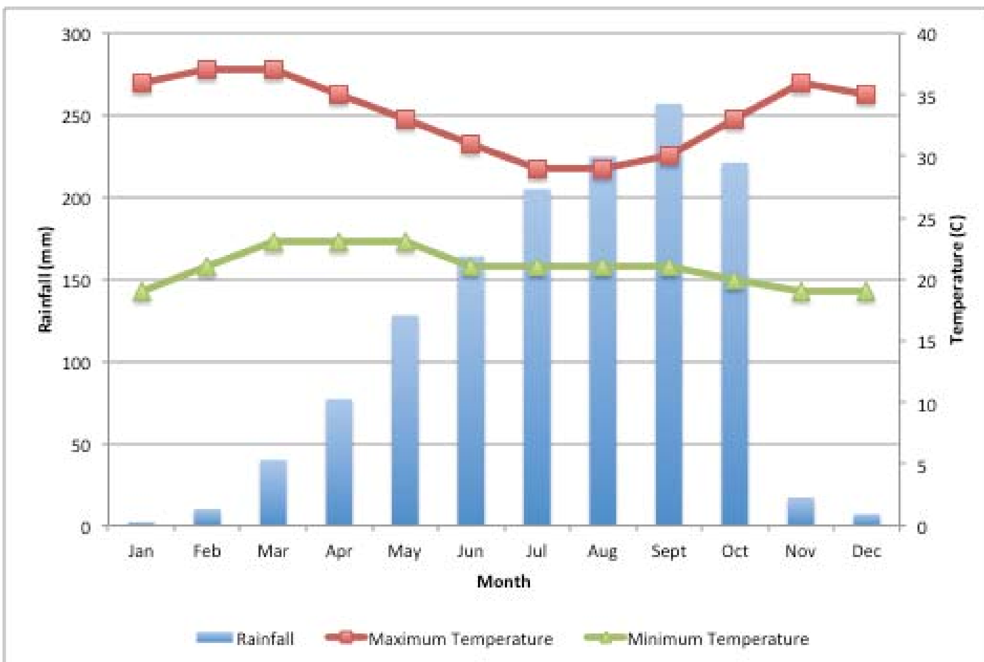

Figure 2.3 Average high and low temperatures and rainfall for the Kara region of Togo. Data from World Bank (2015).

2.1.2 Demography

July 2014 estimates suggest that the population of Togo is 7.35 million and growing 2.71% per year, the 22nd highest growth rate in the world. The population is mostly concentrated in the capital of Lomé, where roughly 38% of the population lives (CIA 2015). The remaining population resides in rural villages or larger towns and regional capitals located along the one national highway that transects the country from south to north and continues on to Burkina Faso. An average of 4.5 children are born per woman and over 40%

of the population is under the age of 14, leading to a median age of only 19.6 years (CIA 2015).

While French is the lingua franca for the nation, Togo has a high ethnic and linguistic diversity. Aside from French, there are at least 42 different languages in Togo spoken by an even greater number of ethnic groups. Ewe is the dominant language in the south with 826,000 speakers. Kabye and Kotokoli (Tem) are the dominant languages in the Kara and Centrale regions with 700,000 and 204,000 speakers, respectively. Moba is the dominant language in the Savannes region with 190,000 speakers (Lewis et al. 2014).

Members of each of these ethnic groups hold religion and religious practices as an important part of their daily lives. Some ethnic groups, such as the Kotokoli, predominantly follow Islam, which is practiced by 20% of the population. Nearly all of the ethnic groups have some membership in Christian churches, with 29% of the total population practicing Christianity. But the religious life of most Togolese is guided by indigenous religions, with 51% of the population identifying as followers of these beliefs (CIA 2014). Even those who attend Sunday mass or follow the daily call to prayer are likely to hold many indigenous religious beliefs and follow traditional religious customs.

The traditional religions in Togo are commonly referred to as Vodun or Vodou, which is also the basis for Haitian Voodoo. Vodun means “spirit” or “gods” in Ewe. It is a belief system that worships the spirits in all things and especially honors the ancestors and believes that their spirits are part of the physical world. Practitioners of these traditional religions often use objects and ritual sites to interact with the spirits (Springer 2012) (Figure 2.4). For example, a Moba man once explained to the author that through a religious ceremony, each of the small statues located at the entryway to his housing compound was connected to one of his ancestors, so that the ancestor’s spirit knows how to find its home and stay close to its family. Other objects such as bird feathers, animal bones, and stones can hold great spiritual power and are often used in religious and healing ceremonies (Figure 2.5).

Figure 2.4 Ceremonial sites tend to be located near natural areas considered to hold spiritual power, like this sacred forest in Solla, Togo. (Photo by author)

Figure 2.5 A traditional religious leader from the Konkomba ethnic group prepares to perform a protection ritual. Libations are commonly associated in such ceremonies. (Photo by author)

2.1.3 Political and Social History

Each ethnic group in Togo has their own oral history about their origins, partly mythical and partly connected to world events over the past 500 years. There is evidence that the Ewe in the south left Yoruba lands in Nigeria due to political pressures sometime in the 14^{th} or 15^{th} century and

settled in southern Togo (Church 1957). The Kabye people of the Kara region attest that the first Kabye man descended from the heavens, landing in between two mountains in eastern Kara and wandering the plains for several years. Then the call of a bird declared that enemies were coming, and he climbed the mountains, settling there and raising many children who later settled communities on other neighboring mountains (Piot 1999).

This story of fleeing from invading enemies and taking refuge in mountains or caves is common amongst ethnic groups in the northern regions, including the groups in the study area, and it likely took place during the 17th and 18th centuries when the slave trade was highly active along the coast. As Piot explains, these groups inhabited the region between two major kingdoms, the Ashante in Ghana and the Dahomey in Benin. These empires provided certain northern societies, such as the Tchokossi and Bariba, with weaponry and cavalry and utilized them to capture as many as one million slaves from less centralized northern groups, such as the Kabye and Biyobe, for trade with the Europeans. These less centralized groups then took refuge in mountains, caves and riverine areas, and even though many have since re-inhabited the plains, their current traditions are still connected with these refugees (Piot 1999).

The Portuguese were the first European visitors to this region, establishing forts in Elmina, Ghana and Ouidah, Benin. They introduced various crops to the region, including coconuts, mangos, cassava and maize, which are now commonly cultivated throughout the country, so much so that they are now part of the daily diet across the country. The Germans and French also established trade in coastal Togo, and in 1884 the region was declared a German Protectorate, the first German colony in Africa. Togoland was the chosen name for the colony, taken from the word Togo, which in Ewe means “behind the sea” (Church 1957).

Under German rule, members of northern groups such as the Kabre migrated on foot to the southern regions to work on various German projects, such as the cacao fields, the Lome-Blitta railroad and the mines. The colonial powers established a tax system that required the local population to pay

taxes in colonial currency, which they could only gain by working on colonial projects. Local chiefs, established by the colonial powers, collected these taxes and gained great power in the colonial system (Piot 1999). Many of the descendants of these chiefs, such as members of the powerful KAGBARA family in the study area, still hold power in Togo.

After its defeat in World War I, Germany lost ownership over Togoland and France and Britain divided the territory, adding the western portion to the British Gold Coast (Ghana) and turning the eastern portion into an independent French state named Togo (Piot 1999). The French ruled over the colony until Togo achieved independence in 1960 and elected its first president, Sylvanus Olympio, an Ewe man who had served in the colonial government ("Sylvanus Olympio").

Only three years later a group of northerners, led by Gnassingbé Eyadéma and frustrated with southern rule, assassinated Olympio and replaced him with Nicolas Grunitzky from the central region of Togo. Displeased with the Grunitzky's rule, Eyadéma, who was a trained soldier and served for the French in the Algerian and Indochina Wars, led a second coup in 1967 and seized power from Grunitzky. Eyadéma, accompanied by a government largely stocked with militants and northerners then ruled the country for 38 years until his death in 2005, making him one of the longest-ruling leaders in world history (BBC 2014).

In the 1990s, during a particularly violent period in Eyadéma's highly non-democratic rule, France, Germany and the United States suspended aid to Togo and the United Nations suspended diplomatic relations with the country. After Eyadéma's death in 2005, his son Faure Gnassingbé took power but after receiving pressure from the international community he held elections and was formally elected. He was re-elected in 2010, and elections for his third term are expected in 2015. Since he took office in 2005, the UN has re-established relations with Togo and some foreign aid groups have started to return (BBC 2014).

The study area in Solla village, Kara region, is politically divided. A substantial part of the population is in favor of the current President Faure.

One of the richest men from Solla, who holds a high rank in Togolese Customs, is active in the campaigns supporting Faure's political party and he encourages many residents to side with him. Another man from Solla, however, is highly involved in one of the main opposition parties. A member of the influential Kagbara family, he ran for both the Presidential election in 2010 and the Legislative election in 2013. According to a statement made by the Regional Director of the Ministry of Water, Sanitation and Village Hydraulics (MWSVH), localities with such political divisions and powerful residents often get higher consideration when government authorities, such as the MWSVH, are selecting sites for development projects. By providing a potentially divided community with an expensive development project, the politicians may garner greater support. Thus it is of no surprise that Solla would be selected as the recipient of the water distribution system described in this report.

2.2 Water Access in Togo

Target 7C of the ambitious Millennium Development Goals (MDGs) set by the United Nations (UN) in 2000 aims to reduce the number of people lacking sustainable access to improved drinking water sources by 50% by 2015. Figure 2.6 lists the improved and unimproved sources as identified by the UN. The UN defines "protected wells" as wells that are lined to prevent surface water infiltration and consistently covered to prevent contamination from animals and bird droppings. "Unlined wells" are those that do not meet these standards (JMP 2015). In 2000 the UN estimated that 53% of the Togolese population had access to improved drinking water sources. Thus in order to meet the MDGs, the country needed to increase access to 76.5% by 2015.

Improved Drinking Water Sources	• Piped water into dwelling, yard or plot • Public tap or standpipe • Tubewell or borehole • Protected dug well • Protected spring • Rainwater collection
Unimproved Drinking Water Sources	• Unprotected dug well • Unprotected spring • Cart with small tank or drum • Tanker truck • Surface water (river, dam, lake, pond, stream, canal, irrigation channel)

Figure 2.6 Lists of improved and unimproved drinking water sources. Data from JMP (2015)

It is important to note that there is a strong inequality not represented in the numbers above, and that is the division between urban and rural zones. The UN reports that in 2000, urban and rural zones had 85% and 38% access, respectively. In 2012 their estimates for total access increased to 60%, with urban and rural zones having 91% and 40% access, respectively (UNICEF 2014).

In 2010, the UN recognized the unlikeliness that Togo would meet the MDGs for potable water access by 2015. In the UN's most recent country report on the MDGs for Togo, published in 2010, they noted that the country had made little progress towards achieving these goals. They cite a lack of investment in the water sector, lack of a permanent mechanism for water resources monitoring, and poor organization of the General Direction of Water and Sanitation, amongst other factors, as contributing to this slow progress. In addition, the UN pushed the following goals: to allocate more of the budget to potable water services, to construct more drinking water supply

systems, to seek further aid from development partners, and to decentralize control over these systems and "reinforce national capacity" by making the local users the primary decision makers and managers of the WDSs (UNDP 2010).

Therein, these goals will be analyzed in the context of a small-scale WDS implemented by the MWSVH. It is noted that at times the UN reports that the key indicator for Target 7C is the "proportion of population using an improved drinking water source" (UNSTATS 2014). At other times the key indicator is stated as "proportion of population with sustainable access to an improved water source" (Millennium Project 2014). The same numbers are reported regardless of the way the indicator is defined. However, wouldn't the percentage of the population with *sustainable access* likely be different than the percentage of the population *using* an improved water source? What qualifies as *sustainable* access? And what effects have the practices suggested in the 2010 UNDP MDG progress report, such as user control and management over supply systems, had in the study area? These are some of the questions investigated in this report using water use in Solla, Togo and as a case study.

2.3 Background on the Study Area: Solla Village, Binah Prefecture, Togo

The study presented here took place in Solla, a rural village in northern Togo. It is located in the northern section of Binah Prefecture, in the eastern part of the Kara region, about 2km from the border with Benin. The village is actually divided by a small creek into two sub villages, Kouyala and Kouyolo. It is the seat of the canton chief, Abara Kagbara, who rules over the 18 villages that make up Solla canton, a political grouping that is one step below a Prefecture. Mr. Kagbara and his family, who hold high positions in the national government and an opposing political party, as was described in Section 2.2.1, can trace their lineage back to the original chief who was put in place by the Germans in the early 1900s.

In the 2010 census, the population of Solla (assumed to be Kouyala and Kouyolo) was 1426. The community has one elementary school, a middle school and a series of thatch overhangs and chalkboards that serve as a small high school. There is one main dirt road through town that connects the village to the prefectural capital and closest electrified village, Pagouda (20km), and the regional capital, Kara (60km). There is also a small health clinic and birthing room, where one nurse, one midwife, on lab technician and one assistant care to the births, illnesses and minor wounds that occur within the surrounding villages.

The dominant ethnic group in Solla is the Biyobe, although there is also a presence of Kabye, Kotokoli, Batimariba and Ewe. The Biyobe speak a unique language called Miyobe, which is not mutually intelligible with any other language and only has a 47% lexical similarity with its closest known linguistic relative, Ngangam (Lewis et al 2014). In 1991, SIL International reported a total of 8,700 Miyobe speakers worldwide, with 7000 and 1700 residing in Benin and Togo respectively (Lewis et al 2014). Nearly all of the Biyobe reside within 20km of Solla.

All of these ethnically bound members trace their lineage to the mountain villages located adjacent to the study area. Much as was described for the Kabye in Section 2.1.3, the oral history amongst the Biyobe speaks of a time when these mountains were their refuge from predatory groups. The stories say that the first Biyobe came to this area with two wives. While it is not known exactly where they came from, the stories tell that they were fleeing conflicts with more powerful ethnic groups in neighboring areas and they found refuge on the mountain Tsiriyobe in the Atakora mountain chain.

During their time in refuge (likely during the slave wars of the 17th and 18th centuries) the Biyobe fortified their mountain refuges with a stone wall that oral history tells was once tall enough that horses could not jump it. Thus any enemy who approached would be forced to descend and pass through a narrow opening in the wall, limiting their ability to attack unnoticed. Remnants of this wall remain, and the Biyobe consider them sacred (Figure

2.7). It is forbidden to touch the wall, and if one does so accidentally, the perpetrator must place a small amount of earth on the location s/he touched.

Figure 2.7 Remnants of the stone wall that once surrounded the mountain villages and protected the Biyobe from predatory groups. (Photo by author)

At this time, the Biyobe also established ceremonies to initiate their young men into the status of warriors who would defend their autonomy. As of 2014, these ceremonies are still practiced. The largest, known as Oudjombi, happens every two years during the dry season, usually in March or April. Any Biyobe with the means to do so is expected to return to the mountain villages adjacent to the plains of Solla to witness the initiation of the latest class. Based on observations and population data on the number of Biyobe in the region, it is estimated that the population in Solla inflates from roughly 1500 inhabitants to nearly 10,000 during the three-week ceremonial period. Houses that are normally empty become filled to the brim. The Tuesday market becomes so crowded that there is barely space to move. With the increased population, all resources, from meat to corn to local millet beer, are consumed in greater quantities than normal, including what is arguably the most important resource, water.

2.3.1.1 The Solla Water Distribution System

During the rainy season (Apr/May - Oct) and the early parts of the dry season (Oct – Jan), the shallow, hand dug open wells that are common in the

community are an accessible source of water. However, as the dry season progresses (Jan/Feb – Mar/Apr), these wells start to run dry and residents must seek other water sources. The Oudjombi festival also occurs in the dry season, when the open wells are often incapable of providing sufficient quantities of water. To satisfy the community's dry season water needs and increasing demand for improved water sources, a water distribution system was completed in Solla in 2011. Before this system was installed, residents would gather water from one of the three mechanical hand pumps, or they would walk to one of three springs in the area. One of the hand pumps is located in the town center, and the other two are at the northern and southern extremes of the village. All three are properly protected and serve as improved water sources. The springs are located 1-2 km from the town center and are open and exposed to contamination from surface water and animals, making them unimproved sources. Additionally, residents reported that these sources were crowded during the dry season and that it would take a substantial amount of time to gather sufficient water to meet household needs.

The Solla WDS was installed in order to alleviate the pressure on these sources and provide the community with greater access to clean water. In an September 2014 interview, the Director of the Kara Regional MWSVH office said, "When the population surpasses 1500 and they are only using hand pumps, they will break often because people use them often to find water… with these semi-urban zones we will look for another solution and make a water system like if they were in a city. That's like what we've given at Solla." But an increasing population is not the only factor that goes into the decision to build a piped water distribution system. As the Director said, "Politics also enters in the mix. That's to say maybe there is something there and if we put the system there then they will vote for me and I'll stay someone big… We make the list and then the politicians, since they finance things, they decide where the systems get put. And then we start to sensitize the population to see their opinion, if the system will be beneficial for them. Normally no one says that it is not good! They are happy, they play the drums and everything and then after we will see the reality," (Regional Director, personal

communication, Sept 9, 2014). Solla is a politically divided village, with native Biyobe holding high positions in both the current and opposing political parties, and so it is likely that politics played a role in the MWSVH's choice to place a WDS in Solla.

The system consists of a pump that supplies water from a 70 m deep borehole to a 30 m^3 storage tank (Figure 2.8). Initially the tank distributed water to 10 public tap stands, one of which was financed by UNICEF. In February 2013, five private homeowners connected their homes to the system (Figure 2.9). This system was part of a project from the Ministry of Water, Sanitation and Village Hydraulics (MWSVH), which aimed to build nine small-scale water distribution systems- five in the Kara region and four in the Savannes region- install 400 new boreholes and manual pumps, and rehabilitate an additional 100 boreholes between 2010-2012. This project was financed using a loan from the Islamic Bank for Development (CINTECH 2010).

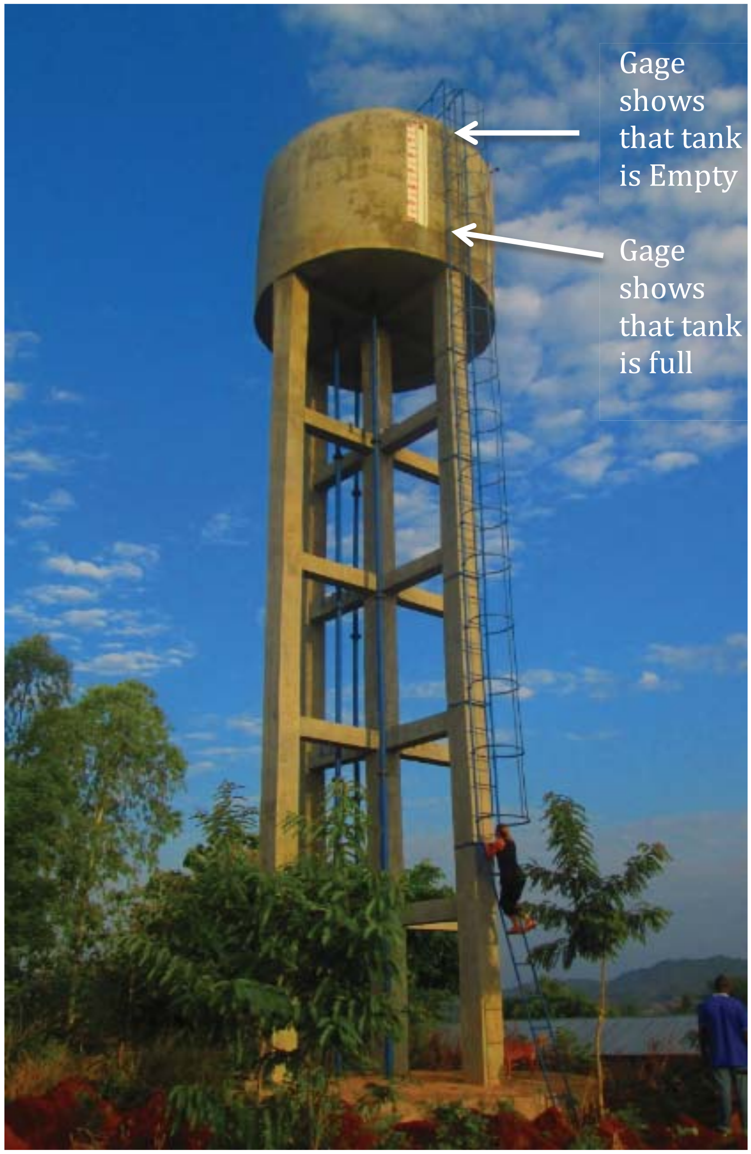

Figure 2.8 The water storage tank for the Solla water distribution system. The 30m³ tank is elevated 14m above ground surface. The red line at the top of the gage indicates that the tank was empty at the time of this photo (12:40pm April 8, 2014). This photo also shows the partly sunny conditions that were typical in April 2014. Photo credit Dominique Krauer.

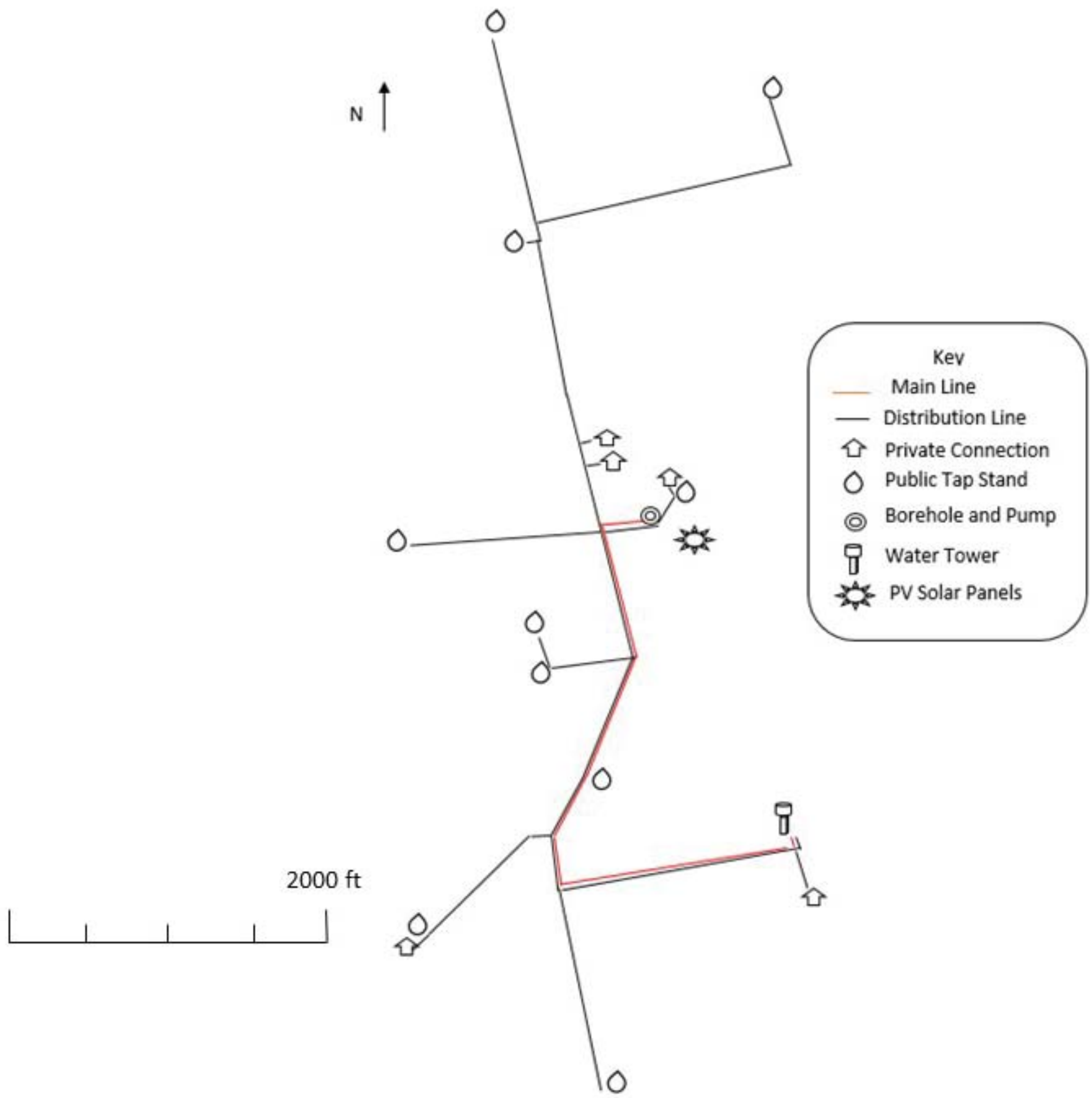

Figure 2.9 Map of the piping, access points, borehole and storage tank for the Solla water distribution system.

The Burkinabe engineering firm CiNTECH managed the project and prepared all the necessary planning and engineering documents. The Togolese/Beninese joint engineering firm CENTRO-AGIR executed the work. As described in the technical report prepared by CiNTECH in April 2011, the project aimed to satisfy the water needs in the selected communities for the next twenty years. To determine the necessary capacity of the water system to meet these needs, CINTECH made the following assumptions in their calculations (CINTECH et al. 2010)

- A growth rate of 2.4% per year
- Water consumption of 20L/person/day
- A maximum of 10 pumping hours per day
- A service rate of 85% of the population
- A 2010 population of 1426 (adjusted from 1997 census data)
- 10% non-domestic consumption
- Losses of 10% of the total consumption

According to the CINTECH report, the 85% service rate was reportedly fixed by Target 7C of the Millennium Development Goals, which set this as the minimum access rate to potable water by 2015. This rate is even higher than the one determined in Section 2.2 (76.5%). From these assumptions, the average supply that the WDS should be capable of providing was calculated for the years 2010 through 2030, as summarized in Table 2.1. These design criteria led to the construction of a 30m^3 capacity storage tank, elevated at 14m above the ground surface. Water is pumped from a borehole to the tank and then distributed by gravity to the water access points. Initially, the pumping power was provided using a diesel-powered electric generator. However, due to challenges with covering the cost of diesel, the diesel-generator was replaced by two 1 m by 2 m solar panels in 2013. This installation was done in collaboration with the MWSVH, but information concerning who conducted and financed this work was not discovered during this study. In 2013, the former AC pump was also replaced with a DC solar pump. In Section 4.2, the reliability of the two different pumping systems and their appropriateness as a water distribution technology in this village will be investigated.

After completing the construction, the MWSVH managed the system and covered the fuel costs for the diesel generator for several months, while providing some training to the local water committee on their roles. The training consisted of a weeklong seminar, during which the committee members attended sessions on basic hygiene, how to record deposits and expenditures in a finances log, and the importance of keeping spare parts on

hand so that the local technician can make repairs quickly and easily. The technician was also given some limited training on how to make small repairs such as broken faucets.

Table 2.1 Calculations for the daily production rate for the design of the Solla WDS from 2010-2030 (CINTECH et al. 2010).

	2010	2011	2012	2013	2014	2015	2030
Total Population	1426	1460	1495	1531	1568	1606	2291
Growth rate (%)	2	2	2	2	2	2	2
Service Rate (%)	85	85	85	85	85	85	85
Served Population	1212	1241	1271	1301	1333	1365	1948
Consumption per person (m^3/d)	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total domestic consumption (m^3/d)	24	25	25	26	27	27	39
Non-domestic consumption (10% of total, m^3/d)	2	2	3	3	3	3	4
Average daily consumption (m^3/d)	27	27	28	29	29	30	43
Losses (10% of daily cons., m^3/d)	3	3	3	3	3	3	4
Average daily production (m^3/d)	29	30	31	31	32	33	47

In line with current development philosophies, the system is intended to be more "demand-driven" than projects in the past so as to increase the sustainability of the system. A "demand-driven" process should involve households during the planning process, give women more power in decision-making and oblige households to cover all the costs of operation and maintenance (O&M), as well as make a contribution to the capital costs (Whittington et al 2009). In order to achieve this, households were involved in general assemblies during the planning and construction process, and two women were assigned roles in the water committee. Additionally, the households surrounding each public tap were supposed to contribute the funds to construct the tap stand, and community members would pay for water services to cover the costs of O&M. The community successfully collected enough funds to pay for five or six tap stands. The community planned to contribute the funds for nine tap stands and UNICEF planned to finance the tenth tap stand.

In August 2012, the MWSVH withdrew from their role in managing the project and placed the local water committee in charge of operations and maintenance. The local water committee, known as the Users Association of Potable Water and Sanitation Services (AUSEPA), consists of six community members selected by the village leaders. The committee members were in the roles of President, Secretary, Treasurer, Funds Collector, Technician, and Hygiene Technician. The most educated member of AUSEPA has completed the equivalent of 7th grade, and two of the members are illiterate. While they are all highly involved in the community, they did not have previous management or bookkeeping experience. The president and technician, however, did have some previous training in masonry and hand pump repair.

There is increasing evidence suggesting that one of the key factors to project success is post-construction support (PCS) from outside of the community management structure (Whittington et al 2009, Prokopy et al 2007). During the first two years of operating the Solla WDS, AUSEPA received some PCS from the MWSVH. In Section 4.3, the challenges faced by the water committee members, as well as the type and effectiveness of the support provided to them, will be investigated with the aim of characterizing the likelihood of long-term project success.

3 Methods

In order to gain an understanding of the use and management of the water distribution system in Solla, a variety of ethnographic methods were used. Through participatory observations, the water sources available to community members were identified. A household survey was conducted to further investigate the water use and decision-making occurring in a sample group of households. To get better insight into the management of the system, semi-structured interviews were conducted with key informants of AUSEPA and the Ministry of Water, Sanitation and Village Hydraulics.

Information gained from the ethnographic approach was then used in the building of a hydraulic model. A comparison between diesel-generator and solar photovoltaic powered pumping systems was conducted because of the challenges presented in the household assessments and key-informant interviews. Information on household water use was used to determine the demand inputs to the model. The ethnographic information also helped provide some of the knowledge that led to the economic analysis of the two pumping systems and the water pricing schemes.

3.1 Household Assessment

A household survey (Appendix A) was used to assess what decisions households were making with regards to their water use and what variables might be affecting these decisions. The survey included factors such as the number of residents in the household, education levels, income and the distance to accessible water sources. The intent of this survey was to identify what roles income, education and distance to water sources might play in decisions a household makes when selecting a water source. Initially, it was planned to train one or two members of the water committee to conduct the surveys with the author. However, after conducting a sample survey at one household with the help of a water committee member, it was noted that having the water committee member present created some complications. For example, when the water committee member was present , residents seemed more hesitant to say why they use or do not use specific water sources. For

this reason, the surveys were conducted in French by the author. When a translator was needed to translate the questions from French to either Miyobe or Kabye, another member of the household, perhaps the husband, a child who is a student, or a neighbor who could speak French, was identified.

The assessments were conducted between March and June of 2014, after the author had lived and worked in the community for over 18 months. In order to gain insights into the water use patterns in Solla and potential inequalities, the household assessment was conducted with 33 households. Typically, multiple people were present during the assessment, including the head of household, his wife or wives, and children. However, since the questions related to water and household demographics, which are regarded as the woman's domain in this culture, most of the assessments were answered by the women of the household (Table 3.1). A total of 227 people resided in the surveyed households, representing 14.5% of the total population. The surveys included most households of water committee members, private connection owners, and tap stand managers, leading the results to be biased towards their responses rather than representative of the general population.

Table 3.1 Summary of the number of household surveys, as well as the gender of the interviewees, and whether or not a translator was used for the household assessment.

Total Number of households	Number of households with only female respondents	Number of households with only male respondents	Number of households with both male and female respondents	Number of households interviewed with a translator
33	17	2	14	18

From participatory observations, it was found that few households in Solla track their income or expenses on a weekly or monthly basis. Thus it was uncertain if accurate estimates of household income could be acquired through the surveys. To accommodate for this, the physical characteristics of the households were noted and used to assess the household income relative

to others in the area. Three dominant housing styles were identified and equated to three different income groups. Households with mud brick houses were classified as low-income (Figure 3.1), whereas those with mud brick houses that were lined with cement mortar to prevent erosion were considered middle-income (Figure 3.2). Households with houses made from entirely from concrete bricks were classified as the high-income group (Figure 3.3).

The mud bricks are inexpensive to produce, requiring only labor costs and a wood mold. They are produced during the early parts of the dry season when water is still available in the local streams. The clay-rich earth near the rivers is mixed with water and then pounded into a rectangular-form using a wood mold. The resulting blocks are then left in the sun for two to three weeks to harden. Once dry, they are moved to the building site and built upon a stone or cement foundation.

Figure 3.1 An example of the mud brick housing style. This housing style indicates "low-income" (photo by author).

Households with the financial means needed will then line these mud bricks with a thin layer of concrete to prevent erosion from rain. This requires disposable income since the cement must be purchased in a sufficient quantity to line the entire house. A 50 kg bag of cement costs 4500 CFA (~9 USD) and multiple bags are usually required to line a house depending on its size. The household must also acquire sand. Sand is only available at one river

about 10 km from the village and is usually purchased and transported to the construction site.

Figure 3.2 An example of a mud brick house lined with cement mortar. This housing style indicates "middle income" group (photo by author).

Households with even greater amounts of disposable income will construct the entire house using concrete bricks. This requires purchasing sand, gravel and cement and paying labor costs for the masons and carpenters. Thus it demands significantly greater financial resources than the other two housing styles.

Figure 3.3 An example of a concrete brick house. This housing style indicates "high-income group" (photo by author).

All of the households in the survey had tin or reinforced concrete roofs. These materials require financial resources, and their presence suggests that all households in the study have some access to cash. In contrast, houses in some neighboring villages are roofed using thatch, which can be collected

from the fields and requires only labor costs. This suggests higher income levels in the study area than some surrounding villages.

The survey also aimed to quantify household water use by assessing the number of basins that household members retrieve from each water source per day. The most commonly used basin size was 40L, although some households reported using 25L or 30L basins. This was accounted for in the calculations of daily household water consumption. The household assessments also included a short semi-structured interview in which participants were asked open-ended questions about their use and perceptions of the WDS.

The participants were selected randomly but in a manner that attempted to get data from households in the vicinity of each public tap stand. To do this, the surveyor started by standing at the tap stand, tossing a pen into the air to ensure randomness, and walking to the nearest house in that direction. After conducting the survey with those homeowners, the pen was tossed again and the surveyor continued to the next house in the new direction. If the homeowners were not home, the process was repeated and a new house selected. The author attempted to collect data from five houses in the vicinity of each of the nine public tap stands, although in some locations only two or three were reached.

3.2 Key Informant Interviews

In addition to the household surveys, formal, semi-structured interviews were conducted with 11 key informants, including the Technician, the Funds Collector, the Secretary and the President of AUSEPA, the Regional Director for the MWSVH and the tap stand managers for 6 of the 10 public tap stands (Table 3.2). These interviews were conducted in French, with the exception of three of the tap stand manager interviews, which were conducted in Miyobe using a translator. The questionnaires and methods were approved by Michigan Technological University's Internal Review Board (IRB).

The interviewees were selected based on their involvement with the Solla WDS. All of the members of AUSEPA were sought out for questioning;

however, the secretary and hygiene technicians were not available. Additionally, all of the current tap stand managers were sought for interviews. However, one tap stand did not have a manager, one TSM declined to be interviewed, and two of the other current managers were not reached despite multiple visits to their households. The interviews focused on the interviewee's role in the operations and management of the WDS and their thoughts on the system's effectiveness. The Regional Director of the MWSVH was also interviewed to get his perspective on the system and also get more information on the construction phase of the project and the post-construction support provided to AUSEPA. All quotations within this report were translated from French to English by the author. With consent from the participants, these interviews were recorded, transcribed and analyzed to identify trends.

The transcribed interviews were coded to identify themes, such as issues with collections, lack of management training, and problems with solar powered pumping. With the exception of the Regional Director for the MWSVH, all interviews with the key informants were guided using the same list of questions (Appendix B). However, given the semi-structured nature of the interviews, other topics were raised as well. A different set of questions was used in the interview with the Regional Director of MWSVH (Appendix C).

Table 3.2 Summary of the key-informant interviews that were conducted between March and September 2014.

Interviewee	Gender	Age	Language	Translator	Date Conducted
BF6 TSM	F	20-50	French	No	April 4, 2014
BF3 TSM	M	>50	French	No	April 2, 2014
BF8 TSM	F	20-50	Miyobe	Yes	April 2, 2014
BF 4 TSM (Health clinic)	M	20-50	French	No	April 7, 2014
BF2 TSM	F	>50	Miyobe	Yes	April 1, 2014
BF5 TSM	F	>50	Miyobe	Yes	March 31, 2014
AUSEPA secretary	F	20-50	French	No	March 21, 2014
AUSEPA technician	M	>50	French	No	March 20, 2014
AUSEPA president	M	20-50	French	No	March 31, 2014
AUSEPA funds collector	F	20-50	French	No	March 21, 2014
Kara Regional Director of MWSVH	M	20-50	French	No	September 9, 2014

3.3 Hydraulic Modeling

In order to evaluate the physical aspects of the piped water distribution system, a hydraulic model was built using the software package EPANET. EPANET is a public domain software developed by the US EPA for analysis of piped water distribution systems. Among other applications, it is capable of analyzing the flow rates and head loss in system pipes, the pressures at various nodes, and the water levels in storage tanks. Extended-period analyses can be conducted to include demand patterns that vary throughout

the day. Different demand patterns can be assigned for different nodes. In EPANET, the user assigns reservoir and storage tank characteristics, friction loss coefficients for pipes, demand patterns, and pump performance curves, as well as other factors important to the analysis (Rossman 2000).

For this study, the behavior of the WDS was analyzed under pumping from a diesel-generator powered pumping system (DGPS) and a solar photovoltaic-powered pumping system (PVPS). Under the DGPS, a Grundfos SP8A-25 pump was used. The associated pump curve provided by the manufacturer was used in the hydraulic model (Appendix D). The electro mechanic studies from MWSVH use a total dynamic head (TDH) of 96.96 m (318 ft) for the DGPS (CiNTECH et al 2010). The total dynamic head is defined as follows (Wurbs and James, 2002):

$$TDH = Static\ lift + Drawdown + Friction\ Loss \qquad (1)$$

where the static lift is the height from the static water level to the discharge level (43.3 m), the drawdown is the distance that the water is pulled below the static water level (SWL) as a result of pumping (Figure 3.4), and friction loss is the head loss due to pipe friction and minor losses from fittings. The friction loss due to pipe friction can be found using the empirical Hazen-Williams equation (Wurbs and James, 2002):

$$h_f = K_w \frac{L}{D^{1.17}} \left(\frac{V}{C_H}\right)^{1.85} \qquad (2)$$

where K_w is a constant equal to 6.82 in SI units, C_H is the unitless Hazen-Williams roughness coefficient, *D* is the pipe diameter in mm, *L* is the pipe length in m and *V* is the velocity in m/s. Using a C_H value of 150 for new PVC piping, a diameter of 81.4 mm and pipe length of 1043 m and a velocity of 0.43 m/s (derived from the max flow rate for this pump at 100 m head), the head loss due to pipe friction along the main line was estimated as 2.6 m. The drawdown can thus be calculated as 51m using Equation 1, corresponding to a

water level of 357m. This is the value used for the reservoir elevation in the hydraulic analysis of the DGPS, as shown in Figure 3.4.

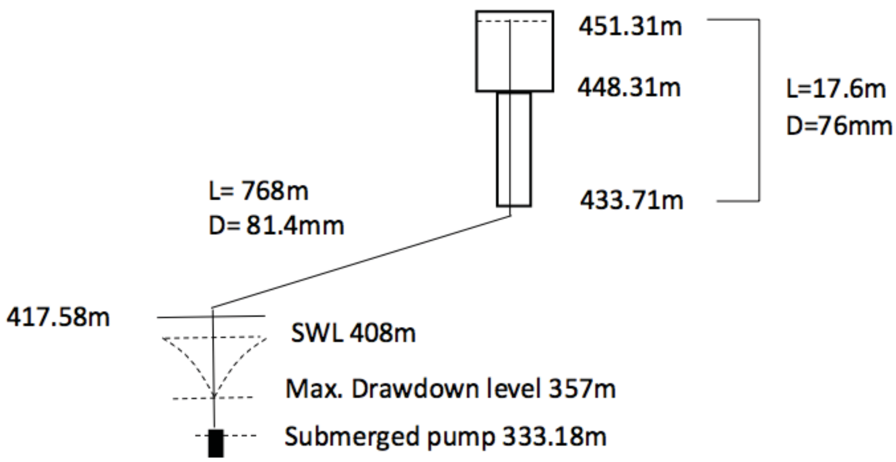

Figure 3.4 Schematic of the submerged pump, main line and storage tank for the Solla WDS. SWL is the static water level.

No data was available on the pump that was installed when the power source switched from a diesel-generator to photovoltaic cells. Thus it is assumed that the solar pump was produced by the same manufacturer as the previous pump, since these are available in Togo. Field data collected from the meter at the pump indicates that it is capable of delivering at least 3 m^3/hr (13gpm). But none of the Grundfos solar pumps are capable of providing this flow rate with a TDH of 97m. However, a pump that operates at a lower flow rate will cause less drawdown in the well. Since the static head from the SWL to the discharge is 43.3 m (142 ft) and the GRUNDFOS pump model 16 SQF-10 is able to operate at flows up to 5 m^3/hr (22GPM) and head ranges up to 70m (230ft), this pump model was used for the EPANET simulation. Performance curves for solar-powered pumps are given in terms of solar output in kW versus flow rate for a variety of heads and the curve for the Grundfos 16 SQF-10 pump is available in Appendix D. EPANET requires a pump performance curve relating head to flow rate. This curve was developed by selecting a given power output and interpolating the maximum flow rates at a range of head levels from the performance curve provided by the

manufacturer. This process was repeated, and new performance curves developed, for various power output values. These curves were then used to model how the pump performs at different solar outputs. Since multiple pump curves cannot be assigned to a single pump in EPANET, the system was modeled as multiple pumps, each with a different performance curve corresponding to a specific power output, pumping into the same node. Only one pump is active at a time and the pumps are turned on and off throughout the day depending on the power output assumed at any given hour (Figure 3.7).

For the solar powered pump, the flow rate, and thus the drawdown and TDH, varies depending on the output from the solar panels. System data was collected over the course of one day showing the average power output and flow rate at various times (Table 3.3). A simple linear regression model was applied to this data, and the resulting equation was used to calculate the flow rate at different solar power outputs used in the hydraulic model. These flow rates were then used to determine the drawdown using Jacob's well-loss equation (Jacob 1947):

$$s = BQ + CQ^2$$

where s is the drawdown (m), Q is the flowrate (m^3/h), B is the aquifer loss coefficient and C is the well loss coefficient. Sufficient pump test data was not available to determine the aquifer and well loss coefficients. However, one data point was available from the MWSVH's documents, which suggests a drawdown of 51 m for a flow rate of 7 m^3/h. As is clear from the equation, the well loss coefficient is important when pumps are operating at high flow rates; however, there is some evidence that it is not as important at low flow rates and that assuming a linear relationship in these situations may be reasonable (Howsam 1990). Thus, the drawdown was calculated using the linear portion of Jacob's well-loss equation, and the one data point was used to calculate the aquifer coefficient. The calculated drawdown levels used in the EPANET model are shown in Table 3.4.

Table 3.3 Average solar power outputs in kW and flow rates in LPS over the course of one day. There was no power output before 7:30am or after 5:15pm. (Note: 1 LPS = 3.6 m^3/h)

Time	Average Power output (kW)	Average Flow rate (LPS)
7:30-8:30 AM	0.16	0.03
8:30-9:30AM	0.42	0.18
9:30-10:30AM	0.675	0.57
10:30-11:15AM	0.775	0.66
11:15AM-12:40PM	0.81	0.64
12:40-1:30PM	0.795	0.67
1:30-2:45PM	0.675	0.58
2:45-4:00PM	0.44	0.44
4:00-5:15PM	0.15	0.16

Table 3.4 Estimated drawdown levels using the interpolated flow rates and pump performance curves for various solar outputs. Note that the pump could not perform at the head and flow values for an output of 0.2kW and 0.4kW.

Solar output (kW)	Linearly interpolated flow rate (LPS)	Drawdown (m)	Drawdown level (m)
0.2	0.12	3.3	404.7
0.4	0.31	8.1	399.9
0.6	0.49	12.9	395.1
0.7	0.58	15.3	392.7
0.8	0.67	17.7	390.3
0.9	0.76	20.1	387.9
1	0.85	22.5	385.5
1.2	1.03	27.4	380.6

Three different scenarios were used for the analysis of the PVPS, one assuming sunny conditions throughout the day, one assuming partly sunny, and one assuming cloudy conditions. The outputs from the solar panels assumed for each scenario are provided in Table 3.5. The partly sunny scenario is based on data collected at the field site on April 28, 2014.

Table 3.5 Assumed power outputs from the PV panels under sunny, partly sunny and cloudy scenarios.

Time of day	Sunny Scenario Output (kW)	Partly Sunny Scenario Output (kW)	Cloudy Scenario Output (kW)
Before 7am	0	0	0
7am-8am	0.2	0	0
8am-9am	0.4	0.2	0
9am-10am	0.6	0.4	0.2
10am-11am	0.8	0.7	0.4
11am-12pm	1	0.8	0.6
12pm-1pm	1.2	0.9	0.8
1pm-2pm	1	0.8	0.6
2pm-3pm	0.8	0.7	0.4
3pm-4pm	0.4	0.4	0.2
4pm-5pm	0.2	0.2	0
After 5pm	0	0	0

The base demand was assumed to be the same under both the PVPS and the DGPS alternatives and was extrapolated from the daily use reported in the household assessments. The total demand for the community was determined to be 28.6 m^3/day, which corresponds to 0.022 l/s per tap assuming that the demand is equal across all taps. The PVPS alternative was also analyzed assuming a reduced demand of 14.3 m^3/d (0.011 l/s per tap). Additionally, a demand pattern was used to represent the water use habits uncovered from the household assessments and participatory observations. The demand pattern is different for the DGPS and the PVPS alternatives. Under the DGPS alternative, water is available throughout the day and thus users can collect water when it is most convenient for them, namely in the early morning and at dusk (Figure 3.5). Under the PVPS alternative, however, the availability is limited to hours when the solar radiation is strong, and thus users adapt and collect water closer to midday (Figure 3.6).

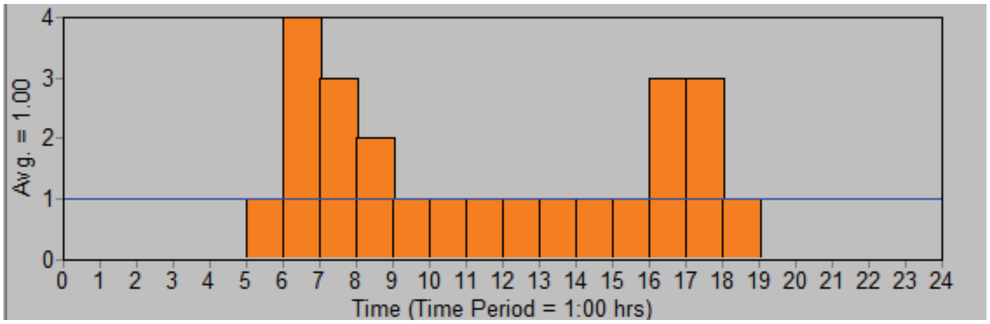

Figure 3.5 Demand pattern assumed with the DGPS. This pattern corresponds with the times that users prefer to collect water.

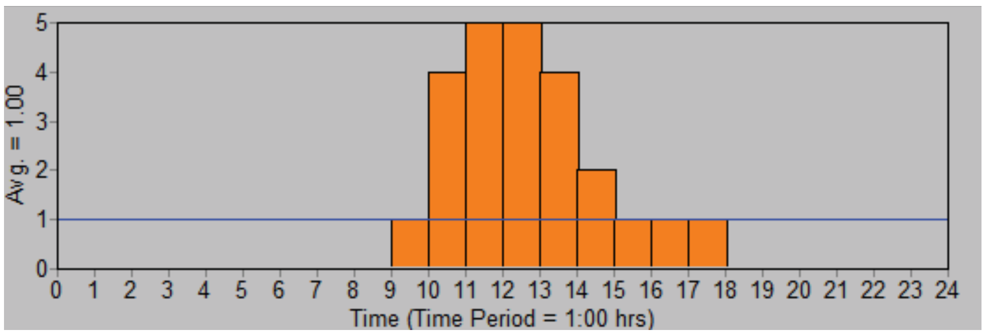

Figure 3.6 Demand pattern assumed with the PVPS. For this pattern, the users have adapted to the time when water is most available, namely near midday.

For both systems, the pipe lengths and node elevations were determined from data provided by the MWSVH. The Hazen-Williams equation was used to determine head loss due to pipe friction, and since the pipes are relatively new and composed of PVC, a head loss coefficient of 150 was assumed. Minor losses from fittings were neglected. It was assumed that the drawdown stayed constant throughout pumping for a given solar output. It was also assumed that the storage tank starts empty at the beginning of the three-day simulation. A hydraulic time step of 10 minutes was used in all of the analyses.

An additional analysis was conducted under the PVPS alternative to evaluate how much water could be pumped if it went directly into the distribution line instead of to the storage tank (Figure 3.7). To do this, the pipes connecting the pump to the storage tank were removed, and a 5 m pipe was added to connect the pump directly to the distribution line. This

alternative is considered because it will reduce the total dynamic head of the system, potentially allowing the pump to provide a greater quantity of water throughout the day.

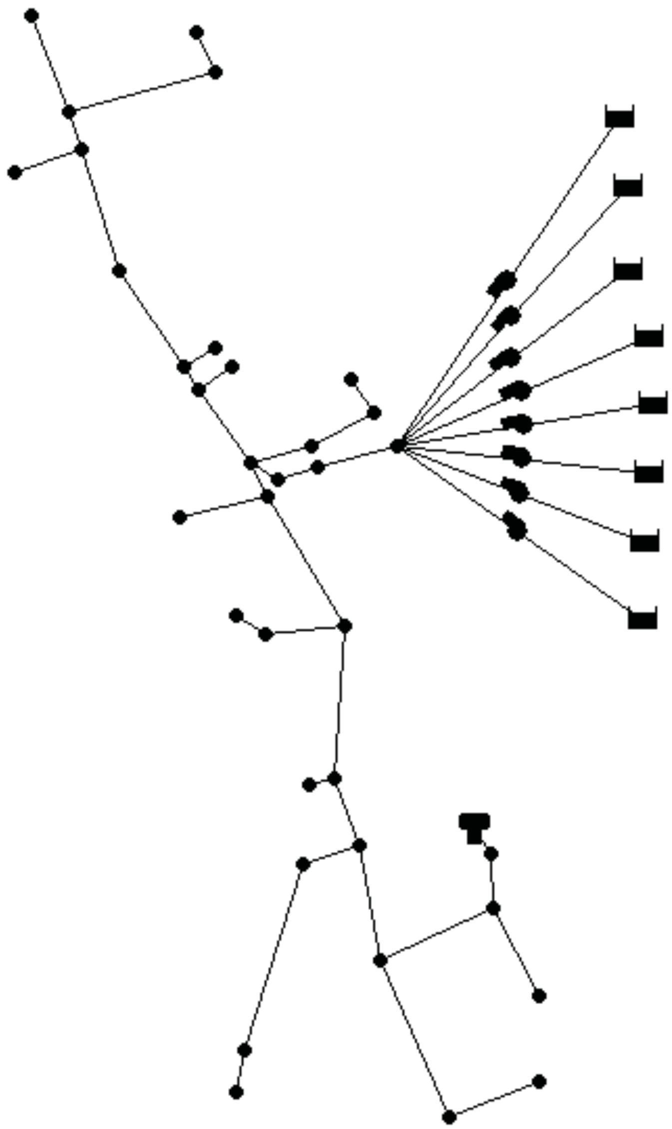

Figure 3.7 Schematic showing the multi-pump system used to model the solar pump in EPANET. This schematic also shows the system design when water circumvents the storage tank and is pumped directly into the distribution line.

4 Results and Discussion

4.1 Household Water Use

Through participatory observations, the water sources used by the community were identified, along with the receptacles used to transport water from the sources to homes and who transported the water. Women and girls usually perform the daily task of water collection, although on rare occasions bachelor men and young boys carry water. Water is most often collected in the early morning or near sunset and transported basin by basin from the source to large jars and/or barrels in the home. Water is transported manually by balancing the basins on the head (Figure 4.1). These basins range from 25-40 L (Figure 4.2) and can weigh up to 80 pounds or more when full, so this is no easy task. As it is nearly impossible to lift a full 40L basin from the ground to the top of one's head alone, it is important to have someone nearby who can help. On occasion, residents collect water in 25 L jerry cans. Sometimes these are attached to motorcycles and transported to the mountain villages. This is especially common during the Oudjombi festival.

Figure 4.1 A woman carrying water from a hand pump to her home. (Photo by Kelsey Jo Corey)

In this section, the various improved and unimproved drinking water sources available to the residents of Solla are explored. Using data gathered through the household assessments described in Chapter 3, the sources used

by the residents are discussed, as well as the quantity of water used on a daily basis and for what purposes it is used. Using this data, patterns were identified to draw a picture of water use, including how it differs across income groups in rural zones such as Solla.

Figure 4.2 A group of girls pulling water from a lined hand dug well (Note: the cover is unused, thus this is still an unimproved source). The small and large basins are 30L and 40L, respectively. (Photo by author)

4.1.1 Available Water Sources

A village such as Solla has many physical components that are essential to the daily life of the community. In Solla, there is the central market, which is the social hub and location of the weekly Tuesday night market. There are also three schools and a local health clinic. There are agricultural fields that provide the sustenance for the residents and perhaps some disposable income. And then there are the water sources, essential to the health and cleanliness of the town and its residents. There is a wide range of both unimproved and improved water sources (as defined in Figure 2.6) available in Solla. Figure 4.3 shows the locations of most of these key physical components of the village; however, the unimproved hand dug wells are omitted. Most of the 200 or so households in Solla have such a well within 60 m of the residence, thus they are too numerous to be adequately displayed on a map of this scale. The various water sources are described below.

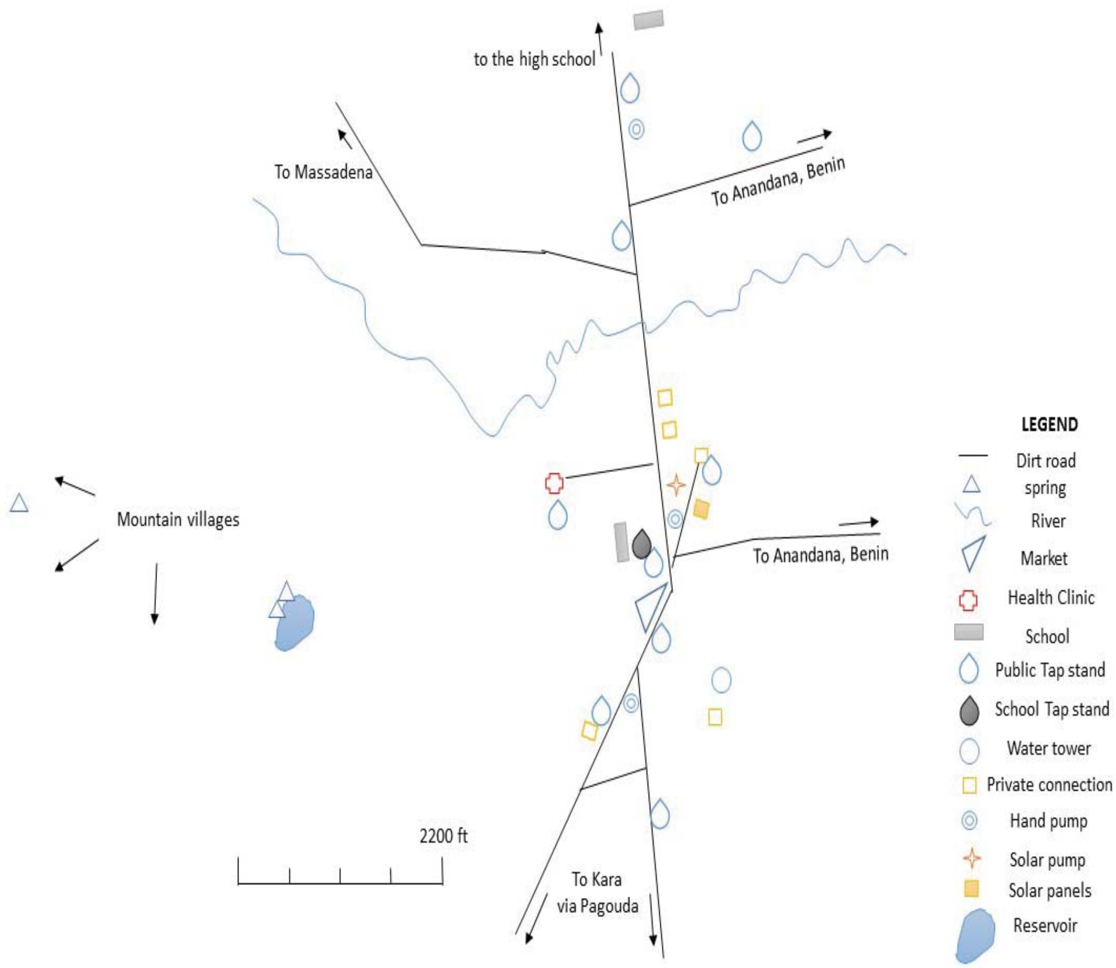

Figure 4.3 A map of Solla showing key physical components. The hand dug, unprotected wells are not shown. The small reservoir and springs are at a higher elevation than the rest of the map area and are along small footpaths that lead to the mountain villages.

4.1.1.1 Unimproved sources

Community members use water from a number of unimproved sources. The most widely used source is the unlined, hand dug well. Many households have dug such wells, usually around 10m deep, adjacent to their homes. The wells generally are not lined, but often a small platform of rocks is placed along the rim of the hole to prevent surface erosion. They are almost always uncovered and therefore exposed to surface water runoff, animals and bird droppings. As the dry season progresses, the water in these wells

recharges more slowly, the water becomes dirty and in some cases the wells dry out completely. This usually occurs in January or February.

The other unimproved sources that are available include a small creek that runs through town and divides Solla into the sub villages of Kouyala and Kouyolo. There are pools of this creek that remain well into the dry season, but most of the accessible stretch is exhausted by February or March. No one surveyed reported using this water for any purpose other than doing laundry or watering gardens, nor did the author observe river water being used for any other purpose.

There is also a reservoir located on the outskirts of town (Figure 4.4). It was created in 2013 when an organization excavated the land adjacent to two local springs and constructed a small dam and spillway to allow the spring water to collect in the reservoir. The intended use for this water was as a supply for dry-season gardening and/or fisheries projects. As of September 2014, it was only being used for livestock and laundry, with the occasional swimmer braving the encroaching algal blooms.

The final unimproved sources available to the population of Solla are a series of at least three unprotected springs located along the mountainside 1-2 km from the town center (Figure 4.4). These are occasionally used for drinking and bathing during the dry season, particularly during the biannual Oudjombi ceremony when the population of Solla is greatly inflated. As one participant explained, “During the time of Oudjombi, when there are a lot of people at the pump and we can’t get water, we get it from the spring. During this time you can pass morning until night and you won’t find a place at the pump. So we go to the spring and the dam.”

Figure 4.4. One of the unprotected springs located adjacent to the reservoir (visible in the upper left). These are occasionally used as a drinking water source, particularly during the Oudjombi festival when the local population increases. (Photo by author)

4.1.1.2 Improved sources

In addition to the unimproved sources described above, the residents of Solla have access to a number of improved sources. First, they have the ability to capture rainwater, and many households do this on a small scale. If collected and stored so as to limit contamination, this is the only improved source in Solla that is essentially free to the user after materials and construction costs are paid. Some homeowners have installed gutters alongside their tin roofs that funnel water into jugs, barrels or buckets. However, only one household in the survey reported storing rainwater for use in the dry season. This is not surprising considering the prohibitive cost of constructing a reservoir large enough to store sufficient quantities of rainwater for a season. The one resident with a rainwater storage tank is a member of the “high-income” group, with many networks to foreign resources, and he has constructed a ~10 m^3 concrete basin beneath his home where he stores rainwater. This household does not use the rainwater as a drinking water source, but does use it for laundry, housecleaning, and gardening.

Next, there are three drilled boreholes that reach greater depths (~60 m) than the hand dug wells and do not run dry during the dry season. A mechanical hand pump is installed at each borehole (Figure 4.5). To use the hand pumps, community members must notify the pump manager, who usually lives adjacent to the pump, and pay 500CFA (1USD) on a monthly basis. Subscribers are then free to take as much water as they want throughout the month.

Figure 4.5 A young girl fetches water from a hand pump. Photo credit: Kelsey Jo Corey

Some of the participants reported that during the rainy season the water from the hand pump located closest to the middle school had a reddish color and tasted metallic. They said that they did not like this taste or color, thus they preferred to use other sources for drinking water, namely unprotected open wells or the WDS, during the rainy season. These characteristics of the water could be caused by anaerobic microbial action by iron-reducing bacteria in the soil. These bacteria take non-soluble Fe^{2+} and reduce it to its soluble form, Fe^{3+}, thus increasing the iron content of the water and changing its color and taste. These bacteria thrive in anaerobic conditions, which can exist in boreholes, particularly during the rainy season when the unsaturated zone is closer to the ground surface and thus more of

the well length is fully submerged. This problem may be remedied by replacing the pump's iron pipe with a PVC pipe (Fader 2011). However, if the local soils are naturally rich in iron (as they are in the study area, judging by the rust-colored dirt suggesting the presence of iron oxides), and the iron-reducing bacteria are naturally present, then the reduction process may occur naturally in the soil and the water may still have a metallic taste even if PVC pipes are used.

The final improved source of drinking water is a water distribution system, which supplies water to 10 public tap stands and 5 connections in private homes. The health clinic manages one of the public tap stands and the elementary school director manages another. At the other 8 public tap stands, tap stand managers collect funds from users on a per basin basis. The cost is 20CFA (0.04USD) for one 40L basin or 25CFA (0.05USD) for two 25L jerry cans or buckets. Residents with private connections are responsible for paying their water bills at 500CFA (1USD) per m^3. All of the pubic taps stands and the private connections are metered.

4.1.2 Inequalities in Water Use Based on Income

Through participatory observation and household assessments, it was revealed that not all households use these water sources equally. One third of the surveyed population reported using the manual hand pumps at some point in the year. About 18% of residents reported using the hand pumps all year as a source of drinking water, although 12% said that they sometimes use the public water taps instead. During the dry season, as wells run low, an additional 15% use the hand pumps to supplement their diminishing well water. The situation was similar for the WDS, with a group using the system year-round, a second group using it to supplement diminishing well water, and a third group stating that they never use the public taps. More participants reported using the WDS (57%) than the hand pumps (24%), not including those who alternated use between the two sources (12%).

Data gained from the household assessments indicate that nearly 80% of the population (26 out of 33 surveyed) uses water from unprotected hand

dug wells. The actual percentage for the entire village is likely higher since this survey included water committee members and tap stand managers, some of whom do not pay to use the public water taps, and four residents with private connections. These individuals are less likely to use well water because of their access to improved sources. Furthermore, nearly half (45%) of the respondents reported using water from these unprotected, open wells as their primary source of drinking water, at least during the rainy season and early dry season (Table 4.1). This is higher than the rate reported by Whittington et al. 2009 (38%) for rural villages of similar size in southern Ghana that had access to similar water sources. Of those surveyed that use well water, 29% reported that the water in their wells was insufficient during the late dry season and they were forced to use the WDS or hand pumps for two or three months.

Table 4.1 Summary of the water sources most used by the survey participants

WDS	Year-round Use	36.4%
	Dry season Use	21.2%
	Never use	30.3%
Hand Pumps	Alternate use year-round	12.1%
	Year-round Use	9.1%
	Dry season Use	15.2%
	Never use	63.6%
Open Wells	Use when available	78.8%
	Drink when available	45.5%

As described in Section 3.1, the physical characteristics of each household were noted during the household assessments. These characteristics were used to classify the residents as belonging to one of three income brackets- low-income, middle-income and high-income. It was then investigated if members of the different income groups tended to choose different water sources. Members of the low-income group (16 respondents)

were the most likely to depend on unimproved sources, with 25% of the low-income group stating that they never use the WDS or hand pumps. In contrast, all members of the middle- or high-income groups reported using these sources at some point during the year. When the low-income users did use the improved sources, it was likely only during the dry season when their wells were no longer a viable source of water. Only 19% of the low-income respondents reported using water from the improved sources to supplement water from open wells throughout the year (Figure 4.6).

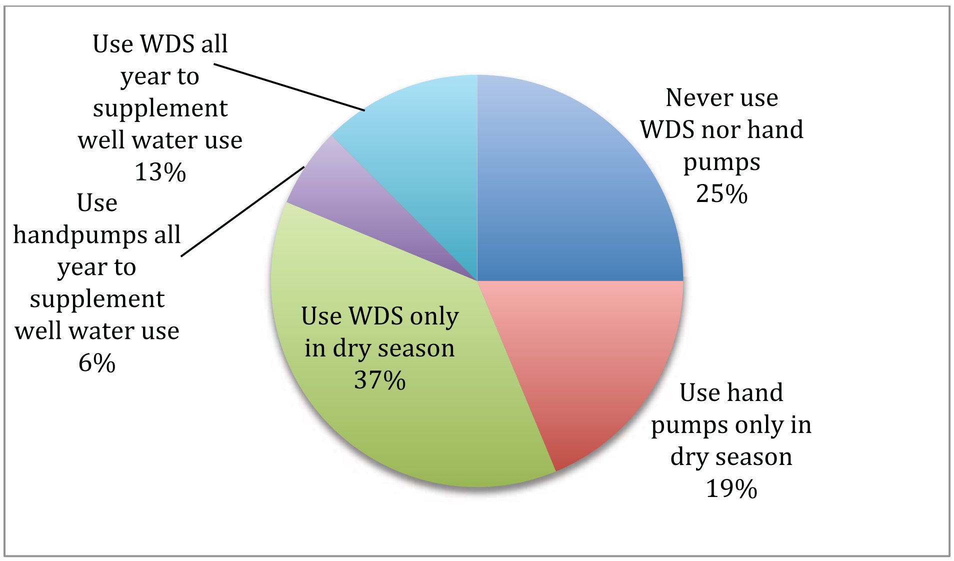

Figure 4.6 Use of paid water systems by low-income users (mud brick homeowners).These users are the least likely to use water sources that require payment. When they do choose to use these sources, it is generally in the dry season when other sources are unavailable.

Users from the middle-income group (11 respondents) were more likely to use the improved sources. In fact, all of them use these sources at some point in the year, but some (20%) still depend solely on unimproved sources when they are available. Twenty-seven percent of the respondents stated that they use water from the public taps all year to supplement their well water use and that they never use the hand pumps. An additional 55% reported that they alternate using the hand pumps and the public taps (Figure 4.7). One resident reported that she alternates use because, while the hand pump and public tap are nearly equidistant from her house, it is much easier and less

tiring to use the public tap. She reported that manually operating the hand pump can be exhausting. Other residents also stated that at times the hand pumps are overcrowded, so they prefer to purchase one or two basins from the public taps rather than to wait for the hand pump. Additionally, some said that there were days or hours when water was not available at the public taps, and so they had to return to using water from the hand pumps. System reliability will be discussed in more detail in Section 4.2.

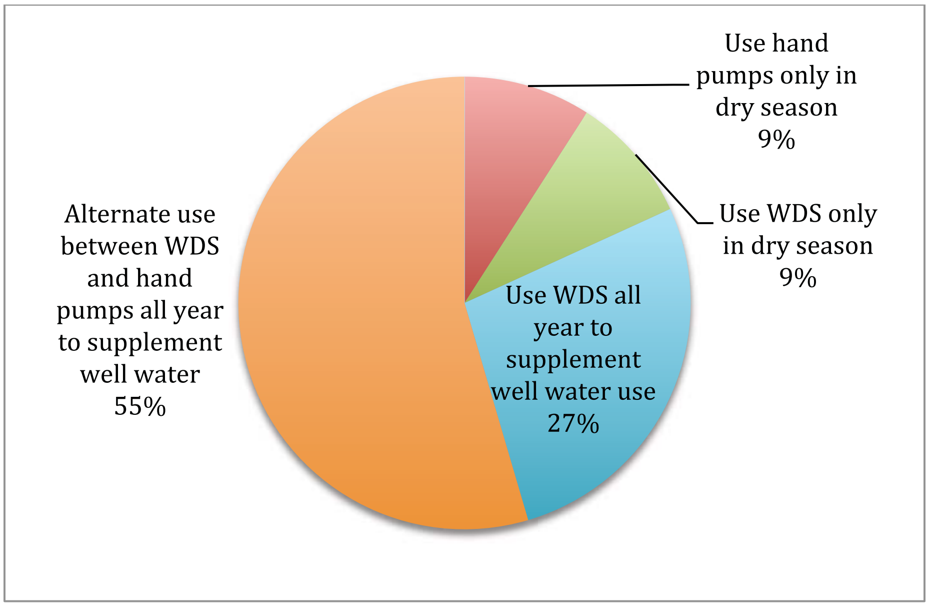

Figure 4.7 Use of improved water sources by middle-income users. This entire group reported using the improved sources at some point in the year, but 18% only use them during the dry season and still rely on unimproved sources during the rainy season.

The high-income users (6 respondents) all reported using the WDS throughout the year. One resident reported that this is the only water source that his household uses, while the rest reported also using well water for activities such as bathing and laundry. Four of the six households in this group have private connections in their homes- two of these are simply taps in the housing compound and two bring running water into the household (for showers, toilets, etc.). One of the private connection owners does not use this water, but instead uses the hand pump to supplement well water use, citing that it is more economical (Figure 4.8). The private homeowner is responsible

for covering the material and labor costs to install a water connection in his/her home and then must pay the monthly water bill for use.

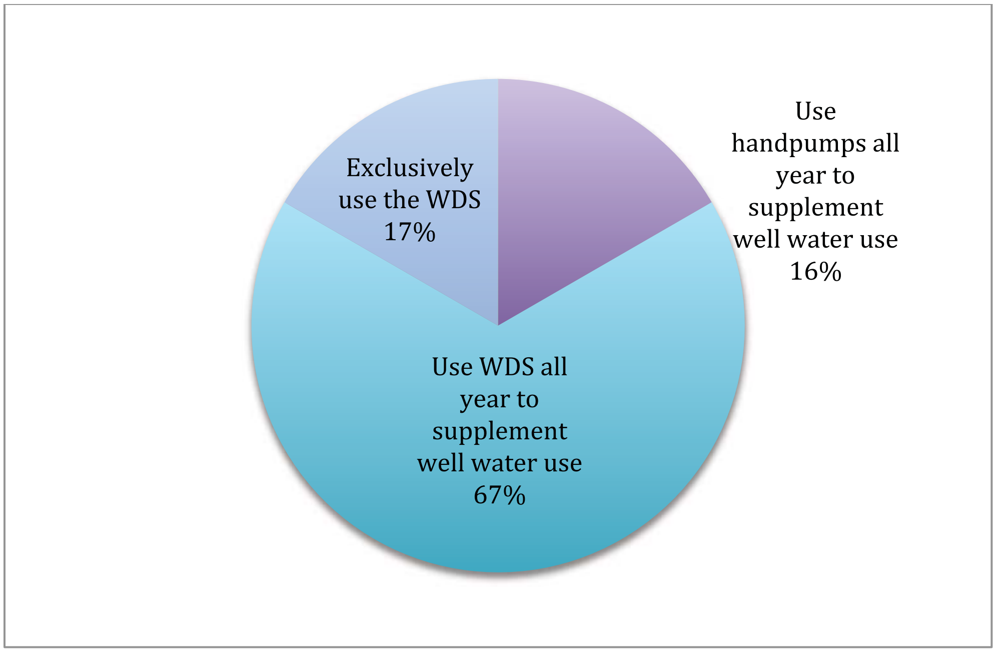

Figure 4.8 Use of improved sources by high-income users. Four of the 6 members of this group have private connections. One of these households uses the private connection for all its water consumption. Another uses the hand pumps instead of his private connection.

4.1.3 Rainy Season versus Dry Season Use

Across all income groups, most community members expressed that they use the WDS taps and hand pumps more frequently during the dry season, when water from other sources, such as open wells, runs low. As one resident reported, "In the rainy season, we get water from the well. But during the dry season there isn't enough water in the well so we get water from the public tap. During rainy season we don't get water from the public tap." This is evident not only from the household surveys and interviews, but also from the gage readings at the various water access points for the WDS. Data collected from these gages indicates that the average use during the dry season (Dec-Apr) is 363 m^3/month, whereas during the rainy season it is only 167.1 m^3/month (Figure 4.9). There is some error in these numbers due to poor bookkeeping on the part of the village water committee, specifically the

technician who may have been inadequately trained in how to read and record gage readings. In section 4.3 the functionality of the village water committee and their management of the WDS will be investigated further.

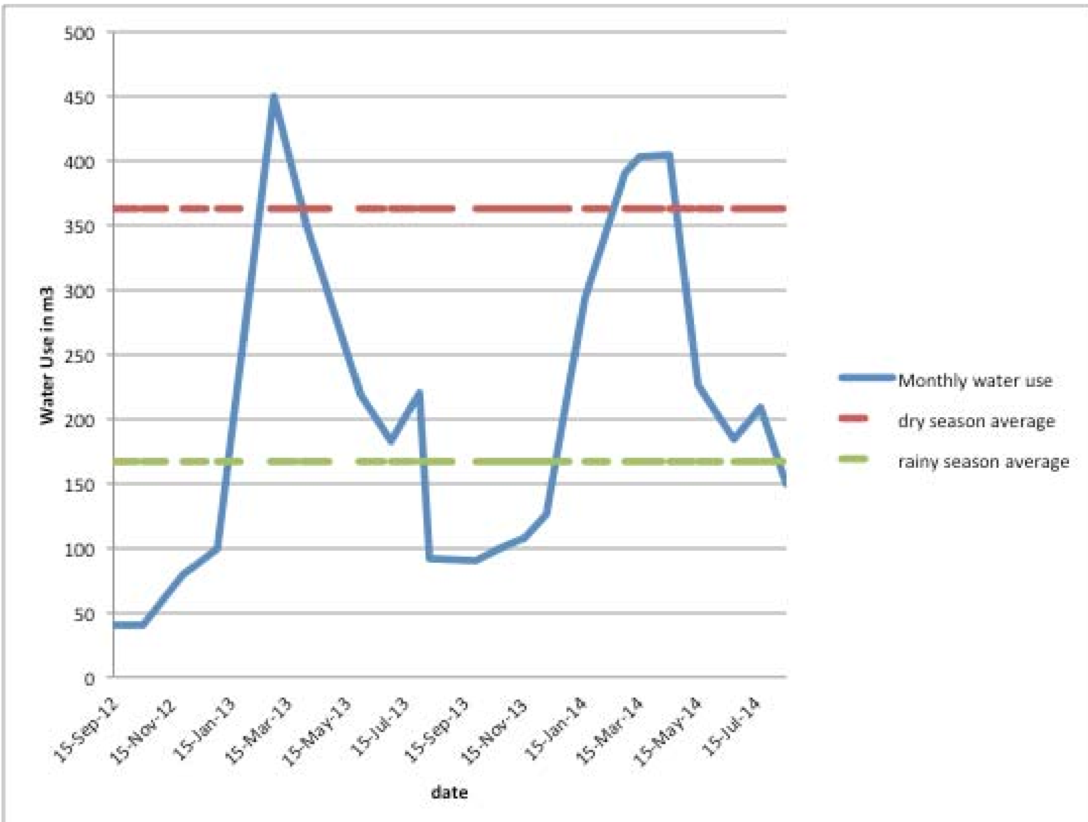

Figure 4.9 Total water use from Sept 15, 2012 to July 15, 2014.The peaks correspond with the dry season (Dec-Apr) when water is less available.

The dry season peak in 2014 also correlates with the biannual Oudjombi festival. It was anticipated that the water consumption in 2014 would be higher than the previous year as a result of the increased population due to this festival. The data, however, does not show this pattern. This is because during the dry season of 2014 the WDS was not providing enough water to meet the demand and water was often unavailable at the taps. Community members would visit the taps multiple times in the morning, only to find that no water was available. The reliability of the system had declined since the previous dry season or else the apparent decline is due to uncertainty in the data.

4.2 System Reliability and Appropriate Technology

While the system was originally designed to provide a maximum of 47m^3 of potable water per day, on April 28, 2014, the system provided only 15.5m^3 over a 24-hour period, failing to meet even half of its designed capacity. April 28th was during the end of the dry season, when wells run dry and the population must turn to other water sources, increasing the demand from the WDS. Additionally, it was during the Oudjombi festival, when the population was higher than normal and demand was likely at its highest. This was a common occurrence during the dry season of 2014, with residents repeatedly noting that water availability was intermittent at the public taps. When there was no water at the public taps, residents are obliged to turn to the crowded hand pumps or to unimproved sources that could compromise their health. As one tap stand manager stated, "When there isn't water at the public tap, we return to getting water from the well. There isn't always good water there in the dry season, but we cope with it."

On most days water would be available at the WDS access points, but as the manager of one public tap stand commented, "Some days water doesn't come until 10 am, then until 4 pm or 5 pm there is water. But after at 6 pm the water is finished." Yet residents prefer to fetch water in the early mornings and evenings, when they will most readily use it for bathing and cooking. This meant residents would spend more time passing by the taps, waiting for when water would flow, and sometimes this caused other issues. As one resident described, "A lot of people will leave their basins and wait for when there is water. Then when there is water and you go back to fill your basins, someone else may have come after you, and even though you put your basin first, they might refuse to let you get water first. Then you might quarrel. This brings problems."

It is clear the difficulties that an unreliable water supply system can cause, especially in a water-stressed region during the driest time of the year. So what happened between 2013 and 2014 that caused this decline in the reliability of the Solla WDS? The biggest change in the system structure over

this year was the shift from a diesel-generator powered pumping system (DGPS) to a solar photovoltaic powered pumping system (PVPS). In 2013, the members of the water committee were able to run the generator and pump water to the storage tank whenever it was empty, allowing water to be available at any time of day. But with a PVPS, power is only available when there is sunlight and thus system managers have limited control over when they can pump water to the storage tank. In this section, the reliability of the Solla WDS with a DGPS and a PVPS, as well as the appropriateness of the two technologies, will be investigated. Additionally, a change in the piping system to allow for direct pumping into the distribution line, instead of to an elevated storage tank, is investigated to see if this can improve the reliability of the solar-powered system.

4.2.1 Hydraulic Modeling Analysis

Following the methods described in Section 3.3, an EPANET analysis was conducted to analyze the reliability of the DGPS and the PVPS. The head in the storage tank and the pressures at each node were analyzed to verify if water was available. After the first pumping cycle under the DGPS, the water level in the storage tank remained above the minimum level and the pressures at each node remained positive throughout the three-day analysis. The lowest pressures existed at PC2 (14.5 m - 17 m) and the highest pressures existed at PC5 (38 m – 40 m). This corroborates what was revealed through the ethnographic studies, that water was always available under the DGPS as long as there was diesel to run the generator. In this analysis the generator ran for 3.5 hours each night, and by the end of the third pumping cycle, the storage tank reached the maximum level (Figure 4.10). It was possible to run the generator for only 3 hours and still prevent the tank from emptying, but the water level never reached the maximum. It may be desirable to maintain reserves in the tank in case repairs are needed and pumping must be stopped for some time. For this reason it is recommended to run the pump for 3.5 hours to ensure greater reserves.

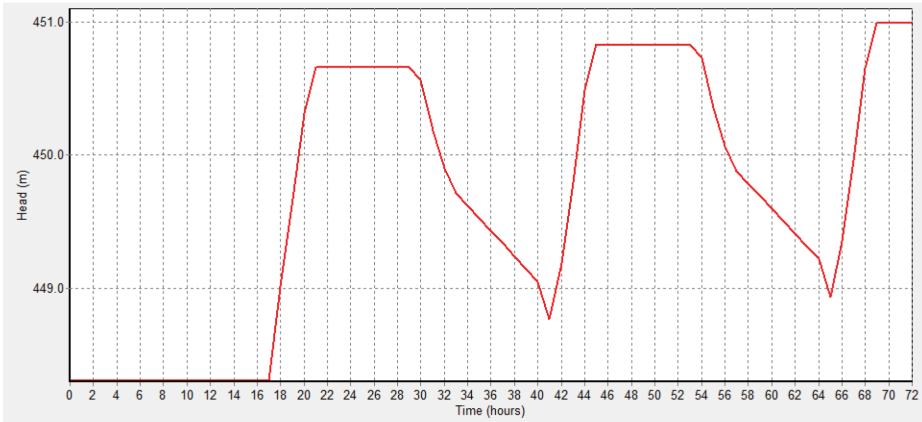

Figure 4.10 Head levels in the storage tank under the DGPS assuming that the pump runs for 3.5 hours each night from 5pm to 8:30pm and that the demand is 28.5 m³/day (0.022 LPS per tap).

The results from a simulation of the PVPS were not as promising, as was expected based on field tests and the results of the ethnographic studies. Even under the sunny day conditions, the system could not meet the demand of 28.5 m^3/day (Figure 4.11). Between 10:30 am and 6 pm, the tank is repeatedly emptied, causing negative pressures to occur at the taps at least every 20 minutes. The system was able to pump 14.4 m^3 of water to the tank over the course of one day under these conditions. Thus, while attempts were made to adjust the demand pattern so that negative pressures did not exist, the system could not meet a demand of 28.5 m^3/day. So the analysis was run under a lower demand of 14.3 m^3/day (0.011 LPS/tap). Under this demand, the tank did not drain over the course of one day (Figure 4.12) but the system did not accumulate a reserve to use during days when the solar output- and the quantity of water pumped- is lower. The pressures are similar as with the DGPS and the lowest and highest pressures are at PC2 (14 m) and PC5 (38 m), respectively.

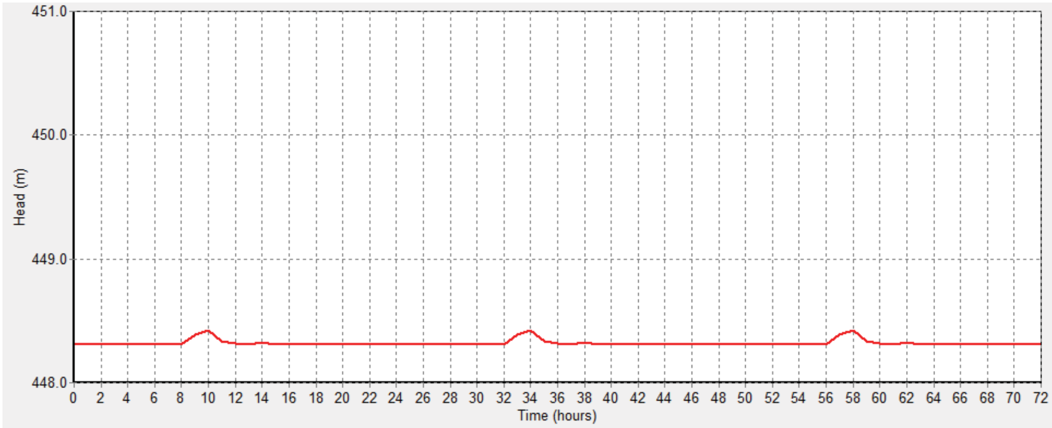

Figure 4.11 Head levels in the storage tank under sunny day conditions for the PVPS and a demand of 28.5 m³/day. The tank is empty when the head is 448.3 m and full when the head is 451.3 m. After 10:30 am, the tank is emptied and any water that is pumped into the tank is runs directly into the distribution line. Negative pressures exist at least every 20 minutes between 10:30 am and 6 pm, when the tank is completely emptied.

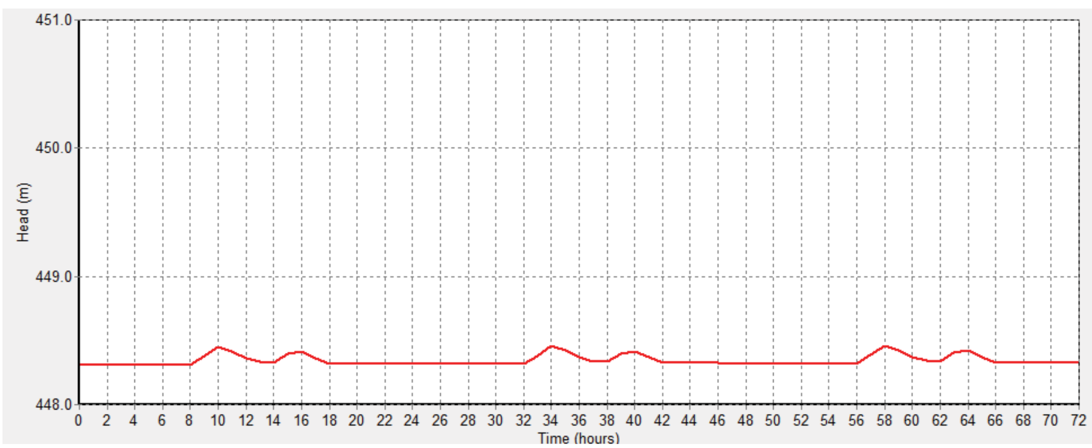

Figure 4.12 Head levels in the storage tank under sunny day conditions for the PVPS and a demand of 14.3 m³/day. Here, the demand is met and no negative pressure are observed but there also is not any reserve accumulated.

Under the partly sunny conditions and a demand of 14.3 m³/day, the demand cannot be met (Figure 4.13). Water is available throughout most of the day after 10 am, however, at 10:30 am the tank is drained momentarily and negative pressures exist at the taps. This occurs five more times before the tank is completely drained at 5:50 pm. A total volume of 11.3 m³ of water is pumped to the tank over the course of the day, so this is the maximum

demand that can be met. Under the cloudy conditions the system cannot meet the demand of 14.3 m^3/day under any demand pattern. Using the same demand pattern as for the sunny and partly sunny conditions, water is unavailable until 10am, and then the tank is emptied by 10:34 pm. Between 10:15 am and 3:00 pm, water is available momentarily but then the tank is drained and negative pressures exist at the taps nearly every 20 minutes. By 3:00 pm the tank is empty and remains so until the following morning (Figure 4.14). Over the course of one day only 6.7 m^3 of water is pumped to the tank under these conditions, so it is not possible to meet a higher demand.

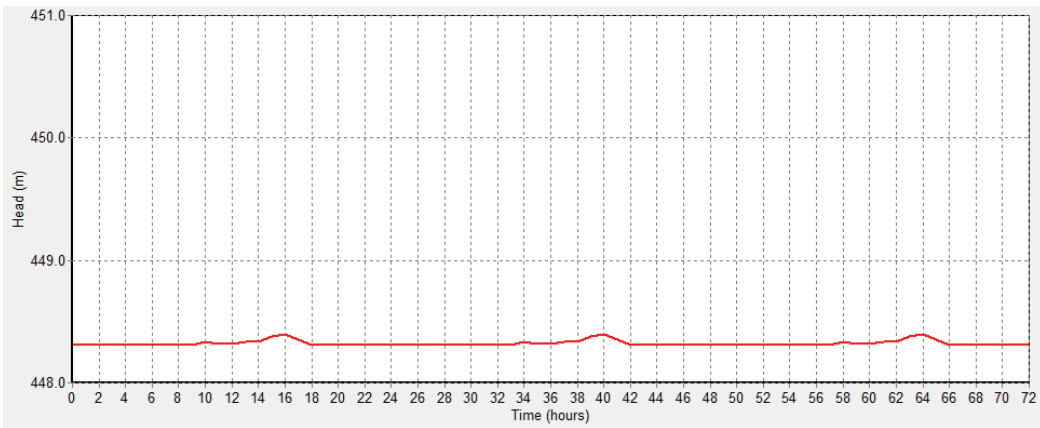

Figure 4.13 Head levels in the storage tank under partly sunny conditions and a demand of 14.3 m^3/day. The demand is not met and the tank is emptied at 10:30 am and negative pressures exist repeatedly throughout the day. The tank is completely emptied again before 6 pm.

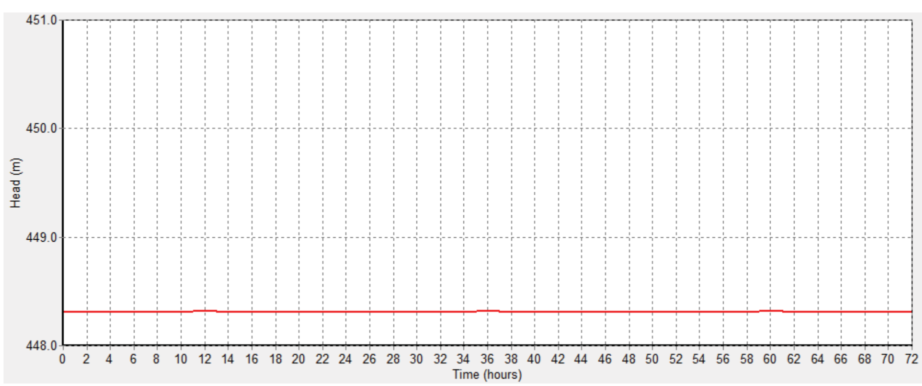

Figure 4.14 Head levels in the storage tank under cloudy day conditions and a demand of 14.3 m^3/day. Here the system cannot meet the demand and negative pressures exist throughout the day. At total of only 6.7 m^3 was pumped to the tank.

It is clear that the current PVPS is not able to meet the water demands of the community. Under sunny and partly sunny conditions, it is capable of providing half of the desired demand. Yet it is not reasonable to ask community members to reduce their demand when a daily demand of 28.5 m^3 only corresponds to 18.2 L/person, which is below the WHO recommended level of 20L/ person/day for *basic* access to water (WHO 2003). Thus, in order to meet the demand, it is necessary to increase the amount of water pumped into the system. This could be accomplished two ways, either by increasing the amount of water that can be pumped under the current head of the water storage tank, or by reducing the head the pump needs to overcome, thus increasing the flow. If a DC solar pump is to be used, the former option cannot be accomplished by pump replacement since no solar pumps were found that can operate at higher flow rates for head values ranging from 40 m to 70 m. However, it may be possible to use an AC pump with a higher head capacity and an inverter to convert the DC solar output to AC power. In this case a larger array of solar panels would be necessary in order to meet the larger power requirements commonly associated with the motors in AC pumps. Also, a second pump could be installed in parallel to double the flow rate to the tank. A second power supply would also be needed under this scenario. This would increase the capital cost and the drawdown effects caused by the two pumps would need to be investigated, but it could be an option.

Another option for increasing the reliability of the system is to reduce the total head that the pump must overcome. To do this, the main line could be connected directly to the distribution line, allowing the water to flow from the pump directly to the lower elevation connections instead of to the higher elevation storage tank. This was modeled using EPANET for the same sunny, partly sunny and cloudy conditions used previously. The demand pattern, however, had to be modified so that demand only occurs when the pumps are operating since there will be little or no water stored in the tank. The relative demand multipliers were also slightly altered so that there are no negative

pressures throughout the pumping period (Appendix D). This is reasonable because the residents will adjust the quantity of water they collect and at what times they do so in accordance with when water is available. Under the sunny day conditions, the pump is not able to provide the desired demand determined from the household assessments (0.022 LPS), but it is able to provide a greater demand than when water is pumped only to the storage tank. In order to ensure that no negative pressures occur, a demand of 0.019 LPS was assigned to public taps BF1-BF8 and BF10, as well as PC1 and PC3-5. Due to the higher elevations at BF9 and PC2, the demand at these two points had to be lowered to 0.014 LPS and 0.004 LPS, respectively, and the demand patterns altered slightly (Appendix D). For example, when the power output is 0.2 kW, the pump cannot overcome the head at PC2, and so the demand at 8 am and 4 pm was set to zero. These changes allowed for positive pressures at these two points at all operational hours. A flow of 0.004 LPS equates to 345 liters per day, which is more than the 200 L this household reports using on a typical day. The total supply provided under this scenario is 22.9 m^3/day, which is significantly higher than the 14.4 m^3/day provided using the model of the existing design. While a greater demand is met, there is no excess water flow to the tank and therefore no storage reserves. Furthermore, the pressures at the demand nodes are not as high as under the DGPS. Low pressures exist at both PC2 (<1 m) and BF9 (1-2 m), while the rest of the demand nodes have pressures between 5 m and 23 m.

Under the partly sunny conditions, the total supply provided drops to 18.3 m^3/day. In order to maintain positive pressures at all the access points during pumping, the demand was reduced to 0.015 LPS at each demand node except BF9 and PC2. Due to the higher elevations at BF9 and PC2, the demands at these points were reduced to 0.014 LPS and 0.003 LPS, respectively. The demand multipliers were also altered slightly so as to maintain positive pressures (Appendix D). Under these conditions, low pressures exist at PC2 (<1 m), but all the other connections have pressures of greater than 5 m.

Under the cloudy scenario, the system is capable of meeting a total demand of 11.9 m^3. In order to avoid negative pressures, the demands at PC2, BF9 and the other access points were reduced to 0.003 LPS, 0.005 LPS and 0.01 LPS, respectively. The demand patterns also needed to be adjusted slightly in order to ensure positive pressures. PC2 has a demand from 10 am,to,3 pm, and the rest of the system has a demand from 9,am to 4,pm. Under these conditions, low pressures exist at PC2 (<1 m) and BF9 (2 m – 5 m), but pressures are above 5 m at all the other connections. Tables presenting the pressures at each node under the various scenarios presented here are available in Appendix F: Pressures at Demand Nodes

This analysis shows that the reliability of the system is greater on a daily basis when water is pumped directly into the system versus when it is pumped only to a storage tank. However, when the solar output is weak such as on cloudy days, the pumps are still not capable of providing the community's desired demand. Another thing to note is that this model assumes a continuous demand. In reality, users will turn the taps off and on, and thus the demand will not be continuous. When water is pumped directly into the distribution line and there are no taps open, the water will rise into the storage tank to be distributed later.

Table 4.2 Summary of the total demand met by the modeled water distribution system when water is pumped into the storage tank and directly into the distribution line.

	Pumping into storage tank				Pumping into distribution line		
Solar conditions	Sunny	Partly sunny	Cloudy		Sunny	Partly sunny	Cloudy
Max. demand (m3)	14.4	11.3	6.7		22.9	18.3	11.9

4.2.2 Appropriate Technology: Diesel-generator versus solar powered pumps

There is a large push for using solar powered pumping in water systems, and substantial evidence from field tests and models showing its success for irrigation systems, livestock use and small-scale WDS (Ghoneim 2006, Meah et al 2008, Ramos and Ramos 2009). But in general these

systems have either a lower total daily demand or lower head to overcome than the WDS presented here. So while many argue that solar pumping is an appropriate technology for these applications, is it equally appropriate for the Solla WDS and how does it compare to the DGPS?

The term 'appropriate technology' has been defined many ways and can take into account social, economic and environmental aspects. In the sustainable international development context, appropriate technologies are often seen as those meeting the following criteria (Dunn 1978):

1. Employ local skills
2. Employ local material resources
3. Employ local financial resources
4. Be compatible with local culture and practices
5. Satisfy local wishes and needs

Thus, in order for a technology to be truly appropriate for a remote village context, it should meet all of the above criteria. In addition, operation and maintenance should employ local skills. This increases the sustainability of the technology because if breakdowns occur or replacements are necessary, the local community can repair the system without waiting for outside support.

While the local technicians in Solla are capable of repairing a wide range of technologies, such as mechanical hand pumps, bicycles, motorcycles and generators, they are not trained in repairing centrifugal submersible pumps. Therefore, the technician for AUSEPA must contact the MWSVH and wait for them to send a technician from the regional capital when the pump breaks down. This also increases the cost of the repair and the time water is unavailable. Since the local capacity to make repairs on more complicated systems (e.g. motorcycles) has increased in recent years, it may be feasible to train local technicians to repair these pumps, and thus employ local skills and meet the first target of appropriate technology. However, this has not been done, and thus both the DGPS and the PVPS of the Solla WDS do not meet this criterion. The local technicians do have some training in diesel generator repair, but not in PV cell repair, making the DGPS slightly more appropriate

under criteria one. Also, none of the parts used in either the DGPS or the PVPS are manufactured in Togo and so they must be ordered from foreign manufacturers, thus not meeting the second criterion of appropriate technology.

To investigate if the PVPS and DGPS can meet the third criterion of employing local financial resources, a life-cycle economic analysis was conducted. Capital costs for the PVPS and DGPS were assumed to be 6850 USD and 2450 USD, respectively (Meah et al 2008). Maintenance costs for the diesel generator can be assumed to be 10% of the capital cost annually (Ghoneim 2006) and it was assumed that the solar panels would not need maintenance until they are replaced at the end of life. The selected Grundfos 8A-10 submersible pump uses a MS4000 pump, which operates at a power of 2.2kW (Grundfos 2015). A 2.5kW diesel engine provided the energy for this pump, and according to AUSEPA's, technician this engine consumes roughly 1L of fuel per hour of operation. In August 2012 the price of diesel in Solla was 1.32 USD/L and, while the price of diesel fluctuates, this value is used to calculate the fuel costs. It was assumed that the diesel engine runs for 3.5 hrs/day. A diesel engine has a lifetime of 5-10 years before it must be replaced (Meah et al 2006), while photovoltaic cells have a life expectancy of over 25 years with little maintenance (Ramos and Ramos 2009). Both the DC solar and AC DG pump will need to be repaired and replaced over this timeframe. A Grundfos SFQ-10 pump costs about 2000 USD. AUSEPA paid 120 USD (60,000 CFA) in repairs to the solar pump during the first year of its installation, and it is assumed that these repairs must be made every three years (Ramos and Ramos 2009). Data for the pump repair and replacement costs for the Grundfos SP 8A were not available, so it was assumed that the costs were equivalent to those in the PVPS (120 USD every 3 years for repairs, 2000 USD for replacement). System maintenance costs such as faucet repair and travel costs for AUSEPA to purchase these items were also included and were assumed equal to the annual costs AUSEPA incurred from 2012-2014. This analysis does not include employee wages or other potential repairs such as pipe replacement. A discount rate of 1% was used on capital costs and other

costs occurring on a non-annual basis. This value assumes that the members of AUSEPA will be able to invest a portion of their revenue into an investment, perhaps a local microfinance, bank or in livestock, that will provide them with 1% interest per year. The annualized costs for these expenditures were then calculated using the following uniform series sinking fund equation:

$$EUAC = C * (A/F\,, i\%, n) = C * \frac{i}{(1+i)^n - 1}$$

where *EUAC* is the equivalent uniform annual cost, *C* is the non-annualized cost, *A* is the annual amount, *P* is the present value, *i* is the discount rate and *n* is the number of years between payments (i.e. 25 years for solar panel replacement). The total EUAC was then calculated and found to be 2458 USD and 535 USD for the DGPS and PVPS, respectively (Table 4.3). These costs are higher than the total annual revenue that AUSEPA accrued between 2012-2014 (340 USD) and thus neither system can fully employ local financial resources under the status quo. Even under a discount rate of 5%, the EUAC of the PVPS still exceeds 340 USD (Table 4.4 Equivalent uniform annual costs for the DGPS and PVPS under various discount rates.

However, Solla has many connections to wealthy and politically powerful individuals, such as the Kagbara family mentioned in Section 2.3. In cultures such as that of the Biyobe, it is expected that wealthier community members will use some of their wealth to help others in the community (Maranz 2001). Thus it may not be unreasonable to expect that the community could garner enough financial resources, from water sales and their greater financial networks, to cover costly replacements. If the community relied on AUSEPA to cover routine O&M costs (such as repairs, travel and fuel, which amount to 102 USD/yr assuming a 1% discount rate) and use its greater financial networks to subsidize the costs of larger capital investments (such as generator, panel and pump replacement), then the PVPS could satisfy this criterion. The high cost of diesel, however, causes the DGPS to fail under this criterion for an appropriate technology even if wealthy community members subsidize capital costs and replacements.

Table 4.3 Non-annualized and annualized O&M costs for the Solla WDS, assuming a 1% discount rate. Worker's wages are not included in this table.

	DGPS	PVPS
Capital cost (USD)	2450	6850
Life-time (yr)	10	25
Discount Rate (%)	1	1
Annualized capital replacement cost (USD/yr)	234	243
Faucet repair (USD/yr)	32	32
Diesel cost (USD/L)	1.32	N/A
Diesel Use (L/hr)	1	N/A
Engine run time (hrs/day)	3.5	N/A
Diesel cost (USD/yr)	1686	0
Generator/panel maintenance (% of capital cost/yr)	10%	0%
Generator/panel maintenance (USD/yr)	245	0
Pump repairs (USD)	120	120
Time frame for pump repair (yr)	3	3
Annualized pump repair cost (USD/yr)	40	40
Pump replacement	2000	2000
Time frame for pump replacement (yr)	10	10
Annualized pump replacement cost (USD/yr)	191	191
Travel costs (USD/yr)	30	30
Routine annual O&M costs excl. capital costs and replacements (USD/yr)	2033	102
Total Equivalent Uniform Annual Cost EUAC (USD/yr)	2458	535

Table 4.4 Equivalent uniform annual costs for the DGPS and PVPS under various discount rates.

	0.50%	1%	2%	5%
EUAC for the DGPS (USD/yr)	2468	2458	2439	2385
EUAC for the PVPS (USD/yr)	555	535	498	403

As for the fourth and fifth criteria, compatibility with local practices and satisfying local needs, it can be argued that the DGPS is more appropriate than the PVPS. For instance, the time of day when community members prefer to gather water is in the early morning and at dusk. The DGPS is

compatible with this practice but the PVPS is not. Also, the community wishes to have water available throughout the day and year, yet their water demands are higher than the current PVPS can provide.

An additional criterion for appropriate technology, and one often used when analyzing projects in the industrialized world, is the environmental sustainability. A DGPS clearly requires burning diesel fuel. The combustion of diesel fuel emits 733 gCO_2/kWh (EIA 2015) and thus contributes to rising CO_2 levels in the atmosphere. Using a DGPS in the Solla WDS contributes 2.3 metric tons of CO_2 to the atmosphere every year, in addition to fumes and particulate matter that contribute to local air pollution. A PVPS, however, does not emit any carbon dioxide, particulate matter or fumes during use. A PV powered WDS is also a silent system and does not contribute noise pollution like one run on a DG. There are certainly emissions associated with the energy used in the production of the PV cells. However, the payback period for this energy use is only 1-4 years depending on the type of PV cell, meaning that within 4 years the emissions offset by using PV versus conventional fuels will exceed the emissions from the production of the panels (NREL 2004). From this information, it is determined that the PVPS is the more appropriate technology under environmental considerations.

To summarize, neither the DGPS nor the PVPS can be classified as a completely appropriate technology for Solla, and comparing the two systems is not clear-cut. While the PVPS performs better under economic and environmental criteria, it also employs fewer local skills and does not fully satisfy the community's water needs or comply with preferred practices for water collection. These factors could change if members of AUSEPA are trained on centrifugal pump and PV cell repair and if the daily flow was increased to meet the demands. While this would require substantial work, it is possible and the PVPS could become an appropriate technology for Solla.

4.3 Management Challenges and Post-Construction Support

Regardless of the appropriateness of the PVPS, it is currently in place and under the management of AUSEPA. Aside from the physical challenges

that the nascent water distribution system is encountering, AUSEPA also faces several managerial challenges. For instance, they are unable to recuperate all payments for water use at both the public and private connections. In addition, there are errors in their bookkeeping, including in the records from the water gages at the public taps that lead to gross miscalculations of the total water use and amounts owed by private households and members of the general public who use the tap stands. While AUSEPA was provided some training in bookkeeping and small repairs prior to being left in charge of the Solla WDS, this training did not fully prepare them for the task they were about to undertake. The MWSVH also provides some post-construction support (PCS), in the form of reviewing the quarterly reports provided by AUSEPA and visiting the village on occasion. Representatives from the MWSVH visit Solla on at least a biannual basis in an attempt to gage the functionality of the system and provide PCS if needed. In this section, the managerial challenges faced by AUSEPA, the PCS provided by the MWSVH, and potential improvements are investigated.

4.3.1 Financial Struggles

As described in Section 4.1.1, users of the public tap stands are expected to pay 20 CFA (0.04 USD) for one 40 L basin or 25 CFA (0.05 USD) for two 25 L jerry cans or buckets. This equates to 500 CFA (1 USD) per m^3. Users of private connections are responsible for paying their water bills, also at 500 CFA (1 USD) per m^3. Over the course of the first two years of AUSEPA's management of the Solla WDS, the technician took monthly readings of the gages at each connection, which he recorded in his logbook. However, the author reviewed the logbook, compared it with readings the author took, and determined there was error in these readings. For example, on May 15th, 2014 the technician reported the meter readings at two connections (BF1 and BF2) as 74 m^3 and 50 m^3. However, on April 29th, 2014 the author recorded the readings at BF1 and BF2 as 691.0 m^3 and 480.6 m^3, respectively, suggesting that the technician misreported the readings by a factor of ten. The funds collector also passes by each tap, roughly on a monthly basis, and collects

what each tap stand manager (TSM) received during the month's water sales. She also visits the private connections to collect payment for the month's water use. Each time she visits the water access points, she records the amount collected in her log.

In order to evaluate the effectiveness of AUSEPA's revenue collection, the total amount that should have been collected at each tap based on the corrected gage readings and the amount actually collected as shown in the fund collector's log were compared from November 2012 through July 2014. While AUSEPA was technically in charge of the system starting in August 2012, they do not have records of funds collected from water sales until November of that year. The difference owed for each public and private access point is shown in Figure 4.15. The total amount owed was nearly 2,000,000 CFA ($4000). This discrepancy can be partly explained by the Technician's error in recording the gage readings, but this does not account for why the TSMs are not collecting funds roughly equal to the number of basins that are actually taken from their taps. Funds collected from each tap represent only about 12% of the total bill. The percentage paid is higher at some of the taps than others, but none have paid more than 30% (Table 4.5).

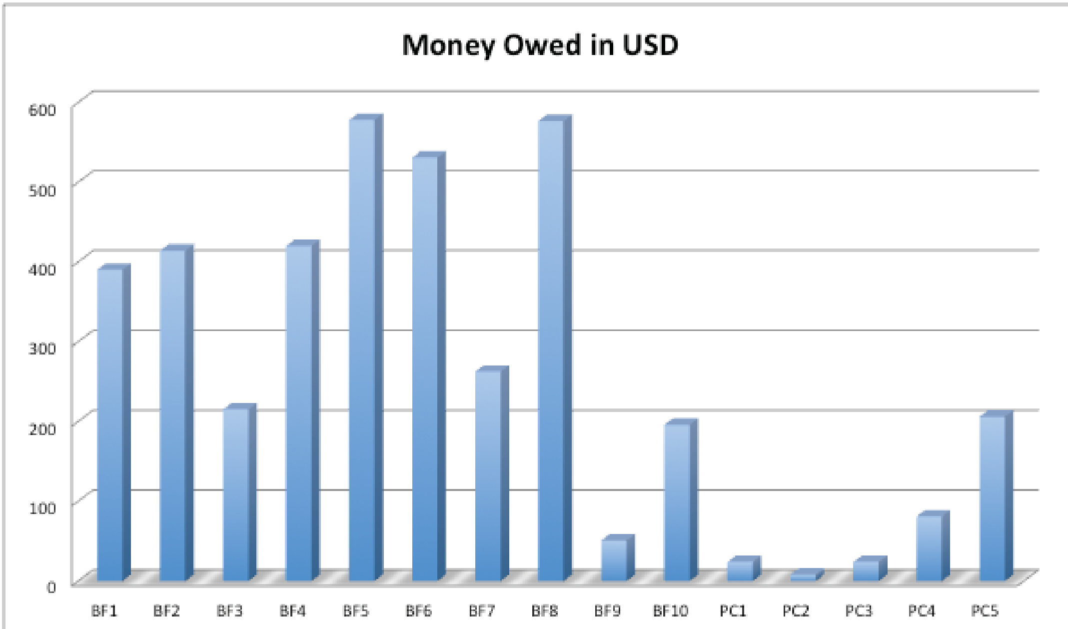

Figure 4.15 Total amount owed at each WDS access point as of July 2014 based on differences between the corrected gage readings and the amount collected as recorded in the fund collector's log. BF1-10 are the public taps and PC1-5 are the private connections. This graph shows BF9 as owing relatively little because the gage at this tap stand was broken.

Table 4.5 Percentage of the total water bill for each public (BF1-10) and private (PC1-5) connection that had been paid as of July 2014. This information for BF9 is unavailable because the water meter was broken and thus water use data was unavailable

BF1	BF2	BF3	BF4	BF5	BF6	BF7	BF8	BF9	BF10
15%	6%	10%	2%	20%	12%	12%	10%	N/A	2%
PC1	PC2	PC3	PC4	PC5		Total			
0%	27%	4%	24%	16%		12%			

Information gathered from the key informant interviews reveals some reasons why the total amount due was not collected for the public tap stands. First, most of the TSMs and members of AUSEPA reported not paying for water. Since they receive no payment for their work, they see access to free water as a perk. This is not officially sanctioned, and some of the TSMs and AUSEPA members reported paying, even though the records do not show

deposits for the amounts of water they claim using. Others were comfortable admitting that they do not pay. As one of the members of AUSEPA expressed, “I used to pay, but now I don’t. I fetch water and I don’t pay. Because… they don’t give us anything and I can’t even get water to drink? That’s why I don’t pay.”

There is also the problem of water theft. One of the public taps does not have a lock and the TSM reported that people sometimes come and get water when she is not there and they do not pay. One tap stand manager reported that the lock had been broken multiple times and people stole water. Another manager reported, “Sometimes people steal water and don’t tell me that they got an extra basin or two when I was in the house and not watching them.” The managers of 7 of the 10 tap stands reported that this is an issue. Two of the public taps, the one at the primary school (BF10) and the one at the hospital (BF4), are managed differently from the others. The school director and head nurse are in charge of paying the water bill for the school and hospital, respectively. Ideally the technician will write them a bill stating their monthly water use and the amount owed. Since the technician has been reporting these values incorrectly, the amount that these institutions paid was less than the amount owed. Additionally, while the technician was motivated to write the monthly water bills in the early months of the project, by June 2013 he had largely stopped. Attempts were made in June and July 2014 to reinstate the monthly water bill process.

The lack of monthly water bills also leads many of the private connection owners to neglect paying for water. In July 2014, one private connection owner reported that he had not received a water bill for over a year and that he had to seek out the technician himself to find out how much he owed. This also frustrates the funds collector, yet she noted other difficulties as well. For instance, even when a water bill has been delivered to the private connections, some do not pay when she passes to collect the funds. Either the households report that the homeowner is not home and they will not cover the bill in his place, or they report not having the money.

The members of AUSEPA express frustrations over the private connections not paying their bills, but they do not seem generally worried about the public connections. It is likely that this is largely due to the fact that they assume less water is being used, and therefore less is owed, because of the technician's error. Also, since they have enough money to cover the costs of small repairs, such as broken faucets, and they no longer need to routinely pay for diesel or generator repairs, they appear to be less worried about finances than they reported being when the pump was powered by the generator. But the current financial situation does not guarantee financial sustainability over the long-term. As shown in Section 4.2.2, small repairs and routine O&M for the pump will be covered, but AUSEPA will likely need to find external financial support for major investments such as pipe and solar panel replacement.

System revenues could be increased substantially, which could allow AUSEPA to independently cover the costs of these repairs or even expand the system to reach other areas near Solla that do not have access to improved water supplies. This is not outside of the realm of possibility for Solla. The Regional Director for MWSVH explained that in two other semi-urban villages with populations similar to Solla, the WDS are functioning well and the water committees have "millions of CFA in their accounts." The difference that the Director pointed out between the Solla WDS and these more financially successful ones lies in the management structure.

4.3.2 Managerial Challenges

AUSEPA faces many managerial challenges, and all of the committee members express difficulties with some aspect of their work. First, they do not receive any payment for their work and this frustrates them, especially the technician and the funds collector who work regularly to make repairs and collect payments. As the technician exclaimed, "[For] the work that I do per month, they don't pay [me]! It is my own willingness. I pay for the fuel in my motorcycle myself to go and examine the taps and make repairs… [Also] there are people that say since I write the bills that I'm taking the money. I hope

that the population helps me so that this is fixed, that they agree to pay me at least for the gas in my motorcycle." As a result of these frustrations, they seem less motivated to find solutions to the problems they face, which is partly highlighted by the technician ceasing to write monthly water bills. The funds collector expressed that both revenue collection and system reliability are inadequate, and this worries her. While she mentioned that the members of AUSEPA had learned a lot and greatly progressed in their work, she also saw that the management and the reliability of the system are not great. She said that if only the MWSVH could send a more experienced technician to identify why the system is not providing enough water and help them to encourage payment for water services, then she, and the Regional Director of MWSVH, would view their work as respectable.

4.3.3 Post-Construction Support and Planned Interventions

The MWSVH recognizes that the challenges described in Sections 4.3.1 and 4.3.2 exist, and this is encouraging for the long-term sustainability of the Solla WDS. The members of AUSEPA are conducting most of the O&M and they only turn to outside help, such as the MWSVH, when they find that their resources, either human or financial, are insufficient. For example, in April 2013 and again in January 2014, AUSEPA independently traveled to a neighboring market town, purchased new faucets and replaced the broken faucets at some of the public taps. Yet some repairs are beyond their capacity. From 2012-2014, the MWSVH responded to calls from AUSEPA reporting system breakdowns on at least three occasions. Once the problem was with a leaking pipe, and twice there were issues with the solar-powered pump. All three times the repairs were made and the system was functioning within about one week. AUSEPA's technician observed the more skilled technicians brought in by the MWSVH and learned to repair leaking pipes, a task that he can now manage, reducing their dependence on outside resources.

The MWSVH also recognizes that AUSEPA could not be left completely on their own in the financial management of the WDS. As the Regional Director explained, "There aren't the skills needed locally for the

management. But we are trying to give them the skills and separate the roles in AUSEPA and train each member." Before they were put in charge of the system, the members of AUSEPA attended a weeklong training where they learned their individual roles, as well as some basics on water and sanitation. However, a single training can only be so effective when the participants lack a solid foundation. The MWSVH recognizes this and provides continued managerial support through additional post-construction trainings and periodic reviews of AUSEPA's reports.

Between 2012 and 2014, Solla received both solicited PCS, indicating AUSEPA's dedication to seeking out the skills necessary to maintain the system, and unsolicited PCS, indicating the MWSVH's oversight. It has been argued that villages that receive solicited technical PCS are more likely to report dissatisfaction with their water systems, likely because it indicates that there are system breakdowns or management problems that the local water committee has not received enough training to fix independently. In contrast, villages that receive unsolicited PCS, especially in the form of further management and/or technical trainings, are more likely to be satisfied and have functioning systems (Whittington et al 2009). The MWSVH has provided AUSEPA with one non-technical training post-construction. They also hope to make another change to the organization of AUSEPA and other village water committees that may improve the management of the systems.

The MWSVH is in the process of developing a new management structure for water committees such as AUSEPA. They have noticed that in many of these small, rural WDS, the local water committees lack the basic foundations to successfully conduct billing and manage the collected funds for planned maintenance and major repairs. To remedy this, MWSVH plans to hire an accountant/manager who will help the village water committees organize their accounts and ensure payments. This person would work for multiple village water committees, perhaps three or four, in the vicinity of a larger town, perhaps a prefectural capital. As the Regional Director explained, s/he would "sell his or her skills to the people who don't have the skills needed to manage the system." AUSEPA would agree upon a contract with this

accountant/manager to pay him/her a monthly fee for their services. This could potentially increase AUSEPA's revenue and allow them to cover the costs of future major repairs, receive payment for their work, and pay the tap stand managers.

Throughout this section, the factors inhibiting AUSEPA's financial and technical independence have been investigated. While these factors are important to the long-term sustainability of the Solla WDS, it is also important to remember the end goal of potable water systems: to prevent all residents from using unimproved sources that may be hazardous to their health. As described in Section 4.1.2, a high percentage of residents are still using unprotected sources for their drinking and cooking needs despite the fact that improved sources are available. The primary deterrent to using the WDS is cost. Perhaps if the new management plan is implemented and AUSEPA's fee collection rate increases as a result, then they could reanalyze the water use fee and perhaps adjust it to a price that is affordable to everyone.

4.4 Water Pricing

All of the respondents to the community assessments mentioned that the cost for water (0.5 CFA/L) was not ideal. Of the 15 respondents who reported never using the improved sources or only using them for part of the year, 100% stated that the cost of using these systems was prohibitive. Additionally, when the manager of BF6 was asked how many people buy water from her, she relied that only "a couple of the houses near me buy water at my tap everyday, most [households] do so only rarely… they say that 20 CFA for a 50 L basin is too expensive." This is not surprising when the average weekly incomes of the residents are considered. Of those surveyed, 21 were able or willing to report an income. Of the households that reported an income, the average weekly incomes of residents in the low-, middle- and high-income groups were 8,000 CFA ($16), 16,000 CFA ($38) and 40,000 CFA ($80), respectively. The average number of people living in a household was seven. Assuming that each resident uses 20 L of water from their drinking

and cooking needs, each household would need an average of 140 L from the improved water source per day. At the current rate, this means the households would pay 490 CFA per week for water, which is 6%, 3% and 1% of the weekly income for the low-, middle- and high-income groups, respectively. For the poorest households in the survey, paying 490CFA per week for water would take a staggering one third of their weekly income. Furthermore, since Solla is an agricultural community and most residents rely on the sale of their excess harvested goods to obtain cash, this income is seasonal and unreliable. Thus residents are hesitant to spend their limited financial resources on water if other options are available. Even members of the high-income group and those who could afford private connections in Solla lamented over the cost of water. One of the private connection holders was astounded to find that the cost per m^3 in Solla was twice what he paid for water at his house in the regional capital.

In contrast, the median household in the United States pays 1.1% of their income on combined water and wastewater services (EPA 2009). Additionally, unlike Togolese households, American households do not have the additional labor and time cost of transporting this water; the water is delivered directly and reliably to their homes. So what would happen if the residents of Solla were only asked to pay 1% of their income for water? If a 40 L basin of water were priced at 5 CFA (125 CFA per m^3), then the lowest income group would be paying roughly 1.5% of their weekly income on potable water. During the survey, seven households who did not use water from the tap year round mentioned that they would be willing to pay for water at the public tap throughout the year if the price was reduced to 10 CFA per 40 L basin, and they would certainly be more inclined to pay if the price were reduced to 5 CFA.

If AUSEPA had collected the money for all of the water used from the WDS between August 2012 and August 2014 at a rate of 125 CFA/m^3 (0.25 USD/m^3), they would have collected $600 annually. This would be enough to cover the routine O&M costs (~100 USD), but not the total annualized costs (~850 USD) described in Section 4.2.2. If water were priced at 10 CFA per 40

L basin (250 CFA or 0.5 USD per m^3), AUSEPA would have collected over \$1200 annually and the total EUAC could be covered. Thus, AUSEPA could cover all the planned O&M costs and have some reserves for other possible repairs if they charged 10 CFA per basin and received all the money from water use. However, this does not account for the workers' wages that AUSEPA and the MWSVH hope to implement. To investigate how paying utilities workers would affect costs, two different payment plans were analyzed (Table 4.7). Plan 1 is a lower wage plan where TSMs, AUSEPA members and the accountant receive \$1, \$4, and \$10 per month, respectively. However, these wages are considered low in the local context and would likely not be accepted, particularly by the accountant who will likely need to travel 20 km to Solla from the prefectural capital. Under Plan 2, TSMs, AUSEPA members, and the account receive \$2, \$10, and \$20 per month, respectively. Based on the author's experience in this community, this plan would likely be acceptable in the local context. By comparing Table 4.6 and Table 4.7, the lowest possible water prices were determined for different payment schemes. It was found that if AUSEPA covers the total EUAC and pays its workers under Plan 2, then the price of water could be lowered to 15 CFA. However, if AUSEPA pays its workers under Plan 1 and/or only covers routine O&M costs, then the price of water could be as low as 0.3 USD/m^3 or 6 CFA per 40 L basin (Table 4.8). However, denominations of 1 CFA are rarely used in Togo, thus the most reasonable prices would be 10 CFA or 15 CFA per basin if AUSEPA decides to lower to price of water.

Table 4.6 Estimated annual revenues in USD for different water pricing schemes. Actual annual revenue collected from 2012-2014 was 340 USD.

Cost per m3 (USD)	Cost per 40L basin (CFA)	Estimated annual revenue (USD)
0.25	5	600
0.3	6	750
0.4	8	1000
0.5	10	1200
0.6	12	1450
0.7	14	1690
0.75	15	1810
0.8	16	1930
0.9	18	2170
1	20	2410

Table 4.7 Two payment plans for TSM, AUSEPA and accountant wages, and the total annual costs when wages are included.

	Plan 1	Plan 2
Salary for Tap Stand Managers (USD/mo for 10 managers)	1	2
Salary for AUSEPA members (USD/mo for 6 workers)	4	10
Salary for Accountant (USD/mo)	10	20
Annual cost for wages	528	1200
Total Annual Cost incl. routine O&M costs from Table 4.3	630	1302
Total Annual Cost incl. total EUAC from Table 4.3	1063	1735

Table 4.8 Lowest possible water prices under different payment schemes

Payments AUSEPA covers	Lowest Possible Cost of Water per m3 (USD)	Lowest Possible Cost of Water per 40L basin (CFA)
Routine O&M and Plan 1	0.3	6
Routine O&M and Plan 2	0.6	12
Total EUAC and Plan 1	0.5	10
Total EUAC and Plan 2	0.75	15

To summarize, if AUSEPA installs a higher payment plan for the utility workers, hires an accountant, and covers all annualized costs for the system, they could still lower the price of water per basin assuming they recuperate all revenue and find a way to invest some of this money. If they use a lower payment plan or cover only routine O&M, thus relying on their greater financial networks to cover replacement costs, then the price of water could be lowered substantially. This may make these potable water services accessible to a greater percentage of the population. Additionally, AUSEPA could keep the price the same and use the greater revenue anticipated by the accountant's work, and contributions from their greater financial network, to expand the system. This could access a greater market for water sales and increase AUSEPA's annual revenue, while also bringing the health benefits of potable water to a greater population. It is important to note, however, that if any of the assumptions made to calculate the costs were changed- for example if it were assumed that the PV cells have a lifetime of 30 years or if the price of PV panels and/or pumps drops- then the cost assessments made here would change and it might be feasible for AUSEPA to lower the price of water further or accumulate greater financial resources to expand the system.

4.5 Future Work

There are several limitations of this study that could be addressed in future work. The drawdown levels, for example, were assumed using a linear equation when, in reality, the relationship between flow and drawdown has both a linear and quadratic component. Thus, it is recommended that a step-drawdown test be conducted on the well to develop a more accurate relationship between flow rate and drawdown. The solar power outputs at various times of the day were also estimates, particularly for the sunny and cloudy day conditions, for which measured values were not available. Gathering more data on the power outputs for this system at various times of the day, and the corresponding flow rates, would enhance the study. It would also be beneficial to collect flow rate data at the tank discharge. It would also

be interesting to investigate the feasibility of using solar tracking systems or concentration devices, such as mirrors, to increase the solar power output and thus the total volume of water pumped.

The social component of this study could be enhanced by surveying a greater portion of the population and conducting a survey that is not biased by the responses of the water committee members. A willingness-to-pay assessment could also prove useful to discover what rate residents who do not currently use the system would be willing to pay for the potable water services. Expanding this study to include other village water distribution systems that were installed by the MWSVH could also provide some insights, particularly into the usefulness of the post-construction support they provide. It is recommended that these aspects be included in any similar studies conducted in the future so that the broader development community can better understand the status of community-managed water distribution systems, particularly those with a solar photovoltaic power supply.

5 Conclusions

It has long been argued that improving access to potable water is an important step in the fight against poverty, both for its health benefits and for the time saved when residents do not need to travel far to access water. This is why increasing access to potable water is Objective 7a of the ambitious Millennium Development Goals, which aim to see a world without poverty. Globally, objective 7a was met before 2015, and the World Health Organization estimated that from 1990-2012, 2.3 billion people gained access to improved drinking water.

It is likely that the entire population in Solla is represented in this statistic, since they gained access to potable water through the Solla WDS that was installed in 2011. However, despite this increased access, 45% of the population in Solla still depends on unimproved sources for their drinking and cooking needs when these sources are available. This is not a unique situation; for example Whittington et al. 2009 reports that 38% of households in a study they conducted in Ghana were still using unimproved sources for drinking and cooking even though improved sources were available. There is great inequality in Solla and similar communities in terms of who is financially capable of utilizing these potable water systems. In poor, rural communities, it is common for a large fraction of the population to be low-income farmers who have minimal access to cash. As shown in this case study, these low-income populations are less likely to use potable water systems that may cost up to 30% of their weekly income. These low-income groups are thus excluded from the benefits that potable water can provide. It is unlikely that the public health benefits of access to improved water sources will be fully realized until all residents of communities like Solla use only improved water sources for drinking and cooking.

Furthermore, in order for this goal to be maintained, the long-term sustainability of the systems providing this potable water must be assured. Community management, demand-driven projects and post-construction support are argued to be some of the most important factors in ensuring long-

term sustainability of potable water systems. However, these aspects of potable water systems are not without their challenges. In Solla the community management and post-construction support systems are keeping the WDS operational for the time being, but they are not as successful, economically nor technically, as they could be. The change from a diesel-generator powered pumping system to one run on solar photovoltaic power has decreased the reliability of the system. This has caused many residents to worry about their water access since the WDS is no longer capable of providing the village's water needs on a daily basis, particularly during the dry season when water from other sources is the scarcest. Changes in the design of the solar photovoltaic-powered system, such as pumping water directly into the system or using an AC pump with a higher head range and an inverter may help to remedy this problem. An advantage to this new system is that the members of AUSEPA are more financially successful since they no longer need to pay for diesel fuel. This will allow for greater financial resources to keep the system functional, and the long lifetime of photovoltaic cells is promising for the long-term functionality of the Solla WDS.

The members of AUSEPA are not receiving all the fees from water use in Solla. Part of this is due to their inadequate training in management strategies such as billing and bookkeeping. The Ministry of Water, Sanitation and Village Hydraulics hopes to put in place a new management structure in which a trained accountant/manager would work for AUSEPA and the water committees for neighboring systems. This shows promise to help AUSEPA increase their revenue and the long-term financial sustainability of the Solla WDS. By ensuring fee collection and increasing revenue, AUSEPA members may also be able to gain a salary and pay the tap stand managers for their work. This would increase the motivation of these utility workers, which could also increase the functionality of the management system. It is also possible that better financial management would allow AUSEPA to lower the price of water, giving lower income members of the population a chance to access the potable water resources. If these managerial and physical challenges of the nascent water distribution system in Solla are addressed, it is possible to

provide the entire population with clean, potable water, thus giving them access to better health, one of the foundations that may help alleviate their poverty.

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Appendix A: Household Survey

1. General

1.1. Family name

1.2. Number of people currently living in household	
1.3. Age and sex of people currently living in household	
1.4. Description of the house/location	
1.5. Education level of mother(s)	
1.6. Education level of father	
1.7. Professions of family members	
1.8. Estimated Household Income	

2. Available Water Supply

	Hand-dug well	Hand pump	Public Tap	Private tap	River	Dam
2.1. What types of water sources are available to you?						
2.2. What are the distances to these sources from your house?						
2.3. How do you perceive the quality of this water? 1=not drinkable, 2=undesirable, 3=satisfactory, 4=good, 5=excellent						
2.4. If you listed 1 or 2 above, what factors make this water source undesirable?						
2.5. For what purposes do you use the different water sources?						
2.6. How many basins do you gather from each source per day?						
2.7. Are all sources available throughout the year?						
2.8. Are there other nearby sources that are not available to you? (I.e. a private connection, private wells, locked fountains)						

Water Distribution System

2.9. Public Taps

2.9.1. Do you use water from the public taps? If yes or no, please describe why.
2.9.2. Have you been able to consistently use the public taps since their installation in 2012?
2.9.3. How much do you pay to use the public taps?
2.9.4. Do you find this rate reasonable? Why or why not?
2.9.5. Would you be willing to pay more if needed to pay for repairs?
2.9.6. Please describe any problems you have found with the public taps

3.2 Private connections

2.9.7. If you have a private connection, what was your monthly usage from the time of installation (March 2013) to present?
2.9.8. Do you allow community members from outside your household to use water from your tap? If yes, who?
2.9.9. Do you limit the quantity of water taken from your tap?
2.9.10. Do non-household members pay to use your tap? Why or why not? If yes, how much?
2.9.11. Please describe any problems you have found with your private connection

Appendix B: Key-Informant Interview Questions

AUSEPA and Tap Stand Managers Interview Questions

In addition to the household assessment listed in Appendix A, members of AUSEPA and the TSMs were posed in following questions in a semi-formal unstructured interview.

1. Are you a member of the village water committee? What is your role?
2. How are funds collected from the private taps?
3. Have you encountered any difficulties with the private connections? Is yes, please describe
4. How are funds collected from the public taps?
5. Have you encountered any difficulties with the public connections? Is yes, please describe
6. Do you collect money for one of the public taps?
7. How do you provide community members with water from the taps and collect funds?
8. Who manages the funds collected from both the private and public taps?
9. For what purposes are these funds used?
10. To date has there been a need to repair any part of the water distribution system? If yes, what part? Who repaired the part and at what cost? How were the costs covered for the parts and labor?
11. Please describe the plan of action to cover the costs for future repairs
12. Do you have any other comments regarding the management of the water distribution system in Solla?

Regional Director of the Ministry of Water, Sanitation, and Village Hydraulics (MWSVH) Interview Questions

ROLES AND RESPONSIBILITIES OF MEMBERS

1. Can you speak a bit about the work of the MWSVH?
2. What is your role with this department? What are your responsibilities?
3. What is the role of M. Karabou (the extension agent who conducts PCS for Solla)? What are his responsibilities?
4. In the construction of Solla's potable water system, what were the roles of the following parties :
    a. MWSVH
    b. CINTECH
    c. CENTRO-AGIRE
    d. The Islamic Development Bank
    e. AUSEPA
    f. The general community that received the water system

Can you speak a bit about the associations CINTECH, CENTRO-AGIRE and BID?

5. Can you speak a bit about the associations CINTECH, CENTRO-AGIRE and BID?
6. What do you think in general about the management of a water supply system? What are the things that make a project well managed and what factors inhibit good management?
7. Do you have other things to add to this topic?

CHOSING SITES FOR WATER DISTRIBUTION SYSTEMS IN TOGO

1. How are sites chosen to receive water distribution systems with the MWSVH?
2. What type of studies are done before the installation of a water distribution system?
3. Are all of the water distribution systems built with an office, a storefront and a bathroom? Why?
4. What type of monitoring do you do after the installation of a water distribution system?
5. Do you build water distribution systems with both solar and electric generator power supplies?
6. What do you think about using solar panels verses electric generators? What are the advantages and disadvantages that you see for these two power sources in water distribution systems?
7. Do you have other things to add on this topic?

THE SOLLA WATER DISTRIBUTION SYSTEM

1. When were the first preliminary studies started in Solla? How did they go?
2. When was the installation of the water distribution system started? Were there any difficulties or things that worked well?
3. When did the construction end?
4. How much did the project cost, from planning to completion?
5. Since the project has been realized, how do you find the maintenance and management of the system on the part of the community?
6. During the operation of the water distribution system in Solla, have there been any major repairs? If so, what were they?
7. Last summer, why was the electric generator replaced by solar panels?
8. When the electric generator was replaced by solar panels, were there other changes made to the system? If so, what were they?
9. This year, during February, March and April, water only flowed from the access points at midday. In the morning there wasn't any water in the storage tank, at noon there was between 5 and 10 m^3, and by the evening it was empty. The population and the technician say that it is because the solar panels do not pump water well. What do you think about this?

Appendix C: Pump Curves

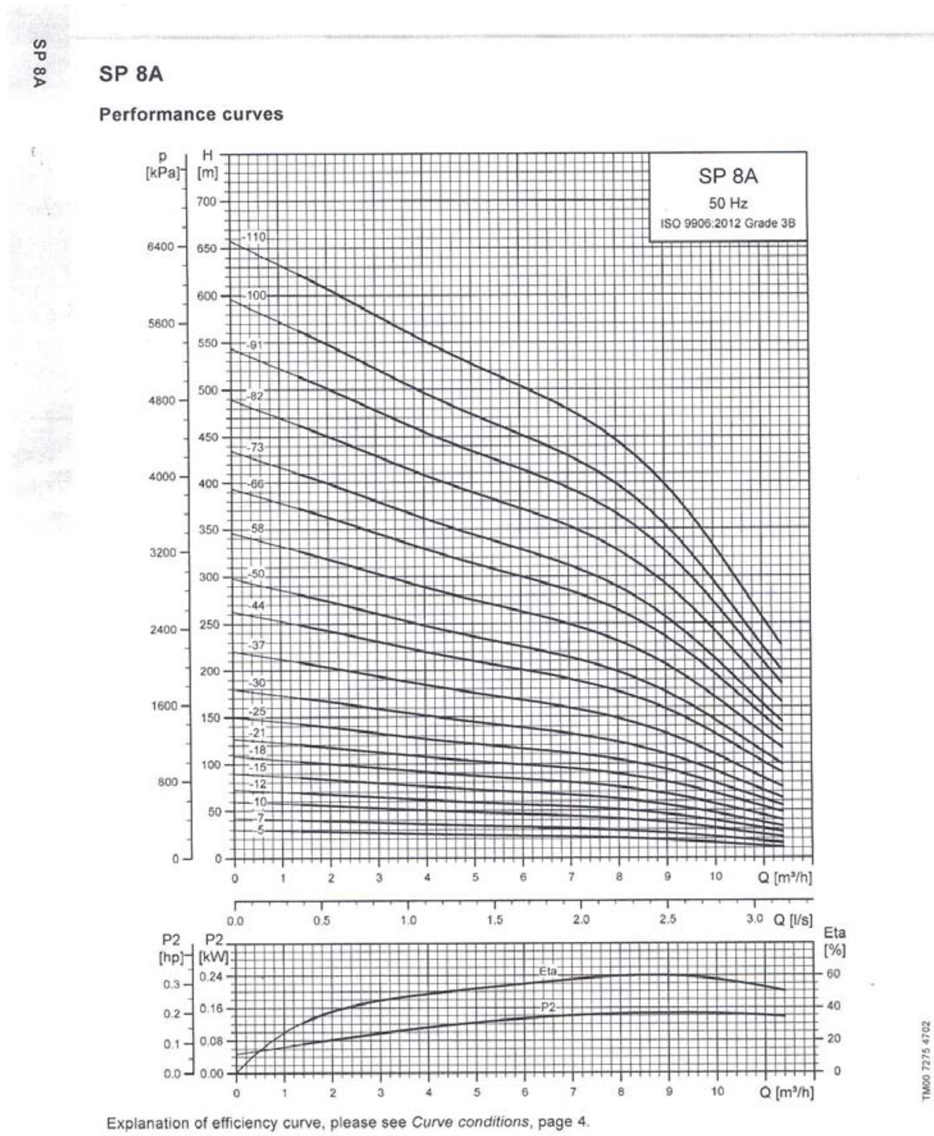


Figure C.0.1 Pump performance curve for the Grundfos SP 8A submersible pump. Refer to line -25 to see the curve used in this analysis.

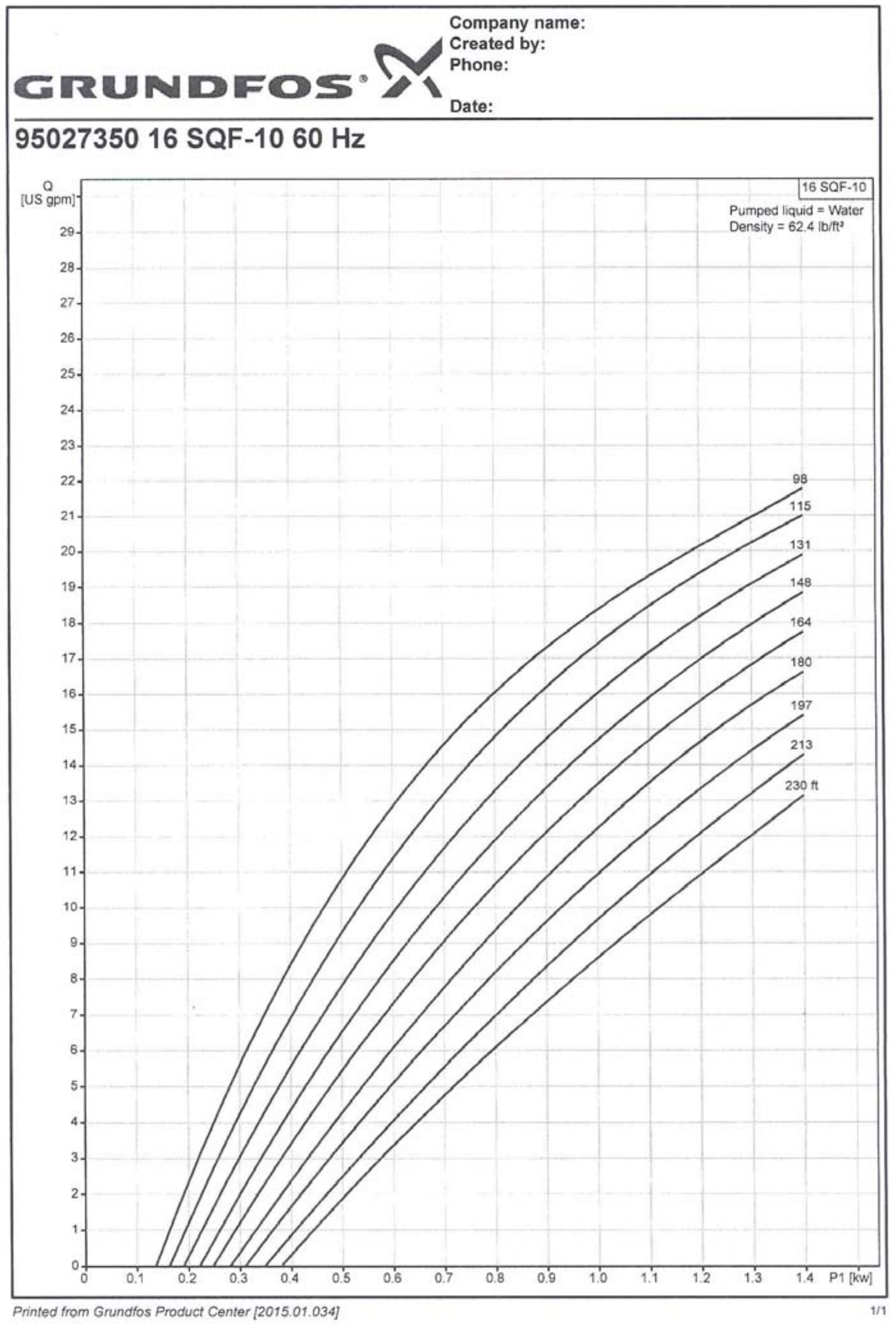
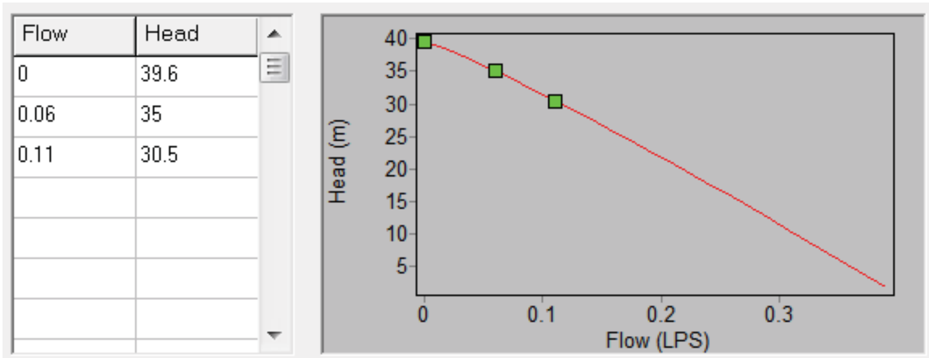
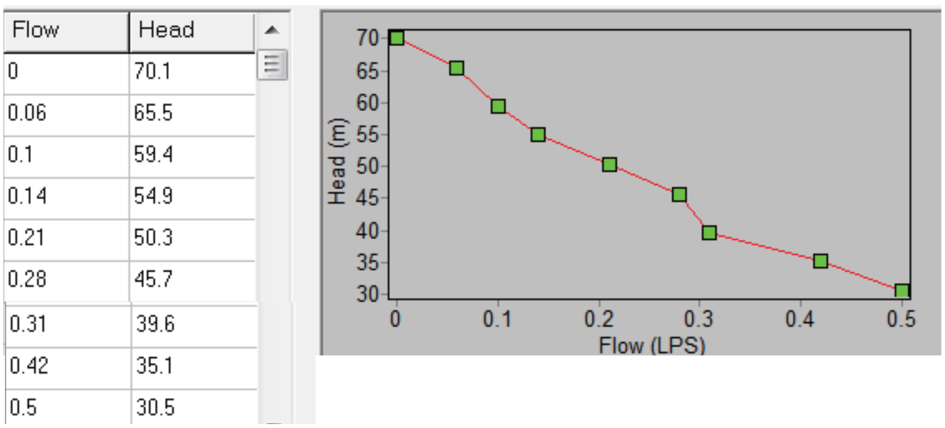


Figure C.0.2 Pump performance curve for the Grundfos 16 SQF-10 submersible pump. The different lines refer to different head values.



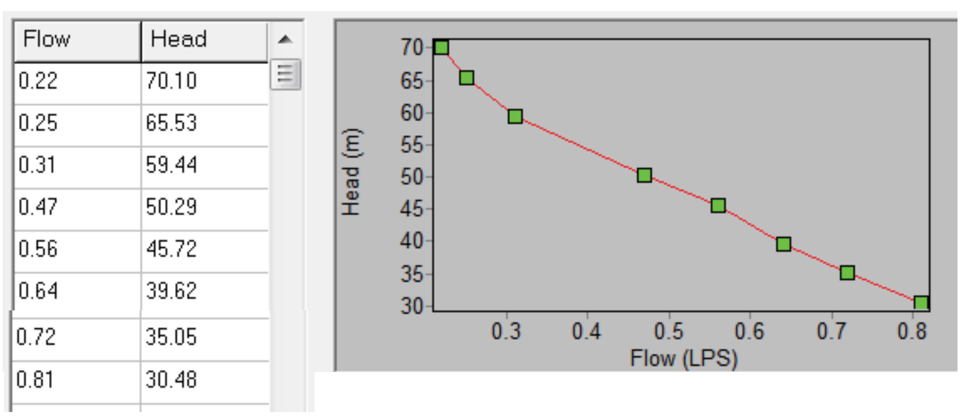
Flow	Head
0	39.6
0.06	35
0.11	30.5

Figure C.0.3 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 0.2 kW.



Flow	Head
0	70.1
0.06	65.5
0.1	59.4
0.14	54.9
0.21	50.3
0.28	45.7
0.31	39.6
0.42	35.1
0.5	30.5

Figure C.4 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 0.4 kW.



Flow	Head
0.22	70.10
0.25	65.53
0.31	59.44
0.47	50.29
0.56	45.72
0.64	39.62
0.72	35.05
0.81	30.48

Figure C.5 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 0.6 kW.

Flow	Head
0.31	70.1
0.33	65.5
0.42	59.4
0.5	54.9
0.58	50.3
0.67	45.7
0.72	39.6
0.83	35.1
0.92	30.5

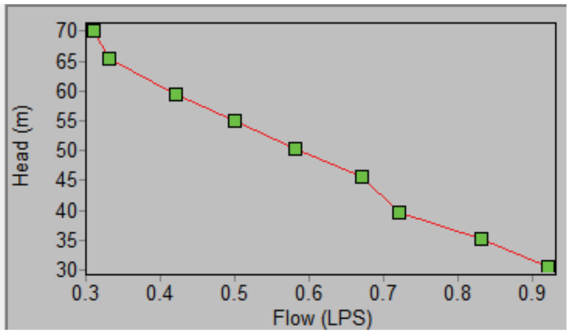


Figure C.6 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 0.7 kW.

Flow	Head
0.39	70.1
0.44	65.5
0.53	59.4
0.61	54.9
0.67	50.3
0.75	45.7
0.83	39.6
0.92	35.1
1	30.5

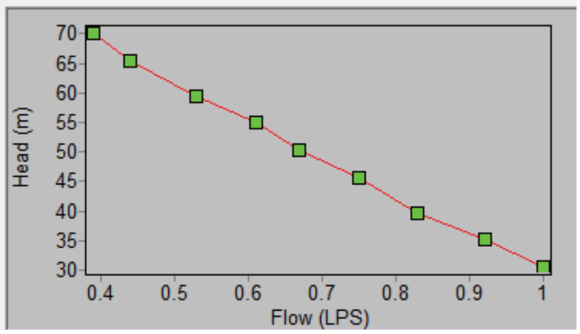


Figure C.7 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 0.8 kW.

Flow	Head
0.44	70.1
0.53	65.5
0.61	59.4
0.67	54.9
0.75	50.3
0.83	45.7
0.92	39.6
0.99	35.1
1.08	30.5

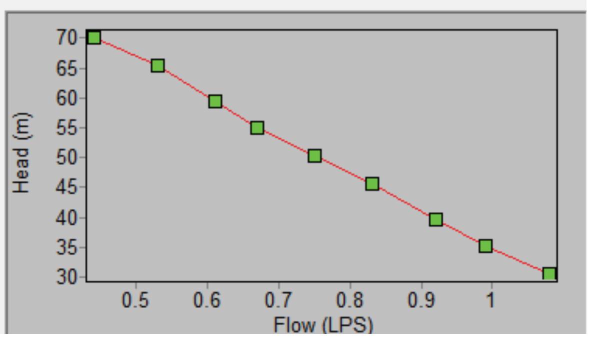


Figure C.8 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 0.9 kW.

Flow	Head
0.56	70.1
0.61	65.5
0.69	59.4
0.78	54.9
0.86	50.3
0.92	45.7
1	39.6
1.11	35.1
1.17	30.1

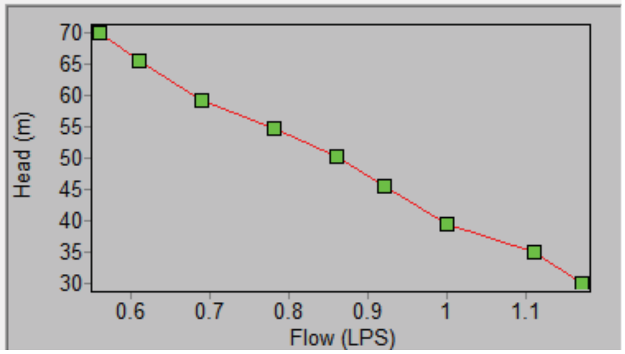


Figure C.9 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 1.0 kW.

Flow	Head
0.69	70.1
0.75	65.5
0.83	59.4
0.92	54.9
1	50.3
1.08	45.7
1.17	39.6
1.22	35.1
1.25	30.5

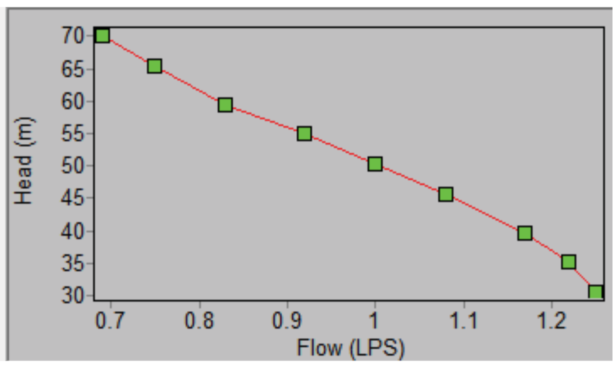


Figure C.10 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 1.2 kW.

Flow	Head
0.83	70.1
0.92	65.5
0.97	59.4
1.03	54.9
1.11	50.3
1.19	45.7
1.25	39.6
1.31	35.1
1.36	30.5

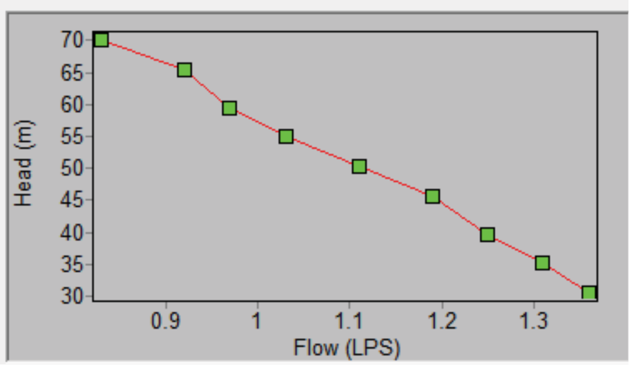


Figure C.11 Interpolated pump curve, relating head and flow, for the 16 SQF-10 at 1.4 kW.

Appendix D: Demand Patterns

Demand pattern for BF1-8, BF10, PC1, PC3-5 under sunny conditions and a demand of 0.019 LPS										
Hour of simulation	8	9	10	11	12	13	14	15	16	17
Demand multiplier	0.5	1.8	2.5	3	3.5	3.8	3.6	3.1	1.7	0.5

Demand pattern for BF9 under sunny conditions and a demand of 0.014 LPS										
Hour of simulation	8	9	10	11	12	13	14	15	16	17
Demand multiplier	0	1.2	3.2	3.3	3.3	4.3	2.9	3.1	2	0.6

Demand pattern for PC2 under sunny conditions and a demand of 0.004LPS										
Hour of simulation	8	9	10	11	12	13	14	15	16	17
Demand multiplier	0	0	3.1	4.3	3.4	4.6	3.1	3	2.4	0

Demand pattern for BF1-BF10 and PC1, PC3-PC5 under partly sunny conditions and a demand of 0.015LPS										
Hour of simulation	8	9	10	11	12	13	14	15	16	17
Demand multiplier	0	0.6	2.2	3.4	3.8	4.1	3.8	3.3	2.1	0.6

Demand pattern for PC2 under partly sunny conditions and a demand of 0.003LPS										
Hour of simulation	8	9	10	11	12	13	14	15	16	17
Demand multiplier	0	0	0	3.3	4.5	4.5	4	5.8	1.9	0

Demand pattern for BF1-BF10 and PC1, PC3-PC5 under cloudy conditions and a demand of 0.01 LPS										
Hour of simulation	8	9	10	11	12	13	14	15	16	17
Demand multiplier	0	0	1	3.2	5	5.5	3.2	1	0	0

Demand pattern for PC2 under cloudy conditions and a demand of 0.003 LPS										
Hour of simulation	8	9	10	11	12	13	14	15	16	17
Demand multiplier	0	0	0	4.3	3.4	9.3	3.4	3.7	0	0

Appendix E: EPANET Data Files

EPANET information for the DGPS and 28.5m³ demand

[TITLE]

[JUNCTIONS]

;ID	Elev	Demand	Pattern	
1	424.24	0.022	1	;
2	412.81	0	;	
5	412.17	0	;	
3	413.5	0	;	
4	417.56	0.022	1	;
6	413.12	0.022	1	;
18	423.92	0	;	
21	425.15	0	;	
23	425.49	0	;	
24	426.2	0	;	
25	427.34	0.022	1	;
27	426.92	0	;	
31	430.32	0	;	
32	432.47	0.022	1	;
28	428.71	0	;	
16	416.79	0	;	
17	414.58	0.022	1	;
19	422.49	0.022	1	;
12	416.11	0	;	
7	406.89	0	;	
13	415.69	0	;	
14	415.88	0.022	1	;
35	416.11	0	;	
9	411.17	0.022	1	;
11	413.61	0.022	1	;
30	434.34	0.022	1	;
26	428.55	0.022	1	;
15	416.97	0.022	1	;
20	420.31	0.022	1	;
8	410.87	0	;	
10	413.61	0	;	
22	425.11	0.022	1	;
41	433.71	0	;	
29	433.71	0	;	
34	417.58	0	;	
36	423.92	0	;	
40	428.91	0	;	
38	425.49	0	;	
39	426.92	0	;	
33	333.18	0	;	
37	425.15	0	;	

[RESERVOIRS]

;ID	Head	Pattern
100	354.35	;

[TANKS]

;ID	Elevation	InitLevel	MinLevel	MaxLevel	Diameter	MinVol	VolCurve
90	448.31	0	0	2.7	4	0	;

[PIPES]

;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status	
1	1	2	116	57	150	0	Open	;
2	2	3	300	57	150	0	Open	;
3	3	4	104	57	150	0	Open	;
4	2	5	31	57	150	0	Open	;
5	6	5	21	57	150	0	Open	;
20	18	21	150	57	150	0	Open	;
22	21	23	70	57	150	0	Open	;
23	23	24	28	57	150	0	Open	;
24	25	24	138	57	150	0	Open	;
26	23	27	59	57	150	0	Open	;
31	27	31	156	57	150	0	Open	;
32	31	32	5	57	150	0	Open	;
27	27	28	183	81.4	150	0	Open	;
16	17	16	260	57	150	0	Open	;
18	19	18	112	57	150	0	Open	;
17	18	16	239	57	150	0	Open	;
15	16	12	21	57	150	0	Open	;
6	7	5	268	57	150	0	Open	;
12	12	13	167	57	150	0	Open	;
13	13	14	87	57	150	0	Open	;
14	14	15	30	57	150	0	Open	;
30	28	30	40	57	150	0	Open	;
19	19	20	35	57	150	0	Open	;
7	7	8	135	57	150	0	Open	;
9	8	10	48	57	150	0	Open	;
11	10	12	115	57	150	0	Open	;
8	8	9	10	57	150	0	Open	;
10	10	11	10	57	150	0	Open	;
25	25	26	23	57	150	0	Open	;
21	21	22	5	57	150	0	Open	;
28	28	29	20	81.4	150	0	Open	;
41	41	90	17.6	76	150	0	Open	;
29	29	90	14	76	150	0	Open	;
34	34	35	75	81.4	150	0	Open	;
35	35	36	239	81.4	150	0	Open	;
40	40	41	20	81.4	150	0	Open	;
38	38	39	59	81.4	150	0	Open	;
39	39	40	80	81.4	150	0	Open	;
33	33	34	84.4	81.4	150	0	Open	;
36	36	37	150	81.4	150	0	Open	;
37	37	38	70	81.4	150	0	Open	;

[PUMPS]

;ID	Node1	Node2	Parameters
60	100	33	HEAD 1 ;

[VALVES]

;ID Node1 Node2 Diameter Type Setting
MinorLoss

[TAGS]

[DEMANDS]

;Junction Demand Pattern Category

[STATUS]

;ID Status/Setting

[PATTERNS]
;ID Multipliers
;diesel generator water demand

1	0	0	0	0	0	1
1	4	3	2	1	1	1
1	1	1	1	1	3	3
1	1	0	0	0	0	0

;Solar power water demand

2	0	0	0	0	0	0
2	0	0	1	3	4	5
2	5	3	2	1	0	0
2	0	0	0	0	0	0

[CURVES]
;ID X-Value Y-Value
;PUMP: SP 8A diesel

1	0	150
1	0.28	145
1	0.56	140
1	0.83	133
1	1.11	128
1	1.39	120
1	1.67	116
1	1.94	110
1	2.22	105
1	2.5	95
1	2.78	80
1	3.06	60

;PUMP: solar pump (16 SQF-10) 0.2kW

2	0	39.6
2	0.06	35
2	0.11	30.5

;PUMP: solar pump (16 SQF-10) 0.3kW

3	0	54.9
3	0.05	50.3
3	0.11	45.7
3	0.19	39.6
3	0.25	35
3	0.36	30.5

;PUMP: Solar pump (16 SQF-10) 0.6kw

4	0.22	70.10
4	0.25	65.53
4	0.31	59.44
4	0.47	50.29
4	0.56	45.72
4	0.64	39.62
4	0.72	35.05
4	0.81	30.48

;PUMP: Solar pump (16 SQF-10) 0.7kW

5	0.31	70.1
5	0.33	65.5
5	0.42	59.4
5	0.5	54.9
5	0.58	50.3
5	0.67	45.7
5	0.72	39.6
5	0.83	35.1
5	0.92	30.5

;PUMP: solar pump (16 SQF-10) 0.8kW

6	0.39	70.1
6	0.44	65.5
6	0.53	59.4
6	0.61	54.9

```
 6                      0.67      50.3
 6                      0.75      45.7
 6                      0.83      39.6
 6                      0.92      35.1
 6                      1         30.5
;PUMP: solar pump (16 SQF-10)1kW
 7                      0.56      70.1
 7                      0.61      65.5
 7                      0.69      59.4
 7                      0.78      54.9
 7                      0.86      50.3
 7                      0.92      45.7
 7                      1         39.6
 7                      1.11      35.1
 7                      1.17      30.1
;PUMP: Solar pump (16 SQF-10) 1.2kW
 8                      0.69      70.1
 8                      0.75      65.5
 8                      0.83      59.4
 8                      0.92      54.9
 8                      1         50.3
 8                      1.08      45.7
 8                      1.17      39.6
 8                      1.22      35.1
 8                      1.25      30.5
;PUMP: solar pumpu (16 SQF-10) 1.4kW
 9                      0.83      70.1
 9                      0.92      65.5
 9                      0.97      59.4
 9                      1.03      54.9
 9                      1.11      50.3
 9                      1.19      45.7
 9                      1.25      39.6
 9                      1.31      35.1
 9                      1.36      30.5

[CONTROLS]
LINK 60 CLOSED AT TIME 0
LINK 60 OPEN AT CLOCKTIME 5 PM
LINK 60 CLOSED AT CLOCKTIME 8:30 PM

[RULES]

[ENERGY]
 Global Efficiency            75
 Global Price           0
 Demand Charge                0

[EMITTERS]
;Junction               Coefficient

[QUALITY]
;Node                   InitQual

[SOURCES]
;Node                   Type                    Quality                 Pattern

[REACTIONS]
;Type     Pipe/Tank           Coefficient


[REACTIONS]
 Order Bulk                   1
```

Order Tank 1
Order Wall 1
Global Bulk 0
Global Wall 0
Limiting Potential 0
Roughness Correlation 0

[MIXING]
;Tank Model

[TIMES]
Duration 72
Hydraulic Timestep 1:00
Quality Timestep 0:05
Pattern Timestep 1:00
Pattern Start 0:00
Report Timestep 1:00
Report Start 0:00
Start ClockTime 12 am
Statistic None

[REPORT]
Status No
Summary No
Page 0

[OPTIONS]
Units LPS
Headloss H-W
Specific Gravity 1
Viscosity 1
Trials 1000
Accuracy 0.01
CHECKFREQ 2
MAXCHECK 10
DAMPLIMIT 0
Unbalanced Continue 10
Pattern 1
Demand Multiplier 1.0
Emitter Exponent 0.5
Quality None mg/L
Diffusivity 1
Tolerance 0.01

[COORDINATES]

;Node	X-Coord	Y-Coord
1	166.67	9726.19
2	452.38	9047.62
5	529.76	8785.71
3	1464.29	9333.33
4	1333.33	9607.14
6	59.52	8630.95
18	2380.95	5452.38
21	2309.52	4380.95
23	2488.10	3904.76
24	2083.33	3773.81
25	1678.57	2476.19
27	2630.95	3107.14
31	3107.14	2011.90
32	3738.10	2261.90
28	3416.67	3464.29
16	1833.33	6357.14
17	1226.19	6214.29

19	1821.43	5380.95
12	1726.19	6595.24
7	791.67	7940.48
13	2142.86	6702.38
14	2583.33	6940.48
35	1916.67	6476.19
9	1476.19	7392.86
11	1595.24	7261.90
30	3738.10	2892.86
26	1619.05	2178.57
15	2428.57	7178.57
20	1619.05	5523.81
8	1250.00	7261.90
10	1357.14	7095.24
22	2130.95	4333.33
41	3297.62	3809.52
29	3404.76	3857.14
34	2190.48	6559.52
36	2619.05	5476.19
40	3297.62	3595.24
38	2678.82	3969.14
39	2904.76	3416.67
33	2750.00	6702.38
37	2566.62	4431.98
100	3750.00	6916.67
90	3285.71	4023.81

[VERTICES]

;Link	X-Coord	Y-Coord

[LABELS]

;X-Coord	Y-Coord	Label & Anchor Node

[BACKDROP]

DIMENSIONS	0.00	0.00	10000.00	10000.00
UNITS	None			
FILE				
OFFSET	0.00	0.00		

[END]

PVPS under sunny conditions and a 28.5 m^3 demand

(Only information that differs from the DGPS is included)

[RESERVOIRS]

;ID	Head	Pattern
100	403.6	;
42	403.6	;
43	403.6	;
44	403.6	;
45	408	;
46	408	;
47	403.6	;
48	403.6	;

[CONTROLS]
LINK 50 CLOSED AT TIME 0
LINK 51 CLOSED AT TIME 0
LINK 52 CLOSED AT TIME 0
LINK 53 CLOSED AT TIME 0
LINK 54 CLOSED AT TIME 0
LINK 55 CLOSED AT TIME 0
LINK 56 CLOSED AT TIME 0

LINK 57 CLOSED AT TIME 0
LINK 50 OPEN AT CLOCKTIME 7 AM
LINK 50 CLOSED AT CLOCKTIME 8 AM
LINK 51 OPEN AT CLOCKTIME 8 AM
LINK 51 CLOSED AT CLOCKTIME 9 AM
LINK 52 OPEN AT CLOCKTIME 9 AM
LINK 52 CLOSED AT CLOCKTIME 10 AM
LINK 54 OPEN AT CLOCKTIME 10 AM
LINK 54 CLOSED AT CLOCKTIME 11 AM
LINK 56 OPEN AT CLOCKTIME 11 AM
LINK 56 CLOSED AT CLOCKTIME 12 PM
LINK 57 OPEN AT CLOCKTIME 12 PM
LINK 57 CLOSED AT CLOCKTIME 1 PM
LINK 56 OPEN AT CLOCKTIME 1 PM
LINK 56 CLOSED AT CLOCKTIME 2 PM
LINK 54 OPEN AT CLOCKTIME 2 PM
LINK 54 CLOSED AT CLOCKTIME 3 PM
LINK 51 OPEN AT CLOCKTIME 3 PM
LINK 51 CLOSED AT CLOCKTIME 4 PM
LINK 50 OPEN AT CLOCKTIME 4 PM
LINK 50 CLOSED AT CLOCKTIME 5 PM

PVPS under sunny conditions and a 14.3 m^3 demand

(Only information that differs from the PVPS under sunny conditions and 28.5 m3 demand is included)

[JUNCTIONS]

;ID	Elev	Demand	Pattern	
1	424.24	0.011	2	;
2	412.81	0	;	
5	412.17	0	;	
3	413.5	0	;	
4	417.56	0.011	2	;
6	413.12	0.011	2	;
18	423.92	0	;	
21	425.15	0	;	
23	425.49	0	;	
24	426.2	0	;	
25	427.34	0.011	2	;
27	426.92	0	;	
31	430.32	0	;	
32	432.47	0.011	2	;
28	428.71	0	;	
16	416.79	0	;	
17	414.58	0.011	2	;
19	422.49	0.011	2	;
12	416.11	0	;	
7	406.89	0	;	
13	415.69	0	;	
14	415.88	0.011	2	;
35	416.11	0	;	
9	411.17	0.011	2	;
11	413.61	0.011	2	;
30	434.34	0.011	2	;
26	428.55	0.011	2	;
15	416.97	0.011	2	;
20	420.31	0.011	2	;
8	410.87	0	;	
10	413.61	0	;	
22	425.11	0.011	2	;
41	433.71	0	;	
29	433.71	0	;	
34	417.58	0	;	

36	423.92	0	;
40	428.91	0	;
38	425.49	0	;
39	426.92	0	;
33	333.18	0	;
37	425.15	0	;

PVPS under partly sunny conditions and a 14.3 m³ demand

(Only information that differs from the PVPS under sunny conditions and a 14.3 m³ demand is included)

[CONTROLS]
LINK 50 CLOSED AT TIME 0
LINK 51 CLOSED AT TIME 0
LINK 52 CLOSED AT TIME 0
LINK 53 CLOSED AT TIME 0
LINK 54 CLOSED AT TIME 0
LINK 55 CLOSED AT TIME 0
LINK 56 CLOSED AT TIME 0
LINK 57 CLOSED AT TIME 0
LINK 50 OPEN AT CLOCKTIME 8 AM
LINK 50 CLOSED AT CLOCKTIME 9 AM
LINK 51 OPEN AT CLOCKTIME 9 AM
LINK 51 CLOSED AT CLOCKTIME 10 AM
LINK 53 OPEN AT CLOCKTIME 10 AM
LINK 53 CLOSED AT CLOCKTIME 11 AM
LINK 54 OPEN AT CLOCKTIME 11 AM
LINK 54 CLOSED AT CLOCKTIME 12 PM
LINK 55 OPEN AT CLOCKTIME 12 PM
LINK 55 CLOSED AT CLOCKTIME 1 PM
LINK 54 OPEN AT CLOCKTIME 1 PM
LINK 54 CLOSED AT CLOCKTIME 2 PM
LINK 53 OPEN AT CLOCKTIME 2 PM
LINK 53 CLOSED AT CLOCKTIME 3 PM
LINK 51 OPEN AT CLOCKTIME 3 PM
LINK 51 CLOSED AT CLOCKTIME 4 PM
LINK 50 OPEN AT CLOCKTIME 4 PM
LINK 50 CLOSED AT CLOCKTIME 5 PM

PVPS under cloudy conditions and a 14.3 m³ demand

(Only information that differs from the PVPS under sunny conditions and a 14.3 m³ demand is included)

[CONTROLS]
LINK 50 CLOSED AT TIME 0
LINK 51 CLOSED AT TIME 0
LINK 52 CLOSED AT TIME 0
LINK 53 CLOSED AT TIME 0
LINK 54 CLOSED AT TIME 0
LINK 55 CLOSED AT TIME 0
LINK 56 CLOSED AT TIME 0
LINK 57 CLOSED AT TIME 0
LINK 50 OPEN AT CLOCKTIME 9 AM
LINK 50 CLOSED AT CLOCKTIME 10 AM
LINK 51 OPEN AT CLOCKTIME 10 AM
LINK 51 CLOSED AT CLOCKTIME 11 AM
LINK 52 OPEN AT CLOCKTIME 11 AM
LINK 52 CLOSED AT CLOCKTIME 12 PM
LINK 54 OPEN AT CLOCKTIME 12 PM
LINK 54 CLOSED AT CLOCKTIME 1 PM
LINK 52 OPEN AT CLOCKTIME 1 PM
LINK 52 CLOSED AT CLOCKTIME 2 PM

LINK 51 OPEN AT CLOCKTIME 2 PM
LINK 51 CLOSED AT CLOCKTIME 3 PM
LINK 50 OPEN AT CLOCKTIME 3 PM
LINK 50 CLOSED AT CLOCKTIME 4 PM

PVPS with the new layout under sunny conditions and a 28.5 m^3 demand

(Only information that differs from the PVPS under sunny conditions and a 28.5 m^3 demand is included)

[JUNCTIONS]

;ID	Elev	Demand	Pattern	
1	424.24	0.022	3	;
2	412.81	0	;	
5	412.17	0	;	
3	413.5	0	3	;
4	417.56	0.022	3	;
6	413.12	0.022	3	;
18	423.92	0	;	
21	425.15	0	;	
23	425.49	0	;	
24	426.2	0	;	
25	427.34	0.022	3	;
27	426.92	0	;	
31	430.32	0	3	;
32	432.47	0.022	3	;
28	428.71	0	;	
16	416.79	0	;	
17	414.58	0.022	3	;
19	422.49	0.022	3	;
12	416.11	0	;	
7	406.89	0	;	
13	415.69	0	;	
14	415.88	0.022	3	;
35	416.11	0	;	
9	411.17	0.022	3	;
11	413.61	0.022	3	;
30	434.34	0.015	4	;
26	428.55	0.022	3	;
15	416.97	0.022	3	;
20	420.31	0.022	3	;
8	410.87	0	;	
10	413.61	0	;	
22	425.11	0.022	3	;
29	433.71	0	;	
34	417.58	0	;	
33	333.18	0	;	

[PIPES]

;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status	
1	1	2	116	57	150	0	Open	;
2	2	3	300	57	150	0	Open	;
3	3	4	104	57	150	0	Open	;
4	2	5	31	57	150	0	Open	;
5	6	5	21	57	150	0	Open	;
20	18	21	150	57	150	0	Open	;
22	21	23	70	57	150	0	Open	;
23	23	24	28	57	150	0	Open	;
24	25	24	138	57	150	0	Open	;
26	23	27	59	57	150	0	Open	;
31	27	31	156	57	150	0	Open	;
32	31	32	5	57	150	0	Open	;
27	27	28	183	81.4	150	0	Open	;
16	17	16	260	57	150	0	Open	;
18	19	18	112	57	150	0	Open	;

17	18	16	239	57	150	0	Open	;
15	16	12	21	57	150	0	Open	;
6	7	5	268	57	150	0	Open	;
12	12	13	167	57	150	0	Open	;
13	13	14	87	57	150	0	Open	;
14	14	15	30	57	150	0	Open	;
30	28	30	40	57	150	0	Open	;
19	19	20	35	57	150	0	Open	;
7	7	8	135	57	150	0	Open	;
9	8	10	48	57	150	0	Open	;
11	10	12	115	57	150	0	Open	;
8	8	9	10	57	150	0	Open	;
10	10	11	10	57	150	0	Open	;
25	25	26	23	57	150	0	Open	;
21	21	22	5	57	150	0	Open	;
29	29	90	14	76	150	0	Open	;
34	34	35	75	81.4	150	0	Open	;
33	33	34	84.4	81.4	150	0	Open	;
42	35	12	5	81.4	150	0	Open	;
28	29	28	20	81.4	100	0	Open	;

PVPS with the new layout under partly sunny conditions and a 19.4 m³ demand

(Only information that differs from the PVPS with the new layout under sunny conditions and a 28.5 m³ demand and the original PVPS under partly sunny conditions is included)

[JUNCTIONS]

;ID	Elev	Demand	Pattern	
1	424.24	0.015	3	;
2	412.81	0	;	
5	412.17	0	;	
3	413.5	0	3	;
4	417.56	0.015	3	;
6	413.12	0.015	3	;
18	423.92	0	;	
21	425.15	0	;	
23	425.49	0	;	
24	426.2	0	;	
25	427.34	0.015	3	;
27	426.92	0	;	
31	430.32	0	3	;
32	432.47	0.015	3	;
28	428.71	0	;	
16	416.79	0	;	
17	414.58	0.015	3	;
19	422.49	0.015	3	;
12	416.11	0	;	
7	406.89	0	;	
13	415.69	0	;	
14	415.88	0.015	3	;
35	416.11	0	;	
9	411.17	0.015	3	;
11	413.61	0.015	3	;
30	434.34	0.015	3	;
26	428.55	0.015	3	;
15	416.97	0.015	3	;
20	420.31	0.015	3	;
8	410.87	0	;	
10	413.61	0	;	
22	425.11	0.015	3	;
29	433.71	0	;	
34	417.58	0	;	
33	333.18	0	;	

PVPS with the new layout under cloudy conditions and a 13.3 m³ demand

(Only information that differs from the PVPS with the new layout under sunny conditions and a 28.5 m^3 demand and the original PVPS under cloudy conditions is included)

[JUNCTIONS]

;ID	Elev	Demand	Pattern	
1	424.24	0.011	3	;
2	412.81	0	;	
5	412.17	0	;	
3	413.5	0	3	;
4	417.56	0.011	3	;
6	413.12	0.011	3	;
18	423.92	0	;	
21	425.15	0	;	
23	425.49	0	;	
24	426.2	0	;	
25	427.34	0.011	3	;
27	426.92	0	;	
31	430.32	0	3	;
32	432.47	0.011	3	;
28	428.71	0	;	
16	416.79	0	;	
17	414.58	0.011	3	;
19	422.49	0.011	3	;
12	416.11	0	;	
7	406.89	0	;	
13	415.69	0	;	
14	415.88	0.011	3	;
35	416.11	0	;	
9	411.17	0.011	3	;
11	413.61	0.011	3	;
30	434.34	0.008	4	;
26	428.55	0.011	3	;
15	416.97	0.011	3	;
20	420.31	0.011	3	;
8	410.87	0	;	
10	413.61	0	;	
22	425.11	0.011	3	;
29	433.71	0	;	
34	417.58	0	;	
33	333.18	0	;	

Appendix F: Pressures at Demand Nodes

Table F.1 Pressures at the demand nodes under the DGPS and a demand of 28.5 m^3/day.

	Min. pressure (m)	Time	Max. Pressure (m)	Time
BF1 (Node 1)	23.32	5:00 PM	26.35	9 pm - 5 am
BF2 (Node 4)	29.99	5:00 PM	33.03	9 pm - 5 am
BF3 (Node 6)	34.44	5:00 PM	37.47	9 pm - 5 am
BF4 (Node 17)	33.12	5:00 PM	36.01	9 pm - 5 am
BF5 (node 14)	31.79	5:00 PM	34.71	9 pm - 5 am
BF6 (Node 19)	25.44	5:00 PM	28.1	9 pm - 5 am
BF7 (node 22)	23.05	5:00 PM	25.48	9 pm - 5 am
BF8 (Node 25)	20.93	5:00 PM	23.25	9 pm - 5 am
BF9 (Node 32)	15.95	5:00 PM	18.12	9 pm - 5 am
BF10 (Node 20)	27.62	5:00 PM	30.28	9 pm - 5 am
PC1 (Node 26)	19.72	5:00 PM	22.04	9 pm - 5 am
PC2 (Node 30)	14.17	5:00 PM	16.25	9 pm - 5 am
PC3 (Node 15)	30.7	5:00 PM	33.62	9 pm - 5 am
PC4 (Node 11)	34.03	5:00 PM	36.98	9 pm - 5 am
PC5 (Node 9)	36.46	5:00 PM	39.42	9 pm - 5 am

Table F.2 Maximum and minimum pressures at the demand nodes under the PVPS, sunny conditions, the existing layout and a demand of 14.3 m^3/day.

	Min. pressure (m)	Time	Max. pressure (m)	Time
BF1 (Node 1)	23.43	12:00 PM	24.14	4:00 PM
BF2 (Node 4)	30.11	12:00 PM	30.82	4:00 PM
BF3 (Node 6)	34.55	12:00 PM	35.26	4:00 PM
BF4 (Node 17)	33.19	12:00 PM	33.8	4:00 PM
BF5 (node 14)	31.87	12:00 PM	32.5	4:00 PM
BF6 (Node 19)	25.44	12:00 PM	25.9	4:00 PM
BF7 (node 22)	22.99	12:00 PM	23.29	4:00 PM
BF8 (Node 25)	20.94	12:00 PM	21.06	4:00 PM
BF9 (Node 32)	15.81	12:00 PM	15.94	4:00 PM
BF10 (Node 20)	27.62	12:00 PM	28.08	4:00 PM
PC1 (Node 26)	19.63	12:00 PM	19.85	4:00 PM
PC2 (Node 30)	13.97	12:00 PM	14.07	4:00 PM
PC3 (Node 15)	30.78	12:00 PM	31.41	4:00 PM
PC4 (Node 11)	34.12	12:00 PM	34.77	4:00 PM
PC5 (Node 9)	36.55	12:00 PM	37.21	4:00 PM

Table F.3 Maximum and minimum pressures at the demand nodes under the PVPS with the new system layout under sunny conditions and a demand of 22.9 m^3/day. Note the negative pressures should be interpreted as zero pressure since at night the pump cannot pump and there is no water stored in the tank.

	Min. Pressure (m)	Time	Max. pressure (m)	Time
BF1 (Node 1)	*-110.13*	6:00 PM	10.83	10:00 AM
BF2 (Node 4)	*-103.45*	6:00 PM	17.55	9:00 AM
BF3 (Node 6)	*99.01*	6:00 PM	21.99	9:00 AM
BF4 (Node 17)	*-100.47*	6:00 PM	20.59	9:00 AM
BF5 (node 14)	*-101.77*	6:00 PM	19.29	9:00 AM
BF6 (Node 19)	*-108.38*	6:00 PM	12.6	9:00 AM
BF7 (node 22)	*-111*	6:00 PM	9.96	9:00 AM
BF8 (Node 25)	*-113.23*	6:00 PM	7.71	9:00 AM
BF9 (Node 32)	*-118.36*	6:00 PM	2.59	9:00 AM
BF10 (Node 20)	*-106.2*	6:00 PM	14.78	9:00 AM
PC1 (Node 26)	*-113.23*	6:00 PM	7.71	9:00 AM
PC2 (Node 30)	*-120.23*	6:00 PM	0.72	9:00 AM
PC3 (Node 15)	*-102.86*	6:00 PM	18.2	9:00 AM
PC4 (Node 11)	*-99.5*	6:00 PM	21.54	9:00 AM
PC5 (Node 9)	*-97.06*	6:00 PM	23.98	9:00 AM

Table F.4 Maximum and minimum pressures at the demand nodes under the PVPS with the new system layout under partly sunny conditions and a demand of 18.3 m^3/day. Note the negative pressures should be interpreted as zero pressure since at night the pump cannot pump and there is no water stored in the tank.

	Min. pressure (m)	Time	Max. pressure (m)	Time
BF1 (Node 1)	*-97.64*	5:00 PM	12.38	2:00 PM
BF2 (Node 4)	*-90.96*	5:00 PM	19.05	2:00 PM
BF3 (Node 6)	*-86.52*	5:00 PM	23.5	2:00 PM
BF4 (Node 17)	*-87.98*	5:00 PM	22.1	2:00 PM
BF5 (node 14)	*-89.28*	5:00 PM	20.8	2:00 PM
BF6 (Node 19)	*-95.89*	5:00 PM	14.1	2:00 PM
BF7 (node 22)	*-98.51*	5:00 PM	11.46	2:00 PM
BF8 (Node 25)	*-100.74*	5:00 PM	9.21	2:00 PM
BF9 (Node 32)	*-105.87*	5:00 PM	4.09	2:00 PM
BF10 (Node 20)	*-93.71*	5:00 PM	16.28	2:00 PM
PC1 (Node 26)	*-101.95*	5:00 PM	8	2:00 PM
PC2 (Node 30)	*-107.74*	5:00 PM	2.22	2:00 PM
PC3 (Node 15)	*-90.37*	5:00 PM	19.71	2:00 PM
PC4 (Node 11)	*-87.01*	5:00 PM	23.06	2:00 PM
PC5 (Node 9)	*-84.57*	5:00 PM	25.49	2:00 PM

Table F.5 Maximum and minimum pressures at the demand nodes under the PVPS with the new system layout under cloudy conditions and a demand of 11.9 m³/day. Note the negative pressures should be interpreted as zero pressure since at night the pump cannot pump and there is no water stored in the tank.

	Min. pressure (m)	Time	Max. pressure (m)	Time
BF1 (Node 1)	*-113.36*	6:00 PM	13.44	12:00 PM
BF2 (Node 4)	*-106.68*	6:00 PM	20.11	12:00 PM
BF3 (Node 6)	*-102.24*	6:00 PM	24.56	12:00 PM
BF4 (Node 17)	*-103.7*	6:00 PM	23.17	12:00 PM
BF5 (node 14)	*-105*	6:00 PM	21.87	12:00 PM
BF6 (Node 19)	*-111.61*	6:00 PM	15.16	12:00 PM
BF7 (node 22)	*-114.23*	6:00 PM	12.52	12:00 PM
BF8 (Node 25)	*-116.46*	6:00 PM	10.27	12:00 PM
BF9 (Node 32)	*-121.59*	6:00 PM	5.15	12:00 PM
BF10 (Node 20)	*-109.43*	6:00 PM	17.34	12:00 PM
PC1 (Node 26)	*-117.67*	6:00 PM	9.06	12:00 PM
PC2 (Node 30)	*-123.46*	6:00 PM	3.28	12:00 PM
PC3 (Node 15)	*-106.09*	6:00 PM	20.78	12:00 PM
PC4 (Node 11)	*-102.73*	6:00 PM	24.12	12:00 PM
PC5 (Node 9)	*-100.29*	6:00 PM	26.55	12:00 PM