ANALYSIS AND DESIGN OF HOUSEHOLD RAINWATER CATCHMENT SYSTEMS FOR RURAL RWANDA

By
Daria Cresti

Diploma di Specializzazione in Architettura dei Giardini e Progettazione del Paesaggio
Universitá di Firenze, Italy, 2005

Laurea in Architettura
Universitá di Firenze, Italy, 1999

Submitted to the Department of Civil and Environmental Engineering
In Partial Fulfilment of the Requirements for the Degree of

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2007

Signature of the Author....................
Department of Civil and Environmental Engineering
May 11, 2007

Certified by..................
Peter Shanahan
Senior Lecturer, Department of Civil and Environmental Engineering
Thesis Supervisor

Accepted by..
Daniele Veneziano
Chairman, Departmental Committee for Graduate Students

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ABSTRACT

The Dian Fossey Gorilla Fund International (DFGFI) contacted MIT in September 2006 for technical assistance to analyze the water-supply potential within the Bisate Sector, Musanze District, Rwanda.

The present study focuses on designing low-cost household rainwater catchment systems to improve the quantity and quality of water available and therefore achieve higher standards of living for the Bisate village. Given the climatic and geographic characteristics of Bisate, rainwater harvesting represents one of the most appropriate solutions to improve water supply.

The designed low-cost household rainwater catchment system consists of an excavated cistern of 6 cubic meters volume, lined with a plastic tarpaulin sheet and covered with a wood and iron lid, and with a hand pump to extract water. The cistern should provide an average of 16 liters/day/person for the entire year for medium-size houses (roof area of 35 m^2) and 21.5 liters/day/person for large-size houses (82 m^2). The excavated cistern is designed with walls to stop surface runoff from entering into the cistern, and a hard cover and hand pump to extract water and minimize water contamination from faecal bacteria.

The implementation of these small-scale rainwater harvesting systems should improve water quality and supply for the families of Bisate Village. Indeed, household rainwater catchment systems should improve water consumption from less than 5 liters/day/person to at least 16 liters/day/person.

The household rainwater catchment system can provide water inside or nearby the house, which is very important as it would drastically reduce travel time for women and children to fetch water. Freeing up time from daily "water walks" could significantly improve school attendance and trade activities, leading to increased education levels and average annual income.

Thesis Supervisor: Peter Shanahan
Title: Senior Lecturer, Department of Civil and Environmental Engineering

ACKNOWLEDGEMENTS

My family - always supporting my decisions

Prof. Eric Adams and Patricia Glidden - for making this experience possible

Prof. Peter Shanahan - for offering advice and support during the MEng program and Rwandan experience

Prof. Alicia Lilly and DFGFI - for the incredible and unforgettable opportunity

Karisoke Research Center - for its assistance and support in Rwanda

Jean Pierre Nshimyimana - Murakoze cyane - for the precious assistance and friendship!

Laura Clauson - for her invaluable hospitality and enjoyable atmosphere

A particular thanks to Kiki and Kelly - it's been wonderful experiencing Rwanda together, sharing unforgettable emotions that strengthen our bond.

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1. INTRODUCTION

The Dian Fossey Gorilla Fund International (DFGFI) contacted MIT in September 2006 for technical assistance to analyze the water-supply potential within the Bisate Sector (Musanze District, Rwanda). The DFGFI is a non-profit organization dedicated to the preservation and protection of the endangered mountain gorillas and their ecosystem, the Virunga Volcanoes Conservation Area. The mountain gorillas of the Volcanoes National Park in Rwanda are threatened by close interaction with the local Rwandan villagers. Villagers, in particular women and children, access the Volcanoes National Park on a daily basis to fetch water due to the lack of local water supply. Most of the villagers are affected by infectious diseases and parasitic worms, which contaminate the gorillas' habitat, threaten their health and eventually their existence. The DFGFI believes the implementation of a sustainable water-supply system in the villages near the Park is critical not only to improve the health and life conditions of the villagers, but also to reduce some of the main threats to the gorillas (Lilly 2006).

Portions of Sections 1.1 and 1.2 are the result of a collaborative effort of an MIT Master of Engineering project team that included the author, Christiane Zoghbi, and Kelly Doyle.

1.1. Dian Fossey Gorilla Fund International

Named after the late Dr. Dian Fossey, the Dian Fossey Gorilla Fund International (DFGFI) was created in 1978 to promote the conservation and protection of the endangered mountain gorillas in Central Africa. Through the encouragement of continued research on both the gorillas and the ecosystems in which they live (DFGFI 2006), the foundation works to keep alive Dian's strong passion and love for primates. The Fund has been instrumental in protecting the endangered mountain gorillas since Dian's tragic death in 1985. Thanks to the foundation members' efforts, the gorillas largely survived the horrors of the 1994 genocide.

Working with local communities is one of the Fund's priorities and includes both educational assistance and economic development support, including tourism. Indeed, the tourist industry continues to rely heavily on the gorillas to attract wealthy foreign tourists and increase income of this poor region.

The DFGFI supports many types of research in an effort to promote increased knowledge and maintain a culture of conservation. The research activity includes primarily: monitoring and protection of the gorillas within the Volcanoes National Park, dissemination of common monitoring procedures, collection of demographic data with the help of local universities, financial support of small-scale development activities in local communities, training of rangers and trackers, GIS data collection, and collaboration with local conservation groups (DFGFI 2006).

In the year 2000, the foundation introduced a Conservation Action Program that included community-based conservation plans, ecosystem health projects, education programs, economic initiatives, and conservation science (DFGFI 2006). With the Ecosystem Health Program, the fund wanted to analyze and study the transmission of infectious diseases between human beings and gorillas. The foundation discovered that gorillas are highly susceptible to humans' intestinal parasitic diseases, leading to the conclusion that better health conditions for Rwandans, especially those living near the gorillas' habitat, could greatly reduce risks for that endangered species. Last year, the DGFGI—in collaboration with the Ministry of Health of Rwanda (MoH)—initiated a project to provide clean water, sanitation facilities, intestinal parasite treatments, and hygiene education to the poor people living in the rural area of the Bisate Sector (Lilly 2006).

1.2. Rwanda

Rwanda is a landlocked country in the middle of Africa (*Figure* 1). It borders with the Democratic Republic of Congo to the west, Uganda to the north, Tanzania to the east, and Burundi to the south. Rwanda has a unique geography, with its six volcanoes, twenty-three lakes, and rivers that feed the Nile (Govt. of Rwanda 2006). The entire nation is 26,340 square kilometers (SEARNET 2006) with 25,000 square kilometers of land area, making it only slightly larger than the state of Massachusetts. About 90% of the population works and live through subsistence farming. Kigali is the main city and capital. As with many underdeveloped countries, Rwanda has been plagued by poverty, ignorance and injustice, and not long ago went through a devastating civil war and genocide.

Figure 1: Rwanda's Geographic Location in Africa (TuTiempo 2006)

Rwanda's infamous genocide began on April 6, 1994, following the death of President Habyarimana in a controversial and mysterious airplane crash (Percival 1995). Without focusing too much on the history of Rwanda, the events that took place in the last two decades have had such a dramatic impact on the country and its current welfare that it is important to give it some consideration. The genocide of 1994 killed an estimated 800,000 people during three months of intense fighting, while twice that many were displaced to neighboring countries (DOS 2006). The genocide disrupted the entire country, leaving many people without basic needs and destroying most of the infrastructure of this small country. The magnitude of those events was such that Rwanda now defines itself in terms of pre- and post-genocide. The aftermath of the killings completely redefined the country and its goals, leaving deep scars in all aspects of Rwandan society.

About 84% of the estimated 8.6 million people living in Rwanda are Hutu, while the remaining 15% are Tutsi and a small percentage Twa. The genocide primarily targeted the Tutsi communities, a minority ethnic group, as noted above. Approximately 94% of the population considers themselves to be Christian, a likely result of the Belgian colonization, which began in 1915. As a result of sub-par health and hygiene conditions, diseases, and the rampant spread of HIV/AIDS, Rwandans' average life expectancy is only 47 years (DOS 2006).

The current density of 320 people per square kilometer (Census 2002) makes Rwanda one of the most densely populated countries in Africa (Wikipedia 2006). Considering that most of Rwandans rely on subsistence agriculture, there is an enormous pressure on available land and the country's natural resources. Due to the disruptions suffered during the genocide, many citizens fled the cities towards rural areas. Over time, the extreme poverty, high population density, and unabated land erosion has forced people to clear more and more land in the mountains. The reduction in vegetation, the extensive farming and soil degradation further exacerbated the pre-existing serious shortage of water, especially in the northwest region of the country (Bangs 2006).

1.3. Volcanoes National Park

1.3.1. History and Administration

The origin of the Parc National des Volcans (Volcanoes National Park or PNV, *Figure 2*) dates back to 1925, when Rwanda was a Belgian colony under King Albert I, who created the Albert Park between Rwanda, Congo, and Uganda. A few years earlier, the American naturalist Carl Akey had discovered the mountain gorillas on the three volcanoes Mikeno, Karisimbi and Bisoke. In order to protect the gorillas and their natural habitat, King Albert I decided to create the Albert Park. In 1960, when Congo became independent from Belgium, the Albert Park became the Volcanoes National Park. When Rwanda also became independent in 1962, the Rwandan portion of the park became state property. Current preservation of the Volcanoes National Park is regulated under the Decree of 24 April 1974, under the supervision and management of the Office Rwandais du Tourisme et des Parcs Nationaux (ORTPN 2005).

According to a report published by the United Nations Environmental Program (UNEP) and the World Conservation Monitoring Centre (WCMC), the Volcanoes National Park in Rwanda is about 15 km to the northwest of Ruhengeri, in the Virunga Mountains (northwest section of Rwanda). It borders with the Democratic Republic of Congo and Uganda (1° 21'–1° 35'S, 29° 22'–29° 44'E). (UNEO-WCMC 1985)

The PNV covers the southern portion of the Virunga Massif, and is almost 40 km long and 1 to 8 km wide. The altitude varies from 2,400m at the edge of the volcanoes to 4,507m at the highest point of Karisimbi Volcano. With its total surface of about 160 km^2, the park is the smallest of the three Rwandan parks. The surface is distributed over the two Provinces of Ruhengeri (85%) and Gisenyi (15%). (ORTPN 2005)

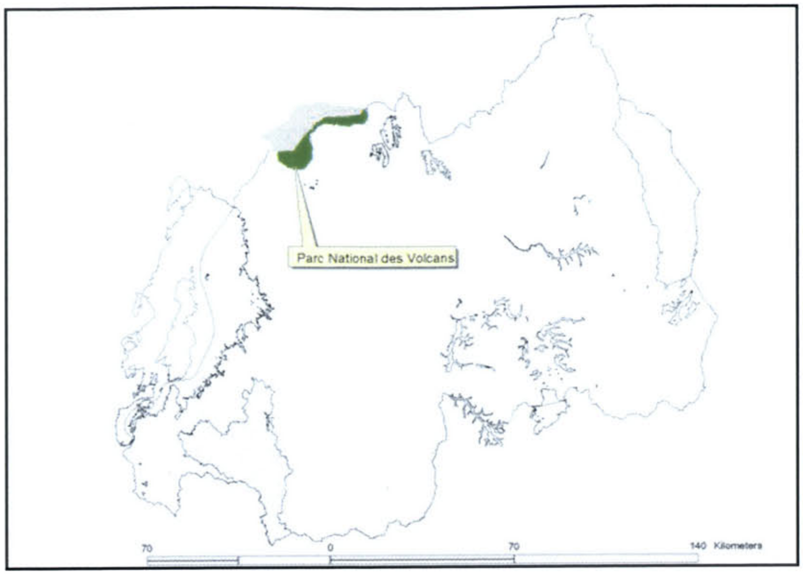

Figure 2: Volcanoes National Park location (ORTPN 2005)

1.3.2. Physical characteristics

As mentioned earlier, the Volcanoes National Park covers the south part of the Virunga Massif. The mountain chain comprises six volcanoes, five of which border with Uganda and Congo. The six volcanoes are divided into two geographical groups. The first group—in the west—includes Karisimbi (4,507 m), Bisoke (3,711 m) and Mikeno (4,437 m, in the DRC); the second group—in the east—includes Sabyinyo (3,634 m), Gahinga (3,434 m) and Muhabura (4,127 m), *Figure 3*. The two groups of volcanoes are separated by a large valley and a number of small volcanoes. Each volcano is characterized by steep slopes, with the Sabyinyo presenting particularly steep and eroded slopes, which form deep gullies (ORTPN 2004).

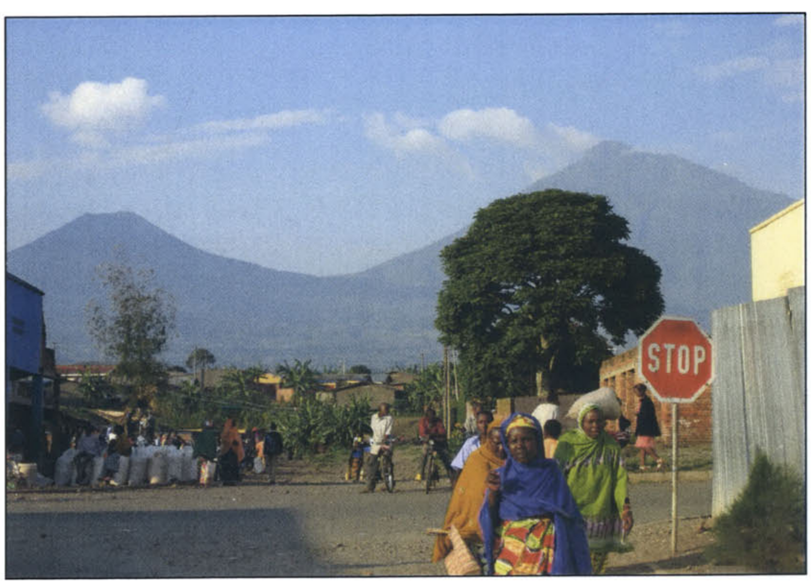

Figure 3: Gahinga and Muhabura Volcanoes (Picture by Author)

The PNV is characterized by this unique volcanic region. While now considered inactive, the five volcanoes in Rwanda have greatly shaped the landscape in the past. In fact, lava covers a significant portion of rock formations and greatly contributed to a rich and fertile soil. Two volcanoes in the DRC are still active and sometimes cause seismic activities within the park area (ORTPN 2005). The Virunga Massif is a branch of the Western Rift, or Albertine Rift, which is part of the Great African Rift Valley (Wikepedia 2007).

The hydrologic system of the region is so peculiar that sometimes the volcanic mountains are also called the "château d'eau," or water castles (ORTPN 2004). Due to the high permeability of the volcanic soil and rocks, the abundant rain quickly infiltrates into the ground, leaving only a small amount of water to the seasonal river flows. The large amount of rainwater that infiltrates within the soil cannot provide water supply to the people living on the volcanoes' slopes. In fact, the water either flows underground or re-surfaces in a few springs inside the park and its surroundings (ORTPN 2005).

The villages near the park are located in dry areas along the volcanoes' slopes. The absence of permanent rivers and water bodies in those areas forces villagers to travel into the PNV to fetch water. Unfortunately, the water they find in the seasonal rivers is rich in sediments (very high levels of turbidity) and therefore difficult to use domestically. Also, the extensive use of land outside the park for agricultural purposes tends to exacerbate land erosion and creates additional turbidity in surface water (Gurrieri 2005).

This mountain region is characterized by a fresh-humid climate typical of high altitude areas. Compared to the rest of the country, this region has the maximum annual rainfall concentration, reaching 2,000 mm at an altitude of between 2,000 m and 3,000 m. The rainfall is not constant across the entire area. In fact, at the top of Karisimbi, the highest volcano with 4,507 m, the annual rainfall can reach 900 mm (ORTPN 2005). Above 4,000 m, snow can be found seasonally at the top of the Karisimbi volcano. Although it rains year-round, the climate of the region is defined by two major rain seasons. The first and longest is from February to June, while the second, somewhat shorter, from September to December (ORTPN 2005).

1.3.3. Biotic characteristics

The vegetation aspect is strictly related to the land morphology and the microclimatic factors of the mountain region. Generally, the vegetation of the park (*Figure 4*) is characterized by the typical flora of Central Africa and East African Mountains (ORTPN 2004). Five vegetation zones are present in the region, with their distribution is related to both altitude and microclimatic differences between the two volcanic groups (Karisimbi and Bisoke to the West; Sabyinyo, Gahinga and Muhabura to the East). (ORTPN 2005)

The first zone is the *Neoboutonia* forest, which covers the lower mountain forest between the altitudes of 2,400 m and 2,500 m. The second zone is the *Arundinaria alpina* (bamboo) forest, which covers the West volcanoes group from an altitude of 2,500 m to 2,800 m and the East group from 2,500 m to 3,200 m. The third zone is the *Hagenia-Hypericum* forest. This zone covers the most humid belt between the altitude of 2,600 m and 3,600 m. The forest of the Bisoke volcano is one of the largest *Hagenia abyssinica* forests in Africa (UNEP-WCMC 2007).

The fourth vegetation zone is characterized by the presence of *Lobelia wollastonii*, *L. lanurensis*, and *Senecio erici-rosenii,* covering the region between 3,550 m and 4,200 m of altitude. The last zone is the highest belt on top of the Karisimbi and Muhabura volcanoes, from 4,000 m to 4,500 m. This region is constituted by the typical alpine grassland (UNEP-WCMC 2007).

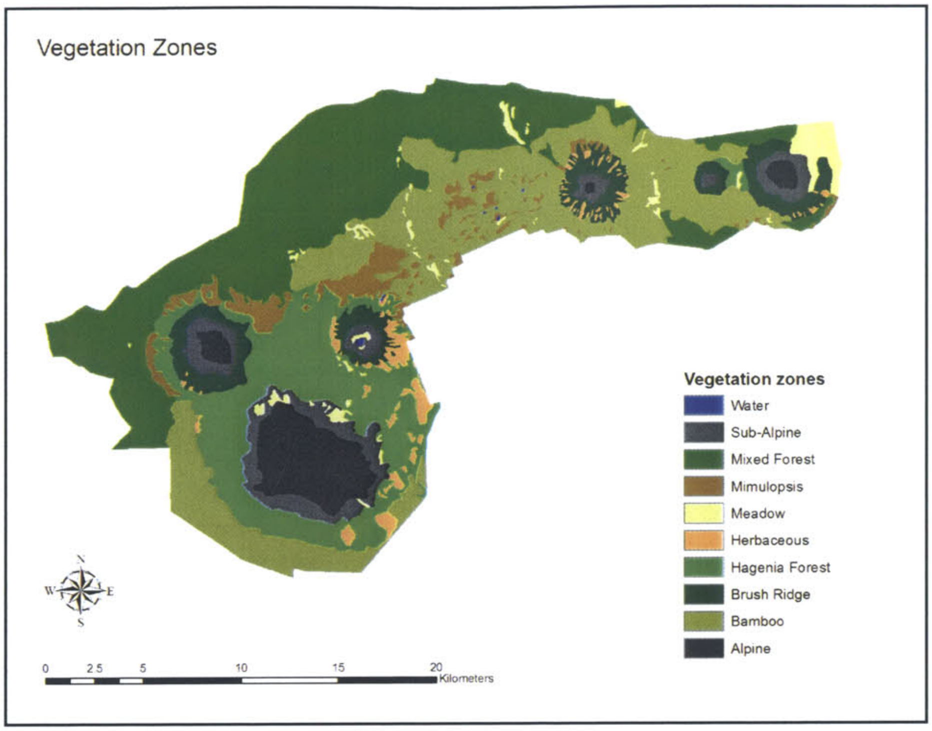

Figure 4: Vegetation Zones (Karisoke Research Center DFGFI, 2007)

In spite of the small size of the park and the relatively high altitude of the PNV, the local fauna includes a number of endemic species and sub-species. The Virunga Massif is known for the presence of mountain gorillas (*Gorilla beringei beringei*), golden monkeys (*Cercopithecus mitis kandti*) and blue monkeys (*Cercopithecus mitis stuhmani*). The park herbivore species include elephants (*Loxodonta africana*), buffalos (*Syncerus caffer*), black-fronted duikers (*Cephalophus nigrifrons*) and the tree hyrax (*Dendrohyrax arboreus*). For carnivores, it is possible to find hyenas (*Crocuta crocuta*), jackals (*Canis adustus*) and some small "cats". Some of the mammal species have been reduced in number over the years, while some others, like the elephant or the black-fronted duiker, continue to be main targets of poachers (ORTPN 2005). The birds are rich in species. Inside the park 294 bird species have been documented.

The Mountain Gorillas (*Gorilla beringei beringei*) live only in the Virunga Massif and in the Bwindi Impenetrable National Park of Uganda. The Mountain Gorilla was first sighted by a non-African on October 17, 1902, when the German Captain Oscar Von Beringei shot two animals and sent them to Europe for identification (BBC 2007). Despite this effort, the first comprehensive study was not completed until fifty years later in 1959-1960 by the scientist George Schuller. At that time, the population of gorillas was estimated at around 400-500. It is true, though, that this specie became widely popular and protected only after deeper and more analytical studies conducted by Dr. Dian Fossey.

Based on the research of the ORTPN, the change in the number of gorillas seems directly related to human activities. In fact, during the period 1960-1970, the population decreased from 400-500 to 260-290, somewhat proportional to the reduction in surface area of the National Parks in the Virunga Massif and in Uganda. When Dian Fossey began her studies on this species, she quickly realized the need for a campaign to protect and preserve the gorillas and their habitat. During the period 1980-2004, the agencies of the National Parks and several NGOs, such as DFGFI, combined their efforts to protect and preserve the gorillas and their ecosystem. The joint efforts resulted in an increase of the population from 250 to 380 animals (ORTPN 2004). *Figure 5* shows the evolution in the number of gorillas during the period from 1960 to 2004.

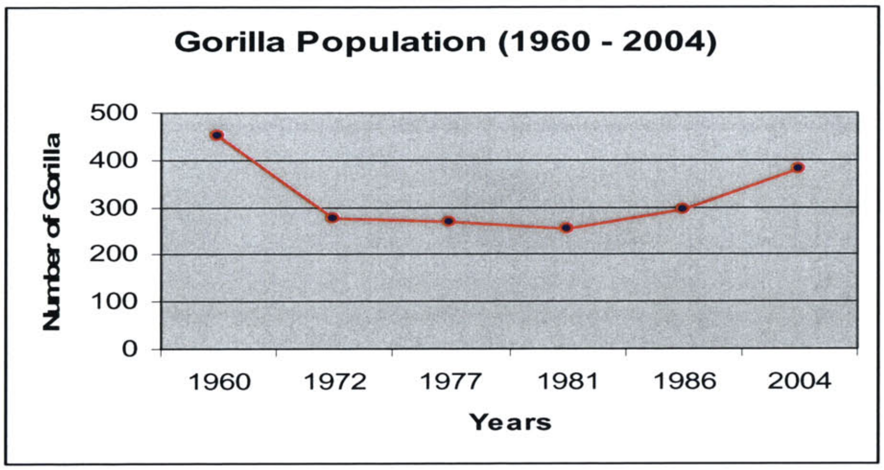

Figure 5: Gorilla Population 1960 - 2004 (ORTPN 2005)

1.3.4. Demographic parameters and education

The PNV borders the two Provinces of Ruhegeri and Gisenyi for about 60 km. These two provinces are densely populated, creating an issue of high impact from human activities to the neighboring park. Bisate Sector, the area of study, is in the Province of Ruhengeri and precisely in the District of Kinigi. Based on the *Park Management Plan 2005-2009* (ORTPN 2005), the District of Kinigi had a population of 55,200 in 1991 and 62,800 in 2002. Comparing these numbers from the last two censuses, the population of the District of Kinigi increased 14% during the eleven years' period. In 2002, the population density was 390/km^2 (***Error! Not a valid bookmark self-reference.***).

Table 1: Population density in 2002 (ORTPN 2005)

District / Town	Total population 30/08/2002	Total surface area (Km^2)	Habitable area km^2	Physical density	Physiological density
Kinigi	62,798	162	110	390	570

According to the *Park Management Plan 2005-2009* (ORTPN 2005), the structure by age of the population in the District of Kinigi is the same as in the rest of the country. The people under 30 years of age represent 70% of total population. In terms of distribution by sex, the plan shows a higher percentage of women within the population (*Table* 2).

Table 2: Percentage of the population on gender basis (ORTPN 2005)

District	Men	Women	Total
Kinigi	45.2	54.8	100

Based on the *Parc National des Volcans – Plan de Zonage* (ORTPN 2004), the average household has 5.1 members, with the following age distribution: 49% younger than 15, 47% between 15 and 64, and 4% older than 64 years. Therefore, more than half of household members (53%) can be considered "inactive" (ORTPN 2204).

According to the *Park Management Plan 2005-2009* (ORTPN 2005), the rate of illiteracy within the District of Kinigi is 42%. Moreover, only 54% of people living in these two provinces completed primary school, 7% secondary school and 0.2% university-level degrees. One of the primary causes behind this poor situation lies in the long distances to reach the school. The study indicates that the average walking distance is about 46 minutes to primary school (1.5 km) and 1 hour 16 minutes to secondary school (3.5 km). The District of Kinigi has two secondary schools and 11 primary schools on a total surface area of 162 km^2.

1.3.5. Economy and employment

The economy of the rural areas near the park is based on agriculture. In fact, 91.8% of the population is engaged in subsistence farming. Almost the entire land is cultivated, with the exception of some rocky areas. The fertile volcanic soil and the cold temperatures are favorable conditions for productive cultivations, including Irish potatoes, sorghum, beans, wheat, etc. The local population is engaged also in growing "cash crops," which include pyrethrum, tobacco, tea and coffee (ORTPN 2005).

In spite of the high land productivity and frequency of crops, the average annual income remains very low. In 2004, the District of Kinigi average annual household income was 104,196 Frw (about 190 US dollars). The reasons for this low annual income are many and include the following: first, the lack of credit, which limits the access to proper equipment and fertilizers; second, the lack of training, which does not allow improvement in agricultural methods; third, the high population growth reduces the amount of land per capita. In 2003, the average land per capita was estimated at 0.25-0.80 hectares (ORTPN 2004).

The unemployment rate is high because of the population density, the scarcity of cultivable land and low propensity to enter in non-agricultural activities—such as craftsmanship—due to the required financial help. According to the Park *Management Plan 2005-2009* (ORTPN 2005), the rural people are not willing, if not scared, to approach the banks for financial assistance.

1.3.6. Water issue

1.3.6.1. Water distribution

As mentioned earlier, the mountain region has the largest annual rainfall concentration within the whole country. The surface morphology, the humid forest and the permeable volcanic soil facilitate water storage in the subsurface. However, the abundant rains infiltrate so fast that only a small amount of water is able to flow into the seasonal rivers. The water supply sources of those districts near the park tend to be located at groundwater discharge points due to the difficulty to collect surface water (Guerrieri 2005). Other than the geological reasons, the lack of water supplies reflects the poor status of the hydraulic infrastructure after the 1994 genocide, when the country was affected by social insecurity, particularly during the period of 1997-1998 (ORTPN 2004).

According to the *Parc National des Volcans – Plan de Zonage* (ORTPN 2004), within the region surrounding the park only 41.3% of households have access to clean water, while 42.8% have access to alternative water sources. Half of the population living near the park has significant difficulties in fetching water. The three main concerns about accessing water are: the time spent to reach the water source, the effort to transport the water, and the threat to the gorillas and their habitat from the high human interaction. *Table 3* shows the water supply situation for the District of Kinigi compared to the average situation of the Provinces of Ruhengeri and Ginsenyi and to the WHO Standards (ORTPN 2004).

Table 3: supply situation: District of Kinigi and mountain region (ORTPN 2004)

District - Region	District of Kinigi	Park region	WHO standards*
Improved sources	1	N/A	N/A
Public standpipes	50	N/A	N/A
Private connections	7	N/A	N/A
People with access to alternative water [%]	40.3	42.8	0
Water consumption [liters/day/capita]	6	6.3	20
Distance to water sources [km]	4.4	4.1	0.1-1

* WHO, Domestic Water Quantity, 2003

1.3.6.2. Social Water Issues

As in many developing countries, it is women's and children's responsibility to fetch water for the family's domestic needs. Residents of the Virunga Mountains' hillsides are, as already mentioned, in a region particularly scarce in water, due primarily to its geology and hydrology. The people living in this "dry zone" often spend many hours a day walking to find water

(Gurrieri 2005). Many people are trekking into the Parc National des Volcans in order to retrieve surface water. The amount of time spent to walk, find and retrieve water severely hampers the potential of women and children in the region. If alternative sources of water were secured and utilized, women and children now imprisoned by their "water walks" could attend school, work to increase family income, or have more time to spend on productive domestic tasks (DFGFI 2006). Additionally, improved water conditions would decrease the occurrence of water-borne and water-washed diseases such as diarrhea, cryptosporidium, etc. Rather than drinking contaminated water from a stream and carrying it many kilometers back to their homes, the people of Rwanda deserve at least clean water in close proximity to their homes.

1.4. Thesis objectives

The overall objective of the present study is to provide a design of low-cost household rainwater catchment systems for the rural community of Bisate Village. The household rainwater catchment system is designed to reach three primary goals: first, increasing the water quantity; second, improving the water quality; and third, improving the quality of life.

1. **Improving the water quantity**: household rainwater catchment systems can provide a larger amount of water to the families, improving water consumption from less than 5 liters/day/person to 15 liters/day/person;
2. **Improving the water quality**: household rainwater catchment systems must be covered and furnished with a hand pump to extract water, in order to reduce the possibility of faecal bacteria contamination by dirty hands and/or containers; the implementation plan must include also a hygiene education program directed to adults and children;
3. **Improving the quality of life**: household rainwater catchment systems can provide water inside or nearby the house, thereby drastically reducing the travel time for women and children to fetch water; freeing up time from "daily water walks" would improve school attendance and trade activities and ultimately raise the community education level and the family average annual income.

The overall objective of the present study has been pursued through the following steps:

- Surveying and analyzing the existing water supply in Bisate Village and nearby areas
- Reviewing the literature on small scale rainwater catchment systems
- Calculating the capacity of the rainwater storage system
- Designing a household excavated cistern
- Analyzing the cost of the household rainwater catchment system
- Final considerations and recommendations

2. SURVEY OF THE WATER SOURCES IN BISATE VILLAGE

2.1. Bisate Village introduction

2.1.1. Generalities

Bisate Village is located at the edge of the Bisoke volcano (*Figure* 7), one of the five volcanoes of the national park in the northern region of Rwanda. The village borders the national park. The village covers an area of 28.1 square kilometers and comprises two cells: Kaguhu and Bisoke. The total number of people living in the two cells is 8,364 and the total number of households is 1,860.

As shown on *Figure 6*, Bisate Village is located along a regional road which also includes a number of local roads. The entire road system is unpaved and, except for the main street, is generally not well maintained.

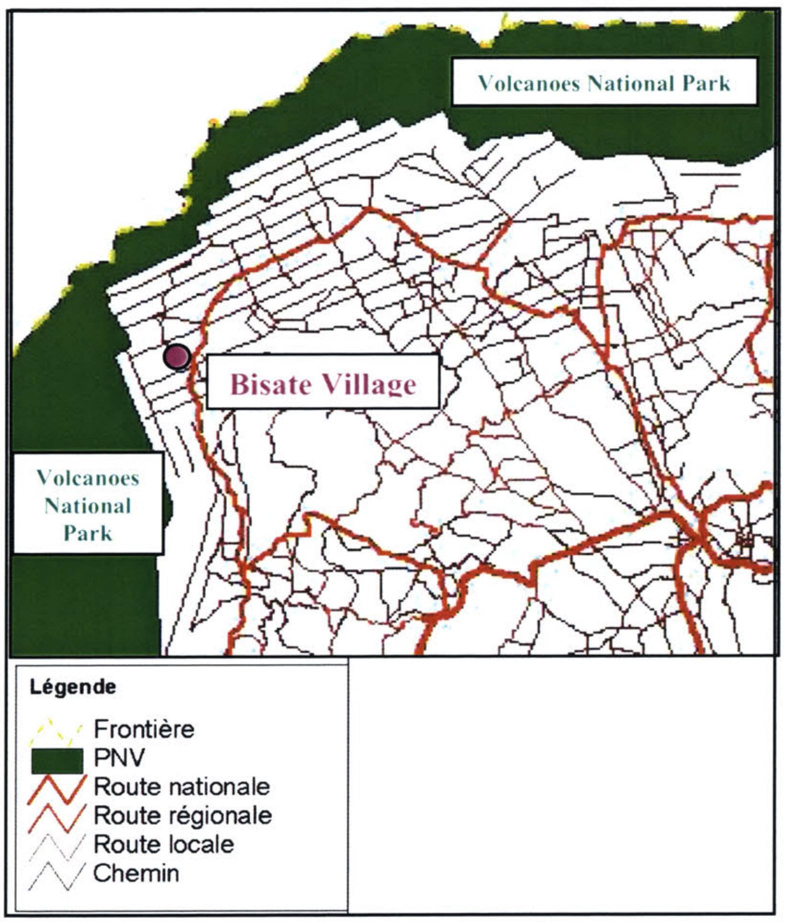

Figure 6: Road system (ORTPN 2004)

None of the village has electricity or a public water connection. The public buildings include a primary care clinic (*Figure 8*), a primary school for about 1,800 children (*Figure 9*), a trade center and two churches (*Figure 10*).

Figure 7: Bisate Village view from the Clinic (Picture by Author)

Figure 8: Clinic (Picture by Author)

Figure 9: Primary School (Picture by Kelly Doyle)

Figure 10: Bisate Church (Picture by Christiane Zoghbi)

2.1.2. Population health condition

Based on Lilly (2006), the Dian Fossey Gorilla Fund International Ecosystem Health Program affirms that 99% of the population living in Bisate Village suffers from intestinal diseases. The widespread illness weakens the population and reduces the opportunities to develop the community. In fact, intestinal parasites often lead to gastro-intestinal episodes, long hospital stays, and, ultimately, low productivity.

The principal causes of intestinal diseases include lack of water, faecal contamination in the water and absence of hygiene education. The transmission of intestinal diseases occurs mainly when fecal pathogens are ingested by people through water-borne and water-washed routes (Cairncross 2003):

- **Water-borne route**: transmission occurs when fecal pathogens contaminate drinking water;
- **Water-washed route**: transmission occurs when pathogens passing through the feces of an infected person are indirectly ingested by other persons.

The current health situation could be improved by reducing the incidence of intestinal diseases, through actions directed against those two transmission mechanisms. Specifically, improving hygiene conditions, water quality and water quantity (Cairncross 2003). First, children and adults should be introduced to specific hygiene education programs, both in school and through community-based presentations. Second, the hygiene education program should explain water disinfection and filtration. Finally, to improve water quantity it would be necessary to implement water supply systems. This study focuses on household rainwater harvesting, in the form of covered cisterns to collect water and hand pumps to extract water. This solution aims at improving water quantity for households and reducing water contamination from dirty hands and/or jerrycans.

2.2. Bisate Water supply

During our stay in Bisate, we had the opportunity to survey the village's main water sources. In the following paragraphs, we summarize the existing situation with brief descriptions and pictures of these sources.

2.2.1. Tap water

In the entire area of the village of Bisate, there are only two public stand-pipes providing water for 8,364 people. The sources of water supply for these two stand-pipes are located inside the Volcanoes National Park and have seasonal patterns.

The first stand-pipe, shown in *Figure 11*, is located at the center of the village. The stand-pipe serves water only during the wet season and is alimented by a pipe coming from a large up-hill stone tank. The tank collects water from the Bushokoro source (see *Figure 12*), which is located inside the park. The pipe which aliments the stand-pipe is broken, causing chronic emptying of the storage tank. We had the opportunity to test water quality from the stand-pipe and we found total coliform contamination.

Figure 11: Stand-pipe in the village center (Picture by Author)

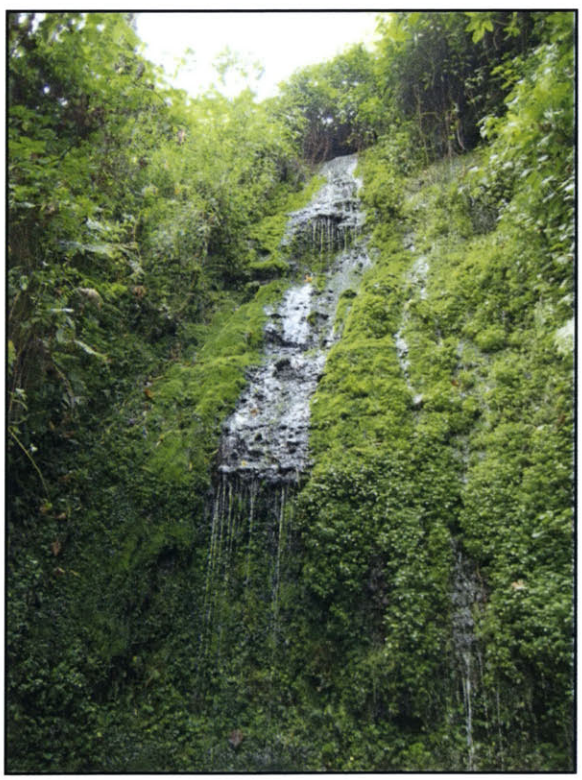

Figure 12: Bushokoro source in the Park (Picture by Jean Pièrre Nshimyimana DFGFI)

The second stand-pipe, shown in *Figure 13*, is located along the main street outside the center of the village. The system is alimented like the first stand-pipe, through an up-hill brick tank. The tank collects water from the Bunyenyeri source, located inside the park (*Figure 14*). Here again, our tests of water quality from the stand-pipe showed total coliform contamination.

Figure 13: Stand-pipe along the main street (Picture by Author)

Figure 14: Bunyenyeri source in the Park (Picture by Jean Pièrre Nshimyimana DFGFI)

2.2.2. Community tanks

There are several rainwater tanks in the village: one metal tank at the Primary School (*Figure 15*), one metal tank at the Tracker House, one stone tank at the Church (*Figure 16*) and one stone tank at the Trade Center. Despite the number of tanks within the village, people tend to fetch water only from the tank near the Church. Interestingly, tests of water from the various tanks showed that all tanks were contaminated with total coliform except for the stone tank near the Church.

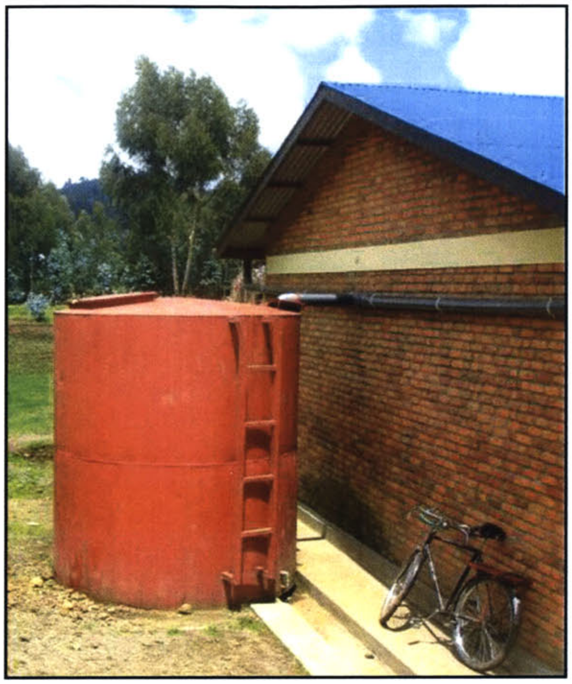

Figure 15: Metal School Tank (Picture by Kelly Doyle)

Figure 16: Stone Church Tank (Picture by Kelly Doyle)

2.2.3. Small scale water supply

While people of Bisate Village are accustomed to using only few liters of water per day and to walking long distances to fetch water, they never considered small scale rainwater harvesting systems. As mentioned in *Chapter 1*, in the area of the Volcanoes National Park there is considerable precipitation at about 1,500 mm/year. Surprisingly, the people of Bisate know how to use and manage rainwater for agriculture, but they never consider collecting rainwater for other purposes, such as drinking, cooking or washing.

While performing the houses' survey in the village, we noticed that just two or three houses had implemented systems to collect rainwater. The simplest system observed included a very short piece of gutter attached to the roof and a small container to collect the rainwater, as shown in *Figure 17*.

Figure 17: Small scale rainwater harvesting system (Picture by Author)

During the survey, we also found an outdoor wood-covered pond to collect water from nearby roofs. This relatively more sophisticated small-scale rainwater harvesting system is able to collect larger amounts of water per day per person compared to the simpler system observed above. In fact, the pond of 2.1 m length x 1.8 m width x 1.4 m depth is able to collect potentially 5,290 liters. The pond is made of wood boards, which are lined with plastic, covered with wood tables and locked, as shown in *Figure 18*. We had the opportunity to test the water, which showed total coliform and E. coli contamination.

Figure 18: Wood pond to collect rainwater in Bisate (Picture by Kelly Doyle)

2.2.4. Summary of Bisate Village water supply

The main conclusion is that Bisate Village has insufficient water sources for its population. Given the existing situation, we observed that water resources are concentrated on the main street and center of the village. This situation explains why the majority of the people—who live away from the village—need to walk long distances to fetch water. In addition, these limited water sources provide poor quality water, often contaminated with faecal bacteria. The summary of the water sources of Bisate Village is illustrated in *Table 4*.

Table 4: Summary of Bisate water sources

Bisate Village water sources	Number	Quality
Public tap water	2	100% faecal contamination
Rainwater community tanks	4	75% faecal contamination
Small rainwater harvesting system	Few	N/A

2.3. Experience in Kabatwa Village

In the Village of Kabatwa at the edge of Karimsimbi Valcano, we observed that every household has an excavated pond to collect rainwater from their own roofs. Each owner of these "collecting systems" agreed that the ponds provide water for a large part of the year. When the season is hit by a particularly deep drought, people walk to the public water sources of their village. We were surprised by the incredibly different water situation compared to the village of Bisate. At the very least, women and children of Kabatwa do not need to travel long distances to fetch water every day and are free to spend more time working and attending school.

We surveyed the collecting systems of Kabatwa and noticed that the ponds were generally 2 m x 3 m x 1 m (about 6,000 liters of volume), lined with tarpaulin plastic sheets provided by UNHCR (United Nations High Commissioner for Refugees). The ponds varied in location (indoor-outdoor) and type (covered-uncovered). The cover also varied in materials: wood, bamboo, plastic or iron sheets. We surveyed some of the ponds and tested the water, with the main characteristics illustrated in *Table 5.*

Table 5: Kabatwa ponds' characteristics and pictures

POND'S CHARACTERISTICS	POND'S PICTURE
1. Indoor pond • Indoor pond, bamboo room, plastic lining • House roof in iron sheets with iron gutters • Size: Length 3 m, Width 2 m, Depth 0.9 m • Results of bacterial tests of water: Total coliform contamination, no E. coli contamination	 Picture by Author

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2. Uncovered outdoor pond

- Outdoor pond, uncovered, plastic lining
- House roof iron sheets with iron gutters
- Size: Length 3 m, Width 2 m, Depth 0.9 m
- Results of bacterial tests of water: Total coliform contamination, no E. coli contamination

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3. Covered outdoor pond

- Outdoor pond, plastic covered, plastic lining
- House roof iron sheets with iron gutters
- Size: Length 2.6 m, Width 2.1 m, Depth 0.9 m
- Results of bacterial tests of water: Total coliform contamination, E. coli contamination

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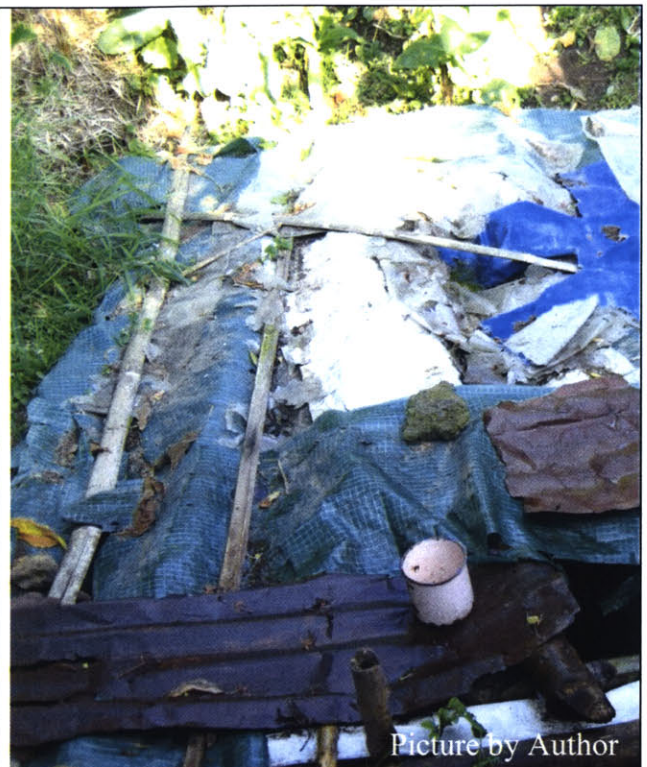
4. Covered outdoor pond • Outdoor pond, iron and plastic covered, plastic lining • House roof iron sheets with iron gutters • Size: Length 2.3 m, Width 2 m, Depth 0.9 m • Results of bacterial tests of water: Total coliform contamination, no E. coli contamination	 Picture by Author
5. Covered outdoor pond • Outdoor pond, bamboo covered, plastic lining • House roof iron sheets with iron gutters • Size: Length 2.6 m, Width 1.8 m, Depth 0.9 m • Results of bacterial tests of water: Total coliform contamination, E. coli contamination	 Picture by Author

2.4. Pond water quality

While surveying the ponds in Bisate and Kabatwa, our team had the opportunity to sample and test water from different ponds. We consider it very important to compare the water quality in Kabatwa with that from the Bisate rainwater tanks. In fact, we wanted to understand the potential for water quality improvement in case of the implementation of small scale rainwater harvesting systems in Bisate.

2.4.1. Parameters tested and methods

We tested the water to find basic water quality characteristics. The list of the parameters tested is listed below:

- E. coli
- Total coliform
- Turbidity
- Conductivity
- pH
- Alkalinity
- Hardness
- Nitrate/Nitrite
- Chloride

Test methods utilized are described below (HACH 2007):

- **E.coli and total coliform** – A 3M™ Petrifilm E. coli/coliform Count Plate was placed on a level surface and the top film lifted. A 1 mL of water sample was placed onto the center of the bottom film with a pipette. Carefully, the top film was rolled down without entrapping air bubbles. Before the gel was formed, the inoculum was distributed over the circular area of the film by the flat side of the spreader. After more than one minute, the plate was incubated for 24 hours at a temperature of 20°C. After the incubation, the E. coli and coliform were counted: red and blue colonies with associated gas bubbles for coliform and blue colonies associated with bubbles for E. coli (*Figure 19*).

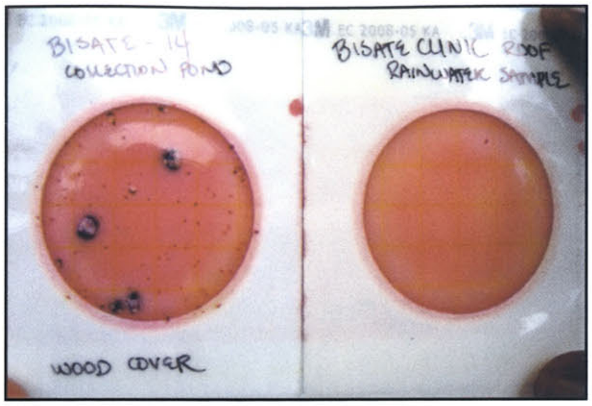


Figure 19: 3M™ Petrifilm E. coli/coliform Count Plates (Picture by Author)

- **Turbidity** – After cleaning the interior, a sample cell was filled to the scribed line with water sample (about 15 mL). Handling the cell by the top, the cell was wiped with a soft, lint-free cloth to remove water spots and/or fingerprints. Then, a light film of silicone oil was applied to the cell over the entire surface wiping it with a soft cloth. The instrument was turned on and the sample cell was inserted in the sample compartment of the HACH 2100P Portable Turbidimeter (*Figure 20*). The cell was inserted in the compartment so that the orientation mark was aligned with the raised orientation mark in front of the cell compartment. Once the instrument cover was closed, the read-key was pressed and the turbidimeter display showed the water turbidity in Nephelometric Turbidity Units (NTU).

Figure 20: HACH 2100P Portable Turbidimeter (Picture by Author)

The calibration of the instrument was performed using four StablCal® Stabilized Formazin standards: <0.1 NTU, 20 NTU, 100 NTU and 800 NTU. The four samples were inserted in the sample compartment for the turbidity reading. The sequential order followed the instructions shown on display. Since the readings matched the NTU standards, the instrument was well calibrated.

- **Conductivity** – The Pocket Pal™ Conductivity Tester (*Figure 21*) was turned on and its cap was removed. The bottom of the instrument was immersed for 1.5" into the water sample. The sample was gently stirred for several seconds. After the digital display stabilized, the conductivity value was read. The tester, then, was rinsed, closed with its cap and turned off.

Figure 21: Pocket PalTM Conductivity Tester (Picture by Author)

- **pH/Alkalinity/Hardness** – A HACH 5-in-1 Water Quality Test Strip (*Figure 22*) was quickly immersed into a water sample. After the color development occurred on the test strip, the pad was compared to the chart printed on the bottle to read the value of the parameters. From the multi-parameter test, only three of the five parameters were tested: Total Hardness (as $CaCO_3$, 0-425 mg/L), Total Alkalinity (as $CaCO_3$, 0-240 mg/L), and pH (6.2 – 8.4).

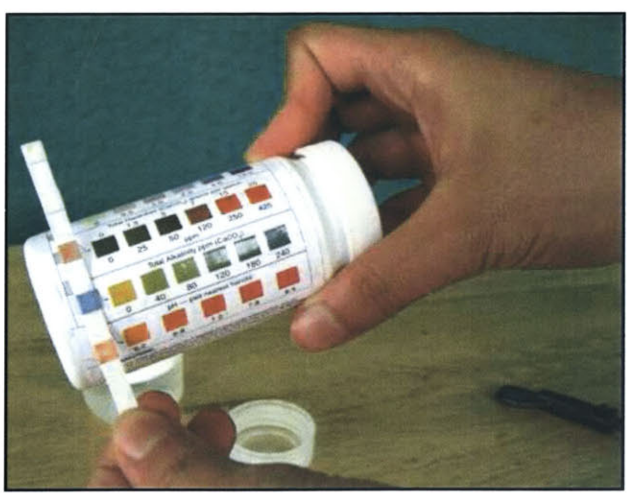


Figure 22: HACH 5 in 1 Water Quality Test Strip (Picture by Author)

- **Nitrate/Nitrite** – The procedure for the Nitrate/Nitrite analysis is very similar to that for pH/Alkalinity/Hardness. A HACH Nitrate and Nitrite Test Strip was rapidly dipped into the water sample. Once the color development occurred on the test strip, the reacted pad was compared to the chart printed on the bottle to read the value of the parameters.

Figure 23: HACH Nitrate and Nitrite Test Strip (HACH 2007)

- **Chloride** – A HACH Chloride QuanTab® Test Strips, 30-600 mg/L, was dipped into the water sample until the strip pad reacted and changed in color. The length of the color change was compared to the printed scale on the bottle to read the value of the parameter.

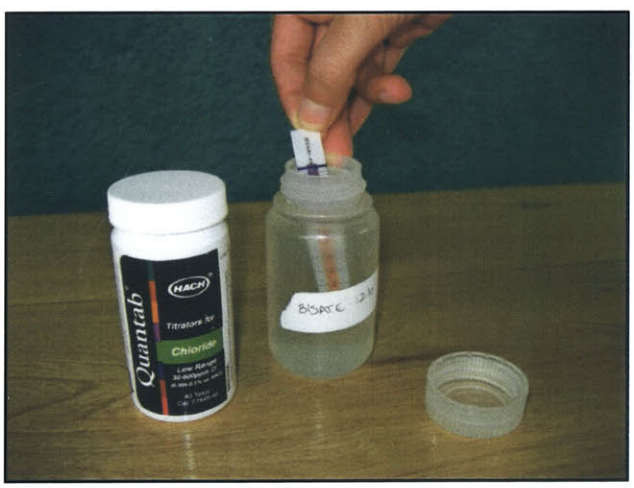


Figure 24: HACH Chloride QuanTab® Test Strip (Picture by Author)

2.4.2. Test results

The team tested the water quality of six ponds surveyed in Bisate and Kabatwa; the results are summarized in *Table 6*.

Table 6: Summary of the water quality of the ponds in Bisate and Kabatwa

Ponds	**Hardness**	**Alkalinity**	**pH**	**Nitrate**	**Nitrite**	**Chloride**	**Conductivity**	**Turbidity**	**Total coliform**	**E. coli**
	(ppm as $CaCO_3$)	(as $CaCO_3$)	-	(ppm)	(ppm)	(ppm)	(μS/cm)	(NTU)	(/100 mL)	(/100 ml)
WHO Standards	*No standard*	*No standard*	*< 8.5 for chlorination*	*10 ppm*	*1 ppm*	*No standard*	*No standard*	*<5 NTU for Chlorination*	*0 colonies / 100 mL*	*0 colonies / 100 mL*
Bisate 1	25	10	6.8	x	x	x	47	2.15	700	400
Kabatwa 1	0	0	6.2	1.5	0	<31	21	1.40	400	0
Kabatwa 2	0	0	6.4	0.15	0	<31	14	3.67	1300	0
Kabatwa 3	0	0	6.4	0.15	0	<31	36	2.35	1200	300
Kabatwa 4	<10	0	6.6	0.15	0	<31	32	2.01	4500	0
Kabatwa 5	<10	0	6.4	0.15	0	<31	44	3.19	4700	100

The results of the sample tests show that the water of the ponds of Bisate meets WHO standards (conductivity, hardness, alkalinity, pH, nitrate, nitrite and chloride). However, the results also showed that the water is generally contaminated with total coliform and, in 50% of the cases, E. coli.

The water samples from the rainwater tanks of Bisate showed that water is generally contaminated with total coliform, but not with E. coli. Comparing the results of the water from the tanks and the ponds, we can conclude that the water from the ponds is more contaminated by faecal bacteria than the water from the tanks.

The main difference between the two collecting systems is that tanks have a device to extract the water (generally situated at the bottom of the tank), while the excavated ponds do not. The higher level of contamination by faecal bacteria of the ponds could be caused by the different water extraction system. In fact, the owners of the ponds extract water manually with jerrycans or other type of containers. As shown in *Table 5*, these containers are not always clean, which is also true for their hands. Thus, dirty hands and containers are the primary sources of ponds' contamination.

Moreover, in most of the cases the ponds are located outside of the houses, at ground level. These conditions favor runoff entering directly into the pond, another source of water contamination. The runoff is often highly contaminated with faecal bacteria because of the ponds' proximity to open latrines. Location and elevation are other relevant sources of water contamination.

2.5. Conclusion

From the water supply survey in Bisate and the experience in the village of Kabatwa, we observe two major problems: 1) the people of Bisate Village do not have sufficient water for drinking, cooking and washing; and 2) the "community water" is generally contaminated by total coliform.

As mentioned earlier, we observed that the community water supply is limited and not homogenously distributed throughout the entire village. This situation leads to many families living far from the center of the village to walk long distances to fetch water. Women and children cannot transport large amounts of water for long distances, resulting in very small water consumption, sometimes less than 5 liters/day/person.

We also observed that almost all sources of water in the village of Bisate are contaminated by faecal bacteria. This situation carries the strong negative effect of a high number of people suffering from intestinal diseases.

One of the possible solutions to these problems is offered by the experience of Kabatwa Village. There, families use the rainwater collected in household excavated ponds for almost the entire year. They have more water available and do not spend time traveling to fetch water. The implementation of this household rainwater catchment system could definitely improve the quality of life for the people of Bisate Village. If the excavated pond is improved with walls to stop surface runoff from entering into the pond, as well as a stronger cover and a hand pump to extract the water, the implementation of small scale rainwater harvesting system could significantly improve water supply and quality for the families of Bisate Village.

3. LOW-COST HOUSEHOLD RAINWATER HARVESTING

In most cultures and traditions of Africa, women and children have the responsibility of fetching water. The travel time to reach water sources and the distance from the houses usually determines the quantity of water consumption as well as the type and quality of other activities pursued during the "free time". The water sources in Bisate Village are few and not homogenously distributed throughout the area. Consequently, women and children must walk long distances to fetch water, often at the expense of small trades or businesses and school attendance. Also, the limited amount of water available often causes the proliferation of water-borne and water-washed diseases, which further compromises the already precarious hygiene conditions.

Given Bisate Village's location in the humid region of the volcanoes, where precipitation reaches the highest levels in the country, the most natural way to improve water supply is to implement rainwater harvesting. Roof-water or rainwater harvesting (RWH) is a technique that has been in use since ancient times. Great examples can be found in Roman history, Indian tradition and also in our times. Rainwater harvesting system can be implemented at different scales, for entire communities or single households. Having learned of the Bisate situation, the current study focuses on household rainwater harvesting. The primary goal is to improve water supply (from less than 5 liters/day/person to 15 liters/day/person) and provide water as near as possible to households, in order to effectively reduce travel times to fetch water. The idea of domestic rainwater harvesting also reflects results from the survey of Bisate houses, which shows that the majority of roofs are made with corrugated-iron, one of the best materials to build catchment surfaces within rainwater catchment systems.

The domestic rainwater catchment system can be summarized in four principal components and three possible treatment processes. *Figure 25* illustrates the sequence of the processes:

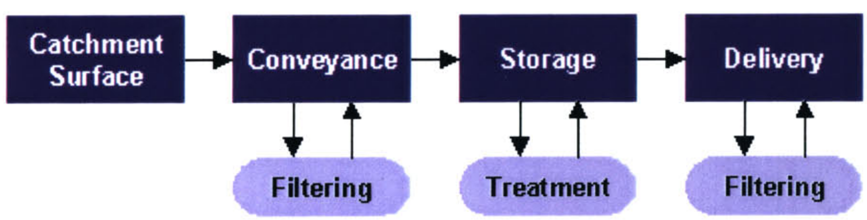


Figure 25: Process diagram of domestic rainwater harvesting (DTU 2000-2003)

These four components constitute the base of the processes for household rainwater systems (*Figure 26*), which can range from very elementary to highly sophisticated. The following analysis focuses on very low-cost technologies with the objective of finding an efficient system that is also affordable by most families of Bisate Village.

3.1. Component overview

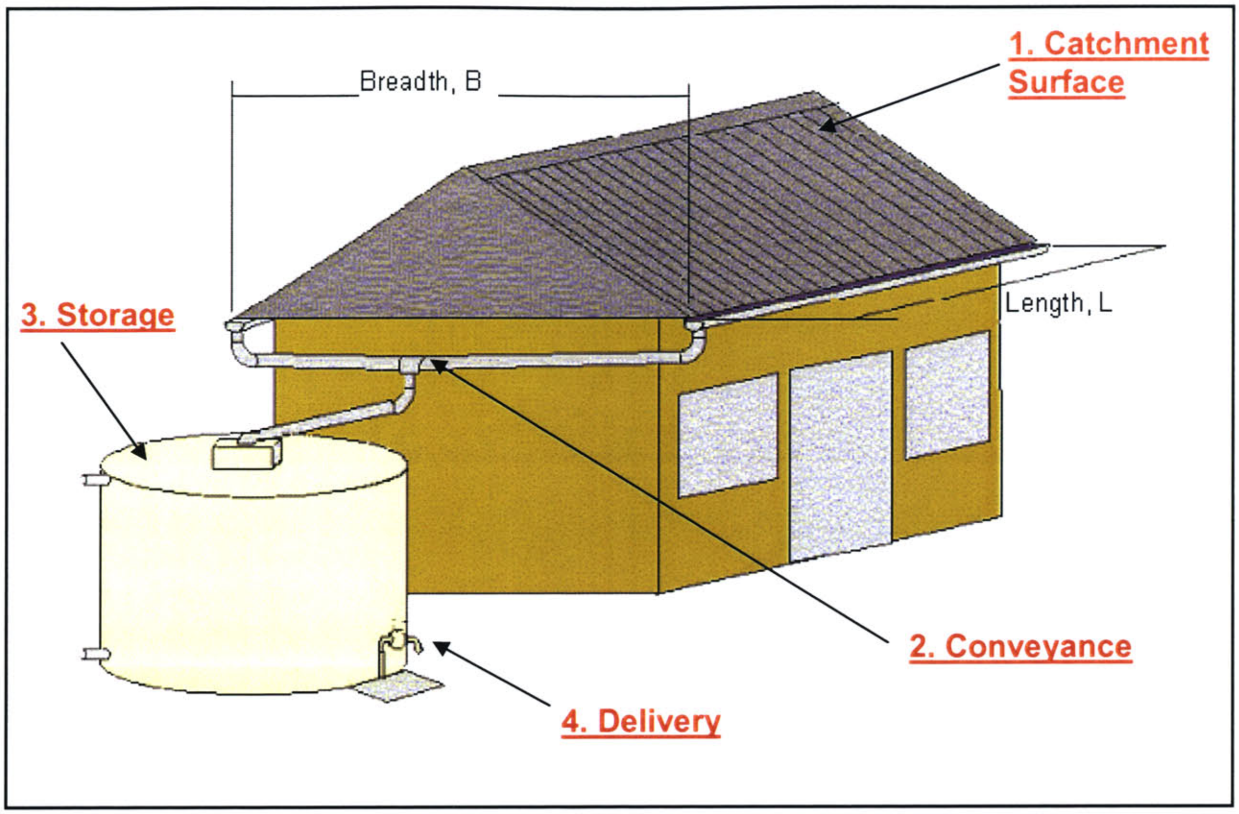


Figure 26: Main components of roof-water harvesting (DTU 1999)

3.1.1. Catchment surface

For household rainwater harvesting, the collection surface most commonly utilized is the roof. There are other possible catchment surfaces people can use, such as courtyards, threshing areas, paved walking areas, plastic sheeting, trees, and so on.

The most common materials used to build roofs are corrugated, galvanized iron sheet (GI), tiles, and thatch from different organic materials. Thatched roofs can create good catchments when they are made of tightly thatched materials such as coconut or anahaw palm. Most other organic materials, however, do not harvest high quality water. Potentially toxic coatings include zinc and lead-based paint. *Table 1* summarizes the different types of roofs, including their respective runoff coefficients and quality of water harvested (DTU 2000-2003).

The runoff coefficient represents the ratio of the volume of water that runs off a catchment surface to the volume of rainfall that falls on the catchment surface. To calculate the volume of water that runs off a catchment surface, the following water losses need to be considered: spillage, leakage, wetting and evaporation of the catchment surface. As can be observed in *Table 7*, the runoff coefficient varies from a high percentage of 90-99% to a very low percentage of 20-30%.

Table 7: Roof types, runoff coefficient and water quality (DTU 2000-2003)

Type	Runoff coefficient	Notes
Galvanized iron sheets	>0.9	• Excellent quality water • Surface is smooth and high temperatures help sterilization
Tile (glazed)	0.6 - 0.9	• Good quality water • Unglazed can harbour mold • Contamination can exist in tile joints
Organic (thatch, cadjan)	0.2	• Poor quality water (>200 FC/100ml) • Little first-flush effect • High turbidity due to dissolved organic material which does not settle

3.1.2. Conveyance system

Gutters and downpipes are the most common devices to deliver water from the catchment surface to the storage. The efficiency of a rainwater collecting system depends not only on the materials utilized and the proper construction of the catchment surface (the roof), but also on the careful design and construction of the gutter system. When gutters and downpipes are properly mounted and maintained, the conveyance system can deliver between 80 and 90% of the rainwater collected by the roof into the storage vessel (Gould 2006).

To reduce runoff losses during heavy storms, gutters need to be large enough to collect the rainfall. The rule of thumb to help define the most appropriate dimension of gutters for different catchment surface size is the following (Gould 2006):

1 cm^2 of gutter cross-sectional area for every 1 m^2 of catchment surface area

Domestic Roofwater Harvesting Technology (DTU 2000-2003) shows several examples found in the literature for a general idea of gutter sizes (*Table 8*). There are different shapes of gutter cross-section areas and one of the most recommended is the semi-circular. It should be noted that the system should be installed with a steepness gradient of between 1-3%, in order to limit the possibility of blockage by leaves and dirt. Generally, downpipe cross-sections should be smaller than those of gutters, since downpipes are vertically oriented and are less affected by blockages from the fast running water passing through them.

Table 8: Gutter size and slope related to the roof area (DTU 2000-2003)

Source	Section	Roof size	Slope	Cross sectional area
(Herrmann & Hasse, 1996)	Square	40 - 100m^2	0.3 - 0.5%	70cm^2
	Half Round	40 - 60 m^2	0.3 - 0.5%	63cm^2
(Nissen-Petersen & Lee, 1990)	45° Triangle	Not specified	1.0%	113cm^2
(Edwards et al., 1984)	Not specified	Not specified	0.8 - 1.0%	70-80cm^2

Gutters and downpipes can be made of various materials: aluminium, steel, plastic, wood, bamboo, and so on. Aluminium and steel gutters are quite expensive in developing countries, or 2-3 times more than gutters produced on-site (DTU 2000-2003). Organic material gutters, such as wood and bamboo, are cheap because of the direct sourcing of local materials. However, these types of gutters suffer from lack of longevity and frequent replacements. Also, their characteristic surface creates a favorable environment for the accumulation of bacteria, which can easily be washed into the storage.

During torrential rainfall storms, it is possible that large quantities of runoff could be lost by gutter overflow and spillage. This situation usually occurs in the presence of steep slopes and with gutters of a long roof hung several centimeters below the eaves of the roof. To reduce and control such losses, one solution is to hang a long strip of metal (30 cm wide and bent at an angle) over the edge of the roof to direct the runoff inside the gutters. This device, called a "splash-guard", is shown on *Figure 27 (DTU 2000-2003).*

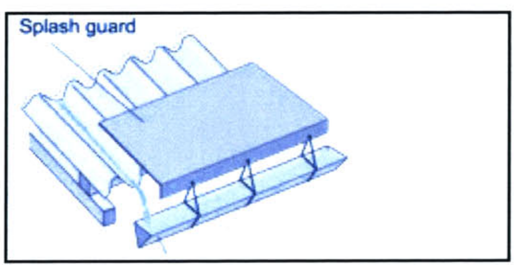


Figure 27: Splash-guard device (DTU 2000-2003)

3.1.3. Storage

A storage system is the main component of a rainwater catchment system, since it provides water during the dry periods of the year. Indeed, storage is necessary to collect and conserve the rainwater in excess of demand for periods when precipitation is not frequent or even absent.

The different types of storage can be grouped in three size classes: small, medium and large. In terms of small size storage systems, the most common examples used by populations of developing countries include plastic bowls or buckets, clay or ceramic jars, old oil drums and similar containers. These storage vessels can supply household water demand for the day and save women and children the time usually spent to fetch water. These small size storage vessels could also be considered for the entire year if precipitation is sufficient and relatively homogeneous during the year.

When weather also presents dry seasons, however, greater storage is required to supply water all year round. The larger storage vessels include medium and large tanks or cisterns ranging in size from 1 cubic meter to a maximum of 20-30 cubic meters for domestic rainwater catchment systems. *Table 9* illustrates the tank scale classification (Rees et al. 2000):

Table 9: Tank scale classification (Rees et al. 2000)

Scale of domestic tank	Description
Small	Any tank or jar up to seven days storage or up to 1,000 liters
Medium	A tank up to several weeks storage or between 1,000 and 20,000 liters
Large	Any tank with several months of storage or above 20,000 liters of capacity

The difference between tanks and cisterns lies in their location, above-ground for tanks and below-ground for cisterns. There are a large number of options for storage systems, varying in shapes, materials and sizes. One of the main concerns in selecting the appropriate storage is in the affordability of the tank. It may be possible that certain families could not afford a tank suitable for catching optimum amounts of water. As a consequence, several considerations become important when choosing an adequate storage (DTU 1999):

- Water storage tradition
- Space available
- Options available locally
- Materials and skills available locally
- Cost to buy new storage
- Cost materials and labor to construct new storage
- Geology and soil conditions

The first step to find the most appropriate storage is to choose between tanks and cisterns. The above considerations should help identify the primary benefits and drawbacks of tanks versus cisterns. A schematic list of pros and cons is illustrated in *Table 10* (DTU 2000-2003).

Table 10: Tanks versus cistern (DTU 2000-2003)

STORAGE TYPE	PROS	CONS
Tank (Above-ground storage)	▪ Easy inspection for cracks or leakage ▪ Water extraction by tap from gravity ▪ When raised above ground, water pressure is increased	▪ Requires space ▪ Generally more expensive ▪ More easily damaged ▪ Subject to weather conditions ▪ Failure can be dangerous
Cistern (Below-ground storage)	▪ Surrounding ground gives support, reducing wall thickness and therefore costs ▪ More difficult to empty if leaving the tap on ▪ Requires little or no space above ground ▪ More difficult to damage ▪ Water is cooler	▪ Water extraction more difficult (requires pump) ▪ Leaks or failures are difficult to detect ▪ Possible contamination from groundwater or runoff ▪ Possible damages from tree roots ▪ If cistern is left uncovered children could fall in ▪ If cistern is left uncovered animals could contaminate water ▪ Cannot be easily drained for cleaning

Since the goal of this study is to design a very low-cost rainwater catchment system, we prefer to focus on cisterns. The advantages behind the decision are the following: 1) as cisterns are located below-ground, it is possible to reduce the thickness of its wall and therefore use less material; 2) cisterns require little or no space above ground; 3) it is less likely to be damaged. The highlighted disadvantages can be reduced to: 1) need for hand pumps to extract water; 2) need for cistern covers to reduce the possibility of water contamination by dirty hands or jerry cans; 3) need for hand pumps to drain cisterns for cleaning.

3.1.4. Delivery system

As highlighted before, the delivery system differs for tanks and cisterns. With tanks, water extraction occurs by gravity and uses a tap. Conversely, water extraction from cisterns requires a pump. The major advantage of using a pump instead of a tap is that if the pump breaks, the cistern will not empty as quickly as when a tank tap breaks. In addition, when the pump breaks it is always possible to extract water with a rope and a bucket. Unfortunately, pumps require careful operation and regular maintenance, which sometimes can be difficult in developing countries due to lack of local expertise to repair pumps and/or the availability of replacement parts (Gould 2006).

There are many types of pumps, ranging from mechanically driven or electric pumps, wind or solar-powered pumps and hand pumps. In developing countries hand pumps are the most commonly used pumps. In this group, there are pumps designed to lift water from underground sources and other direct-action pumps, such as rower pumps and bucket pumps (Gould 2006).

Many different handpumps can be found in stores, some of them are quite affordable (*Table 11*).

Table 11: Hand pump examples (<http://www.comparisonwarehouse.com/search.php?keyword=Hand+Water+Pump&tc=01>):

	Advanced Elements Double Action Hand Pump Features both inflation and deflation capabilities for greater versatility; large handles and foot plate increase comfort during use. For extreme emergencies, pump can serve as a bilge pump to expel water from boat	$25.00
	Northern Industrial Hand Press Pump Needs no gas or electric power to draw well water. Simple, durable hand pump is engineered to last. Old-time styling 19 1/2ft. suction head. Constructed of Cast Iron Rubber Diaphragm 19 1/2ft	$24.99
	Hand Pump, 12.75" W/Tube Self-priming Non-corrosive and rust-proof. Includes a kit of tubes, hoses, reducing foot and adapter. Polyvinyl grey body and shaft 1-1/2" (38mm) diameter. Removable foot valve for cleaning 1-1/2" (38mm) diameter Model 212PC: 8 oz./stroke, one 1/4" intake	$21.51

Certain organizations have attempted to design even lower cost hand pumps. In particular, the DTU School of Engineering, University of Warwick, which in 2000 published "*The Manufacture of Direct Action Handpumps for use with Domestic Rainwater Harvesting Tanks*" (Whitehead 2000). The main object of the study was to design a low cost hand pump which could be manufactured and maintained locally through available materials and skills. The study proposed the design of four hand pumps, including a list of required materials, assembly drawings and a cost analysis. The four pumps are direct-action hand pumps for domestic systems. The four types include: 1) the DTU hand pump, a simple lift pump; 2) the Tamana hand pump, a suction pump; 3) the "Harold" hand pump, a lift pump; and 4) the enhanced inertia hand pump, a lift pump.

3.2. Water quality protection

The quality of the water collected by the roof and stored in the cistern or tank is really important, since it is mostly used for drinking and cooking purposes. Considering the water cycle, rainwater is the result of the process of evaporation and condensation, which leads to a quite clean/pure form of water (Gould 2006). Atmosphere can also contain pollutants processed by human activities and generate rainwater contamination. Although pollutants can be transported for very long distances, the level of contamination in large rural regions or islands is usually fairly low. The primary concern in those areas lies in the contamination from catchment surfaces and/or from water extraction from storage. Specifically, the water supplied can be contaminated by faecal bacteria.

Water supplied by household rainwater catchment systems is contaminated by materials entering the storage system. The principal sources of contamination are: 1) materials on the roof surface, such as dirt or small animals' defecation; 2) materials washed into the storage, such as leaf debris and organic materials; and 3) insects, birds and other small animals drowning in the stored water.

The quality of water can be protected by designing adequate systems and executing proper operation and maintenance. It is possible to design a variety of systems to reduce faecal contamination by treating the water during one (or combining more treatments) of the tree stages of storage: before entering the cistern/tank, during the storage and after the storage.

3.2.1. Screen filter

A screen filter operates before the water enters the storage. This method keeps large debris (such as leaves, insects, birds, and small animals) out of the catchment system. The screen is usually made of a mesh. The filter should be easily removable for periodic cleaning. Mesh filters can be installed in many different places: over the gutters, at or inside downpipes and over tank entrances (DTU 2000-2003).

Screen over gutter length. If screens are placed at angle, so that leaves and other objects can slide off, the main advantage is in the prevention of leaf build-up in gutters, which tend to cause blockage and potential overflow. However, this solution carries high costs for the large areas covered and is a significant downside for implementation in developing countries.

Screen at downpipe. The filter is placed where gutters convey to the downpipe. The advantage of this solution is the lower price compared to the former solution, thanks to the smaller filter area. Despite its low cost, the elevated filter location creates difficulties in cleaning.

Screen in downpipe. This solution requires a more complex design and usually is too expensive for developing countries. In addition, this solution uses more than 10% of water for self cleaning.

Screen at the tank entrance. The screen location is the most visible of all other solutions. This provides the advantage of easy cleaning. The screen can be as simple as a cloth over the tank inlet. The main disadvantage is the possibility of accidental or deliberate contamination caused by the proximity of the filter to the tank entrance.

3.2.2. First flush

Faecal bacteriological contamination of the water stored in the tank comes mainly from the first roof runoff (or "first flush"). The first runoff washes the roof and all the contaminants into the storage tank. After this first runoff, the water is considerably less contaminated. There are three prevalent techniques used in developing countries to reduce this type of contamination: manual method, fixed volume method and fixed mass system (DTU 2000-2003).

Manual method. The manual method consists in manually removing the downpipe from the storage entrance at the first rainfall for a determined period of time. The method is very simple and practical, but has the downside of relying on the presence of the user.

Fixed volume method. This method consists in filling a downpipe (a chamber of a defined size) with the first runoff until it overflows. The system has a floating ball seal that reduces the mixing between earlier and subsequent water. *Figure 28* illustrates an example of such system:

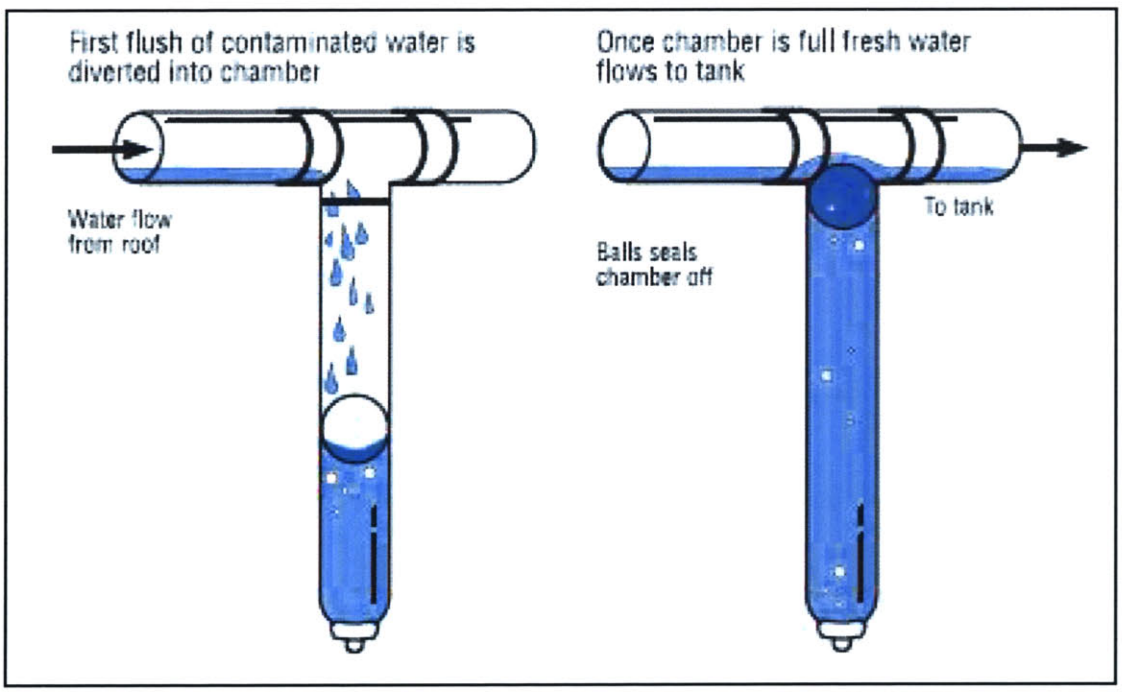


Figure 28: First flush fixed volume method (http://www.reuk.co.uk/OtherImages/firstflush.jpg)

Fixed mass system. This technique relies on a mass of water that tips a bucket. The method can also be called seesaw system. *Figure 29* illustrates the schematic process of the system.

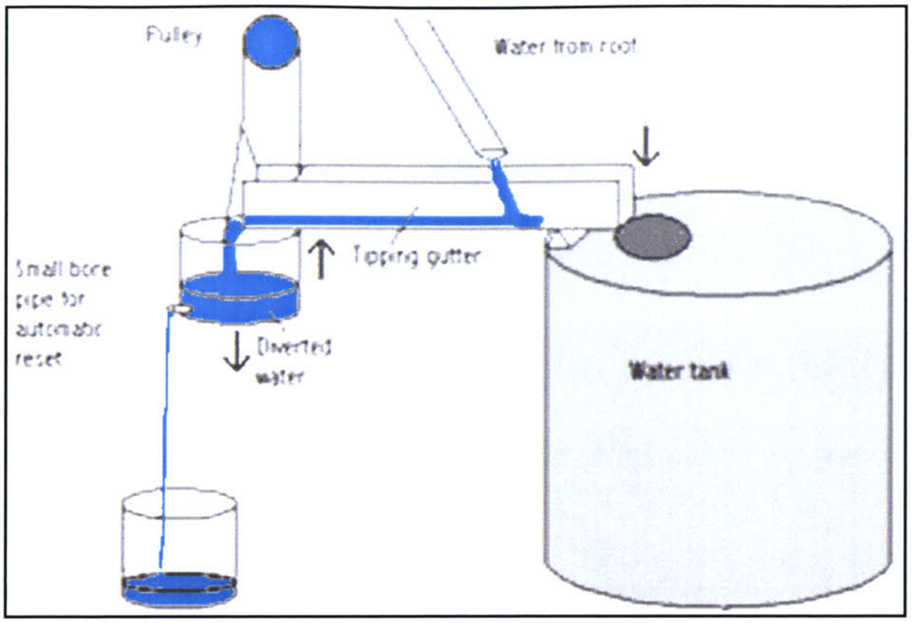


Figure 29: First flush seesaw system (DTU 2000-2003)

3.2.3. Filtration

Filtration techniques are largely used to treat contaminated water. These techniques usually employ gravel, sand and fine sand and operate at various rates. The most effective technique is slow-sand filtration. This technique, extensively studied and now well-established, improves the quality of water by removing bacteria and other water-borne pathogens (Skinner 2003).

Slow-sand filtration, in its standard form, infiltrates water at a rate of 200 mm/hour through a bed of sand of 1 meter depth (Way & Thomas 2005). Because of the slow rate, the filter cannot be utilized at the storage inlet of a rainwater catchment system. In fact, during a tropical downpour the inlet has to support flow rates that can be very high, with short-term peaks sometimes exceeding 1.5 L/s^{-1}.

Based on "*Underground storage of rainwater for domestic use*" (Thomas 1997), an inlet filter can be created with a gravel-filled plastic bucket with holes at the bottom. The first filtration of the system occurs through a coarse cloth stretched over the bucket top. The second filtration occurs through the gravel layer. The filter reduces the access of large particles into the water, while the smaller particles settle into the tank. The filter requires periodical cleaning and maintenance.

In *"Slow filtration within rainwater tanks"*, Way and Thomas (2005) build a shallow filter for the intermittent flow of water drawn off for a few minutes several times a day. They demonstrate that even very shallow filters (as little as 5 cm deep) can be very effective and reduce faecal coliform by approximately 95%. They perform field tests for two filter designs: 1) tank floor filter and 2) floating tank filter. The field tests confirm the effectiveness of the two techniques. The two filters are designed to be used as outflow from the tank operated by a pump.

3.2.4. Treatment of water

With appropriate hygienic practices and careful maintenance of operations, the rainwater stored in the cistern/tank is potentially clean and safe to drink. However, if none of the previously-mentioned treatments are provided, treatment of stored water becomes necessary. Water treatment in storage or upon extraction makes sense only if done carefully and with the assurance that existing hygienic conditions minimize the risk of water re-contamination after the treatment.

The most used treatments of stored water are the following: 1) chlorination; 2) filters; 3) boiling; 4) sunlight. *Table 12* illustrates the benefits and drawbacks of the four treatments (Gould 2006).

Table 12: Pros and cons of treatment methods for stored water

Treatment	Pros	Cons
Chlorination	▪ Purifies water	▪ Affects the taste ▪ Over-application can cause problems ▪ Different forms and brand names can create confusion ▪ Does not remove Giardia, Legionella
Filters	▪ Cheap and simple ▪ Very effective	▪ Not widely used ▪ Periodic cleaning and maintenance
Boiling	▪ Very effective in 2-3 minutes ▪ Kills every armful bacteria or pathogens	▪ Cost of energy (gas, gasoline, wood) ▪ Waiting time for water to cool
Sunlight	▪ Cheap ▪ Very effective	▪ Not effective against pathogenic human enteric virus

3.3. Case studies

3.3.1 Tarpaulin Tanks, Southern Uganda (Rees 2000)

Tarpaulin tanks for rainwater catchment systems were developed in 1997 by Rwandan refugees in Uganda. The size tank is 6,000 Liters (6 m^3). The pit (length=3 m, width=2 m, height=1 m) is lined with a standard UNHCR (United Nations High Commissioner for Refugees) polypropylene tarpaulin (5 m x 4 m). Walls of wood poles and mud up to 1 meter surround the tank. The building is roofed with corrugated iron sheets. Rainwater enters from a cloth-covered hole in the roof sheeting and the tank is fed by a sloping metal downpipe. The water is then extracted by dipping a modified 10 liter jerrycan into the water from a small wooden door in one of the walls. The tank is not provided with an overflow, thus the households need to move aside the downpipe when water reaches the tarpaulin edge.

The agency ACORD (Agency for Cooperation and Research in Development) built tarpaulin tanks in Southwest Uganda in 2000. The simple design and the use of local materials kept the price at very low levels. *Table 13* summarizes the tank's cost profile (actual construction costs during the July 2000 are by Rees 2000).

Table 13: Tarpaulin tank cost table (DTU 2000)

Item	Quantity	Cost [$]
UNHCR tarpaulin (4x5m)	1	20
Iron roofing sheet	1	20
Wood & mud from site	-	-
Labor provided by householder	-	-
Total cost		**$40**

3.3.2. Underground storage of rainwater for domestic use, Western Uganda (Thomas & McGeever 1997)

Thomas and McGeever (1997), together with members of URDT (Uganda Rural Development and Training), describe the construction and initial testing of low-cost underground rainwater storage tanks built with a 20 mm cement/lime-plastered chamber of 8,000 liters. The description also includes the construction of an inexpensive hand pump. The low-cost underground cistern design is illustrated in *Figure 30.*

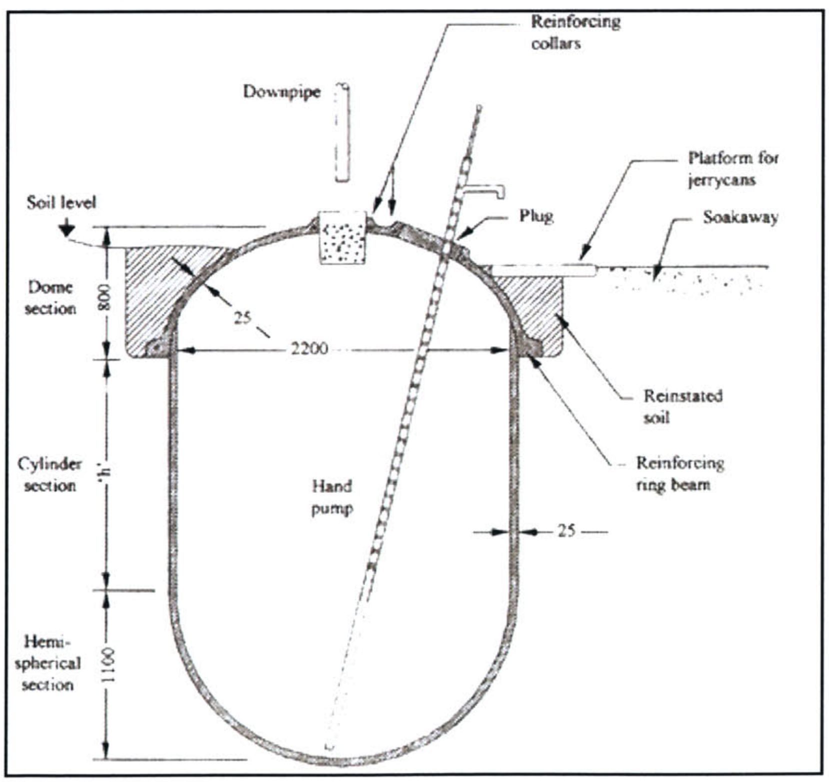


Figure 30: Low-cost underground cistern with pump (Thomas 2000)

The authors provide the cost of producing both the cistern and the pump. Costs are based on prevailing conditions in rural Uganda in 1996-97 and are converted to US dollars at the rate of 1$ = 1,000USh. The total cost of the cistern (8,000 Liters capacity with 20 mm dome and 2-coat chamber lining) and hand pump was approximately $160.

4. RAINFALL DATA ANALYSIS AND STORAGE SIZE CALCULATION

When a rainwater catchment system is selected to provide water supply, the first step is to verify whether the system is suitable in a given situation. The specific situation is determined by two very important characteristics: the potential rainwater supply and the water consumption and demand. To establish the potential water supply, it is necessary to have monthly rainfall data of the area or region where the catchment system is to be located. The process to estimate water consumption and demand for a household is fairly complex, with demand estimate subject to variability according to climatic and geographic conditions. Often, rainwater catchment systems are used together with other kinds of water sources. This situation is particularly common when rainwater catchment systems supply water for specific periods (wet seasons), whereas alternative water sources (main supply) work during other periods (dry seasons). As mentioned above, the water sources in the village of Bisate are seasonal in nature and not homogenously distributed. Consequently, women and children must travel far from their houses to fetch water. In this particular situation, the household rainwater catchment system should constitute the main supply of water for both the wet and dry season.

4.1. Rainwater supply

4.1.1. Rainfall data

In order to estimate the potential water supply for a specific rainwater catchment system, reliable rain data are necessary. A minimum historical period should include 10 years, preferably the most recent 10 years. For a more comprehensive and careful analysis, the historical rainfall data should contemplate a 20-30 years rainfall series. A longer rainfall series could also be appropriate, except a long series usually does not give particular attention to potential regional climatic changes. Indeed, to properly represent local situations, rainfall data sources should be as close as possible to the actual location and/or have the same geographic-climatic conditions of the selected location (Gould 2006).

During our stay in Rwanda, we obtained rainfall data from various sources including Karisoke Research Center (Musanze), the Institute of Agriculture (Busogo), and GIS Center (Butare). Other rainfall data were obtained from the NOAA National Climatic Data Center (NCDC 2007).

For our case study, the collected rainfall data were selected to properly correlate with the geographic location and climatic characteristic of Bisate Village. The village has an altitude of 2,500 meters and is located at the edge of Bisoke Volcano. The region is characterized by a fresh-humid climate. Due to the particular elevation and proximity of the high mountains, the region presents a variable temperate climate. The entire mountain chain registers the highest rainfall of the country, about 2,000 mm between 2,000 m and 3,000 m of altitude. The average temperature is around 23°C at Ruhengeri (1,878 m). (ORTPN 2004)

4.1.2. Rainfall data analysis

The rainfall data analyzed for the rainwater supply and storage calculations are inventoried in *Table 14*. (Note that the town of Musanze was formerly called Ruhengeri.)

Table 14: Rainfall data for Bisate, Musanze and Kigali

LOCATION	PERIOD	DATA TYPOLOGY	STATION LOCATION	SOURCE
Bisate	10/1996 – 08/1997	Daily	Bisate	Karisoke Research Center
	01/2000 – 12/2001	Daily	Bisate	Karisoke Research Center
Musanze (Ruhengeri)	01/1977 – 12/1992	Monthly	Ruhengeri Airport (Musanze)	Institute of Agriculture (Busogo)
	01/1997 – 12/2001	Daily	Musanze (Ruhengeri)	Karisoke Research Center
	01/2002 – 12/2005	Monthly	Ruhengeri Airport (Musanze)	Institute of Agriculture (Busogo)
Kigali	01/1986 – 12/2005	Hourly	Kigali	NOAA

From the table above, it is possible to observe that rain data for Bisate—the study area—cover a relatively short period: 11 months (between 1996 and 1997) and 24 months (between January 2000 and December 2001), three years in total. Despite the small number of years covered, the daily data provide a relatively good picture of weather conditions in Bisate in such a short period of time. The situation for Musanze is quite different: in fact, rainfall data cover a period of 29 years (1977-2005), with the sole exception of 4 years (1993-1996), for a total period of 25 years. Here, the types of data are more mixed: two thirds of the data are monthly and the remaining one third is on a daily basis. The data for Kigali, obtained from NOAA NCDC, cover a period of 30 years on a daily basis.

The rain data for Bisate Village are not sufficient to verify whether the rainwater catchment system is sustainable because, as mentioned earlier, a minimum rain data series of 10 years is necessary to obtain a good approximation. Therefore, we need to consider the rainfall data of Musanze and Kigali and see whether a sufficient correlation exists to use such data as a proxy for the Bisate potential rainwater supply. The first step of the analysis is to determine whether a correlation (Pearson Correlation Coefficient) exists between rainfall data for Bisate with that of Musanze and Kigali in the overlapping years of 2000 and 2001. The monthly data for 2000 and 2001 are reported in *Table 15*.

Table 15: Monthly Rainfall data [mm] of years 2000 and 2001 for Bisate, Musanze and Kigali

Year	Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	Bisate	56.8	165	160.7	155	113.5	0	0	35	66	202.7	177	87.3
	Musanze	49	89	73	175	63	8	0	26	77	119	110	70
	Kigali	26.1	101.5	307.4	31.7	261.7	2.1	0	9.9	42.2	49	179.1	114.7
2001	Bisate	78.8	137.4	226.7	185.3	172.8	40.9	53.9	108.5	131	214.1	182.6	199.5
	Musanze	68	60	213	189	115	22	20	113	110	190	214	47
	Kigali	13.6	0	0	21	96.1	0.3	201.9	39	136	229.2	321.9	72.9

The analysis of the three rainfall datasets shows that Kigali has a low correlation with either Musanze or Bisate (*Table 3*). In fact, the geographic and climatic conditions of the capital city are different from those of Musanze and Bisate. The main difference is that weather conditions in Musanze and Bisate are determined by the Volcanoes Chain. Indeed, the analysis shows that Bisate and Musanze weather conditions are highly correlated (*Table 16*).

Table 16: Pearson Correlation between Bisate, Musanze and Kigali for the years 2000 and 2001

Locations	Year	Correlation [0-1]
Kigali Bisate	2000	**0.53**
	2001	**0.18**
Kigali Musanze	2000	**0.20**
	2001	**0.31**
Bisate Musanze	2000	**0.83**
	2001	**0.76**

As a second step, we use data from October 1996 until August 1997 to further verify the potential correlation between Bisate and Musanze. This analysis indicated a correlation of 0.89, which is significantly higher than that registered in 2000 and 2001. The graphs in *Figure 31*, *Figure 32*, and *Figure 33* show rainfall trends of Bisate and Musanze and their respective correlation coefficients for the three periods 1996-1997, 2000 and 2001.

The analysis of the respective correlations leads to the conclusion that rain data of Musanze can be utilized as an approximation of the potential rainwater supply for Bisate Village. The stations at Ruhengeri Airport and Bisate together provided the necessary rain data to verify the suitability of the rainwater catchment system. The location of the two stations is illustrated in *Figure 34*.

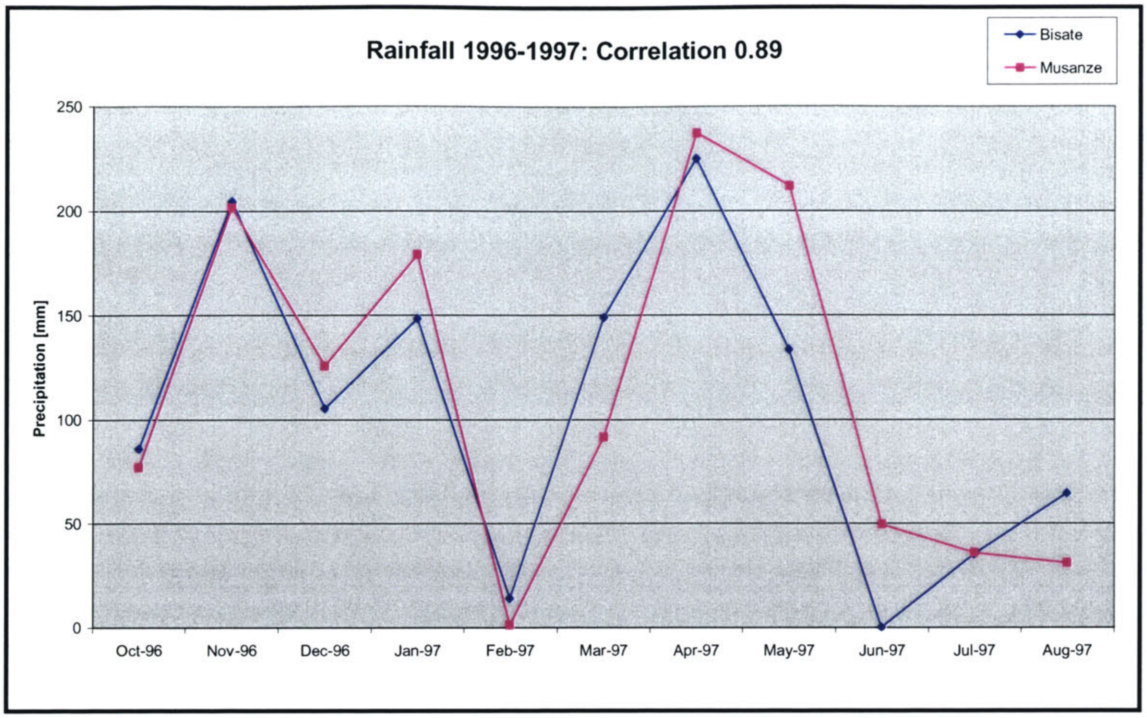


Figure 31: Bisate – Musanze Correlation for the period 1996-1997

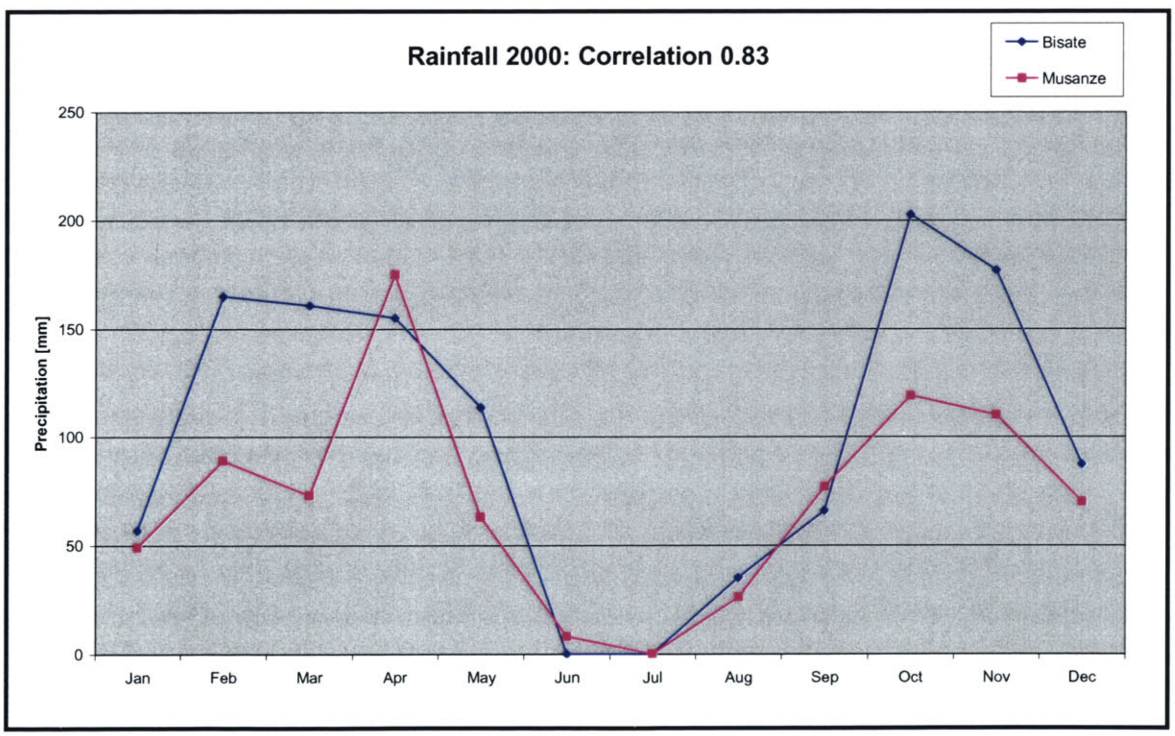


Figure 32: Bisate – Musanze Correlation for year 2000

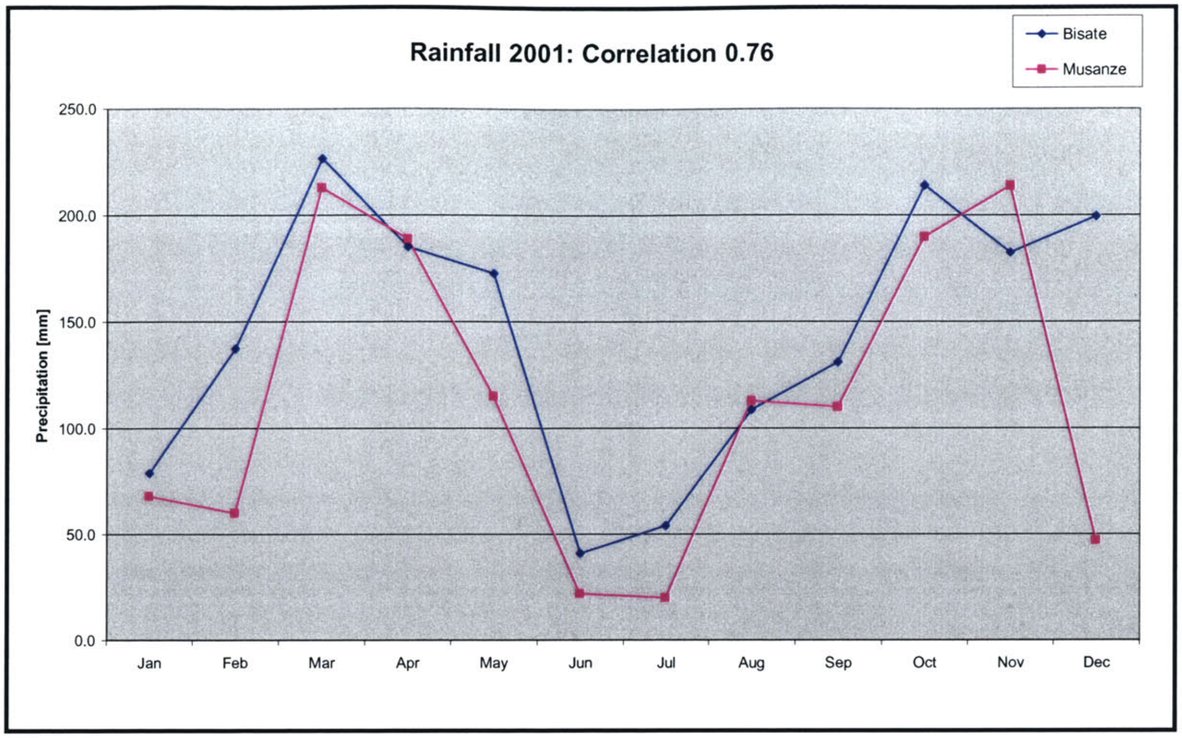


Figure 33: Bisate – Musanze Correlation for year 2000

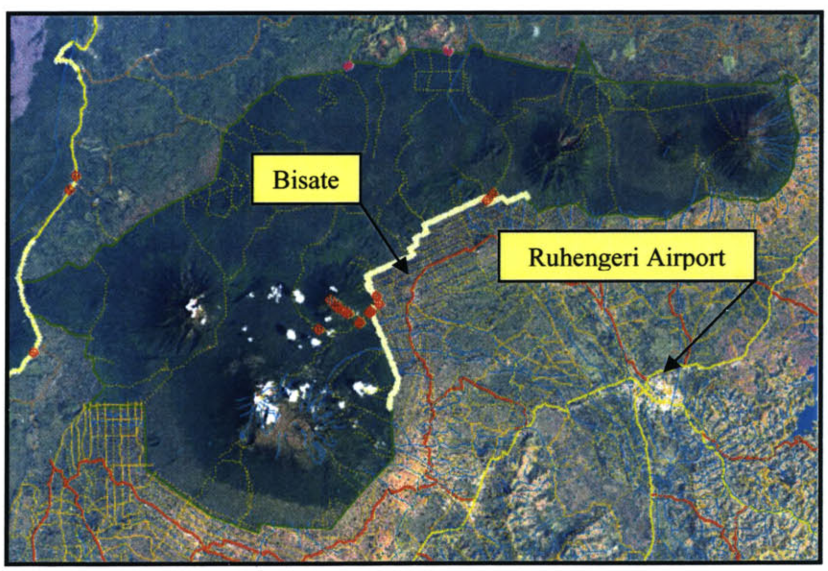


Figure 34: Location of the Stations (Base map – Karisoke Research Center)

4.2. Water Demand

Domestic water consumption varies significantly between poorer developing countries and wealthier developed countries. The level of consumption ranges significantly between those two categories, from less than 5 L/d/person to more than 1000 L/d/person. Such a large difference is mainly related to the availability and level of service. In fact, the average water consumption tends to increase with improving water access and consequent shortening of travel times to fetch water.

Many studies for developing countries show the relationship between domestic water consumption, accessibility and travel time. Two significant examples are reported by Howard and Bartram (2003). The first, from Mozambique, shows that daily water consumption per person is 12.30 liters in a village with a standpipe (or within 15 minutes walking distance) and only 3.24 liters in a village where people need to walk five hours to collect water. The authors explain that the extra water used in the village with the standpipe was primarily used for hygiene purposes. The second example relates to studies performed in Kenya, Tanzania and Uganda to estimate water consumption for washing dishes and clothes and for bathing. When villagers have water sources right outside their homes, they tend to use 6.6 L/d/person to wash dishes and clothes and 7.3 L/d/person for bathing. By contrast, villagers that have a pipe connection within their homes tend to use 16.3 L/d/person to wash dishes and clothes and 17.4 L/d/person for bathing (Howard and Bartram 2003).

One of the conclusions is that estimating daily water demand per capita is very complex, due to the numerous factors involved. One of the best ways to define water demand is to survey a large number of households and find an average value based on hundreds of responses. However, accurate surveys would not be enough for a precise estimate of water demand, simply because the survey tends to measure only water consumption and not total water demand (which includes also the potential demand). As mentioned earlier, when water supply is improved, in particular with the shortening of travel times, water consumption increases materially (Gould 2006).

Based on several studies, water consumption in the village of Bisate can be approximated to less than 5 L/d/person. This assumption is based on average travel times of more than 30 minutes to fetch water (Howard and Bartram 2003). As mentioned in *Chapter 2*, the actual water sources for the population of Bisate are few and not homogeneously distributed throughout the area. The lack of water, particularly clean water, has a direct role in the low level of hygiene and high risk of water-borne and water-washed diseases. The design of household rainwater catchment systems should permit an increase in the potential water consumption by substantially reducing the travel times and efforts to fetch water.

As shown on *Table 17*, the design for household rainwater catchment system should be able to improve water supply from a "No access" level to a "Basic access" level (or, from less than 5 L/d/person to about 20 L/d/person). Based on rain data collected for Musanze, the average annual rainfall over the last 10 years was 1,230 mm. This rainfall amount alone could provide 15 L/d/person. If we consider that the catchment system is on-site, the design could provide a level of water supply closer to the "Intermediate access", which would considerably reduce health concerns from "Very high" to "Medium-Low" (meaning that basic hygiene needs would be met).

Table 17: Service level descriptors of water in relation to hygiene (Howard & Bartram 2003)

Service level description	Distance / time measure [meters and minutes]	Water collected [L/d/person]	Level of health concern
No access	More than 1000 m (more than 30 minutes total collection time)	Very low (often less than 5 L)	Very high. Hygiene and consumption not assured. Water quality not assured.
Basic access	Between 100 and 1000 m (5 to 30 minutes total collection time)	Low (unlikely to exceed 20 L). Laundry and/or bath occur at water source with additional volume of water.	Medium. Not all requirements may be met. Water quality difficult to assure.
Intermediate access	On-site (single tap in house or yard)	Medium (likely 50 L). Higher volumes unlikely as energy/time requirements still significant.	Low. Most basic hygiene and consumption needs met. Bathing and laundry possible on-site. Quality more readily assured.
Optimal access	Water piped into the home through multiples taps	Between 100 L and may be up to 3000 L	Very low. All uses can be met. Quality readily assured.

4.3. Rainwater storage calculation

4.3.1. Bisate houses survey

In order to estimate the rainwater storage capacity, one of the most critical variables is the potential quantity of rainwater the catchment surface system can collect. When monthly or annual rainfall data are known, there are two possible alternatives. One is to determine the catchment surface area based on each household's water demand, or when the system is part of a new housing construction. The second is to design rainwater catchment systems on existing buildings (the situation of Bisate Village). In this case, to properly define the quantity of water collected from the catchment surface, we need to know the surface area of each domestic roof. During our stay in Bisate, we surveyed a representative sample of residences:

1) The first selected group is a sample of "mid-level" houses (*Figure 35* and *Figure 36*). The residents explained that all houses in the area had been built by the priest of a nearby church, and therefore carry similar size. The three residences in this group have rock or concrete foundations, mud walls with a bamboo structure and corrugated iron roofs. In addition, these houses are almost of the same size:

$RoofArea = Length * Width = 6.40m * 5.48m = 35.1m^2$ (Measurements of roof projection)

2) The second group includes two "lower-level" houses (*Figure 37* and *Figure 38*). The first is a circular construction with mud walls and thatch roof. The diameter of the roof projection is 5 meters:

$$RoofArea = \pi * \left(\frac{D}{2}\right)^2 = 19.6m^2$$

The second is a rectangular construction with wood-branch walls, a wood structure and corrugated iron roof. The roof projection measurement is the smallest found:

$$RoofArea = Length * Width = 4.7m * 3m = 14.3m^2$$

3) The last group includes three "higher-level" houses (*Figure 39* and *Figure 40*). These houses look like "mid-level" houses, except for their larger size. The houses have foundations of rock or concrete, mud walls with a bamboo/wood structure and iron roofs. Average roof projection is:

$$RoofArea = Length * Width = 9.5m * 8.6m = 81.7m^2$$

For the estimate of the storage capacity, we need to define the quantity of rainwater the catchment system's surface can collect and use average roof projections for the three different houses (*Table 18*): "lower-level" roof 15.4 m^2, "mid-level" roof 35.1 m^2 and "higher-level" roof 81.7 m^2.

Table 18: Bisate houses' roof area [m^2]

HOUSE ROOF AREA [m^2]	
Small	15.4
Medium	35.1
Large	81.7

Figure 35: Mid-level house in Bisate Village (Picture by Author)

Figure 36: Mid-level house in Bisate Village (Picture by Author)

Figure 37: Poor-level house with thatch roof in Bisate Village (Picture by Author)

Figure 38: Poor-level house with branch walls in Bisate Village (Picture by Author)

Figure 39: Higher-level house in Bisate Village (Picture by Author)

Figure 40: Higher-level house in Bisate Village (Picture by Author)

4.3.2. Storage calculation methodology

Water storage capacity is required to balance water supply and household water demand. When rainwater exceeds the water consumption for the day, the excess water can be stored to supply water in the following days. During the rainy season, if available water consistently exceeds demand, the surplus must be stored to serve during the coming dry season. A rainwater catchment system is sustainable for the entire year when it is able to provide sufficient water during each season, wet or dry. Two conditions are indispensable for a successful system: first, annual rainfall must exceed annual demand; second, the designed storage must have a capacity large enough to collect the rainwater surplus needed during the dry periods.

Different techniques can be used to estimate the appropriate storage capacity. Fundamentally, all techniques follow two main estimation criteria: maximizing supply for a given catchment system and satisfying the required water demand. These criteria also need to consider the cost and available space for a properly designed storage. Finally, the accuracy of the estimation depends on the quality of the available rainfall data. As mentioned earlier, there are only two years of available data for Bisate area and, because of this short period, we use data for Musanze for the storage capacity approximation. The relatively high correlation between the rainfall data of the two locations gives us enough comfort to model Bisate Village rainfall estimates using data collected at Musanze.

To achieve the best approximation, different techniques can be used to maximize results while minimizing design errors for the storage capacity. The methods considered to determine the storage size are the following:

- Dry-season demand versus rainwater supply
- Mass curve analysis
- Graphical Method
- Mass balance curve analysis

4.3.2.1. Dry-season demand versus rainwater supply

This technique can be utilized when the dry season is clearly distinct within the year. In fact, the method calculates the storage capacity based on water consumption during the dry periods. The storage capacity is designed to supply water when rainfall inflows are not sufficient for the water consumption of the season. The idea is to store the excess rainfall of the wet season for future use during the dry season (Gould 2006).

Analyzing the available rainfall data for Musanze for the period 1977-2005, two dry seasons are observed during the year: 1) January and February: while the precipitation levels vary across the years, the analysis of average monthly rainfall data shows that January and February are below the 1977-2005 period average (Jan: 79.8 mm, Feb: 82.9 mm, period average: 104.6 mm); 2) June, July and August: this is the longest and most severe dry season of the year. In fact, the average monthly rainfall of the three months is not only below the period's mean but also below January and February (*Table 19*). The water consumption during this extensive dry season requires longer times to restore the appropriate storage and provide enough rainwater supply for the following periods.

Table 19: Musanze Mean Monthly Rainfall data of the period 1997-2205

MUSANZE MEAN MONTHLY RAINFALL DATA 1977-2005 [mm]													
Values	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Monthly Mean**
Mean	79.8	82.9	135.3	179.6	146.1	33.6	16.7	50.3	123.4	164.4	155.0	87.7	104.6

When the dry seasons are clearly identified, one important step is to determine whether the rainwater catchment system can be used to verify that total annual rainwater supply exceeds total annual water demand. The method we used to estimate annual rainwater supply is the following. First, we analyzed Musanze annual rainfall data for the period of twenty-five years (1977-2005) and for the most recent period of nine years (1997-2005). Second, we compared the two averages of annual rainfall for Musanze with the two averages for Bisate during the years 2000 and 2001 (*Table 20*). Third, we selected the minimum average annual rainfall data to avoid issues with underestimating capacity (the minimum average of Bisate is almost equal to that of Musanze).

Table 20: Average Annual Rainfall of Musanze and Bisate

MEAN ANNUAL RAINFALL	
Musanze 1977-2005	1,254 mm
Musanze 1997-2005	1,230 mm
Bisate 2000	1,235 mm
Bisate 2001	1,718 mm
Selected Mean	1,230 mm

The amount of water supply depends on the annual rainfall, the surface catchment area and the related runoff coefficient. The average annual water supply is calculated using the following equation (UN-HABITAT 2004b):

*Water supply = Rainfall * Surface Area * Runoff Coefficient*

The runoff coefficient is the ratio of the volume of water that runs off a catchment surface to the volume of rainfall that falls on the catchment surface. The coefficient accounts for the following water losses: spillage, leakage, wetting and evaporation of the catchment surface. Several studies show that a well-conceived roof catchment, made of corrugated-iron sheets or tiles, is able to collect more than 90% of rainfall. The runoff coefficient also accounts for losses from gutter overflow during severe rain storms or due to blockage from leaves. For this reason, the runoff coefficient for a well-built roof in corrugated iron or tiles should have a value of between 0.80 and 0.85 (Gould 2006).

From the Bisate houses survey, we observed that almost all roofs are made of corrugated-iron sheets and are relatively well-built. Therefore, we use a runoff coefficient of 0.80, assuming a rainfall loss of 20% from gutter overflow. The above-mentioned equation returns an average annual water supply of about 15,000 liters from the small roof, 35,000 liters from the medium roof, and 80,000 liters from the large roof.

To verify if the system is suitable, we need to calculate the annual water demand. As mentioned in *Chapter 2*, the average household size in Bisate Village is 4.5 people. To estimate annual water demand, for convenience we assume a number of 5 members per household. The average annual water demand is calculated with the following equation:

*Annual Water demand = Liters/day/person * 5 persons * 365 days [Liters]*

Table 21: Annual water demand and annual water supply [Liters]

WATER DEMAND AND WATER SUPPLY				
L/d/person	**Annual Water Demand**	**Water supply 15.4 m²**	**Water supply 35.1 m²**	**Water supply 81.7 m²**
10	18,000 L	15,000 L	35,000 L	80,000 L
15	27,500 L			
20	36,500 L			

As mentioned earlier, a sustainable system is one that provides water supply in excess of water demand. The rainwater catchment system for the smaller houses does not satisfy the condition of a sustainable system for any of the proposed daily water consumption levels, as can be observed in *Table 21*. In fact, annual water demand (18,000 L) consistently exceeds annual water supply (15,000 L). The system for the medium houses satisfies the condition of 15 L/d/person. The potential rainwater that can be stored is 7,500 liters. Finally, the system for large houses easily satisfies the condition of 20 L/d/person. In fact, the rainwater catchment system provides as much as 40 L/d/person. With an average water demand of at least 15 L/d/person, it is possible to conclude that this rainwater catchment system does not work for small houses. Since both systems for medium and large houses are sustainable, we now need to calculate the most appropriate storage capacity that allows a sufficient rainwater surplus for the dry periods.

Between the two dry seasons identified, the second one (June, July, and August) is the longest and more severe. In this case, an adequate storage has to supply water for 3 months, or 93 days. The storage capacity is calculated with the following equation (UN-HABITAT 2004b):

*Storage capacity = dry season [days] * 5 persons * Liters/day/person [Liters]*

During the dry periods, we assume a minimum consumption level of 10 liters/day/person (drinking and cooking – UN-HABITAT 2004b). The annual requirement for drinking purposes is 4,650 liters for a family of five. In order to be safe, the storage capacity needs to be 20% larger than this minimum requirement, or 5,580 liters. In conclusion, we approximate the storage capacity as 6,000 liters, or 6 cubic meters.

The method conclusion is summarized in *Table 22.*

Table 22: Conclusion from the method - Dry-season demand versus rainwater supply

Dry-season demand versus rainwater supply		
Roof size [m^2]	**Dry-season water demand [L/d/person]**	**Storage capacity [m^3]**
Small roof (15.4)	10	N/A
Medium roof (35.1)	15	6
Large roof (81.7)	20	6

4.3.2.2. Mass curve analysis

The mass curve analysis is one of the techniques used to estimate storage capacity from a maximum supply perspective. Fundamentally, this method identifies the critical periods over a long period of time (at least 10 years), where the difference between the cumulative water supply and the cumulative water demand is at its peak. The main idea is to store the largest possible volume of water—represented by the maximum difference between supply and demand—for future uses. Therefore, the necessary storage capacity is designed to maximize water supply (Gould 2006).

For the mass curve analysis, we used the available data for Musanze for the period between 1977 and 2005 (25-year series) to build a model, which is illustrated in *Table 35* (Appendix 1).The model shows two mass curves, representing the cumulative monthly water supply and the cumulative monthly water demand over the entire 25-year period. Different mass curves are generated to analyze different scenarios. The first scenario shows that the rainwater catchment system for small houses is not sustainable. As can be observed from *Figure 41*, the system cannot work for the small roof surface (15.4 m^2), even if the water consumption is 10 Liters/day/person. In fact, the cumulative water demand is increasingly higher than the cumulative water supply.

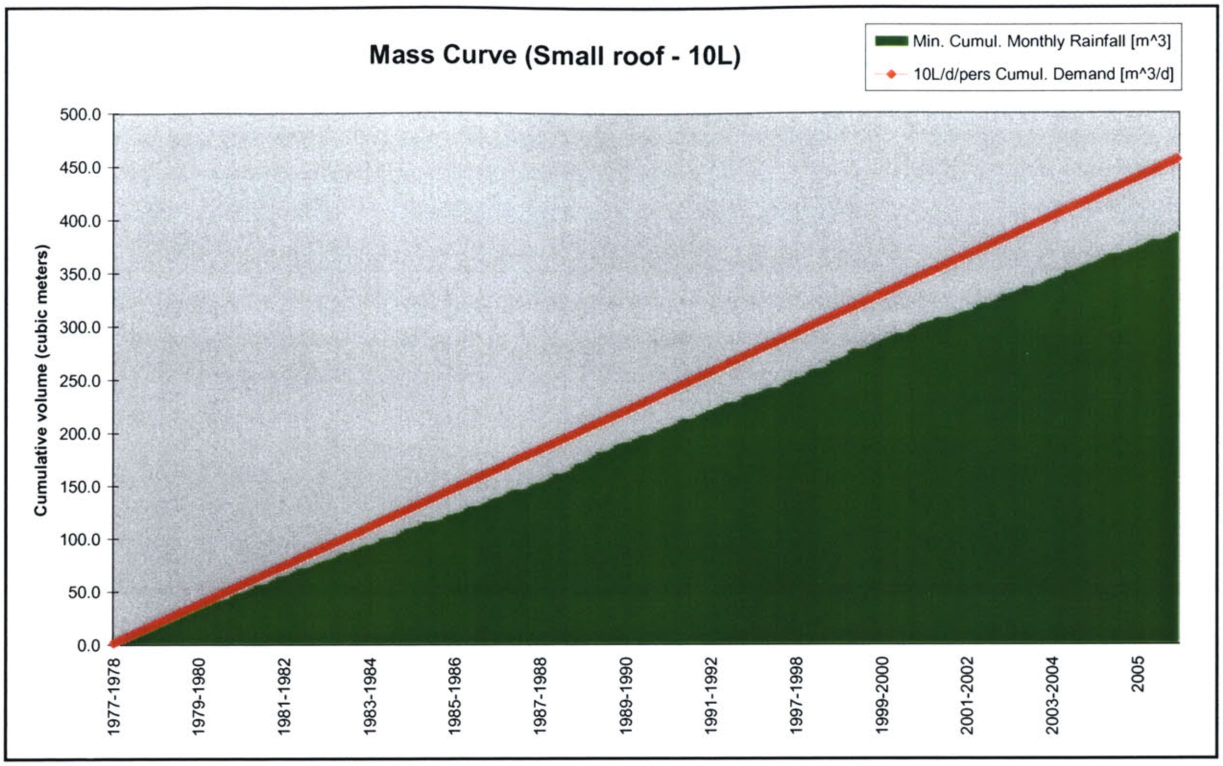


Figure 41: Mass curve analysis for small roof (15.4 m^2) and 10/L/d/person

The second scenario considers the rainwater catchment system of a medium-sized roof surface (35.1 m^2) when water demand is 15 Liters/day/person. From *Figure 42,* we can observe that while water supply and water demand initially grow simultaneously, water supply tends to outpace water demand over the long term. We conclude that the system is sustainable, as the spread between cumulative water supply and cumulative water demand increases indefinitely. From this mass curve analysis, we also conclude that it is not relevant to estimate storage capacity of the catchment system.

The third scenario (*Figure 43*) contemplates a rainwater catchment system for a medium-sized roof (35.1 m^2), but this time with a water consumption of 20 Liters/day/person. This scenario is created to verify that the system cannot sustain a water demand of 20 L/d/person. As we concluded earlier with the method "*Dry-season demand versus rainwater supply*", the system is not sustainable due to a water demand curve that is consistently higher than the water supply curve. However, since the two cumulative curves are not dramatically different, we can create a new scenario with different water consumption for each of the dry and wet seasons. What we find is that the system should be sustainable with a water demand of 15 L/d/person in the longer dry season and 20 L/d/person for the rest of the year.

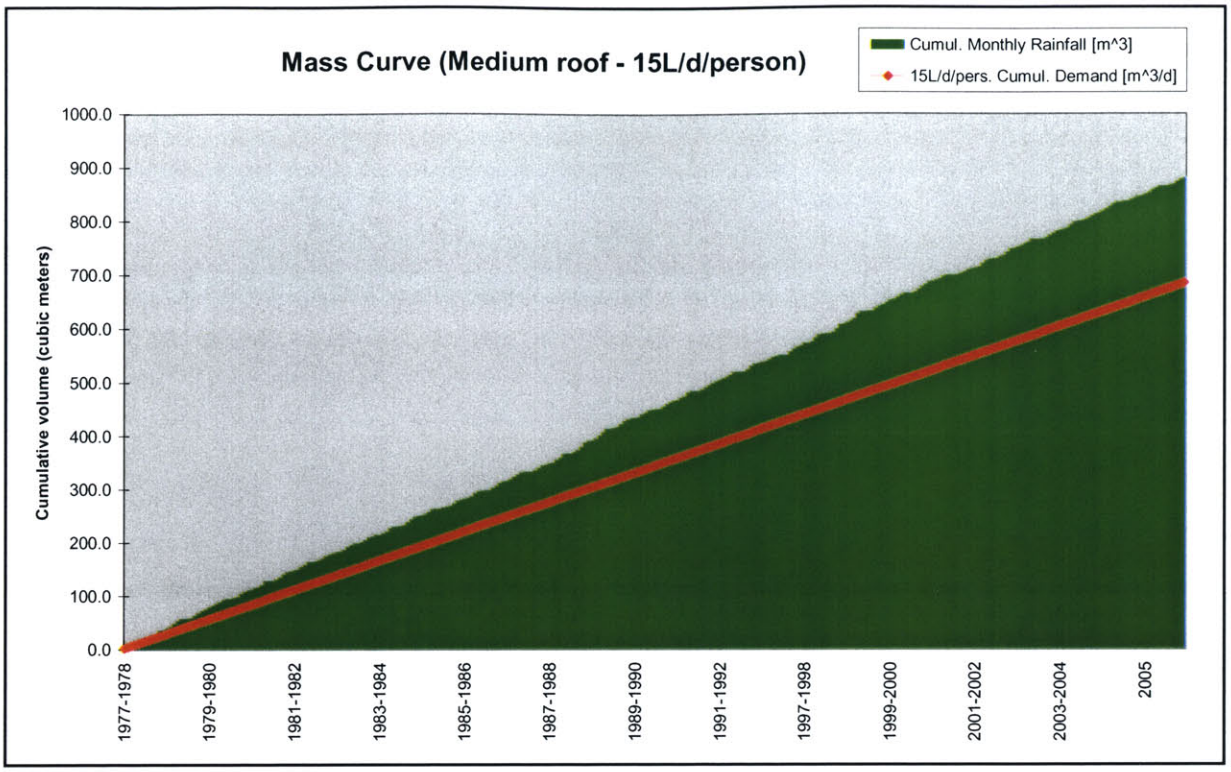


Figure 42: Mass curve analysis for medium roof (35.1 m^2) and 15/L/d/person

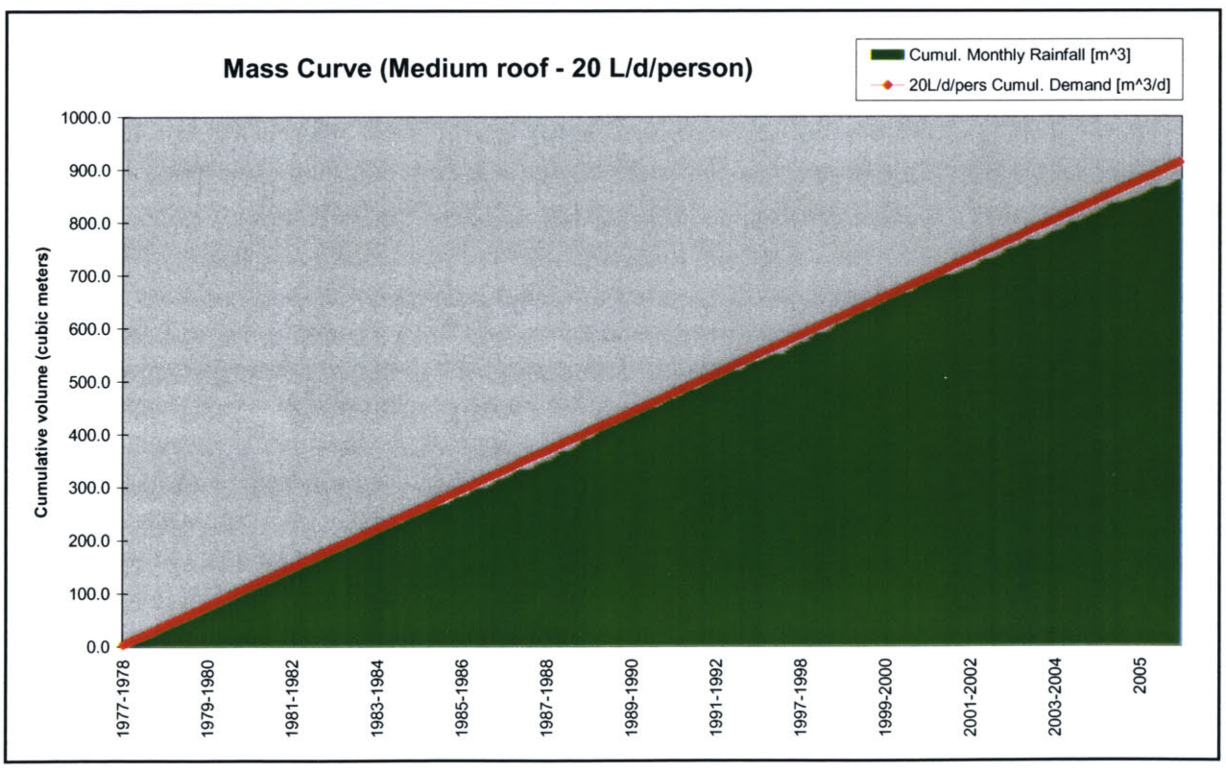


Figure 43: Mass curve analysis for medium roof (35.1 m^2) and 20/L/d/person

The method conclusion is summarized in *Table 23*.

Table 23: Conclusion from the method – Mass curve analysis

Mass curve analysis over a period of about 25 years			
Roof size [m^2]	**Water demand [L/d/person]**	**Sustainable water supply**	**Figure #**
Small roof (15.4)	10	NO	8
Medium roof (35.1)	15	YES	9
	20	NO	10

4.3.2.3. Graphical method

The graphical method is another technique following the maximum supply criterion. This method is similar to the "*Mass curve analysis*" in that it graphically estimates the storage capacity with the objective of maximizing the potential volume of water supply. The main difference is that the cumulative water supply curve uses monthly averages over the total period, instead of each month's data for the entire series. The procedure uses a bar chart to determine the storage capacity as follows (Gould 2006):

- First, plot a bar chart of average monthly roof runoff, beginning with the first month after the dry season when rainwater supply meets water demand;
- Second, plot the cumulative monthly roof runoff graph by adding up the monthly runoff totals;
- Third, in the same graph, draw a line showing cumulative water demand;
- Fourth, identify the greatest difference between the two lines (water supply and water demand) on the cumulative plot. That difference is the required storage volume.

It is possible to create different scenarios to better approximate the storage capacity. We utilize two models: the first is based on the rainfall data of Musanze for the period between 1977 and 2005; the second is based on the available rainfall data of the nine most recent years (1997-2005). The two models differ because the monthly averages differ during periods of different length (twenty-five versus nine years). The process analysis is illustrated in *Table 36* and *Table 37* (Appendix 1).

The first scenario is built using rainfall data during the longest period (1977-2005). The rainwater catchment system is estimated for medium-sized houses and for non-constant water demand. We assume 15 liters/day/person consumption during the longest dry season (June-July-August) and 20 liters/day/person during the rest of the year (September-May). The bar chart (*Figure 44*) shows that the system can support this demand level, with a graphical estimate of the storage capacity of 5.1 m^3. We also draw another line to estimate the required storage capacity to meet the water demand during the dry season. The required storage to meet water demand during the dry season is 4.1 m^3. As can be noted, the required storage capacity is smaller than the one found with the method "*Dry-season demand versus rainwater supply*" (about 6 m^3). The main reason is that in the first method we assumed complete absence of rainfall during the dry season, while in the graphical method we used the actual monthly rainfall averages during the dry season, which—as can be observed from the graph—is greater than zero.

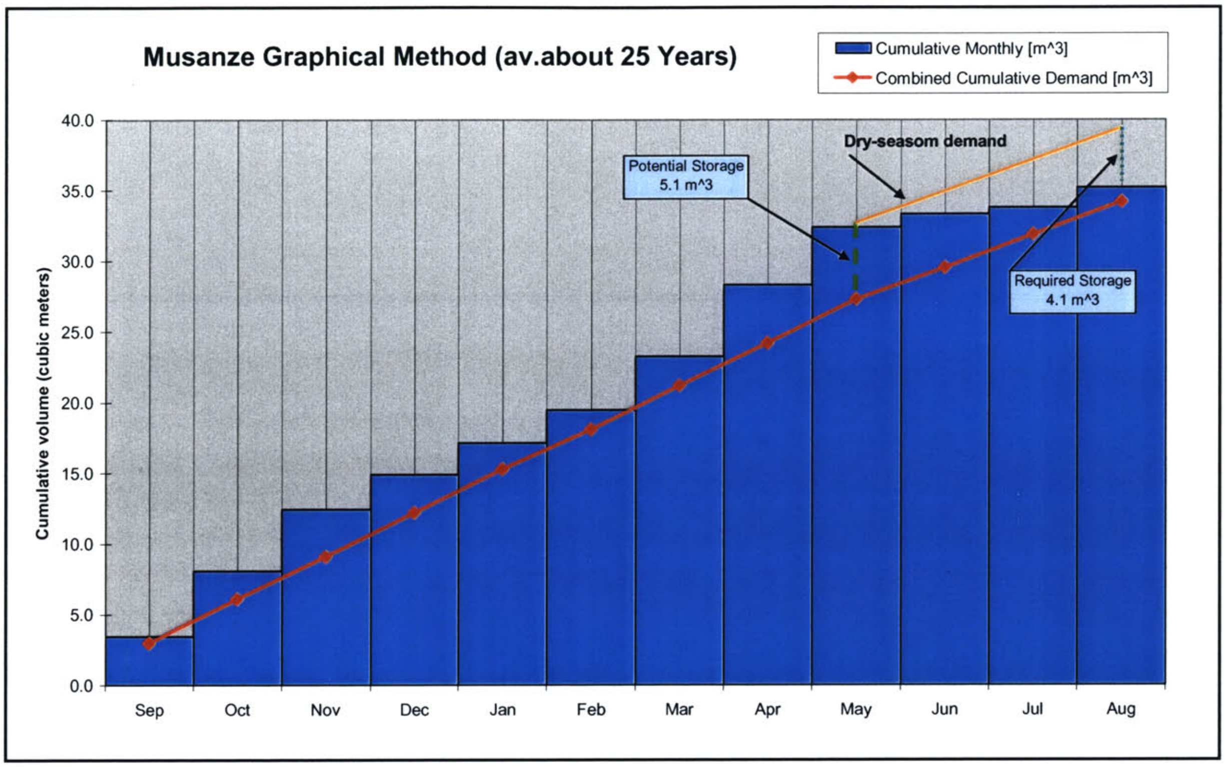


Figure 44: Graphical method for medium roof (35.1 m^2) over the period 1977-2005 with non constant water demand

The second scenario is built with available rainfall data during the nine most recent years (1997-2005). The rainwater catchment system is designed for medium sized houses with non constant water demand of 15 liters/day/person during the longest dry season and 20 liters/day/person during the rest of the year. Fundamentally, the rainwater catchment system is the same as in the previous scenario, with the exception that this scenario is built with most recent years' data and could provide potentially better approximations. In fact, using the most recent available nine years, it is possible to avoid errors related to potential weather changes. The bar chart (*Figure 45*) shows that the system is appropriate and the estimate for the storage capacity is 5.2 m^3. The new estimate is 100 liters larger than the previous estimate. We draw a second line to estimate the required storage capacity for the dry season and we graphically find that the estimate storage capacity is 4.7 m^3. In this case the required storage capacity for the dry season is larger than the preceding estimate by 600 liters and closer to the estimate of the "*Dry-season demand versus rainwater supply*" (about 6 m^3). The storage capacities of 5.2 m^3 and 6 m^3 should be verified with another methodology, potentially utilizing the two years of rainfall data for Bisate Village.

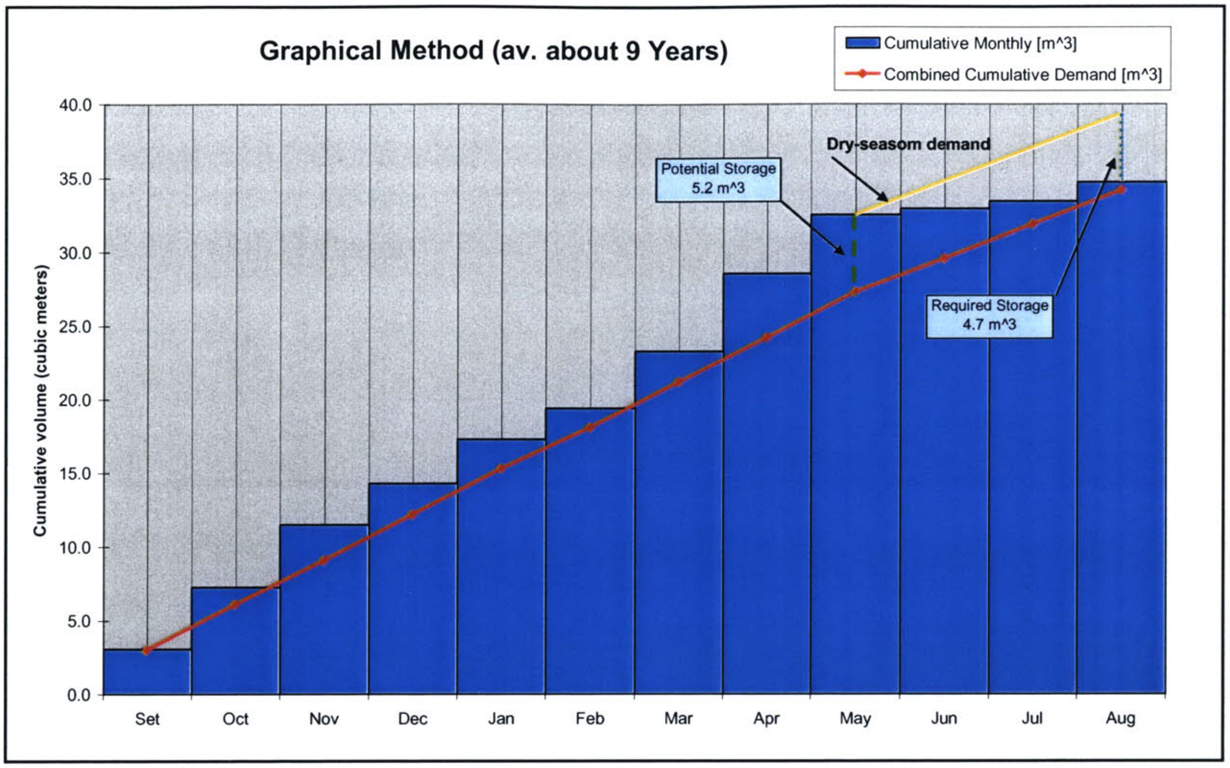


Figure 45: Graphical method for medium roof (35.1 m^2) over the period 1997-2005 with non constant water demand

The method conclusion is summarized in *Table 24*.

Table 24: Conclusion from the method – Graphical method

Graphical method				
Roof size [m^2]	**Period covered [year]**	**Water demand [L/d/person]**	**Storage capacity [m^3]**	**Figure #**
Medium roof (35.1)	1977 - 2005	20 – 15 (Wet – Dry)	5.1	11
	1997 - 2005		5.2	12

4.3.2.4. Mass balance curve analysis

The mass balance curve analysis is one of the techniques that estimate the appropriate storage capacity to collect rainwater surplus for the dry periods. The model is based on daily rainfall data of Bisate between 2000 and 2001. The model's primary goal is to identify a cyclical trend of stored water and understand the entire rainwater catchment system behavior over a longer period (in this case five years). Because the rainfall data of Bisate represents a short period of time (two years), this period needs to be extended to create a longer period (five years). The five year period is composed as follows: 2000, 2001, 2000, 2001, and 2000. The five years are named: 2000, 2001, 2002, 2003, and 2004. The two years of rainfall data represent two overall different years. In fact, 2000 was a dry year (1,235 mm) compared with the annual average for Musanze over 1997-2005. The year 2001 was particularly wet (1,718 mm), compared with the annual average.

The mass balance curve computes the water in storage continuously through the period considered with the following equation:

$$y_{n+1} = y_n + Qin_{n+1} + Qout_{n+1} \quad \text{(y = the water in the storage [m}^3\text{])}$$

The process analysis is illustrated in *Table 38* (Appendix 1). The mass balance curve graphs show whether the storage vessel is empty throughout the period considered.

Various scenarios are designed to better identify an appropriate storage capacity. The first scenario is created for medium-sized houses with non-constant water demand. We assume the system will provide 10 liters/day/person for the first two months (Jan.-Feb. 2000), 20 Liters/day/person during the wet season and 15 Liters/day/person during the two dry seasons. The longest dry season (usually Jun.-Aug.) also includes the month of September in this scenario, because after a severe drought (in this case during the year 2000) the system needs at least a month's time to be restored. As can be observed from *Figure 46*, the rainwater catchment system cannot provide water during the long period. In fact, starting from the first year (2000) and then every two years, the system is not able to provide water for about two months (from Aug 6 to Oct 20). The chart shows that during the driest years (in the case of year 2000), the water supply depletes during the dry season and restores after only two months. This chart contrasts with similar scenarios offered by the "Graphical method" and the "Mass curve analysis". The reason may be that daily data provide more accurate estimates of water storage than monthly data.

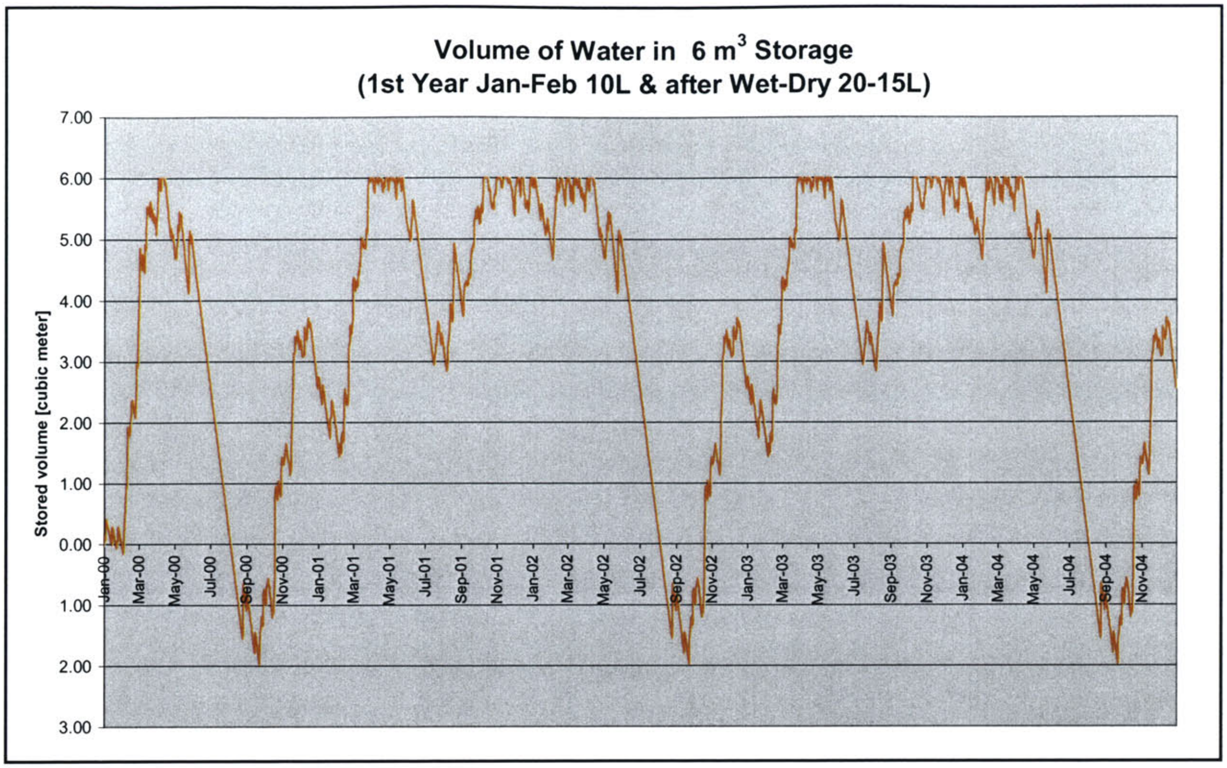


Figure 46: Mass balance curve for medium roof (35.1 m^2), 6 m^3 storage, and non-constant water demand of 20 L/d/person for wet season and 15 L/d/person for dry season

The second scenario is designed for rainwater catchment systems of medium-sized roofs with non-constant water demand. We assume the system must provide 10 liters/day/person during the two dry seasons and 20 liters/day/person during the wet season. We applied the same criterion of the previous scenario to determine the length of the second dry season (June-September). The system can provide water supply for the long period, as it is possible to observe from *Figure 47*. The behavior is similar to the previous scenario, since the system looks weak during the dry periods every two years (from Aug. 6 to Oct. 20). This characteristic shows that if rainfall is almost nonexistent during the dry season, the system takes a long time before being restored (about two months). The capacity selected for this scenario is 6 m^3, the same as with the method "Dry-season demand versus rainwater supply". It may be possible to increase water consumption by a few liters during the wet season, assuming strong rainy seasons, as shown by Figure 14.

The third scenario is created to verify that the storage capacity of 5.2 m^3, identified with the *"Graphical method"* between 1997 and 2005, is sufficient to provide water over a longer period. The rainwater catchment system is designed for medium-sized houses with a non-constant water demand. The water demand is exactly the same as the previous scenario: 10 liters/day/person during the two dry seasons (Jan.-Feb. and June-Sep.) and 20 liters/day/person during the wet seasons (Mar.-May and Oct.-Dec.). As can be observed from *Figure 48*, the system is weak in the same periods as the previous two scenarios. However, the rainwater catchment system can provide water for a longer period, with the exception of four days every two years (Aug. 23-Aug. 26).

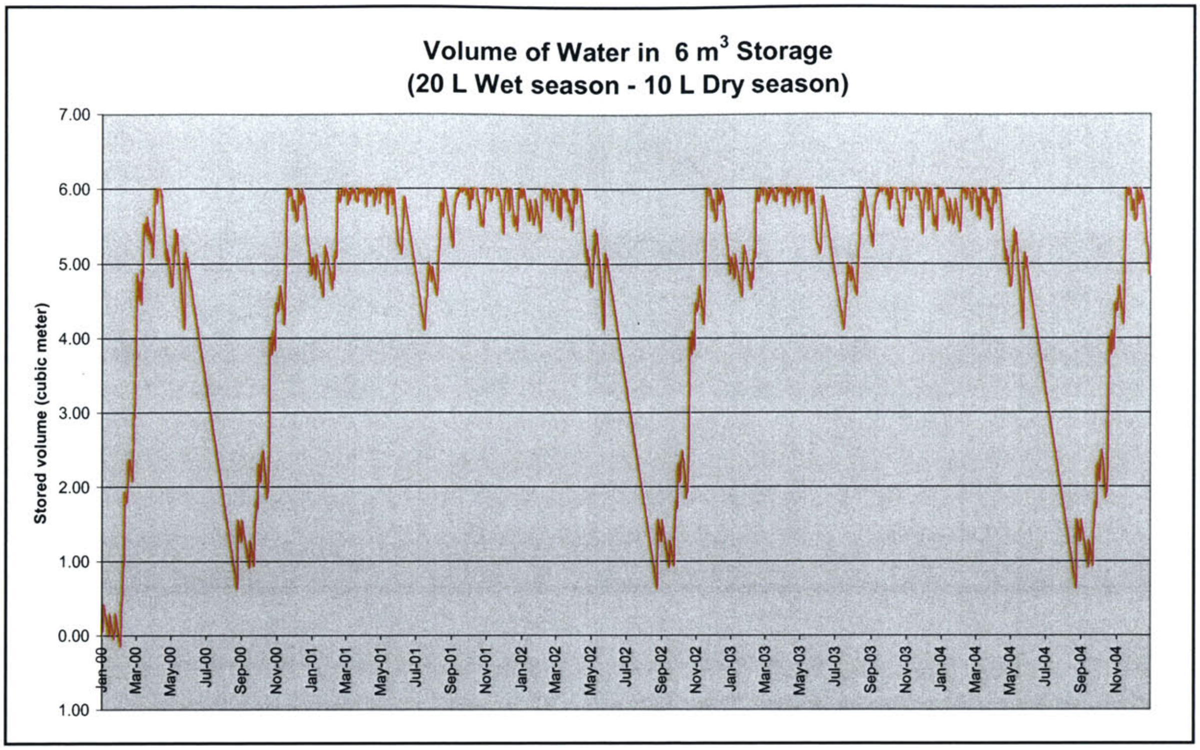


Figure 47: Mass balance curve for medium roof (35.1 m²), 6 m³ storage, and non-constant water demand of 20 L/d/person for wet season and 10 L/d/person for dry season

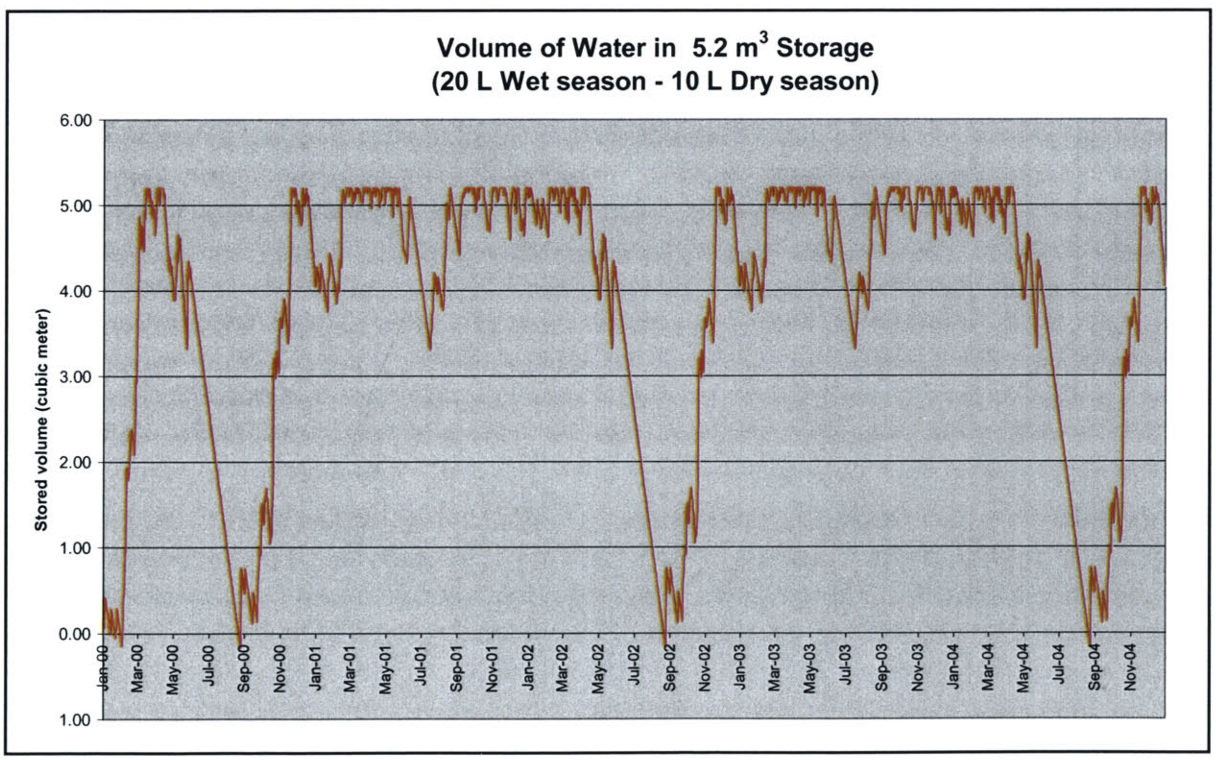


Figure 48: Mass balance curve for medium roof (35.1 m²), 5.2 m³ storage, and non-constant water demand of 20 L/d/person for wet season and 10 L/d/person for dry season

The fourth scenario is designed to verify whether the rainwater catchment system can provide a few liters more than the 20 liters/day/person assumed for the wet season. The system is the same as in the second scenario: 6 m^3 of storage capacity and medium-sized roof. However, the water demand is different: 10 liters/day/person during the dry seasons (Jan.-Feb. and Jun.-Sep.) and 22 liters/day/person during the wet season (Mar.-May and Oct.-Dec.). The same criterion of the previous scenarios has been followed to determine the length of the second dry season (June-September). As we can observe on *Figure 49*, the system is weak during the same dry periods of the previous scenarios but can support increased water demand during the wet season and also provide water during the entire length of the period.

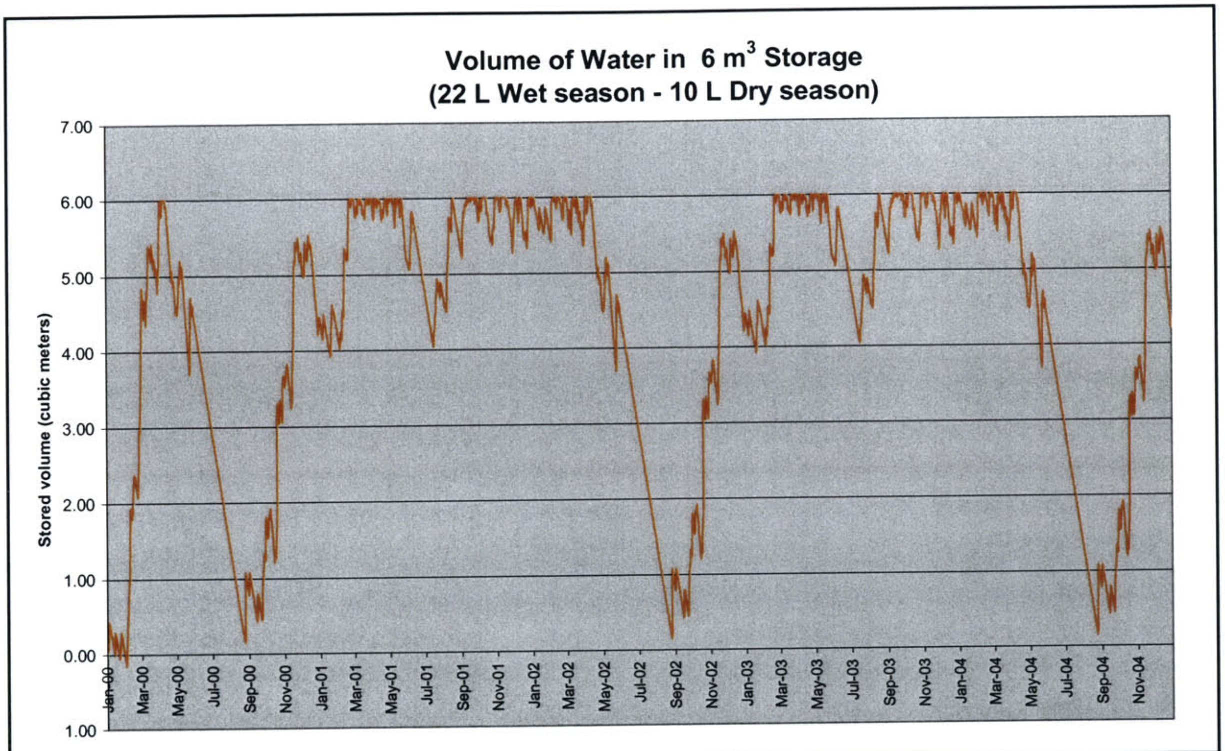


Figure 49: Mass balance curve for medium roof (35.1 m^2), 6 m^3 storage, and non-constant water demand of 22 L/d/person for wet season and 10 L/d/person for dry season

The next two scenarios are created for rainwater catchment systems of large-sized roofs (81.7 m^2). 1) The scenario is designed to estimate water supply for a storage volume of 6 m^3. The system can provide water over the long period of 10 liters/day/person during the first two months (Jan.-Feb. 2000), 30 liters/day/person during the wet season (Mar.-May and Oct.-Dec.) and 13 liters/day/person during the following two dry seasons (*Figure 50*). As in previous scenarios, the longest dry season (Jun.-Aug.) includes the month of September because after a severe drought (in this case the dry season of year 2000) the system needs a month to be restored. From this scenario, it is possible to conclude that the same rainwater catchment system (with a similar capacity of 6 m^3, but a larger catchment surface area) can supply more water than other systems with a smaller catchment surface.

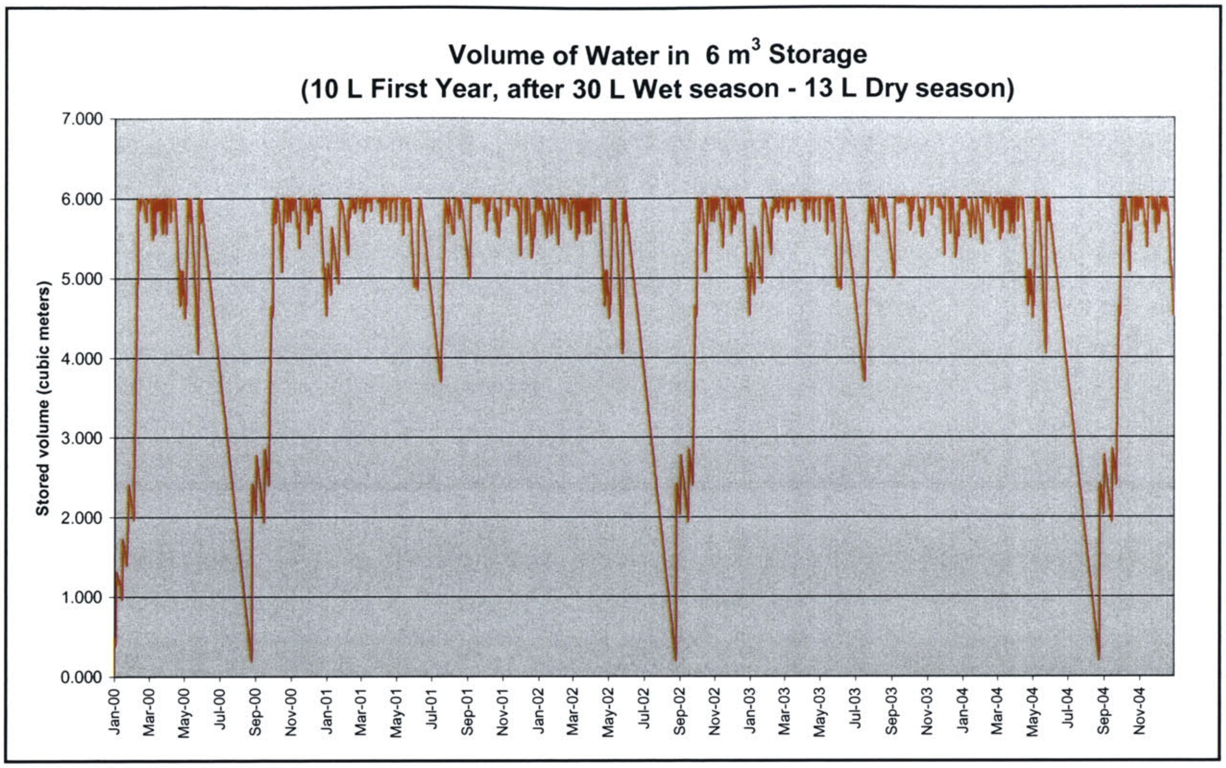


Figure 50: Mass balance curve for medium roof (81.7 m^2), 6 m^3 storage, and non-constant water demand of 30 L/d/person for wet season and 13 L/d/person for dry season

2) The scenario is created for rainwater catchment systems with a larger storage capacity (10 m^3) in large-sized houses. We assume that households owning large-sized houses can afford a larger storage. As can be observed from *Figure 51*, the system provides water for the entire duration of the period at a rate of 10 liters/day/person in the first two months (Jan.-Feb. 2000), 40 liters/day/person during the wet season (Mar.-May and Oct.-Dec.) and 20 liters/day/person during the two dry seasons (Jan.-Feb. and Jun.-Sep.). We followed the same criterion of previous scenarios to determine the length of the second dry season (June-September). We can affirm that a larger rainwater catchment system (in terms of roof size and storage capacity) is able to support more consistent water consumption.

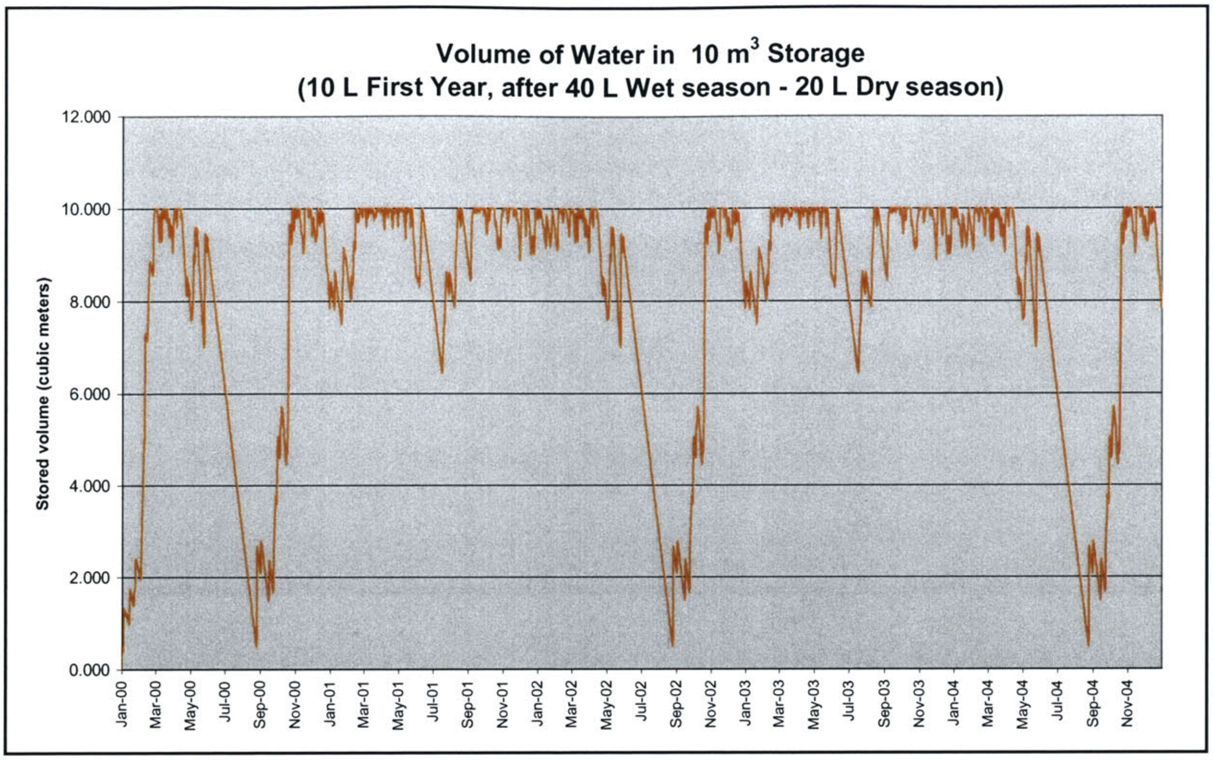


Figure 51: Mass balance curve for medium roof (81.7 m^2), 10 m^3 storage, and non-constant water demand of 40 L/d/person for wet season and 20 L/d/person for dry season

The method conclusion is summarized in *Table 25*.

Table 25: Conclusion from the method – Mass balance curve analysis

Mass balance curve analysis				
Roof size [m^2]	**Water demand Wet – Dry season [L/d/person]**	**Storage capacity [m^3]**	**Sustainability**	**Figure #**
Medium roof (35.1)	20 - 15	6	NO	13
	20 - 10	6	YES	14
	20 - 10	5.2	ALMOST	15
	22 - 10	6	YES	16
Large roof (81.7)	30 - 13	6	YES	17
	40 - 20	10	YES	18

4.3.3. Conclusion

The methods of analysis to approximate the storage capacity use different scenarios and models of rainwater catchment systems with different techniques. The different scenarios combine the two variables of water demand and storage capacity to better identify the most appropriate rainwater catchment system for pre-determined roof dimensions.

The first technique, "*Dry-season versus rainwater supply*", gave us the ability to verify if each system would be sustainable for the entire year and then estimate the storage capacity. From this initial analysis, we conclude that the rainwater catchment system for small-sized houses does not satisfy the condition of a successful system for any of the proposed daily water consumption levels (10-20 liters/day/person). The system for medium houses satisfies the successful condition of 15 L/d/person, whereas the system for large houses easily satisfies the condition of 20 L/d/person (*Table 22*). The method estimates a storage capacity of 6 m^3.

The "*Mass Curve analysis*" is the second technique utilized (*Table 23*). This method could not provide an estimate of storage capacity, since the spread between cumulative water supply and cumulative water demand increases indefinitely. However, the technique confirms that the rainwater catchment system for small-sized houses is not sustainable (*Figure 41*) and that the system for medium-sized houses can supply at least 15 Liters/day/person (*Figure 42*).

The "*Graphical Method*" allows verifying the efficiency of rainwater catchment systems with non-constant water demands (*Table 24*). The method utilizes two different models: one based on Musanze monthly rainfall data from 1977 to 2005, and the other based on Musanze rainfall data from 1997 to 2005. The technique estimates a potential storage capacity of 5.2 m^3 for rainwater catchment systems for medium-sized houses (*Figure 45*).

The final model, "*Mass Balance curve analysis*", is utilized as a tool to verify the sustainability of different systems and to calculate the appropriate storage capacity for the potentially greatest water consumption of every rainwater catchment system (*Table 25*). The method utilizes Bisate daily rainfall data between 2000 and 2001. The technique confirms that the most appropriate storage volume for rainwater catchment systems for medium-sized houses is 6 m^3 (same as the "*Dry-season demand versus supply*" method). The designed system supplies 22 liters/day/person during the wet season (Mar.-May and Oct.-Dec.) and 10 liters/day/person during the two dry seasons (Jan.-Feb. and Jun.-Sep.), as shown in *Figure 49*. In addition, the method allows analyzing the rainwater catchment system for medium-sized houses with the storage capacity of 5.2 m^3, estimated through the "*Graphical Method*". The system is almost sustainable (*Figure 48*); in fact, it can supply water for the entire length of the period except for about a week every two years of severe droughts. The technique demonstrates that, as anticipated by the "*Dry-season demand versus supply*" method, rainwater catchment systems with larger roofs and storage volumes can provide more water than smaller systems (*Figure 50*).

An overall summary of the defined results is provided in *Table 26*. The final choice of the most appropriate storage capacity, whether 6 m^3 or 5.2 m^3, will result after comparing differences in rainwater catchment systems in meeting potential water demand and their respective costs.

Table 26: Summary of the proposed rainwater catchment systems

RAINWATER CATCHMENT SYSTEMS			
Roof size [m^2]	**Storage capacity [m^3]**	**Water Demand**	
		Liters/day/person	**Average L/d/person**
Minimum (15.4)	N/A	N/A	N/A
Medium (35.1)	6	Wet-Dry 22-10	16.0
	5.2	Wet-Dry 20-10	15.0
Maximum (81.7)	6	Wet-Dry 30-13	21.5
	10	Wet-Dry 40-20	30.0

5. DESIGN OF LOW-COST HOUSEHOLD EXCAVATED CISTERN

This study focuses on the improvement of the Bisate Village water supply. After analyzing the weather conditions in the region, we concluded that rainwater catchment systems can be one of the most appropriate solutions. In addition to improving the water supply of the village, we decided to provide a household rainwater catchment system design with the purpose of reducing the travel time for women and children to fetch water.

Considering that all families should have a household rainwater catchment system, we based our design on the existing roofs of Bisate Village. Therefore, we direct our design towards a low-cost household cistern to complete the potential domestic rainwater catchment system.

Based on existing research of rainwater catchment systems within developing countries, we selected one of the low-cost solutions for rainwater storage: an excavated cistern lined with plastic sheets. The decision to select this technique is based on the low cost of tarpaulin tanks built in Uganda and on our survey of the plastic ponds used in Kabatwa Village. Professor Rees from Warwick University and ACORD agency provided the design and the cost analysis of tarpaulin tank built in the southwest of Uganda (Rees 2000). The price was relatively low compared to other cistern technologies, as the tarpaulin tank can be easily constructed with locally available materials. The survey in Kabatwa confirmed that people in the Volcanoes region already know this technique. Thus, plastic ponds should not be difficult to be implemented in Bisate Village. The design of household excavated cisterns lined with plastic includes two main improvements to reduce water contamination: a cover and a hand pump to reach and collect water.

Our analysis and calculation of available rainfall data showed that the most appropriate storage capacity for the medium size roof (about 35 m^2) is $6m^3$. As outlined in *Chapter 4*, the storage of $6m^3$ provides an average of 16 Liters/day/person for the entire year for medium houses and 21.5 Liters/day/person for large houses (81.7 m^2). For both sizes, we decided to design an excavated cistern of 6,000 Liters (6 m^3).

5.1. Catchment surface

Following the survey of the Bisate houses, we grouped the roofs in three general sizes: small (15.4 m^2 = 5 m x 3.15 m), medium (35.1 m^2 = 5.5 m x 6.4 m) and large (81.7 m^2 = 8.6 m x 9.5 m). We found that the smallest roofs are not sufficient to provide the amount of water desired (about 15 Liters/day/person) for our household rainwater catchment system. Therefore, we only considered the medium and large size roofs to realize the household catchment system.

Almost all medium and large roofs in Bisate Village are made of corrugated iron, which is showed in *Figure 52*. As explained in *Chapter 3*, iron sheets have a very high runoff coefficient, between 80-90%. Thus, the existing Bisate roof situation is ideal for domestic rainwater catchment systems.

Figure 52: Bisate iron roofs (Picture by Kelly Doyle)

5.2. CONVEYANCE SYSTEM

5.2.1. Gutters

Chapter 3 provides the following rule of thumb to calculate the gutter cross section area:

1 cm^2 of gutter cross-sectional area for every 1 m^2 of catchment surface area

Using this rule of thumb, the gutter cross section area should be at least 35 cm^2 for the medium roof (35 m^2) and at least 82 cm^2 for the large roof (81.7 m^2). However, based on Thomas (1997), we can assume a semicircular gutter of 100mm diameter at a slope of 2% for medium houses (35 m^2) and a semicircular gutter of 100mm diameter at a slope of 3% for large houses (81.7 m^2). Considering the type of gutters found in Bisate Village (*Figure 53*), we recommend using semicircular gutters of polyvinyl chloride (PVC) or the delivery system of the household rainwater catchment system. Semicircular gutters of 100mm of diameter should convey runoff from a tropical storm of 4mm/minute for the two roofs (Thomas 1997).

Figure 53: PVC semicircular gutters in Bisate Village (Picture by Author)

To prevent the entrance of leaves or small animals into the storage tank, a first filter (with a mesh not too small in diameter) could be inserted where gutters connect to the downpipe. The decision to adopt the screen at the downpipe lies in its much lower cost compared with other types of screen, as previously introduced in *Chapter 3*.

Table 27 summarizes the gutter shape, size, slope, length and quantity for medium and large roofs. More specific measurements must be taken for every household rainwater catchment system to verify the correct length.

Table 27: Gutter shape, size, slope, length and quantity for medium and large roof

Roof size	Shape	Size	Slope	Length	Quantity
Medium	Semicircular	100 mm	2%	6.4 m	2
Large	Semicircular	100 mm	3%	9.5 m	2

5.2.2. Downpipes

The downpipes of the conveyance system can be smaller than the gutters, because the risk of forming blockages is reduced by the usually vertical orientation. However, for convenience the size of downpipes should be the same as that of the gutters.

As mentioned in *Chapter 3*, the first runoff from the roof is highly contaminated by faecal bacteria due to the potential defection of small animals and birds. If the first runoff is deviated and not conveyed in the cistern, the successive water is considered less contaminated. Of the previously mentioned three methods to divert the first runoff, we recommend two: the fixed volume and the manual method.

One of the two methods must be selected when the household rainwater catchment system is constructed, knowing what the market can offer and which materials are available. If the necessary materials are available and are not too expensive, the best solution is the fixed volume method because it does not require the presence of a person. However, the manual method is a very good solution too. While the cost is lower, its design incorporates a manual mechanism that does not compromise the strength of the system.

Table 28 summarizes the downpipe shape, size, length, and quantity for the medium and large roofs. The more specific measurement of length must be verified for every household rainwater catchment system.

Table 28: Downpipe shape, size, length, and quantity for medium and large roof

Roof size	Shape	Size	Length	Quantity
Medium	Tubular	100 mm	2.60 m	2
	Tubular	100 mm	From roof to cistern	1
	Tee	100 mm	0.15 m	1
	Elbow	100 mm	-	2
Large	Tubular	100 mm	4.60 m	2
	Tubular	100 mm	From roof to cistern	1
	Tee	100 mm	0.15 m	1
	Elbow	100 mm	-	2

5.3. Storage

When considering the household rainwater storage, we adopt a cistern with two main advantages. First, since the cistern is located below ground, we use the ground as structure and therefore reduce the thickness of the cistern walls to a mere plastic lining of the pit. Second, the location below ground makes the storage occupy much less space as compared with a tank of same size (in this case 6,000 Liters).

The cistern is a pit of 3 meters by 2 meters with 0.85 meters depth. The cistern walls are extended 0.15 meters above ground. There is a 1-meter high wood frame, with walls of dirt located 0.85 meters below ground and mud walls 0.15 meters above ground. The wood poles and walls must be coated with old engine oil to prevent and reduce termite problems (Rees 2000). The cistern is lined with tarpaulin sheet (4 meters by 5 meters, UNICEF). The tarpaulin is held up with string from nails down to these eyelets. The cistern is covered by the wood and iron cover. Rainwater enters from a hole on the iron sheet. In the hole is inserted a bucket (10 Liters) felled of coarse sand (d>6mm) and gravel. The bottom bucket has holes (about 80 holes of d=6mm) (Thomas & McGeever 1997). A hand pump extracts the water from the cistern. The hose of the hand pump exits the cistern from a second hole on the iron sheet.

The decision to improve the cistern is based on results from water quality tests from the ponds in Kabatwa and in Bisate. As shown in *Chapter 2*, the water from the pond was contaminated by total coliform and E. coli. The sources of contamination included the runoff entering the pond, dipped hands and containers to collect the water. To reduce this type of contamination, we designed walls of 15 cm to stop the runoff, a cover to reduce the light inside the pond and a hand pump to extract water. In addition to the walls and cover, we also designed a filter at the entrance of the pond. The filter consists of a bucket filled with gravel and coarse sand from its bottom. The filter is not efficient as a slow sand filter because the sand is not fine but coarse. The filter needs to have coarse sand because at the storage entrance it needs to support a rate of 140 Liters/ minute – 4 mm/minute falling in a roof of about 35 m^2 (Thomas & McGeever 1997). Of course, the filter will be tested before its final placement.

The cistern is designed to be located inside the house, with the surface of the cistern (the wood and iron cover) acting like a piece of furniture. The structure in wood of both the cistern and cover could facilitate alternative uses as seats or even as a bed. During the survey of some houses of Bisate and Kabatwa, we observed that few houses had furniture. Also, it looked like people were sleeping and sitting on the floor. The surface of the pond could serve as furniture. Moreover, the cistern is quite large and from the survey we observed that there was not always enough space outside of the house. With the cistern inside the house, the families would better protect them, reducing the possibility of damage.

5.3.1. Cistern construction

5.3.1.1. Digging the pit

The pit has to be 2 meters by 3 meters by 0.85 meters. Along the borders of the cistern, the pit should have a number of indentations to host the wood poles for the structure, as illustrated in *Figure 54* and *Figure 55*. The indentations must be one in every corner, 3 along the shorter side of the cistern (every 0.50 meters) and 5 along the longest side (every 0.50 meters).

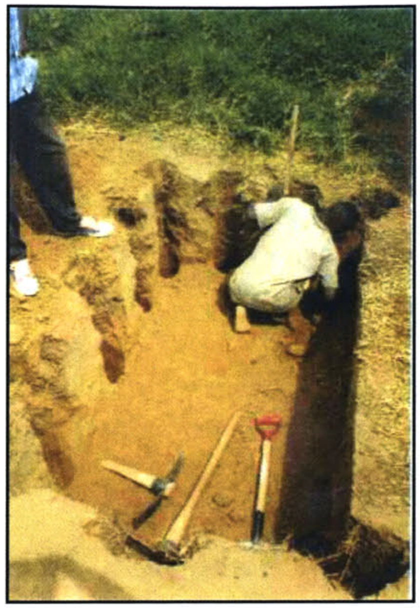


Figure 54: Digging the pit and the alcoves for the wood poles (Rees 2000)

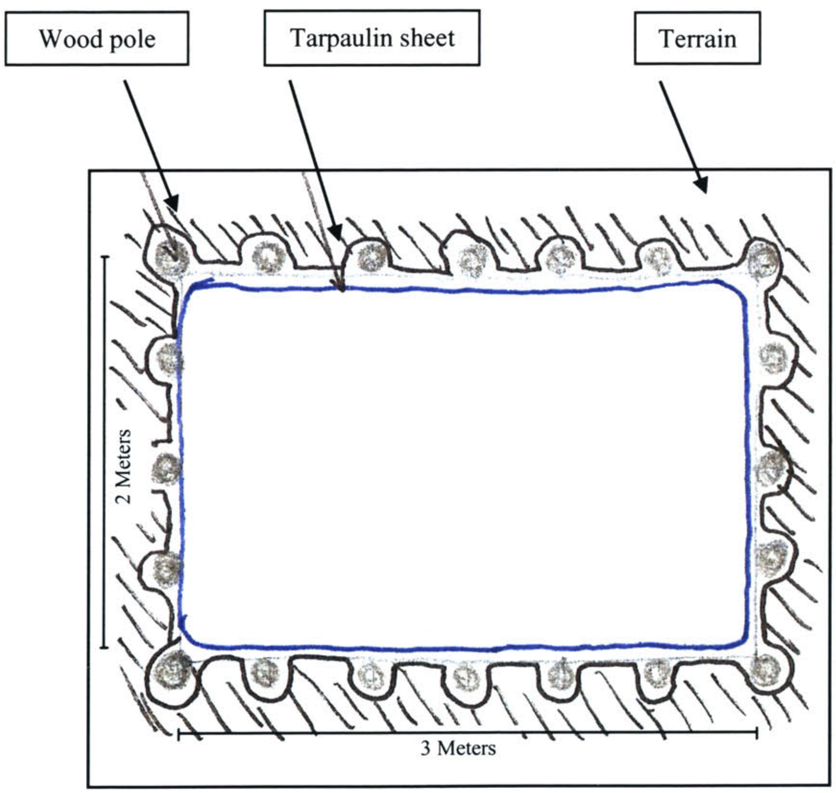


Figure 55: Sketch of the cistern plan view

5.3.1.2. Coating with old engine oil

The poles forming the framed structure and the walls of the cistern must be coated with old engine oil to reduce the risk of termite problems, as shown in *Figure 56* (Rees 2000). It is important to coat also the indentations for the poles to give wood a double treatment: directly to the pole and also in its location.

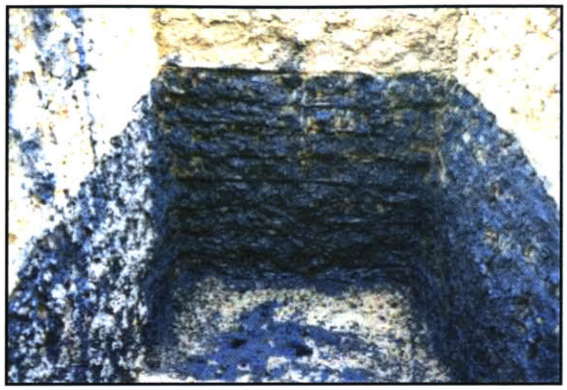


Figure 56: Coating the cistern's walls with old engine oil (Rees 2000)

5.3.1.3. Building the frame

The oil-coated poles must be positioned within the previously prepared indentations, as illustrated in *Figure 57*. The poles must be driven 0.30 meters into the ground to provide better stability. The poles can be sourced locally from woods near the village or acquired from local suppliers. The poles should have a diameter of about 5cm and a length of 130cm; they should be driven 30cm below-ground and extend 15cm above the edges of the pit (which is 85cm deep). The frame consists of 20 poles (*Figure 58*).

Figure 57: Building the frame (Rees 2000)

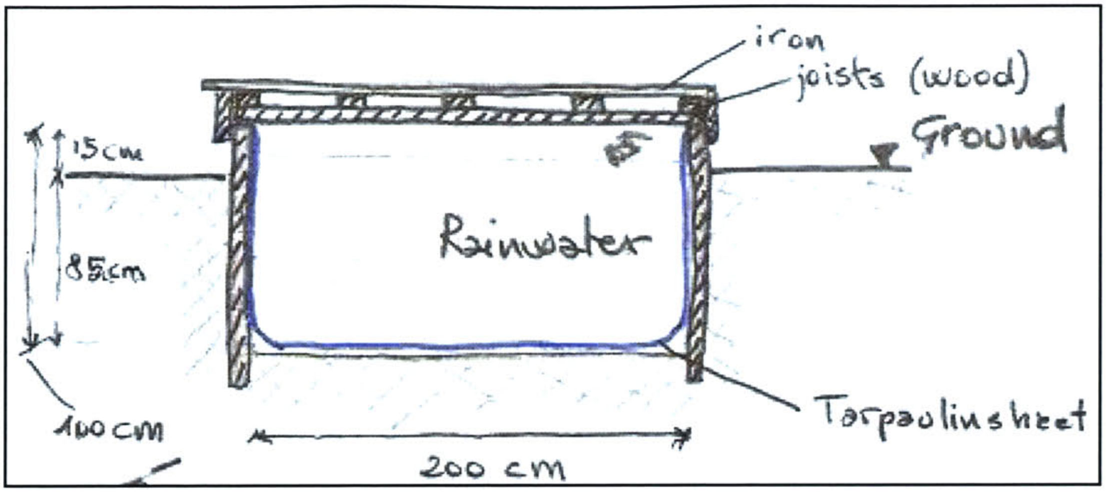


Figure 58: Sketch of the section of cistern with cover

5.3.1.4. Plastering the higher part of walls with mud

The above-ground walls of the cistern (15cm high) must be plastered with mud. *Figure 59* shows an example of plastering walls with mud. This technique follows the local tradition of building the walls of a house. Local people initially build the structural frame and then complete the frame using bamboo or other similar type of woods. Subsequently, they plaster the walls with mud. Building the 15cm above-ground walls should not cost much because all the necessary material is available locally.

Figure 59: Illustration of plastering walls with mud (Rees 2000)

5.3.1.5. Lining the cistern

After digging and coating the pit, indentations and poles with old engine oil, as well as building the frame and plastering the above-ground walls, the cistern must be lined with plastic. Finally, the cistern should be lined with the tarpaulin sheets, as shown in *Figure 60*. The tarpaulin sheet (reinforced polyethylene) must be a continuous sheet of 4 meters by 5 meters with a thickness of 0.25mm. Sheets provided by UNICEF and UNHRC have strong eyelets that are used to hold up the sheet with string from nails down to these eyelets.

Figure 60: Lining the cistern with tarpaulin sheet (Rees 2000)

5.3.1.6. Cistern overflow

The overflow is necessary in a cistern or tank to discharge excess water from the cistern. In the case of the proposed cistern, the overflow could be located at the edges of one of the border walls, which determines the maximum water level. If the cistern is located inside the house, the overflow could be located on the cistern border facing the exterior wall of the house. The overflow consists of pipe inserted in a hole created in the muddy border to divert the excess water outside the house.

Another option could be a manual mechanism to divert the downpipe. As mentioned earlier, one of the methods to divert the first roof runoff with a manual mechanism is to divert the downpipe from the inlet. This solution could be used as manual overflow. The householder should regularly check the level of water in the cistern to divert the downpipe from the inlet when the water reaches the maximum level. The two solutions need to be tested on-site when constructing the household rainwater system. Moreover, careful research on the available materials should be performed before constructing the manual mechanism to divert the first roof runoff.

5.3.2. Cistern cover

As previously mentioned, the cover has the function of reducing the potential contamination from dipped hands and jerrycans as well as from small animals falling into the cistern. The cover also decreases the amount of light entering the cistern, therefore reducing the risk of algae formation which makes water unsafe to drink (Gould 2006). The cover should be built carefully to fit as well as possible the mud walls of the cistern.

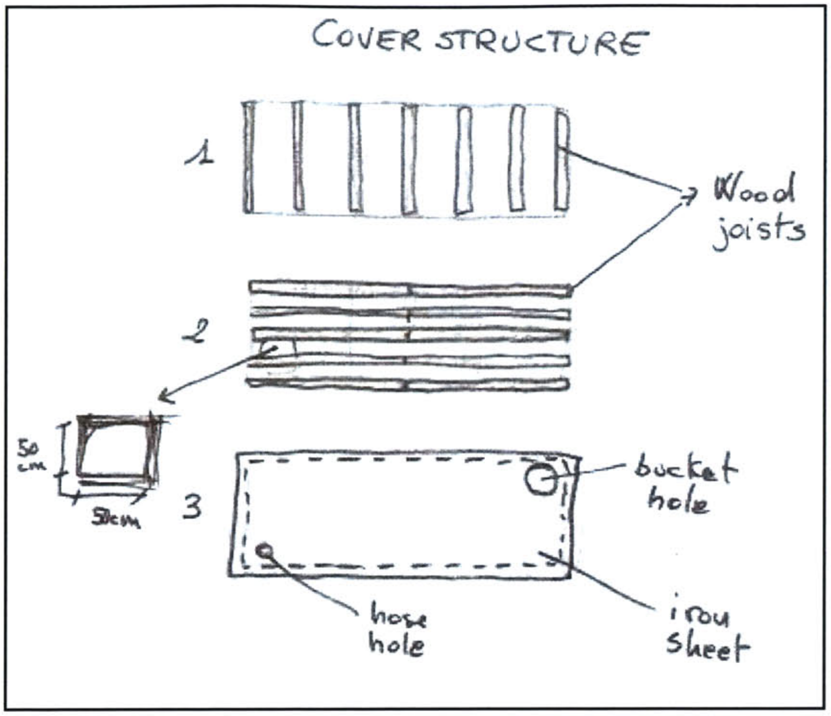


Figure 61: Sketch of the cover structure

The cover should be made of wood and iron sheets (*Figure 61*). The structure in wood is described below and summarized in *Table 29*. Seven joists of 220cm should cross the shorter side of the cistern (2m). The joists must be parallel and positioned every 50cm, so that the total length approximates 3 meters. A second layer of joists crossing the longest side of the cistern (3m) must be positioned above the first level of joists. The joists, 5 or 10 depending on length, must be perpendicular to the first layer of joist and positioned every 50cm so that the total length is about 2 meters.

Table 29: Cover materials –Description, Size, and Quantity

Description	Size	Quantity
Wood joist	220 [cm]	7
Wood joist	320 [cm]	5
Iron sheet	230 x 330 [cm^2]	1

The cover is completed with a third layer: a sheet of galvanized corrugated iron of 230cm by 330cm. The sheet must be positioned on the center of the wood structure and must have 5cm of excess border on all sides of the structure. The iron sheet must have two holes: 1) water inlet; 2) water outlet (*Figure 62*). The following paragraphs provide the general dimension of the holes.

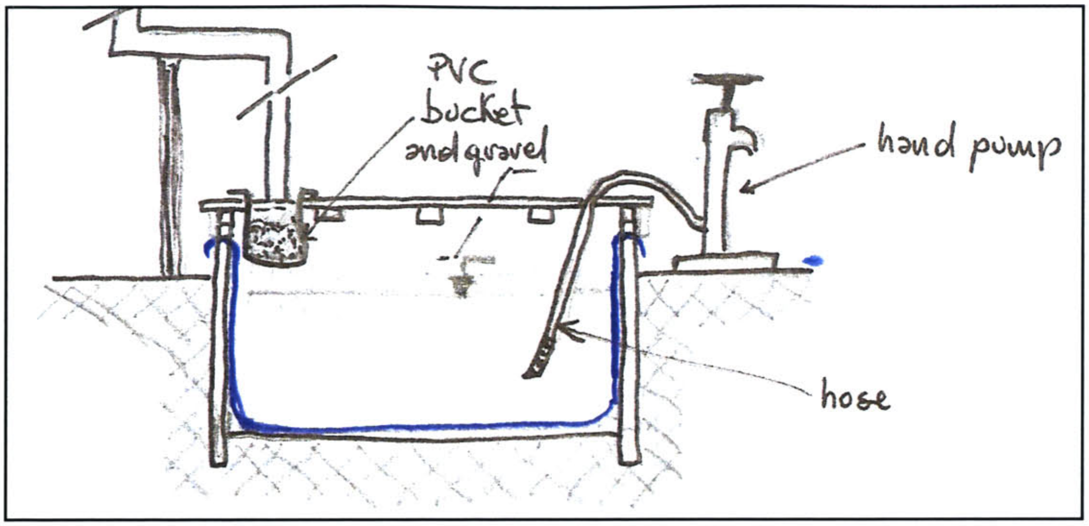


Figure 62: Sketch of the section of cistern with inlet filter and hand pump

5.3. Delivery system – Hand pump

The designed cistern requires a hand pump to extract water. The cover and extraction systems should definitely improve the quality of the water. Once the household rainwater catchment system is built and is working, it is necessary to test the water for quality and eventually design a system of filtration.

The hand pump should not cost more than $30, considering what is available in the markets and the possibility of constructing a hand pump on-site for as low as $15 (Whitehead 2000). The pump must satisfy the following specifications (Thomas & McGeever 1997):

- Be simple and cheap;
- Be located on the ground near the cistern and at the opposite corner of the inlet;
- Have a maximum lift of 0.90 meters;
- Able to extract 10 Liters/minute (operated by an adult or child of at least 6 years);
- Be able to deliver water with few strokes (even when not in use for days);
- Have a floating valve, to allow water extraction without sediment;
- The hose must fit tightly the hole of the iron cover to avoid intrusion of light, insects and surface water;
- Lift at least 100,000 Liters before replacement (equal to 3.5 years of supply for a family of 5 lifting an average of 75 liters/day);
- Lift at least 10,000 Liters before maintenance (or 4 months of supply for a family of 5

lifting an average of 75 liters/day);

- Maintenance should be possible with the skills and tools available in Bisate or Musanze;
- Discharge into a jerrycan or other collection vessel.

An example of a floating valve is provided by Whitehead (2000) and shown in *Figure 63*. The floating valve design is part of the Tamara pump design. It consists of: 1) two floating plastic bottles; 2) an insulated copper wire; 3) a flexible hose; 4) a hose clip; 5) ½"-diameter PVC pipe (approx. 150mm long); 6) rubber inner-tube strip; 7) ½"-diameter PVC pipe (approx. 200mm long); and 8) a wood inlet valve.

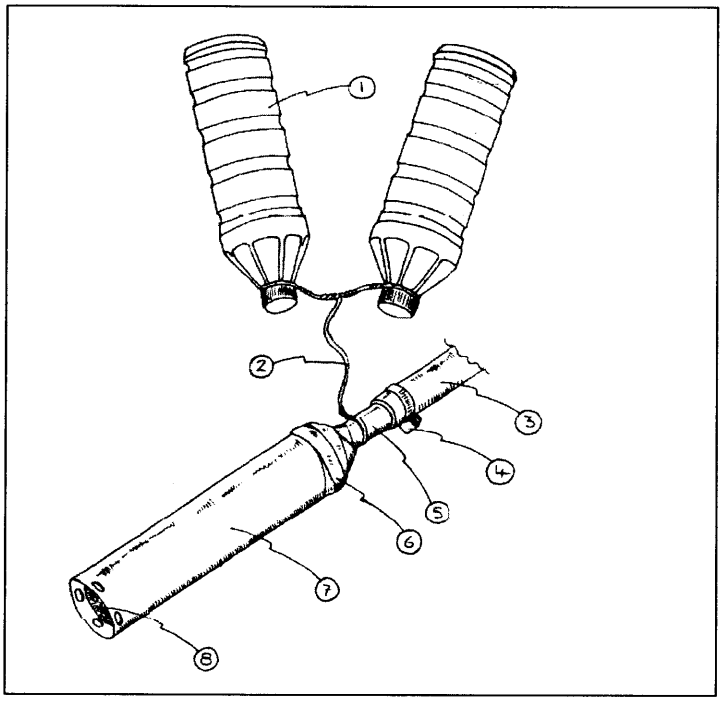


Figure 63: The floating valve (Whitehead 2000)

5.4. Water filtration

The quality of the water collected in the cistern and extracted with the hand pump is very important, because this water is used to drink and cook. The design of the cistern is compatible with two possible filters. One is located at the inlet of the cistern, to prevent the entrance of dirt, large particles, insects, or other small animals, that may accidentally fall from the downpipes. This filter, as previously discussed, must support a rate of about 140 Liters/minute – equal to 4mm/minute of rain over the medium-size roof of $35m^2$. The other filter is located at the outlet of the cistern. The idea is that the foot valve must withdraw the water after passing through a slow-sand filter. The filters must be tested on site and designed based on the quality of the water. In the following two paragraphs, the two filters are better explained.

5.4.1. Gravel filled bucket solution

A good example of filtration at the inlet of a cistern/tank is provided by Thomas and McGeever (1997). The filter consists of a plastic bucket of 10 Liters filled with coarse sand (grain size > 6mm). The bucket must fit tightly the iron sheet hole so that no light, insect or surface water can enter the cistern. The bucket must be easily removable because the filter must be cleaned to remove any retained material. A coarse cloth should be positioned at the top of the bucket to provide first filtration. The cloth must be easily removable for cleaning. The second filtration occurs by passing through the coarse sand layer. The weight of the sand keeps the bucket down, which makes it more difficult to remove it by accident. The lower and bottom parts of the bucket should be pierced in several places. The holes' area should exceed $20cm^2$. The holes should be about 80 and have a diameter of a least 6mm, so that coarse sand cannot pass through. The numerous holes transform the usual downwards jet into a spray inflow, which reduces the impact into the bottom of the cistern. The inlet – the bucket – must be located at the opposite corner from the outlet, the hose of the hand pump. The total number of holes depends on the rate supported by the bucket, so it is necessary to verify the filter design on site before setting it on the iron sheet. A schematic drawing of the filter is illustrated in *Figure 64*.

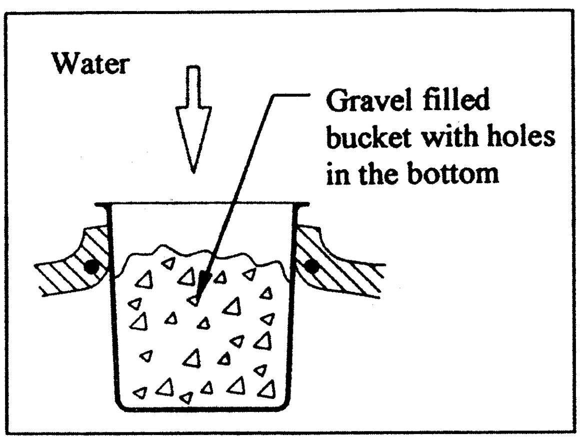


Figure 64: Water inlet filter (Thomas & McGeever 1997)

5.4.2. Slow-sand filter solution

As mentioned in Chapter 2, slow-sand filtration is one of the most efficient filter processes. In fact, the filter can remove about 95% of faecal bacteria. Basically, slow sand filtration uses four removal mechanisms. First, the larger particles are trapped into the first few centimeters of sand (physical straining). Second, the particles are adsorbed onto each other and onto the sand (attachment). Third, the particles (now trapped on top of the fine sand layer with dissolved oxygen and nutrients from the water) generate a biological population around sand grains within the fine sand layer and on top of few centimeters of sand. This "biofilm" consumes the incoming pathogens (predation). Finally, due to many different causes, such as age, stress or lack of oxygen, pathogens naturally die (natural die-off). The end result of the four removal mechanisms is a highly effective removal of pathogens (ENPHO 2006).

In this case, the filter is located at the outlet of the cistern. A very good example of outlet slow-sand filter is provided by Way and Thomas (2005). The filter consists of a floating 10-Liter plastic bucket, with a plug covered by fine wire mesh on its base, which is attached to a hose. Over the fine wire mesh there is a 100mm layer of 2-5mm sand; above that, there is another 50mm layer of less-than-2mm sand. This layer is the active layer, which is topped up with water. The bucket floats because of empty plastic bottles tied onto the outside with a bicycle inner-tube. The hose and the filter work as a foot valve. The hose exits the cistern from the hole on the iron sheet. To verify the efficiency of the filter, it is necessary to test the quality of the water extracted from the hand pump, once the filter is working. *Figure 65* shows an example of the floating filter.

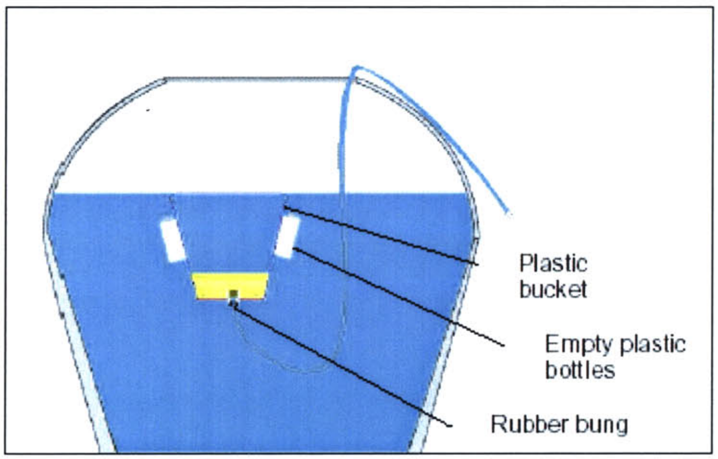


Figure 65: Floating slow sand filter in Rainwater tank (Way & Thomas 2005)

5.5. Cost Analysis of the Household rainwater catchment system

As mentioned above, this study focuses on designing a low-cost household cistern to complete a domestic rainwater catchment system. The proposed excavated cistern is based on research of a low-cost solution and the available experience found in the village of Kabatwa. On the other hand, the selection of a solution for the delivery system is based on the type of gutters and downpipes found during our Bisate water supply survey: PVC semicircular gutters and downpipes. Notably, these types of gutters and downpipes have been adopted for the current project of creating rainwater harvesting systems for the Bisate Clinic.

The primary goal of identifying the cost of the rainwater catchment system is to understand whether the proposed solution is feasible and affordable for the community of Bisate. As mentioned in *Chapter* 1 and reported by the ORTPN, the 2004 average annual household income for the District of Kinigi was 104,196 Frw, about 190 US dollars (ORTPN 2004). Since Bisate Village was a cell of the district of Kinigi in 2004, we can assume a similar level of income for Bisate, or about 190 US dollars.

As shown in *Tables 4* and *5*, the cost of the various materials utilized for the household rainwater catchment system is based on prices available in shops selling building materials in Musanze and Kigali (provided by Jean Pierre Nshimyimana, DFGFI) as well as on the budget for the rainwater harvesting project for the Bisate Clinic (provided by Laura Clauson, DFGFI). Therefore, the prices represent what the market is offering as of April 2007 (rate of exchange 1$ for 550 Frw). This study would recommend a more thorough research on local market conditions in the future, in order to better optimize the total cost for the household catchment systems. The future research should focus on the cost of wood for the frame and the cover of the excavated cistern, hand pumps and conveyance system.

This study offers two different scenarios to define the total cost of the household rainwater catchment system. The first scenario, shown in *Table 30*, assumes that all the materials needed for construction are purchased from local manufacturers. The second scenario, shown in *Table 31*, assumes that part of the construction items are available in surrounding areas and thus can be supplied directly by the householder. For both scenarios, we assume that labor is provided by the householder.

These two different scenarios show that the cost for the construction of cistern, cover, inlet filter and hand pump can vary considerably. The cost for the system constructed with material purchased from manufacturers is more than three times higher than that for systems built with a mix of items locally sourced and purchased. The item primarily responsible for the large difference in prices is wood. Because of such large difference in cost, we recommend in-depth research of the available prices for the joists needed for the construction. It may be necessary to contact some "joiner" in Bisate to negotiate a better price for a large quantity of joists. It may be possible also to utilize a combination of joists from manufacturers and locally sourced to further reduce the cost for the wood structure, the cistern and the cover.

In both scenarios we did not change anything for the delivery system, therefore leaving that part of the price the same. The cost for the delivery system is considerable, leading to the conclusion that an in-depth study must be done to identify the most appropriate material for gutters and downpipes to reduce costs. The actual prices of the delivery system assume that all items are bought from local manufacturers with gutters, end caps, and hangers as the most expensive items (*Table 30* and *Table 31*).

One option to reduce costs could be the following: the two gutters of W=100mm and L=2.60m could be made of two half tubular downpipes of W=100mm and L=2.60, as downpipes are definitely cheaper than gutters; the end caps could be just two and located at the lower extreme of the gutters, considering that gutters have a slope of 2%; the hangers could be made from local materials, assuming that the cost with local materials is around half that for manufactured hangers. The cost for this delivery system is illustrated in *Table 32*.

Table 30: Cost of household rainwater catchment system built with materials purchased from manufacturers

HOUSEHOLD RAINWATER CATCHMENT SYSTEM			
Object	**Item**	**Quantity**	**Cost [$]**
Excavated Cistern	Tarpaulin sheet (UNICEF) 4x5 m	1	25.0
	Wood pole (d=0.05m & L=1.30m)	20	73
	Old engine oil to coat the pond and the poles	10 Liters	10.0
Sub-Total cost			**108**
Cover	Wood joist (d=3cm & L=2.20m)	7	56
	Wood joist (d=3cm & L=3.20m)	5	58
	Iron sheet (W=2.30m x L=3.30m)	1	10
Sub-Total cost			**124**
Inlet Filter	PVC bucket (10 Liters)	1	5
	Coarse cloth	1	5
	Coarse sand (>6mm) to fill the bucket	10 Liters	20
Sub-Total cost			**30**
Hand pump	Hand pump locally manufactured	1	30
Sub-Total cost			**30**
Total cost for cistern, cover, inlet filter and hand pump			**292**
Conveyance System (medium roof 5.5m x 6.4m = 35m^2)	PVC Semicircular gutter (W=0.10m L=6.50m)	2	48
	End caps	4	26
	Gutter hangers	6	39
	Elbows	2	13
	PVC Downpipe (W=100mm L=2.60m)	3	10
	PVC elbow fitting	2	17
	PVC tee fitting	1	8
	Chicken mesh (15cm x 40cm)	1	10
Sub-Total cost			**171**
TOTAL COST			**$463**

Table 31: Cost of household rainwater catchment system built with a mix of materials locally sourced and purchased

HOUSEHOLD RAINWATER CATCHMENT SYSTEM			
Object	**Item**	**Quantity**	**Cost [$]**
Excavated Cistern	Tarpaulin sheet (UNICEF) 4x5m	1	25
	Wood pole (d=0.05m & L=1.30m)	20	Locally from trees
	Old engine oil to coat the pond and the poles	10 Liters	10
Sub-Total cost			**35**
Cover	Wood joist (d=3cm & L=2.20m)	7	Locally from trees
	Wood joist (d=3cm & L=3.20m)	5	
	Iron sheet (W=2.30m x L=3.30m)	1	10
Sub-Total cost			**10**
Inlet Filter	PVC bucket (10 Liters)	1	5
	Coarse cloth	1	5
	Coarse sand (>6mm) to fill the bucket	10 Liters	Locally
Sub-Total cost			**10**
Hand pump	Hand pump locally constructed	1	30
Sub-Total cost			**30**
Total cost for cistern, cover, inlet filter and hand pump			**85**
Conveyance System (medium roof 5.5m x 6.4m = 35m²)	PVC Semicircular gutter (W=0.10m L=6.50m)	2	48
	End caps	4	26
	Gutter hangers	6	39
	Elbows	2	13
	PVC Down pipe (W=100mm L=2.60m)	3	10
	PVC elbow fitting	2	17
	PVC tee fitting	1	9
	Chicken mesh (15cm x 40cm)	1	10
Sub-Total cost			**172**
TOTAL COST			**$257**

Table 32: Lower cost delivery system option

Conveyance System (medium roof 5.5m x 6.4m = 35m²)	PVC Half downpipe (W=0.10m L=6.50m)	2	9
	End caps	2	13
	Gutters' attaches	6	20
	Elbows	2	13
	PVC Down pipe (W=100mm L=2.60m)	3	10
	PVC 'L' tube	2	17
	PVC 'T' tube	1	9
	Chicken mesh (15cm x 40cm)	1	10
Sub-Total cost			**$101**

5.7. Summary

5.7.1. Design variations and future work

While some design variations are discussed above, the most appropriate design must be selected on site during construction of the first system. Because the household excavated cistern proposed in this study offers a new solution, it must be tested for its performance once built. The summary of potential design variations that could be considered in future work are listed below:

- First flush runoff diverter: the study recommends the manual method and the fixed volume method. The selection of the best solution must be found on site.
- Cistern overflow: the study proposes a pipe overflow located at one edge of the walls of the cistern and a manual mechanism to divert the downpipe from the inlet of the cistern. The most appropriate solution must be found during the construction of the system.
- Hand pump: the study provides the necessary characteristics for the appropriate hand pump. Market research should be conducted on site to find the best solution.
- Outflow slow sand filter: the study recommends an outflow slow sand filter to treat the stored water. When the system is completed, it is necessary to test the water to define the quality and eventually find the most appropriate solution to treat it.

5.7.2. Conclusion

Given the prevalent characteristics of the environment of Bisate Village, rainwater harvesting represents one of the most appropriate solutions to improve water supply. In this study, we propose the design of a low-cost household rainwater catchment system that focuses on household excavated cisterns to store collected rainwater. This option consists of an excavated cistern of 6 cubic meters, lined with tarpaulin sheet, covered with a wood and iron lid and with a hand pump to extract water. The cistern should provide an average of 16 liters/day/person for the entire year for medium houses (roof area of 35.1 m^2) and 21.5 liters/day/person for large houses (81.7 m^2). The ideal location for the cistern would be inside the house, because it is more protected and therefore less subject to external damages. The surface of the cistern is 15 centimeters above ground, providing a sort of furniture for these unfurnished houses; in fact families could use the surface as support, seats or even beds.

Table 33 and *Table 34* summarize the specific costs for the cistern, cover, inlet filter and hand pump and for the delivery system and the total cost for the entire system in two different scenarios. The first scenario consists of purchased materials; the second scenario assumes the cistern is built with a mix of locally-sourced and purchased materials.

Table 33: Cost of the cistern built with items purchased from local manufacturers

ITEM GROUP	**COST [$]**
Cistern, cover, inlet filter and hand pump	292
Delivery system	171
TOTAL COST	**463**

Table 34: Cost of the cistern built with a mix of locally-sourced and purchased items

ITEM GROUP	**COST [$]**
Cistern, cover, inlet filter and hand pump	85
Delivery system	100
TOTAL COST	**185**

Despite the much lower cost of the second scenario, we do not believe the average household of Bisate could afford the cost of a rainwater catchment system. The $185 cost for the second solution approximates the 2004 average annual household income of 104,200 Frw (about $190).

The key conclusion is that the project requires external contributions from governmental authorities and/or NGOs donations to take effect. Even if a large portion of the project is financed by the government and/or NGOs, the local population could contribute a small and symbolic part of the total expenses to better appreciate the value of the rainwater catchment system.

6. CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

The present study focuses on designing low-cost household rainwater catchment systems to improve water quantity and quality and the overall standard of living of the rural village of Bisate, Musanze, Rwanda.

Given the climatic and geographic characteristics of the Bisate Village, rainwater harvesting represents one of the most appropriate solutions to improve water supply. The designed low-cost household rainwater catchment system consists of an excavated cistern of 6 cubic meters (lined with tarpaulin sheet and covered with a wood and iron lid) and a hand pump to extract water. The cistern should provide an average of 16 liters/day/person for the entire year for medium-size houses (roof area of 35.1 m^2) and 21.5 liters/day/person for large-size houses (81.7 m^2). The designed low-cost household rainwater catchment system should improve the family water consumption from less than 5 liters/day/person to at least 16 liters/day/person.

We observed that almost all sources of water in the village of Bisate are contaminated by faecal bacteria. This situation has the strong negative effect of many people suffering from intestinal diseases. If the excavated ponds are improved with walls to stop surface runoff from entering the pond, a stronger cover and a hand pump to extract water, then the implementation of small-scale rainwater harvesting systems could really improve water quality for Bisate. To optimize the process, the implementation plan should also include a hygiene education program directed to adults and children.

The Bisate community water supply is limited and not homogenously distributed throughout the entire village. This situation forces many families who live away from the center of the village to walk long distances every day to fetch water. Household rainwater catchment systems can provide water inside or nearby the house and therefore can drastically reduce such travel times; freeing up time from daily "water walks" could significantly improve school attendance and trade activities, leading to increased education levels and average annual income.

The cost analysis showed that the \$185 needed to build the system with a mix of locally sourced and purchased materials approximates the 2004 average annual household income of 104,196 Frw (about \$190). The key conclusion is that the project requires external contributions from governmental authorities and/or NGOs to take effect. Even if a large portion of the project is financed by the government and/or NGOs, the local population could contribute a small and symbolic part of the total expenses to better appreciate the value of the rainwater catchment system.

6.2. Recommendations

As mentioned in *Chapter 5*, because the proposed household excavated cistern offers a new solution, the most appropriate design must be selected on site during construction. The summary of potential design variations to be considered in future works is listed below:

- First flush runoff diverter: the study recommends the manual method and the fixed volume method. The selection of the best solution must be found on site.

- Cistern overflow: the study proposes a pipe overflow located at one edge of the walls of the cistern and a manual mechanism to divert the downpipe from the inlet of the cistern. The most appropriate solution must be considered during construction of the system.
- Hand pump: the study provides the necessary characteristics for the appropriate hand pump. Market research should be conducted on site to find the best solution.
- Outflow slow sand filter: the study recommends an outflow slow sand filter to treat the stored water. When the system is completed, it is necessary to test the water to define the quality and eventually find the most appropriate solution to treat it.

In addition to find the most appropriate design solution, the implementation plan should include an information and education program on household water management directed to adults and children. The education program should explain how the family should manage the stored water to ensure enough water over the entire period of the dry season.

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APPENDIX 1 – STORAGE CALCULATION METHODOLOGY

Mass curve analysis

Table 35: Mass curve analysis

Month	Monthly Precipitation [mm]	Min. Cumul. Monthly Rainfall [m³]	Cumul. Monthly Rainfall [m³]	Max. Cumul. Monthly Rainfall [m³]	10L/d/pers Cumul. Demand [m³]	15L/d/pers. Cumul. Demand [m³]	20L/d/pers Cumul. Demand [m³]	15L/d/pers Potential Storage [m³]
Jan-77	79.8	1.0	2.2	5.2	1.5	2.28	3.0	**-0.04**
Feb-77	82.9	2.0	4.6	10.6	3.0	4.56	6.1	0.00
Mar-77	135.6	3.7	8.4	19.5	4.6	6.84	9.1	1.53
Apr-77	211.1	6.3	14.3	33.3	6.1	9.13	12.2	5.17
May-77	145.6	8.1	18.4	42.8	7.6	11.41	15.2	6.97
Jun-77	51.4	8.7	19.8	46.2	9.1	13.69	18.3	6.13
Jul-77	6.3	8.8	20.0	46.6	10.6	15.97	21.3	4.03
Aug-77	76.5	9.7	22.1	51.6	12.2	18.25	24.3	3.89
Sep-77	123.6	11.3	25.6	59.7	13.7	20.53	27.4	5.08
Oct-77	103.5	12.5	28.5	66.4	15.2	22.82	30.4	5.70
Nov-77	247.1	15.6	35.4	82.6	16.7	25.10	33.5	10.35
Dec-77	54.1	16.3	37.0	86.1	18.3	27.38	36.5	9.59
Jan-78	88.9	17.4	39.5	91.9	19.8	29.66	39.5	9.80
Feb-78	124.6	18.9	43.0	100.1	21.3	31.94	42.6	11.02
Mar-78	171.5	21.0	47.8	111.3	22.8	34.22	45.6	13.55

Runoff Coef.	Min. Roof Area	Av. Roof Area	Max Roof Area
0.8	15.4	35.1	81.7

Household members	Water Demand [L/d/person]	Household Water Demand [m³/d]
5	10	0.05
5	15	0.075
5	20	0.1

Min. Cumul. Monthly Rainfall [m^3]

$$y_{n+1} = y_n + Monthly\Pr ecipitation_{n+1} \div 1000 \times RunoffCoeff \times MinRoofArea_{n+1}$$

Cumul. Monthly Rainfall [m^3]

$$y_{n+1} = y_n + Monthly\Pr ecipitation_{n+1} \div 1000 \times RunoffCoeff \times AvRoofArea_{n+1}$$

Max. Cumul. Monthly Rainfall [m^3]

$$y_{n+1} = y_n + Monthly\Pr ecipitation_{n+1} \div 1000 \times RunoffCoeff \times MaxRoofArea_{n+1}$$

10L/d/pers Cumul. Demand [m^3]

$$y_{n+1} = y_n + HouseholdWaterDemand(10L/d/p) \times 30.42(days)$$

15L/d/pers Cumul. Demand [m^3]

$$y_{n+1} = y_n + HouseholdWaterDemand(15L/d/p) \times 30.42(days)$$

20L/d/pers Cumul. Demand [m^3]

$$y_{n+1} = y_n + HouseholdWaterDemand(20L/d/p) \times 30.42(days)$$

15L/d/pers Potential Storage [m^3]

$$y_n = CumulMonthlyRa\inf all_n - 15L/d/persCumulDemand_n$$

Graphical method

Table 36: Graphical method – Musanze 1977-2005

MUSANZE 1977-2005 (about 25 Years) GRAPHICAL METHOD

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Precipitation [mm]	79.8	82.9	135.3	179.6	146.1	33.6	16.7	50.3	123.4	164.4	155.0	87.7

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Rearrange Average [mm]	123.4	164.4	155.0	87.7	79.8	82.9	135.3	179.6	146.1	33.6	16.7	50.3
Cumulative Monthly [m^3]	3.5	8.1	12.4	14.9	17.1	19.4	23.2	28.3	32.4	33.3	33.8	35.2

Runoff Coef.	Min. Roof Area	Av. Roof Area	Max Roof Area	Household members	Water Demand [L/d/ person]	Household Water Demand [m^3/d]
0.8	15.4	35.1	81.7	5	10	0.05
				5	15	0.075
				5	20	0.1

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Cumulative Demand 15L/d/p [m^3]	2.3	4.6	6.8	9.2	11.5	13.6	15.9	18.2	20.5	22.7	25.1	27.4
Cumulative Demand 20L/d/p [m^3]	3.0	6.1	9.1	12.2	15.3	18.1	21.2	24.2	27.3	30.3	33.4	36.5

	20 L/d/ person	20 L/d/ person	20 L/d/ person	20 L/d/ person	20 L/d/ person	20 L/d/ person	20 L/d/ person	20 L/d/ person	20 L/d/ person	15 L/d/ person	15 L/d/ person	15 L/d/ person
Combined Cumulative Demand [m³]	3	6.1	9.1	12.2	15.3	18.1	21.2	24.2	27.3	29.6	31.9	34.2
Potential Storage [m³]	0.5	2.0	3.3	2.7	1.8	1.3	2.0	4.1	5.1	3.8	1.9	1.0
New Line	8.1	11.2	14.2	17.3	20.4	23.2	26.3	29.3	32.4	34.6	37.0	39.3
Required Storage [m³]	4.6	3.1	1.8	2.4	3.3	3.7	3.0	1.0	0.0	1.3	3.2	4.1

Cumul. Monthly [m³]

$$y_{n+1} = y_n + Monthly\,\mathrm{Pr}\,ecipitation_{n+1} \div 1000 \times RunoffCoeff \times AvRoofArea_{n+1}$$

Cumul. Demand 15L/d/p [m³]

$$y_{n+1} = y_n + HouseholdWaterDemand(15L/d/p) \times 30(days)$$

Cumul. Demand 20L/d/p [m³] $y_{n+1} = y_n + HouseholdWaterDemand(20L/d/p) \times 30(days)$

Combined Cumul. Demand [m³]

$$y_{n+1} = y_n + HouseholdWaterDeman \times 30(days)$$

Potential Storage [m³]

$$y_n = CumulMonthlyRa\,\mathrm{inf}\,all_n - CombinedCumulDemand_n$$

Table 37: Graphical method – Musanze 1997-2005

MUSANZE GRAPHICAL METHOD (20-15 L/d/person) 1997 - 2005

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot. Ann.	Source
1997	179	1	91.5	237.1	211.8	49.6	36	31	67.5	210.8	274.5	64.12		Karisoke Research Center
1998	104.8	91.6	172.2	320	143	0	26	14	158	154	88	150	1421.6	
1999	162	72	132	122	156	0	0	72	183	153	156	175	1383	
2000	49	89	73	175	63	8	0	26	77	119	110	70	859	
2001	68	60	213	189	115	22	20	113	110	190	214	47	1361	
2002				116.3	167.4	2.7	14.4	16.2	93.7	140.4	131	154.2		Institute of Agricult. (Busogo)
2003	82.4	36.4	99	205.9	192.8	41	26.8	71.9	120.3	139.7	126	64.9	1207.1	
2004	111	159.8	154.2	173.7	119.3	0.8	36.4	28.7	104.6	88.3	109.2	66.6	1152.6	
2005	99.8	93.1	161	152.9	110.9	9.7	0.9	41.9	73.8					
Average	107.0	75.4	137.0	188.0	142.1	14.9	17.8	46.1	109.8	149.4	151.1	99.0	1230.7	

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Tot. Ann.
Monthly Precipitation [mm]	109.8	149.4	151.1	99.0	107.0	75.4	137.0	188.0	142.1	14.9	17.8	46.1	*1237.5*

Monthly Precipitation [m]	0.110	0.149	0.151	0.099	0.107	0.075	0.137	0.188	0.142	0.015	0.018	0.046
	3.08	4.19	4.24	2.78	3.00	2.11	3.84	5.27	3.99	0.42	0.50	1.29

Roof Area [m^2]	35.1
Runoff Coef. [-]	0.8

Cumulative Monthly [m^3]	3.1	7.3	11.5	14.3	17.3	19.4	23.2	28.5	32.5	32.9	33.4	34.7

Water Use [L/d/person]	20.0
Household members	5.0
Household Water Use [m^3/d]	0.100
Water use per Year [m^3]	36.5

[L/d/ person]	20.0
Dry season [day]	93.0
Storage required [m^3]	11.2

[L/d/ person]	15.0
Dry season [day]	93.0
Storage required [m^3]	8.4

	20 L	20 L	20 L	20 L	20 L	20 L	20 L	20 L	20 L	15L	15L	15L
	3	3.1	3	3.1	3.1	2.8	3.1	3	3.1	2.25	2.325	2.325
Combined Cumulative Demand [m^3]	3	6.1	9.1	12.2	15.3	18.1	21.2	24.2	27.3	29.55	31.875	34.2
	Set	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**

Potential Storage	0.1	1.2	2.4	2.1	2.0	1.3	2.0	4.3	5.2	3.4	1.6	0.5

New Line	8.2	11.3	14.3	17.4	20.5	23.3	26.4	29.4	32.5	34.8	37.1	39.4

Required Storage	5.1	4.0	2.8	3.1	3.2	3.9	3.2	0.9	0.0	1.8	3.7	4.7

The equations are on page 110

Mass balance curve analysis

Table 38: Mass balance curve analysis

Month Year	Day	Daily Precipitation [mm]	Qin [m^3]	Qout Combo 20-15L [m^3]	Volume of Water in 6 m^3 Storage	Qout Combo 15-10L [m^3]	Volume of Water in 6 m^3 Storage	Qout Combo 15-10-20-15L [m^3]	Volume of Water in 6 m^3 Storage	Qout Combo 15-10-20-10L [m^3]	Volume of Water in 6 m^3 Storage
January 2000	1	1	0.03	0.075	-0.05	0.050	-0.02	0.05	-0.02	0.05	-0.02
	2	8	0.22	0.075	0.10	0.050	0.15	0.05	0.15	0.05	0.15
	3	0	0.00	0.075	0.03	0.050	0.10	0.05	0.10	0.05	0.10
	4	0	0.00	0.075	-0.05	0.050	0.05	0.05	0.05	0.05	0.05
	5	15	0.42	0.075	0.30	0.050	0.42	0.05	0.42	0.05	0.42
	6	0.7	0.02	0.075	0.24	0.050	0.39	0.05	0.39	0.05	0.39
	7	0	0.00	0.075	0.17	0.050	0.34	0.05	0.34	0.05	0.34
	8	0	0.00	0.075	0.09	0.050	0.29	0.05	0.29	0.05	0.29
	9	0	0.00	0.075	0.02	0.050	0.24	0.05	0.24	0.05	0.24
	10	1.6	0.04	0.075	-0.01	0.050	0.24	0.05	0.24	0.05	0.24

Volume of Water in 5.2 m^3 Storage	Qout Combo 10L & 22-10L [m^3]	Volume of Water in 6 m^3 Storage	Qin Large roof [m^3]	Qout Combo 10 & 30-13L [m^3]	Volume of Water in 6 m^3 Storage	Qout Combo 10 & 40-20L [m^3]	Volume of Water in 10 m^3 Storage
-0.02	0.05	-0.02	0.07	0.05	0.015	0.050	0.015
0.15	0.05	0.15	0.52	0.05	0.488	0.050	0.488
0.10	0.05	0.10	0.00	0.05	0.438	0.050	0.438
0.05	0.05	0.05	0.00	0.05	0.388	0.050	0.388
0.42	0.05	0.42	0.98	0.05	1.319	0.050	1.319
0.39	0.05	0.39	0.05	0.05	1.314	0.050	1.314
0.34	0.05	0.34	0.00	0.05	1.264	0.050	1.264
0.29	0.05	0.29	0.00	0.05	1.214	0.050	1.214
0.24	0.05	0.24	0.00	0.05	1.164	0.050	1.164
0.24	0.05	0.24	0.10	0.05	1.219	0.050	1.219

Dry Seasons		Runoff Coef.	Min. Roof Area	Av. Roof Area	Max Roof Area	Household merbers	Water Demand [L/d/ person]	Household Water Demand [m^3/d]
Jan -Feb		0.8	15.4	35.1	81.7	5	10	0.05
Jun-Jul-Aug-Sep						5	15	0.075
						5	20	0.1
Max Precip./d [m^3]						5	22	0.11
1.54						5	25	0.125
						5	13	0.065
						5	30	0.15
						5	20	0.1
						5	40	0.2

Qin [m^3]

$$y_n = Daily\,\mathrm{Pr}\,ecipitation_n \div 1000 \times RunoffCoeff \times RoofArea$$

Qout [m^3]

$$y_n = HouseholdWaterDemand$$

Volume of Water in the Storage [m^3]

$$y_{n+1} = y_n + Qin_{n+1} - Qout_{n+1}$$