Master's thesis

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Performance of solar-powered water pumping systems for rural water supply

A case study from Tanzania

Master's thesis in Civil and Environmental Engineering
Supervisor: Sveinung Sægrov
June 2020

Solar-powered water pumping system in Endagaw chini village, Mbulu district

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Abstract

Safe drinking water is crucial for the health and prosperity of human beings. Still, the United Nations (UN) has estimated that two billion people live in countries facing high water-related stress. This thesis evaluates the performance of a number of solar-powered water pumping systems that were installed in Tanzania by the Norwegian Church Aid (NCA) from 2015 to 2019. The main topics investigated are water quantity and quality, hydrogeology, management, and remote monitoring. The purpose is to suggest strategies for improving the performance of existing and future pumping stations.

The results are mostly based on a case study which was conducted in the regions of Manyara and Singida in February 2020. A wide range of methods were employed in the fieldwork, including measurements of borehole hydraulics and water quality parameters, testing of a remote monitoring system, and interviews. In addition, relevant literature and technical documents were analyzed.

Demand and supply estimations show that the pumping stations do not cover the water demand in the dry season, even if the pumps run efficiently for eight hours a day. In addition, the pumps tend to stop in cloudy weather reducing the quantity of water provided and threatening reliability. Current pumping rates appear to be sustainable considering data from the fieldwork and pumping tests carried out before installation. This indicates that the boreholes might have the potential to supply greater water quantities.

Water quality measurements were performed at 14 pumping stations and show that pH, conductivity, alkalinity, and turbidity are mostly within acceptable limits. One pumping station however has a turbidity significantly exceeding the upper limit specified in the Tanzanian drinking water quality standard. Two pumping stations have fluoride concentrations greater than the upper limit in Tanzania, and five have concentrations above the limit of the World Health Organization (WHO) but below the Tanzanian limit.

A number of the management practices employed at the pumping stations, such as having a water committee and a caretaker, are associated with satisfactory pumping system functionality in literature. The project would nonetheless benefit from continued support in the next couple of years to make sure that management practices are fully incorporated. Water fee collections are in most cases insufficient to cover major repairs, and the pumping stations are thus partly dependent on support from the local government. Limited funds for planned maintenance threaten pumping system resilience.

Remote monitoring was tested at three pumping stations and worked satisfactory for the most part as mobile network services supported data transmission with only minor interruptions. In theory, remote monitoring can improve pumping system resilience by providing data that enables service providers to prioritize when and where to perform repairs and maintenance. This thesis however argues that remote monitoring is not easily integrated in current management practices and is consequently thought to be better suited as a tool used by NCA during post-construction support.

The results of the thesis imply that the performance of the pumping stations can be improved by increasing the power supply, for instance by installing batteries, additional solar panels or a diesel-generator. In addition, water should be treated for fluoride at the pumping stations with elevated concentrations to avoid dental and skeletal fluorosis. Fecal contamination of water was not successfully measured in field and should therefore be tested once more to confirm that the water is safe. These are all important topics for future research.

Sammendrag

Trygt drikkevann er avgjørende for menneskers helse og velferd. FN har anslått at to milliarder mennesker lever i land som er utsatt for alvorlige vannrelaterte utfordringer. Denne oppgaven evaluerer ytelsen til en rekke solcellepaneldrevne vannpumpesystemer som ble installert i Tanzania av Kirkens Nødhjelp fra 2015 til 2019. Hovedtemaene som blir undersøkt er vannmengde og -kvalitet, hydrogeologi, styringspraksis og fjernovervåkning. Hensikten er å foreslå strategier for å forbedre ytelsen til eksisterende og framtidige pumpestasjoner.

Resultatene er i stor grad basert på en casestudie som ble gjennomført i regionene Manyara og Singida i februar 2020. Et bredt spekter av metoder ble brukt i feltarbeidet, inkludert måling av brønnhydraulikk og vannkvalitetsparametere, testing av et fjernovervåkningssystem og intervjuer. I tillegg ble relevant litteratur og tekniske dokumenter analysert.

Estimater for vannbehov og -produksjon viser at pumpestasjonene ikke dekker vannbehovet i tørketiden, selv når pumpene går effektivt åtte timer om dagen. I tillegg har pumpene en tendens til å stoppe ved overskyet vær, noe som reduserer levert vannmengde og truer påliteligheten til systemene. Nåværende pumperate ser ut til å være bærekraftig ut ifra data fra feltarbeidet og pumpetester utført før installasjon. Dette indikerer at brønnene kan være i stand til å levere større vannmengder.

Vannkvalitetsmålinger ble utført på 14 pumpestasjoner og viser at pH, konduktivitet, alkalitet og turbiditet stort sett er innenfor akseptable grenser. Én av pumpestasjonene har imidlertid en turbiditet som betydelig overstiger den øvre grensen spesifisert i drikkevannsforskriften til Tanzania. To pumpestasjoner har fluoridkonsentrasjoner som overstiger den øvre grensen i Tanzania, og fem har konsentrasjoner over grensen til Verdens helseorganisasjon (WHO), men under den tanzanianske grensen.

En rekke faktorer relatert til styringspraksisen som benyttes på pumpestasjonene, for eksempel det å ha en vannkomite og en dagansatt, blir ofte forbundet med god pumpefunksjonalitet i litteraturen. Prosjektet ville likevel hatt nytte av støtte de neste par årene for å sikre at styringspraksisen blir fullstendig integrert. Innsamling av vannavgift er i de fleste tilfeller utilstrekkelig til å dekke større reparasjoner, og pumpestasjonene er derfor delvis avhengige av støtte fra lokale myndigheter. Begrensede midler til planlagt vedlikehold truer pumpestasjonenes resiliens.

Fjernovervåkning ble testet på tre pumpestasjoner og fungerte for det meste bra da mobilnettet støttet dataoverføring med få avbrudd. I teorien kan fjernovervåkning forbedre pumpestasjoners resiliens ved å skaffe data som gjør det mulig for tjenesteleverandører å prioritere når og hvor de skal utføre reparasjoner og vedlikehold. Denne oppgaven argumenterer imidlertid for at fjernovervåkning ikke uten videre kan integreres i gjeldende styringspraksis, og antas følgelig å være bedre egnet som et verktøy brukt av Kirkens Nødhjelp til å støtte prosjektet etter installering.

Oppgavens resultater innebærer at pumpestasjonenes ytelse kan forbedres ved å øke strømtilførselen, for eksempel ved å installere batterier, ekstra solcellepanel eller dieselgenerator. I tillegg bør man implementere fluoridfjerning på pumpestasjonene med høye konsentrasjoner for å forebygge fluorose. Fekal vannforurensing ble ikke målt riktig i felt og burde derfor testes på nytt for å gi en bekreftelse på at vannet er trygt å drikke. Dette er viktige tema for framtidig forskning.

Preface

This master's thesis has been conducted at the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) in the spring of 2020. It equals 30 ECTS and is the end of a five-year program in Civil and Environmental Engineering with a specialization in Water and Wastewater Engineering. The research has been carried out in collaboration with Norwegian Church Aid (NCA) and their Tanzanian partner organization 4 Corners Cultural Program (4CCP), as well as Engineers Without Borders Norway (EWB-N). The results are largely based on a case study carried out in the regions of Manyara and Singida in Tanzania in February 2020.

First and foremost, I thank my supervisor Sveinung Sægrov, who provided valuable support in terms of knowledge and enthusiasm during the entire research process. I also express my sincere gratitude to my mentor, Vibeke Brandvold, who was appointed to the project by EWB-N. She made the fieldwork successful by sharing practical and theoretical knowledge regarding hydrogeology. In addition, she believed in the project from the beginning and was a great source of inspiration. I also thank EWB-N, and especially Federico Orioli, for choosing Vibeke as a mentor, supporting the fieldwork financially, and for providing a close follow-up during the stay in Tanzania. Manfred Arlt and Zachayo Makobero, who work in NCA, shared their knowledge and insights, and provided useful technical information. I am very grateful that Zachayo Makobero participated in parts of the fieldwork. Furthermore, I thank the employees of 4CCP, including Eliminata Awet, James Mmbando, and Ahadi Mollel Ladeson, for the incredible help and support I received in Tanzania. I also express my sincere thanks to several employees in the technical staff of the Department of Civil and Environmental Engineering at NTNU. Trine Margrete Hårberg Ness and Thuat Trin chose appropriate equipment and gave a detailed initial training on how to conduct water quality measurements in field. Endre Våland Bø gave a thorough introduction to remote monitoring systems and explained how the systems should be installed. In addition, I thank El-Watch, and especially Hallvard Helgetun and Gard Hansen, for providing equipment for remote monitoring and for giving training on how the equipment may be used. Furthermore, I thank Clas Brodtkorb for helping out in installing the remote monitoring equipment. The Neuron Pressure sensors would not have been installed without his help. Last but not least, the master's theses of Rebecca Martinsen (2018), and Sigrid Elizabeth Stang Møller and Ingvild Misund (2019) have provided excellent background information.

The fieldwork was conducted in collaboration with Trine Ånestad Røer who has written her master's thesis on a similar topic. It has been useful to discuss our results together and to learn from each other. Although the master's theses are independent from each other it should be noted that there are some inevitable similarities since they are based on data from the exact same case study.

Trondheim, 24th of June 2020

Maria Asklund

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List of Abbreviations

4CCP	4 Corners Cultural Program
AC	Alternating Current
CBM	Community Based Management
COWSO	Community Owned Water Supply Organization
DC	Direct Current
DWE	District Water Engineer
DWL	Dynamic Water Level
GDP	Gross Domestic Product
GDWQ	Guideline for Drinking Water Quality
GNI	Gross National Income
HDI	Human Development Index
HLH	Haydom Lutheran Hospital
ICT	Information and Communication Technology
IDS	Intelligent Digital Sensor
IoT	Internet of Things
LGA	Local Government Authorities
MPN	Most Probable Number
NAWAPO	National Water Policy
NCA	Norwegian Church Aid
NGO	Non-Governmental Organization
PETS	Public Expenditure Tracking System
PV	Photovoltaic
RWH	Rainwater Harvesting
SSA	Sub-Saharan Africa
TTC	Thermotolerant Coliforms
WASH	Water Sanitation and Hygiene
WHO	World Health Organization
WSDP	Water Sector Development Program

1 Introduction

Safe drinking water and sanitation are recognized as basic human rights, as they are fundamental for the health and dignity of human beings. Global cost-benefit studies have established that water, sanitation and hygiene (WASH) services give good social and economic returns compared to their costs (UNESCO, 2019). Universal access to WASH services is essential for ending preventable deaths from water-related diseases like diarrhea (United Nations, 2018). Also, improving the provision of WASH services in schools and in the workplace enhances educational outcomes and economic productivity. Water is a crucial ingredient in agriculture and food production, and thus fundamental for ending hunger, achieving food security and improving nutrition.

Global water use has been increasing by about 1% per year since the 1980s, due to factors such as population growth, socio-economic development, and changing consumption patterns (UNESCO, 2019). Today, over 2 billion people live in countries facing high water-related stress, and around 4 billion people experience severe water scarcity during at least one month of the year. Nearly half of people drinking water from unprotected sources live in Sub-Saharan Africa (SSA) (ibid). In Tanzania, only 60% of the population have access to an improved drinking water source (World Bank, 2018a). Rural areas are worse off with an improved water coverage of 48%, as compared to 87% in urban areas. Improved drinking water sources are defined as “those that have the potential to deliver safe water by nature of their design and construction” (UNICEF and WHO, 2019, p. 82). Many rural dwellers rely on unimproved sources such as traditional open-dug wells or surface water. Although considerable investments have been made in water supply infrastructure through both government and donor funding, water supply coverage in Tanzania has not increased correspondingly (Joseph et al., 2019).

One persistent problem that has affected Tanzania’s effort in increasing access to improved WASH services is that water supply systems typically fail to function over time. According to the 2015 Tanzania Water Point Mapping data, about 29% of all water points were non-functional, of which 20% failed within the first year (ibid). Similar situations have been documented in other countries in SSA, such as Nigeria (Andres et al., 2018) and Ghana (Fisher et al., 2015). Research has shown that factors including technology choice, hydrology, and management to varying degrees contribute to water point failures (World Bank, 2018a). A World Bank study from 2018 indicate that hydrogeological conditions play a major role in determining the likelihood of failure within the first year after installation (Joseph et al., 2019). Whereas management practices as well as the choice of pump and technology matter considerably more in a larger timescale.

1.1 Research questions

This thesis evaluates a water supply project in Tanzania that was started by the Norwegian Church Aid (NCA) in 2015. During a four-year period, 27 solar-powered water pumping systems were constructed in the districts of Mbulu and Hanang in Manyara region, as well as the district of Mkalama in Singida region. The project was funded by the Norwegian NRK Telethon Campaign and supported by NCA’s Tanzanian partner organization 4 Corners

Cultural Program (4CCP). The results of the thesis are largely based on fieldwork carried out in February 2020.

The following research questions will be addressed:

1) To what extent do the pumping systems succeed in supplying sufficient quantities of water to the beneficiaries? (Chapter 4)
2) Do current pumping rates influence groundwater levels significantly, and is over-abstraction of the aquifers likely to occur? (Chapter 5)
3) Are the pumping systems providing water of adequate quality for human consumption? (Chapter 6)
4) To what extent do current management practices ensure pumping system resilience? (Chapter 7)
5) How may the implementation of remote monitoring influence pumping system resilience? (Chapter 8)

The main purpose of any water supply project is to cover a specific demand. Therefore, research question 1 and 3 will be addressed to assess the degree to which the project is succeeding in supplying water of sufficient quantity and quality to the beneficiaries. It is crucial that pumping rates do not exceed aquifer recharge rates to ensure environmental sustainability. Research question 2 asks whether the systems alter groundwater levels significantly over time, consequently leading to over-abstraction of the aquifers. Research question 4 asks whether current management practices ensure resilience of the systems. In infrastructure asset management, *resilience* may be defined as "the degree to which the system minimizes level of service failure magnitude and duration over its design life when subjected to exceptional conditions" (Butler et al., 2014, p. 349). In other words, *resilience* refers to the ability of a system to withstand service failure as much as possible and to recover from it when it occurs. Research question 5 asks how remote monitoring as a management practice may impact system resilience. The expansion of mobile network services in Tanzania has encouraged the use of remote monitoring as a tool for managing water supply infrastructure in rural areas.

Research question 1 to 5 are addressed in chapter 4 to 8. Chapter 2 provides a case description, focusing on the economic, social, and environmental characteristics of Tanzania, as well as the water supply situation in the study area and details regarding the WASH project of NCA. Chapter 3 describes the research methods employed including measurements of borehole hydraulics and water quality, testing of a remote monitoring system, and interviews. Chapter 9 gives a summary of the discussions in chapter 4-8, chapter 10 is the conclusion, and chapter 11 presents suggestions for future work.

1.2 Groundwater abstraction for rural water supply

Groundwater makes a significant contribution to water supply for both domestic and productive uses in SSA (Upton and Danert, 2019). In many cases, groundwater is the only viable option for covering dispersed rural demand, as alternative water sources can be unreliable (MacDonald et al., 2005). For instance, surface water is prone to contamination and typically seasonal, whereas rainwater harvesting requires rainfall throughout the year to provide water security. Groundwater, on the other hand, generally requires little treatment because it is naturally protected from pollution, it tends not to vary significantly between seasons, and it is often resistant to drought (ibid). With the appropriate methods and expertise, groundwater can be found in most environments.

In the majority of rural, low-income communities in SSA, the handpump is the most common type of pump for groundwater abstraction (Misstear et al., 2017). A handpump is a device for lifting water by means of a piston, plunger, or washers in a pipe, powered by human effort from hands, arms, or feet (MacArthur, 2015). Three of the most common types of handpumps in SSA are the India Mark II, Afridev and Vergnet pumps. There has been a trend towards standardization in the last few decades: in 2014, around 13 types of handpumps were being installed in SSA, compared to 35 types in Burkina Faso alone in 1985 (ibid). Standardization can lead to a number of benefits such as pumps being manufactured to clearly defined technical specifications and performance criteria (Baumann and Furey, 2013). However, even with greater standardization, the failure rate of handpumps is still a major problem. Estimates indicate that 30% of all handpumps in SSA are not working at any given time (Baumann, 2009).

Motorized pumps powered by electricity or diesel are commonly used for groundwater abstraction. Diesel-driven pumps typically consist of a small diesel engine coupled with a generator that drives a submersible pump (Baumann, 2000). These systems have the advantage of being independent from the power grid and thus they are suitable for isolated villages. However, diesel generator systems require frequent maintenance and may require the attendance of an operator (Baumann et al., 2010). Where extensions from the national power grid reach the villages, boreholes with electric pumps can be installed. These systems are generally economically feasible for communities of more than 2500 people (ibid).

Solar-powered water pumping systems are becoming increasingly common (Misstear et al., 2017). These systems use energy from solar panels to power an electrical water pump. Solar-powered pumps have several advantages compared to conventional motorized pumps. Firstly, fuel and electricity are not required, which reduces running costs, and avoids the challenges of unreliable power supply as well as costs and availability of diesel in rural areas (World Bank, 2018b). Secondly, solar pumps have few moving parts and hence require little maintenance compared to diesel pumps. Thirdly, solar pumps do not generate noise and pollution, unlike diesel-based systems. There are also numerous benefits of solar pumps compared to handpumps. For instance, they can be used where the groundwater level is too low to be reached by traditional handpumps (Bamford and Zadi, 2016). In addition, fetching water is faster and does not require manual labor. Solar-powered water pumping systems typically have water storage tanks, which can provide an important buffer, allowing spare water to be used during night and when the weather is cloudy (ibid).

Solar-powered water pumping is becoming a viable water supply option in rural low-income settings because the technology and costs of such systems have evolved rapidly over the last few years (World Bank, 2018b). However, there are still challenges related to the implementation of these systems. For instance, the initial capital costs are higher than those of diesel-based systems (ibid). In addition, some servicing is required, and specialized technicians may be unavailable in rural areas. Also, solar-powered water pumping can lead to excessive groundwater abstraction since there are practically no running costs. Another major challenge is that when breakdown occurs, the cost of repairs is higher than for other systems (Bamford and Zadi, 2016). In addition, solar water pumping technology is dependent on sunlight and thus cloudy whether gives reduced output.

1.3 Solar-powered water pumping system theory

Solar-powered water pumping is based on photovoltaic (PV) technology that transforms sunlight into electricity to pump water (Chandel et al., 2015). The solar panels are connected to a motor converting electricity from the solar panels into mechanical energy which is converted to hydraulic energy by the pump. Then, the pump lifts the water to the point of use or storage. Figure 1 shows the schematic of a solar-powered water pumping system, including PV-module, well, pump, and water storage tank. The schematic also has water level sensors inside the well and tank.

A PV cell is a semiconductor device which directly converts solar radiation into electricity (Rawat et al., 2016). The radiated energy of sunlight energizes electrons in the PV cells, and when the energy exceeds a certain level, a potential difference is established (Baumann et al., 2010). This potential can be utilized to create an electrical current. The PV cells are connected electrically and packaged into a solar panel. The solar panels are designed as easily installable units, they are fastened together, wired, and have a glass cover (ibid). There are different types of PV cells available on the market, such as mono-crystalline silicon, multi-crystalline silicon, and cadmium telluride (Rawat et al., 2016).

Solar-powered water pumping systems for groundwater abstraction use a submersible pump, which means that the pump is located inside the borehole and is completely submerged in water, as shown in Figure 1. The motor and pump are built together as one unit in submersible systems (Chandel et al., 2015). Two types of pumps can be used, either a centrifugal pump or a positive displacement pump (Muhsen et al., 2017). The motor can run on either direct current (DC), where the electricity does not change direction periodically in the wires, or alternating current (AC), where it does (World Bank, 2018b). A power conditioning unit (PCU) is used to optimize the transferred energy between the solar panels and the motor-pump set (Muhsen et al., 2017). The power generated by the solar panel is DC, and thus the PCU may be either a DC-DC converter or DC-AC converter depending on the type of motor used. DC motors are suitable for systems with low water demand and short cabling distance between the solar panels and the motor, whereas AC motors are preferred for high-power systems, and long cabling distances to minimize the power loss in the cable (World Bank, 2018b).

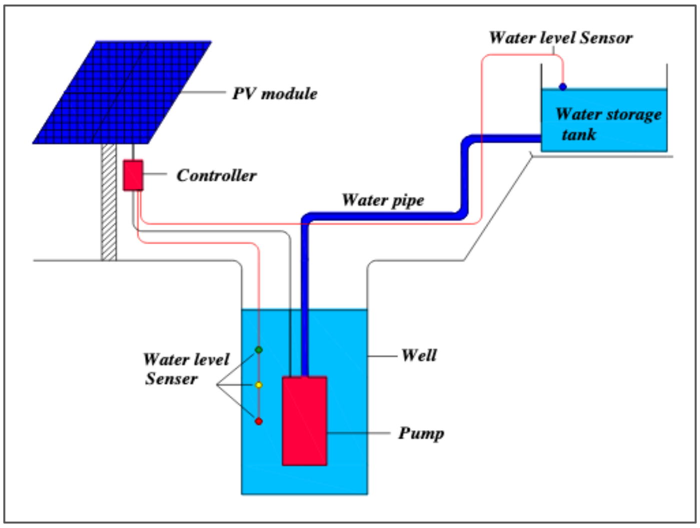


Figure 1: Schematic diagram of a solar-powered water pumping system (Girma et al., 2015)

2 Case Description

This chapter aims to put the thesis into context. Section 2.1 looks into economic and social characteristics of Tanzania, policies that deal with water service delivery, as well as nature-based conditions such as climate and hydrogeology. Section 2.2 describes the study area (Mbulu, Hanang and Mkalama districts), the water supply situation, the WASH-program of NCA and 4CCP, and the components of the solar-powered water pumping systems.

2.1 Tanzania

Tanzania is located in East Africa and consists of the mainland and Zanzibar (Kashaigili, 2010). The country borders to Kenya and Uganda in the north, the Indian Ocean in the east, Mozambique in the south, and Rwanda, Burundi, the Democratic Republic of Congo, Zambia, and Malawi in the west. Its total land area is 945 000 km^2. The population is 58 million, according to 2019 estimates (United Nations, 2019). Swahili is the national language, and English servs as a joint official language (Ammon et al., 2006). Tanzania is however the most linguistically diverse country in the East African region, with approximately 135-150 languages spoken (ibid).

2.1.1 Socioeconomic development

Tanzania gained its independence from Great Britain in 1961 (World Bank, 2018a). Since then, the political party Chama Cha Mapinduzi (CCM) has been in power. In the beginning, Tanzania was a socialist country. However, the government started carrying out macroeconomic reforms in the 1980s, such as removing direct controls on prices and exchange and interest rates and opening up industry to private investment (World Bank, 2017). The reforms continued into the 1990s with cuts in public spending, which in turn contributed to a transition from fiscal deficits to surpluses. Inflation was brought under control and the exchange rate stability was restored (ibid). In addition, the government carried out reforms to increase exports, liberalize domestic markets, and reduce public sector involvement in the economy.

Reducing poverty in Tanzania has been slow considering its significant economic growth (Belghith et al., 2019). The increase in Gross Domestic Product (GDP) averaged 6.3% from 2007 to 2017 (ibid). Some of the fastest growing sectors in the economy were construction, information and communication technology (ICT), and real estate, which generally employ the more educated and better-off parts of the population (ibid). Tanzanians with more education and skills are thus better positioned to benefit from economic growth. In the period from 2012 to 2018, the growth elasticity of poverty was -0.45, which means that a 10% increase in GDP is expected to result in a 4.5% decrease in the proportion of the poor (ibid). This is low, since poverty is expected to be reduced by over 20% when GDP raises by 10% in developing countries (ibid). Between 2007 and 2018, Tanzania's national poverty rate was reduced from 34% to 26%, and extreme poverty was reduced from 12% to 8% (ibid). The poor are defined as people who have a consumption below the national poverty line and consequently are unable to meet their basic consumption needs, whereas the extreme poor are those who are unable to afford enough food for their basic nutritional requirements. Even though there has been a percentage reduction in poverty, the absolute number of poor people increased from 13 million in 2007 to 14 million in 2018, because of population growth (ibid).

The Human Development Index (HDI) of Tanzania for 2018 is 0.528 (UNDP, 2019). The HDI is a measure for assessing progress in three dimensions of human development: a long and healthy life, access to knowledge, and a decent standard of living. A long and healthy life is measured by life expectancy; access to knowledge is measured by mean years of schooling among the adult population and expected years of schooling for children of school-entry age; and standard of living is measured by Gross National Income (GNI) per capita. Tanzania's HDI value of 0.528 makes it number 159 out of 189 countries and territories (ibid). Thus, Tanzania is in the low human development category. Table 1 shows Tanzania's progress in the HDI indicators as well as the HDI value from 1990 to 2018. The HDI value increased from 0.373 to 0.528, that is an increase of 41.6%. Life expectancy increased by 14.8 years, expected years of schooling increased by 2.5 years, and mean years of schooling increased by 2.4 years. GNI per capita increased by about 88.3%.

Table 1: HDI indicators and HDI value in 1990 and 2018 for Tanzania (UNDP, 2019)

	Life expectancy at birth	Expected years of schooling	Mean years of schooling	GNI per capita (2011 PPP$)	HDI value
1990	50.2	5.5	3.6	1,490	0.373
2018	65.0	8.0	6.0	2,805	0.528

2.1.2 The political framework underlying water service delivery

Water policies in Tanzania have evolved from centralized and free provision by the state to a more decentralized demand-responsive approach (World Bank, 2018a). In 1965, the government decided to take full responsibility for rural water supply funding, and declared that water from public distribution points should be free (Jiménez and Pérez-Fouget, 2010). This promise was put into plans in 1971, when the government stated that the whole population should have access to safe water within easy reach of their homes by 1991 (Giné and Pérez-Fouget, 2008). From the mid 1970s into the 1980s, foreign donors made considerable efforts to improve water coverage, but the projects ultimately proved to be unsustainable (ibid). Water supply infrastructure was built rapidly and then transferred to regional water engineers who did not have the budget to operate them. In response, the government introduced a new National Water Policy (NAWAPO) in 1991 (ibid). A revised NAWPO came in 2002, introducing elements of decentralization, cost-recovery, and the issue of ownership. In order to implement the revised policy, the government collaborated with civil society organizations and donors to establish the Water Sector Development Program (WSDP), which began in 2006 (Carlitz, 2017).

The mainland in Tanzania is divided into 26 regions, which are administrative units of the national government (World Bank, 2018a). The main level of the local government system is formed by elected Local Government Authorities (LGAs), including 133 District Authorities and 39 Urban Authorities. Rural district councils are subdivided into villages for administrative purposes. Under the Local Government Acts, the functional responsibility for providing WASH services lies within the LGAs (ibid). However, the water sector has introduced additional organizations that are supposed to provide water and sanitation services at the grassroot level in coordination with local governments. In 2006, the National Water Sector Development Strategy introduced the concept of Community Owned Water Supply Organizations (COWSOs), which are supposed to be established at each rural water scheme (ibid). These organizations are created by the community to own, manage, operate, and maintain water supply systems. LGAs are supposed to provide technical support to COWSOs, and fund major repairs and rehabilitation when the funds of the COWSOs are insufficient (ibid).

The decentralized approach of water policies in Tanzania aims to generate greater responsiveness to local needs and to thoroughly involve users in service delivery (Carlitz, 2017). However, local governments have limited capacity to fulfil their obligations. The World Bank (2018a) outlines some of the challenges facing the water sector in Tanzania today. Firstly, there is a lack of clarity in the division of responsibilities which in turn places a burden on the maintenance of rural water supply infrastructure. The Water Supply and Sanitation Act No. 12 specifies that LGAs are responsible for "meeting part of the costs incurred by COWSOs in the major rehabilitation and expansions of water schemes and payment for costs of service rendered" (United Republic of Tanzania, 2009, Sec. 39b). However, the Act does not define "major" rehabilitation or specify how this is different from minor repairs, leaving it to the districts to interpret the division of responsibilities (World Bank, 2018a). Secondly, the budget allocations in the water sector tend to be more for construction of new water points, and less for maintenance and repair, which poses challenges to sustainability (ibid).

2.1.3 Nature-based conditions

Nature-based conditions, including climate and hydrogeology, determine the constraints of water provision. The topography of Tanzania is characterized by lowland coastal plains, a central plateau of 1000-1500 masl, and highlands in the north and south of more than 2000 masl (Smedley, 2000). The climate varies from tropical along the coast, to temperate in the highlands, and semi-arid in the central plateau. Annual precipitation ranges from 2500-3000mm around Mount Meru in the north, to 1000mm along the coast, down to 550mm at the central plateau (ibid). There are two types of seasonal rainfall distributions in Tanzania (Zorita and Tilya, 2002). In the coastal belt, the northern highlands and around Lake Victoria, maximum rainfall usually happens in two periods during the year, that is from March to May and from October to December. Whereas southern, central, and western Tanzania only has one rainy season, which usually lasts from October to April. The coastal areas including Zanzibar are hot and humid, with an average daily temperature around 30 °C (Kashaigili, 2010). October to March is the warmest season, whereas June to September is cooler with temperatures falling to 25 °C. In the Kilimanjaro area, temperatures vary from around 15 °C in May to August to 22 °C in December to March.

The geology of Tanzania largely follows topographic variations (Smedley, 2000). The central plateau consists of crystalline basement rocks, which primarily are faulted and fractured metamorphic rocks with some granites. The northern and southern highlands are parts of the East African Rift system which extends from Ethiopia to South Africa. In Tanzania, the Rift Valley forms two branches, called the Gregory Rift and the Western Rift. The geology of the Rift zones is characterized by volcanic and intrusive rocks, largely of basaltic composition, but with some sporadic sodic alkaline rocks and igneous carbonates (ibid). In most of the south-eastern part of the country, the geology comprises sedimentary rocks including sandstones, mudstones, and limestones. The coastal plains are mostly composed of unconsolidated sediments, in addition to some limestone deposits (ibid). Unconsolidated sediments are also present in depressions in parts of the eroded crystalline basement in central Tanzania. The fieldwork of this thesis was carried out in the regions of Singida and Manyara, which are located on the central plateau. The aquifers in these regions are predominantly weathered and/or fractured granites and gneisses (Baumann et al., 2005). However, aquifers of sedimentary rocks such as shale are also present. Shale is made from silt and clay that has been consolidated (MacDonald et al., 2005). Highly weathered and/or fractured crystalline basement rocks have a moderate groundwater potential, whereas shale has a low groundwater potential according to MacDonald et al. (2005).

2.2 Mbulu, Hanang and Mkalama

The fieldwork was carried out in the districts of Mbulu and Hanang in Manyara region, as well as the district of Mkalama in Singida region. This area is in the northern part of Tanzania, as shown in Figure 2. The red placemark is Haydom town, which lies approximately in the center of the area.

Figure 2: Map of Tanzania, screenshot from google.com/maps

NCA and 4CCP installed 29 pumping stations in various villages in this area from 2015 to 2019. Two of the pumping stations receive electricity from the power grid, whereas the remaining 27 run on solar power. Fourteen water points were visited during the fieldwork, indicated by blue placemarks in Figure 3. All of the pumping stations visited run on solar power, except for Haydom Secondary School which is connected to the power grid.

Figure 3: Map of pumping systems visited during fieldwork, made in https://earth.google.com

The villages visited are rural with populations in the range from 1000 to 3000. The majority source their income from farming. Typical crops grown in the area are corn, beans, and sunflower, and most families also have livestock such as cattle, goats, and poultry. The population density is low since farming is an area intensive activity. People from four different ethnolinguistic groups live in the area around Haydom; Datoga, Hadzabe, Iraqw, and Isanzu/Iramba (Ahadi Mollel Ladeson, personal communication, 24.02.2020). Each of these groups have their own culture, language, history, and ways of living. The Datoga speak a Nilotic language and typically source their income from large-scale livestock keeping (4CCP, 2020a). The Hadzabe speak a Khoisan language and are hunters and gatherers traditionally. The Iraqw speak a Cushitic language and generally do large-scale agriculture. The Isanzu and Iramba speak Bantu languages and practice mixed economy. Most Tanzanians speak Swahili, 10% speak it as a first language, and as many as 90% speak it as a second language (Ammon et al., 2006). Thus, Swahili is the means of communication between the different groups.

Haydom Lutheran Hospital (HLH) is located in Mbulu district and was started by the Norwegian Lutheran Mission (Norsk Luthersk Misjonssamband) in 1954. Today, HLH is classified as a regional hospital and is owned and operated by Mbulu Diocese and the Evangelical Lutheran Church in Tanzania (Stiftelsen Haydoms venner, 2020b). HLH is collaborating closely with NCA and receives yearly support from the Norwegian Agency for Development Cooperation (Norad). Since the establishment of HLH, Haydom town has grown rapidly. Today, it is one of the larger towns in the area, with a population of approximately 20 000 people (James Mmbando, personal communication, 12.02.2020).

2.2.1 Water supply situation

The water supply situation around Haydom is characterized by a high water demand and insufficient water supply installations. In Mbulu district, 48% of the population has access to an improved drinking water source close to their home, according to the district water engineer (DWE). Mkalama district is better off than Mbulu with an improved water coverage of 65%, according to the DWE. Numbers were not available for Hanang district. The average improved water supply coverage in rural areas in Tanzania is 48% (World Bank, 2018a). Handpumps, as well as pumps driven by diesel, electricity, or solar power, are examples of improved water sources used in the area. General descriptions of those water supply options are given in chapter 1.2 (page 2). In addition, systems for rainwater harvesting (RWH) are utilized in the rainy season for both households and institutions such as schools. RWH typically relies on collection of rainwater from roofs into tanks (Figure 4). Roofs and tanks must be cleaned regularly to ensure safe water provision.

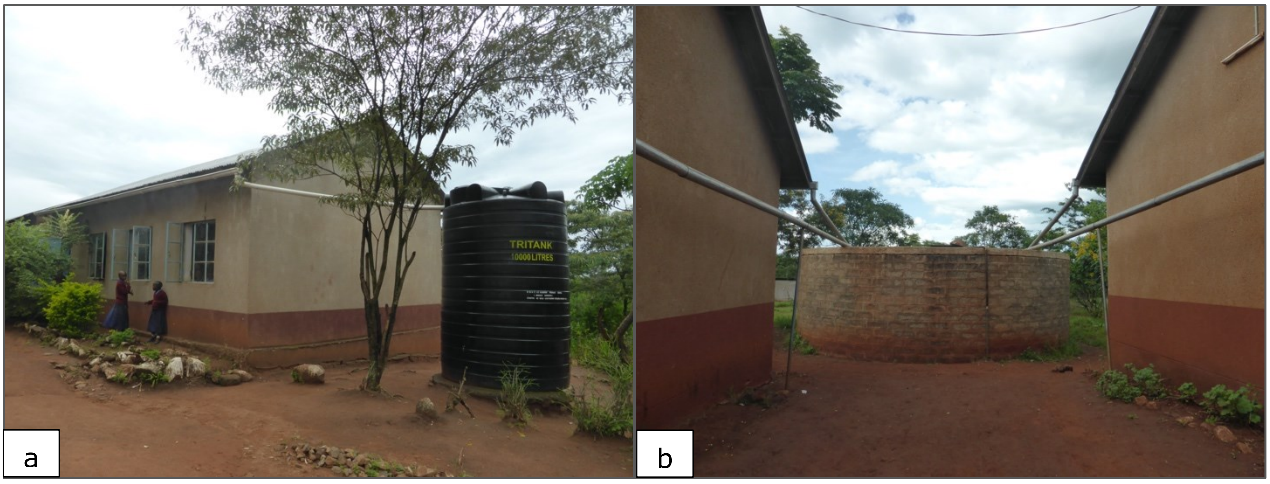


Figure 4: RWH in a) Mewadani Primary Scool, and b) Haydom Secondary School

Unimproved water sources such as dams, rivers, and traditional open-dug wells are still used. Untreated surface water is generally not recommended for drinking because it is vulnerable to contamination. Hand-dug wells are constructed without machinery, as opposed to drilled wells. Groundwater from a hand-dug well is typically healthier than most surface water sources (Misstear et al., 2017). However, a hand-dug well is far more prone to contamination than a drilled well, as it tends to be shallow and open to infiltration of polluted stormwater. There is also a risk of spilled water or animal wastes flowing into the well if the lining and headwork of the well are poorly constructed (ibid).

The water supply system of HLH was developed more than 30 years ago and relies on a water source called Endagulda Spring. A spring is a location where groundwater discharges from an aquifer, creating a visible flow of water on the land surface (Kresic, 2010). Water is transported in pipes by means of diesel-driven pumps from Endagulda Spring to storage tanks on a hill (Figure 5). Then, water is transported in pipes by gravity from the water storage tanks to HLH. Endagulda Spring also provides water for two primary schools, located in Murukuchida and Endanachan, as well as for villagers living nearby the water storage tanks. HLH is planning to make a transition from diesel to electricity-driven pumps in 2020, as the power grid is expected to expand to reach Endagulda (Stiftelsen Haydoms venner, 2020a).

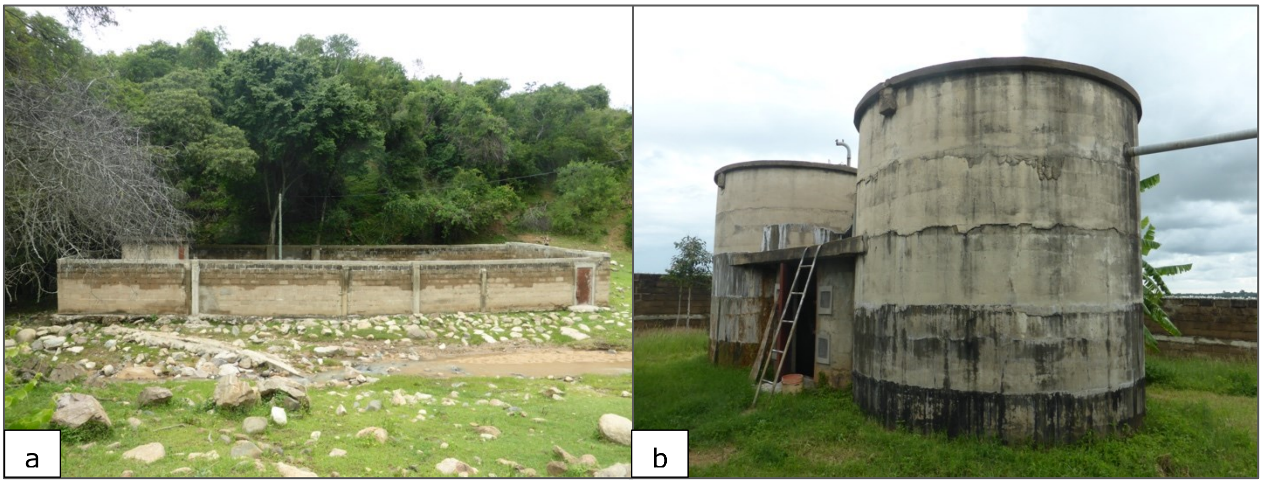


Figure 5: Photographs of a) Endagulda Spring, and b) Storage tanks

Haydom town receives water from three boreholes that are installed with hybrid water pumps which can run on both electricity and diesel (Interview with Haydom COWSO, 12.02.2020). Water is pumped from the boreholes to storage tanks on a hill and then supplied in pipes by gravity into town (Figure 6). The power supply from the national power grid can be unreliable, so diesel is used as a backup. In Haydom town, pumping by diesel started in 1976, whereas pumping by means of electricity started in 1996. Unimproved water sources were used before 1976. In the last few years, an increasing number of households receive water directly into their homes. However, the majority still fetch water from water kiosks (Figure 6c).

Figure 6: Water supply in Haydom, a) Borehole, b) Water tank, c) Water kiosk

2.2.2 Norwegian Church Aid and 4CCP: WASH Program

4CCP is a community development organization that focuses on topics such as economic empowerment, gender equality, youth leadership, and WASH. It was established in 2006 as a sister organization to HLH and works in three districts; Mbulu, Hanang, and Mkalama (4CCP, 2020b). The name 4CCP means Four Corners Cultural Program and refers to the four main ethnolinguistic groups in Tanzania. People from each of these groups live in the area around Haydom. The goal of 4CCP is to maintain a peaceful coexistence and to celebrate the uniqueness of each culture. 4CCP's slogan; "Nipo kwa sababu upo", means "I am because you are", which illustrates the interconnectedness of people. 4CCP has seven employees and is sponsored by NCA.

NCA and partner organizations in Tanzania implemented a WASH program from 2015 to 2019. The program was funded by the NRK telethon campaign. The goal was to expand access to WASH services and enhance sustainability of water supply infrastructure and services in the vulnerable communities of Tanzania by 2019 (NCA, 2015). The program was implemented in Mbulu, Hanang and Mkalama in collaboration with 4CCP, and involved both rehabilitation of old water facilities and construction of new ones. For instance, 27 solar-powered water pumping systems were built. The program focused on the social aspects of infrastructure asset management to ensure project sustainability. Community mobilization was seen as particularly important and the involvement and participation of women was encouraged. A COWSO and a public expenditure tracking system (PETS) committee, consisting of community members, were established at each water point. The COWSO deals with operation and maintenance, whereas the PETS committee ensures transparency and accountability in the use of funds in community projects.

2.2.3 Solar-powered water pumping systems

The solar-powered water pumping systems installed in Mbulu, Hanang and Mkalama consist of PV-panels, a borehole, a motor/pump set, an inverter, water storage tanks, water taps, and a water meter. A conceptual drawing is given in Figure 7. The area is protected by a fence.

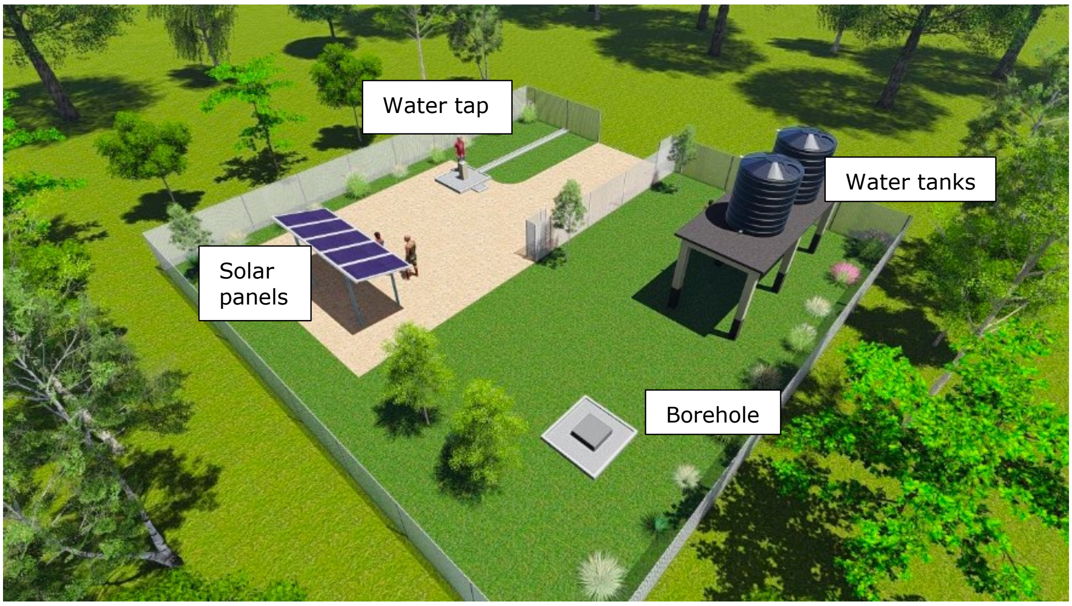


Figure 7: Illustration of a solar-powered water pumping system (Zachayo Makobero, personal communication, 16.01.2020)

Each pumping stations has 8 or 10 Dayliff PV panels from Davis and Shirtliff (Figure 8). The PV panels deliver a peak power of 195 W each.

Figure 8: PV-panels at Mewadani pumping station

The Dayliff Sunverter from Davis and Shirtliff (Figure 9) is an AC/DC inverter which transforms the DC-power generated by the solar panels into AC-power, which is then transferred to the motor/pump set. The Sunverter is located on the wall inside the building which the water tanks stand on and is used by the operator to start and to stop the pump.

Figure 9: Dayliff Sunverter at Endanachan pumping station

The pumping stations have a motor-pump set from Davis and Shirtliff. However, the particular type of motor-pump set differs among the villages. The most common ones are

DSP 3-16 and DSP 5-16. The motor-pump set is installed inside the borehole. Figure 10 shows the top of the borehole. Two cables enter the borehole; one supplies power to the motor/pump set, and the other one is connected to a sensor that stops the pump if the water level drops below the pump intake to prevent the pump from running dry.

Figure 10: Top of borehole at Isene pumping station

Each pumping station has two water tanks of either 2x5000 L or 2x10000 L, situated on top of a small building (Figure 11). When the water tanks are full, excess water is discharged through an outlet pipe. The operator may stop the pump when he or she discovers that water is released from the pipe.

Figure 11: Water tanks at Isene pumping station

Each pumping station has at least one water tap (Figure 12). A water meter is located under the lid on the right in Figure 12.

Figure 12: Water tap at Gidbyo pumping station

The water meter (Figure 13) measures the water flow from the tanks to the tap. Thus, water usage can be monitored.

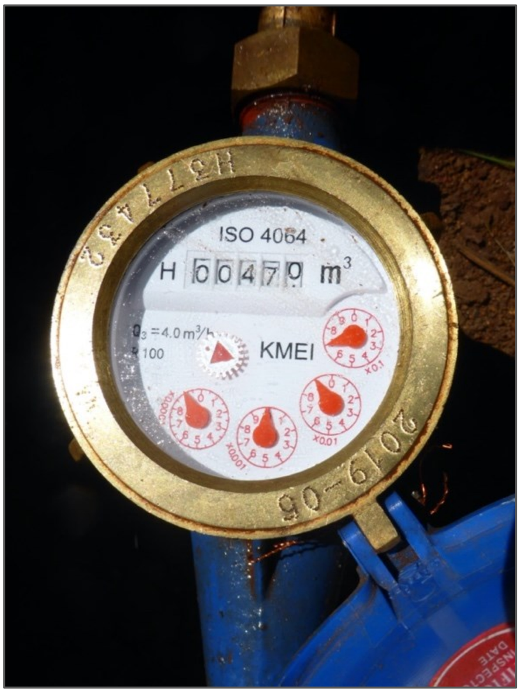


Figure 13: Water meter at Gidurudagew pumping station

2.2.4 Fieldwork

The fieldwork was carried out from the 28th of January to the 24th of February 2020, with the purpose of collecting data for answering the research questions listed in chapter 1.1 (page 2). The main activities were:

- To measure the water level inside the boreholes by the Pocket Dipper and/or Electric Contact Meter
- To measure the flowrate of the boreholes by a bucket test (using a bucket and a stopwatch)
- To measure drawdown and recovery curves in boreholes by a pressure sensor (the TD-Diver/CTD-Diver from Van Essen Instruments)
- To measure water quality parameters such as pH, conductivity, alkalinity, turbidity, fluoride concentration, and fecal contamination
- To install remote monitoring systems
- To interview key stakeholders, such as district engineers, COWSOs, and 4CCP
- To conduct a survey for community members

Detailed descriptions of the fieldwork are given in the next chapter. A fieldwork program with a brief overview of the activities carried out each day is included in Appendix 1.

3 Methods

Research is typically divided into two categories; qualitative and quantitative. The term *quantitative research* refers to systematic empirical investigations that collect, analyze, and display data in numerical rather than narrative form (Given, 2008). In general, quantitative research tends to be committed to hypothesis testing, procedural objectivity, identifying systematic patterns of association, and controlling variables (Hammersley, 2012). *Qualitative research*, on the other hand, tends to adopt a flexible and data-driven research design (ibid). Qualitative research typically uses relatively unstructured data, emphasizes the role of subjectivity in the research process, and studies a small number of naturally occurring cases in detail (ibid). This work has used a combination of quantitative and qualitative research methods. Data collection and analysis of parameters related to water quality and borehole hydraulics were carried out to evaluate the performance of the pumping stations quantitatively. Whereas interviews were used to capture the thoughts and impressions of various stakeholders to evaluate the performance of the pumping stations qualitatively.

This chapter describes the methods employed in the thesis including test procedures, specifications of equipment, and methodical limitations.

3.1 Water borehole measurements

Various borehole measurements were conducted at the pumping stations to find water levels, flowrates, and drawdown and recovery curves.

3.1.1 Water level in borehole

Water levels were measured manually by two different devices; the Pocket Dipper and the KLL-Light Electric Contact Meter. The Pocket Dipper by Groundwater Relief is a small water level monitoring device with a switch and a battery. When the operator turns on the switch, the device makes a continuous high-pitched sound. The device is then lowered down the borehole with surveyor tape. When the device reaches the water level the sound is dulled, and the operator can record the water level. The KLL-Light Electric Contact Meter by SEBA Hydrometrie is a water level monitoring device that comes with a battery, a graduated cable, a cable drum, and a senor with light and sound signals. The sensor is lowered down the borehole by the operator and when it reaches the water level, the light and sound signals are activated. The water level is then read from the graduated cable by the operator. The process of measuring the water level with the Pocket Dipper and the KLL-Light Electric Contact Meter is shown in Figure 14a and Figure 14b, respectively.

Figure 14: Water level measurement with a) The Pocket Dipper and b) KLL-Light Electric Contact Meter

The Pocket Dipper and the Electric Contact Meter differ in price, accuracy and robustness. The price of the Pocket Dipper is approximately 500 NOK (Manfred Arlt, personal communication, 22.04.2020), whereas the Electric Contact Meter costs approximately 4500 NOK if it has a cable length of 50m (Geonor, personal communication, 31.01.2020). The accuracy of the Pocket Dipper is approximated to ±0.5m in this work, because the sound of the device is difficult to hear when it is lowered down a narrow borehole. The Electric Contact Meter was found to measure the water level more accurately than the Pocket Dipper. The lamp and buzzer which make the light and sound signals when the sensor reaches the water level are located on the cable drum, which means that the water level is easily recorded also for deeper wells. The accuracy of the Electric Contact Meter is set to ±1cm, in line with the product catalog (SEBA Hydrometrie, 2019). The Pocket Dipper worked reasonably well for boreholes with a high water level. However, if the water level was located more than 30m below the ground surface, the sound was not strong enough for the operator to record the water level. This is consistent with the product specifications (Groundwater Relief, n.d.). After the first week of fieldwork, the Pocket Dipper stopped making the high-pitched sound when turning on the switch. It is uncertain why the device stopped working as the battery life is supposed to be ten years (ibid).

3.1.2 Flowrate

The flowrate of the boreholes was measured in field by a simple "bucket test". In this test, the pipe connecting the borehole to the water tanks was disconnected. Then, the pump was turned on and the time taken to fill a bucket of known volume was recorded by a stopwatch (Figure 15). Usually, a bucket of 13 or 23 liters was used. The flowrate was simply calculated by dividing the bucket volume by the time elapsed. This method is not very accurate, since some water spurts back out of the bucket if the flowrate is high. Also, the bucket cannot be held completely vertically, and thus it cannot be filled to the edge, which makes it difficult to determine the exact time at which the bucket is full. Nevertheless, the calculated value gives an indication of the magnitude of the flowrate. It must however be noted that the rate at which water is delivered to the tank is less than what the bucket test indicates since the pipes connecting the borehole to the tanks add extra head losses to the system.

Figure 15: Bucket test

3.1.3 Drawdown and recovery curves

Pressure sensors from Van Essen Instruments were used to find drawdown and recovery curves at three pumping stations. Three types of pressure sensors were used in field; a TD-Diver with 50m measuring range, a CTD-Diver with 10m measuring range, and a Baro-Diver. The TD- and CTD-Divers are submersible dataloggers which measure the hydrostatic pressure of the water above the sensor to calculate the total depth of water. Both of them measure temperature in addition to depth, and the CTD-Diver also measures conductivity. The Baro-Diver is a datalogger that measures atmospheric pressure and temperature and is used to compensate Diver-measurements. The TD-Diver or the CTD-Diver was typically installed in a borehole for one to two days and programmed to record new measurements every ten seconds. The Baro-Diver was programmed to log the atmospheric pressure for the same period of time and with the same measurement frequency. A software by Van Essen Instruments called Diver-Office was used to program the sensors, download the recorded data, and barometrically compensate the Diver data to convert them into water levels. Data was then exported to Microsoft Excel to make drawdown and recovery curves, which show how the water level drops and recovers during and after pumping, respectively.

Figure 16: TD-Diver and borehole

3.2 Water quality measurements

Water quality parameters were measured at 14 pumping stations. The parameters measured were pH, alkalinity, conductivity, turbidity, fluoride concentration, and presence of hydrogen sulfide (H_2S)-producing bacteria. The purpose was to assess whether the water is safe for human consumption and whether it is likely to be accepted by consumers. Measurements were usually carried out at the pumping station, but in some cases water samples were collected in a clean bottle and tested in another location due to time constraints. Water samples were collected from the water tap at the pumping station and not directly from the borehole.

3.2.1 pH

pH was measured by two different methods in field, by an intelligent digital sensor (IDS) pH sensor (WTWSenTix 940-3) connected to WTW's Multi 3630 IDS digital meter, and by pH paper (Universal pH 0-14). The IDS pH sensor was used to test the majority of the water samples, whereas pH paper was used to test water at five pumping stations, because of problems with calibration of the IDS pH sensor. pH was measured once at each sampling point. The following steps were followed to measure pH by the IDS pH sensor:

- Collect a representative water sample in a clean container
- Connect the sensor to the digital meter
- Wash the sensor with distilled water
- Wipe the sensor with a clean tissue
- Immerse the sensor in the water sample
- Stir the sensor slowly in the water sample
- The display of the measured parameter on the digital meter flashes until a stable measured value is available
- Record the stable pH value and the temperature of the water sample

pH paper changes color depending on the pH of a solution. The following steps were followed to measure pH by pH paper:

- Collect a representative water sample in a clean container
- Dip a piece of pH paper into the water sample
- Remove the piece of pH paper after a few seconds
- Compare the color of the piece of pH paper to the color chart provided with the pH paper kit
- Record the measured pH value

Figure 17: pH paper

The stability control function of the IDS pH sensor checks whether the measured values are stable within the monitored time interval (Xylem Analytics Germany, 2017). A time interval of 15 seconds is the minimum duration until a measured value is assessed as stable, with a stability better than 0.01 pH (ibid). Thus, the accuracy of the IDS pH sensor is set to ±0.01 pH. The accuracy of the pH paper test method is set to half the interval between each measurable unit, which is ±0.5 pH. The pH measurements were not adjusted for temperature, since the water temperature was in the range from 21 to 30 °C, which makes negligible impacts on pH. Figure 17 shows the pH paper test method, where the color of the paper resembles the color of both 7 and 8 on the color chart. In cases like this, pH was set to 7.5. The IDS pH sensor test method looks similar to the conductivity test method displayed in Figure 19.

3.2.2 Alkalinity

Alkalinity was measured by the Contour Comparator by Palintest. In this test, a tablet is dissolved into a water sample, and the emerging color of the water sample is compared to the colors on a disc, where each color represents an alkalinity concentration. The color disc and the test tube containing the water sample are placed inside a box called a *Comparator* to determine the concentration. The color varies from yellow to blue, representing alkalinities of 0-250 mg/L $CaCO_3$. Bright yellow means no alkalinity and bright blue corresponds to an alkalinity of 250 mg/L $CaCO_3$. The accuracy was set to half the interval between each measurable unit. The following test procedure was followed:

- Fill a square test tube with sample to the 10mL mark
- Add one alkavis tablet, crush and mix thoroughly to dissolve
- Place the test tube inside the Comparator and match against the disc
- The disc reading represents the total alkalinity in the sample as mg/L $CaCO_3$

Figure 18: Test tube containing water sample and a dissolved alkavis tablet

3.2.3 Conductivity

Conductivity was measured by an IDS conductivity sensor called TetraCon925, connected to WTW's Multi 3630 IDS digital meter. The following test procedure was followed once at each sampling point:

- Collect a representative water sample in a clean container
- Connect the sensor to the digital meter
- Wash the sensor with distilled water
- Wipe the sensor with a clean tissue
- Immerse the sensor in the water sample (Figure 19)
- Stir the sensor slowly in the water sample
- The display of the measured parameter on the digital meter flashes until a stable measured value is available
- Record the conductivity value and the temperature of the water sample

Figure 19: Conductivity measurement with IDS sensor

The stability control function of the IDS conductivity sensor checks whether the measured values are stable within the monitored time interval (Xylem Analytics Germany, 2017). A time interval of 10 seconds is the minimum duration until a measured conductivity value is assessed as stable, with a stability better than 1.0% of measured value (ibid). Thus, the accuracy of the IDS conductivity sensor is set to ±1.0% of measured value. The conductivity measurements were adjusted for temperature automatically.

3.2.4 Turbidity

Turbidity was measured by HACH's 2100Q*is* turbidity meter (Figure 20a). The following test procedure was followed, in line with (HACH, 2013):

- Collect a representative water sample in a clean container
- Fill a sample cell to the line (about 15 mL) (Figure 20b)
- Put the cap on the sample cell
- Wipe the sample cell with a soft cloth
- Gently invert the sample cell
- Insert the sample cell into the instrument so that the orientation mark of the cell aligns with the orientation mark of the instrument
- Close the lid of the instrument
- Push the *Read*-button: The display then shows *Stabilizing*, then the turbidity in NTU
- Record the turbidity value

At least two turbidity measurements were carried out at each sampling point. A representative water sample was collected in a clean container once. Then, a sample cell was filled with water from that container and tested for turbidity at least twice. The accuracy of the turbidity meter is ±2% of reading plus stray light (HACH, 2013). Stray light is less than 0.02 NTU (ibid). However, the actual uncertainty of the measurement is greater than this, since particles are not evenly distributed in a water source. Thus, the difference in turbidity between two sample cells filled with water from the same source are likely to be greater than indicated by the instrument accuracy.

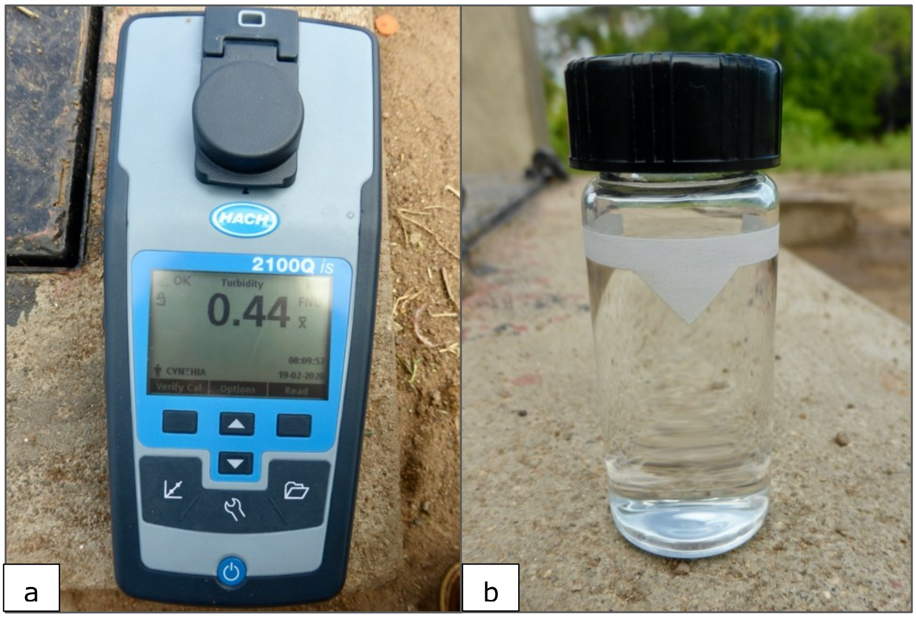


Figure 20: a) Turbidity meter and b) Sample cell

3.2.5 Fluoride content

Fluoride concentration was measured by the Contour Comparator by Palintest, in the same way as alkalinity. The emerging color varies from red to orange, representing fluoride concentrations of 0-1.5 mg/L. The accuracy was set to half the interval between each measurable unit.

The following test procedure was followed:

- Fill a square test tube with sample to the 10mL mark
- Add one fluoride No 1 tablet, crush and mix to dissolve
- Add one fluoride No 2 tablet, crush and mix to dissolve
- Stand for five minutes to allow for full color development
- Place the test tube in the Comparator and match against the disc (Figure 21a)
- The disc reading represents the fluoride concentration in mg/L F^-

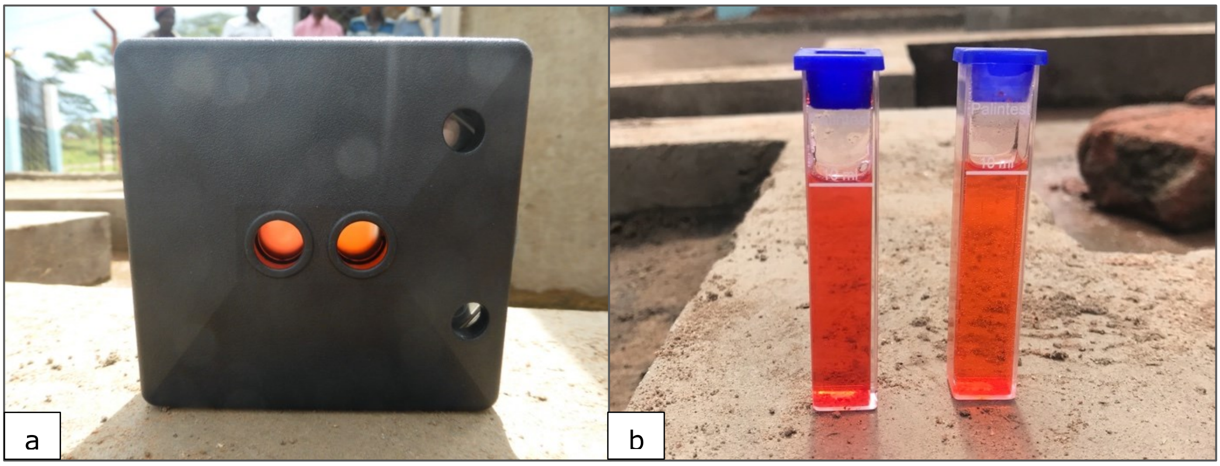


Figure 21: a) Test tube and color disc inserted into the Comparator, b) Test tubes with water samples containing different concentration of fluoride

3.2.6 H_2S-test

Fecal contamination was tested by HACH's PathoScreen Field Test Kit, which is a H_2S-test kit. The test is based on the fact that water containing coliform bacteria also consistently contain H_2S-producing bacteria (UNICEF, 2008). H_2S reacts rapidly with iron to form a black iron sulfide precipitate. The PathoScreen Field Test Kit comes with an iron rich growth medium, called PathoScreen Medium powder pillows, which is to be added to a water sample. If the water sample contains H_2S-producing bacteria, the color changes from yellow to black during the incubation time due to the formation of iron sulfide precipitate.

The following test procedure was followed, in line with HACH (2016):

- Collect a representative water sample in a clean bottle in field
- Rinse a sterilized test bottle several times with sample water from field
- Fill the sterilized test bottle to the shoulder with the sample water from field (approximately 20 mL)
- Add the contents of one PathoScreen Medium powder pillow to the sample
- Put the cap on the bottle immediately
- Invert to thoroughly mix the sample with the medium
- Place the bottle for incubation for 24 to 48 hours
- Evaluate the reaction after 24 hours. If temperatures have varied significantly, continue to incubate negative samples for an additional 24 hours
- Record the test result: If the color changes from yellow to black or black precipitate forms, the test is positive. If there is no color change after 48 hours, the test is negative. Figure 22 shows two negative and two positive test samples.

The test bottles were sterilized between every test. The following sterilization procedure was followed:

- Add 10-12 drops of bleach solution to the test bottle, and put the cap on the bottle

- Swirl and invert the test bottle to completely cover the walls of the bottle and the inner surface of the cap
- Wait for two minutes
- Rinse with distilled water

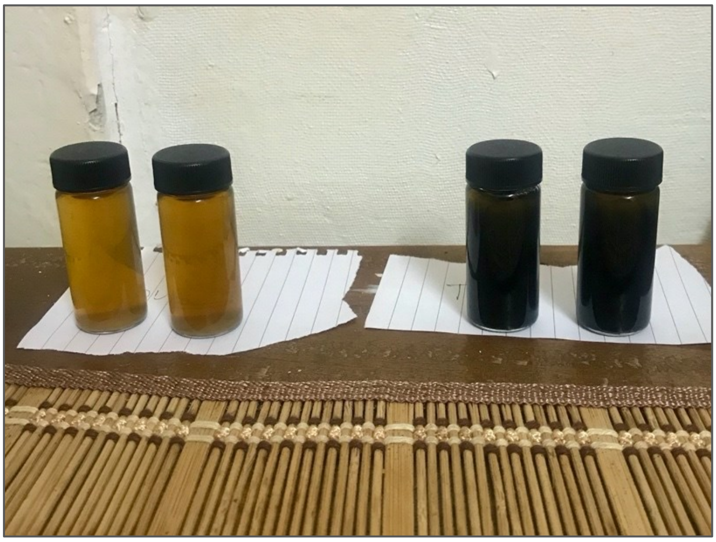


Figure 22: H_2S-test, two negative test samples (left) and two positive test samples (right)

The test samples were supposed to incubate at a constant temperature at 25-35 °C. However, the actual incubation temperatures were typically less than 25 °C. The PathoScreen Field Test Kit can be used to estimate the most probable number (MPN) which is the viable number of bacteria in a sample. However, that would require five test samples from the same water source to be incubated at the same time. This was not practical in field because the PathoScreen Field Test Kit only has five test bottles, and several water sources of interest were visited within few days. Therefore, the test was performed as a simple presence versus absence test without an estimation of the MPN.

3.2.7 Limitations of water quality testing

Water quality parameters were only tested once at each pumping station. Thus, the values obtained give an impression of the water quality at that particular time. However, water quality parameters may change over the course of time due to seasonal changes in rainfall and temperature, or due to pollution. Water samples were collected from the water taps instead of the borehole, to get samples that were representative for the water that was consumed. The water quality can however change during storage in the water tank. In the rainy season, the storage time is relatively long, because the water demand is low. The fieldwork was conducted in the rainy season, and it was observed that the water tanks were typically full and only a small amount of water, often less than 1000L, was collected each day. In the dry season, on the other hand, the water tanks can be filled and emptied several times a day. Increased storage times can cause particles to settle, reducing the turbidity. It is therefore possible that the water collected from the water taps has a higher turbidity in the dry season than in the rainy season.

3.3 Remote monitoring

A remote monitoring system, developed by a Norwegian company called El-Watch, was installed at three pumping stations, namely Endagaw chini, Basonyagwe and Mewadani. The purpose was to demonstrate that such a system can work in rural areas, and to evaluate the impact it may have on pumping system resilience.

3.3.1 System components

The remote monitoring systems consist of several sensors, a data transmission unit (gateway), a power supply, a regulator, and a user interface. The sensors record data which are transmitted to the gateway. Then, the gateway uses the mobile network to transfer data to the El-Watch cloud solution. Data is recorded by the sensors and sent by the gateway every 10 minutes. The gateway has an integrated eSIM that roams freely among most available networks and chooses the mobile operator with the best signal. Data can be downloaded from any browser with a protected login. A number of sensors were installed at each pumping station. All pumping stations have a pressure sensor (Neuron Pressure 0-2 Bar) installed on the outlet pipe of the water tanks, to measure the water level in the tank. Two of the pumping stations, Mewadani and Basonyagwe, also have another type of pressure sensor (UNIK5000) installed inside the borehole, submerged in water. UNIK5000 measures the water level inside the borehole, it needs a 7-32 V supply and has a measuring range of 0-100m. The remote monitoring systems also have two digitizers. The Neuron mA Digitizer converts the signal of UNIK5000 from mA (milli ampere) to a digital signal that the gateway can receive, whereas the Neuron VDC Digitizer measures the voltage of the electrical network.

The following list provides a complete overview of the remote monitoring system components:

- Solar panel: 4W, El-Watch
- Battery: VBT motorcycle battery 12V 9Ah
- Regulator: Solar LCD Controller 6A
- Cable with resistance
- Pressure sensor 1: UNIK5000 316SS, Druck
- Pressure sensor 2: Neuron Pressure 0-2 Bar, El-Watch
- Pressure sensor 3: Atmospheric pressure sensor, El-Watch
- Gateway: Neuron cellular gateway, El-Watch
- Digitizer current: Neuron mA Digitizer, El-Watch
- Digitizer voltage: Neuron VDC Digitizer, El-Watch
- User interface: https://neuronsensors.app

The following two additional sensors were tested in field but did not function satisfactory for the intended purposes:

- Temperature sensor: Neuron temperature air sensor, El-Watch
- Vibration sensor: Neuron vibration basic, El-Watch

Most of the system components were provided by El-Watch, including solar panel, gateway, Neuron Pressure, and digitizers. The pressure sensor called UNIK5000 was donated by NGI (Norges Geotekniske Institutt). The remaining system components, that is battery, cable with resistance, and regulator, were bought in Haydom, Tanzania.

3.3.2 System configuration

Figure 23 shows the remote monitoring system configuration (Endre Våland Bø, 28.01.2020). Most of the system components are connected in parallel through the regulator. The gateway and UNIK5000 run on electricity which is supplied by the battery during night and the solar panel during the day if it is sunny. The regulator makes sure that the battery is not over charged by the solar panel during daytime, and that power does not run backwards from the battery to the solar panel during night. One of the two types of pressure sensors, Neuron Pressure, is not included in Figure 23, because it is wireless. It does not need a power supply because it has internal batteries that can last for up to 15 years, and data is transmitted wirelessly to the gateway. Figure 23 displays the system configuration in Mewadani and Basonyagwe. Endagaw chini does not have the UNIK5000 sensor and thus the system configuration is a bit different at that pumping station.

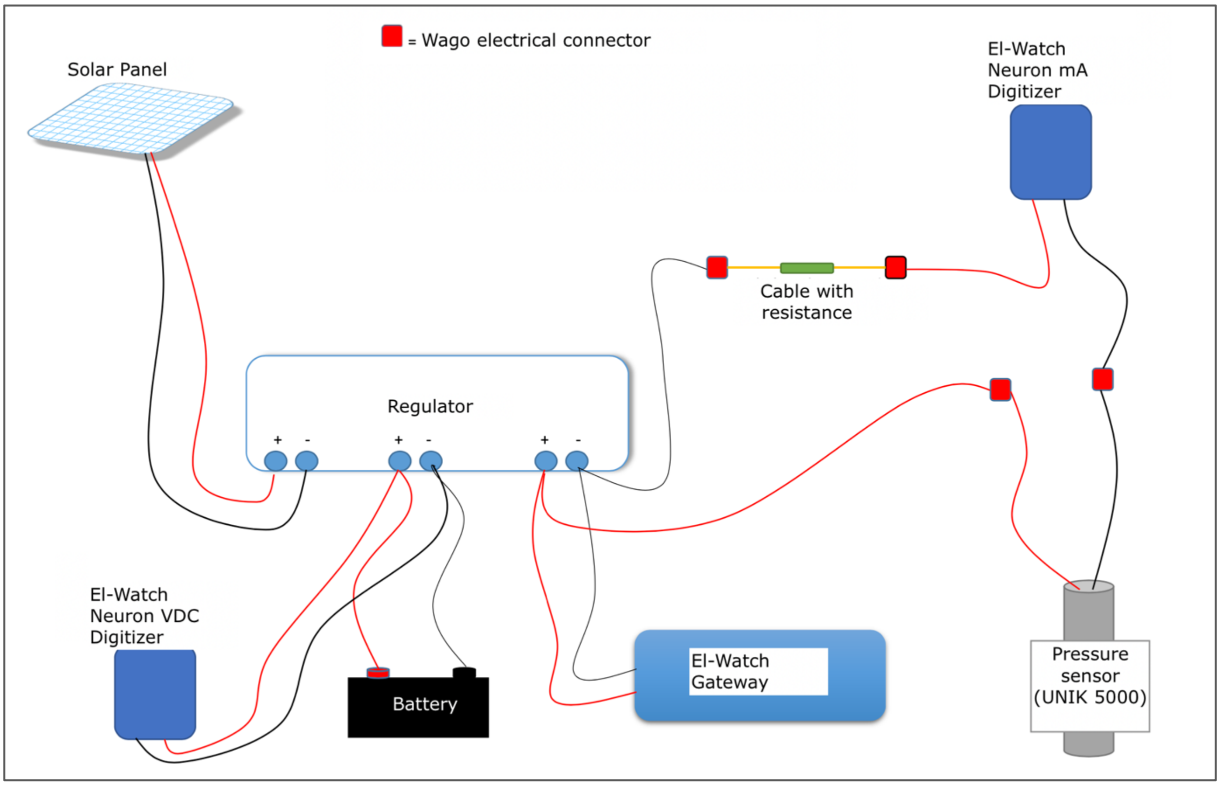


Figure 23: Remote monitoring system configuration (Endre Våland Bø, 28.01.2020)

3.3.3 User interface

The user interface of the El-Watch remote monitoring system is a webpage called *https://neuronsensors.app*. Special permission and a user account are required for access. The frontpage of the webpage shows the most recent updates of each parameter at a given pumping station (Figure 24). The user can navigate between different pumping stations by choosing different tabs. When choosing a parameter, a graph that shows how that parameter has varied in the last 24 hours is displayed. If the user then chooses *details*, the time interval of the graph can be changed according to the preferences of the user. Time series of data can be exported to Microsoft Excel as well as to other spreadsheet programs.

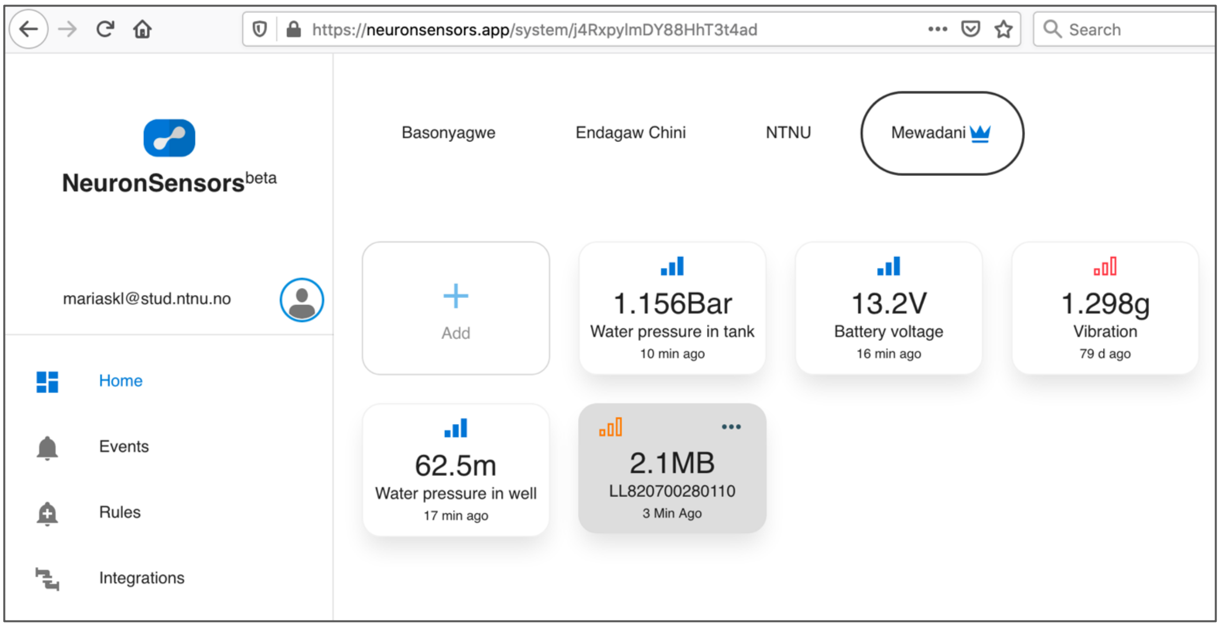


Figure 24: User interface, https://neuronsensors.app

3.3.4 System installation

The remote monitoring systems were installed on the 29-31th of January 2020. The majority of the system components need protection from sun and rain. Therefore, the gateway, the cable with resistance, and the Neuron mA Digitizer were placed inside a plastic box (Figure 25a). The plastic box, the battery, the regulator, and the Neuron VDC Digitizer were placed inside a wooden box (Figure 25b). Wood and plastic were recognized as suitable materials since they do not block the signal of the gateway. The wooden and plastic boxes were purchased from the workshop of HLH. A padlock protects the contents of the wooden box against theft. The wooden box is attached to the solar panels for protection against sun and rain (Figure 25c). The sensors and the gateway have QR-codes, as shown in Figure 25a. To add the components to the El-Watch system, the QR-codes were scanned with a smartphone. The solar panel of the remote monitoring system is attached to the solar panels of the water pumping station for optimum insolation (Figure 26).

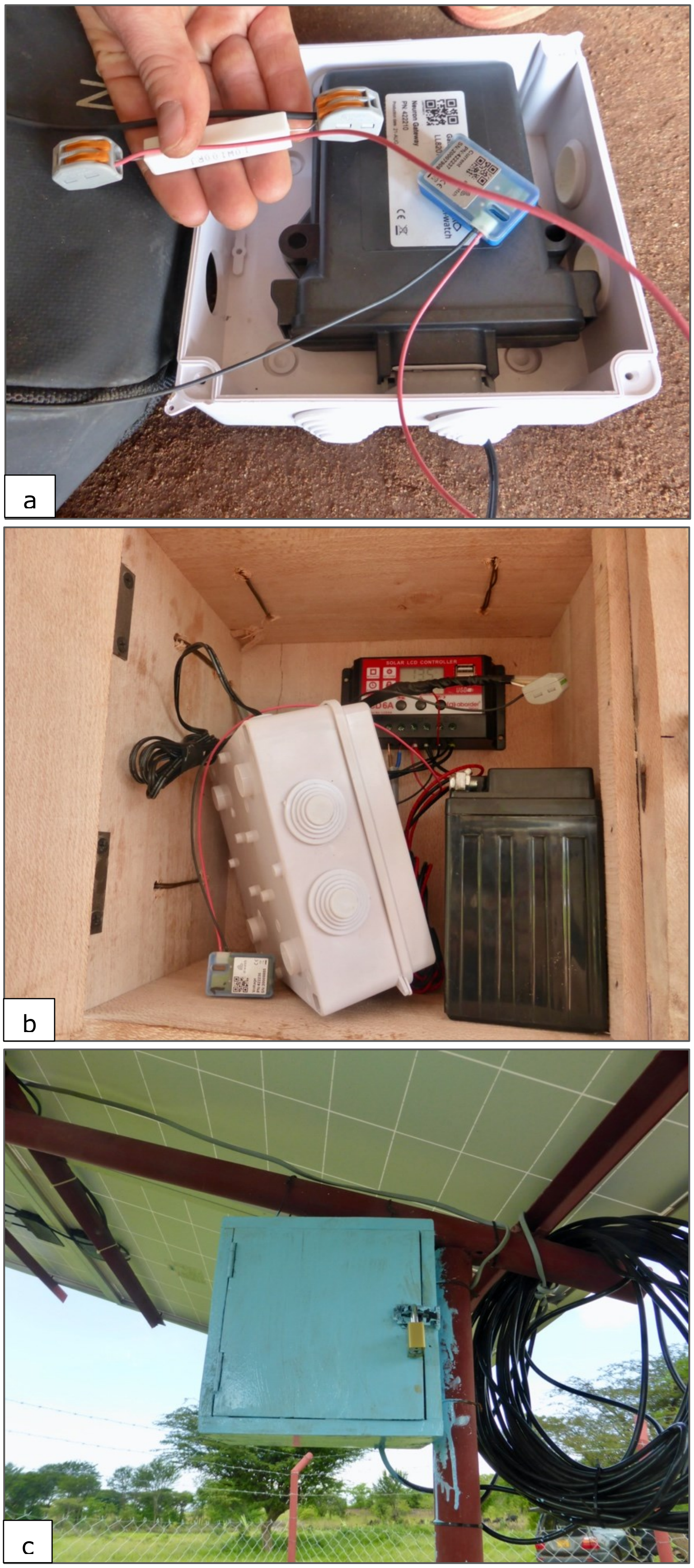


Figure 25: a) Plastic box containing gateway, cable with resistance and Neuron mA Digitizer b) System components inside wooden box, c) Wooden box attached to solar panels of pumping station

Figure 26: Solar panel of remote monitoring system attached to solar panels of water pumping station

The UNIK5000 Pressure sensor was installed inside the borehole. Figure 27a shows the cable of the sensor entering the borehole. The cable runs from the borehole to the wooden box protected inside a tube which was buried underground (Figure 27b). The excess part of the cable was coiled and hung next to the wooden box (Figure 25c).

Figure 27: a) Cable of UNIK5000 entering the borehole, b) Tube containing the cable of UNIK5000

The Neuron Pressure 0-2 bar sensor (Figure 28a) was installed by a plumber volunteering at Haydom Lutheran Hospital. The sensor was installed on the outlet pipe of the water tanks, below the valve that controls the water flow between the water tanks and the water tap. The valve was closed during installation. Sensors developed by El-Watch are not designed to tolerate rain and heat exposure. A plastic basin was therefore installed for protection (Figure 28b).

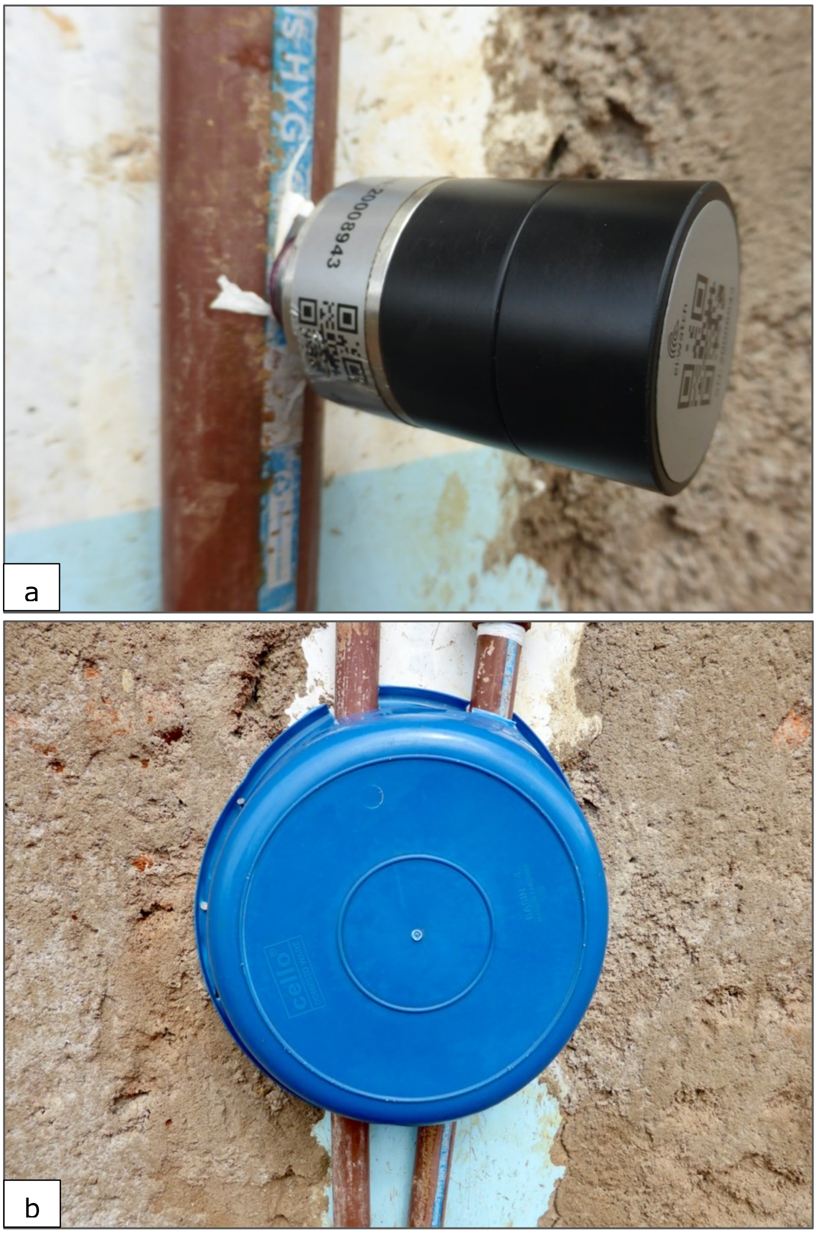


Figure 28: a) Neuron Pressure 0-2 bar and b) Plastic basin for protection

3.4 Interviews with key stakeholders

Stakeholders were interviewed to gather information about a wide range of topics including repairs, operation and maintenance, division of responsibilities, water consumption habits, and attitudes towards remote monitoring. The informants were COWSO and PETS committee members, district water engineers (DWEs), and 4CCP employees. Three types of interviews were conducted; namely focus group interviews, in-depth interviews, and surveys. Focus group interviews and in-depth interviews were recorded on tape and transcribed. The respondents were always asked for permission. Notes were taken during interviews in case something would go wrong with the audio files. The participants of the survey filled in their answers on printed question sheets. Interview questions for the various stakeholders and the survey are given in Appendix 3-7.

3.4.1 Focus group interviews

A focus group interview is an interview in which a group of informants are gathered to discuss one or several topics of interest (Tjora, 2017). This is an efficient way of generating information because data is collected from several informants at the same time. Focus group interviews were used to interview COWSO and PETS committees. It was thought that interviewing a group of committee members would give a more nuanced impression of the general opinion within the committee than just interviewing one member. The interviews were done at the pumping stations and the number of people participating depended on the number of committee members showing up. Usually, there was approximately ten members present from the COWSO and PETS committee combined.

Figure 29: Focus group interview in Basonyagwe village

There are several challenges and sources of uncertainty related to the method of focus group interviews. According to Morgan (1997), focus group interviews should have 6-12 participants. The number should be high enough to represent several different opinions, but small enough for participants to feel comfortable talking in front of the group. Although there usually were less than 12 participants, some participants were considerably more active than others. In addition, men were typically more involved in the discussion than women. Thus, it is likely that certain opinions did not get expressed. A 4CCP employee was present to translate between Swahili and English. Translation is a difficult task, as it requires substantial knowledge of the two languages and nuances and details can easily get lost. 4CCP did a good job at translating, but we could have been better at asking for clarification to avoid misunderstandings. The process of translating took a lot of time and made the interview tiering for both researchers and informants. It is possible that the presence of 4CCP employees affected the informants. 4CCP has mobilized communities to contribute to the water supply project and they have been in charge of the training of COWSO and PETS committee members. The presence of 4CCP could have made informants less inclined to criticize the support they receive from 4CCP or the project in general. In addition, the presence of the researchers is also likely to have affected the informants to some degree. For instance, the researchers may have been perceived as representatives of NCA thereby making informants less inclined to criticize the project.

3.4.2 In-depth interviews

An in-depth interview uses open-ended questions which give the informants the possibility of describing what they want to tell in detail (Tjora, 2017). This type of interview is used where one wants to study opinions, attitudes and experiences. Interviews of DWEs and 4CCP employees were in-depth interviews. Some simple questions about work tasks and responsibilities were typically asked in the beginning of the interview. Then, questions requiring more reflection were asked regarding topics such as the potential of remote monitoring and challenges of solar-powered water pumping. The interviews were always carried out at the office of the informant.

3.4.3 Surveys

A survey uses close-ended questions with rigid answer alternatives (Tjora, 2017). The survey conducted in field had 87 respondents in total. The purpose was to generate some statistics on topics such as willingness to pay for water services, water consumption, and water collection time and distance. Each survey participant got a printed copy with questions to answer. The question sheets were handed out after the focus group interviews with the COWSO and PETS committee. Anyone who was present at the pumping station at that time could participate in the survey. However, the majority of people volunteering to participate were committee members. This could ultimately have affected the results, since it is probable that the average committee member answered differently than the average villager. The question sheet was in English and thus the questions were translated to Swahili orally by a 4CCP employee. Most of the survey participants wrote their answers in English assisted by the 4CCP employee. There could have been some misunderstandings in this process because the 4CCP employee had to answer many questions in a short period of time. In retrospect, the question sheet should have been in Swahili, and participants should have been encouraged to answer in Swahili. The answers could have been translated to English later together with 4CCP.

Figure 30: Survey participants filling out question sheets together with 4CCP employee Ahadi Mollel Ladeson

3.5 Literature review and analysis of technical documentation

A literature review is an examination of published sources on a specific topic. This is an important part of the research process as it increases the understanding of a subject area (Given, 2008). The background sections of chapter 4 to 8 aim to put the research questions of each of those chapters into context by presenting relevant theories and research results from various literary sources. A wide range of sources were used including research articles, documents from international institutions such as the World Bank and the World Health Organization (WHO), and books that are on the curriculum of the civil engineering course. Research articles were generally found on Web of Science, which is a website that provides articles from a number of academic disciplines. Technical documentation about the pumping stations was provided by NCA, and included water well drilling reports, pumping tests, and pumping station specifications. These documents were used to complement the data collected during the fieldwork. However, some documents were unavailable. For instance, drilling reports and pumping tests were only available for five of the 14 pumping stations visited, and pumping station specifications were available for nine of the 14 pumping stations visited. This ultimately put some limitations on the analysis carried out in this thesis.

4 Water quantity

When COWSO members were asked about the challenges regarding the solar-powered water pumping systems, a reoccurring answer was that water provision in the dry season does not cover the demand. A COWSO member in Murukuchida village described the problem in the following way: "Inlet is less than outlet. For these two tanks to be filled it takes one day. But it can take two to four hours to complete the tanks. The pumping capacity is very low compared to the consumption."

This chapter investigates the issue of water quantity by addressing the following research question: *To what extent do the pumping systems succeed in supplying sufficient quantities of water to the beneficiaries?*

4.1 Background

The effectiveness of solar-powered water pumping systems depends on the relationship between supply and demand. Supply is determined by factors related to hydrogeology, pump choice, and pipe system. Demand, on the other hand, is typically determined by factors such as price of water, reliability, distance to source, and time to wait in line. The time of year also makes a significant impact on demand, as a number of water sources are unavailable in the dry season thereby putting additional pressure on the pumping stations. This section gives a brief introduction to the theory behind water demand and supply estimations.

4.1.1 Water supply estimation theory

To determine the quantity of water supplied by a pumping system one has to consider the characteristic curve of both the pump and the pipe system. The purpose of a pump is to add energy, usually expressed as head (energy per unit weight) to a liquid (Butler and Davis, 2011). The hydraulic performance of a pump is described by the pump characteristic curve, which is typically provided by the pump manufacturer, and gives information about the pump's ability to produce flow against certain head (ibid). Figure 31a shows a typical pump characteristic with generally reducing head for increasing flowrate.

The pipe system that the pump is connected to also has its own characteristic curve: the system characteristic curve (ibid). Water must be given head to:

- Be lifted physically
- Overcome energy losses due to pipe frictions and local losses at bends, valves etc.
- Provide velocity head if the water is discharged to the atmosphere at significant velocity

Thus, the system characteristic can be determined from:

$$Head = static\ lift + losses + velocity\ head \qquad \text{Equation 1}$$

Figure 31b shows a typical system characteristic curve. If a specific pump is to be connected to a specific system, there is only one point where the pump is capable of offering what the system requires: it is the point where the system characteristic curve and the pump characteristic curve meet (Figure 31c). This is called the operating point (ibid).

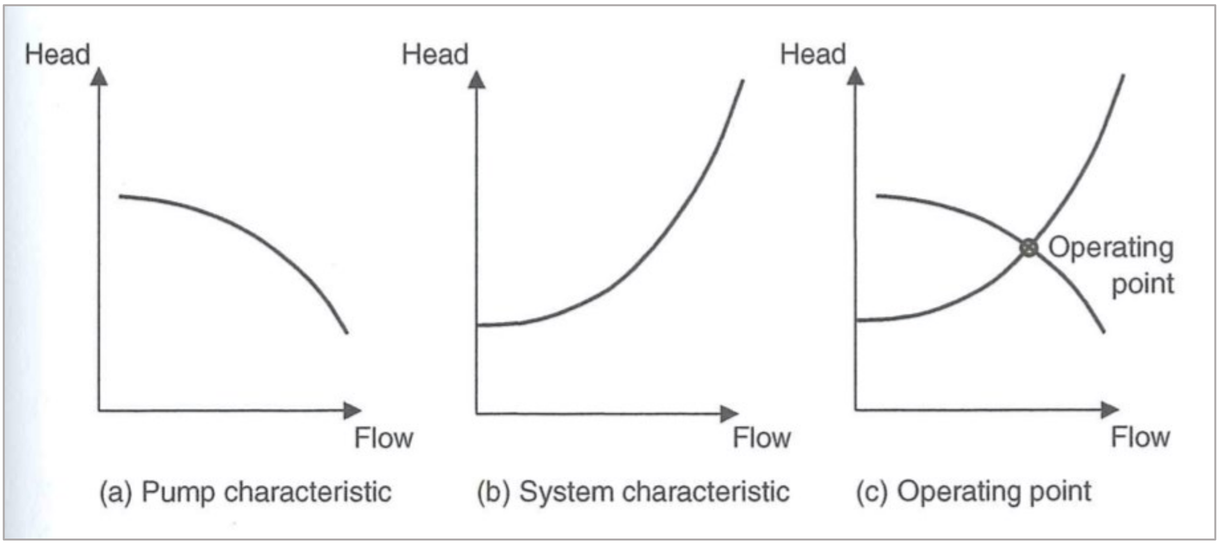


Figure 31: Pump and system characteristic curves (Butler and Davis, 2011)

Static lift, in the case of solar-powered water pumping systems, is the vertical distance from the water surface in the well to the inlet of the water tanks. In practice, this is the dynamic water level (DWL) in addition to the height of the water tank inlet above the ground surface. Theoretically, if the water level inside the tank is above the inlet to the tank, the water level adds to the head. However, that is not the case for the water tanks in question. The DWL is the vertical distance from the ground surface to the water level within the borehole during pumping. When pumping occurs, water is extracted from the aquifer, and thus the water level drops inside and around the borehole. This is called a drawdown. The DWL is usually determined by a pumping test (World Bank, 2018b).

Energy losses can be divided into friction losses and local losses. When water flows through a pipe, friction occurs between water and the pipe walls and within the fluid due to turbulence (Ødegaard, 2014). This causes a friction loss along the pipe which is turned into heat. The friction loss can be determined according to the Darcy-Weisbach equation:

$$h_f = f\frac{L}{D}\frac{v^2}{2g} \qquad \text{Equation 2}$$

Where *f* is the friction factor (-), *L* is the pipe length (m), *D* is the pipe diameter (m), *v* is the water velocity (m/s), and *g* is the acceleration of gravity (m/s^2). The friction factor can be determined iteratively from the implicit Colebrook-White equation (Butler and Davis, 2011). Moody's diagram, which is a graphical representation of the Colebrook-White equation, eliminates the trials otherwise necessary to find an accurate solution for the friction factor (Swamee and Jain, 1976). This is a plot of the friction factor (f) against Reynolds number (R_e) for a range of values of relative roughness (k_s/D). The equivalent sand roughness size (k_s), is a measure of the pipe wall roughness (Butler and Davis, 2011). Numerous approximations of the Colebrook-White equation have been proposed. This thesis uses the explicit equation suggested by Swamee and Jain (1976), which has an error of less than ±1% for Reynolds numbers (R_e) between 5000 and 10^8:

$$f = \frac{0.25}{\left[\log\left(\frac{k_s}{3.7D} + \frac{5.74}{{R_e}^{0.9}}\right)\right]^2} \qquad \text{Equation 3}$$

Where Reynolds number (R_e) is given by:

$$R_e = \frac{vD}{\nu} \qquad \text{Equation 4}$$

Where ν is the kinematic viscosity of the fluid (m^2/s).

Local losses occur at points in the pipe system where the flow is disrupted, such as bends and valves (Butler and Davis, 2011). Local losses are usually expressed in terms of velocity head:

$$h_L = k_L \frac{v^2}{2g} \qquad \text{Equation 5}$$

Where k_L is the local loss coefficient.

In solar-powered water pumping systems, *velocity head* is not included in the total head because water is not discharged to the atmosphere with a high velocity. Thus, the system characteristic is determined from:

$$Head = DWL + (vertical\ distance\ from\ gound\ surface\ to\ inlet\ of\ water\ tanks) + friction\ losses + local\ losses \qquad \text{Equation 6}$$

The quantity of water delivered by a solar-powered water pumping system is likely to vary between days and over the course of a year. For instance, cloudy weather may cause reduced output or no output depending on the intensity of the cloud cover and the features of the pumping system. The duration of cloud cover is also essential, especially for variable speed drives coupled with AC pumps which tend to give worse performance under stop-start solar conditions, since they require minimum power conditions to start, and take considerable time to spool up once threshold levels are reached (World Bank, 2018b). Groundwater levels vary naturally over the course of a year in accordance with precipitation levels, which in turn affects the DWL, the system characteristic, and hence the flowrate of the pump. Seasonal variations in solar radiation will also have an impact on water output.

4.1.2 Water demand estimation theory

Studies on domestic water demand in developed countries have focused mostly on price of water and income elasticities (Nauges and Whittington, 2010). In economics, the term *income elasticity* refers to the responsiveness of quantity demanded for a good or service to a change in income. Households in developed countries typically receive water from piped water networks and tap water of good quality is generally used for all water consuming activities (ibid). These characteristics make it relatively straightforward to do domestic water demand estimations. In developing countries however, households typically rely on a variety of sources with different characteristics related to for instance water quality, price, reliability, and distance to source (ibid). This makes water demand estimations complex.

Fedrizzi et al. (2009) described some of the challenges related to the determination of water demand in rural low-income communities. For instance, in areas where obtaining water is difficult due to for example distance or cost, the demand is typically repressed. If the situation changes so that water becomes easily available, water use is likely to increase considerably. The exact amount by which the water use will increase is not easily calculated since beneficiaries might find it difficult to determine their repressed demand until their access to water is improved (ibid). However, the fewer restrictions of the new water supply system, in terms of for instance price and accessibility, the larger the increase in water use is likely to be. This should be taken into account when planning a project. Anticipated population growth must also be considered in water demand calculations (ibid). In addition to the natural demographic growth, there could be migration of people who are looking for better access to water supply services. This is likely to occur if only a few communities in an area gets access to improved water supply infrastructure (ibid).

Efforts have been made to determine minimum water consumption requirements. Research indicates that 20 liters per person per day is the minimum quantity of water required to realize minimum essential levels for health and hygiene (Reed and Reed, 2013). However, even if vast amounts of water are provided, there may be other limits to its use, such as distance to source and the time to wait in line to collect it. Factors such as reliability of the water source and costs of water also have an impact on volume used by households (Howard and Bartram, 2003). Thus, it has been argued that defining a minimum amount has limited significance. Accessibility can be categorized in terms of service level. Table 2 shows how different service levels, with associated distance and collection times, influence the needs met and the level of health concern.

Table 2: Requirement for water service level to promote health (Howard and Bartram, 2003)

Service Level	**Access measure**	**Needs met**	**Level of health concern**
No access (quantity collected often below 5 L/person/day)	More than 1000m or 30 minutes total collection time	Consumption – cannot be ensured Hygiene – not possible (unless practiced at source)	Very high
Basic access (average quantity unlikely to exceed 20 L/person/day)	Between 100 and 1000m or 5 to 30 minutes total collection time	Consumption – should be ensured Hygiene – handwashing and basic food hygiene possible; laundry/bathing difficult to ensure unless carried out at source	High
Intermediate access (average quantity about 50 L/person/day)	Water delivered through one tap on-plot (or within 100m or 5 minutes total collection time)	Consumption - ensured Hygiene – all basic personal and food hygiene ensured; laundry and bathing should also be ensured	Low
Optimal access (average quantity 100 L/person/day and above)	Water supplied through multiple taps continuously	Consumption – all needs met Hygiene – all needs should be met	Very low

Water used for domestic purposes cannot always be easily distinguished from productive use at the household level. In fact, there are cases in which water for domestic animals and irrigation is part of a household’s basic needs because these activities are crucial for survival (Fedrizzi et al., 2009). Ensuring access to water for small-scale productive activity, for example where this involves food production, may also give important health and social gains (Howard and Bartram, 2003).

4.2 Results

This section presents the results of the water supply and demand estimations, as wells as an evaluation of whether the water provision is sufficient to cover the demand.

4.2.1 Water supply estimations

The supply estimations are based on technical information from NCA, the pump manufacturer (Davis and Shirtliff), as well as field investigations. The estimations were carried out for nine of the fourteen pumping stations visited, due to lack of data for the five remaining pumping stations.

The head was calculated by Equation 6 (page 37). The DWL was given by NCA based on pumping tests carried out prior to the installation of the solar-powered water pumping systems. The vertical distance from the ground to the inlet of the water tanks is approximately 5.4m, according to information from NCA. The friction loss can be divided into four parts as indicated in Figure 32: Friction loss in riser main (1), friction loss in the pipe running along the ground from the borehole to the building that the tanks stand on (2), friction loss in the vertical pipe (3), and friction loss in the horizontal pipes that go into the water tanks (4).

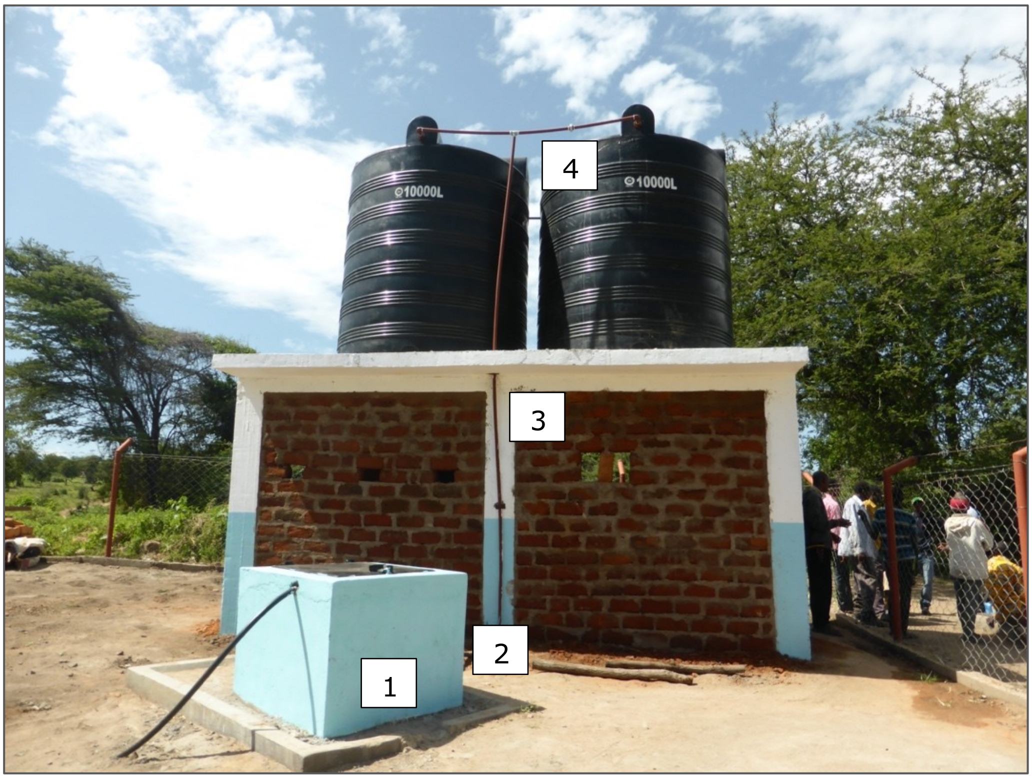


Figure 32: Borehole and water tanks at Hilamoto pumping station. The numbers 1-4 illustrate different sections for friction loss measurements

The local losses are due to two 90° bends, pipe inlet, outlet to the water tanks, and a T-cross. Table 3 describes how the different parameters to calculate friction losses and local losses were found.

Table 3: Parameters used in estimating friction losses and local losses

Parameter	Method to find parameter
Pipe length, L (m)	• (1) Riser main: Distance from pump to borehole top. Values given by Dennez Engineering Limited. • (2) Pipe along ground: Values were assumed based on photos taken in field. These are only approximate values, since the length was not measured. • (3) Vertical pipe: Approximately 5.4 m based on information from NCA • (4) Horizontal pipes: Approximately 2m based on photos from field, the actual length was not measured
Pipe diameter, D (m)	• (1) Riser main: Given in pump specifications of Davis and Shirtliff (1½"=38.1mm or 1¼"= 31.75mm, depending on the pump type) • (2) Pipe along ground: Assumed to be equal to (1) • (3) Vertical pipe: The pipe is SAM-UK 1"x4.9mm, which means that the outer diameter is 1"=25.4mm and the wall thickness is 4.9mm, which gives an inner diameter of 15.6mm • (4) Horizontal pipes: Same as (3)
Velocity of water, v (m/s)	Calculated by the following equation: $v = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}D^2}$ Where Q is flowrate (m^3/s), and A is cross-sectional area of the pipe (m^2)
Acceleration of gravity, g (m/s^2)	9.81
Friction coefficient, f (-)	• Found using the explicit equation of Swamee and Jain (1976), Equation 3 (page 36). R_e, and therefore also f and h_f, changes with velocity and diameter. • The water temperature in the well is approximately 24 °C, according to Diver-measurements. Thus, the kinematic viscosity (ν) of water was set to $9.121 \cdot 10^{-7} m^2/s$. • The roughness ($k_s$) was set to 0.2mm which is commonly assumed for plastic materials such as PVC (VA/Miljø-blad, 2016)
Local loss coefficient k_L	From Butler and Davis (2011, p. 159): • Pipe entry from pump k_L = 0.5 • 90° pipe bend (sharp bend) k_L = 1.0 • Pipe exit (sudden) k_L = 1.0 From Ødegaard (2014, p. 74) • T-cross: k_L = 1.0

The pump characteristic curve and the system characteristic curve were plotted in the same diagram for each of the nine pumping stations to find the operating points. The pump curves were provided with the product specifications of the pumps, and the system curves were calculated as described above. Figure 33 shows the pump and system curves of Murukuchida, which has an operating point at a flowrate of 3.3 m^3/h and a head of 88.4m. Appendix 8-9 shows the details of how the system characteristic curves were calculated.

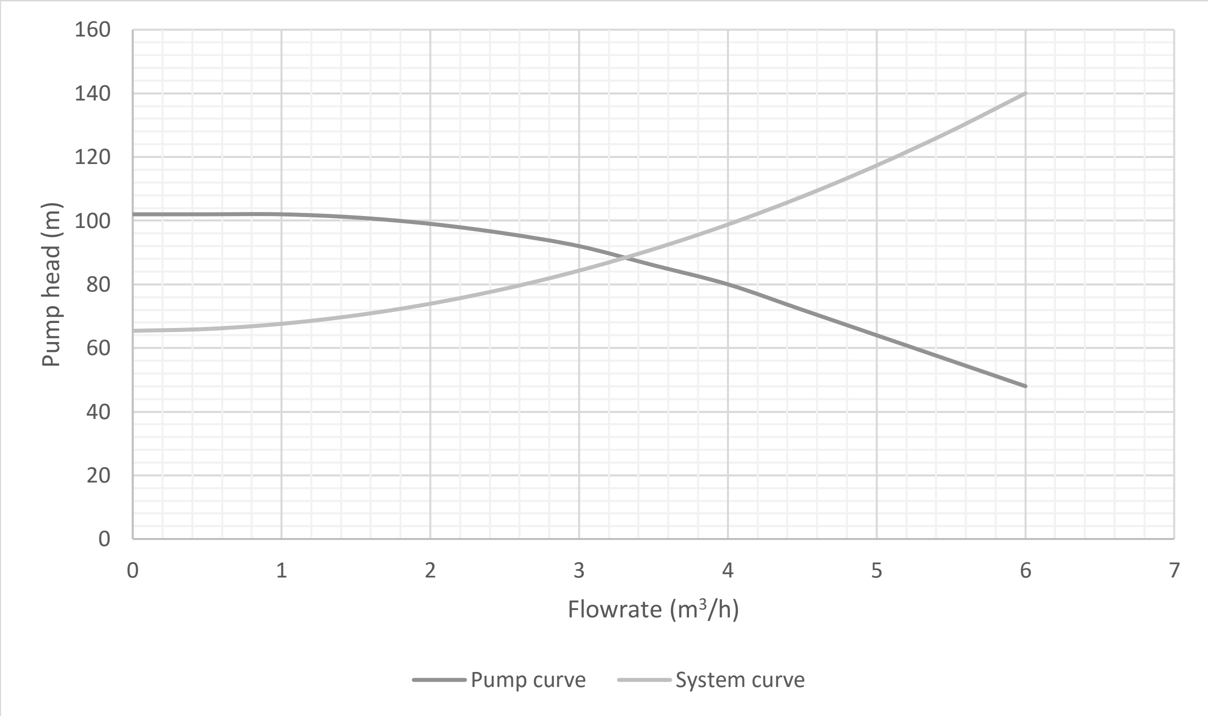


Figure 33: Pump characteristic curve and system characteristic curve for Murukuchida

Table 4 presents operating points of the nine pumping systems considered. Values for pump yield and borehole yield specified by the contractor (Dennez Engineering Limited) are included for comparison. The borehole yields were determined by pumping tests carried out by Trust Engineering and are perceived as the maximum flowrates that the boreholes can give. It is assumed that the term *pump yield* refers to the flowrate during operation and thus is directly comparable to the flowrate calculated in this chapter. However, it is not known how the pump yields were determined. Table 4 shows that the flowrates found from the procedures described above deviate from the pump yields given by Dennez Engineering Limited by ± 0 – 0.7 m^3/h. The exception is Mewadani, which has a significantly smaller flowrate than indicated by the pump yield specified by Dennez Engineering Limited.

Table 4: Operating points compared to pump and borehole yields

Village	District	Pump type	Assumed DWL (m)	Operating point		Pump yield (Dennez) (m^3/h)	Borehole yield (Dennez) (m^3/h)
				Head (m)	Flowrate (m^3/h)		
Mewadani	Mbulu	DSP 3-16	70	87,8	2,2	6	39
Basonyagwe	Mbulu	DSP 5-16	56	86,9	3,4	4	5
Murukuchida	Mbulu	DSP 5-16	60	88,4	3,3	3	6,6
Harar	Mbulu	DSP 5-16	54	85,9	3,5	4	4,5
Gidurudagew	Mbulu	DSP 3-16	75	90,8	2,0	2	2,5
Diling’ang	Hanang	DS 2-23	86	99,8	1,7	1	2
Hilamoto	Mkalama	DS 3-18	55	79,5	2,8	2,5	3
Gidbyo	Mbulu	DSP 3-16	47	73,8	2,8	2,5	3,2
Isene	Mkalama	DSP 5-12	17	56,8	4,1	4	5,4

A bucket test was conducted at several pumping stations to determine the flowrate of the boreholes in field. The test procedure is described in chapter 3.1.2 (page 19). Table 5 compares theoretical flowrates to those measured by the bucket test. It should be noted that the theoretical flowrates in Table 4 are not directly comparable to the flowrates found by the bucket test, since the losses in the pipes connecting the riser main to the water tanks were included in the calculations. Therefore, new system characteristic curves which only consider the friction loss in the riser main and the singular losses in the pipe inlet and one bend, were used to find the theoretical flowrates in Table 5. There are several uncertainties related to the bucket test as explained in chapter 3.1.2. Thus, the uncertainty was set to ±1 L and ±1 s for the measured volume and time, respectively. The percentage uncertainty of the flowrate of the bucket test was found by adding the fractional uncertainties of volume and time in quadrature.

Table 5: Theoretical flowrate compared to flowrate measured in field

Village	District	Pump type	Assumed DWL (m)	Operating point		Flowrate, bucket test (m^3/h)
				Head (m)	Flowrate (m^3/h)	
Mewadani	Mbulu	DSP 3-16	70	75,3	2,8	1,4 ± 0,3
Basonyagwe	Mbulu	DSP 5-16	56	63,1	5,1	2,7 ± 0,1
Murukuchida	Mbulu	DSP 5-16	60	65,7	5,0	3,0 ± 0,3
Harar	Mbulu	DSP 5-16	54	60,7	5,3	3,7 ± 0,2
Gidurudagew	Mbulu	DSP 3-16	75	79,3	2,6	2,5 ± 0,2
Hilamoto	Mkalama	DS 3-18	55	89,2	3,6	3,1 ± 0,3
Gidbyo	Mbulu	DSP 3-16	47	61,0	3,5	3,3 ± 0,3
Isene	Mkalama	DSP 5-12	17	56,0	6,5	5,1 ± 0,5

The flowrate found in field by the bucket test is lower than the theoretical flowrates for all nine pumping stations considered, as shown in Table 5. Diling'ang is not included in the table, because a bucket test was not performed at that pumping station. The gap between theoretical and measured flowrate is largest in Basonyagwe and smallest in Gidurudagew.

4.2.2 Water demand estimations

The demand estimations are based on interviews with COWSOs and on a survey in which 87 community members participated.

The COWSOs were asked about average domestic water use. However, the answers were not based on records, but rather on the perception within the COWSO of the typical daily water quantity used. Usually, the answer was given in daily water use per household, with the exception of Murukuchida village who specified the daily water use per person. Most COWSOs gave an average value, but Gidurudagew, Diling'ang, and Murukuchida gave a range that the average value is likely to be found within. The average number of people per household is seven, according to the survey. Table 6 presents the answers of the COWSOs as well as the average water use per person per day assuming seven people per household. The values vary from 14 to 69 L/person/day and the average is 42 L/person/day.

Table 6: Average domestic water consumption based on answers from COWSOs

Village	District	What is the average domestic water use in the village?	Average domestic water use per person (assuming 7 people per household)
Endagaw Chini	Mbulu	480 L / household	69 L/person
Mewadani	Mbulu	100 L / household	14 L/person
Basonyagwe	Mbulu	480 L /household	69 L/person
Murukuchida	Mbulu	40 - 60 L / person	50 L/person
Endanachan	Mbulu	200 L / household	29 L/person
Harar	Mbulu	480 L / household	69 L/person
Gidurudagew	Mbulu	60 - 720 L / household	56 L/person
Diling'ang	Hanang	100 - 400 L / household	36 L/person
Hilamoto	Mkalama	250 L / household	36 L/person
Gidbyo	Mbulu	120 L / household	17 L/person
Isene	Mkalama	100 L / household	14 L/person

Data from the survey gave an average water use of 24 L/person/day. This value was calculated from answers to the following two questions:

- Number of people in household: ________
- How much water does your household use on an average daily basis?

For each respondent, the water use of the household was divided by the number of people in that particular household. Then the average for all the respondents was calculated.

Factors that are likely to have an impact on water use were investigated based on the survey. Answers to the following questions were looked into:

- How much do you currently pay for water?
- What is the distance to your water source?
- How long do you normally wait in line at your water point?
- How much time is usually spent collecting water in total (travel + waiting time)?

For each question, the respondents were divided into groups according to their answers. The results are displayed in Figure 34 - Figure 37. The labels on the horizontal axis divides the respondents into groups according to their answers. Median water use within the household of the respondents is plotted on the vertical axis, indicated by grey dots. The median water use within each group is also shown in the figures, indicated by black squares.

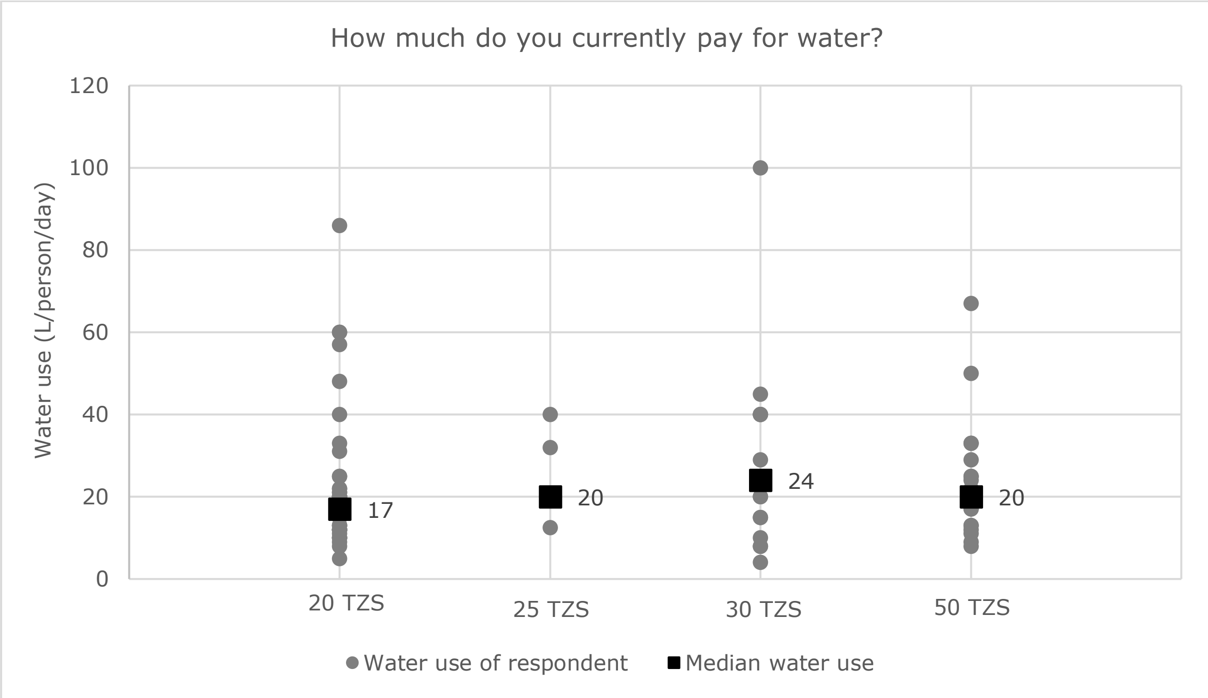


Figure 34: Water use in relation to price per 20 L bucket of water

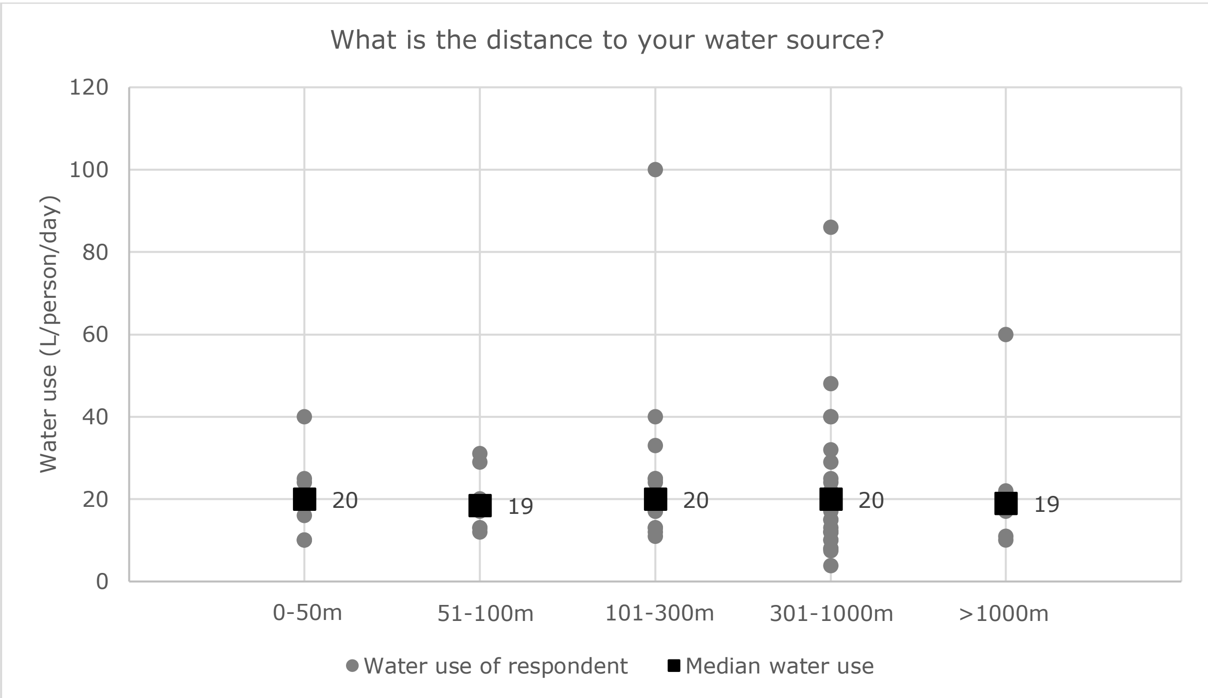


Figure 35: Water use in relation to distance to water source

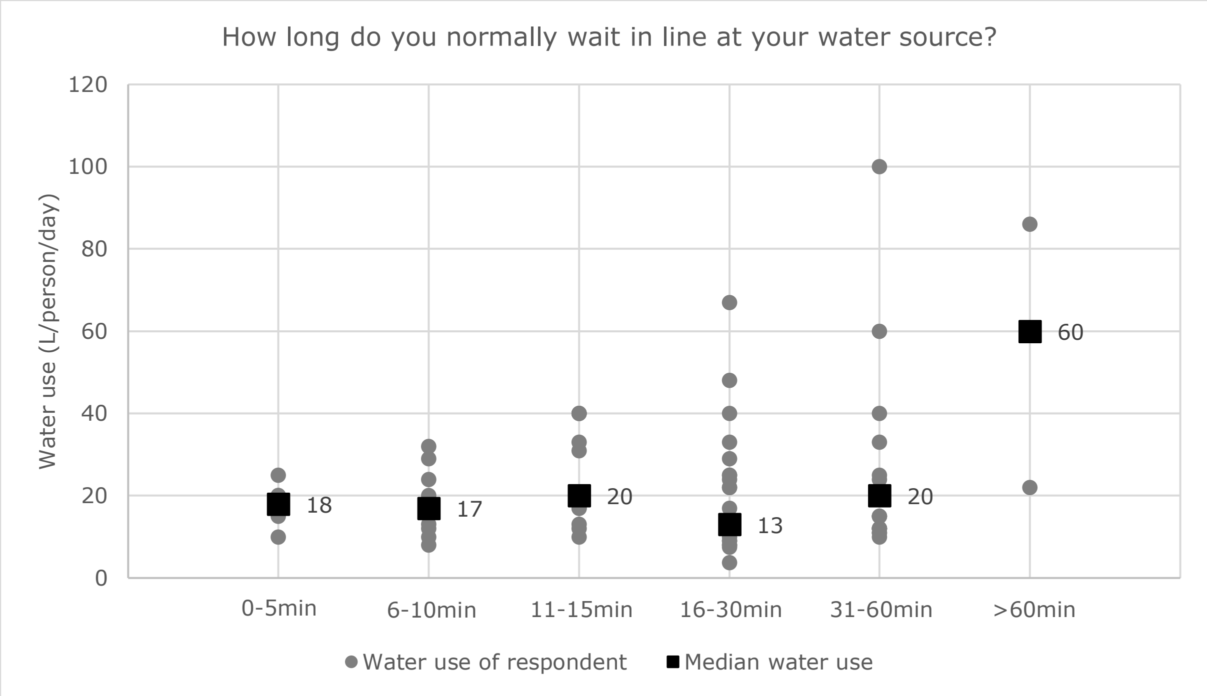


Figure 36: Water use in relation to time to wait in line at water source

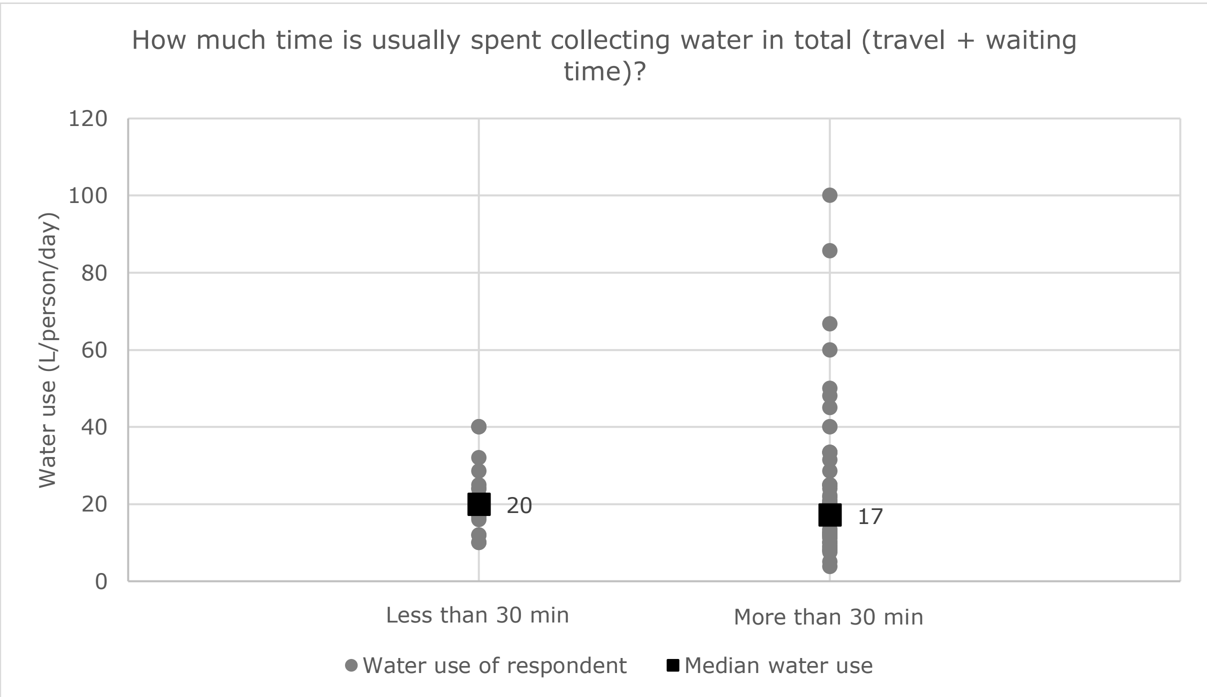


Figure 37: Water use in relation to time spent on fetching water

It was expected that beneficiaries would use less water with a higher price per bucket, longer distance to water source, and longer time to wait in line. These relationships are not very prevalent in the study area, as shown in Figure 34 - Figure 37. The group who pays the least per bucket of water even has the lowest median water use (Figure 34). Figure 37 does however show that the median water use is lower for those who spend more than 30 minutes collecting water compared to those who spend less than 30 minutes.

4.2.3 Comparison of supply and demand

This section combines the supply estimations of chapter 4.1.1 and the demand estimations of chapter 4.1.2. The number of people connected to each pumping station was reported by the respective COWSOs. A water demand of 24 L/person/day was used in the calculations. Some of the villages use water for productive activities in addition to domestic purposes. The main water consuming productive activity is keeping livestock such as cattle. Therefore, COWSOs were asked whether water is used for cattle and how many cattle they have in the village. It was found that the following five villages use water for cattle: Basonyagwe, Murukuchida, Harar, Hilamoto, Gidbyo. It was reported in the interviews that one cow consumes on average 20 L of water per day. For the supply calculations, it was assumed that the pump runs efficiently for eight hours per day. Table 7 shows water supply minus domestic demand as well as water supply minus total demand.

Table 7: Water supply and demand of nine solar-powered water pumping systems

Village	Number of people	Number of cattle	Domestic water demand (m^3/day)	Productive water demand (m^3/day)	Flowrate (m^3/hour)	Water supply (m^3/day)	Supply minus domestic demand (m^3/day)	Supply minus total demand (m^3/day)
Mewadani	805	-	19,3	-	2,2	17,4	-1,9	
Basonyagwe	900	1900	21,6	38,0	3,4	27,4	5,8	-32,2
Murukuchida	2900	6600	69,6	132,0	3,3	26,3	-43,3	-175,3
Harar	2324	3320	55,8	66,4	3,5	28,2	-27,6	-94,0
Gidurudagew	960	-	23,0	-	2,0	16,1	-7,0	
Diling’ang	1800	-	43,2	-	1,7	14,0	-29,2	
Hilamoto	2300	850	55,2	17,0	2,8	22,7	-32,5	-49,5
Gidbyo	1800	1000	43,2	20,0	2,8	22,8	-20,4	-40,4
Isene	2500	-	60,0	-	4,1	32,5	-27,5	

From Table 7 it is evident that the pumping stations only partly meet the demands of the beneficiaries. According to the calculations, Basonyagwe is the only village that has its domestic demand fully covered. None of the villages have enough water for both domestic uses and for cattle. It should be noted that these estimations assume that no other water sources are available, and therefore they represent the situation in the dry season rather than the rainy season. The demand for water from the pumping stations is lower than indicated in Table 7 in the rainy season because alternative water sources are available, such as rainwater harvesting. Five COWSOs mentioned water scarcity in the dry season as one of the challenges of the pumping systems. Those villages were Basonyagwe, Murukuchida, Harar, Diling’ang, and Hilamoto.

4.3 Discussion

It is particularly challenging for water supply projects to fully cover the demand in areas with severe water scarcity. The water supply situation in the study area is characterized by high water demands and insufficient water supply infrastructure. According to the DWEs, it is estimated that only 48% of the population in Mbulu district has access to an improved drinking water source close to their home, whereas the improved drinking water coverage is 65% in Hanang district. The results in Table 7 show that the water demand is substantially higher than the supply, which indicates that the supply of the pumping stations should be increased if possible.

The water demand calculations used an average daily water demand of 24L per person, due to the results of the survey. The average water demand specified by the COWSOs was not based on records and thus the results of the survey were thought to be more accurate. In general, the quantity of water used is expected to increase for decreasing collection time, distance to source, time to wait in line, and water price (Howard and Bartram, 2003). However, these relationships do not seem to be significant in the study area, considering Figure 34 - Figure 37, except that the median water use is 17 and 20 L for a collection time of more than and less than 30 minutes, respectively (Figure 37). The reason why consumers who pay more per bucket do not consume less water on average could be the relatively small differences in the price per bucket, as the price is in the range of 20-50 TZS (0.08-0.21 NOK) (Figure 34). The survey shows that 67% of the respondents live within a distance of 100 - 1000m from the water source (Figure 35), which corresponds to the basic access service level of Howard and Bartram (2003) (Table 2). However, 75% have a total collection time of more than 30 minutes (Figure 37), which corresponds to the no access service level. People who are in the no access group are likely to use less than 5L of water per day, according to Howard and Bartram (2003). The reason why this is not the case for most of the respondents is thought to be that people have to prioritize to collect water since it is essential for many aspects of life including health, hygiene, cooking, and cleaning. In addition, people commonly fetch water using a wagon pulled by donkeys or cattle instead of carrying buckets, which makes it possible to collect larger quantities of water.

It appears as if most of the respondents have a basic access service level since only 1% use less than 5 L/day, and only 9% use more than 40 L/day. The average water use is around 20 L/day at the basic service level. Water for drinking, handwashing, and basic food hygiene should be ensured, but laundry and bathing are difficult to ensure (Howard and Bartram, 2003). Research indicates that 20 L/person/day is the smallest water quantity required to guarantee minimum essential levels of health and hygiene, according to Reed and Reed (2013). The average water demand in the study area is only slightly above this limit. The water quantity provided by the solar-powered water pumping systems should be increased if possible so that everyone can collect enough water also during the dry season when alternative water sources are unavailable. This is consistent with feedback from the COWSOs, as the majority would like to expand the WASH-project. The suggestions of each COWSO are given in Appendix 2. Eight COWSOs wish to improve the existing pumping station or to install a new one in order to increase the water supply. In addition, seven COWSOs wish to distribute water to other sub villages by water supply pipes to reduce distance to source and potentially time to wait in line. The survey shows that 61% of the respondents wait for more than 15 minutes at the water source. Reducing distance to source and time to wait in line could improve living standards as people would get more time to engage in economic activities. It is also thought that the water use would increase which in turn would benefit health and hygiene, although the survey shows that people who live close to the water source do not necessarily collect more water on average (Figure 35). However, water use per person cannot currently be increased since the pumping stations do not fully cover existing water demands.

Predicting the water supply of solar-powered water pumping systems is a challenging task. Thus, there are numerous uncertainties related to the water supply estimations conducted in this thesis. For instance, it was assumed that the pumping systems run efficiently for eight hours a day. This assumption was based on initial water supply estimations carried out by NCA. However, it was observed during the fieldwork that the pump stops when the weather becomes cloudy. This was also mentioned as a problem by the COWSOs (Appendix 2). The solar radiation that reaches the Earth's surface is around $1kW/m^2$ in the middle of the day when the sky is clear (Hofstad, 2019). However, clouds may absorb solar radiation thereby decreasing the fraction that reaches the ground by more than 50% (ibid). The solar panels are designed to deliver a power of 0.195kW at a solar irradiance of $1kW/m^2$. The power delivered is however reduced by about 50% in cloudy weather due to reduced solar irradiance. Assuming that the pump runs efficiently for eight hours a day is therefore likely to have overestimated the water supply. Another limitation of the water supply estimations is uncertainties regarding the DWL which was used in Equation 6 to calculate the system characteristic curve. The assumed DWL is based on the results of pumping tests carried out by Trust Engineering. The pump employed in the pumping test provided a flowrate equal to the borehole yield which is considerably higher than the flowrate during operation (Table 4). Therefore, the drawdown is expected to be smaller during operation than it was during the pumping test. Using the DWL from the pumping test is likely to have contributed to an underestimation of the actual flowrate. However, it was used due to the lack of a better estimate.

Another limitation of the water supply estimations is the assumption that the speed of the pump is 48.3Hz consistently. The pump characteristic curves provided by the pump manufacturer, Davis and Shirtliff, state that the speed of the pump is 2900rpm which equals 48.3Hz (Davis and Shirtliff, 2020a). However, it was observed on the display of the Sunverter that the pump starts at a speed of 30Hz (1800rpm). It is unknown whether the pump starts at a speed of 30Hz before making a transition to 48.3Hz or whether the pump runs at a lower speed during lowlight conditions. Nevertheless, a change in pump speed also changes the pump characteristic curve in accordance with the pump affinity laws (Ødegaard, 2014). The change in flowrate is proportional to the change in speed. However, this was not taken into account in the supply calculations since it is unknown how the transition between 30 and 48.3Hz occurs. In turn, this simplification may have overestimated the quantity of water provided. The fact that the pump starts at a speed of 30Hz could however explain why the theoretical flowrates calculated from the system and pump characteristic curves are greater than the flowrates of the bucket test (Table 5).

The pumping stations do not work well in cloudy weather, reducing the quantity of water provided and threatening reliability. It would therefore be beneficial to increase the power supply to ensure a stable water provision. For instance, additional solar panels can be installed, or batteries can be integrated in the system. Every pumping station currently has 8 or 10 solar panels with a peak power of 0.195 kW each. The maximum number of solar panels that may be installed depends on the maximum solar input power of the Sunverter. The pumping stations visited are either installed with a Sunverter of the model type SV2/1.5M or SV2/2.2M, which have a maximum input power of 2.2 and 3.3 kW, respectively (Davis and Shirtliff, 2018). If the Sunverter is equipped with too many solar panels, and consequently receives a higher power than the limit, it may get severely damaged. Another way to increase the power supply is by adding batteries to the system. A regulator could be used to connect the Sunverter, batteries, and solar panels together. The regulator will change between supplying power to the Sunverter from the batteries and from the solar panels and will charge the batteries by the solar panels whenever the Sunverter needs less power or is turned off. This solution would have to be discussed with the pump manufacturer, Davis and Shirtliff, to determine what would be required to make the solution work in practice.

The Sunverter has hybrid capability with the opportunity of receiving power from a generator or from an electrical grid in addition to the solar panels, which in turn could increase the quantity of water supplied by the pumping stations (ibid). Grid electricity is however not an opportunity as it is unavailable in most of the villages visited. A generator running on diesel or petrol could be used to pump water during night or in cloudy conditions. This solution would however increase the running costs and hence the price of water. It may also be inconvenient for the users to acquire diesel or petrol as one has to travel far to purchase it. In general, the solution employed to increase the water supply must be cost-effective. In addition, the COWSOs must be given training on how to operate and maintain the components that are added to the pumping system. It should also be noted that boreholes cannot supply infinite quantities of water, and therefore the hydrogeological conditions must be considered before attempting to increase the water supply. The pumping rate should for instance not exceed the borehole yield. This will be further elaborated in chapter 5 Groundwater level variations and the impact of pumping.

5 Groundwater level variations and the impact of pumping

Pumping systems may fail due to changes in the availability of groundwater in the aquifer (MacDonald et al., 2005). The groundwater level can decline either due to droughts or because more water is abstracted from the aquifer than what is naturally replenished each year. These two causes are often related because the demand for water typically increases during droughts which in turn puts additional pressure on the water source (Calow et al., 1997). In groundwater management, the safe yield may be defined as the rate at which groundwater can be abstracted from an aquifer without causing undesirable results (Şen, 2015). Unsustainable pumping rates are of particular concern for solar-powered water pumping systems, since low running costs may lead to excessive pumping.

This chapter investigates whether current pumping rates are sustainable by addressing the following research question: *Do current pumping rates influence groundwater levels significantly, and is over-abstraction of the aquifers likely to occur?*

5.1 Background

An aquifer may be defined as "a saturated permeable geological unit that is permeable enough to yield economic quantities of water to wells" (Kruseman and de Ridder, 2000, p. 13). Various geological formations may be classified as aquifers, such as unconsolidated sand and gravels, permeable sedimentary rocks like sandstone and limestone, and heavily fractured or weathered volcanic and crystalline rocks. An aquitard is a geological unit that is capable of transmitting small quantities of water, but its permeability is insufficient for the installation of production wells (ibid). Clays and shales are examples of aquitards. An aquiclude is a geological unit that practically transmits no water because its permeability is very low. Aquifers may be classified as either confined, unconfined, or leaky (ibid). A confined aquifer is restricted above and below by an aquiclude, whereas an unconfined aquifer is bounded by an aquiclude below, but it is not restricted from above. The boundaries above and below a leaky aquifer are either both aquitards, or one is an aquitard and the other is an aquiclude (ibid). Water is free to move through the aquitards, either upward or downward.

The availability of groundwater in an aquifer depends on the water balance. In general, water may be added to an aquifer through precipitation, lateral subsurface inflow, recharge from rivers, and recharge due to irrigation and wastewater returns (Şen, 2015). The proportion of the total precipitation which contributes to groundwater reservoirs depends on the size of evapotranspiration and runoff. Water may be extracted from an aquifer for domestic and industrial water uses, as well as for irrigation (ibid). In addition, water may leave the aquifer naturally by contributing to surface waters, subsurface outflow, or evaporation from the groundwater table in unconfined aquifers. The water balance may be considered over the course of a year, since aquifers typically gain water in the rainy season and loose water in the dry season. There are two types of seasonal rainfall distributions in Tanzania (Zorita and Tilya, 2002). In the coastal belt, the northern highlands and around Lake Victoria, rainfall usually happens in two periods during the year, that is from March to May and from October to December (ibid). Whereas southern, central, and western Tanzania only has one rainy season, which usually lasts from October to April.

Pumping tests is one of the most important tools for determining hydraulic properties of the borehole and the aquifer (MacDonald et al., 2005). During pumping, a cone of depression forms around the borehole because groundwater stored in the aquifer moves towards the borehole (Figure 38). The cone of depression gradually moves further out as pumping continues. The principle of a pumping test is to pump water from a well while measuring discharge and drawdown (Kruseman and de Ridder, 2000). In general, pumping tests for determination of aquifer parameters fall into two categories; unsteady state and steady state (Roscoe Moss Company, 1990). In both categories, the pumping rate is typically held constant throughout the test. By definition, unsteady-state tests are time varying tests where the water level changes in response to a constant pumping rate (ibid). In steady-state tests, pumping is continued until near equilibrium conditions are reached, meaning that there is a negligible change in water levels over time. Drawdown and recovery curves may be plotted from the water level measurements conducted in a constant-rate test (ibid). The drawdown cycle is measured from the beginning to the end of pumping, whereas the recovery cycle is measured from the end of pumping to the completion of the test. Drawdown is calculated as the difference between the static and the dynamic water level (Figure 38). Recovery is calculated as the residual drawdown after pumping has stopped. During pumping, the drawdown increases as the cone of depression expands. During recovery, the water levels rise because water from the aquifer refills the cone.

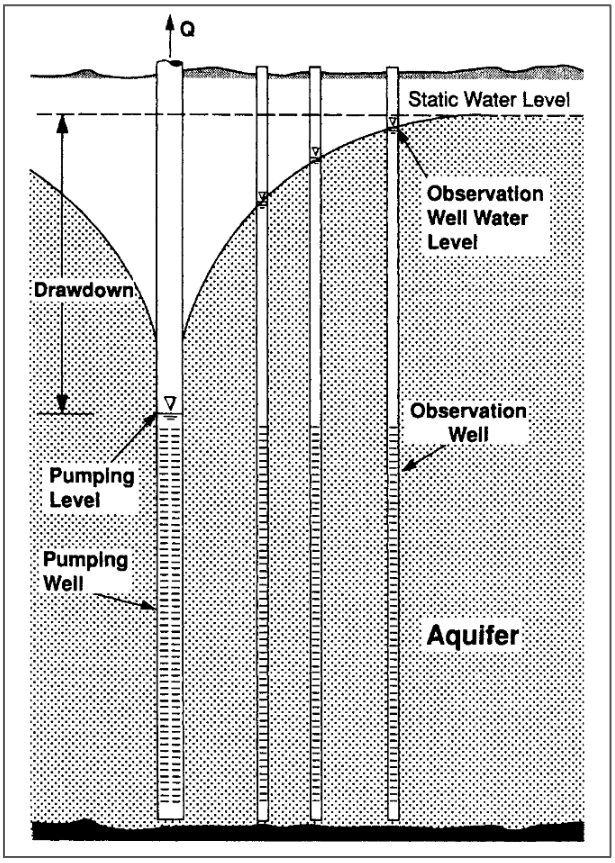


Figure 38: Pumping test (Roscoe Moss Company, 1990)

The measurements of a pumping test can be substituted into an appropriate well flow equation to calculate the hydraulic characteristics of an aquifer (Kruseman and de Ridder, 2000). A number of such equations are available, each of which are based on certain assumptions regarding for instance the aquifer type (confined, unconfined, or leaky) and whether the test is steady-state or unsteady-state. For measurements of drawdown in confined aquifers, the method of Thiem (1906) may be applied for steady-state tests, whereas the method of Theis (1935) may be applied for unsteady-state tests. Both of these methods require that the water level is measured in observation wells or piezometers in addition to the pumping well, as shown in Figure 38. The Theis recovery method may be used to analyze the recovery cycle (ibid). Recovery data is generally more reliable than drawdown data, because recovery occurs at a constant rate, whereas it is challenging to maintain a constant pumping rate in field (Kruseman and de Ridder, 2000). An aquifer parameter called transmissivity can be determined by these methods. Transmissivity is defined as "the rate of flow under a unit hydraulic gradient through a cross section of unit width over the whole saturated thickness of the aquifer" (Kruseman and de Ridder, 2000, p. 22). Storativity is an aquifer parameter that can be determined from unsteady-state tests. It is defined as "the volume of water released from a unit volume of aquifer due to aquifer compression and water expansion under a unit decline in head" (Roscoe Moss Company, 1990, p. 23). Transmissivity is expressed in m^2/day, whereas storativity is dimensionless.

A pumping test can be conducted with a series of constant pumping rates in order to determine the optimum yield and the specific capacities of a well. During a step-drawdown test, the well is pumped at a constant-discharge rate until the drawdown within the well stabilizes (Kruseman and de Ridder, 2000). The pumping rate is then increased to a higher constant-discharge rate and the well is again pumped until the drawdown stabilizes. The pumping rate is held constant at least three times. Figure 39 shows what drawdown measurements from a step-drawdown test might look like. Jacob (1947) was the first to perform this type of pumping test. Rorabaugh (1953) proposed that the drawdown in a pumped well may be modelled by the following equation:

$$s_w = BQ + CQ^P \qquad \text{Equation 7}$$

where P has a value in the range of 1.5 to 3.5 and is commonly set to 2.0. A step-drawdown test makes it possible to determine the values of B, C and P. Knowing these parameters, the drawdown within the well can be predicted for any discharge Q at a certain time t (because B is time-dependent) (Kruseman and de Ridder, 2000). The derived relationship between drawdown and discharge may be used to choose the yield of the borehole. The optimum yield may be defined as "the maximum pumping rate a borehole can sustain for a reasonable drawdown" (MacDonald et al., 2005, p. 211). What is considered a reasonable drawdown depends on the context, but the water level in the borehole must always stay above the pump intake. Specific capacity is defined as "the discharge per unit drawdown in a well", and is usually expressed in L/s/m (Şen, 2015, p. 68). Boreholes are considered productive if a high discharge leads to a small drawdown, and thus a high specific capacity is desirable. It is however important to note that the specific capacity of a borehole is not constant (Kruseman and de Ridder, 2000). For a constant discharge, the specific capacity decreases over the course of time. In addition, the specific capacity decreases if the discharge is increased.

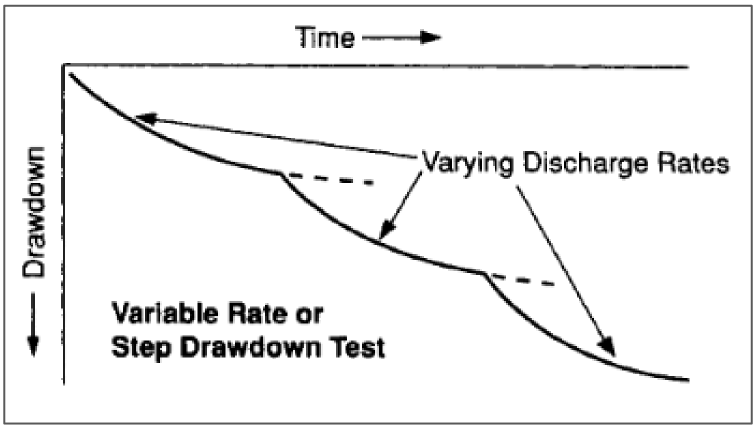


Figure 39: Step-drawdown test (Roscoe Moss Company, 1990)

5.2 Results

The results of this chapter are based on measurements conducted during the fieldwork as well as data provided by NCA.

5.2.1 General geology

NCA has provided access to pumping tests and well logs completed by Trust Engineering, at the following five pumping stations; Endagaw chini, Murukuchida, Endamilay, Gidbyo, and Munguli. A well log or drilling report is a detailed record of the geological formations penetrated by a borehole. The well logs of Endagaw chini, Murukuchida and Endamilay are rather similar. The first three layers underneath the topsoil are clay, shale, and granite, from top to bottom. Shale is a sedimentary rock which consists of clay and silt that has been consolidated, whereas granite is a magmatic rock (MacDonald et al., 2005). There are varying layers of clay, shale and granite further down the boreholes. Some of the layers are described as highly fractured or weathered. In Gidbyo, the two upper layers consist of sand and gravel, overlying a layer of granite. Further down the borehole, there are different layers of granite which to varying degrees are weathered or fractured. In Munguli, the upper layer consists of silt, and the layer underneath is basalt which is a magmatic rock (Selbekk, 2020). There is a metamorphic rock called gneiss under the basalt layer. Below this, there are different layers of gneiss and granite, which to varying degrees are weathered and fractured. The well logs show that the aquifers in question are either composed of weathered and/or fractured granite (Murukuchida, Gidbyo and Munguli) or weathered and/or fractured shale (Endagaw chini and Endamilay). All aquifers have an impermeable layer on top, consisting of either shale, granite or gneiss, which indicates that the aquifers could be confined. For an aquifer to be classified as confined it must also be fed from an area of higher altitude, meaning that the water pressure in the upper saturated zone is greater than the atmospheric pressure (Kruseman and de Ridder, 2000). Consequently, the water level in the well should be situated above the top of the aquifer. The recorded static water levels and the well logs show that this is the case for all the five pumping stations for which data was available. Thus, it is likely that the aquifers in question are confined.

5.2.2 Waterlevel variations

The water levels inside the wells of Mewadani and Basonyagwe were measured by a pressure sensor called UNIK5000 which was installed as a part of a remote monitoring system (chapter 3.3, page 25). The measurements are shown in Figure 40 for the period from February to June 2020. The water level has increased from approximately 10 to 7m below borehole top in Mewadani, compared to an increase from 20 to 3m in Basonyagwe.

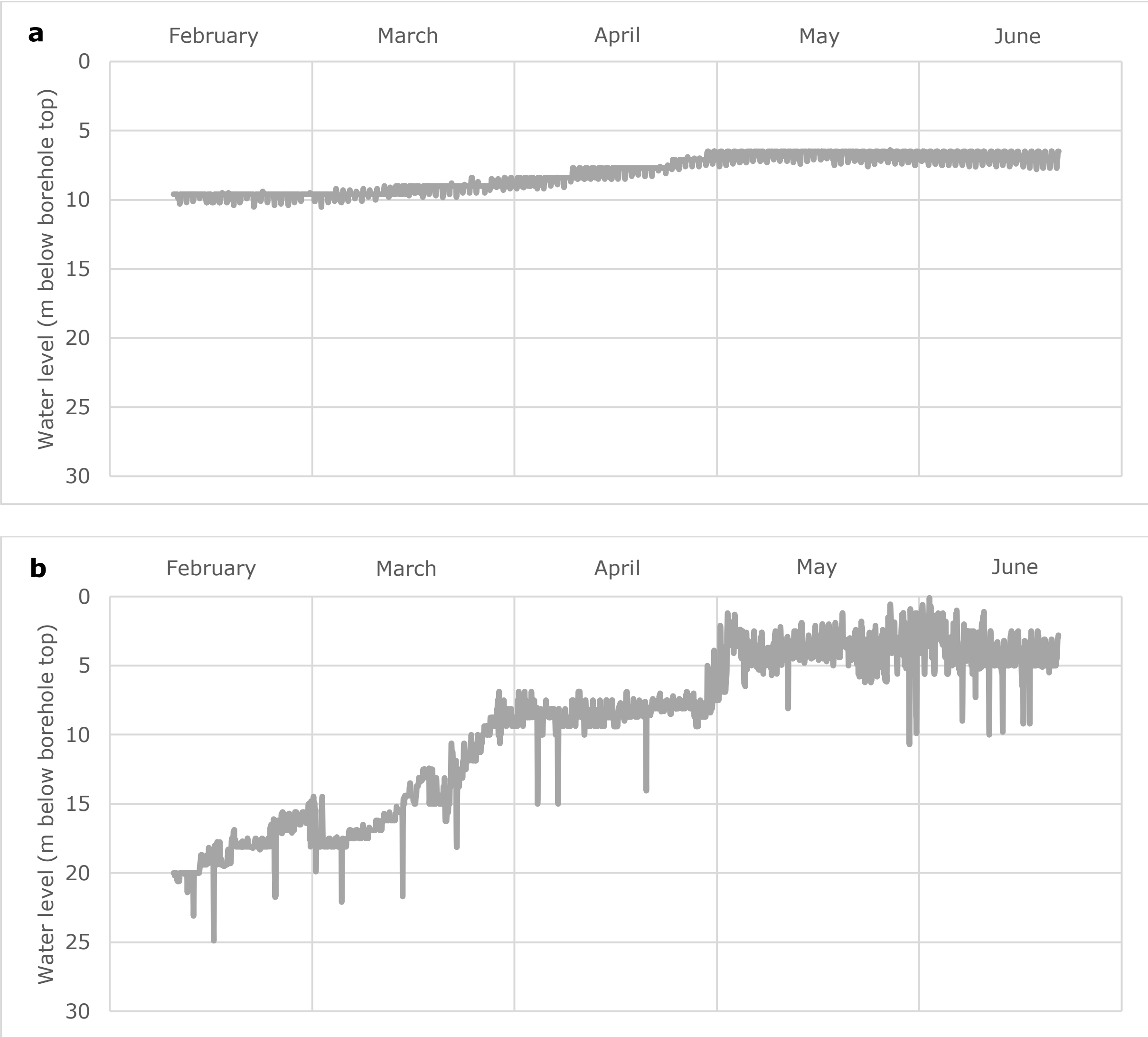


Figure 40: Water level variations within the wells of a) Mewadani and b) Basonyagwe monitored by UNIK5000 pressure sensors, February-June 2020

The apparent increase in water levels must be seen in relation to precipitation data. In Figure 41, the average monthly rainfalls of the last 20 years are compared to those in June-December 2019 and January-May 2020. Data is downloaded from a geovisualization tool that provides access to global climate data, called Global Climate Monitor. Since 2013, the precipitation dataset feeding the system has been the Global Precipitation Climatology Centre (GPCC) First Guess precipitation dataset (Camarillo-Naranjo et al., 2019). Precipitation measurements done by rain gauges are likely to be more accurate than data from global datasets, but there is no weather station in the study area as far as the author knows. Figure 41 shows that the monthly rainfalls from October to December 2019 and from January to April 2020 were considerably higher than the average values. May is the first month of the dry season, but the rainfall in May 2020 was even lower than average. These rainfall patterns could explain why the water levels increased in Mewadani and Basonyagwe from January to April but remained quite stable from May to June.

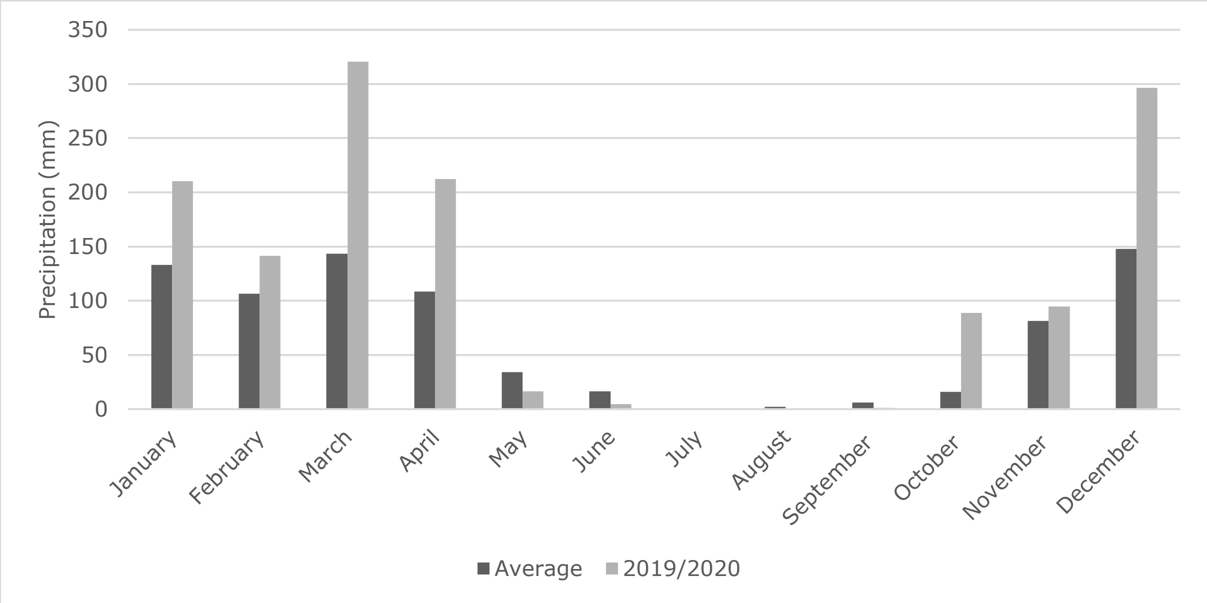


Figure 41: Monthly precipitation for coordinates 35.02, -4.19 (https://globalclimatemonitor.org)

Static water levels were measured manually in field by the Pocket Dipper and the Electric Contact Meter (chapter 3.1.1, page 18). The static water level of a well is the water level when pumping does not occur, as shown in Figure 38. However, this term is slightly misleading as the water level tends to vary naturally due to for instance precipitation, evaporation, and subsurface inflow and outflow. Figure 42 compares the static water levels measured during the fieldwork to those provided by NCA, for 14 pumping stations. The Pocket Dipper was used at four pumping stations (Endagaw chini, Mewadani, Basonyagwe and Harar) and has an approximated accuracy of ±0.5m. The Electric Contact Meter was used at the remaining pumping stations, except from Murukuchida, Endamilay and Diling'ang, and has an accuracy of ±0.01m. The water level measurement in Endagaw chini is perceived as rather uncertain because the Pocket Dipper is unsuitable for water levels greater than 30m below the ground surface. In Murukuchida, the Diver measurements were used to estimate the water level by subtracting the hydrostatic head from the length of the rope extending the Diver into the borehole. At that time during the fieldwork, the Pocket Dipper had stopped working, and the Electric Contact Meter was not yet available. The water levels in Endamilay and Diling'ang were not measured during the fieldwork. For some of the pumping stations, such as Basonyagwe and Harar, the water levels measured in field were approximately equal to those provided by NCA, as shown in Figure 42. Whereas for others, such as Haydom Secondary and Gidurudagew, there were considerable differences between the water level measurements.

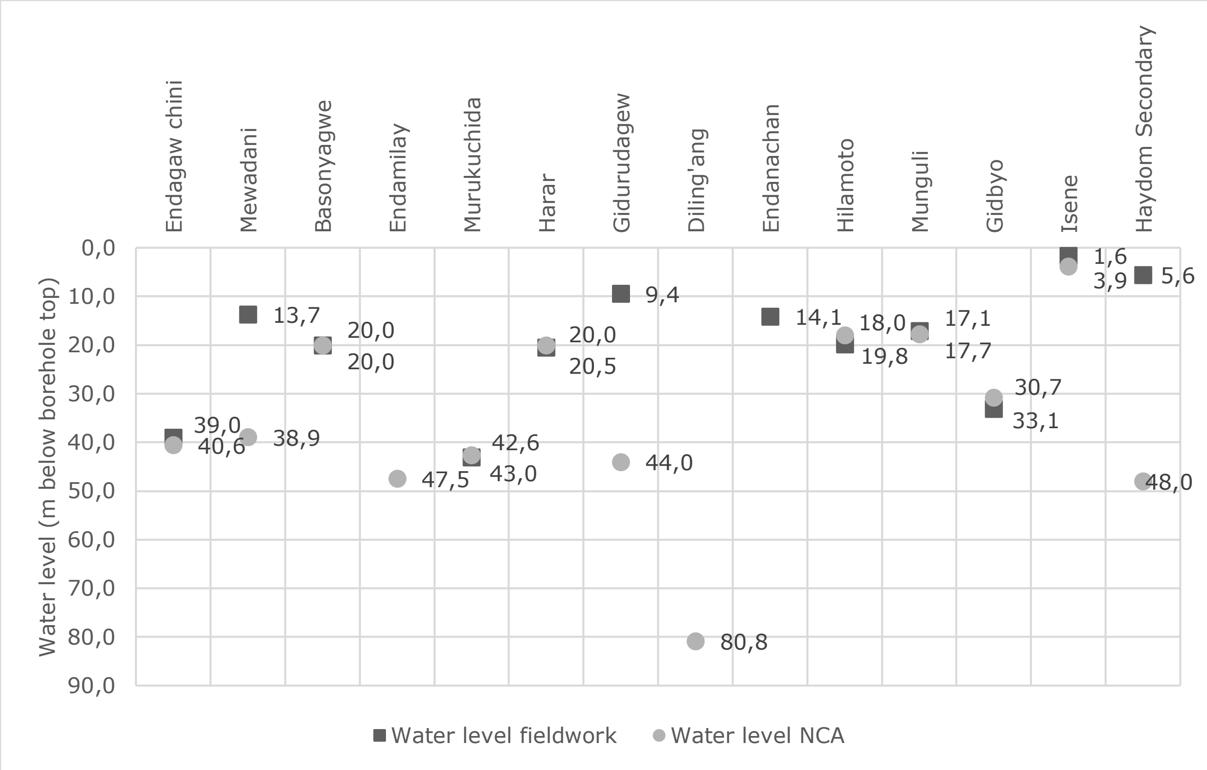


Figure 42: Static water levels at 14 pumping stations

5.2.3 Pumping tests and Diver measurements

NCA has provided access to pumping tests completed by Trust Engineering at the following five pumping stations; Endamilay, Murukuchida, Gidbyo, Munguli and Endagaw chini. In addition, Divers were installed at three pumping stations during the fieldwork, namely Endanachan, Harar, and Murukuchida. Pumping tests and Diver measurements provide useful information regarding the response of an aquifer to pumping.

The pumping tests were carried out after borehole completion, using a stronger pump than the one which is currently used during operation. For instance, an SP-7025 pump was used in Murukuchida during the pumping test, but a DSP 5-16 pump was installed as a part of the solar-powered pumping system. The pumping rate decreased gradually during the pumping tests. Pumping continued for six hours in Endagaw chini, for 12 hours in Munguli, and for eight hours at the remaining pumping stations. The dynamic water level and the discharge were recorded every minute in the first 15 minutes of the test, and then the measuring frequency decreased gradually to 30 and even 60 minutes between each measurement. The water level was also recorded for one hour after pumping had stopped, except in Munguli where the water level was only recorded for 25 minutes of recovery. For some of the pumping stations, such as Endamilay, Murukuchida and Endagaw chini, the drawdown within the well stabilized during the pumping test. This was however not the case for Gidbyo and Munguli. Figure 43 shows how the dynamic water level in Murukuchida changed during the pumping test. The water level decreased gradually during the drawdown cycle until a stable level was reached. In the beginning of the test, the discharge was 20.48 m^3/h. The discharge was gradually reduced and by the end of the drawdown cycle it was 6.59 m^3/h. Pumping stopped after eight hours, thereby allowing the recovery cycle to start. The borehole yield was set to 6.59 m^3/h as a result of the test. Appendix 11 provides graphs displaying dynamic water levels of the pumping tests in Endamilay, Gidbyo, Munguli and Endagaw chini.

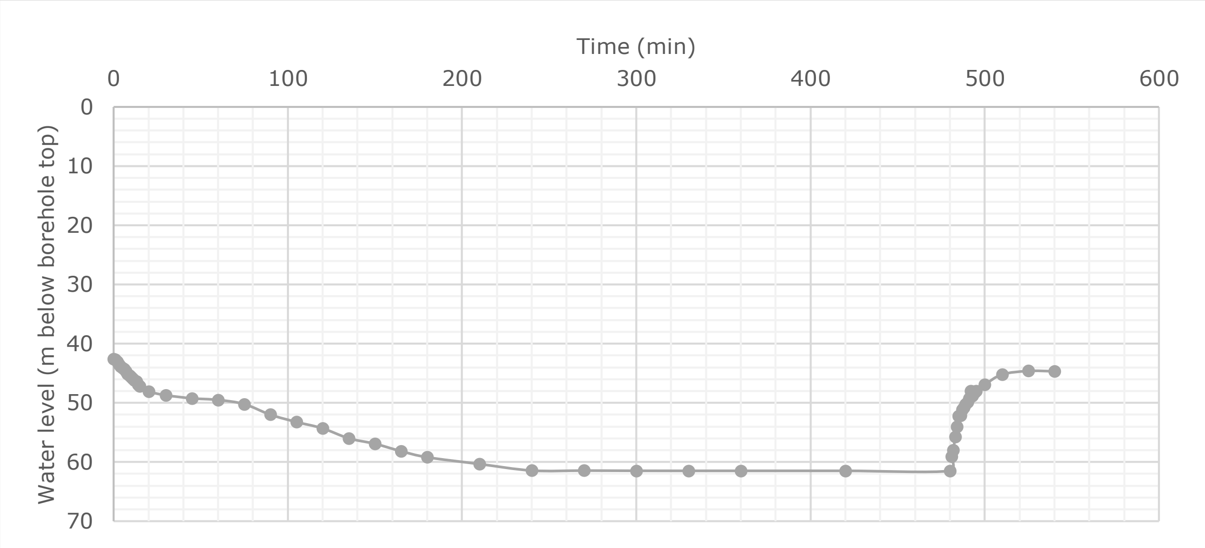


Figure 43: Pumping test in Murukuchida, completed by Trust Engineering, 14.08.2018

A TD-Diver and a CTD-Diver were used to record water levels during the fieldwork, as described in chapter 3.1.3 (page 20). Diver measurements were carried out twice in Murukuchida, on the 3-5th of February. Even though the pump was running during both measurement periods, there was no distinct drawdown and recovery curve, as shown in Figure 44. The theoretical pumping rate in Murukuchida, calculated in chapter 4, is 3.3 m^3/h, whereas the pumping rate measured by the bucket test was 3.0 m^3/h. The graphs displaying the Diver measurements in Endanachan and Harar (Appendix 10) have more distinct drawdown and recovery curves. The drawdowns were 6.06 and 2.16m for Endanachan and Harar, respectively. However, the graphs show that the water level sometimes fluctuates rapidly during pumping, which could be due to unstable power supply.

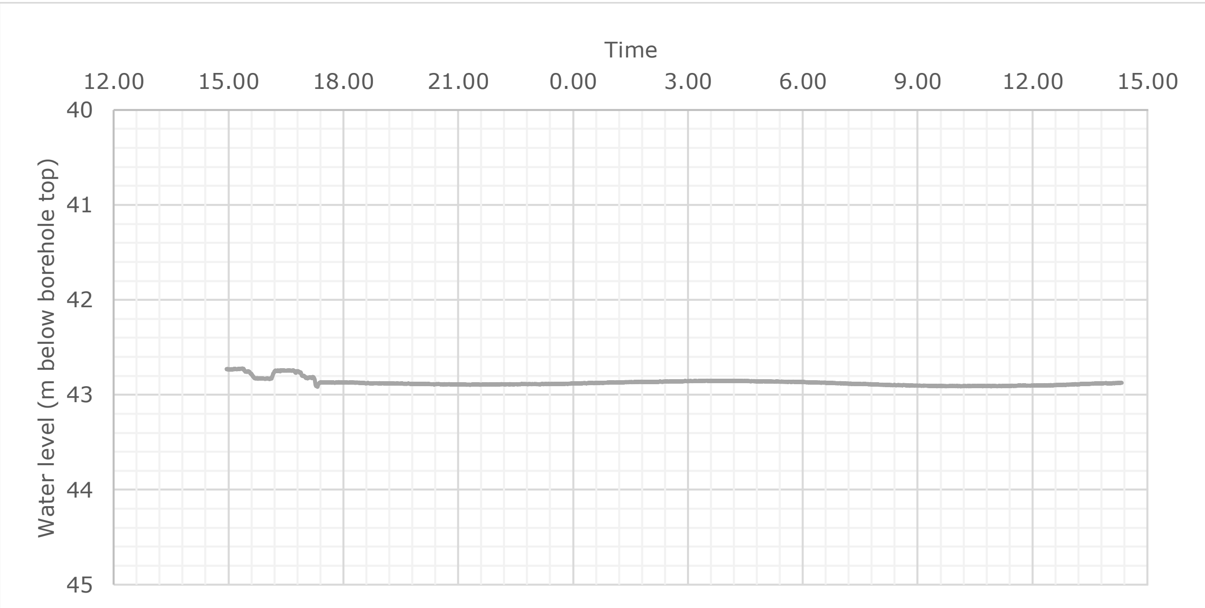


Figure 44: CTD-Diver measurement in Murukuchida, 04-05.02.2020

Table 8 presents specific capacities calculated using data from pumping tests, Diver measurements, and bucket tests. The drawdown is calculated by subtracting the static water level from the dynamic water level. The static water level is the water level that was recorded before pumping started. For the pumping tests, the dynamic water level and discharge were determined from measurements recorded after six hours of pumping, in order to obtain comparable specific capacities. It is common practice to measure the specific capacity after a certain time period in projects where a stable drawdowns is not reached during the pumping tests (MacDonald et al., 2005). For the Diver measurements, the dynamic water level at maximum drawdown was used, and the discharge was determined from bucket tests.

Table 8: Results of pumping tests and Diver measurements

Village	Method	Discharge (m^3/h)	Static water level (m)	Dynamic water level (m)	Depth of pump intake (m)	Drawdown (m)	Specific Capacity (L/min/m)
Endagaw chini	Pumping test	1,042	40,56	94,80	100	54,24	0,32
Munguli	Pumping test	4,200	17,69	48,85	64	31,16	2,25
Endamilay	Pumping test	5,760	47,45	73,35	100	25,90	3,71
Gidbyo	Pumping test	3,168	30,74	44,17	100	13,43	3,93
Murukuchida	Pumping test	6,588	42,64	61,49	80	18,85	5,82
Endanachan	Diver/Bucket test	2,380	14,25	20,31	-	6,06	6,55
Harar	Diver/Bucket test	3,730	21,51	23,67	90	2,16	28,78
Murukuchida	Diver/Bucket test	3,000	42,87	42,91	80	0,04	1250,00

A high specific capacity is desirable because it means that a high discharge causes a small drawdown. Table 8 shows a wide range of specific capacities. In general, the Diver measurements have larger specific capacities than the pumping tests, which is not surprising as the discharge is smaller during operation than it was during the pumping test. The depth of the pump intake is also included in Table 8 to show that none of the dynamic water levels exceed the depth at which the pump was installed. The depth of the pump intake in Endanachan was not specified by NCA.

5.3 Discussion

The traditional definition of the safe yield is that the pumping rate equals the recharge rate (Şen, 2015). However, the link between precipitation and recharge is complex, and depends on the way in which water is fed to the aquifer. In general, water balance models require extensive knowledge of the physical properties of the aquifer and several years of water level measurements and weather data. Therefore, a water balance model was not attempted as a part of this work. However, water level measurements were conducted to evaluate whether groundwater levels are currently declining. Figure 40 shows increasing water levels within the boreholes in Mewadani and Basonyagwe in the period from the 10th of February to the 20th of June 2020. This indicates that the pumping systems did not extract more water than what was naturally replenished in this period. There are some uncertainties related to the data series, as only an initial control was performed to verify the measured water levels. However, precipitation has been greater than average in the study area from October 2019 to April 2020 (Figure 41), so a substantial increase in water levels is plausible. Typically, there is a delay between precipitation episodes and the corresponding increase in groundwater levels depending on the physical properties of the aquifer. The water level rose by approximately 3 and 17 m in Mewadani and Basonyagwe, respectively. It is not known exactly why the increase was greater in Basonyagwe, but it could be due to differences in the geological composition of the aquifers. Unconsolidated materials, such as gravel, sand, and silt have a larger porosity than rocks such as shale and granite (Kruseman and de Ridder, 2000). Larger water level changes are generally seen in aquifers with a low porosity since the same volume of water causes a larger increase in the groundwater table. However, well logs were unavailable for both Mewadani and Basonyagwe, and the geology of the aquifers is therefore unknown.

The static water level varies naturally between seasons and years. Figure 42 compares water levels measured during the fieldwork to water levels provided by NCA for 14 pumping stations. The measured water levels are rather similar for most of the pumping stations, except for Mewadani, Gidurudagew and Haydom Secondary. In general, water levels are expected to be higher during the rainy season as compared to the dry season. The rainy season is from October/November to April in the study area, as shown in Figure 41. The fieldwork was carried out in February which is in the middle of the rainy season. The dynamic water levels provided by NCA were measured in June 2015 in Munguli, in September 2017 in Endagaw chini, and in August 2018 in Murkuchida, Endamilay, and Gidbyo. It is not known when the rest of the dynamic water levels were measured. There is not much difference between the water level measurements for these pumping stations. For Gidbyo, the water level measured during the fieldwork was 2.4m lower than the value provided by NCA, even though the fieldwork was carried out in the rainy season, and the value provided by NCA was from the dry season. This illustrates that groundwater level variations are not always easily predicted. The water level within a well should be monitored for at least a year to get an impression of seasonal variations, but there is also likely to be variations from one year to another. Remote monitoring systems such as those installed in Mewadani and Basonyagwe could be useful for this purpose.

The optimum yield of a borehole may be interpreted as the maximum pumping rate a borehole can sustain for a reasonable drawdown (MacDonald et al., 2005). What is considered a reasonable drawdown depends on the context, but the depth of the pump intake is often the decisive factor. Diver measurements were conducted in field to investigate the drawdown during pumping. The dynamic water levels in Harar and Murukuchida were approximately 24 and 43m, respectively (Table 8). Whereas the pump intakes are located at depths of 90 and 80m, respectively. Thus, there was a rather large distance between the dynamic water level and the pump intake. Endanachan had a dynamic water level of approximately 20m during the Diver measurements, but the depth of the pump intake is unknown. For the pumping stations in question, the pump used during operation has a lower pumping rate than the one that was used during the pumping test. This can be seen in Table 4 (page 41) which compares theoretical flowrates of the pumps used during operation to the borehole yields which were determined from the pumping tests. Unfortunately, Endamilay, Endagaw chini and Munguli are not included in Table 4 due to lack of data regarding the pumps used during operation at these pumping stations. Not surprisingly, a smaller pumping rate causes a smaller drawdown, as seen for Murukuchida in Table 8. The borehole yield, which was determined from the measured discharge at the end of the pumping test, is 6.588 m^3/h, and the pumping test produced a drawdown of approximately 19m. In contrast, the operational pumping rate is approximately 3.0 m^3/h according to the bucket test, which produced a barely noticeable drawdown of 0.04m. Thus, there appears to be a potential for increasing the pumping rate.

A step-drawdown test makes it possible to derive a relationship between discharge, drawdown and time, using Equation 7 (Kruseman and de Ridder, 2000). This means that the drawdown inside the well can be predicted for any realistic discharge at a certain time of pumping. The pumping tests done by Trust Engineering were neither carried out as constant-rate tests nor as step-drawdown tests. Instead, the pumping rate decreased gradually and the discharge which was measured at the end of the drawdown cycle was defined as the borehole yield. The reason is thought to be difficulties of maintaining a constant pumping rate with an increasing drawdown, because the pump would have to provide the same flow for a larger head. The fact that the relationship between discharge, drawdown and time is unknown makes it is difficult to suggest an appropriate pumping rate. It is however thought that current pumping rates can be increased since they are far less than the borehole yield at most of the pumping stations (Table 4, page 41). The dynamic water levels were above the depth of the pump intake during the pumping tests by a reasonable margin, except for in Endagaw chini (Table 8). Therefore, increasing the operational pumping rate by less than the borehole yield could be safe. However, the drawdown emerging during pumping was not given enough time to stabilize in some of the pumping tests. The final drawdown in the pumping tests of Gidbyo and Munguli is consequently likely to be less than the drawdown that would have emerged if the water level was given time to stabilize during pumping. The time of year that a pumping test was carried out must also be taken into consideration when assessing the results (MacDonald et al., 2005). During the dry season, the static water level is typically deep meaning that a particular drawdown will cause a deeper dynamic water level than in the rainy season. The distance between the dynamic water level and the pump intake as presented in Table 8 must hence be evaluated critically. However, the pumping tests which were accessible for this study were all carried out in the dry season.

Table 8 shows specific capacities calculated from pumping tests and Diver measurements. Endagaw chini has the lowest specific capacity and therefore also the lowest productivity, with a small discharge of 1.042m^3/h causing a large drawdown of approximately 54m. In contrast, a discharge of 6.588m^3/h in Murukuchida causes a moderate drawdown of approximately 19m. It is important to note that the specific capacity decreases over the course of time with a constant pumping rate, and also decreases with an increasing pumping rate (Kruseman and de Ridder, 2000). Therefore, the specific capacity cannot be used to calculate the pumping rate corresponding to a particular drawdown. This is especially seen for Murukuchida, which has a specific capacity of 5.82 and 1250 L/min/m determined from the pumping test and Diver measurements, respectively. Using the specific capacity determined from the Diver measurement to calculate the pumping rate corresponding to a particular drawdown would severely overestimate the pumping rate.

6 Water quality

Water provided by the solar-powered water pumping systems is generally perceived as clean and safe according to interviews with the COWSOs. A reduction in water-borne diseases was reported in some of the villages. In Endanachan village, a COWSO member stated: "After having this project, water-borne diseases are no longer here. Children do not have diarrhea. The most affected previously were children. Nowadays, things are well."

This chapter investigates the issue of water quality by addressing the following research question: *Are the pumping systems providing water of adequate quality for human consumption?* Water quality parameters measured in field were; pH, alkalinity, conductivity, turbidity, fluoride, and fecal contamination.

6.1 Background

Access to safe drinking water is inevitable for health and development and a basic human right (WHO, 2017a). In most countries, national government agencies have established drinking water quality standards that public water suppliers must follow, due to the negative health impacts of unsafe water (UNICEF, 2008). When setting national drinking water standards, most countries consider the standards used by other countries as well as the *Guidelines for Drinking Water Quality* (GDWQ) (WHO, 2017a). The most recent version of the GDWQ is the fourth edition incorporating the first addendum published by the WHO in 2017. The GDWQ includes an assessment of the health risks associated with different microbiological, chemical, radiological, and physical contaminants that may be found in drinking water. Where appropriate, maximum concentration guideline values are given. In Tanzania, the National Environmental Standards Committee, which is part of the Tanzania Bureau of Standards, is responsible for establishing minimum quality standards for different uses of water (World Bank, 2018a).

A distinction is typically made between standards based on health impacts and those based on the acceptability of drinking water (UNICEF, 2008). Consumers tend to form their opinion about the quality of drinking water from a particular source based on easily observed parameters including visual appearance, taste, and odor. Therefore, water with high quality with regard to health impacts may still appear unsafe and thus be rejected. In turn, this might lead to the use of other water sources that appear clean but might be chemically or microbiologically unsafe. Examples of water quality parameters related to acceptability are pH, alkalinity, and turbidity. The GDWQ makes no recommendations for these parameters since acceptability depends on local conditions. Generally, the concentrations of these parameters that cause rejection are considerably lower than those of concern for health (WHO, 2018).

6.2 pH

6.2.1 Background - pH

pH is a measure of the acidity of a water-based solution (Pedersen, 2019). The exact definition of pH correlates to the concentration of H_3O^+-ions (Ødegaard, 2014). Usually, the simplified version is used, which is based on the concentration of protons (H^+-ions), specified in mol/L. The definition is:

$$pH = -\log(H^+) \quad \text{Equation 8}$$

Pure water has a neutral pH of 7 at 25 °C (Pedersen, 2019). Acidic solutions have a pH between 1 and 7, whereas basic solutions have a pH between 7 and 14. The lower limit for pH in drinking water in Tanzania is pH 6.5, and the upper limit is pH 9.2 (Tanzania Bureau of Standards, 2005). In a global overview of national standards for drinking water quality done by the WHO, the median lower limit among the countries was pH 6.5, and the median upper limit was pH 8.5 (WHO, 2018).

6.2.2 Results and discussion - pH

pH measurements were carried out by two different methods in field. The majority of the measurements were done using an IDS pH sensor connected to WTW's Multi 3630 IDS digital meter. However, pH paper was used at five pumping stations (Munguli, Hilamoto, Haydom Secondary School, Gidbyo, and Isene) due to problems with calibrating the pH sensor. The accuracy of the pH sensor is ± 0.01 pH (Xylem Analytics Germany, 2017). Whereas the accuracy of pH paper is half the interval between each measurable unit, which is ± 0.5 pH. The results given in Figure 45 show that the majority of the pH measurements were within the limits specified by the Tanzania Bureau of Standards. Gidurudagew had a pH of 6.45 ± 0.01 which is slightly below the lower limit of pH 6.5. None of the pH measurements were close to the upper limit of pH 9.2. The highest value measured was pH 7.67 ± 0.01 in Murukuchida.

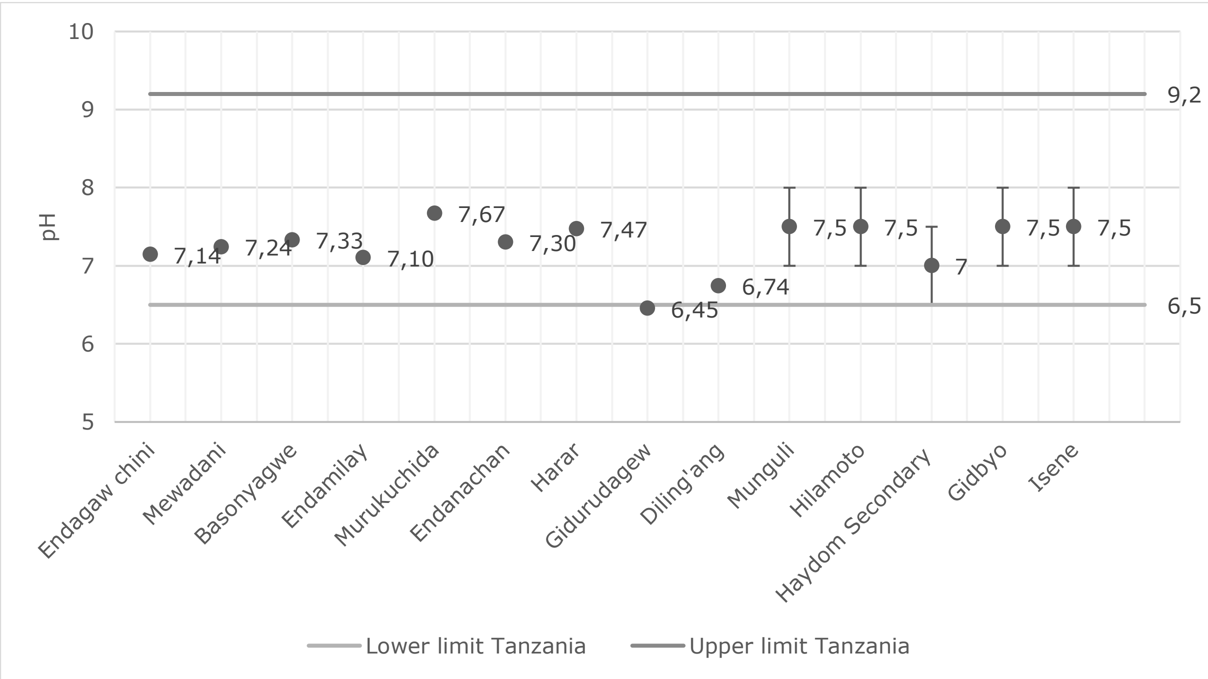


Figure 45: pH of water samples from 14 pumping stations

pH varies with temperature, and thus the temperature of the water samples was measured in addition to the pH. However, temperature ranged from 21.1 to 30.2 °C, which have minimal impacts on pH, and thus the pH was not corrected for temperature.

6.3 Alkalinity

6.3.1 Background - Alkalinity

Alkalinity is a measure of the ability of water to resist changes in pH upon the addition of a strong acid (Snoeyink and Jenkins, 1980). In natural waters, alkalinity is due to bases such as HCO_3^-, CO_3^{2-} and OH^- as well as to species typically present in small concentrations including silicates, ammonia, and phosphates. Analytically, total alkalinity may be determined by titrating a known volume of sample by a standard solution of strong acid to a pH value between 4 and 5, and usually in the range of 4.5 to 4.8 (ibid). Several units may be used to specify alkalinity, such as mmol/L H^+, mg/L HCO_3^-, and mg/L $CaCO_3$ (Ødegaard, 2014). Low values of alkalinity, pH, and calcium concentration in water are associated with corrosion of pipe materials (ibid). Corrosion can cause pipe breakage or significantly reduce the efficiency of water transmission (UNICEF, 2008). In addition, corrosion deteriorates water quality, with increased turbidity and elevated levels of metals such as iron and cupper.

Tanzania does not have an upper limit for alkalinity (Tanzania Bureau of Standards, 2005). However, the upper limit for total hardness is 600 mg/L $CaCO_3$ (Tanzania Bureau of Standards, 2005). Hardness and alkalinity are not directly comparable even though they both can be quantified by the unit of mg/L $CaCO_3$. In natural waters, alkalinity is determined by the presence of bases such as HCO_3^-, whereas hardness is due to cations such as Ca^{2+} and Mg^{2+} (Ødegaard, 2014). The reason for reporting hardness in terms of $CaCO_3$ is that the calcium ion used to be analyzed by adding various reagents to the solution of interest so that the majority of Ca^{2+}-ions precipitated as $CaCO_3$ (Benjamin, 2015). Hardness was then reported as the concentration of $CaCO_3$ that had precipitated rather than the corresponding original Ca^{2+}-concentration. When alkalinity is reported as $CaCO_3$, it means that the real solution contains the same amount of alkalinity as a hypothetical solution containing the stated amount of $CaCO_3$ and no other solutes (ibid). The magnitude of hardness and alkalinity in a water sample are typically somewhat similar when they are both reported in mg/L $CaCO_3$, because they both originate from the same minerals, including limestone and dolomite minerals (Shaw et al., 2009). Thus, water with high values of alkalinity may also be hard. Hard water requires more soap to produce foam, can cause scale in pipes and hot-water heaters, and can deteriorate fabrics (UNICEF, 2008). Therefore, hard water can be rejected by consumers. Water with an alkalinity greater than 150 mg/L $CaCO_3$ may contribute to scaling (Shaw et al., 2009).

6.3.2 Results and discussion - Alkalinity

Alkalinity was measured by the Contour Comparator by Palintest. The measurement range was 0-250 mg/L $CaCO_3$. For alkalinity values greater than 250 mg/L $CaCO_3$, the water sample was diluted with distilled water. The accuracy is half the interval between each measurable unit, which is $\pm$ 25 mg/L $CaCO_3$. For diluted samples, which consisted of 50% distilled water, the accuracy was set to $\pm$ 50 mg/L $CaCO_3$. The results given in Figure 46 show that the alkalinity ranged from 100 $\pm$ 25 mg/L $CaCO_3$ in Isene to 450 $\pm$ 50 mg/L $CaCO_3$ in Munguli.

The majority of the pumping stations have a relatively high alkalinity exceeding 150 mg/L $CaCO_3$ which could cause scaling (Shaw et al., 2009). Nevertheless, scaling was not mentioned as an issue by the COWSOs. There are no direct health concerns related to alkalinity (ibid). The water does not seem to be corrosive. Generally, pH should not be below 7.5, and alkalinity should not be less than 0.6 to 1.0 mmol/L (30-50 mg/L $CaCO_3$)

to prevent corrosion (Ødegaard, 2014). All of the pumping stations have alkalinities greater than 50 mg/L $CaCO_3$, but some of them have a pH less than 7.5.

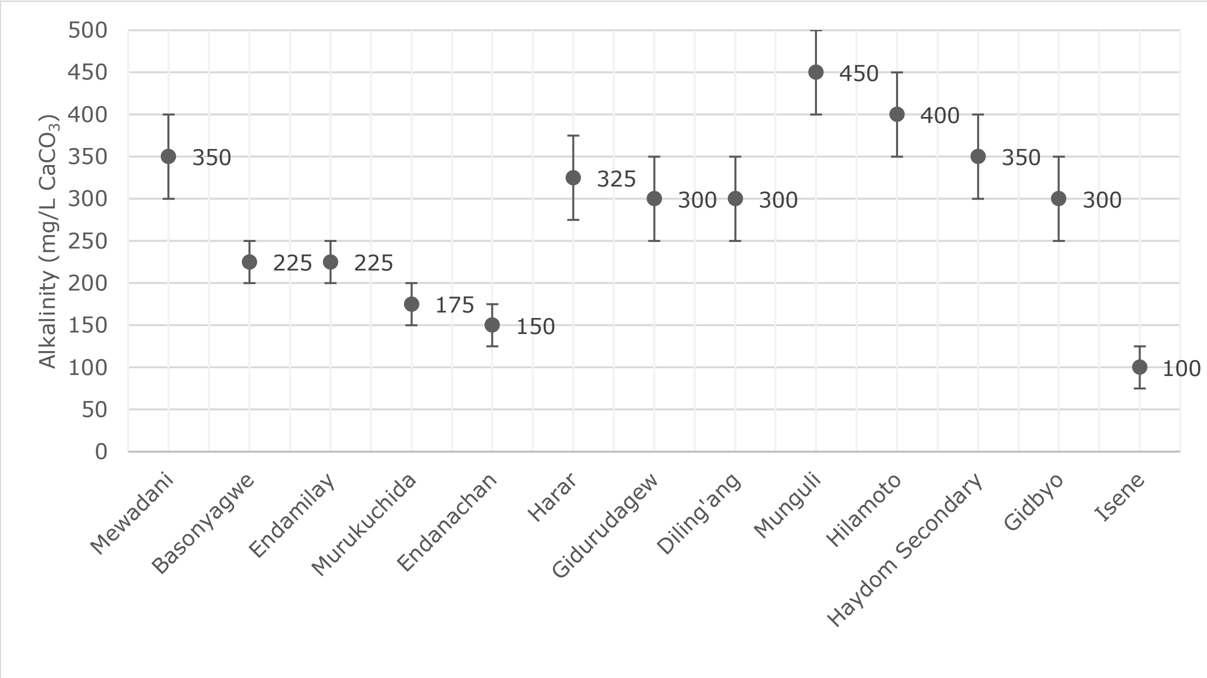


Figure 46: Alkalinity of water samples from 13 pumping stations

6.4 Conductivity

6.4.1 Background - Conductivity

The conductivity (κ) of a solution reflects its ionic composition (Benjamin, 2015). Conductivity may be measured by imposing an electrical field on a solution, causing dissolved cations and anions to migrate towards the oppositely charged electrodes, thereby establishing a flow of current (I) (ibid). This current is directly proportional to the strength of the electrical field and to the cross-sectional area (A) that the ions flow through. The strength of the electrical field equals the difference in the electrical potential (Ψ) between the electrodes divided by their separation (l). The conductivity is defined as the proportionality constant in the following relationship:

$$I = \kappa \frac{\psi}{l} A \qquad \text{Equation 9}$$

$$\kappa = \frac{l}{A}\frac{I}{\psi} = \frac{l}{A}\frac{1}{R} \qquad \text{Equation 10}$$

Where the final expression in Equation 10 reflects that the ratio I/Ψ is the inverse of the electrical resistance (R) by Ohm's law (ibid). According to Equation 10, the conductivity of a solution can be determined by measuring the electrical resistance of the solution in a cell that has a known geometry (l and A). Generally, the geometry of a cell is not known exactly, and other characteristics of the cell can have a small impact on the measured resistance (ibid). Thus, a cell constant (C) is defined that accounts for the l/A ratio and the other factors. The conductivity is then expressed as:

$$\kappa = C \frac{1}{R} \qquad \text{Equation 11}$$

For a given cell, the value of C can be determined by measuring the resistance of a standard solution of known conductivity (ibid). This value of C can then be applied when the same cell is used to analyze other solutions. The unit of conductivity is μS/cm, and typical values are 0.04 for distilled water and 35 000 for seawater (Ødegaard, 2014). All ions in a solution contribute to the conductivity, but they do not contribute equally (Benjamin, 2015). For instance, ions with a higher charge carry more current than those with lower charge. For ions with equal charge, the smaller ones which move through the solution easily carry more of the current than the larger ones. In a global overview of national standards for drinking water quality done by the WHO, almost half (51/104) of the countries and territories specified an upper limit for conductivity. The median guideline value among the countries was 2500 μS/cm (WHO, 2018). Tanzania does not have an upper limit for conductivity in drinking water (Tanzania Bureau of Standards, 2005).

6.4.2 Results and discussion – Conductivity

Conductivity was measured by an IDS conductivity sensor connected to WTW's Multi 3630 IDS digital meter, and the measurements were automatically adjusted for temperature. The accuracy of the conductivity sensor is ±1% of the measured value. The results in Figure 47 show that the conductivities measured at the 14 pumping stations were all below 2500 μS/cm.

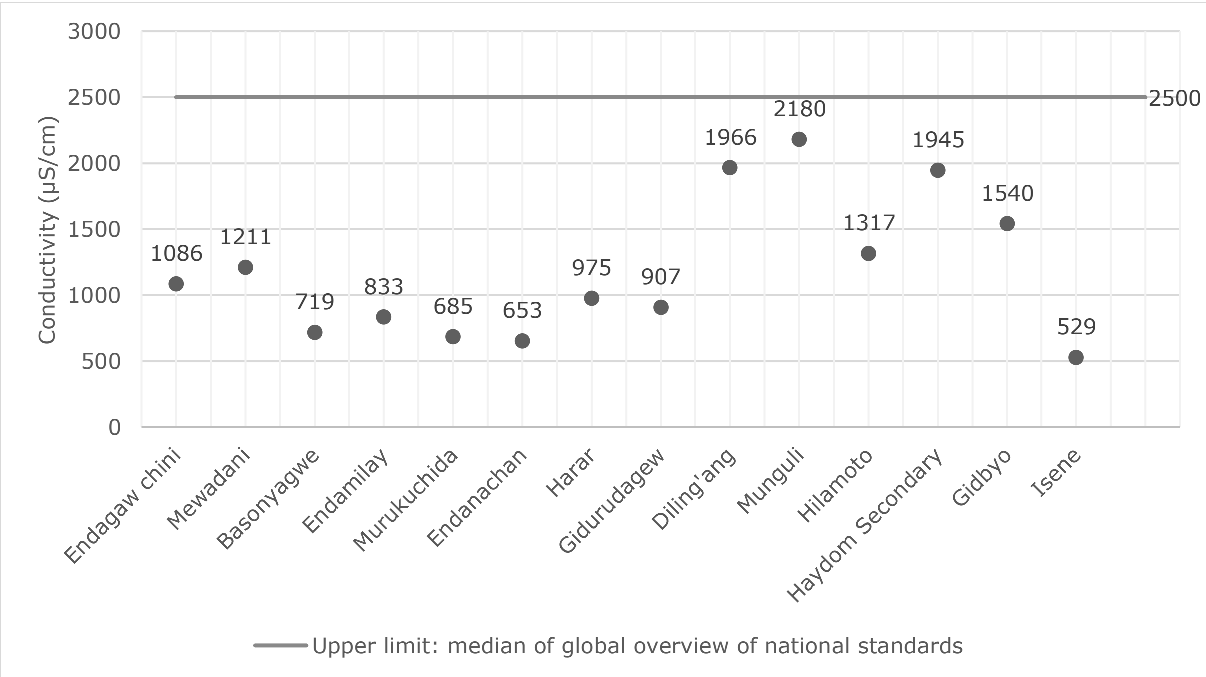


Figure 47: Conductivity of water samples from 14 pumping stations

Groundwater movements can be slow and residence times long, and thus chemical interactions occur between the water and the rocks and sediments it passes through, which in turn adds ions to the water (MacDonald et al., 2005). Thus, groundwater typically has higher conductivities than surface water. Conductivity is nonspecific since electric current can be carried in a solution by any ions present (Gray, 2005). As a result, the concentration of a specific ion cannot be determined from a conductivity measurement alone. However, conductivity says something about the magnitude of ions present in the water sample. Well logs provided by NCA indicate that some of the aquifers in question are composed of shale and others of granite. Shale is a rock that consists of minerals such as quartz (SiO_2) and calcite ($CaCO_3$) (Zendehboudi and Bahadori, 2016). Granite is a rock that consists of minerals such as quartz, alkali feldspars ($KAlSi_3O_8$), and plagioclase feldspars ($NaAlSi_3O_8$, $CaAl_2Si_2O_8$) (Raade, 2020). Thus, various ions formed from these minerals contribute to the conductivity. In addition, fluoride (F^-) is likely to be present as the East African Rift Valley which extends through Tanzania is known for groundwaters containing high concentrations of fluoride originating from the weathering of volcanic rocks and geothermal inputs (Edmunds and Smedley, 2012). The fluoride measurements conducted in this thesis confirm that assertion (chapter 6.6.2, page 68). The conductivities in Figure 47 vary between the pumping stations depending on the residence time of the water in the aquifer and the chemical composition of the rocks and sediments that the water is filtered through. Isene has the lowest conductivity of 529 $\pm$ 5 μS/cm, and Munguli has the highest conductivity of 2180 $\pm$ 22 μS/cm.

6.5 Turbidity

6.5.1 Background - Turbidity

Turbidity is a measure of the cloudiness of water due to particles (WHO, 2017b). Numerous types of particles can cause turbidity, including suspended particles such as clay and silt, chemical precipitates such as manganese and iron, and organic particles such as plant debris. As turbidity increases, the clarity of water is reduced, causing light to be scattered and adsorbed (ibid). A turbidity meter measures the intensity of a light beam directed towards a water sample, where the presence of particles will somewhat scatter the light beam, thereby reducing the intensity of the light beam (Ødegaard, 2014). Turbidity may be measured in NTU (Nephelometric Turbidity Units) which is identical to FTU (Formazin Turbidity Units) and FNU (Formazin Nephelometric Units). The reference for this unit is interference of light passing through a solution of 1mg/L SiO_2. Visible turbidity has an impact on the aesthetic acceptability of drinking water. Turbid water can vary in color and appearance, ranging from white clay-based particles to red-brown iron-based particles (WHO, 2017b). Water with a turbidity of 1 NTU and below is generally perceived as very clear. However, water becomes visibly cloudy at 4 NTU and above. The upper limit for turbidity in drinking water in Tanzania is 25 NTU (Tanzania Bureau of Standards, 2005). In a global overview of national standards for drinking water quality done by the WHO, the minimum upper limit among the countries was 0.3 NTU, and the maximum upper limit was 25 NTU (WHO, 2018). The median upper limit was 5 NTU.

6.5.2 Results and discussion - Turbidity

Turbidity was measured by a portable turbidity meter (HACH 2100Qis). The accuracy of the meter is $\pm$2% of reading plus stray light (0.02NTU) (HACH, 2013). However, the actual uncertainty of the measurements is greater than this, since particles are not evenly distributed in a water source. The results given in Figure 48 show that only one of the 14 pumping stations had a turbidity exceeding the Tanzanian guideline value of 25 NTU. Eleven pumping stations had excellent turbidities of less than 1NTU.

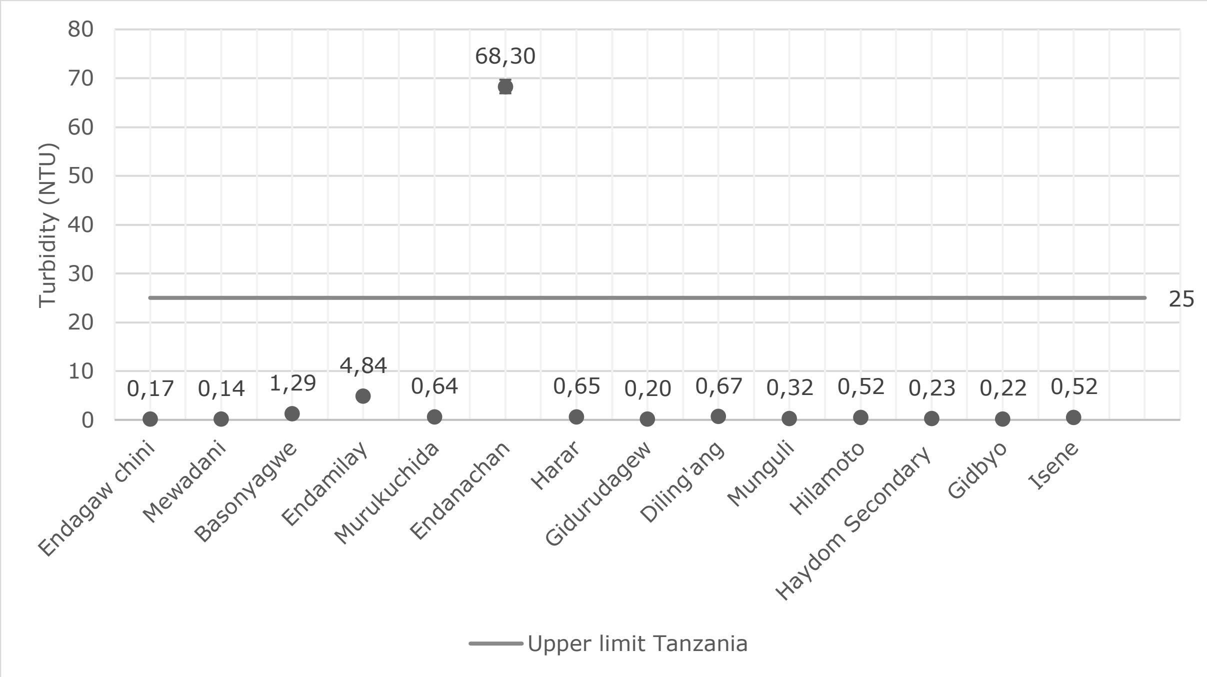


Figure 48: Turbidity of water samples from 14 pumping stations

The turbidity in Endanachan drastically exceeded the guideline value. Measurements were carried out twice at this pumping station due to the unusual results. The first measurements, conducted on the 4th of February, were 69.0 and 67.6 NTU of which the average is shown in Figure 48. The second measurements, conducted on the 15th of February, were 46.6 and 46.3 NTU. This illustrates that water quality can vary significantly between days. The turbidity on both days were nevertheless considerably higher than the upper limit. The exact reason is unknown, but there could be faults in the gravel pack which is supposed to restrain aquifer material from entering the borehole. Although the water was visibly turbid and had a yellow color, the COWSO in Endanachan stated that they are satisfied with the water quality of the well. They reported that the water is clean and has a nice taste and smell. The water is also perceived as safe due to the reduction of diarrheal disease among children after the installation of the pumping system, as the quote in the beginning of chapter 6 indicated. Thus, it is evident that the water source has not been rejected. Turbidity may be caused by various particles, many of which are harmless (WHO, 2017b). However, bacteria may be attached to suspended particles and incidents of elevated turbidity in drinking water have been linked to several outbreaks of disease (ibid). Nevertheless, a direct relationship between removal of turbidity and pathogens has not been established.

6.6 Fluoride

6.6.1 Background – Fluoride

Fluoride has beneficial effects on teeth at low concentrations in drinking water (Fawell et al., 2006). However, excessive exposure to fluoride can cause a number of harmful effects. These range from mild dental fluorosis to crippling skeletal fluorosis as the fluoride concentration and duration of exposure increases. Dental fluorosis is characterized by mottling of tooth surfaces or the enamel which causes yellow or brown stains on teeth (ibid). This condition can only occur in the developing enamel, and thus it can only develop in children and not adults. Crippling skeletal fluorosis is associated with very high levels of fluoride in drinking water which cause excessive accumulation of fluoride in bones (ibid).

This condition is characterized by pain, stiffness and irregular bone growth (Edmunds and Smedley, 2012, p. 17). Table 9 shows different levels of fluoride concentration in drinking water and associated health impacts. In the drinking water quality standard of Tanzania, the upper limit for fluoride is 4 mg/L (Tanzania Bureau of Standards, 2005). Whereas the maximum concentration guideline value specified by the WHO in the GDWQ is 1.5 mg/L (WHO, 2017a).

Table 9: Health impacts of fluoride in drinking water (Dissanyake, 1991)

Fluoride concentration (mg/L)	Health impact
0.0 - 0.5	Dental caries
0.5 - 1.5	Promotes dental health resulting in healthy teeth
1.5 - 4.0	Dental fluorosis (mottling of teeth)
4.0 - 10.0	Dental fluorosis, skeletal fluorosis (pain in back and neck bones)
> 10.0	Crippling fluorosis

The concentration of fluoride in most groundwaters is below the upper limits considered harmful to health (Edmunds and Smedley, 2012). However, aquifers containing water with high fluoride concentrations have been documented in some regions of the world, including the East African Rift Valley that extends through Tanzania. The abnormally high fluoride concentrations in this area originate from both weathering of volcanic rocks and geothermal inputs (ibid).

6.6.2 Results and discussion - Fluoride

Fluoride concentration was measured by the Contour Comparator by Palintest. The measurement range was 0-1.5 mg/L. For fluoride concentrations greater than 1.5 mg/L, the water sample was diluted with distilled water. The accuracy is half the interval between each measurable unit, which is ± 0.1 mg/L. For diluted samples that consisted of 50, 67 and 75% distilled water, the accuracy was set to ± 0.2, 0.3 and 0.4 mg/L, respectively. The results given in Figure 49 show that fluoride concentrations ranged from 0.6 ± 0.1 mg/L in Endagaw Chini to 4.8 ± 0.4 mg/L in Munguli. Two pumping stations, namely Endanachan and Munguli, had concentrations exceeding the upper limit of 4 mg/L specified by the Tanzania Bureau of Standards. Five pumping stations had concentrations above the WHO limit of 1.5 mg/L but below the Tanzanian limit.

Prolonged exposure to drinking water with a fluoride concentration above 1.5 mg/L is associated with dental fluorosis, whereas a fluoride concentration greater than 4 mg/L could cause skeletal fluorosis (Dissanyake, 1991). The reason why Tanzania has implemented a higher upper limit for fluoride than recommended by the WHO might be the fear of putting additional pressure on limited water resources. Implementing water treatment for fluoride removal in the villages with elevated concentrations would be beneficial for preventing cases of fluorosis. It might be more practical to carry out water treatment at the household level since treating water at the pumping station would require additional resources for operation and maintenance. Treating water in the individual households would also be more cost-effective, since it would only involve treatment of water for drinking and cooking and not for other purposes such as laundry and bathing. However, motivating people to treat water at home could be a major challenge since negative health impacts of consuming water with elevated fluoride levels only occur with prolonged exposure.

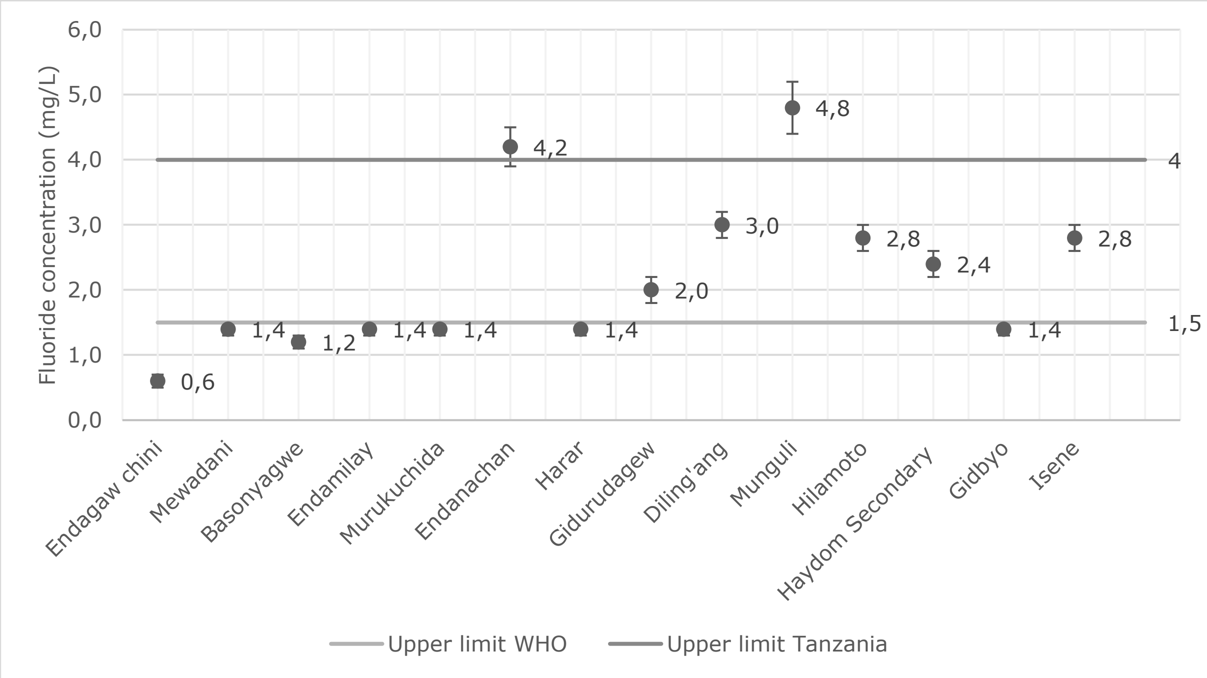


Figure 49: Fluoride concentration of water samples from 14 pumping stations

Treatment methods such as adsorption, membrane filtration, and coagulation can reduce fluoride concentrations in water. Among these methods, adsorption could be implemented at the household level. Adsorption is a process where a constituent, referred to as an adsorbate, becomes attached to a solid, referred to as an adsorbent (Crittenden et al., 2012). In water treatment, adsorbents like for instance activated carbon may be used to remove pollutants such as fluoride by adsorption. A number of adsorbent materials have been tested to identify those capable of removing fluoride efficiently and economically (Meenakshi and Maheshwari, 2006). Activated alumina, activated carbon, coffee husk, rice husk, and bone charcoal are among the adsorbent materials reported in literature. Mjangera and Mkongo (2003) investigated the possibility of using bone char as an adsorbent in a case study in Tanzania. Water with a fluoride concentration of less than 0.1 mg/L was produced from an initial concentration of 12.0 mg/L. Generally, adsorption is a cost-effective and efficient treatment method. However, the treatment efficiency of an adsorbent decreases with time because fluoride is accumulating on the adsorbent (Fawell et al., 2006). When the fluoride concentration in the treated water is no longer acceptable, the adsorbent has to be regenerated. The capacity of the adsorbent decreases with each regeneration, and after 3-4 regenerations the media usually has to be replaced (ibid). The adsorbent should ideally be a low-cost material that can be purchased locally and should work efficiently at a pH around 7 to avoid the need for pH-adjustments.

6.7 Fecal contamination

6.7.1 Background – Fecal contamination

Microbial contamination is the most severe risk associated with drinking water supplies (UNICEF, 2008). A major concern is fecal contamination of water as it can cause a number of health problems including diarrheal disease, cholera, dysentery, typhoid, and infectious hepatitis. For pollution of groundwater to occur, there needs to be both a source and a pathway (MacDonald et al., 2005). The source could be a pit latrine or livestock in the vicinity of the borehole. A distinction is typically made between the aquifer pathway and the local pathway. The aquifer pathway is naturally occurring through the intergranular pores and fractures in the soil and rock. The local pathway is due to failures in the design and construction of the pumping station.

There are various ways to test water for fecal contamination. In general, it is more practical to analyze water for *indicator species* that are present in fecal matter, rather than to analyze for every individual pathogen (UNICEF, 2008). Fecal coliforms, such as E. coli, are commonly used as indicator species. They are recognized as suitable indicator species because they are present in fecal matter in high numbers and relatively straightforward to measure by inexpensive equipment. The drinking water quality standard of Tanzania states that drinking water should not contain any organisms of fecal origin (Tanzania Bureau of Standards, 2005). The microbiological quality requirement is that E. coli must not be detectable in any 100 mL sample. This corresponds to the guideline value specified by the WHO (WHO, 2017a). The drinking water quality standard of Tanzania also states that the water supply system and surrounding land must be protected from contamination (Tanzania Bureau of Standards, 2005). For instance, domestic livestock and other animals should be kept away from the water point by fencing the area of a minimum radius of 50m.

The multiple tube and membrane filtration methods are two traditional methods for measuring coliform bacteria in drinking water (UNICEF, 2008). However, the enzyme substrate and hydrogen sulfide (H_2S) methods have been gaining increasing popularity. Manja et al. (1982) observed that the presence of coliforms in drinking water is consistently associated with organisms that produce H_2S. In addition, some bacteria which may occur in the intestines such as Salmonella, Proteus, and Citrobacter also produce H_2S. A simple method to detect fecal contamination in drinking water was reported by the authors (Manja et al., 1982). The method is based on the easily observable formation of black iron sulfate precipitate as H_2S reacts with iron. The H_2S-method was reviewed in a WHO report which concluded that the test has a number of advantages, including low cost and simplicity (Sobsey and Pfaender, 2002). However, the authors cautioned that some conditions may lead to false positive results.

6.7.2 Results and discussion – Fecal contamination

The HACH PathoScreen Field Test Kit is a H_2S-test which was used to test water for fecal contamination. The test was only conducted at four of the 14 pumping stations visited, namely Endagaw chini, Mewadani, Basonyagwe, and Diling'ang. In addition, four local water sources in Mbulu were tested. Those were the rainwater harvesting (RWH) systems at Mewadani Primary School and Haydom Secondary School, Basonyagwe local dam, and Endagulda local spring. The results in Table 10 show that all water samples tested positive except for Endagaw chini pumping station and Haydom Secondary School (RWH).

Table 10: Results from hydrogen sulfide producing bacteria test

Village	District	Number of positive tests/total number of tests	Test result
Endagaw chini	Mbulu	0/1	Negative
Mewadani	Mbulu	1/1	Positive
Basonyagwe	Mbulu	1/1	Positive
Diling'ang	Hanang	1/2	Positive
Mewdani Primary School (RWH)	Mbulu	2/3	Positive
Haydom Sencondary School (RWH)	Mbulu	0/1	Negative
Basonyagwe local dam	Mbulu	2/2	Positive
Endagulda local spring	Mbulu	4/4	Positive

It is highly concerning that six out of eight water sources tested positive for hydrogen sulfide producing bacteria. However, there are uncertainties regarding the trustworthiness of the H_2S-test (Sobsey and Pfaender, 2002). For instance, any source of H_2S in the water sample can lead to a positive test result. Numerous types of bacteria can produce H_2S in water and in sediments under a variety of environmental conditions unrelated to the occurrence of fecal contamination in water. In addition, groundwaters may contain sulfide (S^{2-}) (ibid). If the H_2S-test turns dark almost immediately it could be due to the reaction of iron with sulfides already present in the sample. A positive result within a few minutes to one hour of incubation cannot be classified as either positive or negative for fecal contamination because it is not evidence for H_2S-production by fecal bacteria. It is uncertain whether some of the water samples in the fieldwork gave a positive result after less than one hour of incubation. Two of the tests done at Endagulda local spring were prepared in the evening and were dark the next morning. However, they were not monitored the first hour after preparation, so it is uncertain when the positive test results occurred. Furthermore, organisms of fecal origin tend to grow more rapidly than those of environmental origin (ibid). Positive test results after incubation times exceeding 48 hours could therefore be due to growth of nonfecal microorganisms. However, the test results were recorded within 48 hours in the fieldwork of this thesis.

The test procedures of the PathoScreen Field Test Kit as described by HACH (2016) were not strictly followed, which ultimately could have affected the test results. For instance, the medium powder pillow was not swabbed with alcohol before opening, since alcohol pads were unavailable. Samples were collected in a 1-liter bottle in field and prepared in 20 mL test bottles in the evening. When samples are not analyzed immediately, they should be stored at a temperature of 4-10 °C. This was however impossible in field. Also, the test bottles should have been placed in a location with constant temperature of 25 to 35 °C during incubation, but the temperature at night was often less than 25 °C. The instructions of the PathoScreen Field Test Kit states that failure to properly collect and transport samples will cause inaccurate results (HACH, 2016). In retrospect, water samples should have been prepared in 20 mL test bottles in field, with the addition of the medium powder straight after collection of the water sample. In addition, water from all pumping stations visited should have been tested for fecal contamination, instead of testing just four. It would also have been beneficial to test for both E. coli and H_2S-producing bacteria because similar results of both tests would be a stronger indication of the occurrence or nonoccurrence of fecal contamination. The tests should also have been quantitative, so that the magnitude of the problem could be evaluated.

The H_2S-test has been investigated by a number of researchers. McMahan et al. (2012) used biochemical and molecular methods and a quantitative test format to identify the types and numbers of microbial community members present in natural water samples, including fecal indicators and pathogens. Water sources in the study included rainwater collected in tanks, a protected lake, and wells in agricultural and forest settings. It was shown that water samples testing positive for H_2S-producing bacteria also had bacteria of fecal origin and waters containing fecal pathogens were positive for H_2S-producing bacteria. Thus, the results of McMahan et al. (2012) documented the validity of the H_2S-test for detecting fecal contamination of water. Yang et al. (2013) assessed how bacterial density affects the accuracy of the presence/absence H_2S-test. The test was found to be more reliable for heavily contaminated samples. Samples with no detectable thermotolerant coliforms (TTC) or E. coli were sometimes H_2S positive, whereas several samples with 1-9.99 cfu/100 mL of TTC or E. coli were H_2S negative. For more heavily contaminated samples with more than 10 cfu/100 mL of TTC or E. coli, the test result was usually positive. It is difficult to say something about the validity of the H_2S-tests carried out in field due to the conflicting results of research on the topic. The results of Yang et al. (2013) indicates that the test is unreliable for sparsely contaminated water, which supports the suspicion of false positives. However, the results of McMahan et al. (2012) suggest that there is a strong correlation between positive test results and bacteria of fecal origin.

The research question of this chapter cannot be fully answered due to the uncertainties related to the validity of the H_2S-test outlined above. However, some general comments about the likelihood of fecal contamination of the water supply systems in question can be made. Possible sources of contamination are pit latrines and livestock. Pit latrines close to the pumping stations were not observed during the fieldwork, but this type of toilet is rather common in the area. Livestock were usually observed grazing close to the pumping stations. Some pumping stations also have cattle troughs where cattle come to drink. The water points are protected by a fence of approximately 15x15m, which is less than the requirement of the Tanzania Bureau of Standards which states that domestic livestock and other animals should be kept away from the water point by fencing the area of a minimum radius of 50m (Tanzania Bureau of Standards, 2005). The depth at which the pump intake is located influences the likelihood of contamination through the aquifer pathway. The pump intake level of the pumping stations varies between 50 and 140m below the surface, according to information from NCA. The average depth is 83m, which is rather deep, and implies a long travel time for water and pollutants from the surface to the pump intake. In addition, well logs for five of the 14 pumping stations visited show that the aquifers are confined, meaning that they have an impermeable layer on top. Local pathways can be through the headworks or along shallow permeable soil layers and down the borehole casing or well lining (MacDonald et al., 2005). Therefore, all borehole designs should include a sanitary seal about 3-6m below the ground surface. A sanitary seal works as a barrier between the casing and the borehole wall and is typically made of bentonite clay or cement (ibid). The seal stops poor quality surface water from entering the space between the outmost casing and the borehole wall thereby contaminating the borehole. The pumping stations in question have sanitary seals to 5 m below the ground surface, according to drilling completion reports by Trust Engineering. The wellhead is located inside a concrete box with a lid and is thus rather protected from pollution (Figure 50). For these reasons, it is in the author’s belief that fecal contamination from the surface is unlikely.

Nevertheless, it is recommended that the water is tested once more, for example by NCA, because of the critical health risks associated with fecal contamination.

Figure 50: Wellhead at Hilamoto pumping station

7 Management

Ensuring resilience of water supply infrastructure is a major challenge in rural low-income settings. When a COWSO member in Gidbyo village was asked about her contribution to the project, she answered: "We are always advising men on how to maintain the project so it can be used in the future. If the project stops working, we will be back to suffering fetching water from far away. We always say that we need to be careful with the project."

This chapter investigates the topic of management by addressing the following research question: *To what extent do current management practices ensure pumping system resilience?*

7.1 Background

There are many plausible definitions of management. To manage can mean "to conduct things and people to achieve some end" (Gray and Hughes, 2001, p. 8). Whereas Best (2006, p. 186) described management in the following way: "In general, management is about day to day operation, and relies on people who know how to get the job done, deliver on time, to budget and specification." In this work, management refers to all organized activities aimed at ensuring proper functionality of the pumping systems, including operation, maintenance, and repairs. The resilience of a system is related to its response after failure to unexpected loading conditions. This work adapts the definition of Butler et al. (2014, p. 349) who defined resilience as "the degree to which the system minimizes level of service failure magnitude and duration over its design life when subjected to exceptional conditions". All water supply systems fail at some point, which makes effective and rapid repairs vital for ensuring continued access to safe drinking water (Klug et al., 2017).

Policies that promote Community Based Management (CBM) have dominated the rural water supply sector in SSA for decades (Whaley et al., 2019). The foundation of the CBM model is the creation of a local water point committee which has the responsibility for operation and maintenance. In Tanzania, the National Water Sector Development Strategy of 2006 established the concept of Community Owned Water Supply Organizations (COWSOs) which are committees started by a community to own, operate, and maintain water supply systems on behalf of the community (World Bank, 2018a). There is a growing recognition among development organizations and academics that the CBM model has struggled to achieve resilient water supply services (Whaley et al., 2019). According to the 2015 Tanzania Water Point Mapping data, 29% of water points were non-functional, and 20% failed within the first year (Joseph et al., 2019). This sub chapter summarizes some of the research done on the relationships between CBM practices and functionality of water points. The handpump is the most common type of pump for groundwater abstraction across rural SSA, and thus the majority of research on pump functionality focuses on boreholes equipped with handpumps. It is however assumed that some of the results are relevant also for solar-powered systems.

Foster (2013) used logistic regression analyses to identify operational, technical, institutional, financial, and environmental predictors of functionality for over 25 000 community managed handpumps in Liberia, Sierra Leone, and Uganda. Risk factors associated with nonfunctionally in all three countries were system age, distance from district capital, and absence of user fee collection. In at least one of the three countries, other variables found to have significant impact on functionality included handpump type, spare part proximity, availability of handpump mechanic, regular servicing, regular water committee meetings, women in key water committee positions, and perceived water quality. Contrary to common belief, the training of water committees in Uganda was not associated with handpump functionality. This was thought to be caused by poor training or the lack of periodic follow-up. The finding that collection of user fees is associated with handpump functionality is consistent with the assertion that funds for operation and maintenance are crucial for resilience of water points. The relationship between handpump functionality and distance to district capital could be due to a lack of spare part supply chains or that remote villages are less likely to receive post-construction support. The relationship between system age and functionality draws attention to the need for long-term support. Foster (2013) concluded that governments and development organizations must significantly strengthen the support for postconstruction operation and maintenance.

Whaley et al. (2019) conducted a survey of community management arrangements at 600 water points in Ethiopia, Malawi, and Uganda, examining the degree to which management capacity is related to borehole functionality. The capacity of water management arrangements was assessed according to four dimensions: finance system; affordable maintenance and repair; decision making, rules, and leadership; and external support. Out of these four dimensions, affordable maintenance and repair was the best predictor of borehole functionality. No strong relationship was found between the overall capacity of the water management arrangements and the functionality of the borehole. This could be due to poorly functioning boreholes forcing water committees to function better to secure even basic supplies of water. The analysis also suggests that physical factors, such as climate and hydrogeology, have a larger impact on functionality than the relative strengths and weaknesses related to water management arrangements.

Kativhu et al. (2017) investigated factors influencing the sustainability of 399 rural water supply systems across three districts in Zimbabwe. Data was collected using a questionnaire, an observation checklist, and interviews with key informants. Statistical analysis was used to assess sustainability of water points in relation to influencing factors. A combination of social, technical, financial, environmental, and institutional factors was found to influence sustainability. Availability of spare parts at the community level proved to be decisive for the downtime of the systems. Water points without user committees were not sustainable and most of them were non-functional. Active participation by the community at the planning stage of the water project was confirmed to be critical for sustainability. Financial factors, such as adequacy of financial contributions and establishment of operation and maintenance funds, were also found to be of great importance. Kativhu et al. (2017) noted that where communities survive in severe poverty, governments may need to subsidize spare parts for repairs in order to achieve sustainability.

Alexander et al. (2015) used linear regression models to assess level of functionality against governance characteristics of 82 water supply systems in two regions of Ethiopia. Features that were strongly associated with higher levels of functionality were: charging slightly higher fees, maintaining good financial records, holding regular committee meetings, having the capacity to do minor repairs, having a pump caretaker, and awarding the caretaker with some type of compensation. Periodic financial audits of the committee's records by a third party were also associated with a higher level of functionality. Alexander et al. (2015) emphasized that financial recordkeeping and basic maintenance skills are beyond the capacity of water committees without initial training and support from governments or development organizations. Also, it is possible that the capacity of a water committee decreases as new members join because they are not trained in these essential skills. In turn, this could negatively impact pumping system functionality.

7.2 Results

This chapter looks into the implementation of the WASH-project as well as the management practices currently employed at the pumping stations. The information was provided by interviews with key stakeholders, such as COWSOs, 4CCP, and district water engineers (DWEs). The COWSOs are water committees which own, operate, and maintain the pumping stations. Out of the 14 pumping stations visited, 12 COWSOs were interviewed because Munguli and Haydom Secondary School do not have a COWSO. Records of water tariff collections from some of the pumping stations were used to evaluate whether incomes cover costs.

7.2.1 Project planning and construction

The pumping stations were built from 2015 to 2019, the majority of which were constructed in 2018 and 2019. NCA provided the funds, while Trust Engineering and Dennez Engineering Limited did the drilling and construction work. NCA and 4CCP supervised the building process. In addition, 4CCP mobilized the communities to contribute to the project, and established COWSOs and Public Expenditure Tracking System (PETS) committees within the villages. During interviews with the COWSOs, it became clear that the communities have participated in the project from planning to completion. They were present during building, drilling and insertion of the pump. Communities typically contributed with labor, local materials such as bricks and sand, and food for technicians. The households within each community also contributed economically. The size of the contribution varied significantly between villages due to differences in income. A typical household contribution could for instance be 10 000 TZS (42 NOK), according to 4CCP. In each village, three different locations were considered for the pumping station, partly based on the preferences of the community. Then, a geological survey was carried out at each site by Trust Engineering. Usually, the location with the best hydrogeological conditions was chosen. However, if the sites had equally good hydrogeological conditions, the community could choose freely among the sites. This was the case in Gidurudagew and Harar, where the communities decided to build the pumping system close to the primary school, so that pupils could access water easily.

7.2.2 Operation

Each pumping station typically has two employees, a caretaker and a security guard. The caretaker works at the pumping station during the day. His or her main tasks are to operate the pump and to sell water to the beneficiaries. In the dry season, the pump typically runs the whole day due to a great demand for water. Whereas in the rainy season, the caretaker turns the pump off when the water tanks are full. If the pump continues to run when the tanks are full, water will flow through the discharge pipe of the tanks and go to waste. Typical opening hours of the pumping stations are 8-18. The caretaker has the key to the gate of the fence surrounding the pumping station. When the caretaker arrives in the morning, he or she opens the valve of the pipe that supplies water to the water taps from the storage tanks. The water taps are located outside the fenced area. The number of buckets of water sold and the corresponding income are recorded in a book by the caretaker. In addition, water meter readings are recorded every day, to check if the number of buckets sold corresponds to the readings of the water meter. A community member is employed permanently as a caretaker at most pumping stations. However, Isene village rotates the caretaker's tasks among the COWSO members.

The security guard works at the pumping station during the night to prevent vandalism and theft. The fence protecting the pumping stations has a height of approximately three meters, but it is possible to trespass. Hilamoto was the only pumping station that had experienced theft. Somebody tried to steal the solar panels during the night of the 14th of February 2020. Fortunately, they did not succeed because of the security guard. Isene was the only pumping station that did not have a security guard, but the COWSO was planning to hire one at the time of the interview (21th of February 2020).

Each COWSO consists of 7-14 members, with an approximately equal number of men and women. The members are chosen at the village assembly. Every third month, the COWSO delivers a report to the village government with records on how much money they have collected and how much water they have sold. Within each COWSO, there is a chairperson, a treasurer, and a secretary. Some COWSOs meet weekly, others monthly, and some meet every third month. The chairperson organizes meetings, whereas the secretary prepares the agenda and takes the minutes. The task of the treasurer is to collect money from the caretaker and take it to the bank if the COWSO has a bank account. The money is typically deposited in the bank weekly or monthly. Nine out of the 12 COWSOs interviewed have a bank account. In the cases where there is no bank account, the treasurer keeps the money, while the village executive officer has an overview of how much money is collected and how much is spent. All COWSOs have female treasurers.

At each pumping station, there is a fixed price per 20 L-bucket of water. The price varies between 20 and 50 TZS, which equals approximately 0.08 and 0.21 NOK. The price at each pumping station is set according to guidelines from the DWE and depends on the number of people fetching water and the expenses. The funds are used for salaries for the caretaker and the security guard as well as for stationaries like pens and books. They should also cover minor repairs. In most cases, COWSO members are not paid. Diling'ang is the only village visited that provides salaries for the chairperson, treasurer, and secretary of the COWSO. Some of the COWSOs reported that they have spent money on upgrading the building that the water tanks stand on. Others said that they want to use the funds to upgrade the pumping system, for example to supply water to sub villages to reduce the water collection time (Appendix 2).

The majority of the villages visited has a Public Expenditure Tracking System (PETS) committee. Each committee consists of 8-10 members with an approximately equal number of men and women. The task of the PETS committee is to make a close follow-up of any development project implemented in the village to ensure transparency and accountability. They supervise monetary collections to make sure that the collected funds are used for the intended purposes. Some PETS committees meet weekly, others monthly, and some meet every third month, depending on whether there is a development project to track. The PETS committee typically participates in the meetings of the COWSO.

Munguli and Haydom Secondary School do not have a COWSO or a PETS committee. At Haydom Secondary School, the students pay 500 TZS (2.1 NOK) per month for operation and maintenance, and the school administration is in charge of managing the system. The pumping station in Munguli provides water to a primary school and to a village through several tap stands. The school pays the salary of the pump caretaker. Currently, the villagers fetch water for free without contributing to the system. 4CCP has tried to establish a COWSO, but it does not function satisfactory yet. A teacher at Munguli Primary School admitted that the school wants the community to take more responsibility. When the water taps that the villagers are using become broken, they wait for the school to pay for repairs.

7.2.3 Maintenance

Maintenance is needed to maintain the operational function of a system and to extend its working life (Butler and Davis, 2011). For the pumping stations in question, local communities perform simple maintenance tasks such as cleaning the solar panels. If dust accumulates on solar panels, the power output is significantly reduced. Most COWSOs reported that they clean the solar panels in the dry season, with a frequency varying among the committees from two times per week to once a month. The solar panels are typically not cleaned in the rainy season, because it rains so often that dust does not accumulate much. The DWE of Mbulu reported that they do not perform any maintenance on the solar-powered water pumping systems, since the water policies require users to maintain the systems instead of the government. They only interfere if there is a big issue that the COWSOs cannot afford to pay for. The DWE in Hanang also reported that they do not perform regular maintenance on the solar-powered water pumping systems. The DWE in Mkalama reported that they perform some maintenance. The pump is taken out of the borehole once or twice per year for cleaning. According to the DWE, the pump gets rusty due to salty water without periodic cleaning, which in turn can cause pump collapse.

7.2.4 Repairs

The pumping systems are relatively new, so only a few repairs have been required so far. The pump at Munguli pumping station broke down in September 2019 and was out of service for three consecutive months. The pumping station was built in 2015 as the first solar-powered pumping system in the NCA WASH project. The system supplies water to a primary school and to a village by several tap stands. In September to November 2019, people had to fetch water from the river, local wells, and dams, where cattle also get water. Pupils and villagers suffered from waterborne diseases in that period. The pump was replaced by the DWE of Mkalama financed by the local government, and hence the system was back in service by December 2019. According to a teacher at Munguli Primary School, the price of the new pump was 3 000 000 TZS (12 468 NOK), whereas the DWE of Mkalama reported a price of 2 500 000 TZS (10 390 NOK). It is uncertain what was the cause of the pump breakdown. According to a teacher at Munguli Primary School, the pump failed because no one was taking care of the pumping system.

In Mewadani, only one out of two water tanks of 10 m^3 is in operation. The second tank had a burst, and thus was disconnected from the rest of the pumping system by local technicians. The tank broke on the 8th of January 2020 according to the caretaker working at the pumping station. At the 20th of February, the tank had not been repaired or replaced. In an interview with the COWSO in Mewadani, it was mentioned that they have a plan of rehabilitating the tank. According to the DWE of Mbulu, the tank should be replaced rather than rehabilitated. If funds are available, the DWE can replace the tank within one week for a price of 1 000 000 TZS (4156 NOK). Local technicians within the villages can perform simple repairs such as repairing water taps. According to 4CCP, there is a toolbox at each pumping station in case simple repairs are required.

7.2.5 Income and costs

The main income of the pumping stations is water tariffs as people pay a fixed amount per bucket of water collected. Figure 51 shows income at three pumping stations in the period of September to December 2019. The pumping stations show the same water demand pattern, with an increasing demand from September to October, a decreasing demand from October to November, and a very low demand in December. This could be caused by seasonal variations in precipitation, because people fetch water by rainwater harvesting instead of pumping stations when it is raining. Figure 41 (page 55) shows that the monthly precipitation was around 1, 89, 95 and 297mm in September, October, November, and December, respectively. Thus, the demand does not strictly follow the precipitation pattern. However, December has the highest rainfall and also the lowest water demand. In Isene, the water demand in December was so low that they stopped charging water tariffs. The income varies between the pumping stations, with Basonyagwe earning the most, and Endagaw chini earning the least among the three pumping stations considered. This is thought to be because Basonyagwe charges a higher water tariff of 30 TZS per bucket, instead of 20 TZS, and because Basonyagwe has a cattle trough and therefore a very high demand for water. Some pumping stations have veggie gardens which were intended as an extra source of income. COWSOs can grow vegetables in the dry season, irrigated by water from the pumping stations. Vegetables can then be sold in local markets thereby providing income for operation and maintenance of the pumping station. However, this has only been partly successful according to 4CCP. In many villages, the water scarcity in the dry season makes beneficiaries hesitant to use water for irrigation. Also, it is difficult to grow vegetables in the dry season due to insects and animals looking for food in a completely dry landscape. Collection of water tariffs therefore remains the main source of income for the pumping stations.

The main costs of operating the pumping stations are the salaries of the caretaker and the security guard. What they earn vary depending on the amount of water sold, and between villages. Usually, they do not earn more than 50 000 TZS (208 NOK) per month, according to 4CCP. At some pumping stations, the security guard can go 2-3 months in the rainy season without getting paid. The caretaker and the security guard are sometimes perceived as volunteers because of their low salaries. They do not have to contribute financially to other development projects in the village, for example the construction of a school, since they are doing a public service by working at the pumping station.

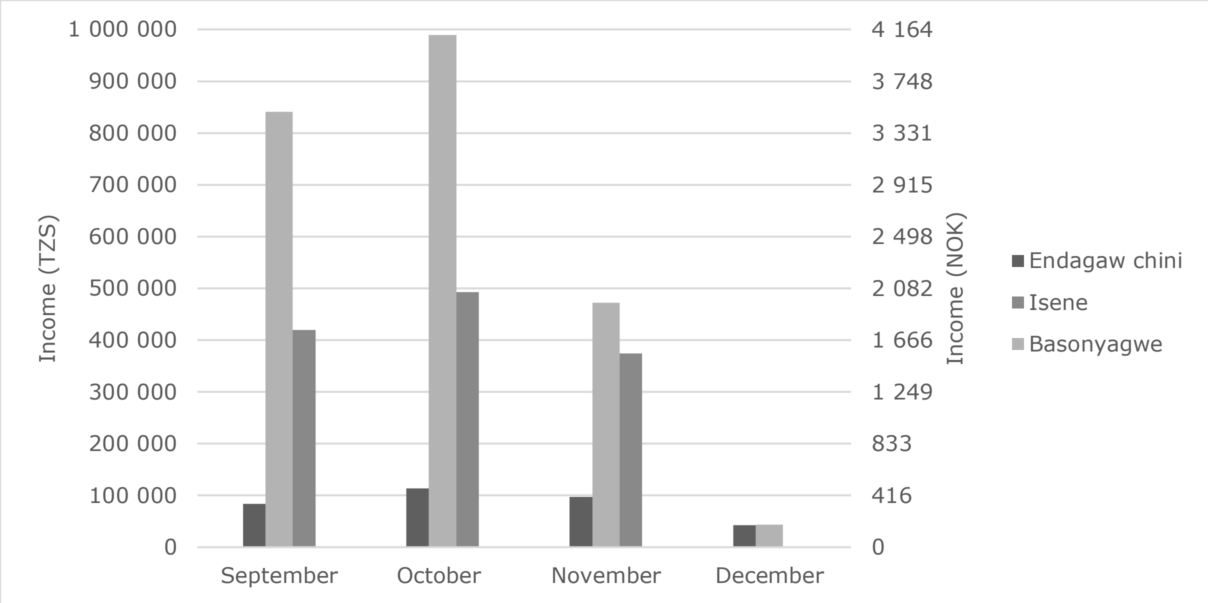


Figure 51: Water tariff incomes at three pumping stations

7.3 Discussion

The resilience of water supply infrastructure depends on the management practices employed. When failure occurs, repairs need to be performed rapidly to bring the pump back into service thereby ensuring continued access to safe water. This requires a COWSO with a substantial organizational and financial capacity.

A number of management practices employed at the pumping stations in question are associated with pumping system functionality in literature. Alexander et al. (2015) found that factors such as keeping good records, holding water committee meetings regularly, having a caretaker, and awarding the caretaker with some type of compensation were strongly associated with higher levels of pumping system functionality. Whereas Kativhu et al. (2017) found that ensuring active participation by communities at the planning stage, establishing a water committee, and having a fund for operation and maintenance, were critical factors for sustaining water supply services. All these considerations were made in the NCA WASH project. Research does however show that community enthusiasm for keeping water committees functioning and for collecting water tariffs to cover the costs of service delivery, can disappear within two or three years after construction of a water point (Carter et al., 1999). It is therefore essential that the supporting government or development organization continues to follow the project until management practices are fully incorporated. Foster (2013) did not find a significant relationship between the training of water committees in Uganda and borehole functionality. Possible reasons are that the training was poorly carried out, or that even if done well there was a lack of periodic follow-up. In an interview with the COWSO in Endanachan, additional training by 4CCP on how to manage the pumping station was requested. 4CCP wants to continue to support the local communities because they recognize that COWSOs would benefit from additional training. Ideally, they would like to follow the project for three years to ensure that correct management practices are followed.

The COWSOs in the villages visited consisted of an approximately equal number of men and women. Research indicates that if both men and women are included in the management of a water service, users are more likely to be satisfied, and the project is more likely to be sustained (Gross et al., 2001). All COWSOs interviewed had a female treasurer. This was a conscious strategy of 4CCP as women tend to suffer the most due to inadequate water supply systems because they are responsible for fetching water. Therefore, it is assumed that women will take good care of improved water supply infrastructure, especially if they are given specific responsibilities. Foster (2013) found that having women in key water committee positions is a significant predictor of handpump functionality in Uganda.

Sustainable financing strategies have been recognized as a prerequisite for sustaining water supply infrastructure by numerous researchers (Carter et al., 1999, Harvey and Reed, 2004). For instance, Harvey (2007) addressed the need for long-term financing mechanisms to ensure continued functionality of existing water services in rural SSA. It was suggested that users should pay a water tariff to cover the overall costs of service delivery. Foster (2013) found that the collection of user fees is a key determinant of handpump functionality in Liberia, Sierra Leone, and Uganda. Similarly, Whaley et al. (2019) found affordable maintenance and repairs to be decisive for borehole functionality in Ethiopia, Malawi and Uganda. At the pumping stations in question, collection of water tariffs by a fixed price per bucket has been an efficient way of raising funds for operation, maintenance and repairs. However, the size of collected funds vary significantly throughout the year and between pumping stations, as shown in Figure 51. Basonyagwe has a higher income than Endagaw chini and Isene. Plausible reasons are that Basonyagwe pumping station charges a slightly higher water fee, 30 instead 20 TZS, and that it has a cattle trough which increases the total water use. The time to raise money for repairs will vary among the pumping stations due to the differences in income. Basonyagwe could afford a new water tank of 1 000 000 TZS in a couple of months with high water demand, and still be able to pay the caretaker and the security guard. Endagaw chini, on the other hand, would possibly spend a year collecting funds to afford to replace a water tank. However, 4CCP mentioned that COWSOs can encourage additional financial contributions from households if there is a lack of funds for repairs. The capacity to make extra contributions does however vary between villages because of differences in household incomes. Raising the water fee could increase funds for repairs. However, this must be done with caution, since community members might revert to using unimproved water sources if the water fee becomes too high.

The resilience of the pumping stations in question will partly depend on government support. In most cases, water fee collections are insufficient to cover the costs of major repairs, since the cost of replacing a pump is approximately 2 500 000 - 3 000 000 TZS. Larger rehabilitations and upgrades are even more expensive. Local government authorities are obliged to meet part of the costs incurred by COWSOs in major rehabilitation and expansions of water schemes, according to the Water Supply and Sanitation Act No. 12 (United Republic of Tanzania, 2009). The district council of Mkalama contributed financially and with technical expertise after the pump breakdown in Munguli in September 2019. This shows that local governments are willing to support major repairs. However, the pumping system was out of service for three months which caused health problems of those affected. A faster response would have implied better system resilience. The fact that Munguli does not have a functioning COWSO could possibly have slowed down the process of organizing the repair. The legal framework underlying water service delivery in

Tanzania has been criticized for a lack of clarity in division of responsibilities, which in turn places a burden on the maintenance of rural water supply infrastructure (World Bank, 2018a). It is largely up to each district council to evaluate at which service failure magnitude they must intervene. Jiménez and Pérez-Fouget (2010) argued that national policies must be redefined to ensure a greater balance between user participation in the management of water supply services and adequate support of local governments.

Planned maintenance means to deal with potential problems prior to failure (Butler and Davis, 2011). In infrastructure asset management, planned maintenance can reduce the frequency or risk of failure, thereby increasing system resilience. This is rarely done at the pumping stations in question. Local communities perform simple maintenance tasks such as cleaning the solar panels. The DWEs of Mbulu and Hanang do not perform regular maintenance at the pumping stations, whereas the DWE of Mkalama cleans the pump once or twice a year. The pump operating manual of Davis and Shirtliff recommends inspecting the installation every three months to check operating parameters including current, water output, closed head pump pressure, and water quality, as well as switchgear condition (Davis and Shirtliff, 2014). A periodic check of motor winding and insulating resistance is also recommended, especially if there is an abnormal operating current or voltage reading. The manual does *not* recommend periodic lifting and checking of borehole installations until an operating fault is noted because equipment is designed for continuous operation. For this reason, it is questionable whether taking the pump out of the borehole for cleaning is good practice. The maintenance procedures recommended in the manual requires technical expertise and can therefore only be performed by an external company. In that case, COWSOs would have to be coupled with a contractor with the relevant competence. This would however be costly, and hence it would reduce the funds available for repairs. Therefore, the common practice is to deal with problems on a corrective basis as they occur. Planned maintenance would enable COWSOs to deal with problems at an early stage thereby limiting service failure magnitude and duration. Limited funds for maintenance is thus a major challenge for system resilience.

8 Remote Monitoring

Pumping systems for rural water supply are typically spread across large geographical areas, which makes it difficult for service providers to have an overview of the condition of each water pump. It has therefore been proposed to remotely monitor operational performance using sensors and data transmission systems that rely on mobile networks (Swan et al., 2018). Partly replacing physical site visits with remote monitoring is thought to reduce time and costs associated with traditional monitoring strategies, and to ease the targeting of pumping systems that need maintenance and repairs.

This chapter addresses the following research question: *How may the implementation of remote monitoring influence pumping system resilience?*

8.1 Background

An increasing number of physical objects are being connected to the internet, establishing the concept of the Internet of Things (IoT) (Al-Fuqaha et al., 2015). Basic examples of such objects include those that enable smart homes, such as heating, ventilation, and air condition monitoring and control systems. There are numerous fields of application of the IoT including transportation, healthcare, and industrial automation (ibid). The IoT can enable physical objects to record information, communicate together, and coordinate decisions. Access to mobile network services is increasing rapidly in SSA, encouraging the implementation of remote monitoring systems based on the IoT to keep track of the performance of water pumping systems. In 2018, 70% of the population in SSA were living within an area with mobile broadband network, compared to 51% in 2014 (GSMA, 2019). There are many possible configurations and uses of a remote monitoring system installed at a solar-powered water pumping station. Usually, various sensors are installed to measure different parameters, such as system voltage, current, and power. Data recorded by the sensors are transmitted through the mobile network and can be downloaded from any browser with a protected login. Remote monitoring systems are not very prevalent in the market, which is partly because the technology is new and there is not much history of such systems being used (Khare and Economu, 2019). Currently, solar-powered water pumping systems are not consistently produced with integrated remote monitoring solutions, which poses compatibility issues.

To the author’s knowledge, no research has been published so far on remote monitoring of solar-powered pumping systems for drinking water supply. However, a few programs have developed and tested technology for remote monitoring of handpumps, most notably the SweetSense program of Portland State University and The Smart Handpumps project of the University of Oxford. The Smart Handpumps technology is based on a waterpoint data transmitter which was designed, built, and tested by Thomson et al. (2012). The data transmitter is attached to the handle of a handpump and automatically monitors the number of strokes made in operating the pump, and then transmits the information over the mobile network. This provides estimations on the volume of water collected, including daily to seasonal consumption patterns. If the volume is critically low, pump failure is likely to have occurred and repairs must be performed. Conversely, large volumes indicate a large water demand and can justify further investments in water pumping infrastructure.

The waterpoint data transmitter consists of three essential elements: an integrated circuit (IC) based accelerometer, a microprocessor, and a GSM modem (ibid). The purpose of the accelerometer is to measure handle movements, the microprocessor is used for signal processing and control, and the GSM modem is used to send information periodically as a short message service (SMS). The Smart Handpumps technology was tested in Kenya by Koehler et al. (2015). The waterpoint data transmitter described by Thomson et al. (2012) was attached to 66 Afridev handpumps, reporting pump usage hourly to a central server via SMS. The new service reduced the average handpump downtime from 27 days to 2.6 days over the 1-year study period (Koehler et al., 2015). In the same period, the average willingness to pay increased from USD 0.2 to USD 1.0 per household per month due to the increased reliability.

The SweetSense program of Portland State University has developed sensor technology able to collect information on the usage and performance of products, which can then be transmitted through the mobile network (Swan et al., 2018). The technology has been applied to monitor water, sanitation, and infrastructure projects in rural low-income contexts. In 2014, the sensor technology was tested by Nagel et al. (2015) on 181 handpumps installed by the nongovernmental organization (NGO) Living Water International (LWI) in three provinces of Rwanda. The enclosure of the sensor had an AA sized battery compartment, a control board, a cellular radio ship and SIM card holder, an accelerometer, and a differential water pressure transducer. The pressure transducer had one port open to the atmosphere and the other submerged within the water pump overflow basin, in order to record water level as pressure. The senor enclosure exterior had a high strength magnet for attachment and a smartphone scannable barcode for tracking. The sensor recorded pump usage, which was reported over the mobile network directly to an online platform. Three different maintenance models were compared to each other; the nominal maintenance model, the "best practice" circuit rider model, and an "ambulance" service model (Nagel et al., 2015). Usually, the community or water district hires an organization to do operation and maintenance. In the nominal service model, the community calls for service as needed. Whereas in the circuit rider model, the organization visits periodically, from every month to once a year, to provide service and fix identified problems with the handpump. In the ambulance model, the pump usage data from the sensors are available to the implementer and used to assign tasks for technicians. In the study period, which lasted for seven months in 2014-2015, the nominal maintenance group had a median time to successful repair of 152 days with a mean pump functionality of 68%. The circuit rider group had a median time to successful repair of 57 days with a mean pump functionality of 73%. The ambulance service group had a median time to successful repair of 21 days with a mean pump functionality of 93%. Nagel et al. (2015) thus concluded that the sensor-based ambulance model was associated with substantial reductions in the repair interval, and thus pump downtime, when compared to the nominal service and circuit-rider models.

Several NGOs are working on developing remote monitoring solutions for rural water supply, including FundiFix and WellDone. The Smart Handpumps research project at the University of Oxford led to the foundation of FundiFix, which provides preventive maintenance and repair services to rural communities in Kenya. WellDone is an NGO that has developed a modular remote monitoring platform called MoMo (mobile monitor) (Swan et al., 2018). MoMo is open source, designed to be low-cost and low-power, and intended for remote monitoring of rural infrastructure in developing countries. No research about the MoMo platform has yet been published as far as the author knows.

8.2 Results

A remote monitoring system developed by El-Watch was installed at pumping stations in the villages of Endagaw chini, Basonyagwe and Mewadani on the 29-31st of January 2020. This chapter looks into the data obtained from the systems and the attitudes towards remote monitoring in the study area. A general overview of the system components, configuration, user interface, and installation is given in chapter 3.3 (page 25).

8.2.1 General functionality

The remote monitoring systems were generally successfully installed, and they are continuing to record and send data. Mobile network services within the study area are sufficient for data transmission to occur with only minor interruptions. The remote monitoring system is designed to record and transmit data every 10 minutes. When downloading data from neuronsensors.app to Microsoft Excel or a similar spreadsheet program, time series with averaged hourly values are obtained. Downloaded data has a smaller time resolution than what is recorded in field due to costs of data storage and processing, according to El-Watch (Hallvard Helgetun, personal communication, 04.06.2020). Out of the three pumping stations, Mewadani has the worst mobile network connection, which results in lack of data occasionally. However, the gap is usually not longer than a couple of hours. The majority of the sensors have continued to function properly. However, the Neuron Pressure sensor installed in Endagaw chini stopped working on the 21th of April. Since then, it has sent a signal of 30 bar, and the normal range is approximately 0.7-1.2 bar. Also, the Neuron VDC Digitizer in Mewadani, which measures the voltage of the electrical network, has displayed odd values since the 19th of March. It is not known exactly what is causing the signal disturbances.

8.2.2 UNIK5000 Pressure sensor

The purpose of the UNIK5000 Pressure sensor is to measure hydrostatic head and hence the depth of the water level inside the well. The sensor produces an analog signal in mA which is proportional to the hydrostatic pressure of the water above the sensor. The analog signal is converted to a digital signal by the Neuron mA Digitizer. Then, the data is transmitted by the gateway through the mobile network. The sensor produces a signal within the range of 4-20mA, which corresponds to a measuring range of 0-100m. Thus, a signal of 4mA equals 0m, and a signal of 20mA equals 100m. The El-Watch system calculates the hydrostatic head from the mA-values, using linear interpolation (Equation 12). H is the hydrostatic head in meters, and I is the sensor signal in mA. H_{min} and H_{max} equal 0 and 100m respectively, and I_{min} and I_{max} equal 4 and 20mA respectively.

$$H = \frac{H_{max} - H_{min}}{I_{max} - I_{min}} * (I - I_{min}) + H_{min} \qquad \text{Equation 12}$$

Equation 12 can be altered by inserting the minimum and maximum values for hydrostatic head and current:

$$H = \frac{100 - 0}{20 - 4} * (I - 4) + 0 \qquad \text{Equation 13}$$

Hence, the sensor signal is converted to hydrostatic head by the following equation:

$$H = \frac{100}{16} * (I - 4)$$ Equation 14

The user interface of the remote monitoring system, neuronsensors.app, reports hydrostatic head in meters.

An initial control of the signals provided by the UNIK5000 sensor was carried out in field using an amperemeter, the Pocket Dipper, and Equation 14. The amperemeter was a Fluke87 True RMS Multimeter, with an accuracy of ±(0.2% + 2)mA and a resolution of 0.01mA (Fluke, 1997). The Pocket Dipper is a water level monitoring device described in chapter 3.1.1 (page 18), with an approximated accuracy of ±0.5m. In Mewadani, a water level of 13.7 ± 0.5m under borehole top was recorded using the Pocket Dipper. The UNIK5000 sensor was installed 69m under borehole top, and therefore the hydrostatic head should be 55.3 ± 0.5m. The amperemeter reading was 13.42mA which, using Equation 14, gives a hydrostatic pressure of 58.88m. The accuracy of the amperemeter reading is ± 0.05 mA (13.42 * 0.002 + 0.02), which is 0.37% of the measured value. If one assumes a linear error propagation, the accuracy of the hydrostatic pressure is ± 0.22 m. Hence, the hydrostatic head should be 55.3 ± 0.5m according to the Pocket Dipper measurement, and 58.88 ± 0.22m, according to the amperemeter measurement. The same analysis was done for Basonyagwe. A water level of 20.0 ± 0.5m was recorded using the Pocket Dipper. The UNIK5000 sensor was installed 70m under borehole top, and therefore the hydrostatic pressure should be 50.0 ± 0.5m. The amperemeter reading was 11.84 ± 0.04 mA, and Equation 14 gives a hydrostatic pressure of 49.00 ± 0.17 m. Hence, the hydrostatic head should be 50.0 ± 0.5m according to the Pocket Dipper measurement, and 49.00 ± 0.17m, according to the amperemeter measurement.

The UNIK5000 sensors were installed in both Basonyagwe and Mewadani on the 31th of January, and data series are thus available from this date onward. The water level is expected to drop when pumping starts, and to recover approximately to its previous state when the pump is turned off. However, data series from both Mewadani and Basonyagwe have some odd trends. Figure 52a shows UNIK5000 measurements for the 13-16th of February from Mewadani, downloaded to Microsoft Excel from neuronsensors.app. From the graph it appears as if pumping started at both 3:00 and 23:00 o'clock on the 15th of February. The pumping system runs on solar power and does not have a battery or generator, which makes pumping during night impossible. The sun rises at approximately 6.45 and sets around 18.30 in Tanzania in February. Several hydrogeologists have been consulted about the odd measurements, but no physical explanation has been found. It is therefore likely that the signal of the UNIK5000 sensors experiences some disturbances. The measuring range of 0-100 meters is rather large, which means that a small change in the signal between 4 and 20mA may result in a relatively large change in hydrostatic head. Figure 52b is a screenshot from neuronsensors.app which shows measurements in Mewadani for the same time interval as Figure 52a. The shaded areas represent uncertainties in the measurements, and it appears that the readings are quite uncertain when the water level appears to drop. There are two hours of time difference between Tanzania and Norway in February. The screenshot (Figure 52b) was displayed in Norway, and therefore the time is offset by two hours. The graph displayed in Figure 52a is adjusted for time difference.

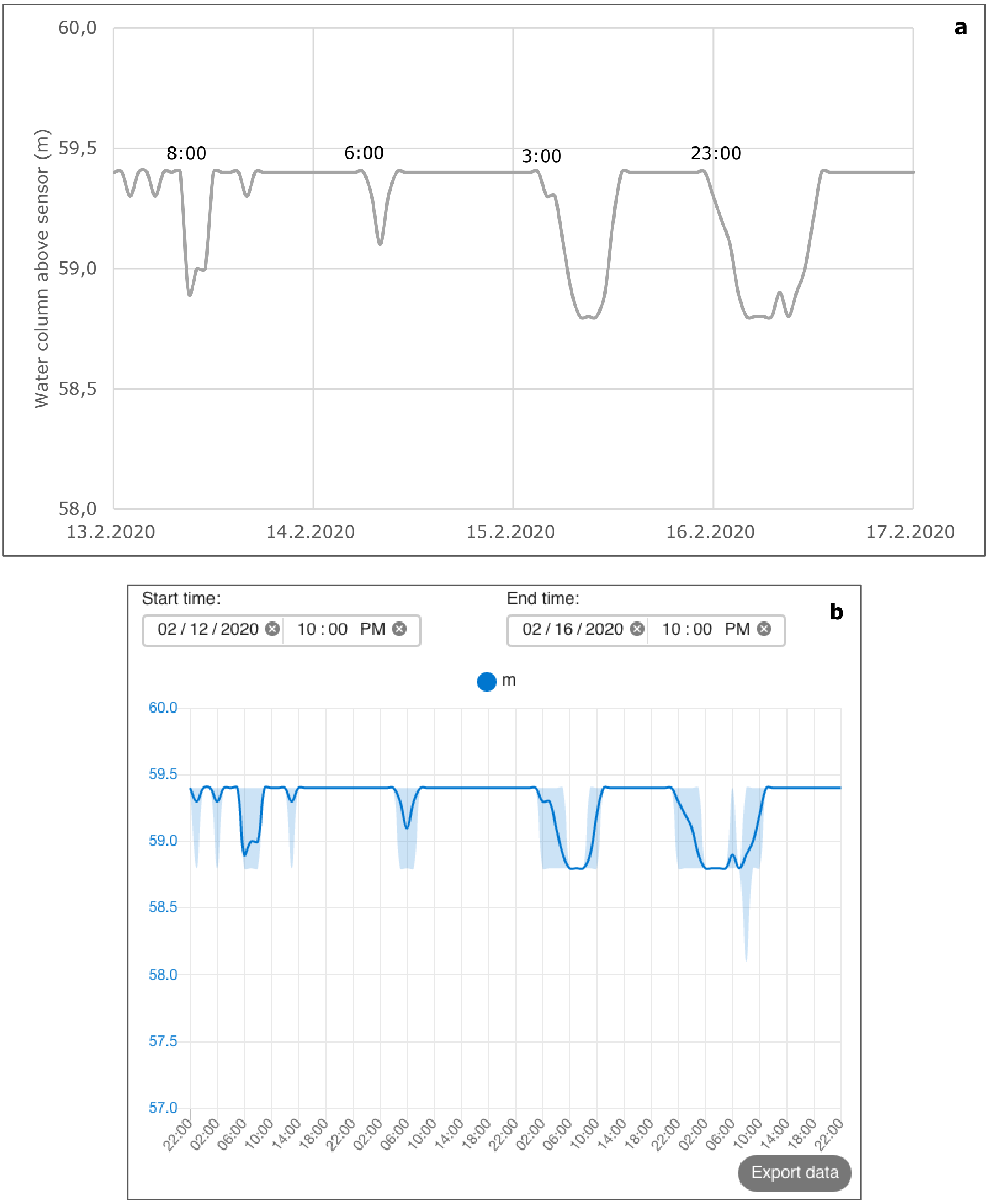


Figure 52: UNIK5000 measurements from Mewadani 13-16th of February 2020: a) Downloaded to Microsoft Excel b) Screenshot from neuronsensors.app

The user interface of the remote monitoring system displays the UNIK5000 measurements as meters of water column above the sensor (hydrostatic head). It could perhaps be more user friendly to display the measurements as the depth of the water level in meters below borehole top. This can easily be calculated by subtracting the hydrostatic head from the vertical distance between the borehole top and the sensor. This is shown for Mewadani in Figure 53, for the same time interval as Figure 52. However, a change like this cannot be done in neuronsensors.app (Hallvard Helgetun, personal communication, 19.03.2020).

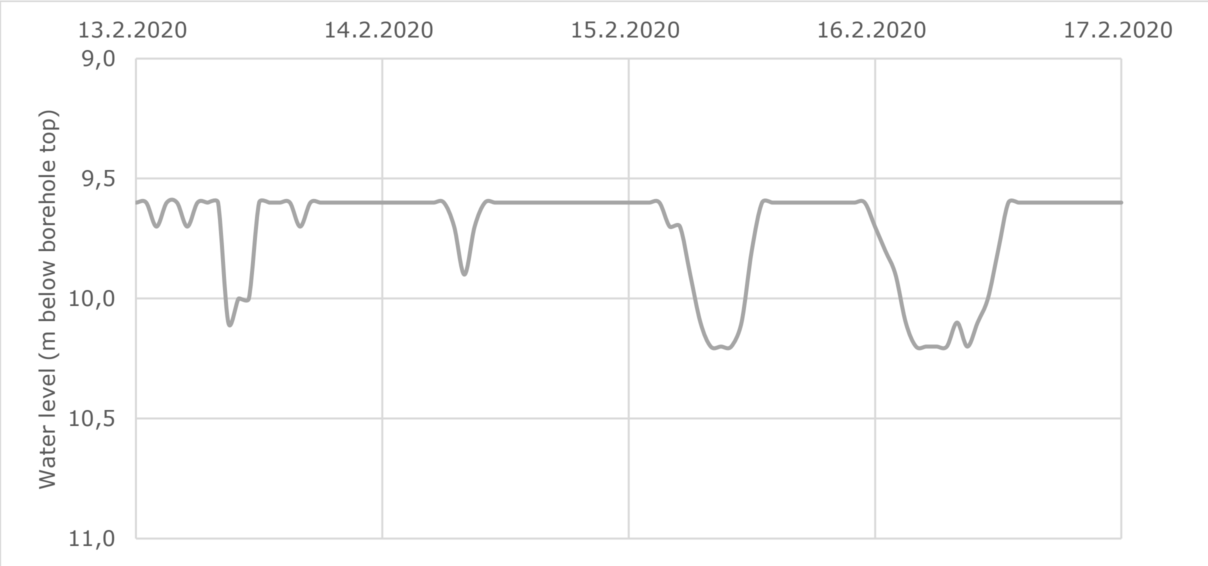


Figure 53: Water levels in Mewadani 13-16th of February 2020 according to UNIK5000 measurements

8.2.3 Neuron Pressure 0-2 Bar

The purpose of the Neuron Pressure sensor is to measure the hydrostatic pressure in the water tanks in order to determine the water level, and hence the volume of water available in the tanks. The Neuron Pressure sensor was installed on the outlet pipe of the water tanks in Mewadani, Endagaw chini, and Basonyagwe, on the 11th, 12th and 13th of February, respectively. In addition, a sensor to measure the atmospheric pressure was put inside the wooden box of the remote monitoring system in Endagaw chini. Photos of the Neuron Pressure sensor and the plastic basin that provides protection are shown in Figure 28 (page 31). Figure 54 shows the location of the sensor on the pumping station. Unfortunately, the photo was taken before the sensor was installed, and therefore the blue plastic basin has been edited into the photo. The Neuron Pressure sensor was installed under the valve that controls the water flow between the water tanks and the water tap. The reason for installing the sensor downstream the valve was the opportunity to close the valve in order to restrict water from entering that part of the pipe during installation. However, this has an impact on the data received from the sensor, as hydrostatic pressure cannot be recorded correctly when the valve is closed. If the valve is shut and the water tap downstream is open, the sensor records the atmospheric pressure. Whereas if the valve is shut and the water tap downstream is closed, the sensor measures the hydrostatic pressure at the time at which the valve was shut.

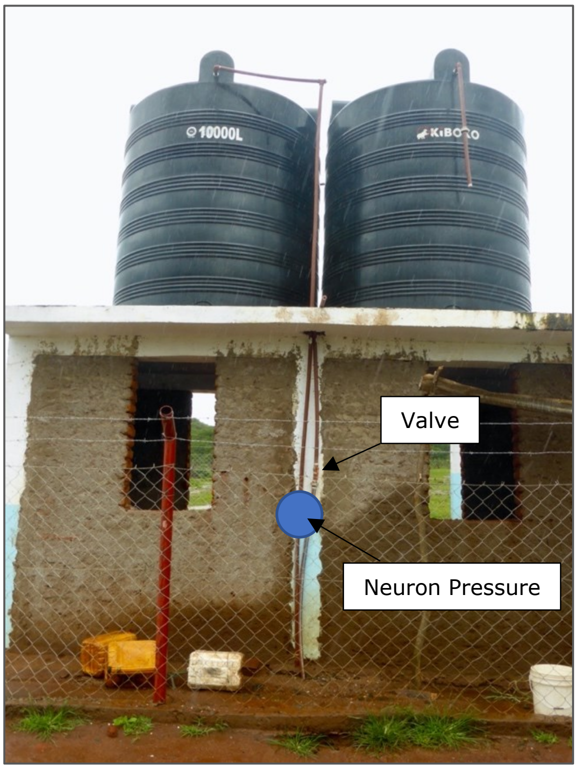


Figure 54: Location of the Neuron Pressure sensor on pumping station

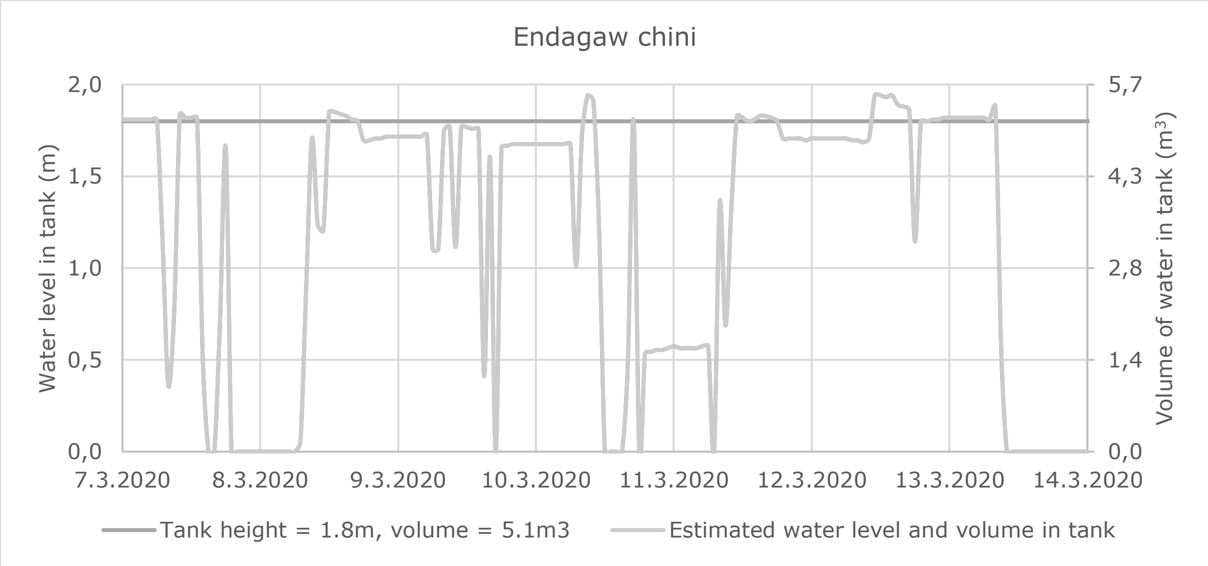
The pressure values are given in *bar* on neuronsensors.app. The following procedure was used to calculate the water level inside the tanks in *meters*:

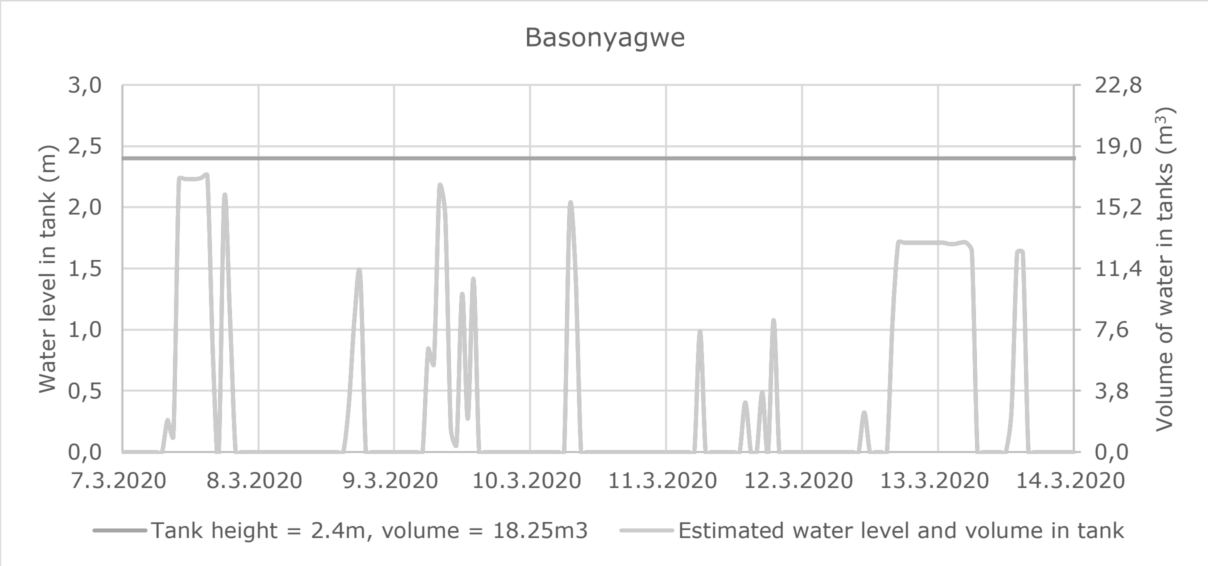
1) Subtract the atmospheric pressure measured by the sensor located in Endagaw chini from the Neuron Pressure measurement
2) Multiply the value obtained from the previous step by 10.19744 to convert from bar to meters
3) Subtract the vertical distance between the sensor and the bottom of the tanks from the value obtained in the previous step. (The vertical distance between the sensor and the bottom of the tanks is 1.2, 1.4, and 1.5 m in Endagaw chini, Basonyagwe and Mewadani, respectively).

If the obtained value in step 1 or 3 in the procedure above was less than zero, the value was set to zero instead. Negative values indicate that the valve is closed or that the tanks are empty. Equation 15 was used to find the volume of water inside the tanks, where D is the diameter of the tank. The equation was multiplied by two for Basonyagwe because two tanks are attached to the system.

$$Volume = \frac{\pi}{4} D^2 * water\ level \qquad \text{Equation 15}$$

Figure 55 shows estimated water levels and volumes based on the procedure described above for Endagaw chini, Basonyagwe and Mewadani on 7-13th of March 2020. The actual height and volume of the tanks is also included in the graphs. The tanks in Endagaw chini have a volume of 5.1m^3 (D=1.9m, H=1.8m) whereas the tanks in Basonyagwe and Mewadani have a volume of 9.1 m^3 (D=2.2m, H=2.4m) (Zachayo Makobero, personal communication, 15.05.2020).





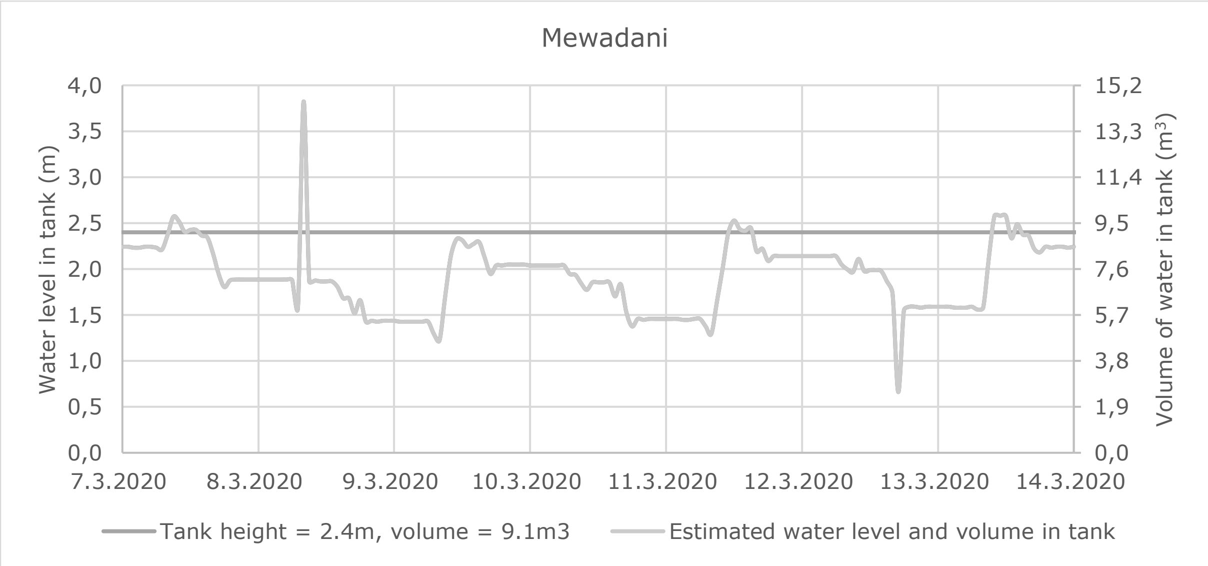


Figure 55: Estimated water levels and volumes in storage tanks in Endagaw chini, Basonyagwe and Mewadani 7-13th of March 2020

Figure 55 shows that water levels can vary significantly over the course of a week. In Endagaw chini and Mewadani, the calculated water levels were sometimes slightly taller than the tanks, which indicates that the estimations are not completely accurate. Impossible values, such as the peak of 3.8m in Mewadani at approximately 8:00 o'clock on the 8th of March, should be disregarded. In Endagaw chini and Basonyagwe, the water level sometimes appears to drop quickly to zero and then to rise rapidly at a later time. This can be understood as the valve being shut and reopened, since the tanks cannot be emptied that fast. The fact that an estimated water level of zero implies either empty tanks or a closed valve makes it challenging to interpret the graphs. In general, a sudden drop to zero indicates that the valve was shut at that time. Whereas a slow decrease in water levels indicates that the tanks are tapped for water without refilling. The water level in Mewadani never appears to be zero in Figure 55. A probable reason is that the valve was never properly closed during this time period, or that the tap always was shut prior to the valve. In addition, there is a reoccurring pattern in the graph in Mewadani, indicating that the pump refills the tank every second day. It seems like Basonyagwe never reached its maximum storage capacity during the period of 7-13th of March, unlike Endagaw chini and Mewadani. This could imply that a high volume of water is collected from the tanks which in turn prevents the pump from completely filling the tanks. Basonyagwe does however have a larger storage capacity than Mewadani and Endagaw chini. All pumping stations have two storage tanks available, but only one of the two tanks are attached to the pumping system in Mewadani and Endagaw chini. Thus, the total amount of water available is greater in Basonyagwe compared to Mewadani and Endagaw chini for the same water level. The second tank in Mewadani has a burst and thus it was disconnected from the pumping system. It is not known why the second tank in Endagaw chini is out of use.

The user interface of the remote monitoring system, neuronsensors.app, only displays primary data from the Neuron Pressure sensors and the atmospheric pressure sensor. The graphs in Figure 55 are made by processing data downloaded from neuronsensors.app in Microsoft Excel. Figure 56 shows how the data is presented in neuronsensors.app. The graphs are not easily interpreted as water levels and volumes. Thus, the data needs to be processed in Microsoft Excel or a similar program to get an overview of the quantity of water available in the tanks. It is not possible to incorporate the data processing and corresponding graphs into the user interface of the remote monitoring system (Hallvard Helgetun, personal communication, 19.03.2020).

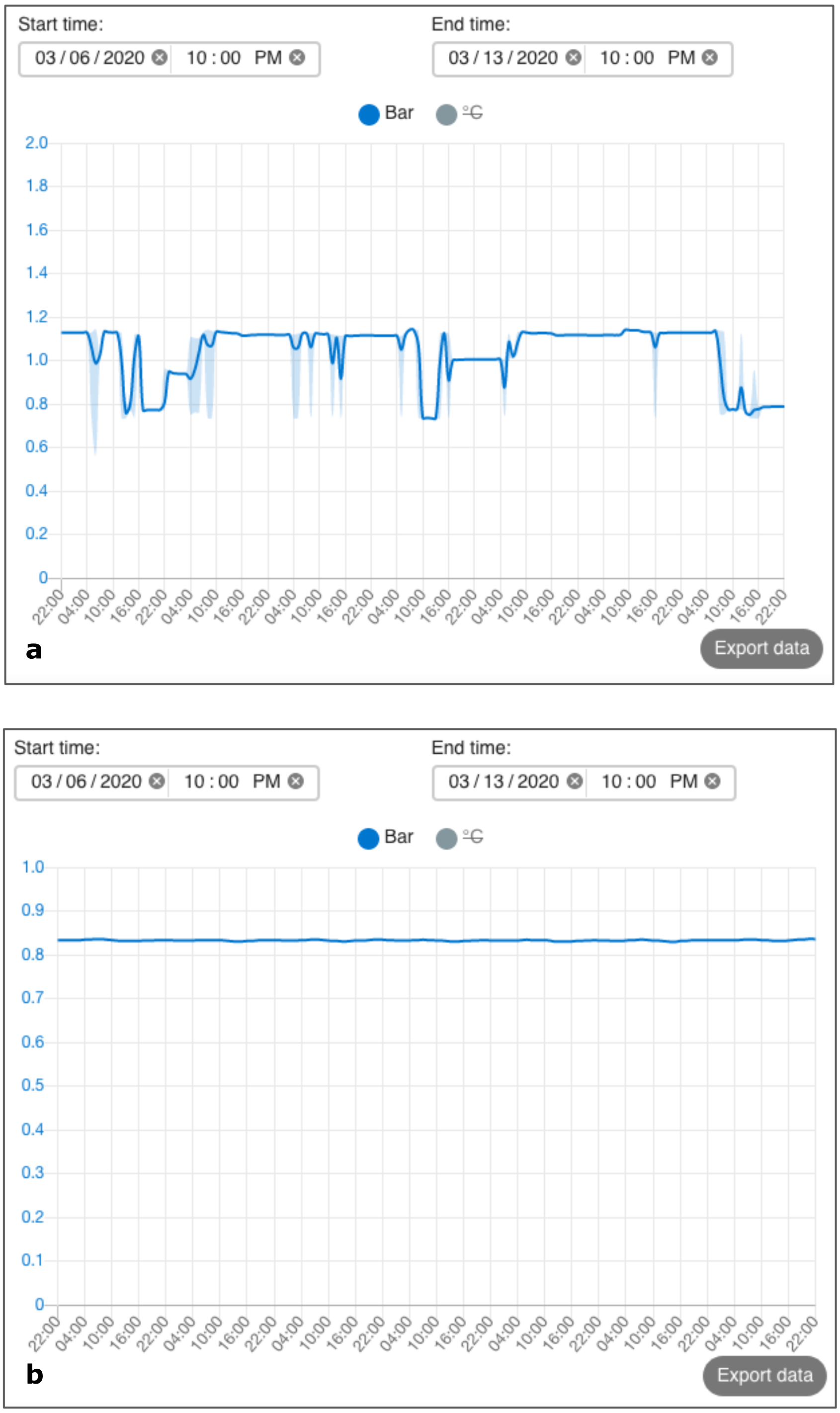


Figure 56: Screenshots from *neuronsensors.app* displaying a) Neuron Pressure measurements and b) Atmospheric pressure measurements, Endagaw chini, 7-13th of March 2020

8.2.4 Attitudes towards remote monitoring

Several interviews were conducted to get an impression of the attitudes towards remote monitoring in the study area. The informants were 4CCP employees and two engineers from the DWE office of Mbulu. The first engineer interviewed was optimistic regarding the concept of remote monitoring. He stated that having an overview of the performance of the pumping systems without going there physically could reduce costs and save time. He was particularly interested in monitoring water use, in order to compare pumping system income to the amount of water pumped, to make sure that the COWSOs are charging the correct water tariff. Water meters are already installed at the pumping stations on the pipe connecting the water tanks to the water taps, measuring the amount of water taken from the taps. These water meters are however analog, and normally the pump caretaker records the number of cubic meters without any decimals. Thus, the DWE office would like to get a more accurate estimate of the quantity of water used. The second engineer interviewed was also interested in the concept of remote monitoring. However, he was skeptical to the sustainability of such a system and worried that it would not be maintained properly. During the interviews it became clear that the COWSOs would be responsible for operating and maintaining a remote monitoring system. The 4CCP employees interviewed stated that remote monitoring has the potential of facilitating the work of the DWEs in the future. The performance of the pumping systems could be tracked from the office, which in turn could reduce costs and make it easier to fix problems. However, 4CCP does not think that the implementation of remote monitoring is realistic in the near future. There are still many people who lack access to clean and safe water in the districts of Mbulu, Hanang and Mkalama, and therefore they think that the priority should be to build additional pumping stations.

8.3 Discussion

The resilience of a pumping system depends on its ability to minimize service failure magnitude and duration over its design life when subjected to exceptional conditions (Butler et al., 2014). In theory, remote monitoring has the potential to benefit pumping system resilience, because operational issues may be discovered easily and dealt with at an early stage. Remote monitoring can provide an overview of system performance for service providers who are responsible for several pumping stations, thereby facilitating the process of prioritizing where to perform maintenance and repairs.

The UNIK5000 sensor monitors the water level. The control performed straight after installation, described in chapter 8.2.2 (page 85), showed that the initial UNIK5000 signals did not correspond exactly to the water levels measured by the Pocket Dipper. However, they were reasonably close. The initial control was the only attempt to verify the sensor measurements. In retrospect, it would have been beneficial to install a TD-Diver, described in chapter 3.1.3 (page 20), in the borehole for a couple of days to compare the data series of UNIK5000 to that of the TD-Diver. It is difficult to say something definitely about the validity of the UNIK5000 measurements due to the lack of comparable measurements. However, there seems to be some disturbances in the signal of UNIK5000 since pumping sometimes appears to happen during night. Therefore, the sensor cannot be used to monitor whether pumping occurs. It could have been useful to monitor pump usage patterns, since no usage could indicate pump failure, and high usage could justify the need for additional investments in water supply infrastructure. In that sense, the sensor could have been used for the same purpose as the data transmitter designed as a part of the Smart Handpumps project at Oxford University (Thomson et al., 2012). Since UNIK5000 cannot be used to monitor pump usage, it is thought to be more suitable for long-term surveillance of the water level. As explained in chapter 5, over-abstraction of groundwater causes the water level to decline. The boreholes are equipped with a sensor that stops the pump if the water level drops to the depth at which the pump is installed, to prevent pump damage. Declining water levels should however be discovered before the water level becomes lower than the pump intake, so that preventive measures can be implemented, such as abstracting less water from the borehole. A sensor like UNIK5000 may provide the opportunity to discover declining water levels at an early stage. Figure 40 (page 54) shows UNIK5000 measurements from the 10th of February to 20th of June.

The Neuron Pressure sensor gives an overview of the filling degree of the storage tanks. The Neuron Pressure readings were compensated by the atmospheric pressure readings measured by a sensor located in Endagaw chini. However, Endagaw chini, Basonyagwe and Mewadani are located at different altitudes of approximately 1695, 1752, and 1615m, respectively. Atmospheric pressure varies with altitude, and this had a minor impact on the estimated water levels in Basonyagwe and Mewadani. It is important to note that the graphs obtained from the Neuron Pressure sensor must be interpreted with care since the estimated water level and corresponding volume are misleading when the valve controlling the water supply from the tanks to the tap is closed. If the water level appears to be zero for several days, it could either be caused by empty water tanks or that the valve is closed because the pumping system is out of use at that particular time. A water level of zero for several days in the dry season is more likely to be caused by empty tanks due to for example pump failure than the system being out of use, since alternative water sources are unavailable during that time of the year.

The El-Watch remote monitoring system has for the most part worked satisfactory. Data transmission mostly occurs without interruptions, and data series can easily be displayed in the user interface as well as downloaded to various spreadsheet programs. The user interface is however not very flexible when it comes to the way in which data is managed and presented. The conversion from current to hydrostatic head is done automatically for the UNIK5000 sensor, but a simple conversion from hydrostatic head to depth of water level below borehole top is impossible to incorporate into the user interface. Similarly, data obtained from the Neuron Pressure sensor cannot be automatically converted to water level and volume. The lack of flexibility of the user interface makes the El-Watch remote monitoring system less user-friendly. However, it is possible to use the El-Watch user interface in combination with a visualization software tool, such as Grafana, to customize a dashboard that displays data in a user-friendly manner. However, that would require some programming skills.

The hardware products of the El-Watch remote monitoring system are not entirely compatible with the design of the pumping stations. For instance, it is challenging to integrate sensors that measure current and voltage. Thus, it could have been beneficial to use an integrated remote monitoring solution provided by the pump manufacturer, Davis and Shirtliff, instead of the El-Watch system. When purchasing Dayliff pumping equipment, a remote monitoring and control system called *iDayliff* is available as an option (Davis and Shirtliff, 2020b). iDayliff is similar to the El-Watch remote monitoring system in that it uses sensors to monitor various parameters and data transmission occurs through the mobile network. A web portal or a mobile application can be used to display data. Users can view operational status, such as whether the pump is on or off, and parameter readings such as current and voltage. Water flowrate, system pressures, and energy consumption can be monitored if additional sensors are installed at the pumping stations. The user can also remotely start and stop the pump. It appears like iDayliff could be more useful for the maintenance procedures suggested in the pump operating manual of Davis and Shirtliff than the El-Watch remote monitoring system tested in field. For instance, operating parameters including current and water output should be inspected at least every three months (Davis and Shirtliff, 2014).

The implementation of remote monitoring involves the installation of various components, such as sensors, a battery and a gateway, which are to varying degrees vulnerable to for instance signal disturbances, heat exposure, rain, and theft. Several members of 4CCP were introduced to the El-Watch remote monitoring system during the fieldwork, both by participating during installation and by making a user account on neuronsensors.app. They also received a user manual which describes the system configuration and components. An engineer from the DWE office of Mbulu was introduced to the remote monitoring systems installed in Endagaw chini, Basonyagwe and Mewadani during a field visit on the 13th of February. Both the 4CCP employees and the engineer expressed concerns regarding maintenance and sustainability of the remote monitoring systems. Overall, the data transmission worked satisfactory for the first couple of months, but some issues emerged after a while. For instance, the Neuron Pressure sensor in Endagaw chini has sent a signal of 30 bar since the 22nd of April, and the normal range is approximately 0.7-1.2 bar. Also, the Neuron VDC Digitizer in Mewadani has displayed odd values since the 19th of March. It is not known exactly what is causing the signal disturbances. The wooden box containing several of the remote monitoring system components is attached to the solar panel by steel wires which could disturb the electrical system. However, it is generally challenging to find the exact cause of issues like this. During the fieldwork it became clear that COWSOs would generally be responsible for operating and maintaining a remote monitoring system. 4CCP took responsibility for the test systems installed in Endagaw chini, Basonyagwe and Mewadani, but they would not be responsible if remote monitoring was implemented on a permanent basis. COWSO members are generally volunteers from the local community who do not have technical expertise. The fact that some of the data received from the test systems already has obvious errors shows that maintenance of such systems is a difficult task which ideally should be handled by professionals.

Research shows that remote monitoring of rural water pumping systems can benefit system resilience. Nagel et al. (2015) and Koehler et al. (2015) found significant reductions in handpump downtime in Rwanda and Kenya respectively, when testing two different sensors that monitored pump performance remotely. The degree to which resilience is affected by remote monitoring will however depend on the operation and maintenance framework employed. Thomson et al. (2012) argued that reliable and frequent flows of information by remote monitoring can facilitate both a professional operation and maintenance regime and effective supervision by a regulatory body. When pump performance data is held at a competent institutional level it may be feasible to sub-contract the operation and maintenance of a group of rural pumps to a private contractor. Information regarding pump performance and failures will be available to the contractor, enabling a reliable, timely, and efficient system to repair and maintain pumps. At the same time, information on the failure of pumps and speed of repair will be immediately available to the regulatory body, allowing a level of oversight which was previously impossible. This could enable performance incentives and penalty clauses to be built into contracts, which in turn could lead to improved service and reduced downtime (ibid). However, this operation and maintenance model is not likely to be easily adopted in Mbulu, Hanang, and Mkalama, because COWSOs are responsible for operation and maintenance instead of the local government. The Water Supply and Sanitation Act No. 12 states that local governments are only responsible for meeting parts of the costs encountered by COWSOs in major rehabilitations and expansions of water supply infrastructure (United Republic of Tanzania, 2009). There is little use in providing the DWEs with pump performance data when they are not responsible for doing maintenance. In theory, a group of COWSOs could employ a private contractor to do operation and maintenance aided by data provided by remote monitoring. However, it would be difficult for the COWSOs to properly hold the contractor accountable in the manner described by Thomson et al. (2012). This would also require strong COWSOs that are willing and able to corporate with each other and that have enough funds to pay the contractor and to cover the costs of installing and maintaining a remote monitoring system. For these reasons, remote monitoring is thought to be better suited as a tool used by development organizations such as NCA. COWSOs would benefit from support in the next couple of years, and remote monitoring could enable NCA to identify where additional support is needed the most. Remote monitoring data could generally be useful for development organizations to get an overview of project performance and to discover areas of improvement.

9 Summary of discussions

This section summarizes the discussions of chapter 4 to 8. The WASH project conducted by NCA and 4CCP has improved the water supply situation of many beneficiaries. In the COWSO interviews it was revealed that there has been a reduction in waterborne diseases and that shorter water collection times has left more time to engage in economic activities and schoolwork. Appendix 2 provides an overview of feedback given by the COWSOs. This thesis has investigated key aspects of the WASH-project, including water quantity and quality, hydrogeological conditions, management, and the potential of remote monitoring.

The results of chapter 4 showed that the pumping systems do not succeed in supplying sufficient quantities of water to the beneficiaries in the dry season. This is not surprising considering the severe water scarcity in the study area. According to 4CCP, more people are using the pumping systems than initially intended because people are willing to travel far to acquire safe water. The gap between supply and demand is likely to grow in the years to come due to population growth. In the COWSO interviews, three challenges related to water quantity were mentioned frequently. Firstly, the total amount of water provided is not enough to cover the demand in the dry season. Secondly, the pump tends to stop in cloudy weather, which reduces the amount of water provided and threatens the reliability of the systems. Thirdly, the queues become very long in the dry season and people sometimes wait for hours to collect water. It would be beneficial to improve the power supply to ensure a stable water provision during cloudy weather and to increase the total quantity of water pumped. For instance, additional solar panels, batteries, or a diesel-generator could be installed. A cost-benefit analysis could be carried out to rank the various alternatives. COWSOs must be given training on how to operate and maintain the added components. The issue of long queues in the dry season could possibly be solved by installing more tap stands. It should be noted that there are uncertainties related to the water supply and demand calculations. For instance, the supply estimations assume that the pump runs efficiently for eight hours a day, that the DWL found in the pumping test can be used directly to calculate the system characteristic curve, and that the speed of the pump is 48.3Hz consistently. The demand estimations are based on a survey in which a limited number of community members participated.

Boreholes cannot supply infinite quantities of water, and therefore the hydrogeological conditions must be considered before attempting to increase the water provision. Chapter 5 investigated whether current pumping rates influence groundwater levels significantly. In general, the pumping rate should not exceed the recharge rate, and the dynamic water level should not reach the depth of the pump intake. Pumping tests were conducted before the installation of the solar-powered water pumping systems. For most of the pumping stations, the dynamic water level emerging throughout the pumping test was located above the depth of the pump intake by a reasonable margin. The pump used during operation has a smaller pumping rate than the pump employed in the pumping test, which in turn should lead to a smaller drawdown. Diver measurements conducted in field confirm this assertion. In addition, water levels were measured manually and by a remote monitoring system, showing that water levels do not appear to be declining. These findings suggest that current pumping rates are sustainable and that they possibly could be increased.

However, it is difficult to suggest an appropriate pumping rate since the relationship between discharge, drawdown and time is unknown. A step-drawdown pumping test must be conducted to be able to predict the drawdown for any realistic discharge and time (Kruseman and de Ridder, 2000). It is important to note that the static water level varies naturally between seasons and years. The static water level is typically deep during the dry season, which means that a particular drawdown will cause a deeper dynamic water level than in the rainy season. Consequently, there needs to be a safety margin between the dynamic water level produced at a particular pumping rate and the depth of the pump intake.

Chapter 6 investigated whether the pumping systems provide water of adequate quality for human consumption. The water is perceived as clean and safe by the users, and a decline in water-borne diseases was reported by the COWSOs. Measurements from 14 pumping stations revealed that the water generally has a neutral pH and a low turbidity. Some of the pumping stations had a rather high conductivity, but not greater than 2500 μS/cm which is a common limit for drinking water (WHO, 2018). The alkalinity was quite high which indicates that the water is hard, which can cause usage problems including scaling and reduced cleaning ability of soap (Shaw et al., 2009). Although most of the pumping stations had excellently low turbidity levels, one of them had a turbidity of about 68 NTU, significantly exceeding the limit of 25 NTU specified by the Tanzania Bureau of Standards. The exact reason is not known, but it could be because of faults in the gravel pack which is supposed to restrain aquifer material from entering the borehole. Two of the 14 pumping stations had a fluoride concentration exceeding the Tanzanian limit of 4 mg/L, whereas five had a concentration greater than the WHO limit of 1.5 mg/L but less than 4 mg/L. Prolonged exposure to drinking water with elevated fluoride concentrations can cause dental and skeletal fluorosis (Fawell et al., 2006). A H_2S-test was conducted at four pumping stations to check whether the water was contaminated by fecal matter. Three out of four pumping stations had a positive test result. There are however doubts concerning the trustworthiness of the test as it has been criticized for giving false positive results (Sobsey and Pfaender, 2002). The boreholes are equipped with a sanitary seal to 5m below the ground surface, which should stop poor quality surface water from entering the space between the outmost casing and the borehole wall. Livestock grazing in the vicinity of the pumping station can however cause contamination of groundwater through the aquifer pathway. The pump intake is rather deep and well logs which were available for five pumping stations show that the aquifers are confined. For these reasons, it is in the author's belief that fecal contamination is unlikely. It is nevertheless recommended that the water is tested once more, for example by NCA, because of the severe health impacts of fecal contamination.

Chapter 7 investigated the extent to which current management practices ensure pumping system resilience. It was found that many of the management practices employed are associated with satisfactory pumping system functionality in literature, such as having a water committee, a caretaker, and funds for operation and maintenance. Research has however shown that community enthusiasm for keeping water committees functioning and for collecting water tariffs may disappear two to three years after the construction of a water point (Carter et al., 1999). It would therefore be beneficial if NCA and 4CCP continued to follow the project until management practices became fully incorporated. Additional training was also requested by some of the COWSOs interviewed. Sustainable financing strategies have been recognized as a prerequisite for sustaining water supply infrastructure by numerous researchers (Foster, 2013, Harvey and Reed, 2004, Whaley et al., 2019). Collection of water tariffs by a fixed price per bucket has been an efficient way of raising funds for operation, maintenance, and repairs at the pumping stations in question. However, the size of the collected funds varies significantly between pumping stations. In most cases, water fee collections are insufficient to cover major repairs, and the pumping stations are therefore partly dependent on support from local governments. Planned maintenance, meaning to deal with potential problems prior to failure, can limit service failure magnitude and duration thereby benefitting pumping system resilience. This is however rarely done at the pumping stations. The local communities do simple maintenance tasks such as cleaning the solar panels, but the maintenance procedures recommended in the pump operating manual are not followed since they require technical expertise. COWSOs could be coupled with a contractor having the relevant competence, but that would be costly and reduce the funds available for repairs. The fact that limited funds are available for maintenance is thus a challenge for system resilience.

Chapter 8 investigated how remote monitoring can influence pumping system resilience. The remote monitoring systems tested in field were generally successful as mobile network services facilitated data transmission with only minor interruptions. However, some issues regarding sensor functionality and signal disturbances occurred. Remote monitoring supported by El-Watch worked satisfactory for the most part, since data was easily displayed in the user interface and downloaded to various spreadsheet programs. However, the system is not very flexible with regard to data management and presentation. In addition, the hardware products of El-Watch are not entirely compatible with the design of the pumping stations. Thus, it could be beneficial to test the integrated remote monitoring system of Davis and Shirtliff, called iDayliff. The impact of remote monitoring on pumping system resilience depends on the operation and maintenance framework employed. Thomson et al. (2012) argued that remote monitoring can facilitate both a professional operation and maintenance regime and its effective oversight by a regulatory body. For instance, a local government can hire a private contractor to do operation and maintenance. Reliable and frequent flows of information by remote monitoring enables the contractor to prioritize when and where to perform maintenance and repairs. Concurrently, data regarding pump failure and the speed of repair will be available to the local government, allowing a level of oversight which was previously impossible. However, it could be difficult to adopt the framework suggested by Thomson et al. (2012) in rural Tanzania, as COWSOs are responsible for operation and maintenance instead of the local government. It may be challenging for COWSOs to properly hold the contractor accountable as well as to acquire enough funds to pay the contractor and to cover the costs of a remote monitoring system. Remote monitoring could however be a useful tool for development agencies such as NCA during post-construction support.

10 Conclusion

This thesis has evaluated the performance of a number of solar-powered water pumping systems that were installed in Tanzania by NCA from 2015 to 2019. The main topics investigated were water quantity and quality, hydrogeology, management, and remote monitoring.

Demand and supply estimations show that the pumping stations do not provide enough water to cover the demand in the dry season even if the pumps run for eight hours a day. Only one pumping station fully covers the domestic demand out of the nine pumping stations considered. None provide enough water to cover both domestic and productive water demands. The pumps tend to stop in cloudy weather which reduces the volume of water provided and threatens reliability. Increasing the power supply, for instance by adding batteries, additional solar panels, or a diesel-generator to the systems, could ensure a stable water provision and increase the total volume of water provided.

Declining groundwater levels due to over-abstraction do *not* appear to be an issue considering water level measurements conducted in field. Current pumping rates are in most cases significantly lower than the borehole yield found from pumping tests carried out prior to the construction of the solar-powered water pumping systems. Thus, current pumping rates appear to be sustainable and could possibly be increased. However, the capacity of a borehole to supply greater quantities of water must be evaluated in each single case before increasing the pumping rate.

Water quality measurements conducted at 14 pumping stations show that pH, turbidity, conductivity, and alkalinity are generally within acceptable limits. However, one pumping station has a turbidity exceeding the upper limit specified in the water quality standard of Tanzania. Two pumping stations have a fluoride concentration greater than the Tanzanian limit (4 mg/L), and five pumping stations have concentrations above the WHO limit (1.5 mg/L) but below the Tanzanian limit. It is recommended to implement water treatment at the household level for these pumping stations since elevated fluoride concentrations can cause dental and skeletal fluorosis. Fecal contamination was not successfully measured in field and should therefore be tested to confirm that the water is safe.

A number of the management practices currently employed at the pumping stations, such as having a water committee and a caretaker, are associated with satisfactory pumping system functionality in literature. Previous research has however shown that community enthusiasm for sustaining management practices may decline over time thereby making water projects vulnerable. It is therefore recommended that NCA and 4CCP continue following the project for at least a couple of years. Water fee collections cover operation and some maintenance costs but are insufficient for larger repairs in most cases. The pumping stations are therefore partly dependent on support from local governments. Limited funds for planned maintenance threaten the resilience of the pumping stations.

The remote monitoring systems tested in field worked satisfactory with only minor data transmission interruptions. However, some issues regarding sensor functionality and signal disturbances occurred. In theory, remote monitoring can improve the resilience of pumping systems by providing data that enables services providers to prioritize when and where to perform maintenance and repairs. This thesis argues that implementing remote monitoring in the study area is unlikely to obtain the benefits described in literature, because COWSOs are responsible for operation and maintenance instead of local governments. Remote monitoring is therefore thought to be better suited as a tool used by development organizations such as NCA during post-construction support.

11 Future work

Several topics in this thesis should be investigated further, such as power supply improvements, water quality and treatment, and remote monitoring.

It would be beneficial to investigate how the power supply of the pumping stations can be improved since the current water provision does not cover the demand in the dry season and the pump stops in cloudy weather. Possible solutions include installing batteries, additional solar panels, or a diesel-generator. The pump manufacturer, Davis and Shirtliff, should be consulted about the feasibility and practicalities of the solutions. It could also be useful to perform a cost-benefit analysis to rank the various alternatives. The chosen solution must be easily operated and maintained.

Fluoride and fecal contamination are water quality parameters that should be investigated further. The H_2S-tests carried out in field gave positive test results at three out of four pumping stations, but there are doubts regarding the trustworthiness of the results. This thesis argues that fecal contamination is unlikely, but the water should nevertheless be tested once more due to the severe negative health impacts of fecal contamination. Water treatment methods for fluoride removal should be evaluated and tested in future work. Fluoride is the most severe and widespread reported groundwater quality problem in Tanzania (Smedley, 2000). However, only two of 14 pumping stations had a fluoride concentration exceeding 4 mg/L, which is the limit specified by the Tanzania Bureau of Standards. Adsorption is a treatment method capable of removing fluoride from water that could be implemented at the household level. It would be difficult to implement the treatment process at the pumping station, since that would require additional resources for operation and maintenance. Treating water at the household level is also thought to be more cost-effective, since it only would involve treatment of water for drinking and cooking and not for other purposes such as laundry and bathing. However, motivating people to treat water at home could be a major challenge since negative health impacts of consuming water with elevated fluoride levels only occur with prolonged exposure.

The iDayliff remote monitoring system should be tested in future work, as it is thought to be more compatible with the design of the pumping stations than the El-Watch system. This thesis argues that remote monitoring is not easily integrated in current management practices, but it could be a useful tool for development organizations such as NCA. A range of helpful data can be collected by the iDayliff system including operating current, voltage, water flowrate and system pressures. The remote monitoring systems tested in this thesis are still operating. It would be beneficial to continue monitoring the water level in the boreholes of Mewadani and Basonyagwe. So far, the water level has been monitored for almost five months. However, at least a year of data is necessary to get an impression of seasonal variations, and there is also likely to be variations from one year to another.

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Appendices

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Appendix 1: Fieldwork program

The following table shows the program of the fieldwork:

DATE	PROGRAM	PLACE
Tuesday 28/01/2020	• Meeting with the district executive director (DED) of Mbulu (in Dongobesh) • Meeting with the district commissioner of Mbulu (in Mbulu town) • Meeting with the district water engineer (in Mbulu town)	Dongobesh and Mbulu town
Wednesday 29/01/2020	• Installation of a remote monitoring system • Water quality measurements • Measurements of the groundwater level in the well (pocket dipper and diver measurements)	Endagaw chini
Thursday 30/01/2020	• Water quality measurements • Measurements of the groundwater level in the well (pocket dipper) (in Mewadani)	Mewadani Basonyagwe
Friday 31/01/2020	• Installation of remote monitoring systems, including pressure sensors in the wells • Measurements of the groundwater level in the wells (pocket dipper)	Mewadani Basonyagwe
Monday 03/02/2020	• Meeting with COWSOs and PETS committees • Water quality measurements (in Endamilay only) • Installation of Diver (in Murukushida only)	Endamilay Murukushida
Tuesday 04/02/2020	• Meeting with COWSO and PETS committee (in Endanachan) • Water quality measurements	Endanachan Murukushida Spring
Wednesday 05/02/2020	• Meeting with COWSO and PETS committee • Water quality measurements	Harar
Thursday 06/02/2020	• Meeting with COWSO and PETS committee • Water quality measurements (Mewadani primary school)	Mewadani
Monday 10/02/2020	• Meeting with COWSO and PETS committee • Visiting Basonyagwe local dam	Endagaw chini Basonyagwe
Tuesday 11/02/2020	• Meeting with COWSO and PETS committee in Gidurudagew • Installation of pressure sensor in Mewadani	Gidurudagew Mewadani
Wednesday 12/02/2020	• Meeting with HANG'WA COWSO • Visit to water source and water tanks of Haydom • Installation of pressure sensor in Endagaw chini	Haydom Endagaw Chini
Thursday 13/02/2020	• Inspection of remote monitoring systems in Basonyagwe, Endagaw chini, and Mewadani with the water district engineer of Mbulu • Installation of pressure sensor in Basonyagwe	Basonyagwe Endagaw chini Mewadani
Friday 14/02/2020	• Meeting with the district executive director (DED) of Hanang (in Katesh) • Meeting with the district water engineer (DWE) of Hanang (in Katesh) • Meeting with COWSO and PETS committee (in Diling'ang) • Water quality measurements (in Diling'ang)	Katesh Diling'ang
Saturday 15/02/2020	• Diver measurements	Endanachan
Tuesday 18/02/2020	• Meeting with district executive director (DED) and district water engineer (DWE) of Mkalama	Mkalama
Wednesday 19/02/2020	• Meeting with COWSO and PETS committee in Hilamoto • Visit Munguli primary solarized system • Water quality measurements	Hilamoto Munguli
Thursday 20/02/2020	• Meeting with COWSO • Water quality measurements	Gidbyo
Friday 21/02/2020	• Meeting with COWSO (in Isene) • Water quality measurements	Isene Haydom secondary school
Monday 24/02/2020	• Training in remote monitoring systems with 4CCP • Interview of 4CCP • Meeting with Dang'ayda village	4CCP office Dang'ayda

Appendix 2: Feedback from COWSOs

This appendix summarizes some of the feedback given by COWSOs in the focus group interviews. COWSOs were asked about the benefits and challenges of the solar-powered water pumping systems.

A number of benefits were mentioned, including:

- There has been a reduction in water-related diseases such as diarrhea
- They gain revenue from water tariffs to spend on operation and maintenance
- Water from the solar-powered water pumping systems is cheap compared to systems that run on diesel or electricity from the grid
- The distance to the water source has been reduced for many beneficiaries, leaving more time to engage in economic activities
- The distance to the water source has been reduced for several schools, and consequently pupils spend more time on schoolwork and less time on fetching water
- Manual labor is not required to pump water, and thus anyone can fetch water including children and the elderly
- The queue to fetch water is shorter than for handpumps, because it is faster to fetch water
- The pumping stations can be used to provide water for cattle

Three challenges were often mentioned regarding water quantity:

- The pumping stations do not provide enough water in the dry season
- The pump stops in cloudy weather
- The pumping station becomes over-crowded in the dry season, and people therefore have to wait in line for hours to fetch water

The table below provides an overview of where these problems were mentioned.

Feedback from COWSOs regarding water quantity challenges

Village	District	Water scarcity in dry season	Pump stops in cloudy weather	Long queues in dry season
Endagaw chini	Mbulu	Yes	Yes	Yes
Mewadani	Mbulu			
Basonyagwe	Mbulu	Yes		Yes
Endamilay	Mbulu	Yes	Yes	
Murukuchida	Mbulu	Yes	Yes	
Endanachan	Mbulu	Yes	Yes	
Harar	Mbulu	Yes	Yes	
Gidurudagew	Mbulu			
Diling'ang	Hanang	Yes	Yes	
Hilamoto	Mkalama	Yes		
Gidbyo	Mbulu			Yes
Isene	Mkalama		Yes	Yes

A number of the COWSOs reported that they would like to expand the WASH-project. The following table gives an overview of the improvements they would like to see regarding water supply.

Feedback from COWSOs regarding water supply improvements

Village	**District**	**Wishes for WASH project expansions**
Endagaw chini	Mbulu	• Distribute water to households • Improve pumping station so that it can provide more water
Mewadani	Mbulu	• Distribute water to other sub villages by water supply pipes The furthest sub village is 5-6 km away. The sub villages are uphill, but they are planning to pump water to a tank on a hill, so that the water can be distributed by gravity.
Basonyagwe	Mbulu	• Distribute water to other sub villages by water supply pipes In total they are 2500 people in the village. Currently, 900 people use the pumping station The sub villages are 4-5 km away, uphill
Endamilay	Mbulu	• Distribute water to the primary school by pumping: Parents have to pay more for children to attend school now, because the school uses water from the pumping station. The school has to pay for the water itself and for the salaries of the person who is fetching water from the pumping station and transporting it to school
Murukuchida	Mbulu	• Distribute water to other sub villages by water supply pipes • Or install pumping stations in other sub villages • Improve pumping system so that it can provide more water
Endanachan	Mbulu	• Distribute water to other sub villages by water supply pipes • Or install pumping stations in other sub villages The sub villages are 9-10 km away In total, they are 3000 people in the village Currently, 1300 people use the pumping station They have collected money within the community, but they need help from NCA or others to complete the project
Harar	Mbulu	• Distribute water to other sub villages by water supply pipes Maybe have 3-5 water taps around the sub villages to reduce distance • Or install pumping stations in other sub villages • Install a cattle trough • Increase the pressure of the water tap, because currently it takes too long to fill a bucket
Gidurudagew	Mbulu	• Distribute water to other sub villages by water supply pipes The sub villages are around 3km away (uphill), and around 720 people live there. Currently, 960 people use the pumping station. • Distribute water to the primary school, which is 1 km away (uphill)
Diling'ang	Hanang	• Install one more pumping station to get more water • Or get an additional power source to the existing pumping station. They want to use grid electricity to power the pumping station, but they are waiting for the grid to go through the village • Distribute water to another sub village by water supply pipes
Hilamoto	Mkalama	• Improve pumping station so that it can provide more water • Or install one more pumping station
Gidbyo	Mbulu	• Install pumping stations in the other sub villages (especially Maritatadu B which is around 10km away, has 250 households and a school) • Install a cattle trough
Isene	Mkalama	• Distribute water to other sub villages by water supply pipes • Or install pumping stations in other sub villages There are four sub villages which are located 1-3 km away • Install more water taps so that the queue will be shorter

Some of the COWSOs also had other development projects they would like to see in the village.

Feedback from COWSOs regarding development projects

Village	**District**	**Wishes for development projects**
Endagaw chini	Mbulu	
Mewadani	Mbulu	• Secondary school • Electricity in homes • Improving infrastructure: roads, culverts, bridges
Basonyagwe	Mbulu	
Endamilay	Mbulu	
Murukuchida	Mbulu	• Health facility
Endanachan	Mbulu	• Health facility • More classrooms
Harar	Mbulu	• Health facility • More classrooms • More toilets in school
Gidurudagew	Mbulu	
Diling'ang	Hanang	
Hilamoto	Mkalama	
Gidbiyo	Mbulu	
Isene	Mkalama	• Health facility: They have started building one, but they need support for finishing it

Appendix 3: Interview questions for COWSOs

The following questions were used as a starting point for the focus group interviews with the community owned water supply organizations (COWSOs):

COWSOs

- What are the main tasks of the water committee?
- How often does the water committee meet?
- Which type of support do you receive from 4CCP?
- Which type of support do you receive from the district engineers?
- How are people chosen for the water committee?
- Which personal characteristics should a member of the water committee have?

Water supply in the village

- What are the benefits of the solar-powered water pumping systems?
- What are the challenges of the solar-powered water pumping systems?
- How has the implementation of a solar-powered water pumping system affected the village?
- Have you participated in the planning of the systems?
- Have you participated in the construction of the systems?
- How satisfied are you with your involvement in the planning and construction of the system? Are there any improvements that can be done?
- What is the average water use in the village?
- What is the water used for? (Drinking, cleaning, cooking, irrigation, livestock)
- Do you use different kind of water sources?
- If yes: Which?
    - If no: Have you heard of rainwater harvesting? Do you see a potential in using rainwater harvesting as a water source? Why?
- Does the water smell and taste nice?
- Do you have any thoughts about the safety of the water?
- Is there enough water for everyone? E.g. are the water tanks sometimes empty?
- Which improvements would you like to see regarding the water supply in the village?
- How often do most families collect water?
- Who in the household is responsible for collecting water?

Willingness to pay:

- How is the price for water determined?
- How is the money collected?
- How often do people pay for water? (annually, monthly, per bucket)
- How would you prefer to pay for water?
- Who is in charge of the funds?
- Are the funds stored in a bank account?
- What are the funds used for?

Operation and maintenance

- Are the solar panels cleaned regularly? If yes, how often are they cleaned?
- What else do you do to take care of the solar water yard?
- Has there been any downtime of the solar-powered water pump?
- What do you do if the pump stops working?
- How long does it take to get help?
- When is the solar water yard open? Is it closed during the night?
- Has there been any problems with vandalism?

Appendix 4: Interview questions for PETS committees

The following questions were used as a starting point for the focus group interviews with the public expenditure tracking system (PETS) committees:

- What are the main tasks of the PETS committee?
- How often does the PETS committee meet?
- Who does the PETS committee collaborate with?
- What are public funds used for in your village?
- Which improvements would you like to see in your village?
- How would you describe the water supply situation in your village?
- Which improvements would you like to see regarding the water supply in the village?

Appendix 5: Interview questions for DWEs

The following questions were used as a starting point for the in-depth interviews with the district water engineers (DWEs):

Water supply in the district

- How would you describe the water supply situation in the district?
- How could the water supply situation be improved, in your opinion?

Solar water pumping systems:

- Many solar-powered water pumping systems have been built in this area in the last few years. What are the benefits of this water supply option?
- What are the challenges?
- How is the responsibility for the solar water pumping systems divided between the different stakeholders?
- Which responsibilities does the district engineer have?
- Which responsibilities does the local community have?
- Which responsibilities does 4CCP have?
- Do you think this is a suitable division of responsibilities?

Operation, maintenance and repairs

- What type of maintenance procedures are followed?
- What can be done to ensure satisfactory operation and maintenance?
- What are the main challenges related to operation and maintenance?
- Have you experienced any failures with the solar-powered water pumping system?
- If so, what were the causes?
- Who is responsible for repairs when failures happen?
- Are failures and repairs registered in a database?

Data handling / Remote monitoring

- What kind of data concerning the water pumping systems is acquired?
- E.g. water consumption, pumping rate
- How is the data acquired?
- What is the data used for?
- How is the data stored and systemized?
- What do you think are the potential uses of remote monitoring?
- What could be the benefits of remote monitoring?
- What could be the challenges of remote monitoring?
- Which parameters could be of interest for remote monitoring?

(Water consumption, water level in storage tanks, information about whether the pump is operating or not)

- In what ways do you think installing a remote monitoring system would affect your job?
- What would be an affordable price level for a remote monitoring system?
- Are there other data acquisition methods that you think would be more suitable than remote monitoring?

Appendix 6: Interview questions for 4CCP

The following questions were used as a starting point for the in-depth interviews with the 4CCP employees:

4CCP

- What are the main tasks of 4CCP?
- When was 4CCP funded?
- How does 4CCP receive its funds?

Water supply

- How would you describe the water supply situation in rural Tanzania today?
- What are the main challenges regarding water supply in rural Tanzania?
- Explain 4CCP's work regarding water supply

Solar-powered water pumping systems

- What has been 4CCP's role regarding the implementation of solar-powered water pumping systems?
- What are the benefits of the solar-powered water pumping systems?
- What are the challenges of the solar-powered water pumping systems?
- How has the improvements in water supply affected the villages?
- Elevated fluoride concentrations in water is known to be a problem in Tanzania. Are elevated fluoride concentrations a problem in this region?
- Are there other water quality parameters that are of particular concern in the area?
- Do you know if the solar-powered water pumping systems provide enough water for the local communities?

Management

- How is the responsibility for the solar water yards divided between the different stakeholders? (NCA, 4CCP, district engineer, water committee)
- Will the division of responsibilities change? E.g. will NCA pull out of the project?
- To what extent was the local community involved in the planning and construction of the pumping systems?
- What is the function of a water committee?
- Has there been any challenges related to the implementation of water committees?
- What type of support does the water committees receive from 4CCP?
- Why are water committees not called COWSOs anymore?
- What are the most important factors for making sure that the water supply schemes are sustainable?

Operation, maintenance and repairs

- What type of maintenance are the local communities in charge of?
- Are maintenance procedures followed?
- What can be done to ensure satisfactory operation and maintenance?
- Who is responsible for repairs?
- Is the necessary competence and equipment available in case of repairs?
- If no, what can be done to acquire the necessary competence and equipment?

Data handling / Remote monitoring

- How is data related to the pumping systems acquired?
- How is the data stored and systemized?
- What is the data used for?
- What do you think are the potential uses of remote monitoring?
- What could be the benefits of remote monitoring?
- What could be the challenges of remote monitoring?

- Which parameters would be of interest for remote monitoring?
- Do you think it is realistic to implement a remote monitoring system in this context?
- What would be an affordable price level for a remote monitoring system?
- Are there other data acquisition methods that you think would be more suitable than remote monitoring?

Appendix 7: Survey

These are the question of the survey in which 87 community members participated. The questions are quite similar to those used by Misund and Møller (2019).

General information

- District: ___________________________
- Age: _________
- Gender:
  □ Male
  □ Female
- Status:
  □ Mother
  □ Father
  □ Son
  □ Daughter
  □ In-law
  □ Grandmother
  □ Grandfather
  □ Other (please specify): ______________________
- Number of people in household: _________
- Who in the household is usually in charge of collecting water: ________________
- Average yearly income (for household): ______________

Current water system

- What is your daily source of water for drinking and cooking?
  □ Hand pump
  □ Solar powered pump
  □ Rainwater harvesting
  □ River or pond (if yes, please answer next question)
  □ Other (please specify): ________________________
- If you use a river or pond, what is the main reason for this?
  □ Price of water
  □ Distance to well
  □ Failure and downtime at well
  □ Waiting time at well
  □ Taste, odour
  □ Habit, tradition
  □ Other (please specify): ______________________________
- What is the distance to your water source?
  □ 0-50 m
  □ 51 – 100 m
  □ 101 – 300 m
  □ 301 – 1000 m
  □ More than 1000 m (please specify): __________________
- How long do you normally wait in line at your water point?
  □ 0-5 min
  □ 6-10 min
  □ 11-15 min
  □ 16-30 min
  □ 31-60 min
  □ More than 60 min (please specify): ____________________

- How much time is usually spent collecting water in total (travel + waiting time)?
  □ Less than 30 min
  □ More than 30 min

- How much water does your household use on an average daily basis? ____________

- How much water is normally collected each trip? ________________

- What do you use the water for?
  □ Domestic uses (cooking, cleaning, drinking etc.).
  □ Productive uses (irrigation, beer making, livestock watering etc.) If yes, please answer the two next questions

- What kind of productive uses do you use the water for?
  □ Irrigation
  □ Livestock watering
  □ Beer making
  □ Other (please specify): __________________________

- How much water do you use for productive uses? __________________

- If the water is only used for domestic uses: What do you think are the reasons why you do not use water for productive uses?
  □ Distance to source
  □ Price on water
  □ Lack of water
  □ Other (please specify): ____

- How satisfied are you with your current water system?
  □ Very satisfied
  □ Somewhat satisfied
  □ Not satisfied
  □ Do not know

- Have there been any interruptions where water from your drinking water source not has been available? If yes, please answer the two next questions
  □ Yes
  □ No
  □ Do not know

- For how long did the last interruption in service last? ___________________

- What was the reason for the interruption? ____________________

- How would you describe your household's situation with food security in the past year?
  □ Very secure
  □ Somewhat secure
  □ Insecure
  □ Do not know

- In the past week, did your family consume any of the following types of food?
  □ Starchy foods
  □ Beans
  □ Nuts
  □ Dairy
  □ Meat
  □ Eggs
  □ Leafy greens
  □ Vegetables
  □ Fruits

- (Among families with at least one child under the age of 10): Has your child(ren) been sick with diarrheal illness within the past month?

□ Yes – How many?: _____
□ No
□ Do not know

- In the past year, has anyone of any age in your home been hurt while collecting water, either along the path or at the water point?
  □ Yes
  □ No
  □ Do not know

- How are you charged for water?
  □ Annual
  □ Seasonal
  □ Per bucket
  □ Other (please specify): __________________________

- How do you pay for water?
  □ Cash at waterpoint
  □ Cash beforehand
  □ Mobile payment water point
  □ Mobile payment beforehand
  □ Other (please specify): __________________________

- How much do you currently pay for water? __________________

- How much would you like to pay for your current water service? _________________

- How much can you accept to pay for your current water service? _________________

- What time of year (month) is preferred for paying a yearly fee for water? _________

Willingness to pay (1 jerry can)

- How much are you willing to pay for using less than 30 minutes for a round trip of collecting water?
  □ 10 TSH
  □ 25 TSH
  □ 50 TSH
  □ 75 TSH
  □ 100 TSH
  □ 125 TSH
  □ 150 TSH
  □ More: ___________
  □ Stated limit: _____________

- How much are you willing to pay if the water comes from solar powered pumps, rather than hand pumps?
  □ 10 TSH
  □ 25 TSH
  □ 50 TSH
  □ 75 TSH
  □ 100 TSH
  □ 125 TSH
  □ 150 TSH
  □ More: ____________
  □ Stated limit: _____________

- How much are you willing to pay if the water point was only shared between your 5 neighbouring households?
  □ 10 TSH
  □ 25 TSH
  □ 50 TSH
  □ 75 TSH

□ 100 TSH
□ 125 TSH
□ 150 TSH
□ More: ____________
□ Stated limit: _____________

- How much are you willing to pay if there was a water tap in your house?
  □ 10 TSH
  □ 25 TSH
  □ 50 TSH
  □ 75 TSH
  □ 100 TSH
  □ 125 TSH
  □ 150 TSH
  □ More: ____________
  □ Stated limit: _____________

- How much are you willing to pay if you can achieve an income using water for productive uses?
  □ 10 TSH
  □ 25 TSH
  □ 50 TSH
  □ 75 TSH
  □ 100 TSH
  □ 125 TSH
  □ 150 TSH
  □ More: ____________
  □ Stated limit: _____________

- How high does the daily income have to be in order for you to be willing to pay more for water?
  □ Under 2000 TSH
  □ 2000-6000 TSH
  □ 6001-10 000 TSH
  □ More than 10 000 TSH (please specify): ________________

- How much are you willing to pay if the water source is less than 5 minutes away, but can only be used for agriculture (because of the water quality)?
  □ 10 TSH
  □ 25 TSH
  □ 50 TSH
  □ 75 TSH
  □ 100 TSH
  □ 125 TSH
  □ 150 TSH
  □ More: ____________
  □ Stated limit: _____________

Appendix 8: System characteristic curve tables

This appendix shows the tables that were made when calculating the system characteristic curve for Murukuchida pumping system. The rest of the pumping systems were calculated in the same way.

Friction loss in riser main and pipe that runs along the ground from the borehole to the construction that the storage tanks stand on

Flowrate, Q		Velocity, v	Reynolds number, R_e	Friction factor, f	Friction loss, Hf
m^3/h	L/s	m/s	-	-	m
0	0	0	0	0	0
0,5	0,14	0,12	5088,74	0,043740	0,075550
1,0	0,28	0,24	10177,48	0,038537	0,266252
1,5	0,42	0,37	15266,22	0,036446	0,566553
2,0	0,56	0,49	20354,96	0,035288	0,975203
2,5	0,69	0,61	25443,70	0,034544	1,491652
3,0	0,83	0,73	30532,43	0,034024	2,115594
3,5	0,97	0,85	35621,17	0,033637	2,846838
4,0	1,11	0,97	40709,91	0,033338	3,685254
4,5	1,25	1,10	45798,65	0,033099	4,630746
5,0	1,39	1,22	50887,39	0,032904	5,683243
5,5	1,53	1,34	55976,13	0,032741	6,842689
6,0	1,67	1,46	61064,87	0,032603	8,109037

Friction loss in vertical pipe

Flowrate, Q		Velocity, v	Reynolds number, R_e	Friction factor, f	Friction loss, Hf
m^3/h	L/s	m/s	-	-	m
0	0	0	0	0	0
0,5	0,14	0,73	12428,27	0,045952	0,428083
1,0	0,28	1,45	24856,53	0,043870	1,634772
1,5	0,42	2,18	37284,80	0,043106	3,614132
2,0	0,56	2,91	49713,07	0,042703	6,365071
2,5	0,69	3,63	62141,33	0,042452	9,887084
3,0	0,83	4,36	74569,60	0,042281	14,179872
3,5	0,97	5,09	86997,87	0,042156	19,243238
4,0	1,11	5,81	99426,13	0,042060	25,077039
4,5	1,25	6,54	111854,40	0,041985	31,681170
5,0	1,39	7,27	124282,67	0,041923	39,055547
5,5	1,53	7,99	136710,93	0,041873	47,200104
6,0	1,67	8,72	149139,20	0,041830	56,114786

Friction loss in horizontal pipes

Flowrate, Q		Velocity, v	Reynolds number, R_e	Friction factor, f	Friction loss, Hf
m^3/h	L/s	m/s	-	-	m
0	0	0	0	0	0
0,5	0,14	0,36	6214,13	0,049565	0,042755
1,0	0,28	0,73	12428,27	0,045952	0,158549
1,5	0,42	1,09	18642,40	0,044594	0,346195
2,0	0,56	1,45	24856,53	0,043870	0,605471
2,5	0,69	1,82	31070,67	0,043417	0,936281
3,0	0,83	2,18	37284,80	0,043106	1,338567
3,5	0,97	2,54	43498,93	0,042877	1,812294
4,0	1,11	2,91	49713,07	0,042703	2,357434
4,5	1,25	3,27	55927,20	0,042565	2,973969
5,0	1,39	3,63	62141,33	0,042452	3,661883
5,5	1,53	4,00	68355,47	0,042359	4,421165
6,0	1,67	4,36	74569,60	0,042281	5,251805

Singular losses

Flowrate, Q		H_L (Pipe entry)	H_L (Bend)	H_L (T-cross)	H_L (Outflow)
m^3/h	L/s	m	m	m	m
0,0	0	0	0	0	0
0,5	0,14	0,000378	0,001513	0,026913	0,006728
1,0	0,28	0,001513	0,006051	0,107651	0,026913
1,5	0,42	0,003404	0,013615	0,242215	0,060554
2,0	0,56	0,006051	0,024205	0,430604	0,107651
2,5	0,69	0,009455	0,037820	0,672818	0,168205
3,0	0,83	0,013615	0,054461	0,968858	0,242215
3,5	0,97	0,018532	0,074128	1,318724	0,329681
4,0	1,11	0,024205	0,096820	1,722415	0,430604
4,5	1,25	0,030635	0,122538	2,179932	0,544983
5,0	1,39	0,037820	0,151282	2,691274	0,672818
5,5	1,53	0,045763	0,183051	3,256441	0,814110
6,0	1,67	0,054461	0,217846	3,875434	0,968858

Pump head (system characteristic curve)

Flowrate, Q		Pump head, H
m^3/h	L/s	m
0,0	0	65,40
0,5	0,14	65,98
1,0	0,28	67,60
1,5	0,42	70,25
2,0	0,56	73,91
2,5	0,69	78,60
3,0	0,83	84,31
3,5	0,97	91,04
4,0	1,11	98,79
4,5	1,25	107,56
5,0	1,39	117,35
5,5	1,53	128,16
6,0	1,67	139,99

Appendix 9: System characteristic curve calculations

This section explains how the values in the tables in Appendix 8 were calculated. The following data was available about Murukuchida pumping station:

- Assumed DWL: 60.0m
- Height from ground surface to water tank inlet: 5.4m
- Pump installation depth: 80m
- Approximated distance from borehole to the construction that the storage tanks stand on: 7m
- Diameter of riser main: 38.1mm

The example is for a flowrate of Q = 1.5 m^3/h.
First, the water velocity in the different parts of the pipe system was determined:
Velocity in riser main (1) and in pipe along ground (2):

$$v_{1,2} = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}D^2} = \frac{1.5/(60*60)}{\frac{\pi}{4}*0.0381^2} = 0.365468\ m/s$$

Velocity in vertical pipe (3):

$$v_3 = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}D^2} = \frac{1.5/(60*60)}{\frac{\pi}{4}*0.0156^2} = 2.179966\ m/s$$

Velocity in horizontal pipes (4):

$$v_4 = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}D^2} = 0.5*\frac{1.5/(60*60)}{\frac{\pi}{4}*0.0156^2} = 1.089983\ m/s$$

Then, the Reynolds number for each segment was determined:

$$R_{e1,2} = \frac{vD}{\nu} = \frac{0.365468*0.0381}{9.121*10^{-7}} = 15266.22$$

$$R_{e3} = \frac{vD}{\nu} = \frac{2.179966*0.0156}{9.121*10^{-7}} = 37284.80$$

$$R_{e4} = \frac{vD}{\nu} = \frac{1.089983*0.0156}{9.121*10^{-7}} = 18642.40$$

Then, the friction factor for each segment was determined:

$$f_{1,2} = \frac{0.25}{\left[\log\left(\frac{k_s}{3.7D}+\frac{5.74}{R_{e1,2}{}^{0.9}}\right)\right]^2} = \frac{0.25}{\left[\log\left(\frac{0.2}{3.7*38.1}+\frac{5.74}{15266.22^{0.9}}\right)\right]^2} = 0.036446$$

$$f_3 = \frac{0.25}{\left[\log\left(\frac{k_s}{3.7D}+\frac{5.74}{R_{e3}{}^{0.9}}\right)\right]^2} = \frac{0.25}{\left[\log\left(\frac{0.2}{3.7*15.6}+\frac{5.74}{37284.80^{0.9}}\right)\right]^2} = 0.043106$$

$$f_4 = \frac{0.25}{\left[\log\left(\frac{k_s}{3.7D}+\frac{5.74}{R_{e4}{}^{0.9}}\right)\right]^2} = \frac{0.25}{\left[\log\left(\frac{0.2}{3.7*15.6}+\frac{5.74}{18642.40^{0.9}}\right)\right]^2} = 0.044594$$

Then, the friction loss for each segment was determined:

$$h_{f1,2} = f_{1,2}\frac{L}{D}\frac{v_{1,2}^2}{2g} = 0.036446 * \frac{80+7}{0.0381} * \frac{0.365468^2}{2*9.81} = 0.5666m$$

$$h_{f3} = f_3\frac{L}{D}\frac{v_3^2}{2g} = 0.043106 * \frac{5.4}{0.0156} * \frac{2.179966^2}{2*9.81} = 3.6141\ m$$

$$h_{f4} = f_4\frac{L}{D}\frac{v_4^2}{2g} = 0.044594 * \frac{2}{0.0156} * \frac{1.089983^2}{2*9.81} = 0.3462m$$

Then, the local losses were determined:

Pipe entry:

$$h_L = k_L\frac{v_{1,2}^2}{2g} = 0.5 * \frac{0.365468^2}{2*9.81} = 0.0034m$$

Bends:

$$h_L = k_L\frac{v_{1,2}^2}{2g} = 2*1*\frac{0.365468^2}{2*9.81} = 0.0136m$$

T-cross

$$h_L = k_L\frac{v_3^2}{2g} = 1 * \frac{2.179966^2}{2*9.81} = 0.2422$$

Outlet:

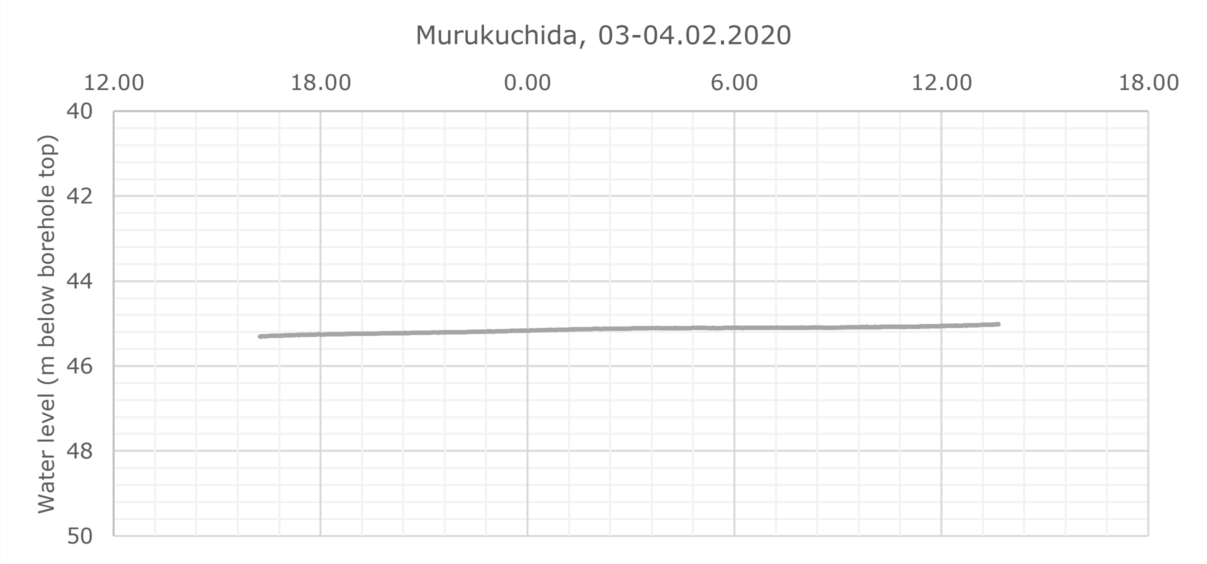
$$h_L = k_L\frac{v_4^2}{2g} = 1 * \frac{1.089983^2}{2*9.81} = 0.0606m$$

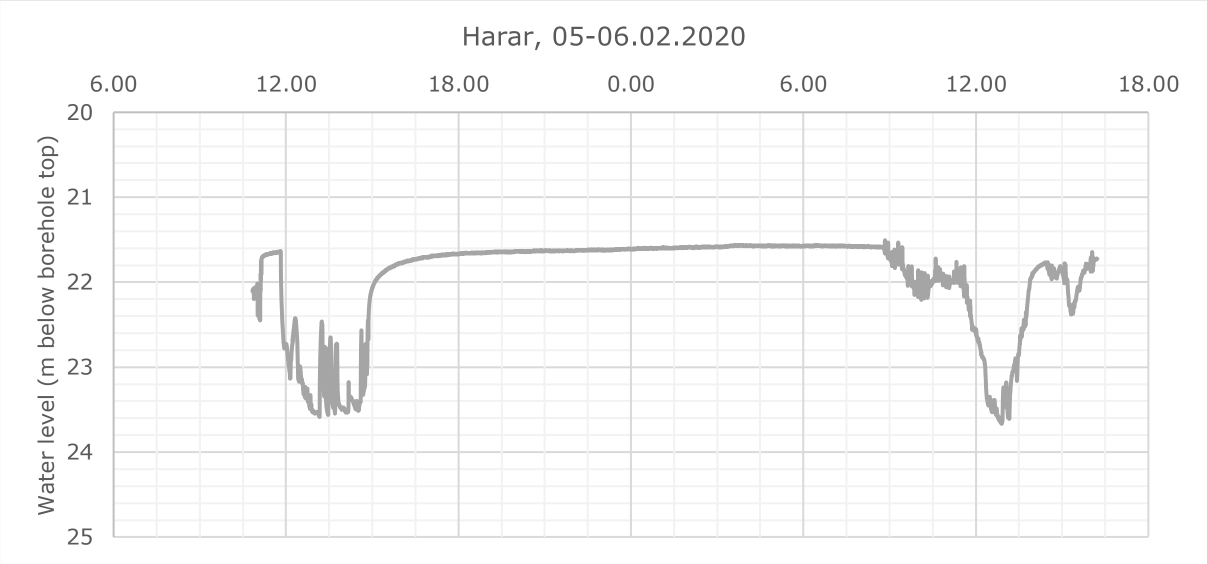
Then, the total head was determined:

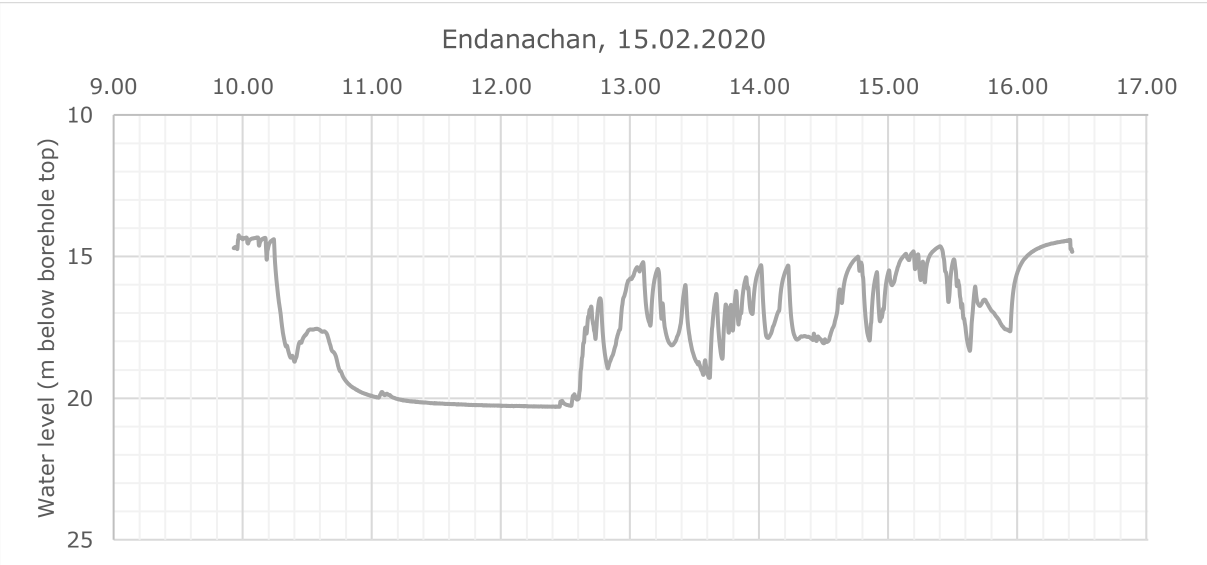
$$Head = DWL + (vertical\ distance\ from\ gound\ surface\ to\ inlet\ of\ water\ tanks) + friction\ losses + local\ losses$$

$$Head = 60.0 + 5.4 + 0.5666 + 3.6141 + 0.3462 + 0.0034 + 0.0136 + 0.2422 + 0.0606 = \mathbf{70.25m}$$

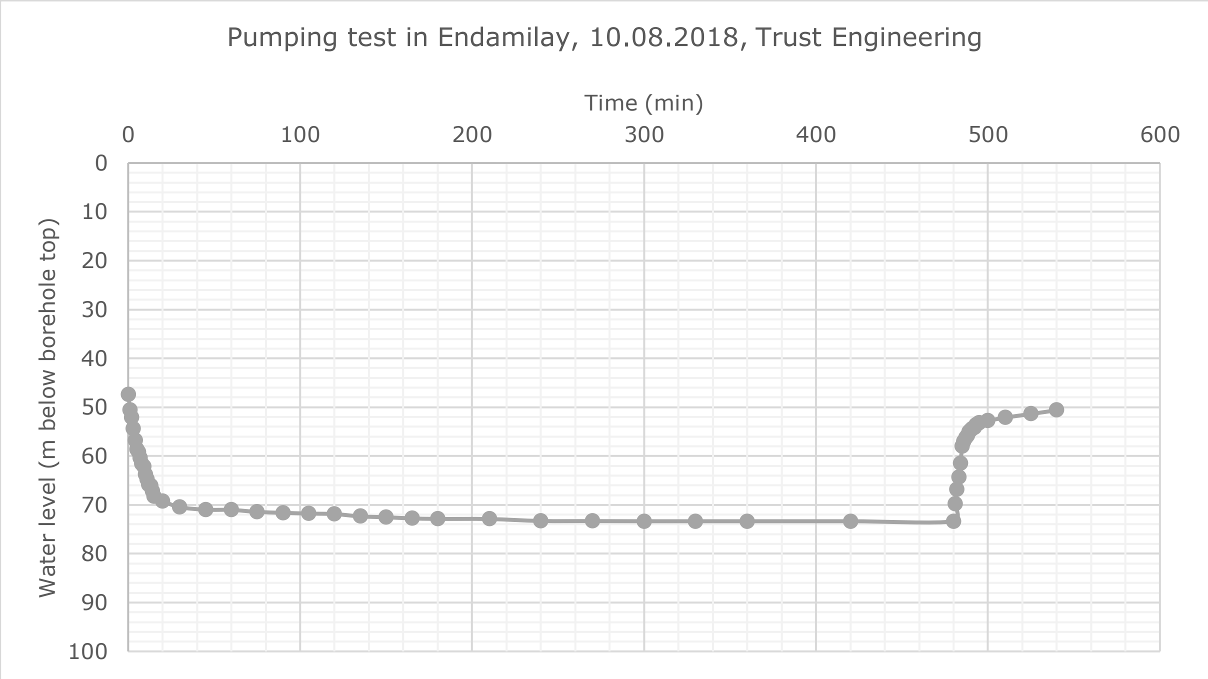
Appendix 10: TD-Diver measurements

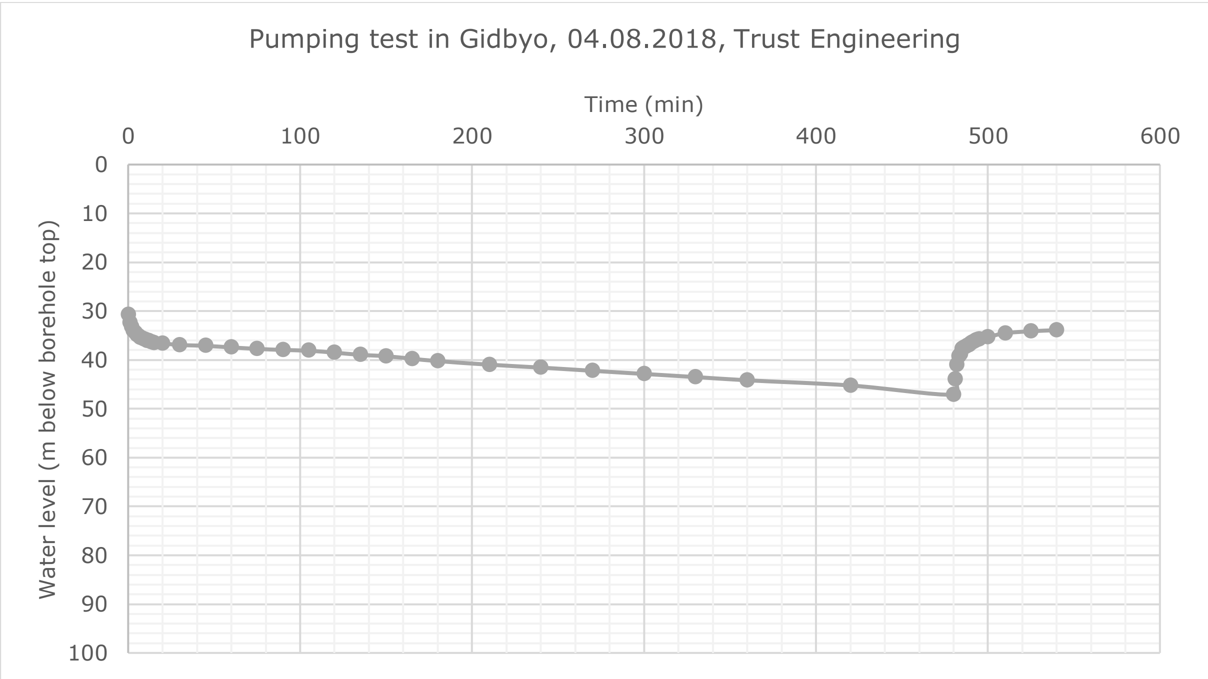


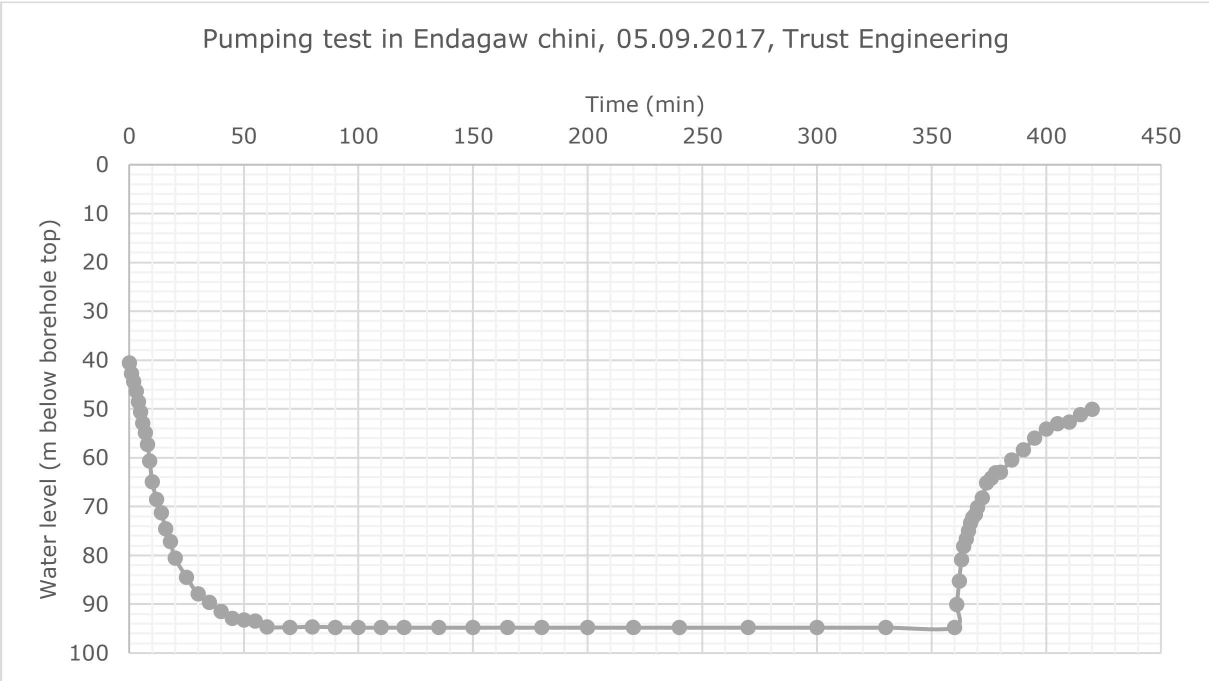


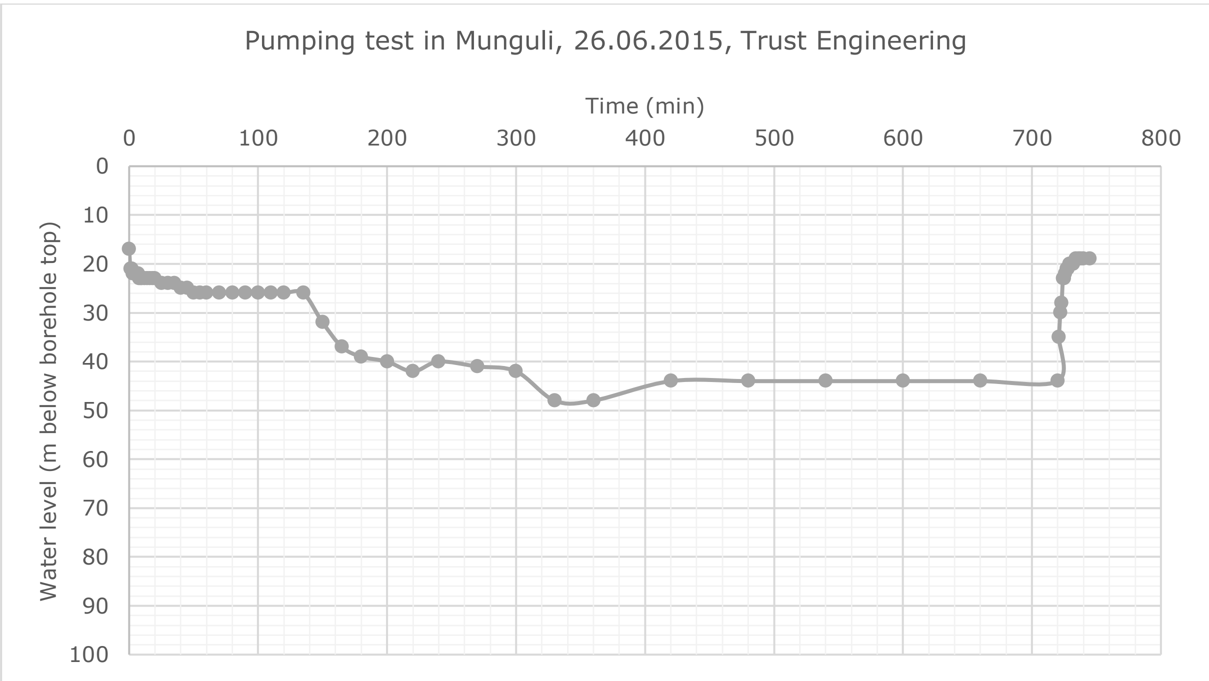


Appendix 11: Pumping tests






Pumping test in Endagaw chini, 05.09.2017, Trust Engineering
Time (min)
0
50
100
150
200
250
300
350
400
450
Water level (m below borehole top)
0
10
20
30
40
50
60
70
80
90
100


Pumping test in Munguli, 26.06.2015, Trust Engineering
Time (min)
0
100
200
300
400
500
600
700
800
Water level (m below borehole top)
0
10
20
30
40
50
60
70
80
90
100

Maria Asklund

Performance of solar-powered water pumping systems for rural water supply

NTNU

Norwegian University of Science and Technology