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UNIVERSITY OF THE WITWATERSRAND
School of Civil and Environmental Engineering

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The Rainwater Harvesting Potential of eZizityaneni and kwaNdela Communities, Eastern Cape, South Africa



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

RESEARCH REPORT

Submitted to the Faculty of Engineering and Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfillment of the requirements for the degree of Master of Science (MSc) in Engineering,

AUTHOR : **Luvuyo Nxulu (746047)**

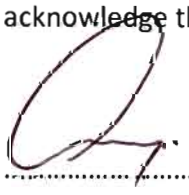
SUPERVISOR : **Prof. J.G. Ndiritu**

DATE : **September 2022**

DECLARATION:

I, ***Luvuyo Nxulu (746047)*** a registered student for Master of Science (MSc) in the year 2022 hereby declare that I am the sole author of all the work reflecting on this document. It is entirely my own unaided work. I also declare that this work has not been submitted in the past for any degree or examination to any other University.

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06 September 2022
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Date

ABSTRACT:

The objective of the study is to determine rainwater harvesting (RWH) potential of the eZizityaneni and kwaNdela communities located in a rainfall-rich area of the Eastern Cape province of South Africa. Furthermore, the study aimed to determine the changes to the existing RWH-based water supply systems that would be required to fully supply the water demands if it cannot be achieved by the existing systems. Two households, a school and a clinic were selected as representative RWH users in the community. The study also aimed to compare financial viability between RWH-based water supply and traditional centralised municipal water supply system, and this was carried out for one household.

The study revealed that, with the existing RWH-based water supply system for two households that had storages of 10 and 15m^3, the level of supply at 96% statistical reliability is 250 and 280 days per year, respectively. However, if the storage capacity is increased to 45m^3 for both households, the full supply of 365 days per year could be achieved at 96% statistical reliability. The study also reveals that, with the existing RWH-based water supply system for the clinic that has a storage of 15m^3, the level of supply is 280 days per year at 96% statistical reliability, while increasing the storage size to 55m^3 could achieve full supply at 96% statistical reliability. The existing RWH-based water supply system for the school with 27.5m^3 storage can supply 86 days per year at 96% reliability and increasing storage to 90m^3 could increase the supply to 132 days per year. Any further increase in storage cannot achieve a higher level of supply at 96% reliability and only an increase in roof area from the current 1246m^2 could lead to higher levels of supply. It was found that the school can achieve full supply at 96% reliability with a roof area and storage size of 2250m^2 and 380m^3, respectively.

For the one household, where comparative life cycle cost analysis (LCCA) was carried out, it was found that installing a fully supplying RWH-based system would result in a payback period of 39 years if the cost of centralized municipal water supply is based on water tariffs which are typically highly subsidized. However, for LCCA based on the actual cost of centralized municipal water supply, the cumulative cost of RWH would be higher than that of municipal water supply for the first 14 years after which the cost of municipal water supply would escalate much faster to a cost that is 3.4 times higher than that of RWH by the end of the 50-year design life of the systems. The results suggest that while the communities could rely primarily on RWH-based

water supply system, the system would be financially unattractive if not subsidized. The comparatively lower total life cycle costs of RWH than the municipal water supply reveals that subsidizing RWH-based water supply system may be the better of the two options for rainfall-rich areas like the one in this study.

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First and foremost, I would like to sincerely thank my God almighty for having given me the ability to pursue my academic goals. My sincerest and special gratitude goes to my self-sacrificing, hard-working, God-servant brother Ayanda Nxulu. His level of involvement in the study and understanding made me discover the potential that God has inculcated in him.

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Author,

Luvuyo Nxulu

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1. INTRODUCTION

1.1 Background

Rainwater harvesting (RWH) is the collection and storage of rainwater for immediate use and has been applied for millennia (Campisano et al., 2017). The latest South African National Master Water Plan (DWS, 2018) informs that RWH is growing in South Africa and is particularly considered as more applicable for improving water supply in rural and urban areas with unreliable centralised water supply.

Rainwater harvesting (RWH) offers an alternative to traditional centralized water supply for South Africa to meet the Sustainable Development Goals of halving the proportion of people without sustainable access to safe drinking water (Mwenge Kahinda *et al.*, 2007). Rainwater harvesting (RWH) is listed as one of the adaptation measures to climate change in Egypt in the sense that it could cope with the water scarcity and if implemented in large scale, it can help reduce inundation problems in settlement areas (Al Zayed *et al.*, 2018).

It has been reported that, in certain countries, some regions once reliant on groundwater are now shifting to rainwater harvesting due to pollution of groundwater (Quigley *et al.*, 2016). Although groundwater is currently under-utilised in some regions in South Africa, it is also often over-abstracted by high pumping rates and is unreliable in many areas (DWS, 2018). On the other hand, RWH is considered as mostly suitable for augmentation (DWS, 2018) although the requisite hydro-economic analysis required to inform this is not evident in the literature.

Water shortage in rural communities has led to increased use of rainwater harvesting but there is a dearth of detailed hydrological analysis to assess the water supply potential and appropriate sizing of RWH systems in South Africa (Ndiritu et al., 2017). Although South Africa is a water-scarce country, some areas receive a relatively high mean annual rainfall (about 1000 mm/year) compared to the average South Africa's mean annual rainfall of 465mm (Anon, 2016).

This study therefore aimed to assess the RWH potential of a selected community located in a rainfall-rich area and to find out if RWH in this community could be the primary source rather than an augmenting source of water supply.

1.2 Problem Statement

Water resources are globally under threat and could experience severe water crisis unless its finite resources, rainwater in particular, are managed in a sustainable manner (Al Zayed *et al.*, 2018). It has been predicted that by 2030, South Africa, will be severely impacted by physical water scarcity (Fisher-Jeffes *et al.*, 2017).

Many rural areas of South Africa have highly underdeveloped or no centralised water supply infrastructure and mostly rely on ground water which is often challenging to operate and manage (DWS, 2018) and is more vulnerable to pollution. Based on household survey in rural areas of South Africa, (Lebek et al., 2021) found the dominant underlying causes of household water insecurity in most rural areas to be the unequal provision and low reliability of municipal water services.

Water infrastructure is often lacking and not well maintained in rural areas administered by the municipalities and the use of raw surface water that may be highly polluted is not uncommon and is often not supported by the municipalities (Lebek and Krueger, 2022). This calls for diversification of water sources which could potentially enhance water security of various households, particularly in the rural areas. Rainwater harvesting could be a realistic augmenting or alternative water source for these areas especially where high rainfall rates are experienced.

Houston and Still (2002) inform that rainwater harvesting is often used as a common sense of response to a lack of water but is frequently done with no prior technical skills or external assistance. Houston and Still (2002) further inform that rainwater harvesting is generally excluded when considering alternative options for new water supplies for remote and dispersed rural settlements while it may have significant ability as a supply water source.

1.3 Rationale and significance of the study

The inadequacy of municipal water distribution and lack of other potable water sources in many areas presents an opportunity to assess the water supply potential of RWH. Many communities in rural South Africa have adopted RWH in various forms but there is mostly no evidence indicating that detailed hydrological analysis has been undertaken to size these

systems. This study therefore seeks to find this out for a selected rural community located in a high rainfall area of South Africa.

1.4 Research questions

The key research questions are:

Question 1: What levels of water supply and statistical reliability could be achieved by selected RWH systems in the selected study area?

Question 2: If the existing RWH supply systems cannot fully meet the water demands, what changes to the systems could be made for them to fully supply the required water demand?

Question 3: How would the life cycle costs of some of the RWH supply systems meeting full supply compare to the life cycle costs of a centralised municipal water supply for the same demands?

1.5 Aims and Objectives

The aim of this study is to assess the rainwater harvesting potential of a selected rural community by studying selected RWH-based water supply systems in the community.

The key objectives of the study are as follows:

Objectives 1: To determine the RWH potential of the selected systems.

Objectives 2: To determine the changes to the existing RWH-based water supply systems that would be required to fully supply the water demands. This would only apply if the existing systems cannot achieve this.

Objectives 3: To compare RWH financial viability with the viability of municipal water supply for some of the selected systems.

1.6 Structure of the thesis

Chapter 1 introduces the research including background, problem statement, rationale and the objectives with associated research questions that the study seeks to answer.

Chapter 2 provides the general information in relation to the study area context, particularly information relative to the RWH-based water supply systems.

Chapter 3 provides a general literature review in relation to previous and mostly recent RWH studies in line with the objectives and research questions.

Chapter 4 describes the methodology that was formulated to fulfil the objectives and ultimately answer the research questions.

Chapter 5 presents and analyses the data obtained from field work conducted on the selected RWH systems and includes the determination of the rainwater collection efficiencies for some of these systems based on the field data.

Chapter 6 presents data as collected, analysed and results in response to first and second research questions regarding RWH potential.

Chapter 7 presents data as collected, analysed and results in response to the third research question regarding financial viability comparison between RWH-based water supply system and a centralised municipal water supply system.

Chapter 8 presents the conclusion and recommendations.

Chapter 9 presents the list of references.

2. STUDY AREA

2.1 Selection and Location of the Study Area

The selected communities are Ezizityaneni and kwaNdela villages located in Mbizana Local Municipality of the Eastern Cape Province of South Africa. The area is in the coastal Indian ocean and experiences high rainfall but still faces water-shortages characterised by increasing water demand, insufficient water resource infrastructure and inadequacy of municipal water distribution. Many members of the communities therefore still obtain water for domestic use from natural streams after exhausting other water sources including RWH. Given that this is a high-rainfall area where RWH is practised but evidently not meeting the water demands, it is a natural choice for this study considering the aims and objectives stated in Section 1.5.

The geographical location of the study area including the individual Erf sizes for the selected water users is shown in table 2.1.

Table 2.1: Geographical information for selected area of study (google earth pro, 2021)

Water User	Village name	Plot size	Latitude	Longitude
Household 1	Ezizityaneni	45m x 75m	-30.5253	29.4410
Household 2	KwaNdela	45m x 100m	-30.5548	29.4328
Household 3	Nomlacu side	45m x 45m	-30.5044	29.4635
Clinic	KwaNdela	116m x 105m	-30.5652	29.4249
School	Ezizityaneni	136m x 245m	-30.5232	29.3700

As figure 2.1 shows, the study area is located along the eastern coast of South Africa which received mean annual rainfalls exceeding 1000mm. It is an advantage that the researcher has lived in the area for more than 35 years and has real-life experience of RWH-based water supply and centralised municipal water supply situation in the selected communities.

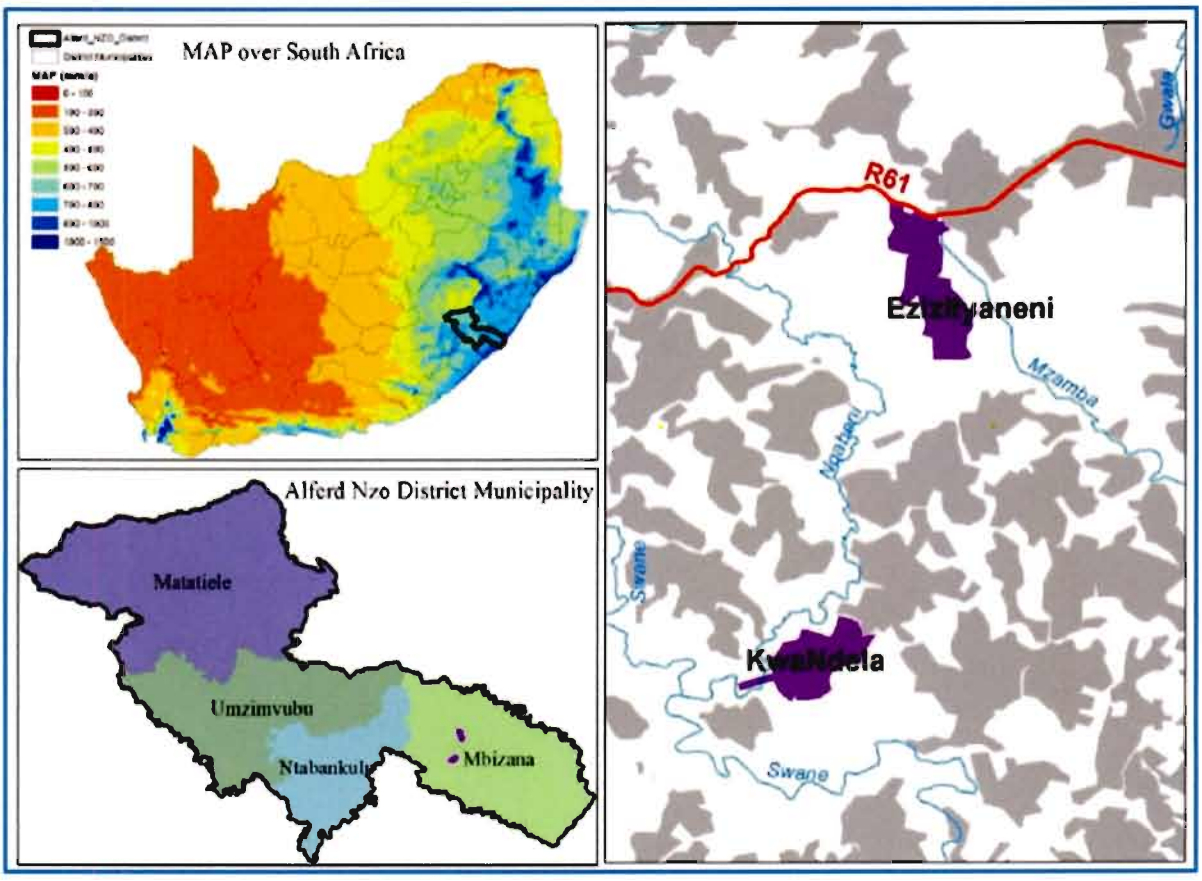


Figure 2.1: Location of study area (Anon, 2016: Google earth pro, 2021)

2.2 Climate

The mean annual rainfall in the study area that exceeds 1000 mm (figure 2.1) is much higher than South Africa's mean annual rainfall of 465mm (Anon, 2016). The graphs in figure 2.2 below respectively illustrate the monthly average rainfall and the associated temperature conditions in the study area.

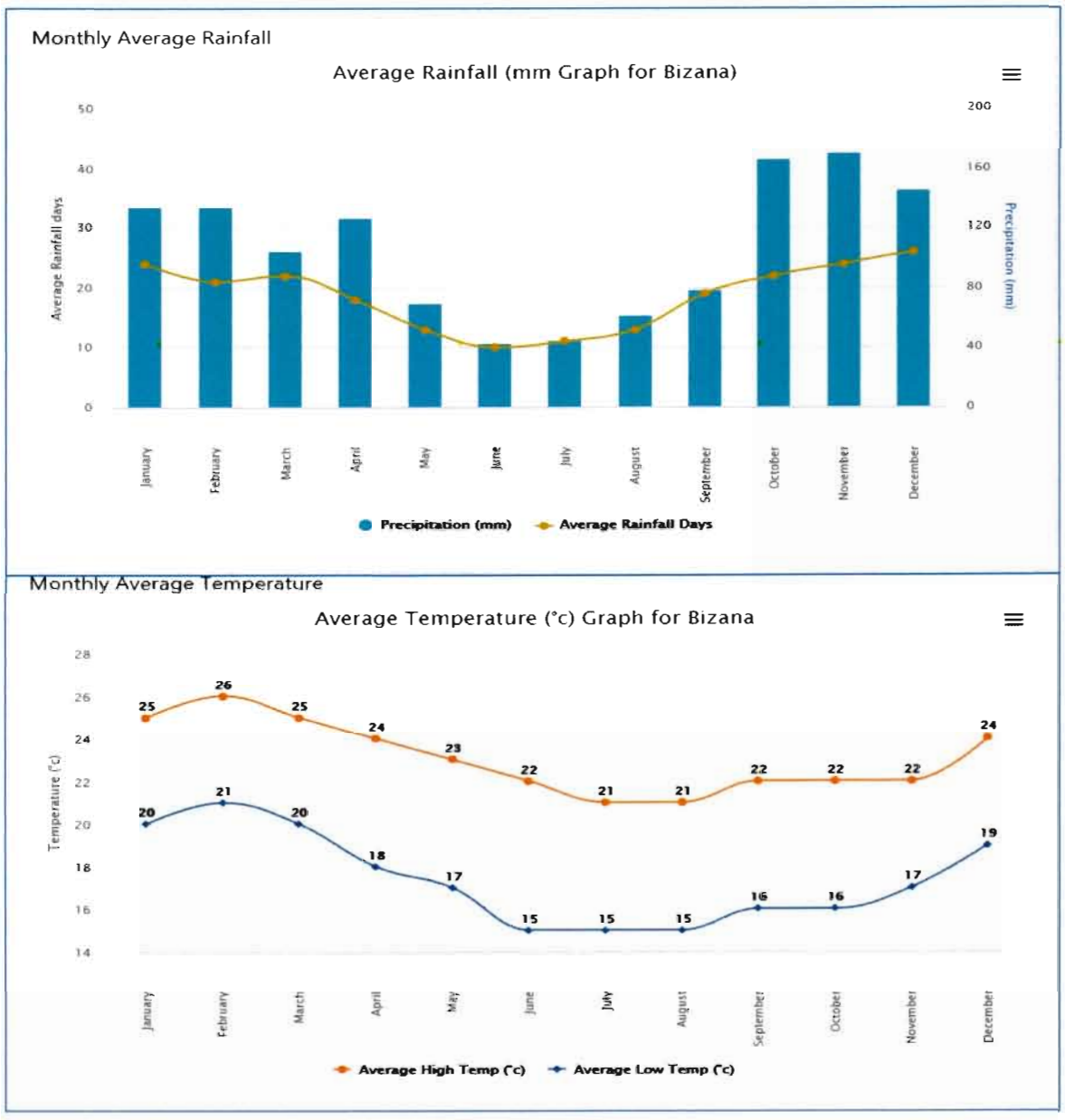


Figure 2.2: Climate condition on the area of study (World Weather Online, 2021)

2.3 Demography

The demographic data which includes population or household size, gender, education, employment and household services was gathered in order to provide a socio-economic background description of the study area. The basic demographic data obtained from Mbizana local municipality and Alfred Nzo district municipality's archive (Mbizana local municipality IDP, 2020) is presented in table 2.2. The data reveals that very low levels of in-dwelling piped water supply and waterborne sanitation.

Table 2.2: Mbizana area general demographics (Mbizana local municipality IDP, 2020)

Household Dynamics	Year 2011	Year 2016
Number of Households	48 447	61 383
Average household size	5.0	5.8
Female headed households	61.7%	60.2%
Formal dwellings	43.7%	40.5%
Education (aged 20 +)		
No schooling	19.4%	12.4%
Matric	13.0%	16.1%
Higher education	4.8%	4.8%
Unemployment status	44%	44%
Household Services		
Flush toilet connected to sewerage	1.1%	1.2%
Piped water inside dwelling	2.3%	0.6%
Electricity for lighting	60.0%	71.8%

2.4 Water supply

The study area falls within uMzimvubu to Tsitsikamma Water Management Area (WMA) on the far east of the rural Eastern Cape Province (NWRS, 2012) and the water service provider in the area is Alfred Nzo District Municipality. An overview of the general water provision status in the selected study area within Mbizana Local Municipality is shown in figure 2.3.

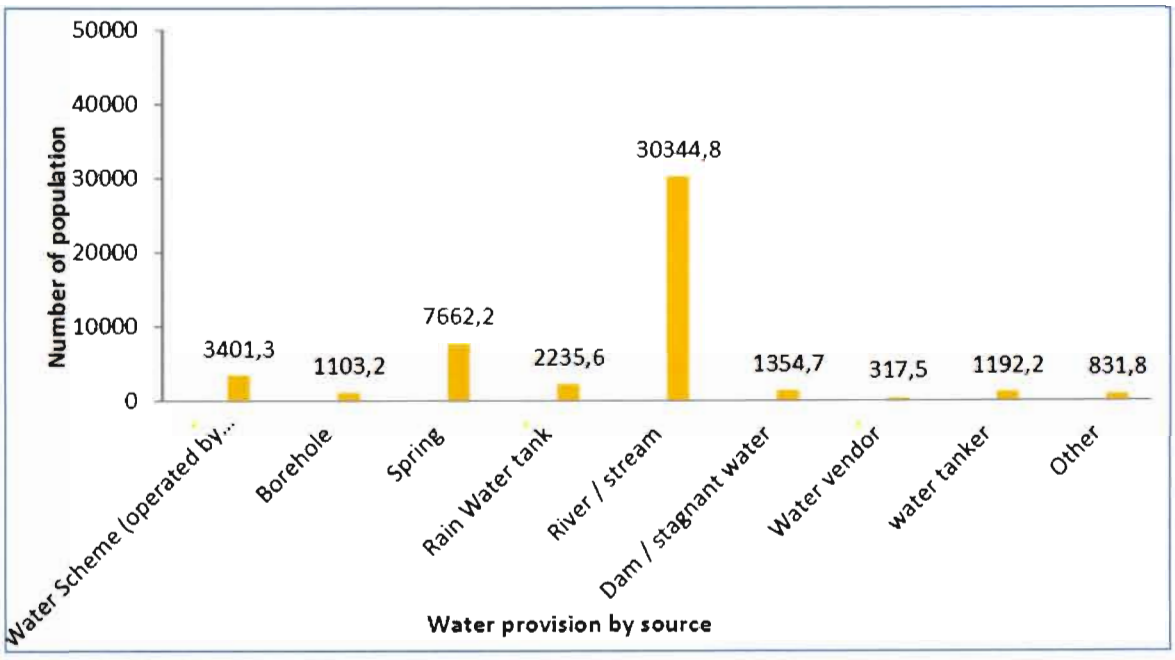


Figure 2.3: Water services status in Mbizana Local Municipality (Mbizana local municipality IDP, 2020)

Some of the villages in Mbizana Local Municipality including part of the selected area of study are equipped with aged and vandalised municipal water distribution systems. The level of service (LOS) in the system particularly in areas that are provided with the municipal water supply system seems to be below minimum water supply level of service (LOS 1) which is described as the rural development programme (RDP) standards (CSIR, 2005). As a result, some people walk for more than 500m to get to the closest standpipe/tap if there is water at all available in the municipal supply system.

Groundwater abstraction using boreholes is the primary source of water for domestic use in parts of the selected study area, but the reliability of supply is low at times, particularly in dry seasons. The communities in the areas of eZizityaneni and kwaNdela therefore do not have an effective, sustainable and highly reliable water supply system.

Given the high rainfall recorded in the selected area of study, some degree of RWH-based water supply system has been implemented in many households, schools, churches, community halls, and clinics.

2.5 Water use

Water in the study area is primarily confined to domestic use which is normally defined as in-house water use (Ratnayaka *et al.*, 2000). In-house water use is for drinking, cooking, sanitation, cleaning and laundry. As illustrated in figure 2.4, the level of waterborne sanitation is very low, and a negligible proportion of the water supply is used for sanitation.

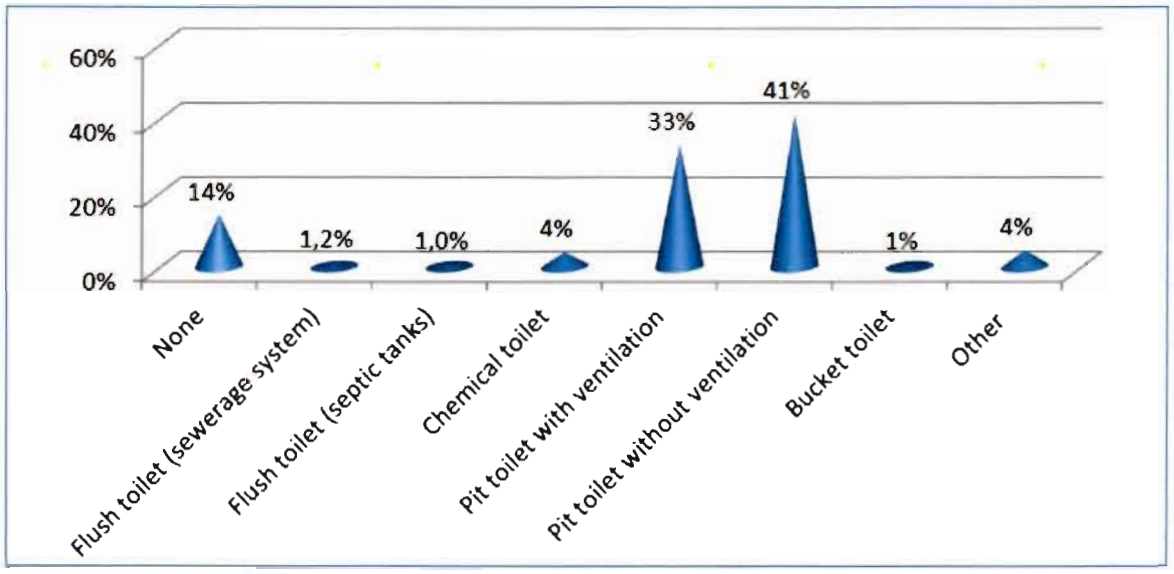


Figure 2.4: Sanitation infrastructure status in Mbizana Local Municipality (Mbizana local municipality IDP, 2020)

Use of water for agricultural activities is negligible in the area of study. Agricultural activities are primarily seasonal rain fed and thus generally undertaken from the month of September to the month of April. It is also evident that the high rainfall in the area provides sufficient water for maize production which is the most dominant agricultural activity in the area.

3. LITERATURE REVIEW

3.1 Introduction

In consideration of the aims and objectives of this study, this chapter provides a review of several aspects of Rainwater Harvesting (RWH) including: RWH system configuration, the roles and advantages of RWH, extent of RWH implementation in South Africa, related legislation and the hydrological analysis for RWH. The hydrological analysis includes water demand estimation, the assessment of RWH system performance and determination of storage size. The chapter also includes a review of RWH life cycle cost analysis.

3.2 Basic Components of a Rainwater Harvesting System

The main components of a typical rooftop RWH system are shown in figure 3.1. The system consists of catchment, conveyance, storage and distribution and could also include a purification system (Al-Batsh *et al.*, 2019). The catchment or surface area is normally a rooftop of a building made of an impermeable material. The conveyance system normally consists of gutters and downspouts that collect rainwater from the roof and convey it to a storage facility. The conveyance often includes first flush diverters and leaf screens to alleviate deterioration of water quality and to ease rainwater delivery to storage.

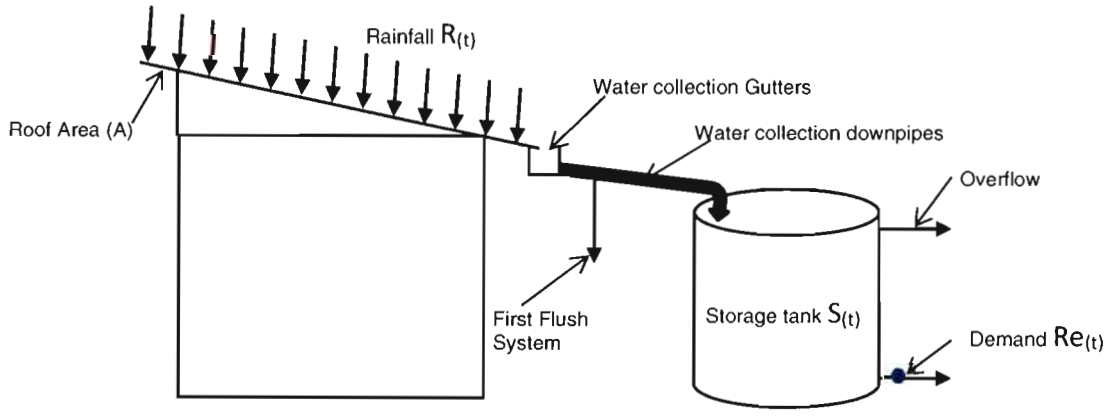


Figure 3.1: Typical Rainwater Harvesting system

3.3 Roles and Advantages of Rainwater Harvesting

RWH implies the collection, storage and use of rainwater for both domestic and agricultural purposes (O Brien, 2014). It is a convenient water source which can be implemented and

operated with limited technical skills. It is one of the set-ups that also promotes responsibility of operation and maintenance to the water user. Increased rainwater harvesting system is also recognised as one of the adaptation measures to climate change (Kundzewicz *et al.*, 2007; Goulden *et al.*, 2009).

Internationally, household rainwater tanks are among the most broadly used water supply alternatives when implementing a variety of water development strategies (O Brien, 2014). A number of countries encourage the use of these systems, either through government subsidies or by introduction of laws, which make the application of such systems mandatory (O Brien, 2014). The escalating global demand on finite water resources is of great concern and is likely to constrain future economic growth and development (Ndiritu *et al.*, 2017).

Rainwater harvesting is a renewable resource, and its environmental impact is minimal, it generally does not require any form of major treatment. In most instances, it is designed to be gravity-driven thus requiring no external energy for its abstraction and conveyance. Materials and spare parts for installing RWH are in most cases locally available. There are financial constraints in the implementation of the system particularly when the system is installed by households, as the storage facility involves a relatively high investment cost. Even in areas with reliable access to the municipal water distribution, the presence of RWH could still be beneficial as it could significantly lower the required municipal system demand (O Brien, 2014).

The installation of RWH system is sometimes due to the unreliable water supply from the municipal distribution system (O Brien, 2014). RWH can potentially support domestic water supply in almost any place either as a sole source or by reducing stress on other sources through water savings (Ojwang *et al.*, 2017)

The latest National Water Resources Strategy by the South African Department of Water and Sanitation (DWS, 2018) considers RWH as useful in improving the reliability of water supply in rural areas and in municipalities with unreliable water supply. Ndiritu *et al.* (2014) analyzed the rainwater harvesting potential on 32 schools in South Africa and found that, in every year, between 42 and 132 days of the daily school demand could be provided at a statistical reliability of 90%.

3.4 Degree of Rainwater Harvesting in South Africa

DWAF (2013) indicated that in South Africa, RWH system is given credence as a valuable water source and indicated that over 45 000 rural households in South Africa use rooftop rainwater harvesting as the main source of drinking water. Nationally a 10% reduction of bulk water supply has been noticed since the implementation of RWH system project in urban areas for 500 low-income households (DWAF, 2013). Allen (2012), indicated that the use of RWH in the South African rural areas is common and in some cases, RWH is relied upon as the primary source of domestic water. This applies mostly in the rural areas of Eastern Cape. Figure 3.2 informs that there were 224,865 water tanks used for primary water in South Africa (Mwenge Kahinda *et al.*, 2018). Out of these 36.8% are located in the Eastern Cape province, while 17.5% and 12% are located in the Western Cape and Kwazulu Natal respectively.

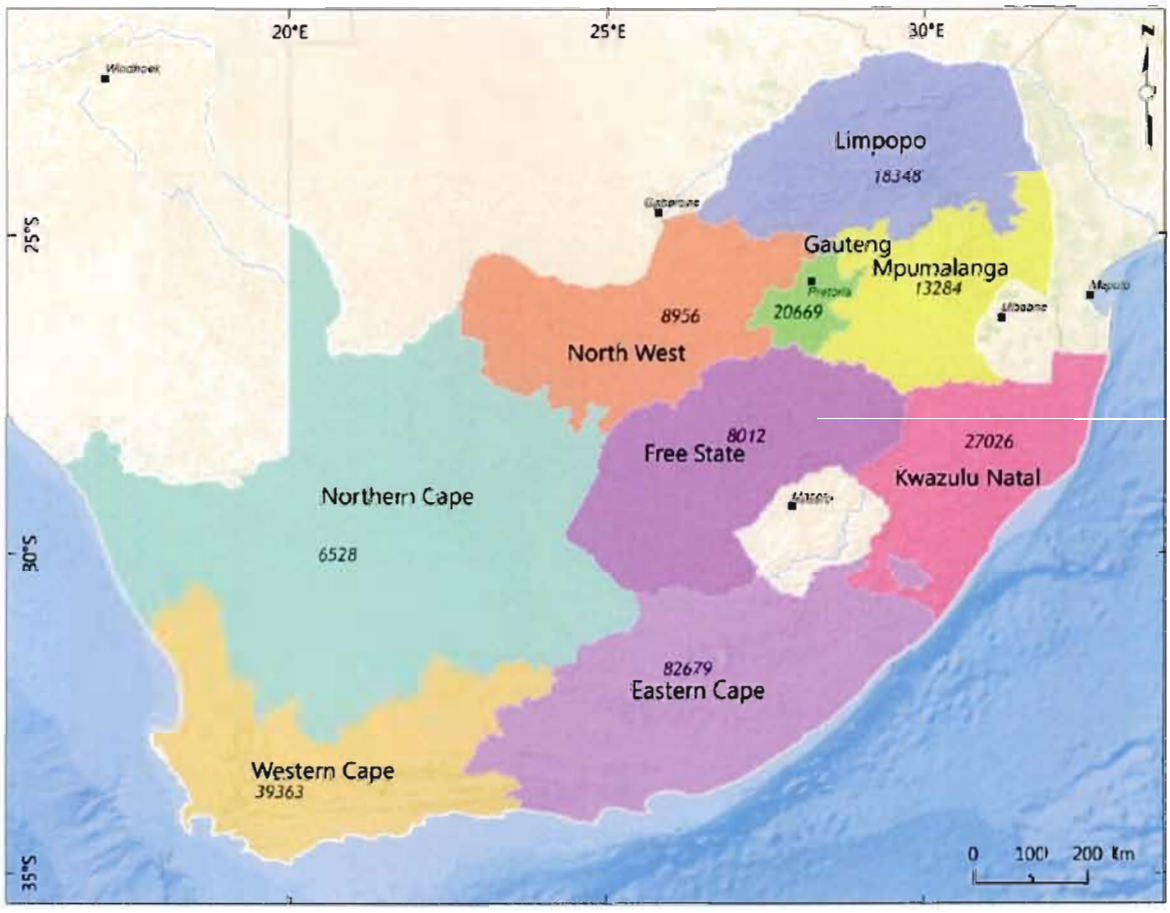


Figure 3.2: Distribution of RWH tanks, used as primary water sources in the nine provinces of South Africa (Mwenge Kahinda et al., 2018)

The higher proportions of RWH tanks in the Eastern Cape and Kwazulu Natal are indeed in alignment with the higher rainfall that occurs in provinces located in the eastern coast of South Africa. It is however likely that RWH could still be enhanced in these regions if RWH potential was systematically assessed and incorporated for implementation in the South African National Water Resource Strategy.

3.5 Challenges to Rainwater Harvesting

The common challenges in RWH system include financial constraints and the quality of harvested rainwater in storage. Mwenge Kahinda and Taigbenu, (2011), indicated that inadequate financial support and lack of national coordination are some of the prominent challenges that limit the effective implementation of RWH in South Africa. The study further informed that opportunities then lie with the government buy-in to facilitate financial support and maximise national co-ordination of RWH. It is also apparent from the on-site experience during physical visits that one of the biggest challenges is poor maintenance and misalignment and damage of conveyance features including gutters and downpipes.

Although Sazakli *et al.* (2007) informed that rainwater collected through the rooftops generally meets the international drinking water quality standards, several studies in South Africa indicate that water quality from RWH system does not meet the south African microbiological water quality standards (Reyneke et al., 2018; Dobrowsky et al. 2014; De Kwaadsteniet et al., 2013). Reyneke et al. (2018) found that solar pasteurization of the rainwater at a temperature of 66 °C achieved the water quality standards. This suggests that for financially constrained RWH users, boiling drinking water and water used to clean utensils could also be an effective approach of meeting the required rainwater quality standards.

3.6 Legislation relating to Rainwater Harvesting in South Africa

Allen (2012) indicated that legal provisions pertaining to RWH system in South Africa are contained in the National Water Act (NWA) (Act No 36 of 1998), with the Water Service Act (WSA) (Act No 108 of 1997). However, the WSA provides limited information regarding the legal aspects of implementing RWH. Allen (2012) further indicated that NWA states that any "abstraction or taking of water from a resource" requires a licence unless stipulated in section 22 of the Act. Allen (2012) thereafter explained that Section 22 of the Act does allow the user to specifically store and use runoff water from the rooftop. Through this study, it is therefore

clear that rooftop RWH does not necessarily require any water use licence application (WULA), as collection of rainwater from the user's own rooftop is deemed to be legal in South Africa.

O Brien (2014) also agreed with Allen (2012) on what has been alluded to above, suggesting that "it is clear from section 22 of the NWA that taking water directly from any water resource to which that person has lawful access for domestic use is deemed legal, with no licence required". Furthermore, he indicated that from this, it can be deduced that runoff water from the roof, which is stored in a tank, would fall within this category. It is therefore apparent that the use of rainwater within your legally owned property can be deemed legal in South Africa and would not need a WULA. It should however be acknowledged that studies done by O Brien (2014) and Allen (2012) are both grey literature.

It is however notable that Mwenge-Kahinda and Taigbenu (2011), who studied RWH more broadly (than rooftop-based harvesting) found that "*Although Section 3 of Chapter 1 of the WSA states that rainwater can be harvested to provide water for basic needs, strict interpretation of Section 6 (1) requires users of rooftop RWH systems in urban and peri-urban areas to get the approval of their service provider.*" Their study further found water-related legislation as one of the factors constraining RWH implementation in South Africa.

3.7 Water Demand Estimation

CSIR (2005) presented a guideline for estimating domestic water consumption based on typical water supply type or level of service (LOS) and type of development in a specific area. Water supply types range from a standpipe 200m walking distance, which translate to LOS 1, to a house connection in developed areas, which equates to LOS 4. The relevant water supply type for the selected study areas is considered to be LOS 1 which is the absolute minimum that should by all possible means be achieved. CSIR (2005) further presented a guideline for estimating water consumption based on stand area. However, this is limited to stand areas that are 2000m^2 and less. The typical water consumption as per CSIR (2005) for LOS 1 or standpipes is 25 l/c/d although it remains unclear as to how this was determined. Furthermore, estimating water consumption based on stand area is not applicable in most rural areas given that stand sizes are almost always larger than 2000m^2.

Van Zyl *et al.* (2008), presented an improved area-based guideline for domestic water demand estimation that was primarily meant to cater for stand areas that are 2000m^2 or larger. They further indicated that their estimated daily water demand compared well with those by CSIR (2005) except for stand larger than 2000m^2. They indicated that the per capita per day water demand estimation was based on historical flow meter recorded data received from relevant municipalities. The guidelines by Van Zyl *et al.*, (2008) are relevant for estimating daily water consumption in the rural areas as they are applicable for stand sizes of up to 3500 m^2.

DWAF (2004) presented a technical guideline document for estimating water consumption which does not take into cognisance water supply type nor stand size but gave an estimated maximum daily water consumption of 60 l/c/d to all referred infrastructure components. The guideline document (DWAF, 2004) further informs about an estimated 25 l/c/d for supply from restricted groundwater sources and states that "a minimum water requirement to ensure a healthy lifestyle is 25 l/capita/day". Once again it is not clearly indicated how these demand rates were obtained.

Tsihrintzis and Baltas (2013) suggested a minimum daily consumption of 20 l/capita/day but did also not inform how this consumption rate was obtained. Ghisi and de Oliveira (2007) studied the water consumption from two houses in a developed area with proper plumbing fixtures over a 28-day period and found daily water consumption ranging from 20 to 120 l/capita/day.

Al Zayed *et al.* (2018) indicated that water demand for domestic use varied from 10 to 122 litres/capita/day for drinking and for full sanitation supply, respectively. Once more, the basis of these daily water demands was not clearly specified.

3.8 Determination of storage size, yield and reliability of supply

The effectiveness of any RWH system can be quantified by the quantity of water it is supplying (yield) and the reliability (assurance) of this yield (Ndiritu, 2021). This effectiveness is highly dependent on the storage capacity and hydrological RWH analysis often involves the determination of storage size for a specified yield and assurance of supply. As Ndiritu (2021) informs, hydrologic RWH analysis may involve statistical reliability using stochastically generated rainfall or the single historic rainfall time series. Methods that do not incorporate statistical reliability are however also commonly applied. It is important to note that the

commonly used RWH performance measures volumetric reliability, which is the proportion of demand that is met as a proportion of the total demand over the simulation period, only provides an average measure of system performance and not how this performance will be impacted by the variability of rainfall. For regions like South Africa that experience high variability occasioned by multi-annual drought periods, statistical reliability that incorporates this variability into the assessment of RWH performance is imperative.

Ndiritu (2021) describes a daily time step RWH simulation (Equation 3-1) for relating storage capacity, yield and reliability for a given demand, rainfall time series and roof area.

$$S_{(t+1)} = S_{(t)} + \eta\, R_{(t)}A - Re_{(t)} \qquad (3\text{-}1)$$

$$0 \leq S_{(t+1)} \leq C$$

Where $S_{(t)}$ is the volume of water in storage at the start of period t, η is the rainwater collection efficiencies, $R_{(t)}$ is the rainfall intensity in the period t, A is the effective roof area and $Re_{(t)}$ is the volume of water released to meet the demand in period t and C is the assumed storage capacity. Equation 3.1 assumes a lumped rainwater collection efficiency η that caters for all the losses but the model could be easily modified to include the individual water losses (splashing, first flush, etc) explicitly, or although the simulation can be used to obtain a single yield (volumetric reliability) over the simulation period, it also outputs a time series of the yields (levels of supply) within each year that can be analysed statistically to provide a yield -reliability relationship for the assumed storage C. This could be done by obtaining the exceedance probability of annual levels of supply computed using commonly used approaches such as the Weibull plotting position formula (Makkonen, 2006) presented as equation 3-2 below.

$$P = m/(n+1) \qquad (3\text{-}2)$$

Where P is the exceedance probability (reliability) of the days of annual supply (yield) ranked m, and n is the total number of years of simulation.

The capacity C can be varied iteratively to determine the desired yield and reliability or to find the range of yields and reliabilities that the RWH can achieve. Ndiritu (2021) informs how the approach could be applied using stochastically generated rainfall and Basinger *et al.* (2010) demonstrated how this could be done. Their study applied stochastic rainfall data and

simulation to develop generalized storage sizing charts presented in figure 3.3. These curves can be used to estimate the tank size required to provide 100 l/day with a "degree of security" varying from 80% to 99% in locations with 100–1200 mm of annual precipitation.

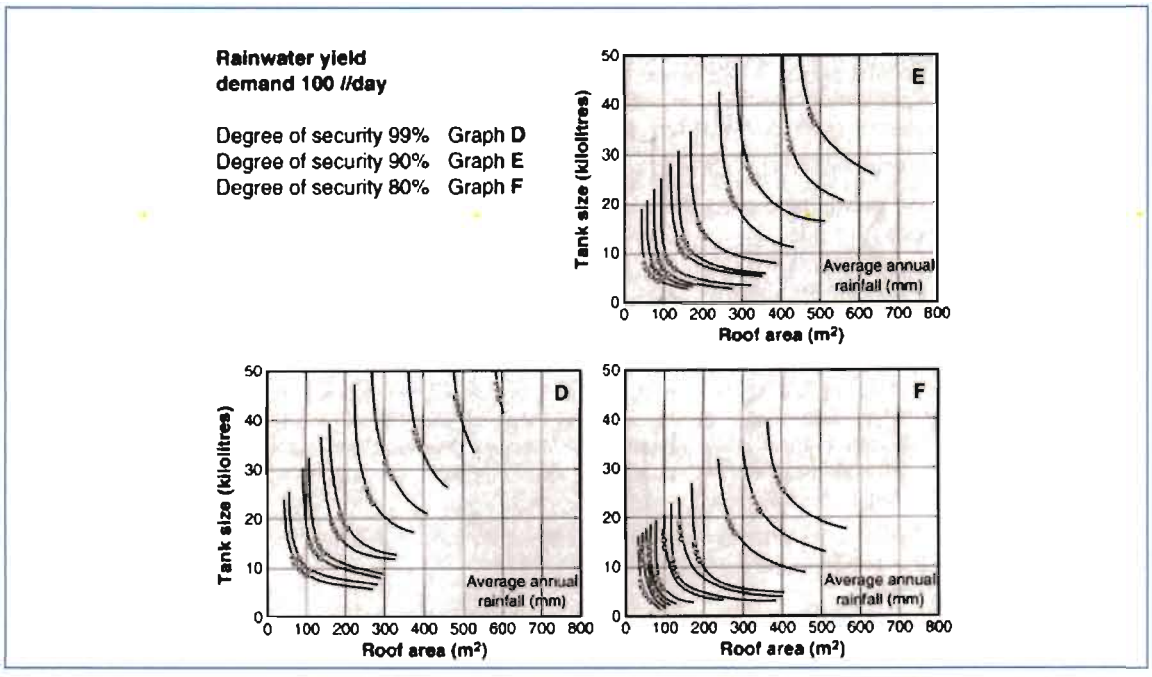


Figure 3 3: Simplified approach to sizing RWH systems using average annual rainfall Basinger et al., (2010)

Campisano *et al.* (2017) conducted a review of urban RWH systems and acknowledged that both rainfall and water demand are temporally variable and that RWH evaluation models are frequently used as a design tool to calculate the volume of storage required to balance these inflows and outflows. Campisano *et al.* (2017) informed that storage sizing design approaches include methods based on empirical relationships (Ghisi, 2010; Palla *et al.*, 2011), methods based on stochastic analysis (Cowden *et al.*, 2008; Basinger *et al.*, 2010) as well as continuous mass balance simulation of the tank inflows and outflows (Fewkes and Butler, 2000; Campisano and Modica, 2012; Sample and Liu, 2014). The review however revealed that most of the recent RWH analysis tools are based on continuous behaviour simulation using historic rainfall. Ndiritu *et al.* (2017) applied this approach to develop a generalized model of dimensionless relationships relating rainwater supply and demand to storage capacity, yield and reliability for shopping centre RWH systems.

Modelling accuracy can be improved by running simulations at reduced time step analysis especially where the specific rainfall datasets are available (Ward *et al.*, 2012) and Ndiritu et

al. (2011) demonstrated the significant differences obtained from RWH simulations based at a daily and a monthly time step. The accuracy of the results is also affected by the length of the available precipitation series and Mitchell (2007) reported that a 30-year long series should provide statistically reliable results.

Among the simpler methods of relating RWH storage to yield are those based on the demand for a set period, those based on the volume of rainwater that could be supplied for a set period, and those based on both demand and supply.

Tsihrintzis and Baltas (2013) proposed that storage tank be sized based on minimum daily water consumption per capita of 20 litres/day, assuming a dry period of four months in a year. The storage capacity is then expressed as.

$$S = \left(\frac{4}{12}\right) \text{AWD} \tag{3-3}$$

Where S is the storage volume and AWD is the annual Water demand

Tsihrintzis and Baltas (2013) further informed that in UK, one of their codes of practice states that the capacity of RWH tank must at least be 5% of the annual rainfall yield or 5% of the annual rainwater demand. The annual rainfall yield computed as shown in equation 3-4:

$$\text{ARY} = \eta \text{PA} \tag{3-4}$$

Where ARY is the annual rainfall yield, η is the rainwater collection efficiency (between 0,8 to 0,9), P is the mean annual rainfall depth, A is rainfall collection area.

The storage required is then obtained as:

$$S = 5\% \text{ x ARY}, \tag{3-5}$$

where S is storage tank size

Allen and Haarhoff (2015), presented three methods of sizing which are, a demand side approach, a supply side approach and a combination of both supply and demand approaches. The combination of supply and demand side approach determines water supply and water demand and thereafter applies the lesser of the two to determine storage. The supply side approach applies equation 3-6 to determine the storage size.

$$S = P\ A \times \eta \times F \times MAP \quad (3\text{-}6)$$

Where: S is storage tank size, P is the user-defined percentage, A is the catchment area, η is the runoff co-efficient factor or rainwater collection efficiency, F is the system filter efficiency and MAP is the mean annual rainfall. For a demand side approach, the MAP on equation 3-6 is replaced by the annual demand (D). Allen and Haarhoff, (2015) further stated that the required size of storage is also influenced by the area of catchment, water demand, and the desired certainty of supply.

Londra *et al*. (2015) applied two methods; the daily water balance method and the dry period demand method, to determine the size of rainwater tanks in most regions of Greece to meet 30% to 50% of total water demands on households of 3 to 5 residents. The daily water balance method was developed based on a heuristic algorithm which uses daily rainfall data, the rainfall collection area, runoff coefficient, storage volume available, water demand and an allowance for spillage. The study found that the tank size is influenced by a variety of environmental conditions which differ among regions, but the dry period length is the one that is most influential. A shorter dry period leads to a reduction in the required tank size.

3.9 Life Cycle Cost Analysis (LCCA)

Batchelor *et al*. (2011) defined Life Cycle Costs Analysis (LCCA) as the aggregate costs of ensuring sustainable and equitable delivery of a certain level of water supply services to an individual household or towards a population of a specified area. It includes a capital design and construction cost and the cost of operation and maintenance of the RWH system for the given life span of the system. Batchelor *et al*. (2011) also indicate that the sustainable water supply services through the system of RWH and its value for money can only be achieved if all the components of the water delivery system are financed properly. They also inform that LCCA aims to increase the ability and willingness of decision makers, both end-users and those involved in service planning, budgeting and delivery, to make financially informed decisions.

Gao *et al*. (2014) stated that financial viability of RWH should be illustrated by life-cycle cost analysis (LCCA) that considers local conditions such as annual rainfall levels, configuration of buildings, typical water demands of a building and local water price.

Gabe *et al.* (2012) found the annual cost of RWH system in New Zealand's urban areas to be lower than that of the traditional water supply system with the only cost to RWH being the electricity used to pump the water. Gabe *et al.* (2012) however did not include capital costs in their analysis.

Farreny *et al.* (2011) demonstrated that the cost-efficiency of existing rainwater harvesting strategies may not be worthwhile in dry areas of Spain or areas where the water price is still low. Gao *et al.* (2014) stated that RWH systems are financially valuable if the catchment area is larger than 900m^2 in Hong Kong and found a payback period of 6 years in both scenarios for buildings with few and a high number of stories.

The RWH review by Campisano *et al.* (2017) revealed a wide range of payback periods from LCCA conducted for RWH systems in various regions; 10 years in Sydney, 15-21 years in Melbourne, and 33-60 years in Barcelona, and 6-11 years in the UK. These long payback periods mostly suggest poor financial viability. The subsidised municipal water supply cost applied in RWH's LCCA could however be contributing significantly to the long payback periods of RWH (Ndiritu *et al.*, 2017).

Hajani and Rahman, (2014) analysed the financial viability of RWH using a concept of nominal cost and a nominal discount rate. They used equation 3-7 to convert a nominal cost (CN) to a discounted cost (Cd)

$$Cd = Cn \left(\frac{1}{(1+dn)^y}\right) \quad (3\text{-}7)$$

Where d_n is the nominal discount rate per annum and y is the appropriate number of years. Hajani and Rahman (2014) presented LCCA results in terms of benefit-cost-ratio as opposed to payback period. Therefore, their financial analysis is not easily comparable with the rest of the studies above which presented their LCCA in the form of payback period. They found RWH as financially unattractive without specifying the payback period.

Roebuck and Ashley, (2007) undertook simulation analysis using a computer-based modelling software titled RainCycle @, which is based on mass balance principles implemented in an excel spreadsheet. It carries out financial simulation of RWH Systems (RWH) considering total capital

cost, operation and maintenance cost, nominal cost and nominal discounted rate. It also does financial modelling of mains water supply system using cost of water supply. Mains water supply in South African context is referred to as municipal water distribution. The analysis compared results from the municipal water distribution system and RWH system. The lifespan of 65 years and discount rate of 3.5% were used for their financial simulation and a payback period of 17 years was reported from RWH system financial simulation which was considered an indication that RWH is not financially viable.

Leong et al., (2019) undertook financial viability analysis using equation (3-8)

$$LCCi = Cn + \sum_{t+1}^{t} \left(\frac{OCi,t}{(1+dn)^t}\right) \quad (3\text{-}8)$$

Where LCC_i is the life circle cost of system (i), Cn is the initial installed cost of system (i), OC_i is the operation and maintenance costs of system (i) for year t after installation and t is the duration.

The difference with this equation from equation 3-7 used by Hajani and Rahman (2014) is that it incorporates a component of operation and maintenance costs. The lifespan of 50 years and a discount rate of 6% were used for their financial viability analysis. RWH for domestic building was found not financially attractive as it obtained a negative net present value (NPV) and a payback period of 17 years. Their study further revealed that RWH system is economically viable for multi-storey buildings with a payback period of 8 years. Subsidised water tariff was used in life cycle cost analyses for municipal water supply and the results from these studies reveal that RWH is generally not economically viable in most instances but could be in some cases.

3.10 Summary

The typical components of rooftop-based RWH systems have been described and RWH with several advantages of RWH systems including ease of operation and use in enhancing water supply in rural areas and municipalities with unreliable water supply was highlighted. The review however indicated that RWH in South Africa needs treatment to achieve the required microbiological water quality standards and that financial limitations pose constraints to the

implementation of RWH in South Africa. The review showed that the South African legislation generally allow household RWH.

A review of water demand estimation indicated a common approach, where a daily water consumption per capita would be sourced from relevant guidelines. Water demand estimation has also been undertaken through field measurement in some studies. Large variations in the per capita water demand estimates were revealed and it is therefore considered suitable for field measurements to be included in the current study as the review did not inform of any such field measurements in the rural areas of South Africa and the Eastern Cape in particular.

A review on storage tank sizing and assessment of RWH performance indicated that various methods are used and that these are mainly based on mass balance principles with varying levels of simplifying assumptions. Based on the review, daily time step simulation using both daily rainfall and daily demand data in a manner that includes statistical reliability is the preferred method for this study as it makes the least assumptions and enables a realistic assessment of assurance of supply in the face of the large temporal variability of rainfall experienced in South Africa.

The literature review revealed that the financial viability of RWH is generally low, although this could partly be as a result of prevalent practice of subsidising centralized water supply costs, particularly for the indigent communities including the two selected communities in the study area. The review shows that financial performance is highly varied and depends on the hydrological aspects, the water price and the discount rates, and RWH system configuration. Most studies reviewed generally conclude that RWH supply is not financially attractive although this could be partly attributed to the highly subsidised prices for centralised water supply.

4. MATERIALS AND METHODS

4.1 Overview

This section presents the methodology adopted in achieving the research objectives and therefore activities carried out to answer the research questions. This includes the selection of representative RWH systems for the area, the collection of data and other relevant information for each of these systems, and the modelling and analysis aimed at achieving the study objectives. Given the large variability of water consumption rates found in the literature (Section 3.7) it was decided to carry out field measurements of actual water consumption for the selected RWH systems.

Mechanical water meters were used for these measurements. It was also decided to collect data that would enable the estimation of the RWH collection efficiencies of the RWH systems although RWH collection efficiencies from the literature could have been adopted. This included rainfall data; the storage water levels and the catchment (roof) areas. This chapter also informs about the acquisition of desktop data required for the study.

The rainfall measurements over the study period were inadequate for assessment of the expected RWH potential over the expected life-times of the systems and long rainfall records close to the study area were therefore required. The method of modelling and analyses for determination of RWH efficiency, the RWH potential and for LCCA are also discussed in this chapter.

4.2 Selection of representative RWH Systems

Given the financial and time constraints of the study, representative water users within the selected communities needed to be identified for the study. Based on the understanding that the main water demands in the communities are domestic and public facility use, the researcher visited several water users within the selected communities in order to find suitable representative water users that would allow collection of the required data and secure the data collection set-ups and equipment. Following this process, 3 households, a school and a clinic were selected. Some pertinent details about the selected water users are as follows.

i) Two households (denoted as household 1 and 2), had operating RWH-based water supply systems, each with one access point for domestic water from the storage tanks.

The two households had roof areas typical to those in the community. One household (denoted as household 3) had no RWH system and had municipal water supply to a level of yard connection and was selected to provide water consumption data for households with this level of service (LOS 3) of water supply. The respective household sizes were 9, 10 and 8 for households 1, 2 and 3.

ii) The school and the clinic had operating RWH-based water supply systems of a larger scale than the households. These systems had various access points for water supply from multiple storage tanks. The average daily number of attendants and staff in the clinic was 65 while the daily number of students and staff in the school was 1123.

4.3 Data collection protocol

4.3.1 Measurement of Water Consumption and Storage Water Levels

Water consumption was measured by the installed mechanical water meters at water supply outlets, while storage water levels of the RWH-based water supply systems were measured using manometers which were installed vertically at the outlet side of the individual storage tanks as illustrated in figure 4.1.

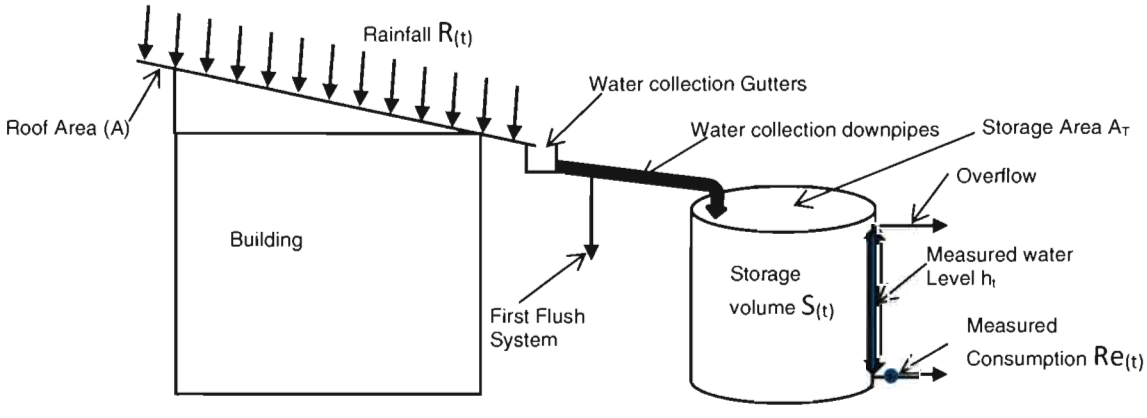


Figure 4.1: Typical RWH system in the identified water users

4.3.1.1 Installation of measuring devices and quality control of data collection

The researcher consulted with the individuals responsible and operating the selected facilities and constituted a data collection team. The team consisted of a student for data capturing at the school; a staff member at the clinic for data capturing from the clinic and three individual household members for data capturing from the three households.

A training workshop for the data collectors was conducted by the researcher to ensure accuracy and consistency in data capturing and recording in a clearly designed data collection form. In addition to capturing meter readings and water levels, the number of individuals from each water user per day was recorded. For the three homesteads, the individual data collectors were full-time members of the families who knew and recorded exactly the number of individuals contributing to daily water use.

One individual who developed interest in the whole exercise at early stages of the project, became involved in the entire conceptualisation and physical installation of the whole data monitoring and capturing system. He then also took responsibility to oversee the data collection by continuously interacting and visiting all data collectors at least once a week, on Fridays. The existing storage capacities and roof areas of the catchments for RWH systems were also measured during the phase of data collection. Water meter readings were captured and recorded daily at 17h00 hours from all the selected water users.

4.3.1.2 Water demand measurement using mechanical water meters

The water consumption data was collected through mechanical water flow meters which were installed on the outlet of each RWH storage tank as indicated in figures 4.2 to figure 4.10 for all 5 selected water users.

The first household (homestead 1) is situated in a section of the village where there is also municipal water supply system (standpipes) that could supply water if storage in the RWH tank is exhausted. The water supplied from the standpipe would however not be included in the installed measurement set up and needed to be excluded. For this, the researcher arranged to replenish water in the RWH storage tanks in bulk using water tankers. All the water used within the household was therefore measured by the installed water meters as seen in figure 4.2 and figure 4.3.

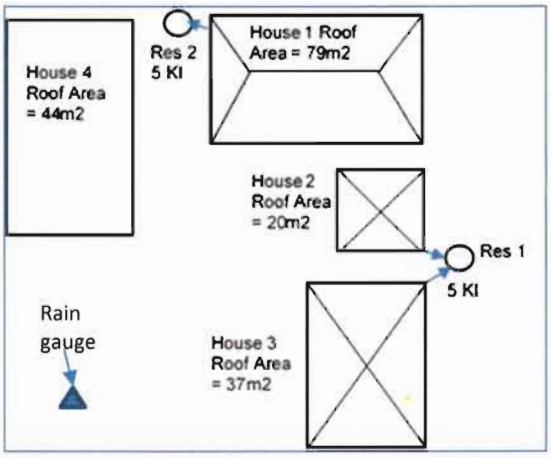


Figure 4.2: Schematic layout homestead 1

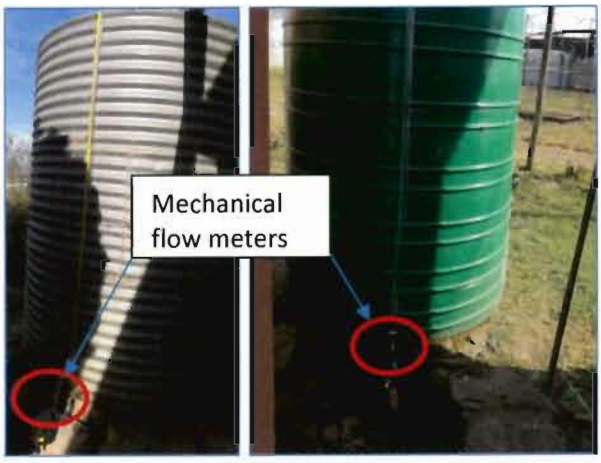


Figure 4.3: Water demand measured from flow meters homestead 1

The second household (homestead 2) is situated in a section of the village that was not subjected or served with any form of municipal water distribution system. In homestead 2, water was sourced from either RWH system or from the nearby watercourse, however during water consumption measurements water sourced from the nearby watercourse was minimal and therefore excluded from the measurements. The water consumption data was also collected through a mechanical flow meter which was installed on the outlet of each RWH storage tank as indicated in figure 4.4 which is a schematic layout of homestead 2 and figure 4.5.

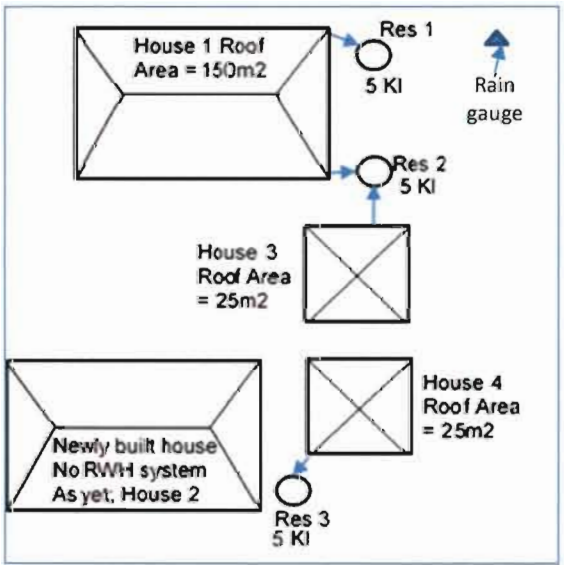


Figure 4.4: Schematic layout homestead 2



Figure 4.5: Water demand measured from flow meters homestead 2.

The third household (homestead 3) was supplied through a municipal water supply system at level 3 of service, which is a yard connection (CSIR, 2005). The source of potable water supply to this homestead is a newly constructed water treatment plant located within the village but meant to distribute water to the whole municipal area in the future. The water consumption data was captured and collected through a mechanical water flow meter which was installed on the outlet of the standpipe as indicated in figure 4.6.



Figure 4.6: Water demand measured from a flow meter homesteads 3.

Water consumption measurements were also done at the public school situated in the same section of the village as homestead 1. The school was also supplied by the municipal distribution system with yard connection. However, the level of reliability as reported by the school principal was relatively low. RWH was the system that primarily provided water to the school.

At the time of research, the school had RWH-based water supply system that was integrated with the municipal water supply system. The municipal water supply system delivers water to storage tanks from where it is distributed to standpipes within the school as indicated through the schematic layout in figure 4.7.

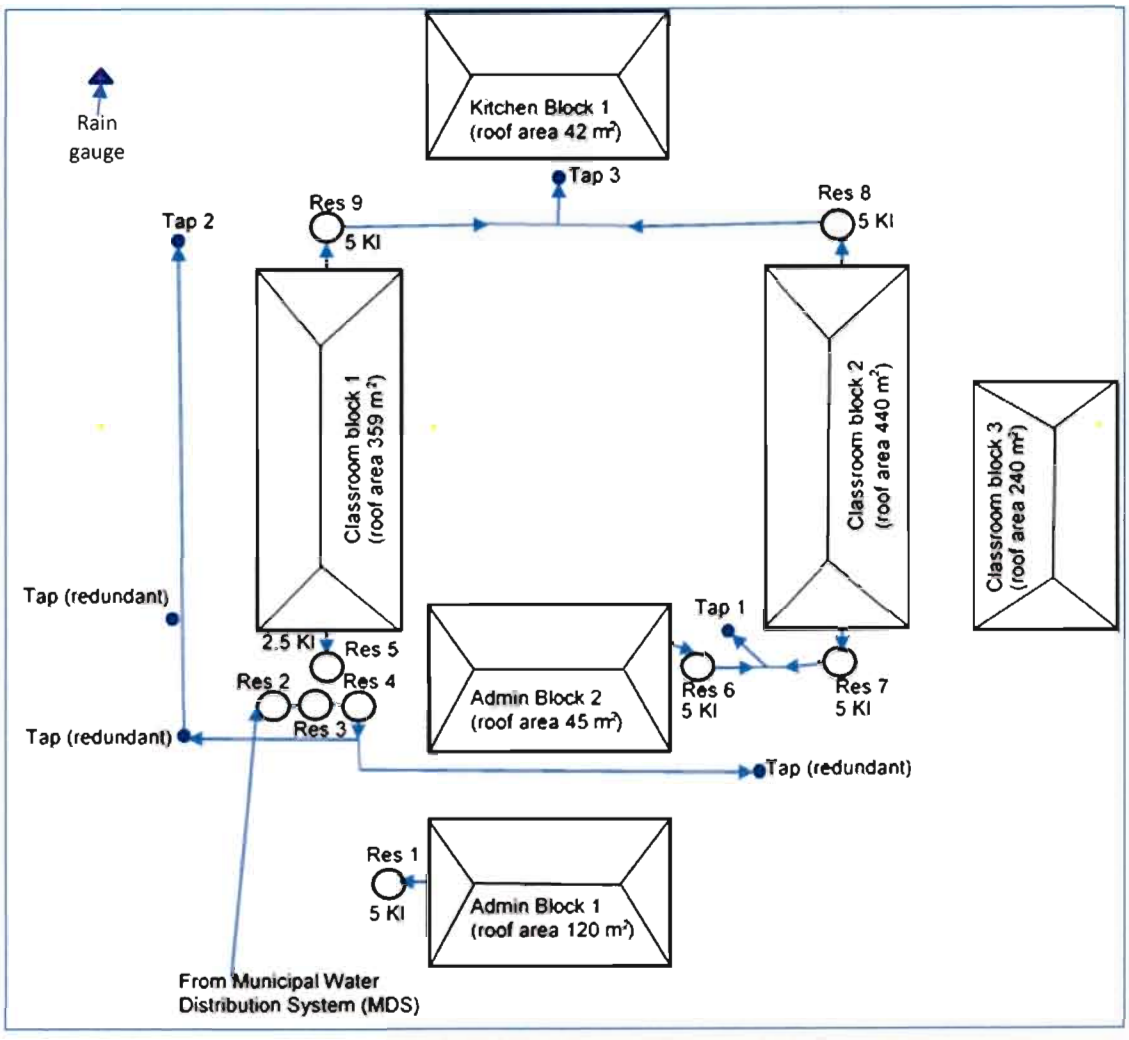


Figure 4.7: Schematic layout for the school's water supply and distribution.

The water consumption data was captured and collected from the mechanical water flow meters which were installed on the outlet of each standpipe (tap 1, 2 and 3) and each RWH storage tank as indicated in figure 4.7 and figure 4.8 which shows a typical measuring arrangement at the school. As figure 4.7 shows, the municipal water supply was measured by the water meter installed at Tap 2.



Figure 4.8: Water demand measured through flow meters at school.

The local clinic is situated in the same section of the village as homestead 2 where no municipal water supply exists. The water consumption data for the clinic was collected through mechanical flow meters which were installed on the outlet of each RWH storage tank as schematically indicated in figure 4.9 and visually in figure 4.10.

At the time of the study, there was also a non-functional borehole facility at the backyard of the clinic and water for the clinic was sourced from either the RWH system or through water tankers from the Municipality. This water would be delivered to RWH storage tanks prior to consumption. All the water consumed within the clinic was therefore measured by the installed water meters.

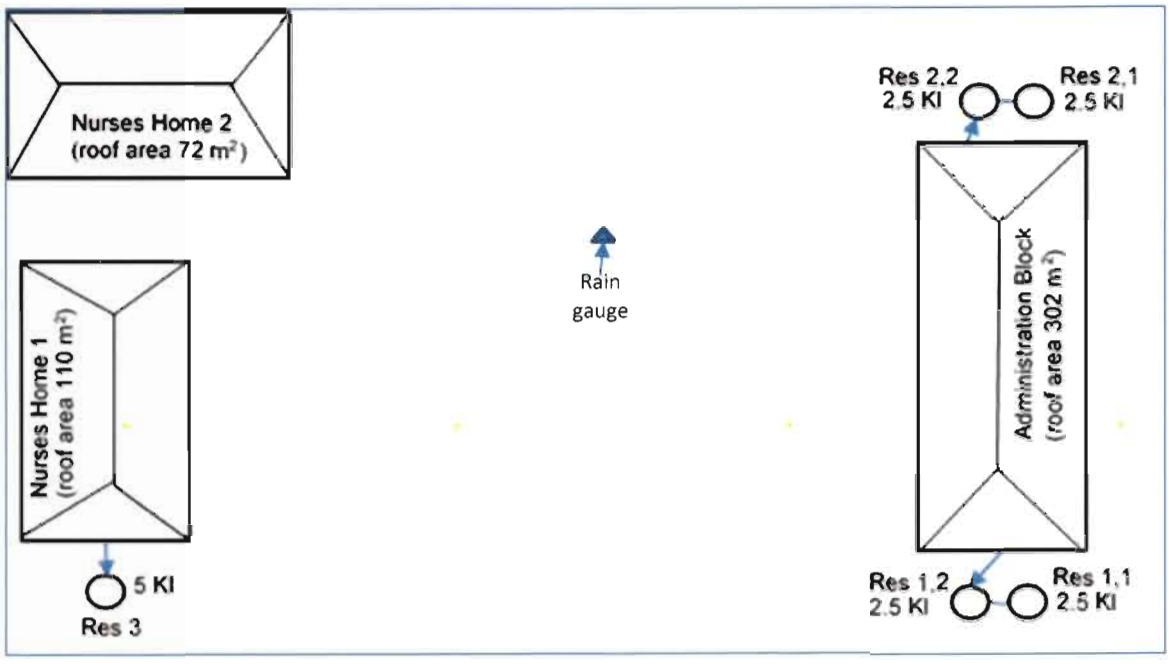


Figure 4.9: Schematic layout of RWH at the Clinic



Figure 4.10: Water demand measured from the flow meters at the clinic.

The study aimed to take daily water meter readings at 17h00 from each RWH storage tank or standpipe for all the individual water users continuously over a period of 12 months starting from July 2019 to end June 2020 to ensure that the range of water consumption across all seasons and periods was captured. This aim was however not accomplished due to several reasons some of which relate to the COVID-19 pandemic, mal-functioning of flowmeters and absence of a data collector at times as well as human error during data capturing.

4.3.1.3 Measurement of storage water levels

The water levels were measured from transparent plastic monometers and tape measures which were vertically installed in line with each RWH storage tank as seen in figure 4.11. The level of water in the storage tanks for each selected water user was therefore measured over a period of 12 months also starting from July 2019 to the end June 2020. The aim was to take these measurements daily at 17h00 hours but this was not achieved due various challenges that the study encountered as stated at the end of section 4.3.1.2. For the school, these measurements were confined to the tanks that were collecting rainwater and reservoirs 2, 3 and 4 on Figure 4.7 were therefore excluded from these measurements as they received water from the municipal water supply system. Reservoir 5 for the school was also excluded as it was in poor condition and not functional during the period of measurements.



Figure 4.11: Typical storage water level measurements.

4.3.1.4 Measurement of rainfall

Four graduated funnel rain gauges (RYOBI RRG-002) as seen in figures 4.2, 4.4, 4.7 and 4.9 were installed in different positions within the individual selected water users that had existing RWH systems. This enabled the rainfall which occurred much closer to the selected RWH systems to be measured in order to enable the determination of their individual rainwater water collection efficiencies.

4.3.2 Historic rainfall data acquisition

The assessment of the hydrological potential of RWH systems requires a time series of rainfall data and the quality of the assessment improves as the length of the record increases (O' Brien, 2014). In many regions of the world including South Africa, the availability of long and reliable rainfall records is a serious challenge (Pegram et al, 2016, Hughes et al, 2011). Given South Africa's land area of 1 219 602 km^2 (Government Communications, 2016) and the estimate of about 1200 active rain gauge stations in 2016, (Pegram et al, 2016), the average inter-rain gauge spacing in South Africa is about 31.8 km. Given this background, a practical approach to obtaining rainfall input for hydrological modelling is the use of the closest rain gauge with a long and reliable record (Schulze, 1995; Jewitt and Schulze, 1999). In a recent analysis of RWH for 8 Australian cities, data from a single representative rainfall station was applied for each city (Preeti and Rahman, 2021) while Snir and Friedler (2021) also applied data from a single rainfall station as the representative RWH rainfall input for a major urban center.

For this study, the same approach was adopted and historical rainfall data ranging from 1958 to 2018 was sourced directly from South African Weather Service (SAWS). The data was obtained from 6 rain gauge stations that were in the vicinity of the study area. The nearest rainfall gauge was located at Ndindindi area, that is about 17.9 km more inland on the northern side of the Eastern Cape Province from the study area (station no. 01811668). Another station is located at Fort Donald area approximately 22.5 km also more inland on the northern side of the Eastern Cape Province from the study area (station no. 01810731) while the rest of the stations are located further away from the study area as seen in figure 4.12.

As seen on Table 4.1, Station 1811668 located in Ndindindi area also has the longest rainfall duration data compared to other rainfall gauging stations with 88% of continuous rainfall data. Ndindindi station was therefore found to be the most suitable and preferred station for RWH analysis in the area of study.

It is also worth informing that since Ndindindi is located further inland in relation to the study area, the rainfall record at Ndindindi is more likely to be lower than that in the study area as Bailey and Pitman (2016) indicates that mean annual rainfall (MAR) increases towards the coastline in the area. The local community also concurs with this finding and using the selected

rainfall station is therefore unlikely to over-estimate RWH potential in the study area and is likely to include a safety margin that is common in engineering practice.

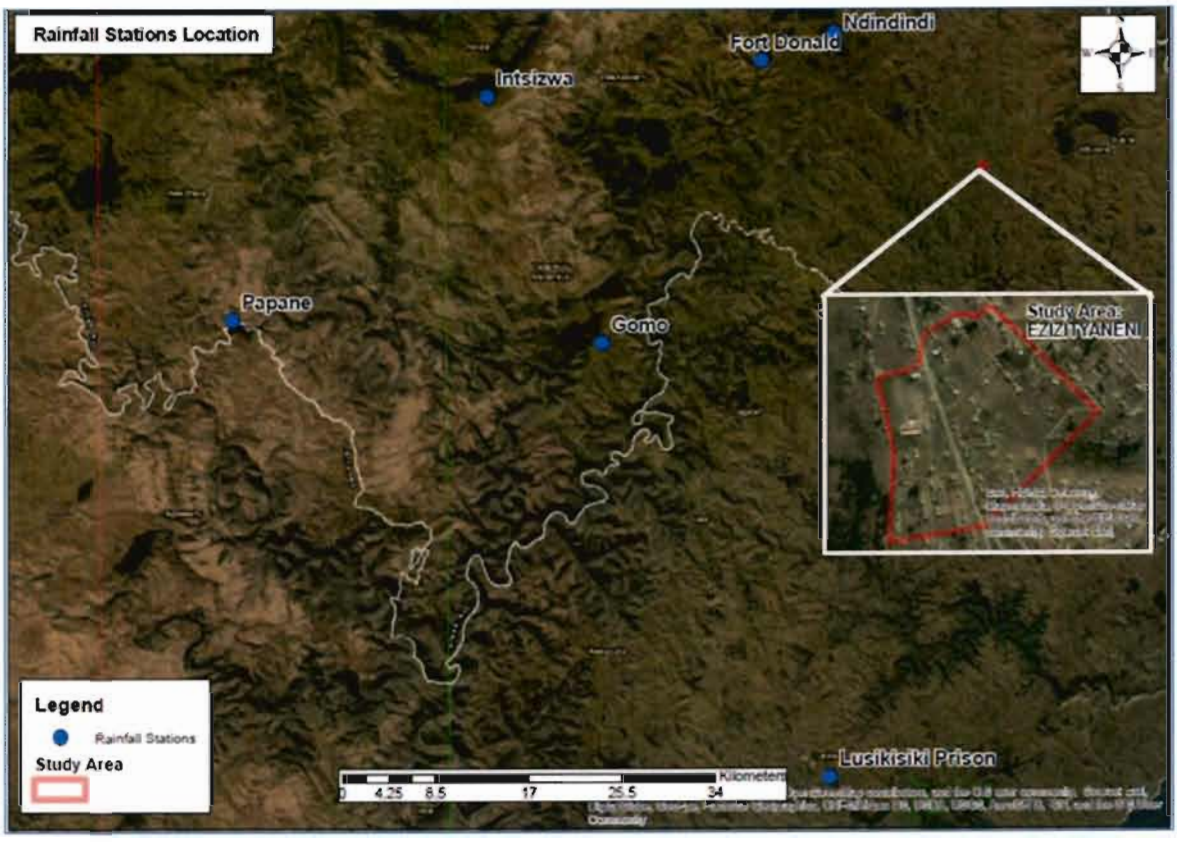


Figure 4.12: Rainfall gauge stations in the vicinity of the study area

Table 4.1: Information on historical rain gauge station data around the study area

Station number	Period of data (years)	% Cont. data	Latitude	Longitude	Area Name	Mean annual rainfall (mm yr^{-1})	Distance from the area of study (km)
1811668	1958-2019	88	-30.7680	29.5900	Ndindindi	1182	17.9
1810731	1958-2019	85	-30.7910	29.5210	Fort Donald	952	22.5
0180439X	1958-2019	68	-30.8200	29.2600	Intsizwa	901	45.7
1800300	1958-2019	65	-31.0020	29.0170	Papane	743	69.9
1536313	1958-2019	66	-31.0200	29.3700	Gomo	1080	37.8
0154143X	1996-2019	70	-31.3730	29.5890	Lusikisiki	904	57.2

4.4. Determination of the rainwater collection efficiencies of RWH systems

The rainwater collection efficiencies of selected RWH-based water supply systems were determined from the measured rainfall, water consumption and storage levels. In this study, there was no direct measurement of the inflow into storage, nor any measurement of spillage from the storage that could have enabled the determination of this inflow. Therefore, a direct

computation of rainwater collection efficiency as the ratio of the volume of inflow into the storage to the volume of rainfall could not be undertaken. Instead, an indirect approach akin to automatic model calibration that determined the runoff coefficients that matched the simulated storage water levels to the measured ones was applied. Using the illustration on figure 4.1 (Section 4.3.1 Page 37), the simulated volumes of water in storage at the start of period *t* and *t+1* can be expressed as:

$$S_{sim,t} = A_T h_{s(t)} and\ S_{sim,t+1} = A_T h_{s(t+1)} \quad (4.1)$$

Where $S_{sim,t}$ is the simulated storage at the beginning of period *t*, A_T is the plan area of the storage tank, $h_{s(t)}$ is the simulated water level at the start of period *t*. The simulation of storage by mass balance can therefore be expressed as:

$$A_T h_{s(t+1)} = A_T h_{s(t)} + \eta R_{(t)} A - Re_{(t)}$$
$$0 \leq A_T h_{s(t+1)} \leq C \quad (4.2)$$

where η is the rainwater collection efficiency, $R_{(t)}$ is the rainfall intensity in the period *t*, *A* is the effective roof area, $Re_{(t)}$ is the volume of water consumption released from the tank in period *t* and *C* is the storage capacity of the tank.

It is worthwhile to note that the calculation of rainwater collection efficiency as the ratio of the volume of inflow into storage to the volume of rainfall is incorporated into the simulation because the rainwater collection efficiency mass balance in equation 4.2 can be expressed as:

$$\eta = \frac{A_T(h_{s(t+1)} - h_{s(t)}) + Re_{(t)}}{R_{(t)}A} \quad (4.3)$$

Where $A_T(h_{s(t+1)} - h_{s(t)}) + Re_{(t)}$ is the volume of inflow into storage in period *t* and $R_{(t)}A$ is the volume of rainfall over the roof in period *t*.

By altering the water collection efficiency, the simulated storage levels could be matched as closely as possible to the recorded storage levels in order to obtain the optimal water collection efficiency of the system. Based on previous field studies, (Liaw and Tsai, 2004; UN-Habitat, 2005: Woods Ballard et al., 2015), the search for the optimum rainwater collection efficiency

studies efficiency was confined within 60 to 90%. The approach adopted for this was to set up the simulation on excel spreadsheet and pose the determination of the water optimal collection efficiency as an optimization problem that adjusts the water collection efficiency with an objective function that seeks to minimize the total of the absolute differences between the simulated and the recorded storage water levels as shown in equation 4.4. This linear objective function was preferred over nonlinear alternatives (such as the square of the differences between the simulated and recorded water levels) because the relationship between the rainwater collection efficiency and the water levels (equation 4.3) is itself linear. The evolutionary (Genetic Algorithm) optimizer available in the Solver Add-In of Ms Excel was applied for this.

$$Minimize \sum_{t=1}^{N} \left| h_{s(t)} - h_t \right| \quad (4.4)$$

where N is the total number of periods simulated, $h_{s(t)}$ is the simulated water level at the beginning of period t, and ht is the measured water level at the beginning of period t.

The determination of rainwater collection efficiency was confined to RWH systems (or parts of them) where the rain collected on a roof was channelled to a single storage only. For a roof draining into more than one storage, the proportions of the roof area draining to the different storages are not known and including them as unknown decision variables would lead to a more complex problem and challenges of decision variable inter-dependence and equifinality.

4.5 Assessment of rainwater harvesting potential

The assessment of RWH potential mainly involves the determination of the range of storage-yield-reliability relationships that a given system could provide although the effect of altering the catchment (roof) area on these relationships could also be included. Out of the various approaches of optimal RWH storage sizing that are reviewed in Section 3.8, continuous daily time step simulation (Campisano *et al.*, 2017; Ndiritu *et al.*, 2017; Ward et al., 2012; Mitchell, 2007) is considered to be most realistic as it seeks to replicate the behaviour of the actual system and incorporates all the basic principles of the simpler methods and was therefore adopted for this study. This approach could apply the yield after spillage (YAS) or the yield before spillage (YBS) approach.

In the YAS approach, the storage is assumed to spill any excess rainfall inflow before supply (yield) is withdrawn from storage while the YBS approach draws the supply (yield) first and then releases any excess rainfall inflow as spillage. The YAS approach therefore leads to a more conservative analysis and daily YAS analysis has been found to match a 6-minute RWH simulations better than daily YBS analysis (Mitchell, 2007). The YAS approach was therefore adopted for this study. Section 3.8 of the literature review informs that continuous daily time step simulation with the application of historic data enables the incorporation of multi and inter-annual rainfall variability including the effect of dry periods if a statistical approach to quantifying reliability is applied. A statistical approach to determining reliability as described in Section 3.8 was therefore adopted in this study rather than the more common approach of using volumetric reliability alone.

Since the use of statistical reliability for RWH assessment is much less common than that of volumetric reliability, the advantage of using statistical reliability is now illustrated. This applies a realistic scenario using the selected daily recorded rainfalls at Ndindindi rainfall station, the existing RWH system for Household 1 with a storage capacity of $10m^3$, and the per capita demand recommended by the guidelines for rural water supply in South Africa (CSIR, 2005).

A daily time step simulation of this system obtains the time series of days of supply for each year as shown on Figure 4.13. It is seen that the annual number of days of supply are highly variable with a large range of 249 to 361 days and averaging 310 days. An assessment of the system based on volumetric reliability would use the average of 310 days to obtain a volumetric reliability of 310/365´100% = 85%. This average level of supply can however be met for only about half of the design life of the system and figure 4.13 shows that continuous periods of 3 and 5 years that the supply would be much lower.

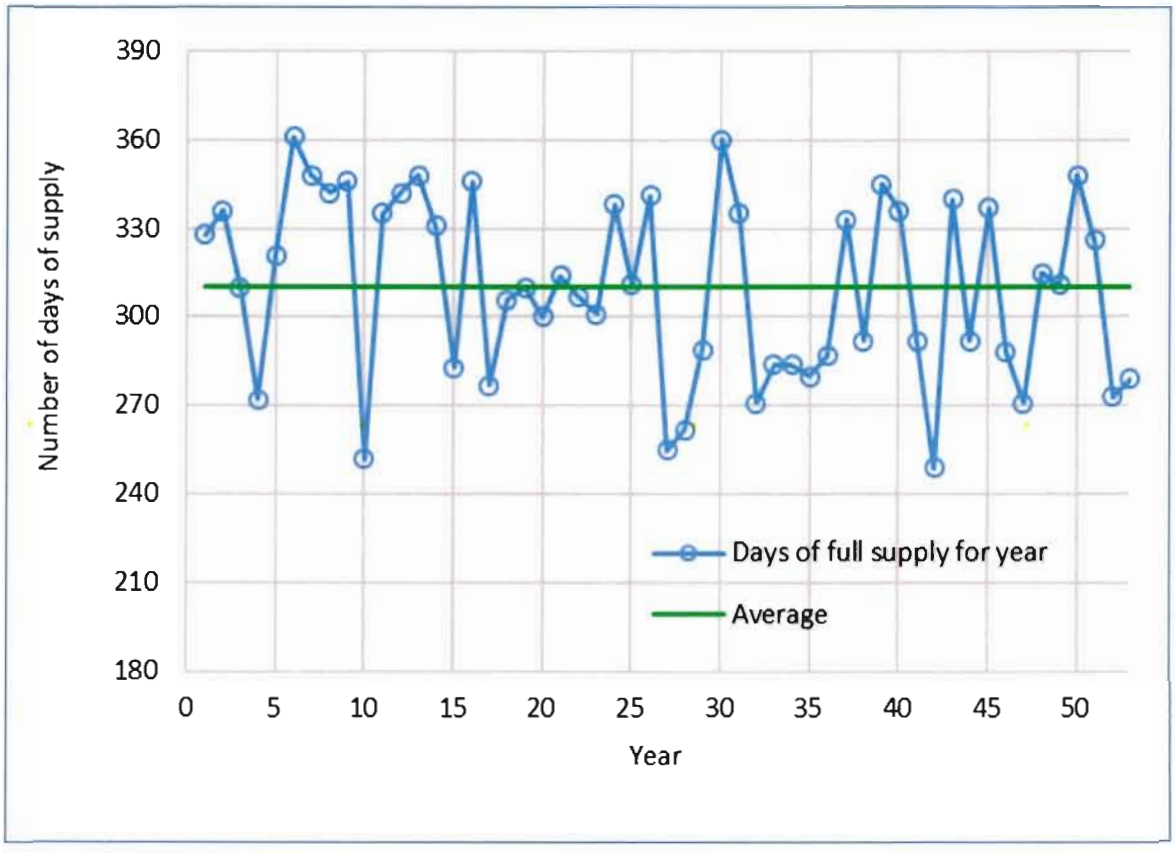


Figure 4.13: Time series of annual number of days of supply for a storage of 10m³ for household 1

A frequency analysis of the time series of the annual number of days of supply using a plotting position approach (equation 3.6, under section 3.8) obtains a relationship between the expected number of days of supply and reliability as illustrated on figure 4.14. Thus, a supply of 241 days would be expected to be met at a reliability of 98% (49 out of 50 years) while a supply of 270 days would be met at a reliability of 90% (in 9 out of 10 years). As seen on figure 4.14, the volumetric reliability of 85% (which corresponds to the average level of supply of 310 days) would only be met at 50% reliability (once in two years). The statistical reliability approach therefore provides a more robust assessment of RWH systems performance and is applied for practical water resource systems planning and management in South Africa (Basson et al., 1994; Basson and van Rooyen, 2001).

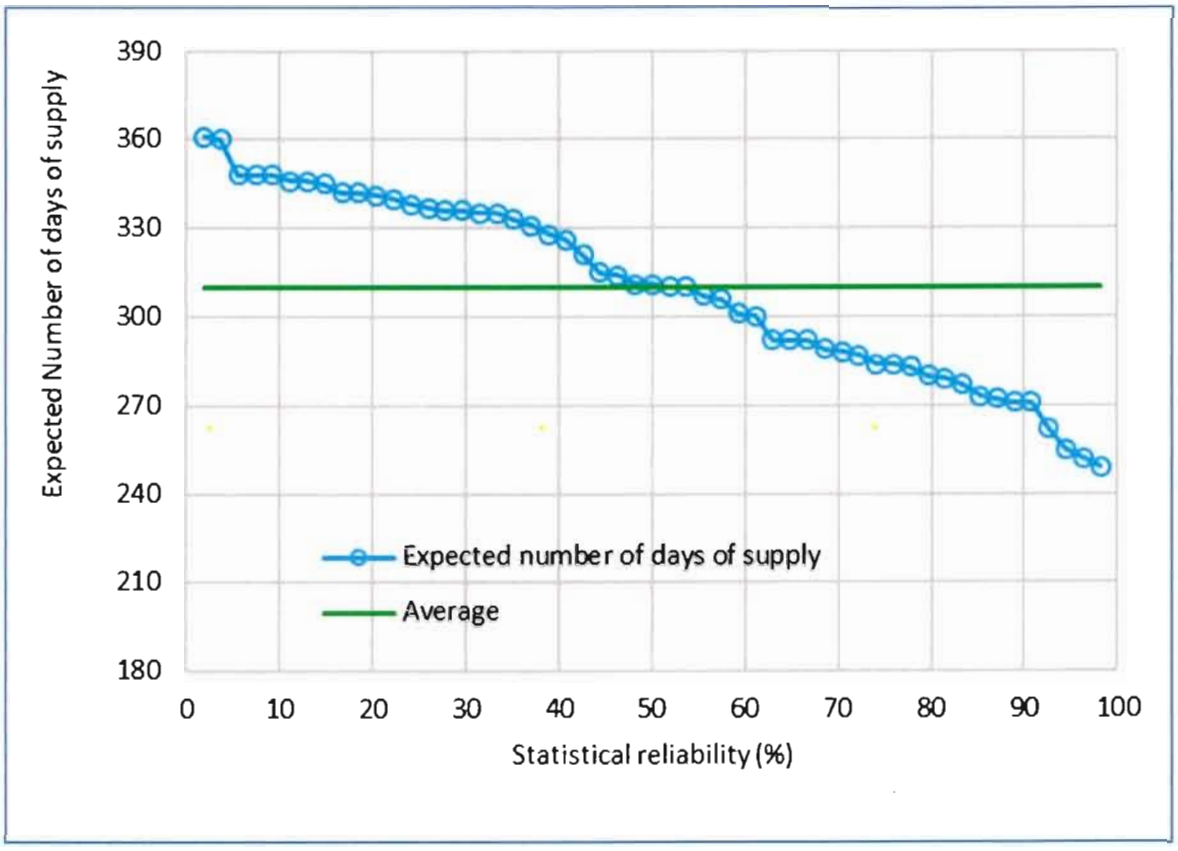


Figure 4.14: Relationship between statistical reliability and level of supply for a storage of 10m³ for household 1.

4.6 Life Cycle Cost Analysis (LCCA)

Life Cycle Cost Analysis (LCCA) needed to be undertaken for RWH-based water supply systems and the equivalent municipal water supply systems in order to meet the study objective that compares the financial viability of RWH with municipal water supply. Since the municipal water supply system is assumed and expected to fully meet the demand at a set level of service (LOS), the RWH systems to be used in the comparison also needed to have the ability to fully supply the water demand at a similar LOS. Table 4.2 provides a description of the LOS stipulated by South African guidelines for rural water supply (CSIR, 2005). Considering that each RWH storage tank provides a single outlet for consumption within the water demand sites, LOS 3 was adopted for the equivalent municipal supply system LCCA. The literature review informed that LCCA for RWH usually applies highly subsidised tariffs of centralised municipal water supply and that RWH is also sometimes subsidised in South Africa (DWAF, 2013) and other regions (Rahman et al., 2012).

LCCA based on estimates of the real Life Cycle Costs of RWH and centralised water supply would therefore form a strong basis of comparing financial viability although the literature review revealed that such comparisons are uncommon. The LCC analysis here therefore aimed to include an analysis based on estimates of the actual cost of centralised municipal water supply in addition to the more common analysis using municipal water tariffs. Two scenarios of municipal water supply were therefore analysed; one seeking to obtain an estimate of the actual LCCA for the municipal water supply infrastructure, and the other one based on municipal water tariffs. The municipal water supply LCCA was based on preliminary designs of the equivalent municipal water supply system which included the capital, operations and maintenance costs of the systems.

Table 4.2: Water supply levels of service (CSIR, 2005)

Service Package	A	B	C	D	E
Water	LOS 1	LOS 2	LOS 3	LOS 4	LOS 4/5
Water supply LOS description	Minimum reticulation, maximum distance to standpipe 250m	Partial reticulation, 1 standpipe to 20 sites, 100 – 150 m walk	Single metered standpipe per site	Metered connection for in-house supply	Metered connection for in-house supply

Future cash flows identified in the process of LCCA were converted to a present-day value and it was assumed that RWH and municipal water supply systems have a design life of 50 years. The RWH system gutters and downpipes having a shorter design life and therefore required numerous replacements within the 50 years. The size of the RWH system that met the full demand (as the municipal water supply system would do) was determined from the analysis of the hydrologic potential of the RWH systems as described in Section 4.5. Nominal capital costs were adopted for the study and were obtained directly from suppliers of RWH system materials while the maintenance and operation costs and discount rates were estimated from desktop sources. South Africa's discount rate at the time of research was 5.25% (SA Interest rate update, 2020). Accumulative future values were determined using equation 4.5:

$$FV = PV\,(1+r)^t \tag{4.5}$$

Where *FV* is the future value, *PV* is the present value, *r* is the nominal interest rate and *t* is the accounting period.

5. FIELD WORK RESULTS AND DETERMINATION OF RWH COLLECTION EFFICIENCY

5.1 Field work results

This section presents the field work data collected over a period of one year. The aim was to obtain continuous and reliable daily datasets for all the variables of interest over this period, but this was not all achieved due to various challenges including those associated with the COVID-19 pandemic, malfunctioning of flow meters and absence of a data collector at times as well as human errors during data capturing. One of the consequences was that, for household 2, data collection in the second half of the study was done at weekly or longer time intervals.

5.1.1 Water consumption measurements

Data on the number of persons in each of the 3 study households is shown graphically on figure 5.1. A family gathering on the 27th of December 2019 for household 3 was attended by many people on the day as circled in red on the figure. The average number of individuals who attended the school per day over the study period was reported to be 1 130 while the average number of individuals who consulted the clinic per day was reported to be 65.

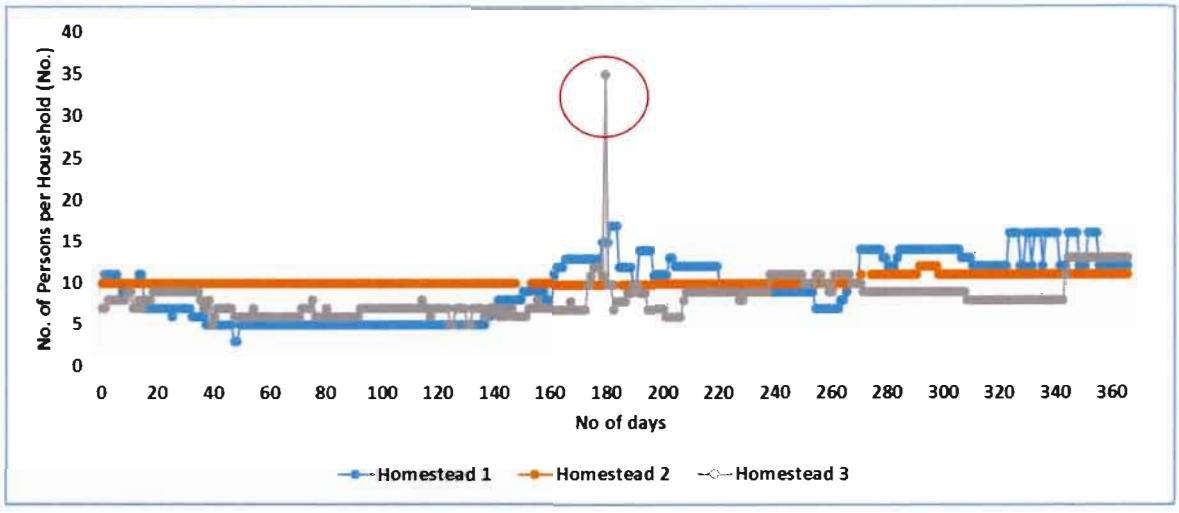


Figure 5.1: Number of water users per day for the 3 households.

5.1.2 Water consumption measured by mechanical water meters

The results presented on figures 5.2, 5.3 and 5.4 show the individual daily water consumption measured in household 1, 2 and 3, respectively. The data reveals the expected variability across days associated with activities such as laundry that do not take place daily. The data for household 1 as shown on figure 5.2 shows a sudden reduction in the rate and variability of daily

water consumption from mid-May 2020 to 30 June 2020 (circled in red) and could probably be attributed to meter malfunctioning. This portion of the data was considered unreliable and not applicable for determination of rainwater collection efficiency nor rainwater harvesting analysis. On the second half of the year for household 2, measurements were recorded over longer time intervals and are circled in red on figure 5.3. Over these periods, the meter records were used to obtain average daily consumption as seen on figure 5.3. This portion of the data for household 2 was also considered unreliable and excluded in the rainwater harvesting analysis.

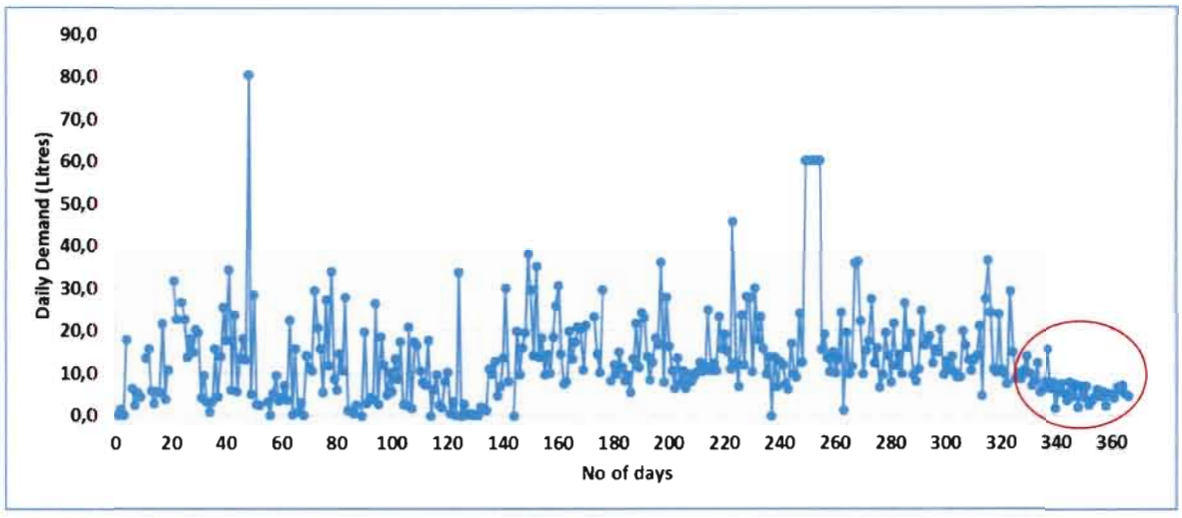


Figure 5.2: Daily water consumption in Homestead 1.

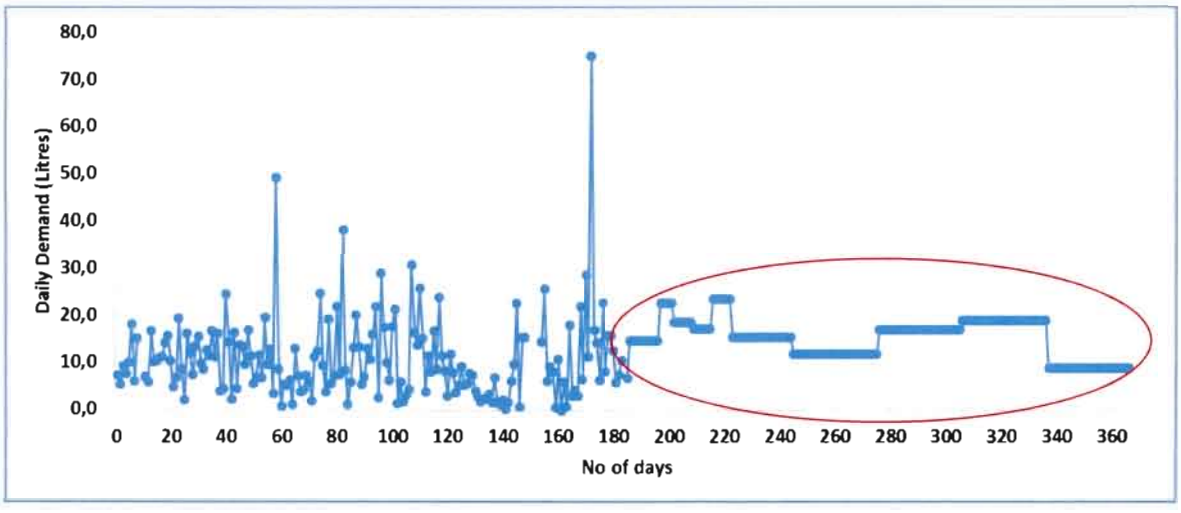


Figure 5.3: Daily water consumption in Homestead 2.

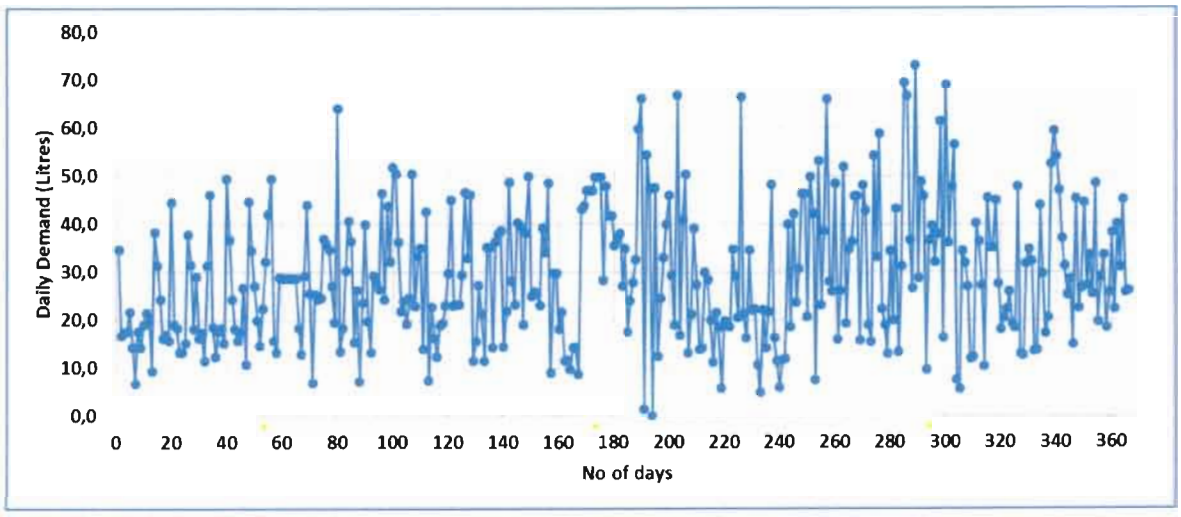


Figure 5.4: Daily water consumption in Homestead 3.

Water consumption in the three households is compared on figure 5.5. It is evident that water consumption in household 3 was higher than that of household 1 and 2. This is because household 3 was supplied from the municipal water supply system and had a higher water supply level of service as it was equipped with yard connection. The average daily consumption over the study period for household 1, household 2 and household 3 was 14 L/day/capita, 13 L/day/capita and 30 L/day/capita, respectively.

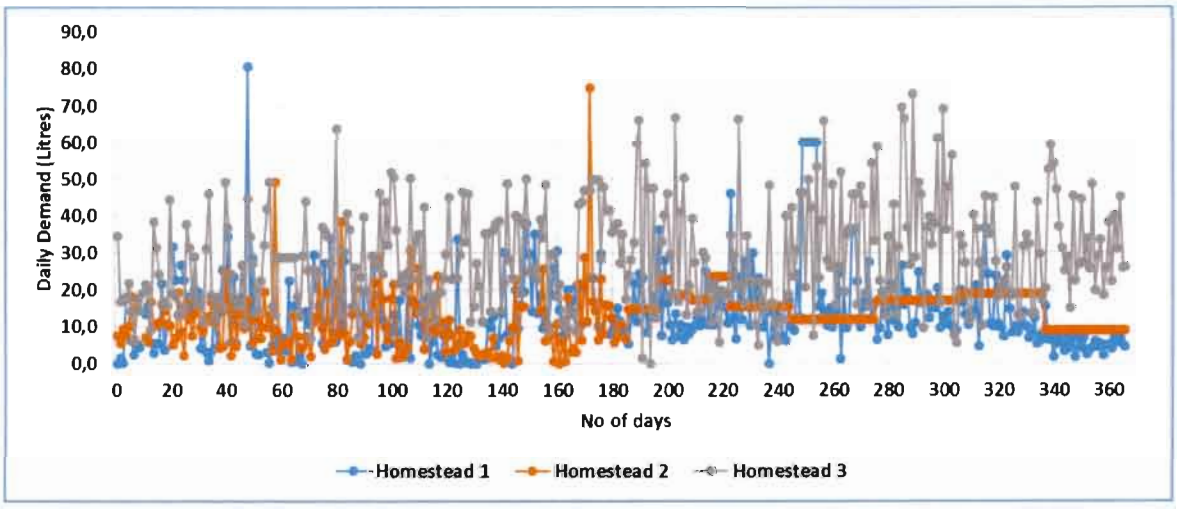


Figure 5.5: Comparison of daily water consumption in the study for all three Homesteads.

The results illustrated on figures 5.6 and 5.7 show the measured daily water consumption from the local clinic and the school. The average daily demand over the study period, from July 2019 to June 2020 for the clinic and the school was 4.3 L/day/capita and 1.42 L/day/capita, respectively.

The gaps in the clinic water consumption data highlighted by the red circle on figure 5.6 are as a result of unrealistic records and the lack of records over some periods of the COVID-19 pandemic national lockdown.

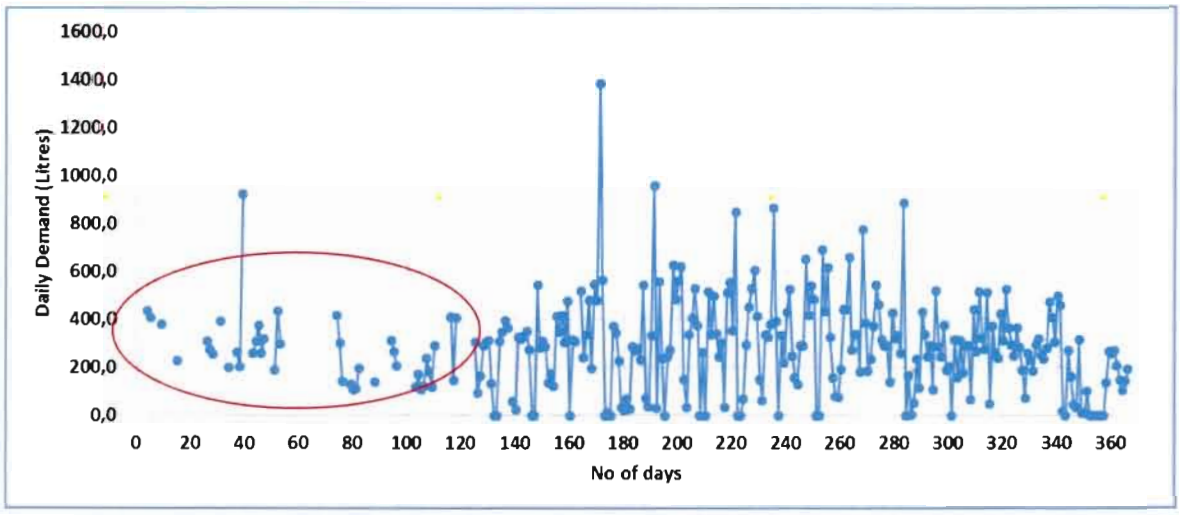


Figure 5.6: Measured daily water consumption at the Clinic.

The gaps in the school's water consumption measurement as seen on figure 5.7 are as a result of school holidays as well as national lockdown due to COVID-19 pandemic. The larger consumption between 65 and 75 days could be associated to days for which the school hosted some other schools for sports activities.

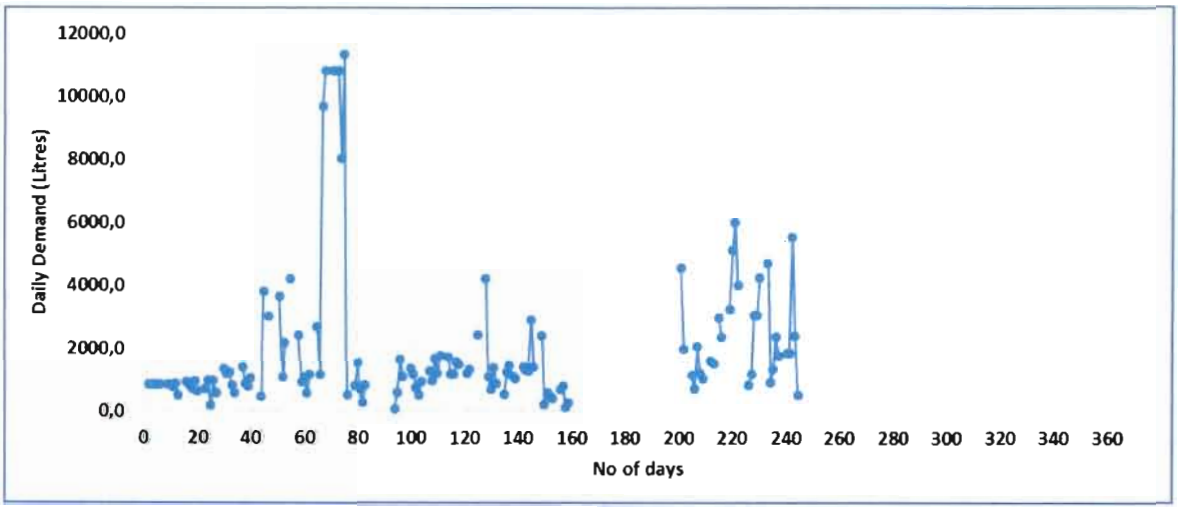


Figure 5.7: Daily water consumption at the school.

The average number of individual water users and the measured daily per capita water consumption for all 5 study sites is as summarized in Table 5.1.

Table 5.1: Water user's size & the associated measured water demand.

Selected Water Users	Persons Per Household per day	Measured per capita Water demand (L/day/capita)
Homestead No.1	9	14
Homestead No.2	10	13
Homestead No.3	8	30
Local Clinic	65*	4.3
Local School	1 123*	1.42

*Data for clinic and the school has been sourced from the operation manager & the deputy principal, respectively.

5.1.3 Storage water level and rainfall measurements

The results illustrated on figures 5.8 to 5.11 show the storage water levels and rainfalls recorded in household 1, household 2, the clinic and the school, respectively. For the measurements of household 2, as seen on figure 5.9, the red circle highlights the period over which measurements were at weekly or longer time intervals. On Figure 5.11, the red circle indicates the time when no measurements were recorded as the school was closed. It is observed that significant rainfalls mainly started from November 2019 to end June 2020. It is evident that the reservoirs were filled up by water tankers on several occasions prior to that and during the period of measurements as indicated on the figures 5.8 to 5.11. During the rainfall period, it is observed that the storage tanks reached full capacity and spilling over in many instances.

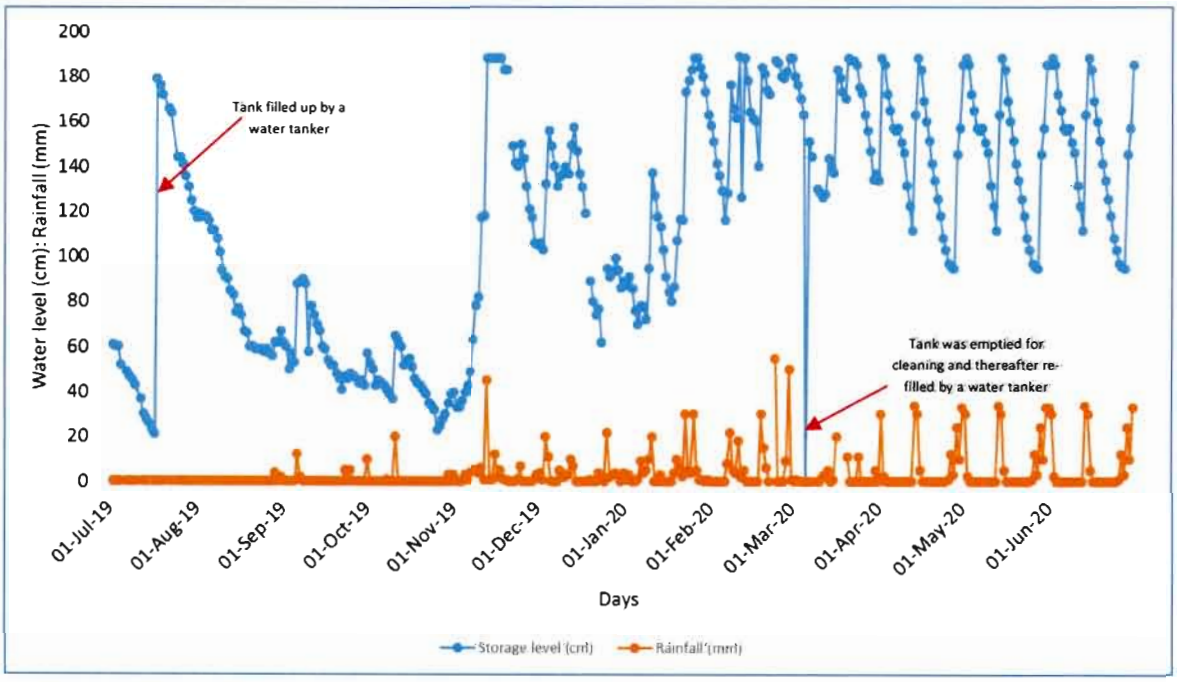


Figure 5.8: Reservoir storage water levels and rainfall for Homestead 1.

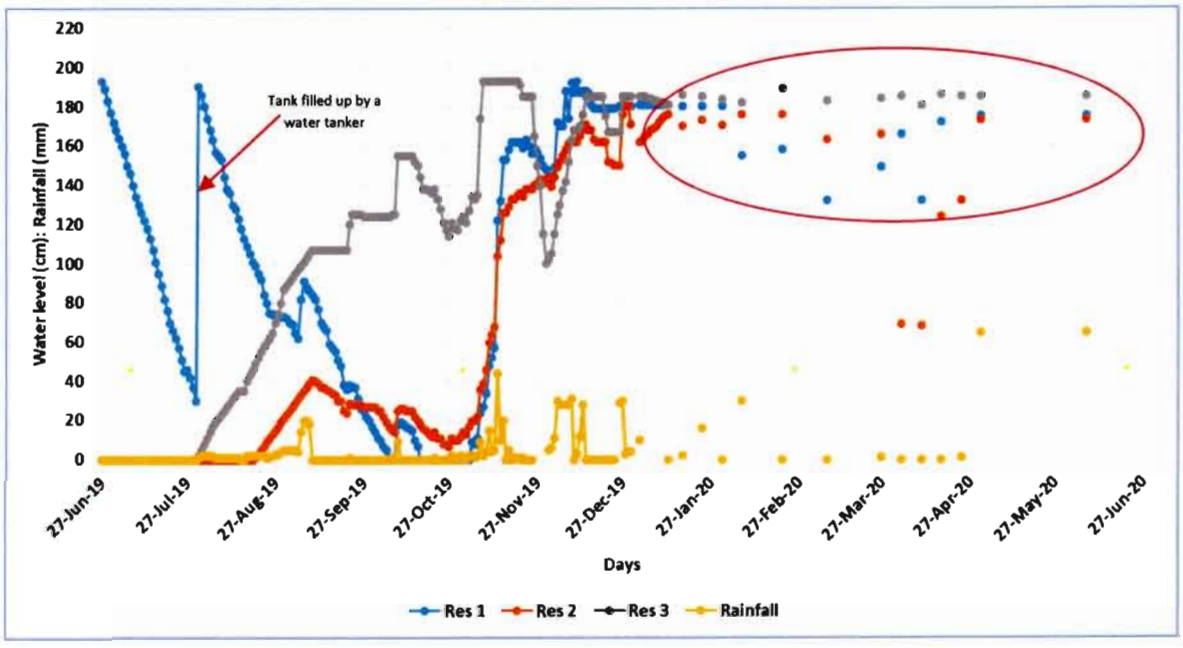


Figure 5.9: Reservoir storage water levels and rainfall for Homestead 2.

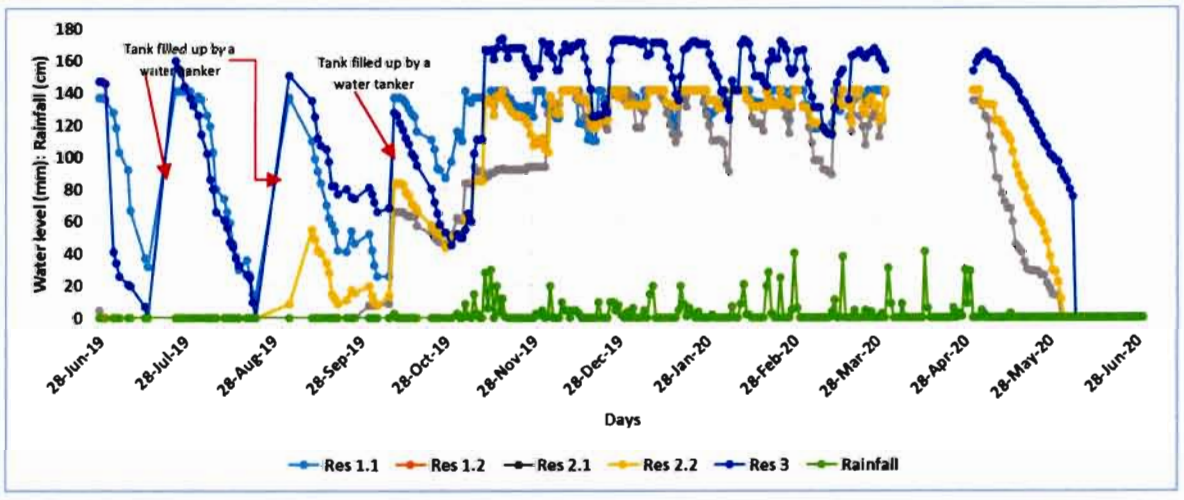


Figure 5.10: Reservoir storage water levels and rainfall for the Clinic

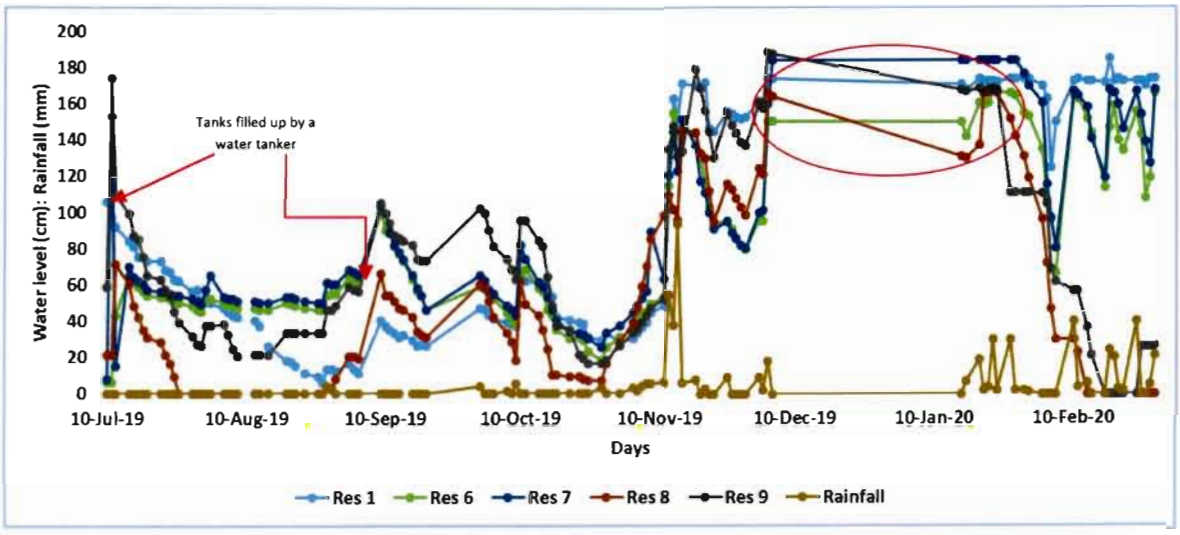


Figure 5.11: Reservoir storage water levels and rainfall for the School.

5.2 Variation of water consumption within the year

Since the daily variations of water consumption are highly variable as seen on Figures 5.2 to 5.7, it is reasonable to also assess this variation at a monthly time step as these could impact on RWH system performance more than daily variations that are more easily damped out by storage. The monthly variations of consumption as obtained by aggregating the daily measurements are shown on figures 5.12 to 5.16. The variations are considerable with the largest monthly consumptions greater than the lowest by multiples exceeding 2 for all the RWH systems.

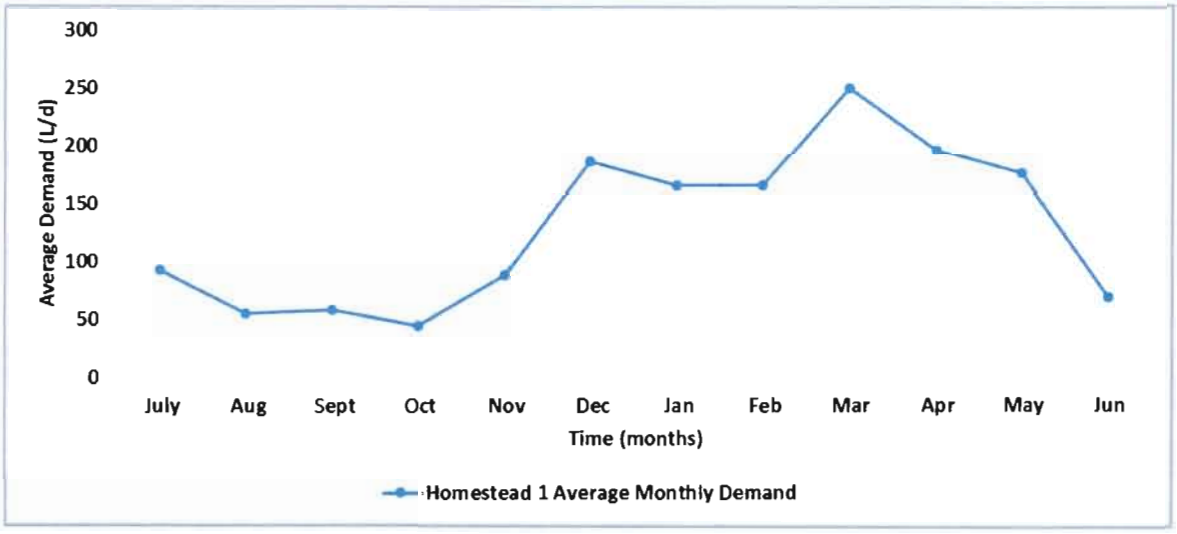


Figure 5.12: Homestead 1 monthly demand.

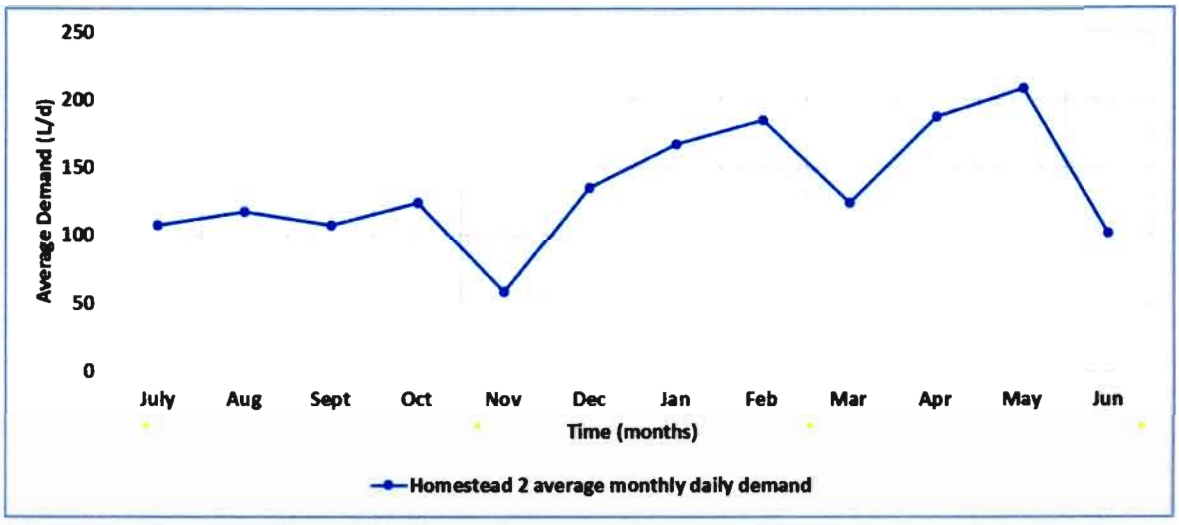


Figure 5.13: Homestead 2 monthly demand.

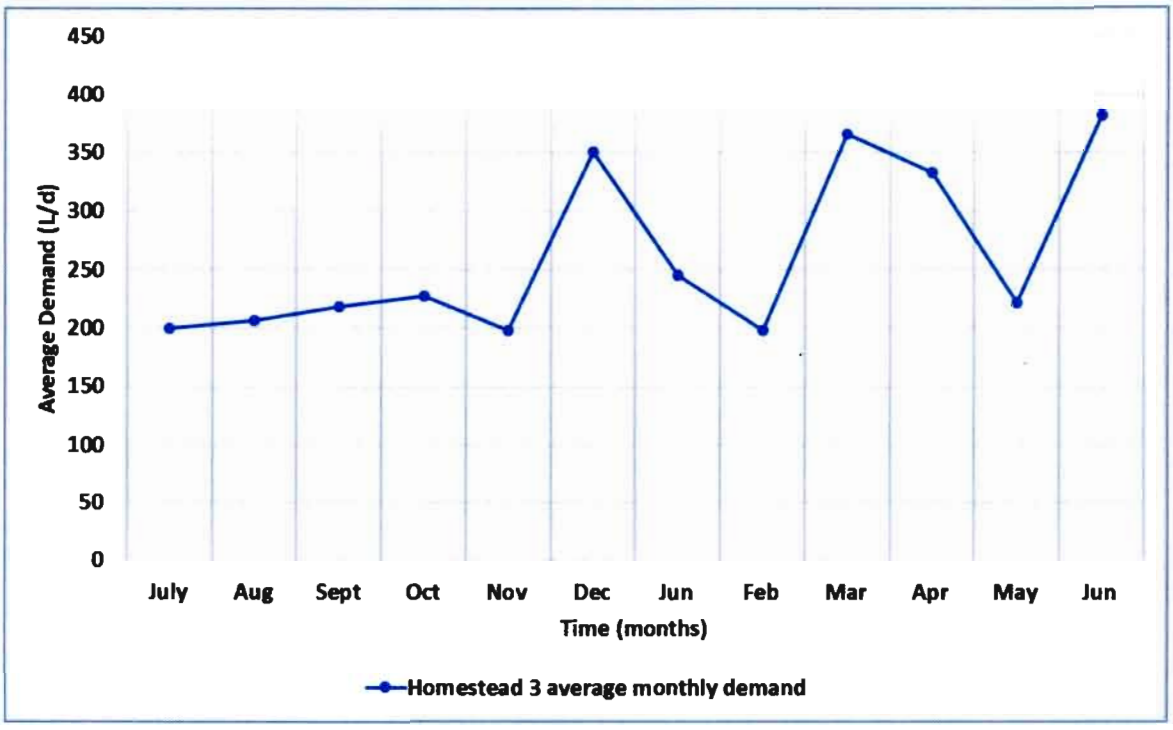


Figure 5.14: Homestead 3 monthly demand.



Figure 5.15: Clinic monthly demand.

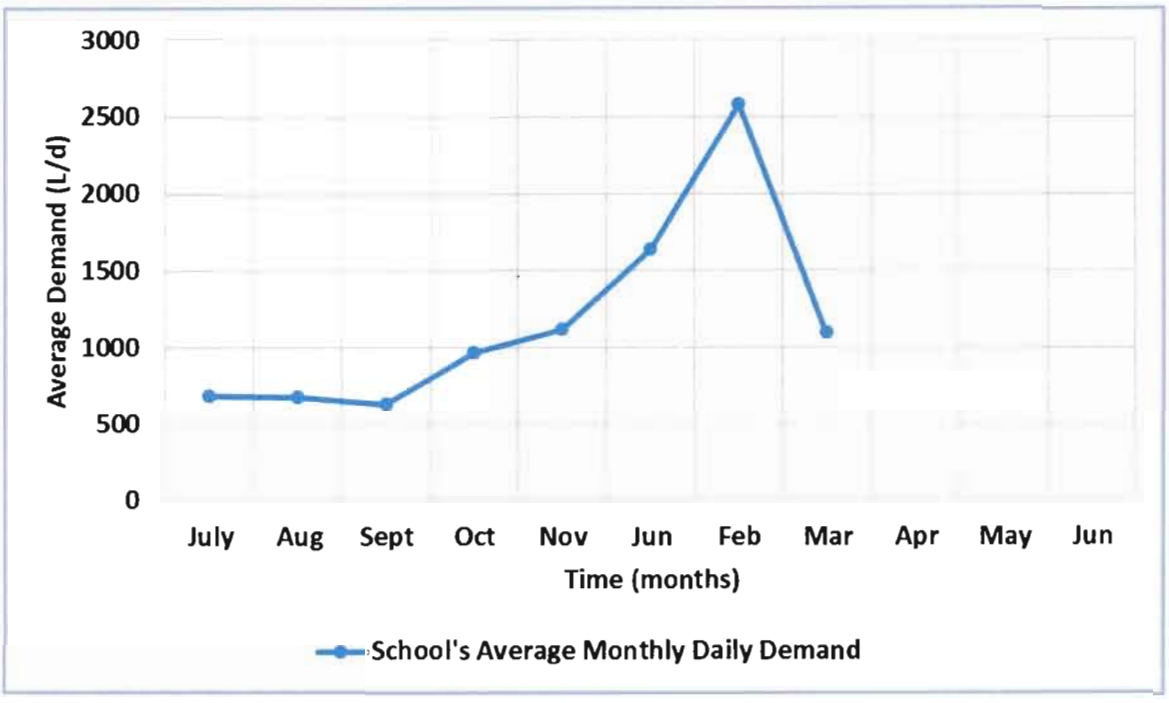


Figure 5.16: School monthly demand.

A comparison of the water consumption rates from the field study to the water demands stipulated by the South African guidelines for rural water supply CSIR (2005) is shown in Table 5.2. It informs that the water consumption rates obtained from the field results were considerably lower than the water demands from the guidelines for households 1 and 2, the school and the clinic. For household 3 that has a municipal supply at LOS 3 (yard connection)

and not RWH supply, the measured consumption rates are slightly higher than the waters specified by the guidelines.

Table 5.2: A comparison of daily water consumption from field measurements to those from CSIR (2005)

Selected Water Users	Average water consumption from field measurements (L/day)	Average number of water users per day	Per Capita Consumption from CSIR (2005) (L/capita/day)	Average water consumption based on CSIR (2005) (L/day)
Household 1	129	8	25	200
Household 2	136	10	25	250
Household 3	262	9	25	225
Local Clinic	278	65	5	325
Local School	1460	1123	5	5615

5.3 Historic Rainfall Data.

South African Weather Service rain gauge station 1811668 (Ndindindi) was selected for use as indicated in section 4.3.2. As seen in figure 5.17, the annual rainfall time series applied after the exclusion of years with missing daily rainfalls is demonstrated. This was the final rainfall data applied to assess the RWH potential.

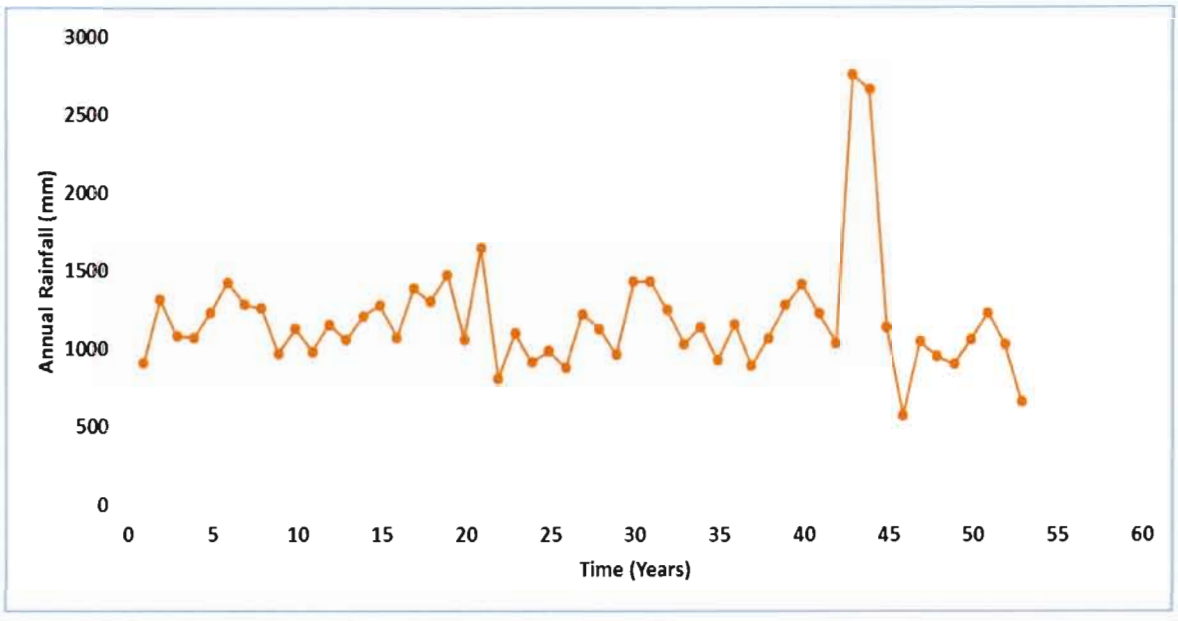


Figure 5.17: Historic annual rainfall data from gauging station 1811668 used to assess RWH potential.

5.4 Survey of RWH systems and availability of space

The selected RWH supply systems were surveyed and qualitatively assessed for functionality. The RWH supply system configurations were established, the roof sizes were measured, and water storage sizes were determined.

Schematics as seen in figures 4.2, 4.4, 4.7 and 4.9 are of the RWH-based water supply systems for household 1, household 2, the school and the clinic respectively and provide the configurations, the surveyed roof areas and reservoir sizes. Table 5.3 provides the total reservoir sizes and roof areas for the individual RWH supply systems.

Table 5.3: Reservoir sizes and roof areas for the existing RWH systems.

RWH system	Total Reservoir Size (m^3)	Roof Area (m^2)
Household 1	10	180
Household 2	15	230
Local Clinic	15	485
Local School	27.5	1246

As seen in table 2.1 (page 17), the residential areas in the community are formalised with identical Erf sizes of 75m x 45m and there is ample land area which could be availed for large storage sizes. The Erf sizes for the school and the clinic in relation to this study are 136m x 245m and 116m x 105m respectively, this indicate that there is also ample land area for large storage sizes.

5.5 Determination of rainwater collection efficiency

As stated in Section 4.4, the determination of rainwater collection efficiency is carried out for RWH-based water supply systems (or components of the systems) that have a single reservoir receiving water from a single roof catchment. In addition, the determination of rainwater collection efficiency is confined to the part of the study period with reliable daily data and significant rainfall. Given these considerations, the rainwater collection efficiency is determined for reservoir 1 (Res 1) household 1, reservoir 3 (Res 3) for the clinic and reservoir 1 (Res 1) for the school. The approach as described in section 4.4 is applied.

As seen in figures 5.18, 5.19 and 5.20, the storage water level trajectories for the recorded and simulated water levels for reservoir 1 of household 1, reservoir 3 of the clinic and reservoir 1 of the school respectively are demonstrated. The respective average differences between the recorded and simulated water levels were 11.41, 20.27 and 8.06cm for the three respective systems in agreement with the larger misalignments of the simulated and measured levels for the clinic in comparison to the household and the school. The rainwater collection efficiencies for reservoir 1 of household 1, reservoir 3 of the clinic and reservoir 1 of the school were 0.798, 0.876 and 0.727 respectively, giving an average efficiency of 0.800. This average water collection efficiency compares well with the rainwater collection efficiencies found from the previous studies (Woods Ballard et al., 2015: UN-Habitat, 2005: Nissen-Petersen and Gould, 1999) and has therefore been adopted for the assessment of the rainwater harvesting analysis discussed in the succeeding chapter.

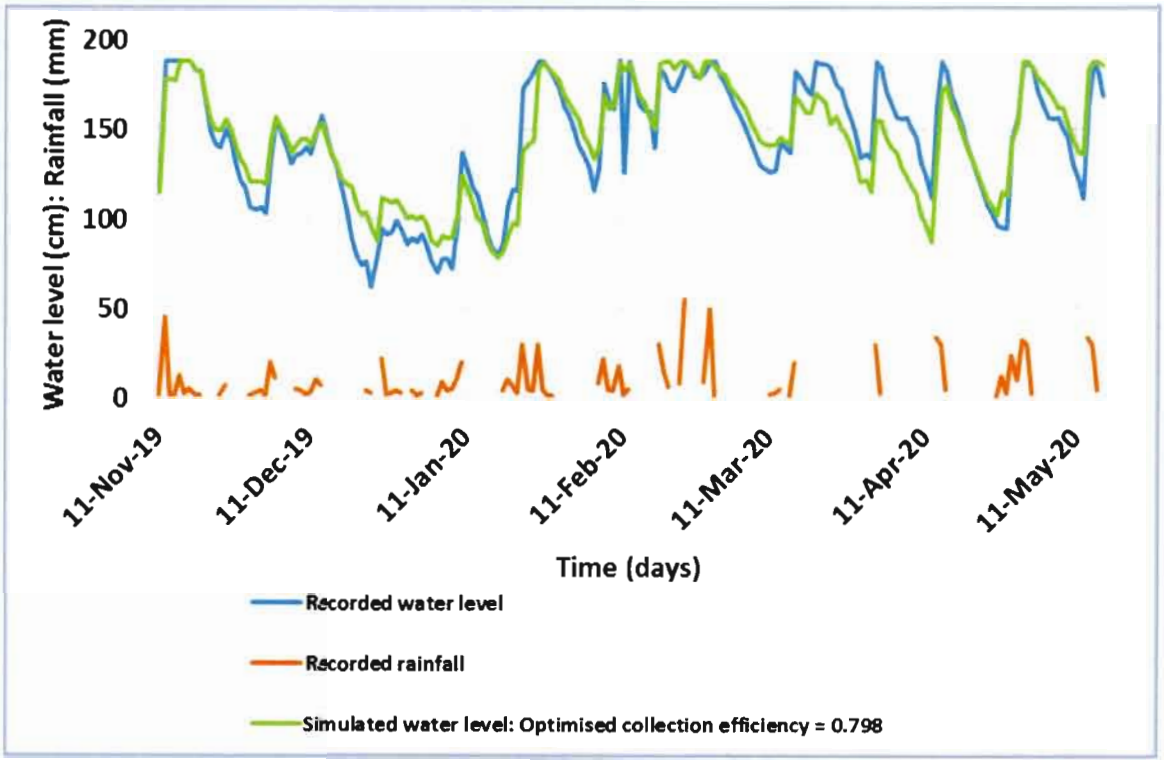


Figure 5.18: Recorded and simulated storage water level trajectories for the optimal rainwater collection efficiency for reservoir 1 of Household 1.

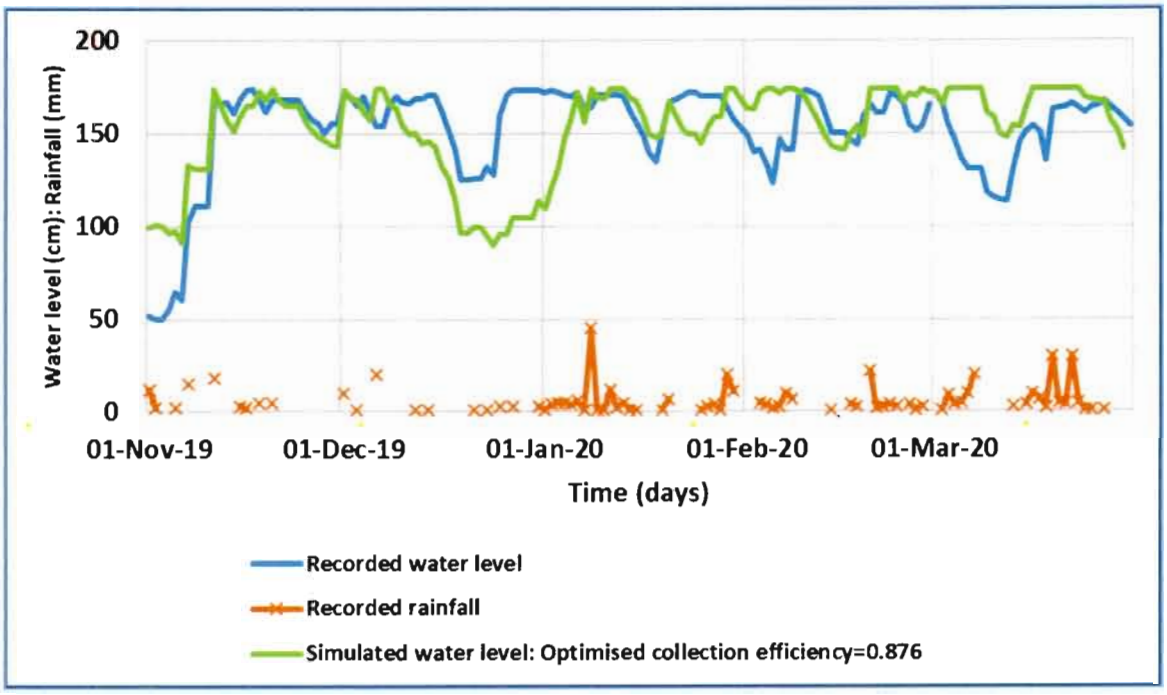


Figure 5.19: Recorded and simulated storage water level trajectories for the optimal rainwater collection efficiency for reservoir 3 of the Clinic.

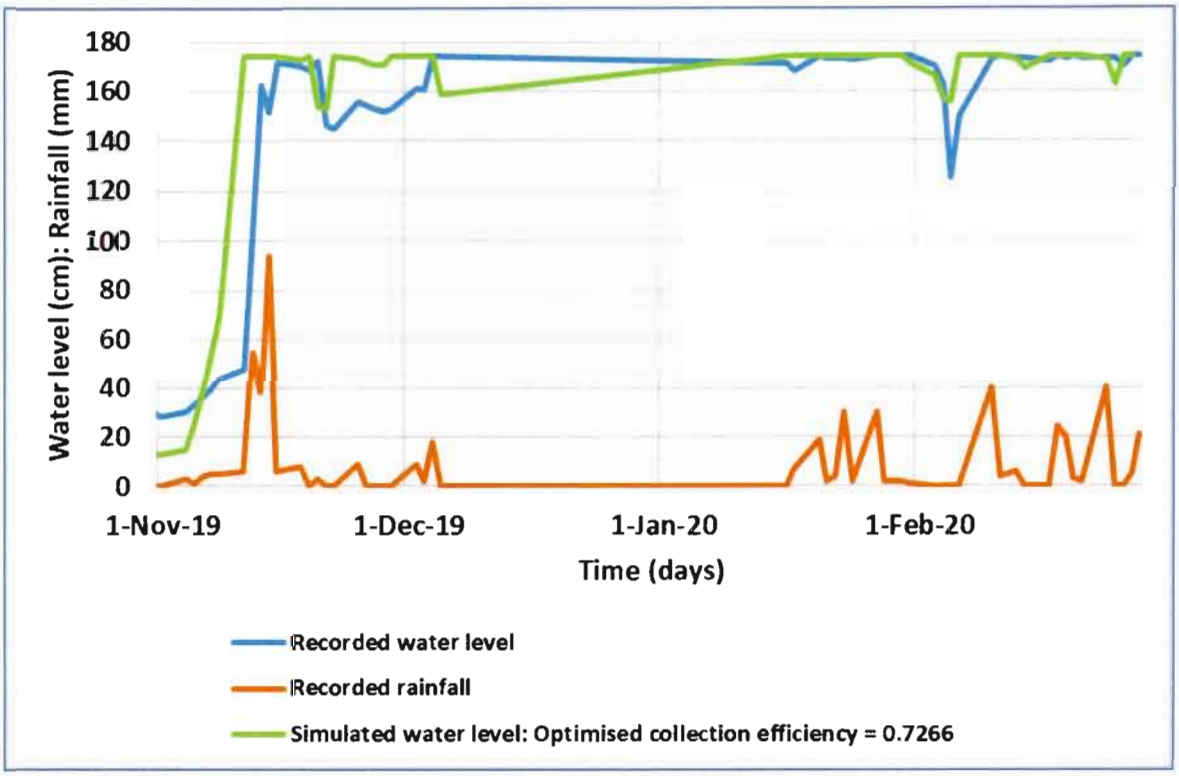


Figure 5.20: Recorded and simulated storage water level trajectories for the optimal rainwater collection efficiency for reservoir 1 of the School.

6. ASSESSMENT OF RAINWATER HARVESTING POTENTIAL

6.1 Overview

One of the primary objectives of this study is to find out whether the community within the selected area of study can fully rely on RWH for water supply. This chapter presents the analysis carried out to achieve this objective. As indicated in section 4.5, daily time step simulation using the yield-after-spillage (YAS) approach while incorporating statistical reliability is applied for the analysis.

Given the large differences between the water consumption rates obtained from the field RWH measurements and the supply levels recommended in the South African guidelines (Table 5.2 in Chapter 5), it was considered necessary to carry out simulations using both the field measurements and water demands as stipulated in the guidelines for rural water supply (CSIR, 2005). The exception to this was the school for which the measured water consumption of 1.42 l/capita/day was considered unrealistically low for assessment of RWH potential and therefore simulation analysis was carried out using only the water demand as stipulated in the guidelines. The water demand of 5 l/capita/day from the guidelines is therefore used for the school. The required water demand of 5 l/capita/day for the clinic and the school are both exclusive of sanitation for water use as both facilities are individually provided with ventilated improved pit latrines.

The field measurements also revealed considerable variations in consumption across the year (Section 5.2, Chapter 5) and scenarios assuming the observed variations and assuming constant demand have therefore been included in the assessment of RWH potential in this Chapter. For each scenario, storage-yield-reliability relationships are first determined for each RWH-based water supply system using the existing roof areas (Table 5.3). Thereafter, relationships between storage and roof area that would provide full supply as stipulated by the guidelines for rural water supply (CSIR, 2005) are determined for various levels of statistical reliability.

The results are presented for statistical reliabilities of 50% (1 in 2 years), 67% (2 in 3 years), 80% (4 in 5 years), 91% (about 9 in 10 years), and 96% (24 in 25 years). For clarity, a reliability of 96% means that the number of days of supply would be expected to be met every 24 out of 25 years and a lower supply would thus be expected in only 1 year out of 25 years. As explained

in Section 4.5, a statistical reliability of 50% provides the number of days of supply corresponding to the classical volumetric reliability measure. However, considering that water supply needs to be provided at a high statistical reliability, emphasis is provided for the high reliability of 96% in this chapter.

6.2 Results Discussion

6.2.1 Rainwater Harvesting potential for Homestead 1

The results from the analysis of RWH potential for household 1 are presented graphically on figures 6.1 to 6.5. A storage capacity of 25m^3 is required to achieve 96% statistical reliability in supplying a constant measured water consumption rate of 14.4 l/day per capita over 365 days in a year as shown in figure 6.1. When the same measured water consumption is supplied variably, as shown in Figure 6.2, the same storage of 25m^3 also achieves 96% reliability for full supply over 365 days in a year. If the roof areas and storages available for this household were integrated into a system operating as a single where the total roof area feeds into the total storage available, figures 6.1 and 6.2 show that the existing storage of 10m^3 would supply 315 days per year of the measured water consumption at 96% reliability.

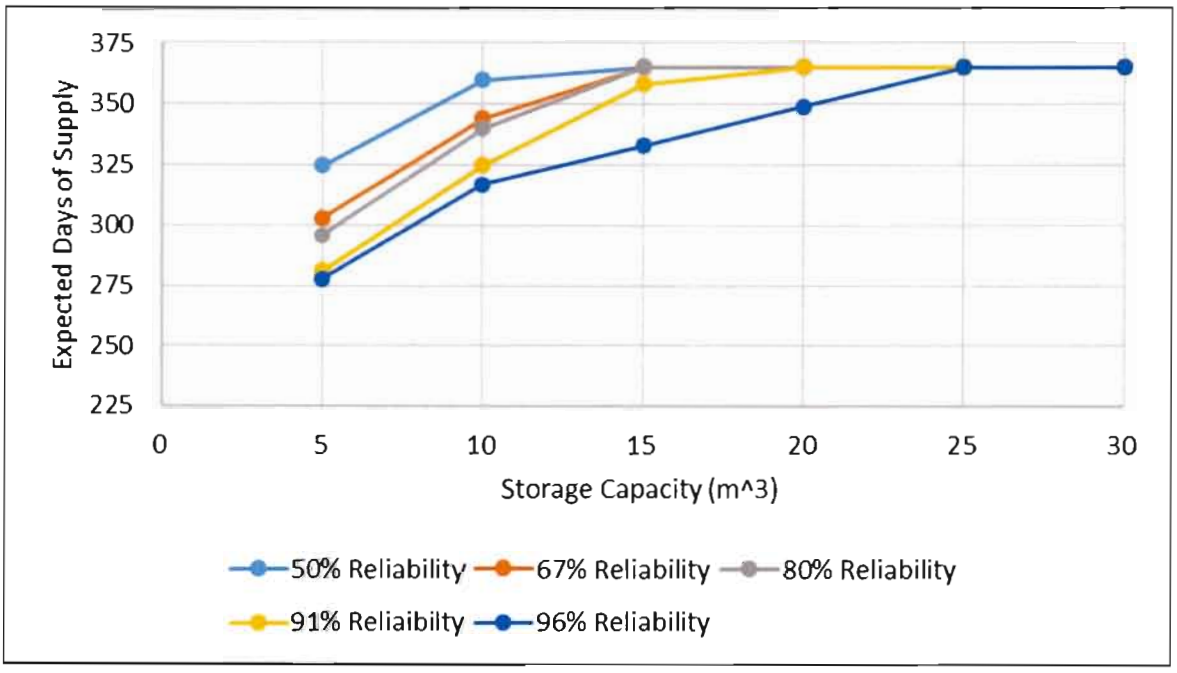


Figure 6.1: Storage-yield-reliability relationship for Household 1 based on measured consumption (14.4 l/d/capita applied constantly).

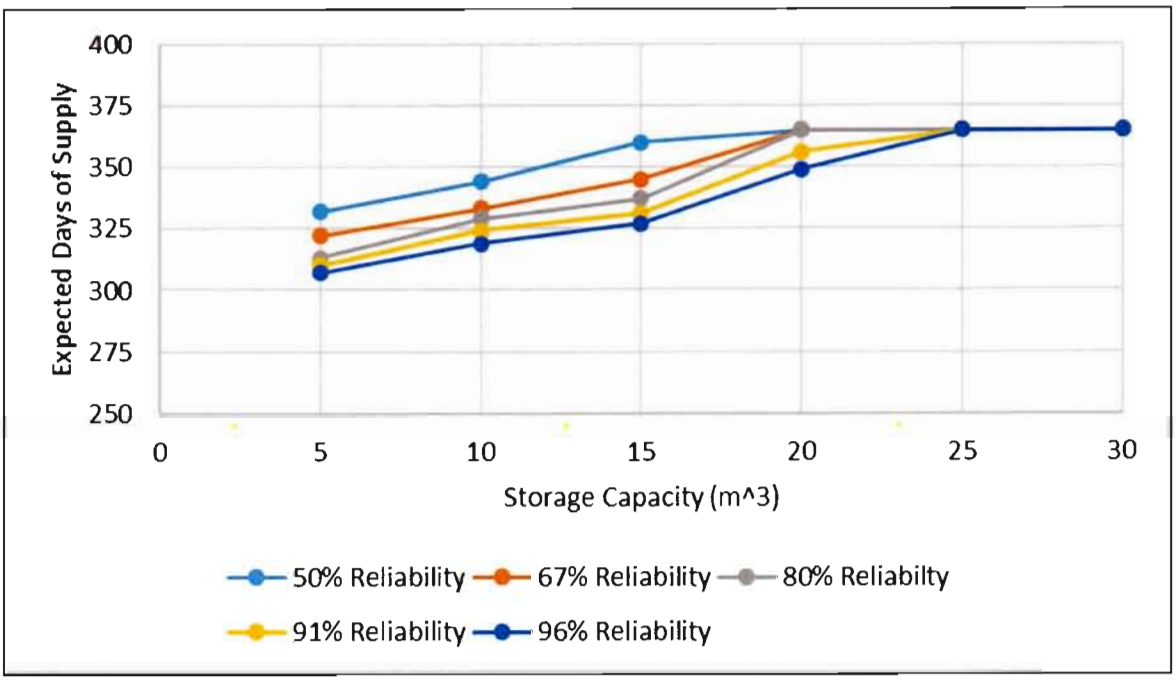


Figure 6.2: Storage-yield-reliability relationship for Homestead 1 based on measured consumption (14.4 l/d/capita applied variably).

Using the water demand of 25 l/day per capita from the guidelines, figure 6.3 shows that a storage capacity of 45m^3 is required to achieve 96% statistical reliability in supplying this demand constantly over 365 days in a year. For a variable demand, figure 6.4 shows that the same storage of 45m^3 achieves a slightly lower supply of 362 days in a year at the same statistical reliability of 96%, figure 6.4 also shows that full supply of 365 days per year at this reliability for variable demand requires a storage capacity of 55m^3. Figures 6.3 and 6.4 show that an integrated system with the existing roof area and the existing storage could respectively supply 250 and 290 days for constant and variable required demand from the guidelines.

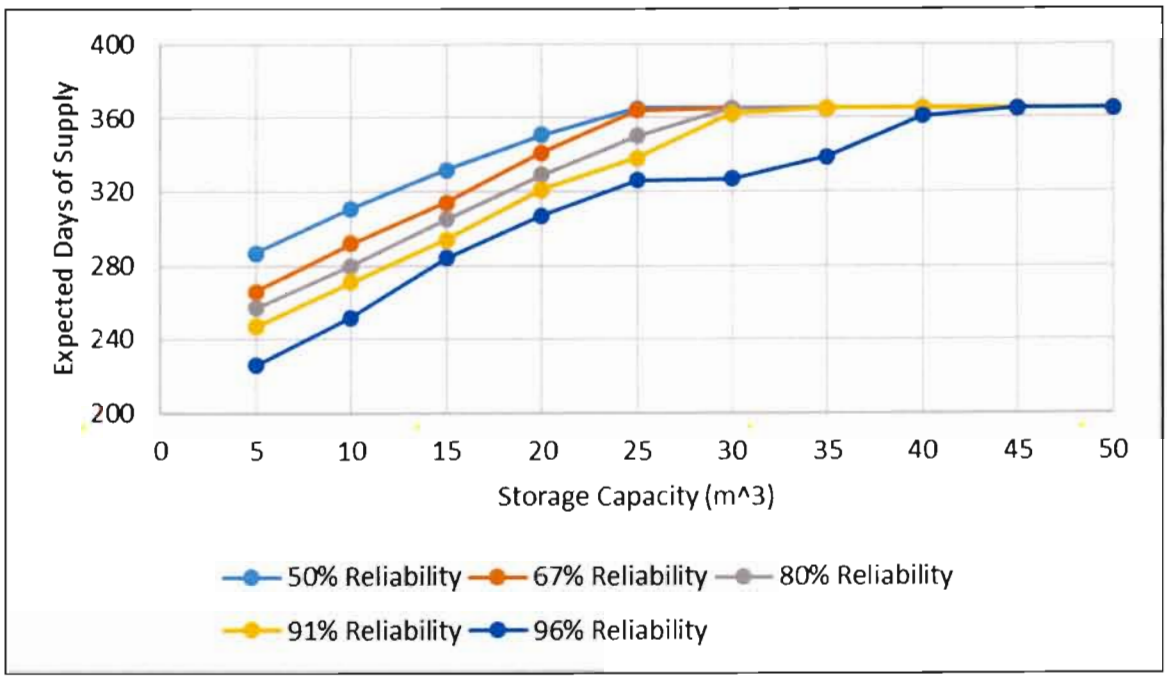


Figure 6.3: Storage-yield-reliability relationship for Homestead 1 based on required demand (25 l/d/capita applied constantly).

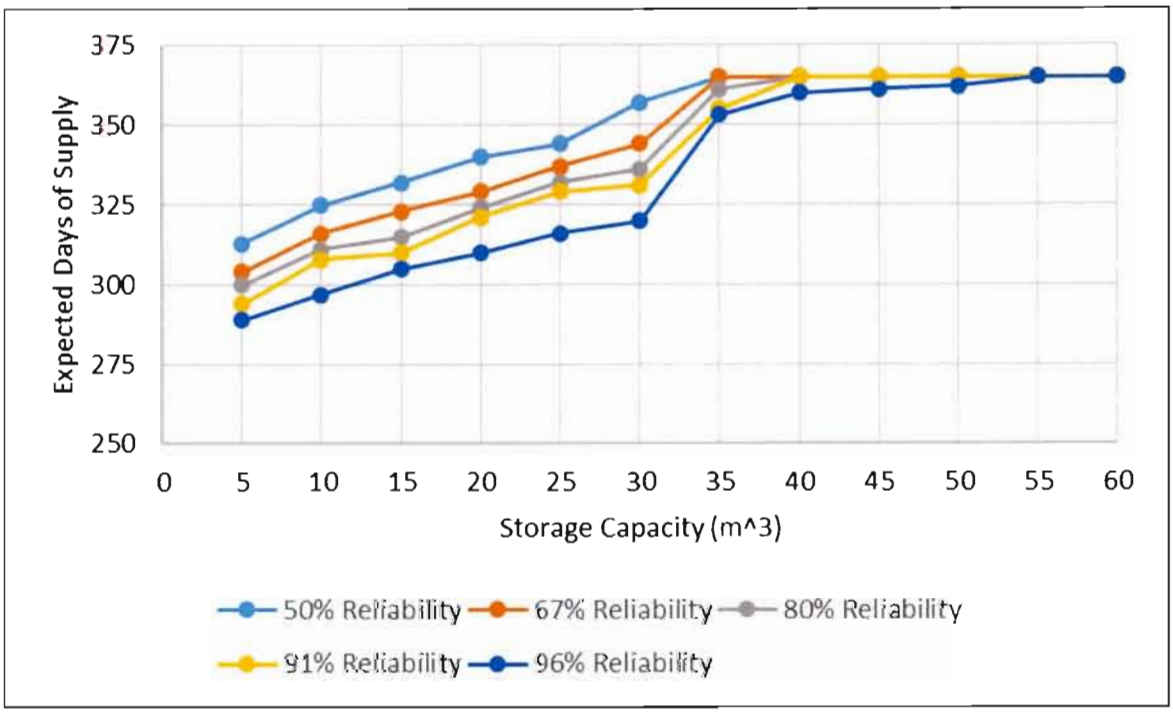


Figure 6.4: Storage-yield-reliability relationship for Homestead 1 based on required demand (25 l/d/capita applied variably)

The relationship between storage and roof area that can achieve full supply of 25 l/d per capita for 365 days in a year for household 1 is illustrated in figure 6.5. For a reliability of 96%, the existing roof area range of up to 180m^2 requires a storage capacity of 45m^3 while much larger

areas lead to only a slight reduction in required storage to 40m^3. Therefore, extending the roof area may be sub-optimal and unnecessary for household 1.

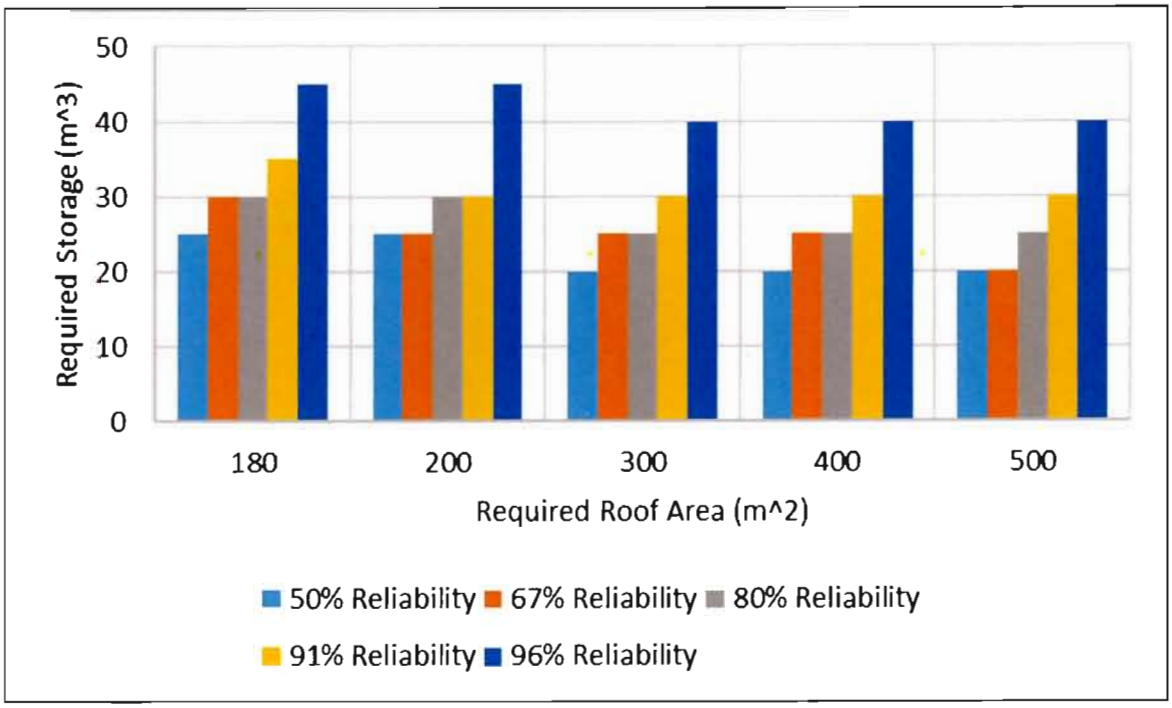


Figure 6.5: Storage-roof area-reliability relationship for Homestead 1 when the required demand is maximized (thus 25 l/d/capita over 365 days of supply in a year).

6.2.2 Rainwater Harvesting Potential for Homestead 2

When the measured consumption of 13 l/day per capita is supplied constantly, a storage capacity of 25m^3 is required to achieve full supply of 365 days per year at a statistical reliability of 96% as shown in figure 6.6, whereas figure 6.7 shows that varying this measured consumption within a year does not change the storage capacity required to achieve the same level of supply and reliability. Once again if the roof areas and storages of household 2 were integrated into a single RWH unit, figures 6.6 and 6.7 show that the existing capacity of 15m^3 could supply 335 days per year at 96% reliability.

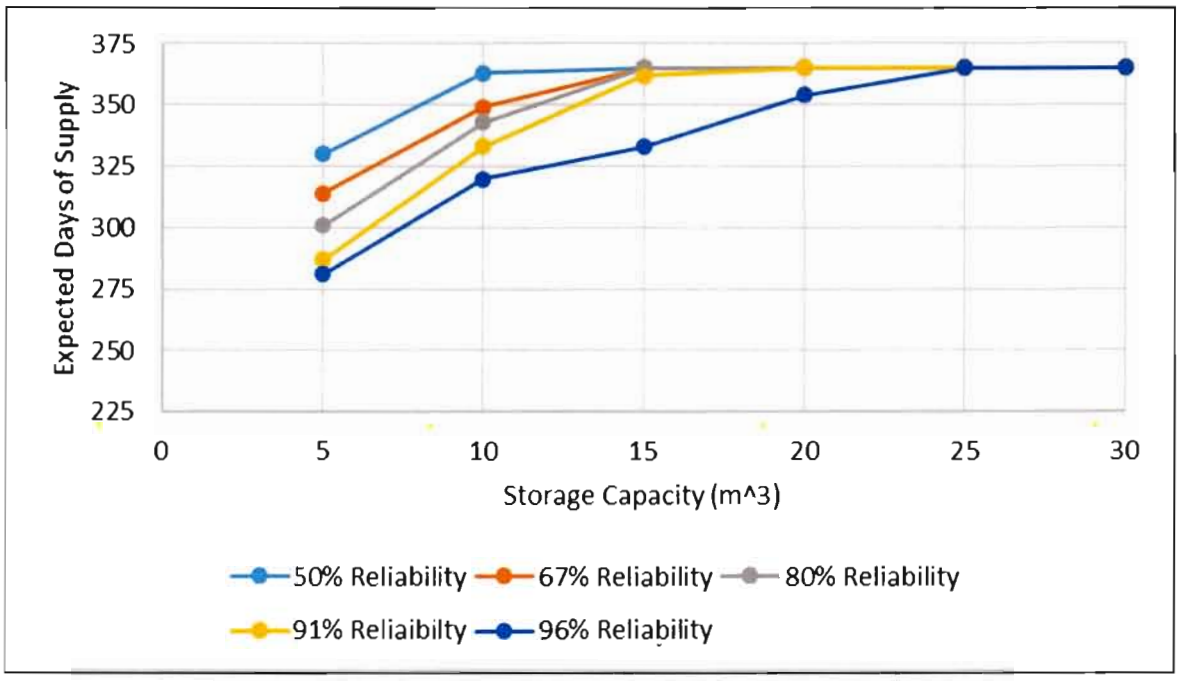


Figure 6.6: Storage-yield-reliability relationship for Homestead 2 based on measured consumption (13 l/d/capita applied constantly).

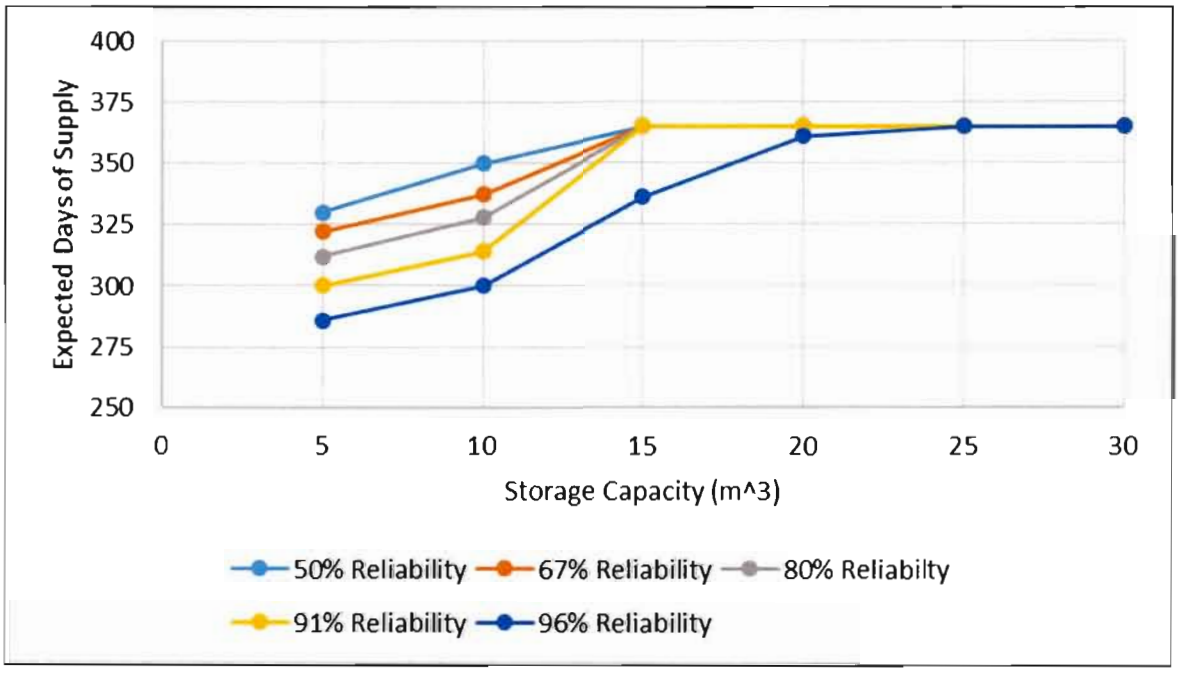


Figure 6.7: Storage-yield-reliability relationship for Homestead 2 based on measured consumption (13 l/d/capita applied variably).

The storage-yield-reliability relationship when the demand from the rural water supply guidelines of 25 l/day per capita is applied constantly is shown on figure 6.8. It is seen that a 45m^3 storage is required to achieve 365 days of supply in a year at a statistical reliability of 96%. Simulations with a variable demand illustrated on figure 6.9 indicate that the same capacity of 45m^3 achieves full supply at 96% reliability. An integrated RWH supply system with

the existing storage of 15m^3 supplying a constant demand from the guidelines could supply 280 days of the year at statistical reliability of 96% as figures 6.8 and 6.9 show.

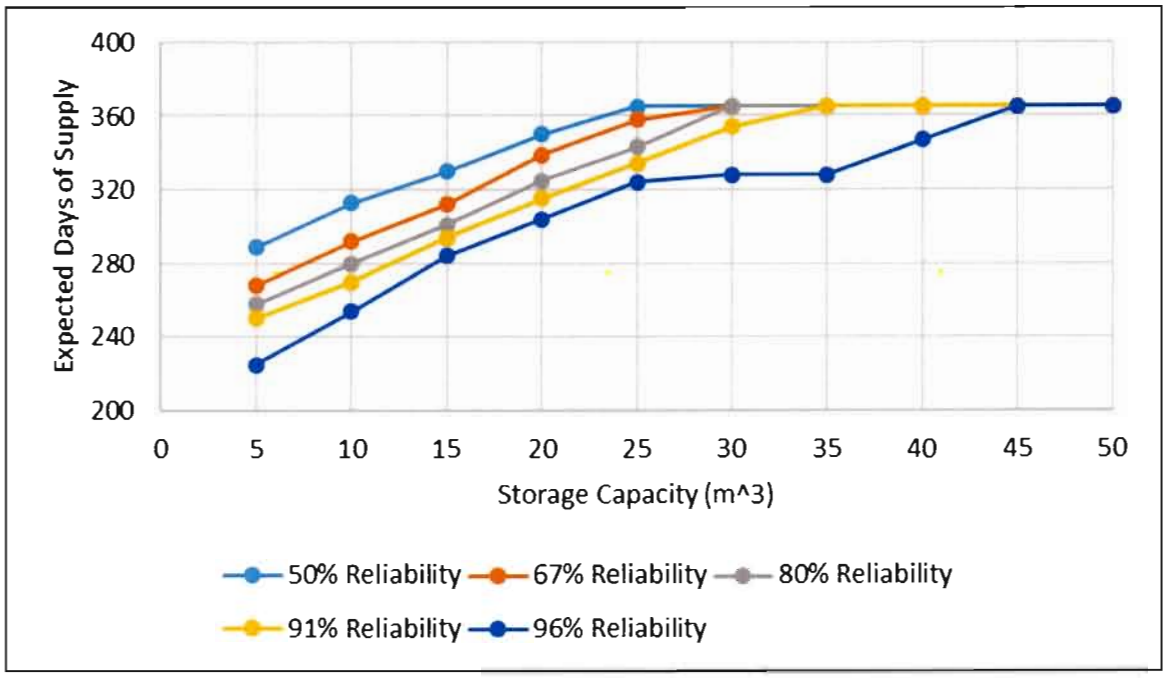


Figure 6.8: Storage-yield-reliability relationship for Homestead 2 based on required demand (25 l/d/capita applied constantly).

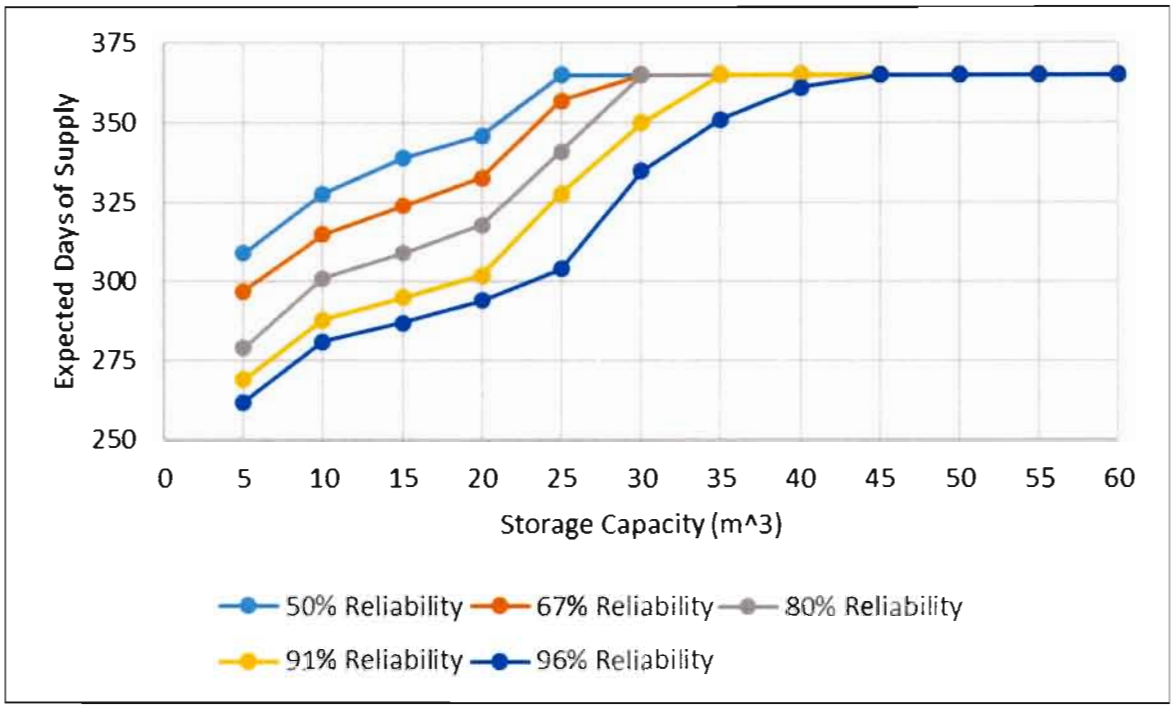


Figure 6.9: Storage-yield-reliability relationship for Homestead 2 based on required demand (25 l/d/capita applied variably).

The storage – roof area – reliability relationships for full supply of the 25 l/day /capita demand applied constantly from the guidelines (CSIR, 2005) are shown on figure 6.10. The existing roof area for household 2 of 230m^2 requires a storage capacity of 45m^3 at a reliability of 96% and only a large increase in the roof area to 600m^2 enables a slight reduction in the required capacity to 40m^3. The provision of extra roof area for this household may therefore not be necessary and obviously be not optimal.

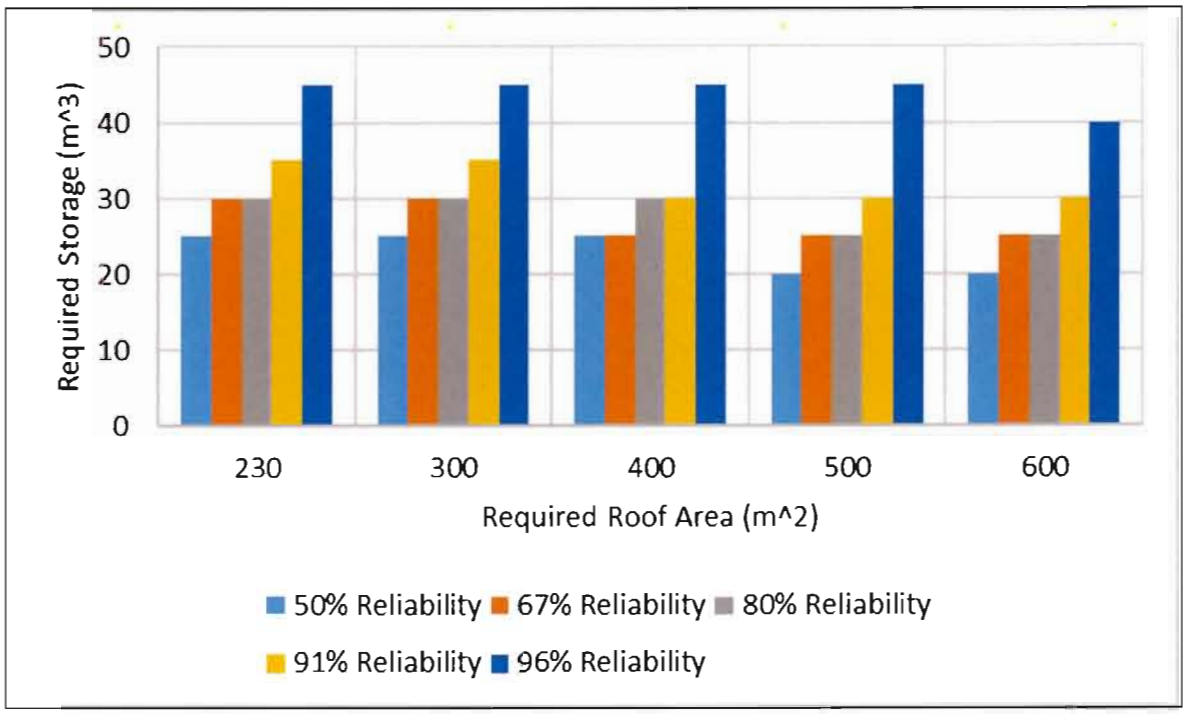


Figure 6.10: Storage-roof area-reliability relationship for Homestead 2 when the required demand is maximized (thus 25 l/d/capita over 365 days of supply in a year).

6.2.3 Rainwater Harvesting potential for the Clinic.

The storage-yield-reliability relationship applying various scenarios for the clinic is shown on figures 6.11 to 6.15. A storage capacity of 50m^3 can supply a constant measured water consumption of 4.3 l/day per capita for 365 days at a statistical reliability of 96% as figure 6.11 shows. When the same measured consumption is supplied variably using the measured variation, figure 6.12 reveals a slight increase in the required storage to 55m^3 for full supply at 96% reliability. Figures 6.11 and 6.12 also show that an integrated system with the existing storage of 15m^3 would supply a measured water consumption for 290 days per year at a reliability of 96%.

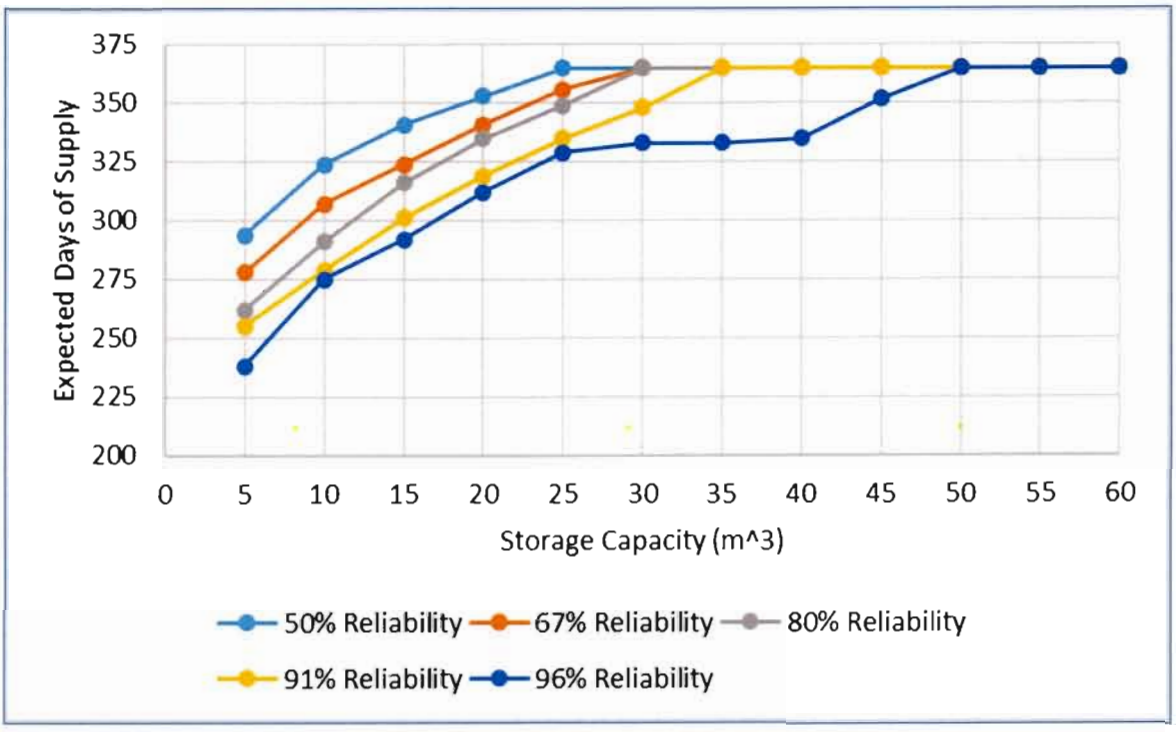


Figure 6.11: Storage-yield-reliability relationship for the Clinic based on measured consumption (4.3 l/d/capita applied constantly).

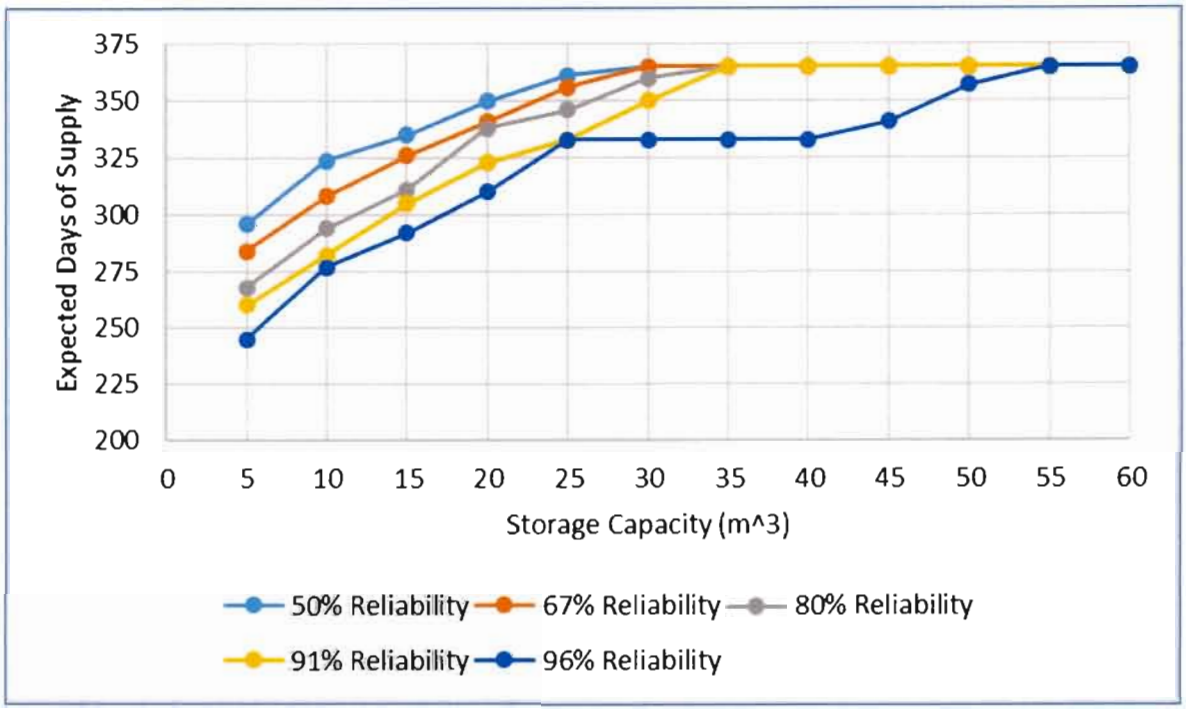


Figure 6.12: Storage-yield-reliability relationship for the clinic based on measured consumption (4.3 l/d/capita applied variably).

For the scenario assuming constant demand of 5l/day/capita from the guidelines, figure 6.13 shows that a storage capacity of 55m^3 can achieve full supply at a statistical reliability of 96%. When the same required demand is supplied using the measured monthly variability, figure

6.14 shows that full supply at a statistical reliability of 96% requires a slightly larger storage of 60m^3. With the existing storage of 15m^3, figures 6.13 and 6.14 reveal that an integrated RWH-based water supply system would supply 280 days of the required demand at 96% reliability.

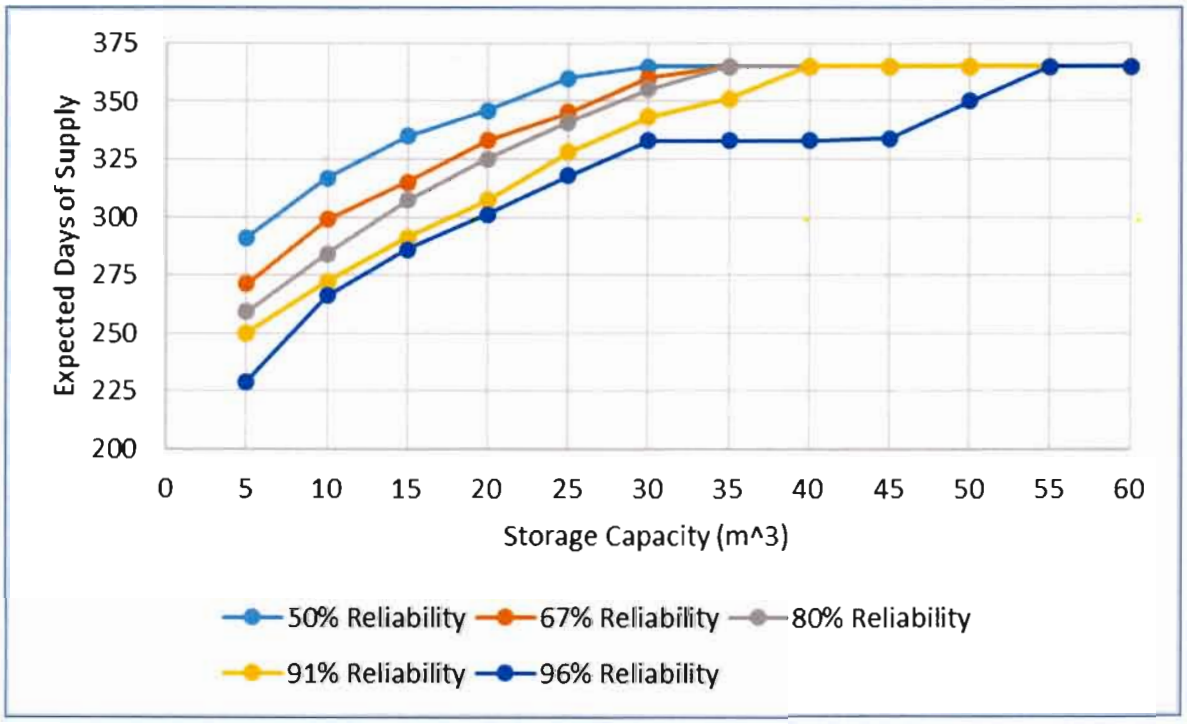


Figure 6.13: Storage-yield-reliability relationship for the Clinic based on required demand (5 l/d/capita applied constantly).

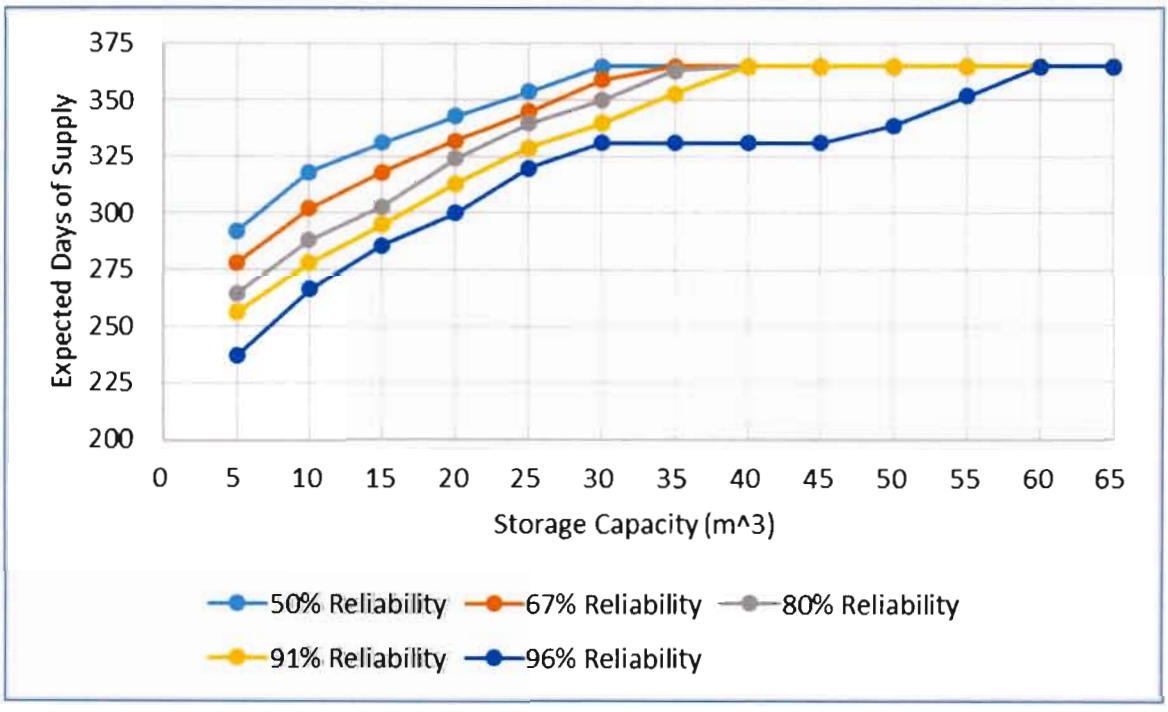


Figure 6.14: Storage-yield-reliability relationship for the Clinic based on required demand (5 l/d/capita applied variably).

The storage-roof area-reliability relationship for a full supply of constant 5 l/day/capita is shown on figure 6.15. The current roof area of the clinic (485m^2) requires a storage capacity of 55m^3 for a reliability of 96% and only an increase in the roof area to 700m^2 could lead to a (small) reduction in the storage requirement at this reliability. Increasing the roof area also leads to a small reduction in required storage at lower reliabilities and would therefore not be advisable for the clinic.

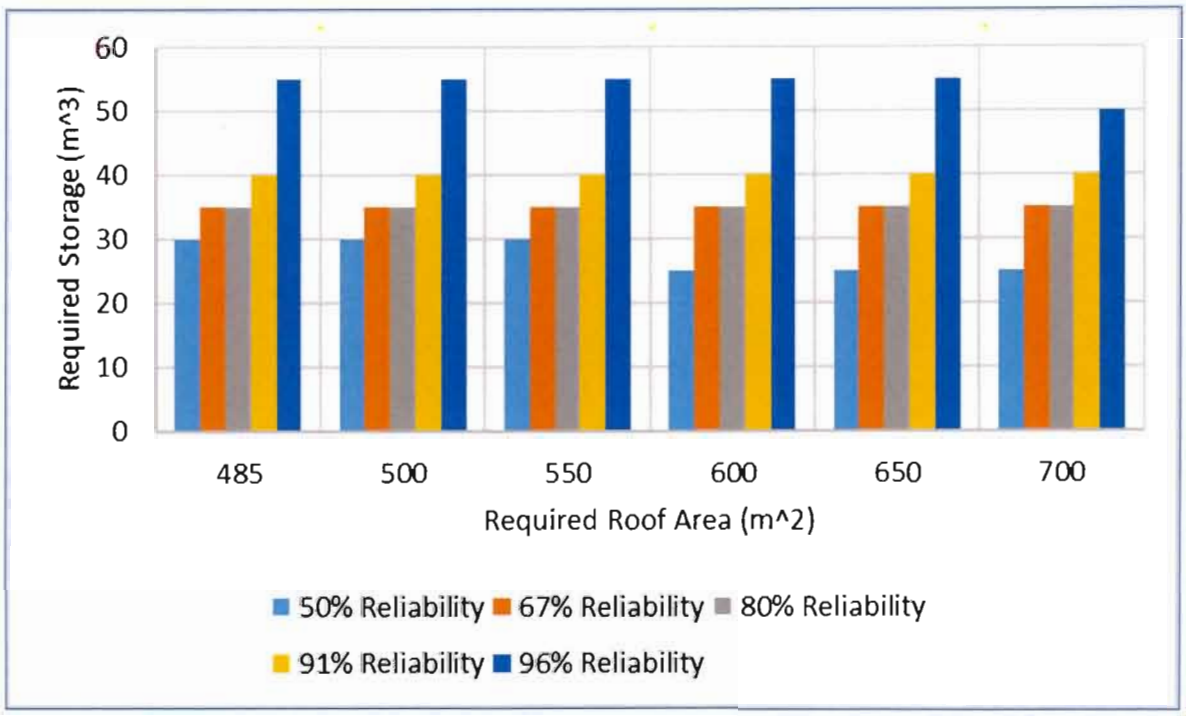


Figure 6.15: Storage-roof area-reliability relationship for the Clinic when the required demand is constantly maximized (thus 5 l/d/capita over 365 days of supply in a year).

6.2.4 Rainwater Harvesting potential for the school.

The average monthly daily water consumption physically measured at school is 1.42 l/day per capita which is exceedingly lower than the demand of 5 l/day per capita stipulated in the guidelines for rural water supply (CSIR, 2005). This low measured consumption might be as a result of limited water availability for the school and was considered too low for a realistic assessment of RWH potential. Furthermore, the water consumption data for the school did not include considerable parts of the year and a complete monthly distribution of water consumption could therefore not be obtained for the school. Analysis was therefore undertaken using only the constant demand of 5 l/day per capita as stipulated in the guidelines (CSIR, 2005).

The storage-yield-reliability relationships on figure 6.16 reveal that a storage capacity of 90m^3 is required to achieve 96% statistical reliability in supplying a constant demand of 5 l/day per capita for 132 days in a year. If weekends and school holidays are considered as demand-free days of the year, the demand of 5/day/capita would be required for 250 days of the year and 132 days implies 53% supply of the school's requirement. Unlike the other RWH-based water supply systems, the school's full demand cannot be met with the existing roof area even if the storage capacity is increased. As shown in figure 6.16, an integrated existing RWH-based water supply system would supply 86 days (34%) of the demand at 96% reliability.

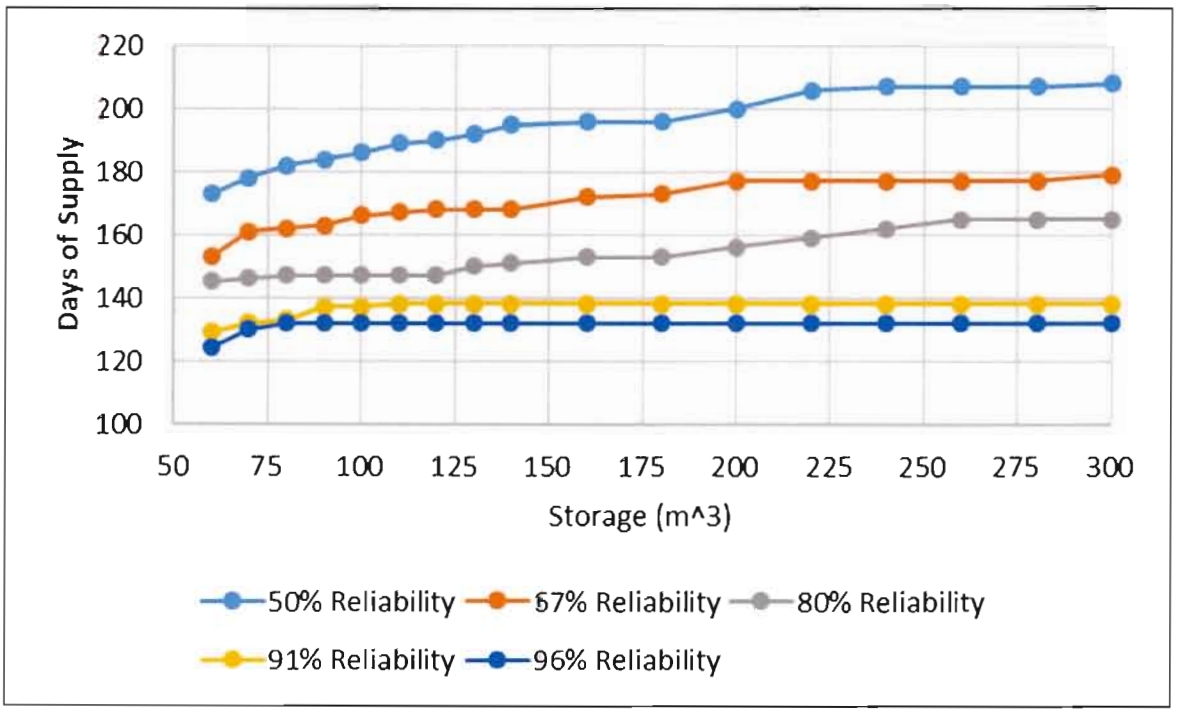


Figure 6.16: Storage-yield-reliability relationship for the school based on required demand (5 l/d/capita applied constantly).

The storage-roof area-reliability relationships for the full supply of 250 days for the school are shown on Figure 6.17. As already seen on Figure 6.16, the existing roof area of 1246m^2 cannot meet the supply of 250 days per year at all reliabilities and is therefore not included on Figure 6.17. A roof area of 1500m^2 could meet the full supply at a reliability of 50% using a storage of 380m^3 but cannot achieve full supply at the other higher reliabilities. Roof areas of 1750 and 2000m^2 can achieve full supply for 2 and 3 of the reliabilities respectively as seen on Figure 6.17 while areas of 2250 and 2500m^2 can achieve full supply at all selected reliabilities.

The figure also reveals that the required storages for full supply reduce as the roof area available increases indicating that the optimization that includes the life cycle costs of both storage and roof area might be a consideration for a RWH-based water supply system for the school to meet full supply.

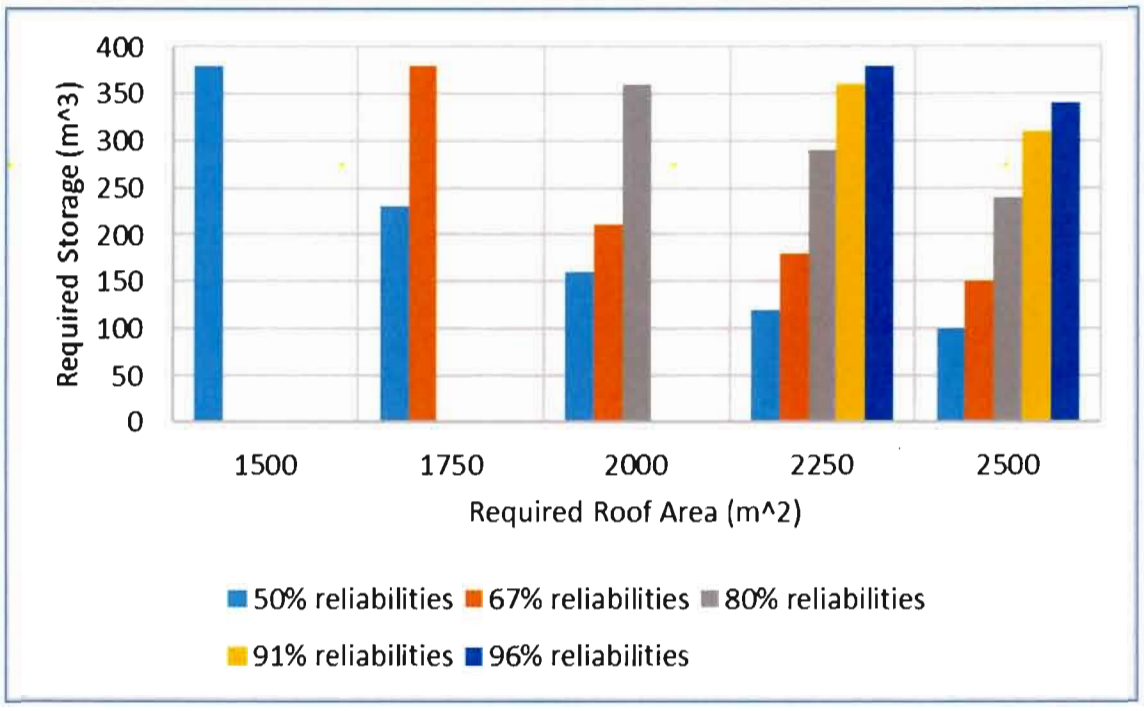


Figure 6.17: Storage-roof area-reliability relationship for the school when the required demand is maximized (thus 5 l/d/capita over 250 days of supply in a year).

6.3 Summary.

A summary of a selection of the results presented in Sections 6.2.1 to 6.2.4 is provided on Table 6.1. These are based on the scenarios applying the constant demands as stipulated in the guidelines for rural water supply (CSIR, 2005) and a statistical reliability of 96%. It is found that the existing RWH systems for households 1 and 2 and the clinic can supply the demand for 8-9 months of the year while the existing school's system can supply only about 3 months of supply per year. Table 6.1 also informs that increasing the storage capacities of the RWH systems of the households and the clinic can achieve full supply with the existing roof areas. For the school however, an increase in both storage capacity and roof area would be required to achieve full supply.

The results reveal that hydrologically, RWH has the potential to meet the water demand requirements for the selected water users at the level of supply 3 (LOS 3) as stipulated in the

guidelines. According to Table 4.3 (Section 4.6) this level corresponds to a demand with a single metered standpipe per site. The next chapter assesses the financial viability of the full-supply RWH-based water supply system in comparison to equivalent centralized municipal water supply system.

Table 6.1: Levels of supply of existing RWH systems and increases in storage and roof areas for full supply of demands stipulated in guidelines at 96% statistical reliability.

RWH system	Level of supply of existing system (Days per year)	Change in storage required to achieve full supply with existing roof area	Storage and roof area required to achieve full supply
Household 1	250	10 to 45m^3	45m^3 with 180m^2*
Household 2	280	15 to 45m^3	45m^3 with 230m^2*
Local Clinic	280	15 to 55m^3	55m^3 with 485m^2*
Local School	86	Full supply not achievable	380m^3 with 2250m^2 340m^3 with 2500m^2

*Existing roof area

7. LIFE CYCLE COST ANALYSIS

7.1 Overview

This chapter presents the analysis responding to the third research question regarding financial feasibility of RWH implementation and includes comparison with equivalent municipal distribution systems. The Life Cycle Cost Analysis (LCCA) for the two households is expected to be similar and analysis is therefore carried out for one of them (household 1). Chapter 6 revealed that the school's RWH system cannot achieve full supply with the existing roof area even when the storage capacity is increased and LCCA that includes the construction of additional classes/buildings to achieve this was considered beyond the scope of the study. The clinic has an overall daily demand that is slightly higher than that of households 1 and 2 and would not therefore require a separate centralized water supply. The LCCA in this chapter is therefore confined to household water supply only assuming that the 170 households (statssa online, 2022) in the community would each be equivalent to household 1.

7.2 Parameters for RWH system's Financial Performance

7.2.1 Total initial or capital cost

This cost comprises of material such as gutters, downspouts (down pipes) including first flush, masonry or concrete base, storage facility (tank) including associated fittings such as lids and taps, the overflow downpipes as well as transport and installation cost.

7.2.2 Maintenance and operation cost

These are time-related costs which comprise of mostly labour, gutters replacement including associated fittings, downspouts (down pipes) replacement including first flush, the associated fittings and the replacement of overflow downpipes also including the associated fittings. The maintenance costs associated with the replacement of pipes and associated fittings within the design life are also incorporated into the LCCA.

7.2.3 Design life and discount rates

For this study, a 50 year design life has been adopted and a discount rate of 5.25% (SA Interest rate update, 2020) was applied in the LCCA.

7.2.4 Electricity, salvaging and disposal costs

In most instances, as indicated in chapter 4.6, RWH systems particularly in rural areas, would be operated through a gravity system and therefore no electricity cost would be anticipated. Decommission and disposal cost or salvage cost is regarded as minor in this research and therefore neglected.

7.3 Parameters for Municipal Distribution System's Financial Performance

As indicated in Section 4.6, one of the LCCA scenarios seeks to estimate the actual cost of municipal water supply, thus generally providing water infrastructure while the other one uses municipal water tariffs that are typically highly subsidised. For the scenario that seeks to determine the actual cost of municipal water supply, households are therefore considered to be individually paying for the total cost of water supply. Practically, however, if the community is categorized as indigent, the water service authority or the municipality could then partially or fully subsidise or absorb the cost. The municipal water supply system adopted for the analysis is groundwater-based infrastructure and consists of the following costs.

7.3.1 Total initial or capital cost

The cost comprises of a high-level total project cost of work including design and construction of a regional or local water scheme in the area of study. This would inter alia entail, siting, drilling and equipping of borehole for water source, construction or installation of bulk water line (rising main including the associated fittings) from the water source to the existing storage reservoir, and construction of gravity reticulation system to a water supply level of service 3 as stipulated by CSIR (2005). The capital cost of such water supply infrastructure is therefore assumed or considered to be shared amongst all households that are supplied with water from the scheme.

7.3.2 Maintenance and operations costs

These are time-related costs which would comprise the general day-to-day operation of the local water supply scheme, including pump station's power consumption of the borehole facility and pump set maintenance and repairs. Ground water in the area is of good quality and any treatment to achieve potable water standards is considered insignificant or comparable to any treatment that roof-based rainwater could require. Water treatment costs are therefore not included.

7.3.3 Design life and discount rates

Although the useful design life of municipal distribution system is normally considered to be 20 years (DWAF, 2004), if the infrastructure is effectively maintained, the useful design life can be extended to as long as 50 years. For the analysis in this study a design life of 50 years is adopted. South Africa's discount rate at the time of research was 5.25% (SA Interest rate update, 2020).

7.3.4 Electricity, salvaging and disposal costs

Power consumption is the primary contributor to maintenance and operation cost in the municipal distribution system, particularly the bulk water supply from the source to the storage reservoir. Decommissioning and disposal cost is regarded as minor in this research and therefore neglected.

7.4 Data Acquisition for RWH financial costs

General financial data was collected from the nearest rainwater harvesting tools or material supplier (Builders Warehouse) and is presented in tables 7.1 and 7.2. LCCA was conducted based on RWH system that meets the required constantly supplied demand as per results reported in section 6.2.1 as well as table 6.1, for homestead 1. The optimal storage capacity derived from a daily time step simulation was 45m^3 to provide water for a period of 365 days in a year at 96% statistical reliability. The costs in the tables 7.1 and 7.2 are all subject to escalation and 5.25% escalation rate has been incorporated into the analysis.

Table 7.1: RWH capital costs for Homestead 1

Item	Material	Unit	Rate	QTY	Amount
1	Gutters white pvc 4m long	No	R 230,00	13	R 2 990,00
2	Galvanised round holderbat pipe clip (100x75mm)	No	R 20,00	52	R 1 040,00
3	Double floor union Clip	No	R 50,00	13	R 650,00
4	Round steel/plastic downpipe to the first flush system	No	R 100,00	7	R 700,00
5	First flush system (estimated)	No	R 1 050,00	7	R 7 350,00
6	Gutter D stop end white	No	R 55,80	7	R 390,60
7	Round socketed downpipe	No	R 120,00	7	R 840,00
8	10 000 litre Jojo tanks	No	R 10 000,00	4.5	R 45 000,00
9	Tap	No	R 200,00	3	R 600,00
10	overflow down pipes (2m long hdpe)	No	R 100,00	3	R 300,00
11	Masonry/concrete stand	No	R 4 000,00	4.5	R 18 000,00
12	Delivery and Installation/labour	Sum	R 12 800,00	1	R 12 800,00
	Total Capital Cost				**R 90 660,60**

The maintenance and operational cost in table 7.2 are estimated and projected from items relative to the capital cost as displayed in table 7.1. Maintenance and operational cost predominantly entail replacement that is presumed to be undertaken at a frequency of five years. The figures in table 7.2 are rounded off to the nearest rands with an escalation rate of 5.25% incorporated.

Table 7.2: RWH maintenance and operational costs for Homestead 1

Item No.	RWHs Parameters (description)	Unit	Escalated Rate	Amount
1	Gutters replacement including associated fittings	sum	R 500,00	R 500,00
2	Downspouts (downpipes) replacement including associated fittings	sum	R 500,00	R 500,00
3	First Flush System replacement including associated fittings	sum	R 500,00	R 500,00
4	Overflow pipes replacement including associated fittings	sum	R 250,00	R 250,00
5	Installation and general routine cleaning of the roof and tank	sum	R 1 000,00	R 1 000,00
	Total Maintenance & Operation Cost (5 years interval)			**R 2 750,00**
	Total Maintenance & Operation Cost (1 year interval)			**R 550.00**

7.5 Data Acquisition for Municipal Distribution System Financial costs

Data acquisition in relation to a centralised municipal distribution system's (MDS) full supply cost was determined for the two scenarios.

Scenario 1 used a preliminary design of a regional water supply scheme at water service authority (municipal) level to estimate the overall cost of relevant water supply infrastructure as illustrated on section 7.3. The cost of providing the infrastructure was considered to be shared equally amongst the water users to obtain costs comparable to those for the household RWH systems.

It was considered sufficient to obtain the costs from a project of similar nature that was implemented in Limpopo Province by Lepelle Northern Water. The project was described as "*Tshikundamalema Integrated Water Resource Management pilot*" (Nxulu et al., 2015). It was

a borehole-based bulk water and reticulation supply project designed to a level of service (LOS 3) with similar geographic and demographic set-up as the selected area of study. It however had 107 number of households (Nxulu et al., 2015) while the current study area has 170 number of households (statssa online, 2022), but, for comparison purpose and accuracy of analysis, 107 households have been adopted for this study. Tables 7.3 and 7.4 present the capital and operation & maintenance costs respectively for the project relative to municipal distribution system.

Table 7.3: Estimated Municipal distribution system: capital costs (adopted from Nxulu et al, 2015)

Tshikundamalema Pilot Project: Borehole siting and drilling, only HDPE pipe at shallower depth, one pumping main considered		
SECTION	**DESCRIPTION**	**AMOUNT**
1	PRELIMINARY & GENERAL	306 497,00
2	Borehole siting and drilling	82 600,00
3	Bulk Gravity Main (Springs to PS)	109 606,00
4	Bulk Pumping Main (PS to Reservoirs)	685 060,00
5	Storage	55 000,00
6	Water Reticulation	1 694 800,00
7	Elect-Mech Works	192 700,00
8	**SUBTOTAL**	**3 126 263,00**
9	ADD 10% CONTINGENCIES	312 626,30
10	**SUBTOTAL B**	**3 438 889,30**
11	Professional fees	
12	Civil and Eletro-Mech (10%)	375 151,56
13	Construction Supervision	300 000,00
14	Sub-Consultant	
15	Topographical Survey	65 000,00
16	Occupational Health and Safety services	55 000,00
17	Environmental Impact Assessment services	50 000,00
18	Disbursements (0.5%)	
19	Travelling	7 815,66
20	Printing, Plotting & Typing	7 815,66
21	**Subtotal**	**4 299 672,18**
22	ADD 14% VAT	601 954,10
23	**TOTAL**	**4 901 626,28**

As also seen in table 7.4, the amount of R 45 900 (R 4 901 626.28/107) is capital cost that would be paid by each household if costs for infrastructure were to be recovered from the individual water users (household) serviced by the water scheme, furthermore R 80.00 (R 8 500/107) subjected to 5.25% escalation rate, is the maintenance and operational cost that would be subsequently paid monthly by each household for provision of water over 50 years. The annual

maintenance and operation costs work out to be R 960.00 (R 80.00 x 12months) and is also subjected to 5.25% escalation rate.

Table 7.4: Municipal distribution system: capital, maintenance and operational costs (adopted from Nxulu et al, 2015)

Item No.	MDS Parameters (description) and material specifications	Unit	Escalated Rate	Amount
1	**Total Capital Cost (TCC, from table 7.3)**- High level total project cost of works typically inclusive of design and construction of regional or local water scheme in the area of study	Sum	**R 4 901 626.28**	**R 4 901 626.28**
2	**Total Maintenance and Operation Cost** (TMOC)	Sum per month	**R 8 500,00**	**R 8 500,00**
2.1	Pump station-electricity consumption per month	sum	R 4 000,00	R 4 000,00
2.2	Labour - Operators	sum	R 4 500,00	R 4 500,00
	TCC per household	Sum		**R 45 900,00**
	TMOC per household per month	Sum per month		**R 80,00**

Scenario 2 considers the user's water bills directly at end-user's level, thus using the subsidised municipal water tariffs to determine the cost of water supply. The daily water consumption of 0.2 m^3/day (25 l/day x 8 no. of individuals for homestead 1) costs between R 13.06 and R 13.68 per m^3 based on water rate from the municipality's water tariff (Alfred nzo district municipality's water tariffs, 2021), thus translating to R 953.00/annum when using R 13.06/m^3. This cost is subjected to an annual compounding escalation rate of 5.25%.

7.6 Results of LCCA and Discussion

The results of the LCCA are presented on figure 7.1. It reveals that RWH could have a payback period of 14 years if the actual non-subsidised cost of municipal water supply is adopted. The figure 7.1 also reveals that RWH would have a payback period of 39 years if subsidised municipal rates are adopted. For both scenarios however, the life cycle cost for RWH over the design life of 50 years is much lower than municipal water supply.

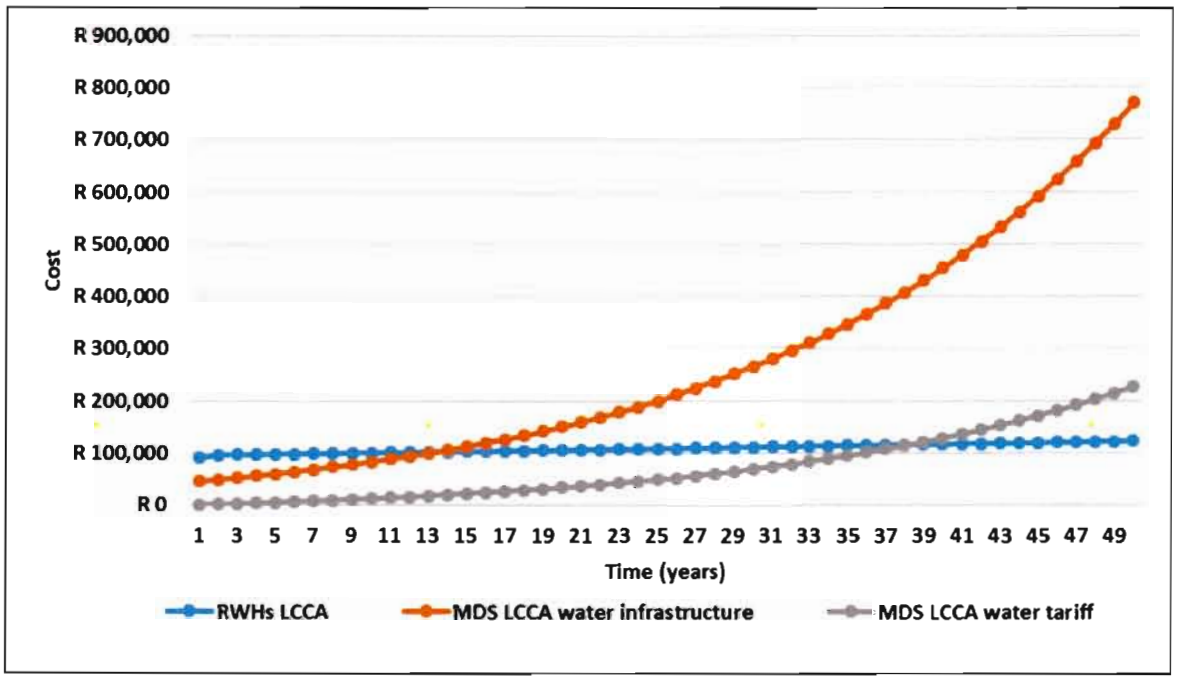


Figure 7.1: Cumulative Life cycle cost analysis and comparison for homestead 1

The study reveals that potable water use from the municipal water supply (both scenarios) would have a significantly lower initial cost than obtaining water from RWH thereby leading to large pay-back periods. Thus, from the perspective of the water users, a full water supply from RWH would be realistic if the high initial cost would be affordable especially for conditions where municipal water supply is unreliable. For users who may not afford the fully supplying RWH system, subsidised municipal water supply would be preferable. However, as probably experienced in the study area and other rural areas of South Africa, water users still implement the RWH systems they can afford where municipal water supply is unreliable or non-existent.

The LCCA results on figure 7.1 also reveal that municipal water supply is largely subsidized as the actual costs of supply are much higher than the monetary returns accrued from payments. It is understood that water remains a social good subsidized by government particularly for indigent community like in the study area. However, since figure 7.1 reveals that the actual life cycle cost of municipal water supply exceeds that of RWH by far (about 3.4 times at the end of the design life), a strategic direction by the government towards increased subsidy for RWH may be advisable.

8. CONCLUSION AND RECOMMENDATIONS

The primary objective of the study was to determine the rainwater harvesting (RWH) potential of the eZizityaneni and kwaNdela communities located in a rainfall-rich area of the Eastern Cape province of South Africa. The study also aimed to find out whether the communities can rely primarily on RWH and how this could be best achieved. It also aimed to determine the RWH financial viability in comparing RWH-based water supply with traditional municipal water supply. Two households, a school and a clinic were selected as representative RWH-based water users in the community for this study.

The first objective of the study was to determine the RWH potential on the selected study area and find out if the community in the area can rely primarily on RWH i.e., without the need for any municipal water supply. The research question aligned to this objective seeks to find out what levels of water supply and statistical reliability could be achieved by the selected existing RWH systems in the study area. The second objective of the study was to determine the changes to the existing RWH systems that would be required to fully supply the water demands.

The study revealed that households can rely on RWH system with a storage capacity of $25m^3$ to supply the measured average total daily water consumption of 129 l/day and 136 l/day for household 1 and 2 respectively over 365 days in a year at 96% statistical reliability. If the demand is increased to the required 25 l/day per capita as recommended by department of water affairs (DWAF, 2004), giving a total daily demand of 200 l/day and 250 l/day for household 1 and 2 respectively, the storage capacity required would increase to $45m^3$ for both household 1 and household 2 to supply water over a period of 365 days in a year at statistical reliability of 96%. It can therefore be concluded that both household 1 and 2 in the selected area of study can rely primarily on RWH-based water supply system without any backup from the municipal water supply system. The levels of supply from the existing RWH systems for household 1 and 2 with storages of 10 and $15m^3$ respectively are 250 and 280 days per year, respectively.

If the required demand is sustained at 5 l/day per capita for the clinic as recommended by department of water affairs (DWAF, 2004), giving a total daily demand of 325 l/day, a storage capacity of $55m^3$ for supply of water over a period of 365 days in year at statistical reliability of

96% would suffice. This study therefore revealed that the clinic can rely primarily on RWH supply system also without any backup from the municipal water supply system. The total average water consumption physically and continuously measured on site over the study period from July 2019 to June 2020 was found to be 278 l/day and the level of supply from the existing RWH systems for the clinic is 280 days per year at 96% statistical reliability.

The study however revealed that the school cannot rely on RWH system without a large increase in the roof collection area from the existing area of 1246m^2 to 2250m^2. The required demand of 5 l/day per capita for the school as recommended by department of water affairs (DWAF, 2004), gives a total daily demand of 5615 l/day. With the existing roof area and storage capacity of 27.5m^3, the level of supply at 96% reliability is 86 days per year. A storage capacity of 90m^3 would maximize supply for the current roof area to 132 of the 250 school days (excluding holidays and weekends) in a year at statistical reliability of 96%. Increasing the roof area to 2250m^2 and the storage to 380m^3 could achieve the full supply of 250 school days at 96% reliability. Alternatively, a roof area of 2500m^2 would also achieve full supply with a storage of 340m^3 at 96% statistical reliability.

The analysis therefore revealed that the RWH supply systems for the households and the clinic can achieve full supply with an increase in storage capacity only while the school's RWH supply system would require increase in both storage and roof area to achieve full supply.

The third objective of the study is to assess financial viability of RWH for the selected rural residential area and the third research question seeks to find out through life cycle cost analysis (LCCA), whether optimal RWH supply system would be more financially viable than municipal water supply system.

For the scenario costing municipal water supply based on water tariffs, the high payback period of 39 years for the household reveals that RWH, unless subsidised, is financially much less viable than municipal water supply. However, for LCCA based on the actual cost of groundwater-based centralized municipal water supply, the cumulative cost of RWH is higher than that of municipal water supply for the first 14 years after which the cost of municipal water supply escalates much faster to a cost that is 3.4 times higher than that of RWH supply

by end of the 50-year design life of the systems. The comparatively lower total life cycle cost of RWH than municipal water supply reveals that subsidizing RWH may be the better of the two options for high rainfall areas as the one studied here.

Given the known historical low level of reliability of the municipal water supply at the study area, RWH is viable and is indeed being practiced. This study has given an indication of the performance of some of the existing RWH systems in the area and what it would take to enable these systems to fully meet the water demands.

Further research towards enhancing RWH in rainfall-rich areas of South Africa is recommended. This needs to be based on comprehensive hydrological analysis and needs to consider the additional social and environmental benefits of RWH. The search for practical approaches for subsidizing standalone water supply systems such as RWH and backyard boreholes as is done for centralised municipal water supply system could also form the basis for further research.

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