Sizing the First Flush and its Effect on the Storage-Reliability-Yield Behavior of Rainwater Harvesting in Rwanda

By

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Abstract

Rainwater harvesting is a technology used to supply water for domestic purposes in developing countries. Rooftop rainwater harvesting involves collection of rainwater from a rooftop via a guttering system and storage in a cistern. During dry weather, dust and other pollutants accumulate on the roof surface and are washed off at the beginning of the next rain. The initial contaminated volume of water flowing from a roof after a rainstorm is known as the first flush and research has shown that diverting it from the main supply can improve the quality of stored water.

This thesis considers a variety of design options for rainwater harvesting, set in the context of rural Bisate Village in northwestern Rwanda. Fieldwork evaluated the potential for rainwater harvesting at three community-scale locations; a health clinic, a primary school, and a house for gorilla trackers and by analysis of the water quality, sought to characterize the first flush phenomenon using an apparatus to collect discrete time-sequenced volumes of runoff.

The reliability of a rainwater harvesting system is a measure of its ability to produce the water needed by the system users and depends partially upon the rainfall distribution of the area, the size of the collection roof, the capacity of the storage tank, and the daily demand for the water. The storage-reliability-yield (SRY) behavior of a rainwater harvesting system indicates trends in reliability as storage (cistern size) and yield (demand) are varied. A SRY simulation model was run to mimic daily use of the system and calculate the reliability. The recommended first flush diversion was simulated and evaluated against several management options. The simulations showed that the reliability is not drastically affected by diversion of the first flush.

The author recommends that the first millimeter of runoff be diverted from the roof after three consecutive days of precipitation less than one millimeter. This recommendation is case-specific but should greatly improve the quality of water stored in the tanks, improving the health of the end users.

Advisor: Peter Shanahan

Title: Senior Lecturer of Civil and Environmental Engineering

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First and foremost, I want to thank my parents for their never-ending love and encouragement of my studies throughout the years, for their adventurous natures, and for their support of my treks across Africa.

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Words cannot express the gratitude I have for Bernie's help throughout this process. From running lab samples at 1:00 a.m. in Rwanda with me, to proofreading my work while trying to complete his own research, he has always been there to help. His generosity made the fieldwork possible and the trip unforgettable.

In Rwanda, Jean Pierre Nshimyimana was my translator, tour-guide, friend, field-assistant, environmental health expert, and colleague. His organization and perseverance allowed the 2008 fieldtrip to happen successfully and his constant help and advice kept everything running smoothly. Even post-fieldwork he has been accessible for last-minute questions and eager to stay in contact. God willing, he will be the one to implement the recommendations of this thesis in Rwanda and will be part of the MIT community soon.

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I am grateful for the help of Lars Hanson from Tufts University, who provided a great deal of information on storage-reliability-yield behavior. I appreciate the help prior to fieldwork provided by my two UROPs, Kelly Huang and Charlie Agoos and hope that they may continue the research I began. I also can't forget my teammates from the 2007 trip: Daria Cresti and Christiane Zoghbi.

Finally, I thank my friends from MIT, Villanova, and New Jersey who provided me with hours of distraction from my thesis, and countless fun times.

Table of Contents

List of Figures

List of Tables

Acronyms

ADWP – Antecedent Dry Weather Period
CL – Sampling location at health clinic with new iron roof
DFGFI – Dian Fossey Gorilla Fund International
DRC – Democratic Republic of Congo (formerly Zaire)
DRWH – Domestic Roofwater Harvesting Programme
DTU – Development Technology Unit
EC – Electrical Conductivity
E. coli – Escherichia coli (indicator organism for fecal bacteria)
EHP – Ecosystem Health Program
EMC – Event Mean Concentration
EPA – U.S. Environmental Protection Agency
FAO – Food and Agriculture Organization
FF – First Flush (Foul Flush)
FRW – Rwandan Frances (currency)
GIZMO – Graduated Inflow-collector for Zero Mixing with Overflow
HS– Sampling location on local house with old, rusty, iron roof
IMF – International Monetary Fund
IRCSA – International Rainwater Catchment Systems Association
MDG – Millennium Development Goals
MEng – Master of Engineering at MIT
MINAGRI – Ministry of Agriculture and Animal Resources
MINITERE – Ministry of Land, Environment, Forests, Water, and Natural Resources
MIT – Massachusetts Institute of Technology
MF – Membrane filtration
NGO – Non-governmental organization
NTU – Nephlometric Turbidity Units
OECD – Organization for Economic Cooperation and Development
PEMC – Partial Event Mean Concentration
PT– Sampling location on building used to store potatoes with old, clay tiled roof
RWH – Rainwater Harvesting
SM – Master of Science at MIT
SRY – Storage-Reliability-Yield
TDS – Total Dissolved Solids
TNTC – Too Numerous to Count
TSS – Total Suspended Solids
UN – United Nations
UNEP – United Nations Environment Programme
UNICEF – United Nations Children's Fund
YAS – Yield After Storage
YBS – Yield Before Storage
VBA – Visual Basic for Applications
VNP – Volcanoes National Park
WHO – World Health Organization

CHAPTER 1: Introduction

Existing low-cost technologies can save lives today. –WHO

Chapter 1: Introduction

1.1. Project Scope

This thesis was written in partial fulfillment of the Master of Science degree (SM) in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology (MIT). The content of the thesis falls under the topic of rainwater harvesting (RWH) with a focus both on the water-supply side and the water-quality side. Work was completed over the 2006-2007 and 2007-2008 academic years and involved in-country fieldwork during January 2007 and January 2008. Rainwater harvesting is widely used in the developing world as a means of domestic water supply, is implemented in the developed world for non-potable uses, and has been studied extensively for many years. Managing the first flush is one common way to improve the quality of collected rainwater by preventing the dirtiest water from entering the tank. The first flush and "losses" associated with evaporation, system inefficiencies, or design features can have a significant impact on the efficacy of a RWH system but have not previously been considered for their effect on storage-reliability-yield behavior. This thesis considers the impact of the first flush on water quality and the storage-reliability-yield behavior of the system. The project is based in Bisate Village in Northern Province, Rwanda.

It is the intention that some of the results of this report be used to improve the water supply and quality of harvested rainwater in Bisate Village and in other locations utilizing rooftop rainwater harvesting technologies.

1.1.1. Audience

I have written this thesis with the express purpose of accessing several different audiences, each of whom may find interest in specific sections of the thesis, but not in others. The groups that I anticipate being interested in this thesis include the Dian Fossey Gorilla Fund International researchers and Ecosystem Health Program coordinators who are in contact with people in Bisate and are considering expanding projects into other local villages at the edge of Volcanoes National Park. Also future MIT students from the Master of Engineering program who may be selected to focus their thesis on water issues in Rwanda. Additionally, there are many students from the Civil and Environmental Engineering Department, the Department of Urban Studies and Planning, and a variety of other departments at MIT that have expressed interest in learning more about rainwater harvesting for their own projects; this thesis can serve as an introduction for them. Finally, the greater academic community and academic researchers will be interested in the more technically rigorous sections related to storage-reliability-yield and the effects of the first flush on that behavior. I wanted to address the multiple target audiences from the beginning to inform the reader that not all sections of the thesis may be directed towards his/her understanding, but hopefully there is a section for everyone somewhere in the thesis.

1.2. Project Background

1.2.1. Rwanda Background

Rwanda is a landlocked country in the heart of Africa, bordered by the Democratic Republic of Congo (DCR) to the west, Uganda to the north, Tanzania to the east, and Burundi to the south.

Chapter 1: Introduction

Known as "the land of a thousand hills," Rwanda is home to twenty-three lakes, rivers that feed the Nile, and six volcanoes (Gov't of Rwanda undated). Figure 1-1 shows Rwanda's geographic location in Africa. The entire nation is approximately 26,000 square kilometers (SEARNET undated) with 25,000 square kilometers of land area, making it about the same size as Maryland. Ninety percent of the population works as subsistence farmers away from the capital city of Kigali. Figure 1-2 is an administrative map of Rwanda and shows the district breakdown. Poverty and injustice have been problems in Rwanda for many years, but long-held tensions and racial dissent took the form of a civil war and genocide in 1994.

Musanze District, the focus of this thesis, is the westernmost district in the Northern Province (*Province du Nord*) and shares its borders with the Volcanoes National Park (VNP), shown at the western edge of the district in Figure 1-2.

Figure 1-1: Rwanda's Geographic Location in Africa ***(ACF undated)***

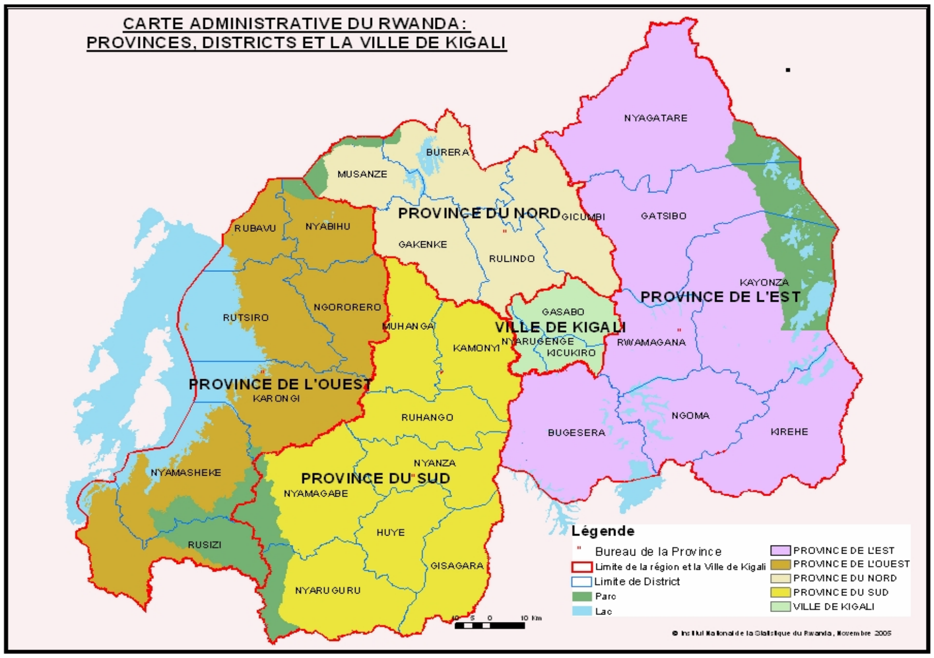


Figure 1-2: Administrative Map of Rwanda: Provinces, Districts and Kigali ***(DFGFI 2007)***

1.2.2. Project Location

Although the implications of this work are applicable to essentially any region of the world that implements rooftop rainwater harvesting, the focus of this work is on a village of ~8,500 people located at the foothills of the Virunga volcano chain in northwestern Rwanda. Best known as the home of the endangered mountain gorillas, the National Park encompassing the volcanoes straddles Rwanda, Uganda, and the Democratic Republic of Congo (DRC). There are five volcanoes whose peaks define the border between the three countries. From West to East: Karisimbi, Bisoke, Sabinyo, Gahinga, and Murhabura. The center of Bisate Village is found at the base of Bisoke Volcano, with the area of the village extending south. The total area affected by this project is outlined in the 2003 satellite photograph in Figure 1-3; the shaded area shows the vegetated regions of the Volcanoes National Park (Rwanda), Virunga National Park (DRC), and Mgahinga National Park (Uganda), including the five Rwandan volcanoes and one Congolese volcano that speckle the parks.

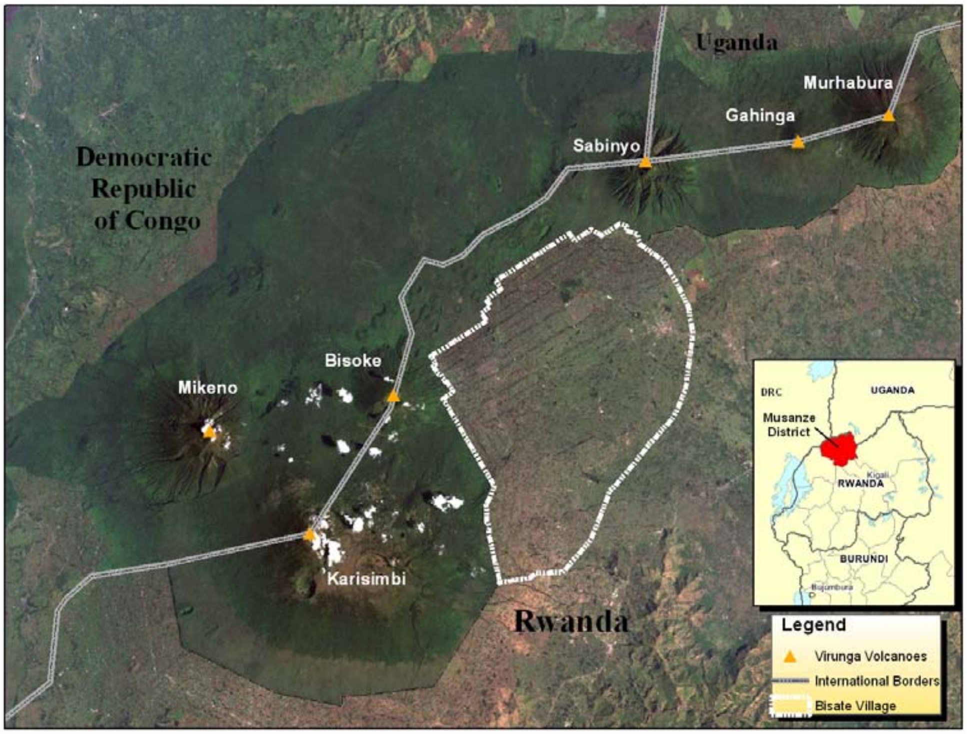


Figure 1-3: Map of Bisate and Volcanoes National Park (Global Land Cover Facility 2003)

1.3. Project Motivation

1.3.1. World Water and the MDG

Water quality and water scarcity issues are of concern in most countries around the world. Most of Africa, particularly sub-Saharan Africa, suffers from a lack of local water, seasonal scarcity, or poor-quality water coupled with unsanitary conditions. Regional rainfall varies by geography and climate, but millions of people, typically the poorest, do not have reliable access to safe drinking water.

Chapter 1: Introduction

In response to the global issue of water and sanitation needs, the United Nations (UN) and other international bodies created the International Development Goals in the 1990s. These were later revised and adopted as the Millennium Declaration. With input from the World Bank (WB), International Monetary Fund (IMF), Organization for Economic Co-operation and Development (OECD) and the UN, the Millennium Development Goals (MDG) were recognized as the principle path to implementing the Millennium Declaration.

There are eight goals and eighteen specific targets that fall under the MDG. The goals are very broad and encompass developing nations around the world.

Goal 1. Eradicate extreme poverty and hunger

Goal 2. Achieve universal primary education

Goal 3. Promote gender equality and empower women

Goal 4. Reduce child mortality

Goal 5. Improve maternal health

Goal 6. Combat HIV/AIDS, malaria and other diseases

Goal 7. Ensure environmental sustainability

Goal 8. Build a global partnership for development

Of particular interest for this report is MDG 7, which includes targets 9, 10 and 11.

Target 9. Integrate the principles of sustainable development into country policies and programs and reverse the losses of environmental resources.

Target 10. Halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation.

Target 11. Have achieved by 2020 a significant improvement in the lives of at least 100 million slum-dwellers.

MDG 7 Target 10 is most applicable to the goal of this thesis. Unclean water and insufficient sanitation are issues on a global scale. Many countries are making progress on their goals but sub-Saharan Africa is lagging behind much of world. Water and sanitation issues are so prevalent in sub-Saharan Africa due in part to conflict and political instability, high rates of population growth, and low priority given to water and sanitation (WHO 2004).

MDG 4 also is an integral part of water supply. Water-borne diseases are the leading cause of death in most Africa countries and more children die from these diseases than die from HIV/AIDS each year, yet water and sanitation issues often take a backseat to the AIDS epidemic and malaria outbreaks.

1.3.2. Water Issues in Rwanda

Having the highest population density in Africa has drawbacks for Rwanda, and the tiny country is not exempt from the issues of water supply and sanitation faced by essentially the entire developing world. Despite two rainy seasons, the country's poor have been left without sufficient, reliable, or clean water in many regions due to a lack of infrastructure, porous volcanic soil, and severe deforestation coupled with erosion.

Chapter 1: Introduction

The history of utilities in Rwanda began with the 1939 foundation of REGIDESO, a Rwanda/Burundi run facility. It later became a public company in 1962 and soon split from its Burundi counterpart. With a new statute, the company became Electrogaz in 1976. The country's only water, electricity and gas supplier, Electrogaz underwent a 5-year management contract in an effort to make the utility suitable for private investment. As of December 2003, the formerly state-owned utility now falls under the management of Lahmeyer International.

The new private company is contracted to rehabilitate and expand the existing distribution system while trying to reduce the water losses through leaks and illegal connections. The company will also try to manage finances more effectively through a planning and reporting system. Raw water quality management, management of natural resources, and training plans are all scheduled improvements to the inadequate public facility (Lahmeyer International undated).

According to a study done by Nairobi's Economic Mission in 2005, only 54% of the total Rwandan population has access to potable water, and in rural areas only 44% of the population has access. Perhaps not surprisingly, 60% of the water sold by Electrogaz is consumed by the habitants of Kigali, the capital city. The daily use in rural areas is estimated to be only eight liters per person, while the World Health Organization (WHO) recommends 20 liters per person per day (WHO 2008). There are a variety of factors influencing the rate of water consumption, notably distance to the water source. If the source is far away, regardless of whether it is contaminated or not, per capital daily water consumption decreases significantly, increasing the likelihood of contracting diseases and skin ailments such as lice. Often the poor are forced to drink more easily accessible unclean water, leading to a host of diarrheal diseases and associated health problems because potable water is not available to them (Missions Economiques 2005).

In Rwanda, people presently obtain their water from a variety of sources, some safer and more reliable than others. According to the Rwanda country self-assessment report released in 2004, more than 30% of the population does not have access to protected wells or piped water, as quantified in Table 1-1 (Nshimyimana 2007b). Since most of the piped water supplies Kigali, the percentage of people with access to safe water in the rural areas is much lower. In Bisate Village, there is no piped water available to the community.

Table 1-1: Sources of domestic water in Rwanda *(Nshimyimana 2007b)*

Source of Water	Proportion of Dwelling Units
Protected wells/ springs	44%
Piped water	24%
Unprotected wells/springs	16%
Surface water	8.5%
River water	6.8%
Rainwater	0.5%

Sanitation is also an overwhelming challenge that must be addressed throughout Rwanda. From Table 1-2, originally taken from a UNICEF report written in 2001, it is obvious that sanitation challenges adversely affect a majority of the country.

Table 1-2: Percentage of people affected by inadequate sanitation in Rwanda ***(Nshimyimana 2007b)***

Sanitation Challenges	Population Affected
Population not washing after defecation	66%
Population keeping livestock in their homes	47%
Rural people infected with parasites	58%
People using dirty domestic water containers	75%
Uncovered water reservoirs	67%

Electrogaz supplies public taps to rural villages, but often the taps are insufficient to supply the entire village with ample water. Additionally, villagers often must walk long distances to reach the public taps. In Nyange Sector, Musanze District, people have to walk eight kilometers to get water, a task typically delegated to women and children (Nshimyimana 2007b). In the study area of this thesis, Bisate Village, Kinigi Sector, it is estimated by the Ministry of Health that over 175,000 people lack access to clean water (Nshimyimana 2007b).

Aquastat, in collaboration with the Land and Water Division of the Food and Agriculture Organization (FAO), issues country profiles describing the state of water resources and agricultural water use in countries throughout the world. For Rwanda, FAO listed several organizations as important players in Rwandan water issues. The Ministry of Agriculture and Animal Resources (MINAGRI) is responsible for the management and conservation of soils for embankments, drainage and irrigation. The Ministry of Land, Environment, Forests, Water and Natural Resources (MINITERE) is responsible for implementing the national policies related to water management and water treatment, developing supply strategies for potable water, monitoring water quality and supporting sanitation education programs. As previously discussed, Electrogaz is the primary distributor of water, gas, and electricity around the country.

In addition to the government agencies and private water company, the individual districts which make up the provinces are responsible for the legal aspects of rural water distribution. Since the decentralization of Electrogaz, more responsibilities have been given to the districts, allowing them to delegate their water management strategies to local communities (FAO undated).

The water sector in Rwanda suffers from a severe lack of infrastructure and it is estimated that more than one-third of the existing water supply system is in need of rehabilitation. Major investments are needed in order to fix and expand the national water network, particularly in Kigali. The African Development Fund has already invested 18.7 million USD to supply potable water in Rwandan rural areas (Missions Economiques 2005).

Although the people living nearby have limited water supply, the area surrounding the Volcanoes National Park receives approximately 1,200 mm of rainfall every year, an abundant amount for Sub-Saharan Africa, similar to New England rainfall amounts (Nshimyimana 2007c). Unfortunately, much of the rainwater falling on the land is absorbed directly into the porous volcanic rock that comprises the subsurface, leading to water-scarce conditions in the dry season. This geologic condition coupled with the extreme poverty of the region leave most people without adequate water for several months each year. Additionally, the high population density strains the available natural resources, leaving the villagers with very few options to sequester water.

1.3.3. Social Water Issues

As in many developing countries, it is typically the responsibility of the women and children to fetch water for the family's domestic needs. As a result of geology and hydrology, water is difficult to collect and store for use during the dry season. The people living in this seasonal dry zone may spend hours a day walking to find water (Gurrieri et al. 2005). Many people trek into the Volcanoes National Park in order to retrieve surface water. The vast amount of time spent walking to find and retrieve water severely hampers the potential of women and children in the region. If alternative sources of water were secured and utilized, the women and children now imprisoned by their water walk could attend school, work to increase family income, or have more time to spend on productive domestic tasks (DFGFI 2007). Additionally, improved water conditions would decrease the occurrence of water-borne diseases such as diarrhea and parasites. Figure 1-4 was taken during the fieldwork in January 2007 and shows a local woman filling her jerrycan at a local untreated water supply. During the dry season, this tap has no water and there are no other sources nearby. Rather than drinking contaminated, untreated water, rainwater harvesting in conjunction with first flush diversion can provide an additional alternative for domestic water supply.

Figure 1-4: Local water supply (Photograph by D. Cresti)

1.4. Project Collaboration in Rwanda

1.4.1. Dian Fossey Gorilla Fund International

The Dian Fossey Gorilla Fund International (DFGFI) is a non-profit organization created in 1978 dedicated to the conservation and protection of the endangered mountain gorillas (*Gorilla gorilla berengei*) and their habitat in Africa. The DFGFI promotes continued research on both the gorillas and the ecosystems in which they live (DFGFI 2007). In addition to supporting research, the foundation also provides educational assistance to local communities and supports economic development initiatives.

Through their research efforts, scientists at DFGFI have discovered that many of the gorillas carry the same intestinal parasites as local people, indicating that human interaction with the gorillas has adverse effects on the gorillas' health (Lilly 2006). One of the most significant reasons for the unintended human-gorilla interaction is the scarcity of water in the region. When the local people enter the forest, they can spread human diseases to the gorillas and potentially contract life-threatening diseases themselves from drinking contaminated water. The health of both populations is negatively affected.

1.4.2. Ecosystem Health Program

One of the many conservation and research initiatives undertaken by DFGFI is the Ecosystem Health Program (EHP). Fieldwork for this thesis was partially sponsored by the EHP. The main purpose of the DFGFI Ecosystem Health Program is to provide a healthy environment for both the mountain gorillas and local people in order to better the lives of both groups.

The EHP seeks to protect the gorillas and humans from parasitic diseases. For humans, having a reliable source of clean water is integral to healthy living, and thus it became mutually beneficial for MIT students to work in tandem with the Ecosystem Health Program coordinators to design alternatives for sustainable sources of domestic water.

This work, completed at MIT, was performed in collaboration with the Ecosystem Health Program staff, DFGFI trackers, researchers and scientists, and local health center staff, in a joint effort to supply water to Bisate Village.

More background information on Rwanda can be found in the supplemental reading in Appendix A.

1.5. Project Research

Described in detail in Chapter 2, rooftop rainwater harvesting (RWH) is a simple method of collecting rainwater for domestic supply. A typical system includes a collection surface (a rooftop), a conveyance system (gutters), a treatment method (first flush diversion), and a storage tank. Design of an efficient and reliable system considers the end use of the water, availability and appropriateness of materials, accessibility and quality of other water sources, the size of the roof, the quality of the roof runoff, and a variety of other parameters.

Diversion of the first flush is a simple and effective way to improve the quality of water entering the rainwater tank. The goal of a first flush diversion system is to prevent the initial portion of runoff flowing off of the roof from entering the storage tank. The assumption is that the initial portion of water contains the most contaminants because the rain washes debris from the roof surface. The most intriguing question in the design of a first flush diversion system is what depth of runoff should be diverted to adequately improve the quality of stored water. Chapters 2 and 3 address the details of the first flush and its quantification.

Rooftop rainwater harvesting systems are rarely 100% reliable, meaning that they are unlikely to meet demand all of the time. RWH systems can be limited by available rainfall, roof size, tank size, cost, or they can be over-taxed with high demand. Each of these will reduce the reliability of the system. A really large tank may be big enough to supply water for a whole year, but the roof area of the building may not be able to collect enough water to fill the tank. Originating from studies of reservoir operation, storage-reliability-yield (SRY) behavior considers how the reliability of the system changes with changing storage volume and daily demand. Chapter 4 considers the SRY behavior of a RWH system and the effects of first flush diversion on that behavior.

1.5.1. Thesis Focus

The remainder of this thesis focuses on improving water quality of rooftop-collected rainwater through foul flush diversion. Later chapters consider the effects of water losses (e.g. from diversion and evaporation) on the reliability of a rainwater harvesting system. The main purpose is to understand the impact of removing contaminated water from the system and to give insight into the volume of water that should be removed to sufficiently improve the water quality without drastically reducing system reliability.

CHAPTER 2: Rainwater Harvesting and the First Flush

An adequate quantity of reasonably safe water is preferable to a smaller quantity of pure water. –UNICEF 1986

Chapter 2: Rainwater Harvesting and the First Flush

2.1. Introduction to Rainwater Harvesting

Water, although one of the most fundamental human needs, is often not readily available for the world’s poor. To address this need, many water-supply and distribution technologies have been successfully implemented in developing nations to provide clean, reliable water in close proximity to its end users. Rainwater harvesting is one of these options available for people of any country or socioeconomic background. It has the potential to provide water for a variety of domestic purposes including drinking, cooking, washing, and cleaning. Rainwater harvesting is one of the most basic forms of water collection and has been used for millennia around the world as a means of collecting and storing water for future use (UN-HABITAT 2005). The basic premise is simple: connect a holding tank to a set of gutters which collect rain from the roof. Figure 2-1 is a metal tank connected to the roof of the primary school building in Bisate, illustrating a typical rainwater collection system.

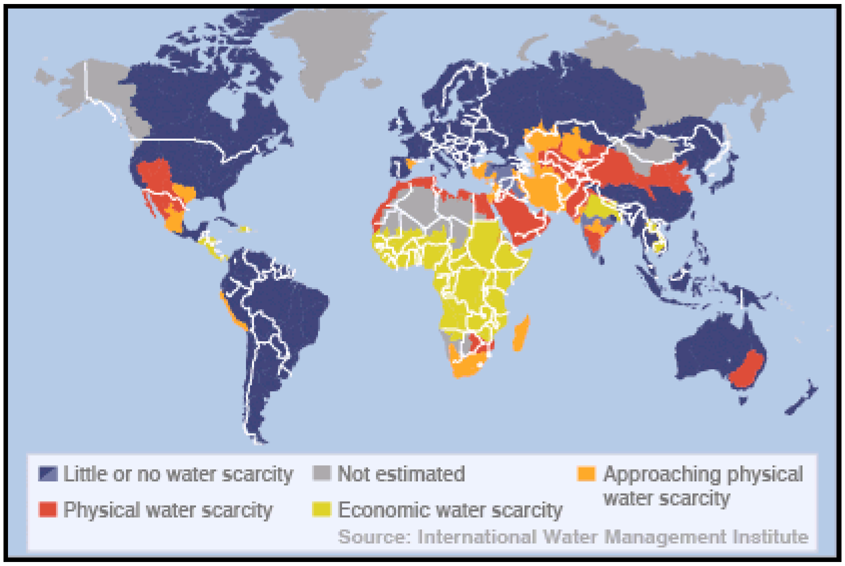
Figure 2-1 : Rainwater Harvesting System at a Rwanda Primary School (2007)

Rainwater harvesting is not limited to rooftops; it can also encompass capturing water that has already fallen to the ground by means of runoff collection. Impermeable material can be placed on the ground to direct water into holding tanks, or untreated ground catchments may be used to corral rainwater. The former may entail the construction of a concrete surface covering while the latter would exploit the use of a steep slope (UN-HABITAT 2005). This thesis will not consider ground runoff as a water source, but will only consider rooftop rainwater runoff as a source of domestic water.

Rainwater harvesting is just one of many options for water supply in poor regions. It has several distinct benefits over other water supply options, yet there are also major drawbacks. Unlike municipal water, rainwater is typically readily available and free to use. Construction logistics and materials are less than those needed for a groundwater well or public distribution network, although the capacity of the system is limited by regional rainfall. Installation costs can be high for poor communities, often limiting the system size, but they are typically cheaper than installing piped networks to rural areas. Financing can come through donor aid, small-scale loans, or projects such as the Ecosystem Health Program. Local labor can be employed to install cisterns and there is an obvious transparency about the source of community drinking water, which is valuable for community involvement. This thesis will focus exclusively on community rainwater harvesting, although much of the research is also applicable to individual family units.

Community rainwater harvesting involves water collection in large tanks (or multiple small tanks) from large communal roofs. Rainwater collection is applicable worldwide, but there are a variety of factors involved in the optimization of a system for a specific region including, supply and demand analysis, economic feasibility studies, and an examination of local social beliefs on water. In Rwanda, rural villages typically do not have access to piped water and rely on water sources with unreliable, contaminated supplies sometimes many kilometers from their homes. Community rainwater harvesting is already being widely practiced, but there is little reliance on technical knowledge related to optimizing tank design.

Rainwater collection has been used for many centuries all over the world and it has been implemented in Rwanda despite the seasonal disadvantages that are presented by the climate. Rwanda has four distinct seasons, two rainy and two dry. The long dry season typically lasts from June through September and is a time of essentially no rain. Seasonality in rainfall, like that observed in Rwanda, causes water shortages, so ideally a system is designed to capture enough water during the rainy season to last the duration of the dry season (Han 2004). In practice, it is often not financially possible to construct a tank large enough to hold the necessary volume of water. For this reason, there must still be alternate supplies of water for the community to use when the tanks run dry. Figure 2-2 below presents a map of world water scarcity. Sub-Saharan Africa is primarily dominated by economic water scarcity, indicating that there is water available for harvesting but inadequate infrastructure and funding to manage it. With proper financing and management, an adequate water supply is theoretically possible.



Source: International Water Management Institute

Figure 2-2: World Map of Water Scarcity *(BBC 2006)*

It is more efficient to collect rainwater than to fetch surface water or groundwater since the source is direct; rainwater feeds both groundwater and surface water (Han 2004). In urban areas construction creates impervious surfaces and increased runoff; in rural areas development creates un-vegetated roadways and impervious rooftops whose runoff contributes to erosion and diminished water quality. By preventing rooftop runoff from reaching the ground, erosion is mitigated and downstream water quality can be improved while at the same time providing a more efficient water source.

2.1.1. International Rainwater Harvesting Implementation

Many countries already practice rainwater collection and many others are considering rainwater as a means of supplying additional water. The movement to use rainwater for domestic supply gained momentum in 1979 when the United Nations Environment Programme (UNEP) commissioned case studies on rainwater harvesting in rural areas. Research included programs in China, India, Mexico, the U.S., Africa, Australia and the South Pacific (UN-HABITAT 2005). International rainwater conferences have been held every other year since 1991 in such places as Taiwan, Kenya, China, Iran, Brazil, Germany, Mexico, and India, giving an indication of the global interest in rainwater collection (IRCSA 2007).

In Africa, Kenya is a proponent of innovative rainwater catchment technologies and has financed construction of tanks as large as 40 m^3 to provide long-term storage of rainwater (Saleh 2004). Kenya has also supported construction of large tanks made from corrugated-iron, ferrocement tanks, and rock catchment systems (Gould 1993).

The Gansu province in China is one of the driest in that country. To help local farmers, the Gansu Provincial Government provided a rainwater collection field, two tanks and crop land to individuals. The project supplied drinking water to 1.3 million people in 1995/6 and by 2004 supplied 1.97 million people (Han 2004).

Although Bangladesh has an ample supply of groundwater, natural arsenic contamination has adversely affected millions of people who rely on that supply. A non-governmental organization (NGO), Forum for Drinking Water Supply and Sanitation, has been instrumental in installing rainwater harvesting systems in areas with particularly severe arsenic contamination. Since 1997, the group has installed over 1,000 systems in rural areas, providing people with a safe water supply (UN-HABITAT 2005).

There are dozens of other nations currently using rainwater harvesting. Each of these countries has a unique rainfall pattern, particular cultural customs, varying beliefs about water collection, large ranges in income levels, and different geographic locations. Although there are numerous success stories regarding the implementation of rainwater harvesting systems throughout the world, it is not a perfect technology nor is it capable of being the sole source of water for a community. The system requires significant maintenance to ensure a safe supply of water, which can be a burden on a community. Even if the water is safe to drink there may be a social stigma against drinking rainwater stemming from the bland taste of water with no mineral content.

The School of Engineering at the University of Warwick in the United Kingdom hosts the Development Technology Unit DTU), a research group that specializes in appropriate technologies for developing countries. An emphasis is placed on using a “bottom up” approach to system design (Warwick undated). There is a wealth of information on rainwater harvesting available through their Domestic Roofwater Harvesting (DRWH) Programme, including a rainwater tank performance calculator, discussed further in Chapter 4 of this thesis.

The Warwick website provides web-links to related research and information regarding sizing a DRWH system. The University also has ties to the International Rainwater Catchment Systems Association (IRCSA) and is a large contributor to the most recent rainwater-harvesting publications.

The International Rainwater Catchment Systems Association (IRSCA) is one of the primary organizations coordinating active work on rainwater harvesting worldwide. Founded in 1989, the organization hosts annual conferences and aims to "promote and advance rainwater catchment systems technology with respect to planning, development, management, science, technology, research and education worldwide; establish an international forum for scientists, engineers, educators, administrators and those concerned in this field; draft international guidelines on this technology and update and disseminate information; collaborate with and support international programs" (IRSCA 2007). The IRCSA records of conference proceedings are useful for individuals interested in learning more about rainwater harvesting throughout the world.

2.2. Rainwater Harvesting Systems

Rainwater harvesting generally refers to the collection of rainwater, but for the purposes of this thesis, it is confined to rooftop rainwater harvesting for domestic supply. Rainwater falls on a collection surface (a roof), flows into a conveyance system (gutters), and then into a storage tank. Some systems also incorporate filtration, diversion, or disinfection options for treating the inflowing water. The user then consumes the water for drinking, cooking, cleaning, hygiene, or any other domestic purpose.

While the system itself is fairly simple, there are many available options for the design of each component, many of which are not appropriate for every situation. The following is a description of the key elements of a rainwater harvesting system. A general overview is presented below; the reader is referred to the supplemental reading in Appendix A for more information on RWH design options.

2.2.1. Building Materials for Storage Tanks

2.2.1.1. Tank Design Considerations

The ultimate goal of design for rainwater catchment systems "is to provide adequately sized components of sufficient structural strength and durability to provide the optimum amount of potable water to the users at the most economical cost" (Schiller 1982). Typically the most limiting factor for people in need of clean water in developing countries is money. Therefore, the ideal design optimizes system size with cost for the community. The size of the collection tank is dependent on available rainfall, seasonal rainfall distribution, and community water demand. It is important to recognize that in most geographic regions, rain does not fall at regular intervals over the entire year, but instead is distributed seasonally through wet and dry cycles.

Rwanda has a cycle of two dry seasons and two wet seasons. The average rainfall during the rainy seasons is 110 to 200 mm per month (Gov't of Rwanda undated). Ideally, a rain tank needs to be large enough to store ample water during the wet season to last through the dry season, but a tank that is too large will not be affordable to the people who need it. If the tank runs dry, the people depending on it will require alternate sources of water. A dry tank could result from structural failure of the tank, poor water management and overuse, an abnormally long dry season, or water theft. If other options for water are scarce or difficult to obtain, people may resort to stealing the collected water, so a more durable tank may provide additional security against theft. While some of the potential reasons resulting in a dry tank cannot be easily accounted for in the initial design, a thorough analysis of rainfall reliability and security considerations should be undertaken.

Related to the annual rainfall for an area is the size of the collecting surface. No more water can be collected than falls on the collection surface. Therefore, a personal, domestic water collection tank will be much smaller than one collecting rain from a community building. It is extremely important in designing a tank to consider what other options the people have for obtaining clean water. If rainwater collection is going to be their primary source of domestic water, the tank must be large enough to ensure that there will still be water at the end of the dry season (Schulze 1983).

The size of the tank is also inextricably linked to the proposed use of the collected water (Watt 1978). Before an appropriate tank size can be calculated, the ultimate use of the water should be determined. Will water be used solely for domestic purposes (drinking, cooking, basic washing), or will some of it be used for irrigation, or for farm animals? How many people will be relying on the water? What other potable water sources are available? Depending on the construction material selected, a personal holding tank may still be too expensive for one family to afford. If funds are limited, it is possible for several neighbors to combine their resources to share a communal tank. It is very common for tanks to be installed beneath the roofs of community buildings, such as schools and churches. The roof area of a community building is typically much larger than that of any single-family home, and the cost and benefits are more easily shared by many members of the community (Gov't of South Australia 1999). There are many benefits to personal water tanks for individual family units, but for the purpose of this report, only large-scale community rainwater tanks will be discussed in depth.

A variety of options for tank construction materials exists, but in some developing areas not all materials will be readily available. The unique needs and abilities of the region need to be considered before a tank is selected and sized. Some of the possible tank options are presented below, but it is important to acknowledge other less common, innovative alternatives as well, many of which are already in place in remote regions.

Rainwater tanks can be constructed from any number of materials, but the most common construction employs one of the following materials: brick, metal, masonry/stone, ferrocement, wood, plastic, or concrete; an underground cistern may also be constructed. A full discussion of the available materials is in the supplemental reading in Appendix A. Plastic and metal tanks are easily installed pre-fabricated options, with comparable price ranges and sizing options. Table 2-1 compares the benefits and drawbacks of plastic and metal tanks (Nshimyimana 2007b).

Table 2-1: Comparison of metal and plastic tanks

Prefabricated Metal Tank	Plastic Tank
More expensive in Rwanda than plastic	(Typically) cheaper than comparable metal tank
Needs complementary protection (painting to protect it from rust)	May need complementary protection (fencing to protect from vandalism)
Resistant to vandalism and accidental damage from use	Prone to vandalism and accidental damage
Unaffected by UV light	If unprotected, affected by UV light
Affected by humidity	Resistant to humidity
Affected by rust and corrosion	No concerns regarding rust or corrosion
Resistant to fire	Affected by fire
Poor maintenance can affect the water quality	Poor maintenance can favor the growth of bacteria inside the tank
Difficult to install if welding is needed	Easy to install if truck delivery is possible

It is important to ensure that the tank opening is covered, regardless of the material selected, the size of the tank, or the final use of the water. Appropriately sized netting or screening should be placed at the water inlet to prevent mosquitoes from laying their eggs in the water. Although malaria is a serious concern in most African countries including Rwanda, the high elevation of Bisate inhibits the breeding of malaria-carrying mosquitoes. Nonetheless, other disease vectors (i.e. flies) are attracted to standing water, so measures to keep the tanks covered and prevent standing water are essential.

2.2.1.2. Summary of Tank Material

Tank construction in Bisate is limited by many factors, including cost and availability of materials. Masonry, plastic, and metal tanks are already in use in the area but ferrocement and underground cisterns provide possible alternatives (discussed in Appendix A). If several tanks are installed simultaneously, it is advantageous to use the same materials for all of them. Having tanks of the same material will decrease the education and training needed for community members who will maintain the systems.

2.2.2. Gutters

In much of the available literature, the primary focus is on tank sizing and material selection while guttering considerations are glossed over as a secondary concern. Neglecting the importance of gutters can leave a system without adequate means to convey the water to the tank. Improper maintenance resulting in broken gutters will render the entire system useless. According to Pacey (1986), "the lack of guttering is sometimes said to be one of the primary limiting factors restricting the wider adoption of rainwater collection". As for tank materials, there are a variety of options for guttering, based on material availability, existing roof construction, and cost. Existing infrastructure needs to be assessed before gutters can be considered. Funds for gutters must be set aside early so that the project does not exceed the available budget without this component for collection. The supplemental reading in Appendix A contains a more thorough discussion of guttering options.

2.2.3. Catchment Surfaces

Rainwater collection systems are primarily installed on existing buildings, so concerns are raised about the quality and safety of the water coming from existing infrastructure. Rainwater can be collected from essentially any roofing surface, although some caution should be taken. Roofs with any lead-based paint or lead flashings should be avoided. Similarly, asbestos roofs with detached fibers should not be considered for rainwater collection due to the safety concerns associated with asbestos (Pacey 1986). Most other roofing materials can be suitable for rainwater collection, including but not limited to: palm leaf, thatch, corrugated iron, plastic, wood, clay tiles and concrete. While all of these materials may be suitable for rainwater collection, roof materials such as leaf, thatch, wood, or degraded clay are prone to collecting dust which has the potential to severely degrade the quality of the water. Thus, it is recommended that roofs used for rainwater harvesting be constructed out of metal or plastic sheeting, or well-cleaned clay tiles. Gutters can be attached to the supports beneath the sheeting, and those materials are relatively easy to maintain. In Bisate Village, most of the community buildings are fitted with corrugated metal roofs, while individual homes see a greater variety of materials.

Rooftops used for water harvesting should be cleaned regularly to avoid contamination of the runoff, even if a first-flush device has been installed. Trees and plants hanging over the roof should be pruned back and the surface should be kept clear of animal droppings. Since Rwanda has two distinct dry seasons, it is important to clean the roof thoroughly before the rains return. A clean roof in conjunction with a first-flush device will minimize the amount of pollution entering the storage vessel.

2.3. Introduction to First Flush Devices

Rainwater harvesting has been used for millennia all around the world as a means of providing a domestic water supply and/or irrigation water. Particularly when the end purpose of the water is for human consumption, water quality is a pressing concern. Rainwater itself can have a range of qualities; acid rain resulting from air pollution is one obvious example.

When designing a rooftop rainwater harvesting system, most of the literature recommends some form of basic treatment: filtration, settling, and diversion are three options. A filtration system can be as simple as installing an angled mesh screen over the tank opening or gutters to divert leaves and large debris away from the main store. It could also incorporate a finer mesh in the outflow pipe to reduce the volume of suspended particles exiting the tank. To allow for settling, the spigot on the tank is typically installed several inches from the bottom allowing debris to collect below the tap and not be released. Sometimes separate chambers are constructed to allow for particulate settling prior to reaching the tank. Diversion involves preventing the dirtiest water from entering the tank by redirecting it to an alternative holding vessel for disposal.

The “first flush” or “foul flush,” used interchangeably, refers to the dirtiest water flowing off a roof at the beginning of a rain event. During dry weather, dust, leaves, animal excrement, dead insects and other particulate matter accumulate on the roof. When it begins to rain, airborne particulates are removed from the air and the particulate matter on the roof is washed off, cleaning the roof. In general, the harder it rains, the cleaner the roof will become, although that is not always the case. The main concept behind first flush diversion is that if the initial dirty water can be prevented from entering the storage tank, only the remaining, cleaner water will fill the tank. The concept of diverting the first flush to improve water quality is the focus of the remainder of this thesis.

2.3.1. Defining the First Flush

The concept of the first flush originated in the urban stormwater and storm-sewer literature; as engineers try to mitigate the impacts of anthropogenic development on receiving waters (streams and rivers) they study the effects of rain on sediment load and other water quality parameters. Within the runoff literature there is some controversy surrounding the first flush phenomenon. There is skepticism as to whether the first flush exists at all and there is other disagreement about how to define the first flush. Although the concept is the same throughout the literature, the first flush is studied in both separate and combined sewers, and also via sheet flow from urban stormwater runoff. This thesis considers the first flush coming from rooftops, which has similarities and differences with both sewer and street flow phenomena. The following discusses the disagreements and consensus regarding the first flush within the urban stormwater and sewer system literature.

2.3.1.1. First Flush for Urban Stormwater and Sewer Systems

There is a clear consensus as to the basic concept of the first flush: it is the first portion of the total discharged volume which contains the main proportion of the pollutant load during a storm event (Bertrand-Krajewski et al. 1998). Disagreement arises in defining “first proportion” and “main proportion” which are both vague, qualitative terms. Some authors leave the definition vague while others explicitly quantify their idea of the first flush. One of the most general and commonly used metrics for studying the phenomenon is the event mean concentration (EMC), defined as:

Equation 2-1 : Event Mean Concentration (EMC)

$$EMC = \frac{M}{V} = \frac{\int_0^{t_r} c(t)q(t)dt}{\int_0^{t_r} q(t)dt}$$

Where M/V is the ratio of total pollutant mass (M) to total storm volume (V), c(t) is the concentration of pollutant at time t, q(t) is the flow rate at time t, and t_r is the storm duration (Sansalone and Buchberger 1997). The EMC integrates the entire pollutant concentration over the full storm duration, t_r. The partial event mean concentration (PEMC) has a similar formula but calculates the concentration at a time other than the end of the storm.

Equation 2-2: Partial Event Mean Concentration (PEMC)

$$PEMC = \frac{m(t)}{v(t)} = \frac{\int_0^{t} c(t)q(t)dt}{\int_0^{t} q(t)dt}$$

Where m(t) is the mass transported up to time t and v(t) is the flow volume up to time t. The most common graphical presentation of the first flush phenomenon in the literature plots a normalized pollution load versus a normalized rainfall volume, called the L(V) or M(V) plot (Figure 2-3). From the EMC equations, the normalized pollution load is simply *m'(t) = m(t)/M* and the normalized rainfall volume is *v'(t) = v(t)/V.*

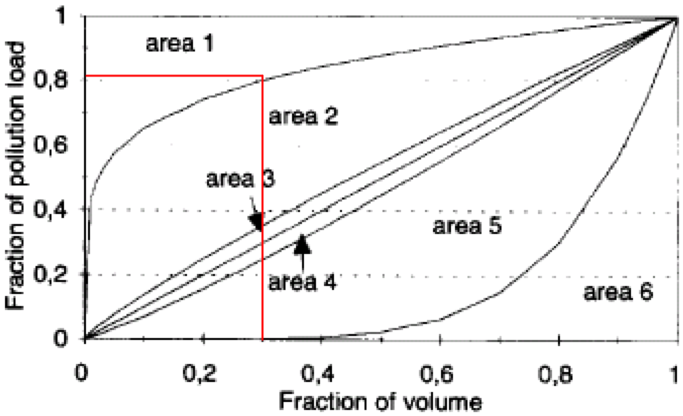


Figure 2-3: Cumulative load vs. total volume plot (M(V) plot) (Saget et al. 1996)

The graph is broken down into six main areas, as designated in Figure 2-3 by the diagonal lines that intercept the origin. A storm event with a constant pollutant concentration over the entire duration of the storm is represented by the main diagonal (the m(t) = v(t) line). Any storm pollutant plot falling above the m(t) = v(t) line is considered to exhibit a flushing effect, meaning that the fraction of pollutant load in the first part of the storm is greater than the corresponding fraction of runoff volume in the first part of the storm. Area 3, Area 2, and Area 1 exhibit flushing effects of increasing intensity. Area 4, Area 5, and Area 6, on the bottom side of the 45º diagonal do not exhibit a flushing effect, but rather represent storms where a larger fraction of the total storm pollution load is passed at the end of the storm than at the beginning. Ideally, for purposes of obtaining clean water, the pollution distribution for a particular storm would fall in Area 1 since the most pollution could be removed with the smallest volume of water, thus maximizing clean water capture. The benefit of analyzing the first flush using the m'(t) vs. v'(t) method is that the analysis normalizes the mass (or volume) of contaminant and duration of the storm. Thus, storms of different durations with different contaminant concentrations are comparable on the same scale to determine the extent to which the flushing behavior is observed.

Saget *et al.* (1996) define the first flush to be significant when at least 80% of the load is transferred in the first 30% of the storm, represented by Area 1 in Figure 2-3 (Saget et al. 1996). As a co-author of the Saget paper, it is not surprising that Bertrand-Krajewski (1998) rigorously defines his idea of the first flush and specifies the same 30/80 rule. He admits that the selection of the 30/80 criterion is arbitrary but maintains that it is an appropriate measure of the first flush phenomenon. Bertrand-Krajewski also uses the M(V) plot from Figure 2-3 and notes that the magnitude of the first flush can be determined by measuring the difference between the m(t) = v(t) diagonal line and the storm-specific curve. A strong flush is characterized by a large positive difference between the storm curve and the diagonal.

Geiger (1984), as reported by Bertrand-Krajewski *et al.*(1998), maintains that a significant first flush exists if the difference between the bisector and mass/volume curve is greater than 0.2, but the position of the maximum difference between the bisector line and storm-specific curve is important. If the maximum difference comes late in the storm, then the first flush would not be seen until part-way through the storm event and thus not be an adequate measure of the first flush (Bertrand-Krajewski et al. 1998). It is useful to recognize that by making such strict definitions, the frequency of the first flush phenomenon decreases significantly. Saget *et al.* found the 30/80 definition satisfied in only 1 of 197 storm events quantified for suspended solids (Saget et al. 1996).

Sansalone and Buchberger (Sansalone and Buchberger 1997) report three references that apply still different rules, using the relationship between m'(t) and v'(t) to define the first flush as:

Equation 2-3

$m'(t) \geq v'(t)$ for all t (Helsel *et al.* 1979)

Equation 2-4

$m'(t) \geq 0.50$ for $v'(t) \leq 0.25$ (Wanielista and Yousef 1993) – a 50/25 rule

Equation 2-5

$m'(t) \geq 0.80$ and $v'(t) \leq 0.20$ (Stahre and Urbonas 1990) – an 80/20 rule

Deletic (1998) provides yet another way to think about the first flush. She defines the FF_{20} as the pollutant load carried by the first 20% of the rain event (Deletic 1998). The FF_{20} definition (really a 20/20 rule) maintains that if more than 20% of the pollutants are transported in that volume, then a flushing behavior is observed.

The presence or absence of the first flush is dependant on the contaminant of interest. Deletic (1998) found that suspended sediments exhibited a flushing behavior in some rain events, but pH (analyzed as concentrations of [H^+] ions), conductivity, and temperature (determined using the cumulative load of temperature) did not exhibit a flushing behavior in her study areas (Deletic 1998). Geiger found that the 0.2 gap described previously occurs in 25% of events measured for total suspended solid but only in 15% of events measured for other pollutants (Bertrand-Krajewski et al. 1998).

While the urban stormwater literature provides some useful generic concepts, they many not be entirely applicable to rooftop drainage. Martinson (2005) notes the inherent differences between rooftops used for rainwater harvesting and urban landscapes producing stormwater runoff. Roof systems tend to be smaller than urban drainage areas, meaning that the lag time for water to reach the outlet is reduced, thereby reducing the dispersed arrival of pollutants; roofing material are typically smoother than urban pavement, thus particulate matter is more likely to wash off easily and sediment is less likely to accumulate in voids; and roof slopes are usually steeper than street slopes, magnifying the first flush effect (Martinson and Thomas 2005).

2.3.2. First Flush for Rainwater Harvesting

Although the first flush concept originated in the urban stormwater and sewer literature, it has also been widely applied to rooftop rainwater harvesting. There is very little agreement as to the amount of water that is to be diverted, the most obvious reason being that the first flush is site-specific. The volume of water diverted for a particular system depends on the acceptable risk for the end users of the water, on the specific site characteristics, and on the value of the water based on its final end use. A variety of site-specific factors come into play when calculating an appropriate size for a first flush diversion chamber, most prominently including proximity to roadways, distance from trees, quality of the roofing material, and abundance of birds, small animals (i.e. lizards), and insects. A more comprehensive list is described later in this chapter. Table 2-2 provides some of the recommendations available in the literature for how much runoff to divert for domestic roofwater harvesting. In some instances the values supplied in the literature were converted to millimeters of rain for easy comparison.

Martison and Thomas's paper entitled "Quantifying the First Flush Phenomenon" (2005) is one of the most comprehensive reports available on the analysis of first flush diversion volumes. He gives a comprehensive review of the literature and uses a model developed by Sartor and Boyd to analyze the first flush efficacy. Sartor and Boyd (Sartor and Boyd 1972) propose that rainwater contamination follows an exponential decay curve defined by:

Equation 2-6: Sartor and Boyd equation for rainwater quality

$$N = N_0 e^{-krt}$$

Where N is the turbidity of the current runoff; N_0 is the initial sediment load on the roof prior to the rain event; k is a constant that varies based on catchment surface texture and varies from 0.01-0.18 mm^{-1} for roadways; r is the rainfall intensity in mm/hr; and t is the storm duration in hours. By basic multiplication, rt is the rainfall depth in mm. Equation 2-6 provides a simple metric for the first flush and assumes that the reductions in pollutants follow exponential decay.

Table 2-2: Literature review on first flush diversion

Reference	Specifications	How much is flushed?
(Yaziz, et al. 1989)	- To safeguard against microbial contamination	0.33 mm
(Ntale, et al. 2003)	- Empirical value - Should be decreased in rainy season	0.83 mm or first 10 minutes
(Martinson and Thomas 2005)	-Based on sample measurements	For each mm flushed away, the contaminant load will halve
(Cunliffe 1998)	- For an "average-sized roof"	20-25 Liters
(Rain Harvesting undated)	– Minimum – Low pollution – High pollution	– 0.20 mm – 0.50 mm – 2.0 mm
(Pacey and Cullis 1986)		First 10 minutes of rain event
(Texas Water Development Board 2005)	- Depending on dry days, debris, trees, and season	0.41 – 0.82 mm
(Michaelides 1987)	- Based on experimental work in Thailand	0.28 mm

Alternatively, Thomas and Martinson (Thomas and Martinson 2007) provide a convenient table to calculate the amount of rainwater to divert, based on the initial turbidity of the water and the target turbidity of the water flowing into the tank (Table 2-3). Many assumptions are inherent in their recommendations, but the table provides a concise reference for easy sizing of a diversion chamber.

Table 2-3: Recommended first-flush amounts (in millimeters) based on target turbidity (Thomas and Martinson 2007)

Initial run-off turbidity	Target Turbidity (NTU)			
(NTU)	50	20	10	5
50	0.0	1.5	2.5	3.5
100	1.0	2.5	3.5	4.5
200	2.0	3.5	4.5	5.5
500	3.5	4.5	5.5	6.5
1,000	4.5	5.5	6.5	7.5
2,000	5.5	6.5	7.5	8.5

2.3.3. Factors Affecting First Flush

Understanding the mechanisms behind the first flush is fundamental to quantifying it and developing site-specific recommendations for treating the water. Unfortunately for those looking for a one-size-fits-all answer to the first flush, its magnitude is affected by a wide variety of factors including, but certainly not limited to (Meera and Ahammed 2006):

- **Roof material** – its chemical composition, roughness, age, durability in adverse weather, and maintenance
- **Roof characteristics** – size, slope, and exposure to sun, wind, rain, and pollution sources
- **Rain-event characteristics** – intensity, wind, and pollutant concentration in rain
- **Meteorological characteristics** – season, antecedent dry weather period, solar radiation, and atmospheric pollution
- **Roof location** – proximity to roadway and overhanging trees, and abundance of animals (rodents, insects, lizards, etc)
- **Pollutant characteristics** – ability of pollutant (bacteria, virus, and protozoa) to be sterilized with solar radiation, and particle density (ability to be carried by wind and water)

It is because of the breadth of these factors and the disagreement on the definition of the phenomenon that there is no single answer to the question of how much water should be diverted in a rainwater harvesting system. The end use of the water also plays a major role in the acceptable risk of contamination. For a system meant primarily for irrigation and washing, higher levels of pollutants are acceptable, but a system that stores water for drinking water needs to be more conservatively designed. At the same time, if the alternate sources of water available to the community are more heavily contaminated or contaminated with more harmful pollutants than even the most degraded rainwater, then the value of the dirty rainwater may be high enough that a lower percentage of the water should be diverted. One needs to choose an acceptable level of risk based on cultural and socio-economic standards and the quality of alternative water sources (Gould 1999).

The Texas Development Board notes that a rainfall intensity of at least 0.025 mm/hour is necessary to properly wash contaminants from the roof surface (Texas Water Development Board 2005). There is a significant amount of research related to roof washing effects and rainfall intensity. While it is a legitimate concern, intensity issues were not considered for this thesis as minute-by-minute rainfall data were not available for the subject site.

2.3.4. Health Risks from Drinking Contaminated Water

There are two very fundamental issues present in the design of a rainwater harvesting system: the provision of adequate supplies of water and the provision of clean water. They have the potential to be entirely independent, but there is often a strong relationship. If too much water is diverted to make it clean, then the volume is not sufficient to meet demand, but if the water is not treated at all, then the entire store has the potential to become contaminated and make the end users ill. In UNICEF’s resource handbook some general principles related to the provision of water in developing countries are presented; the most notable reads, “an adequate quantity of reasonably safe water is preferable to a smaller quantity of pure water” (UNICEF 1986).

Although rainwater itself is typically very clean, there are still some health risks associated with drinking untreated water directly from a rainwater collection system. Simmons (1999) discusses rainwater contamination in the context of domestic water supply. His literature review compiles work of many others and he provides a list of the pathogenic species found in some tank rainwater samples. Those pathogens include: *Clostridium perfringens*, *Salmonella spp.*, *Cryptosporidium spp., Giardia spp*, *Legionella spp.*, *Aeromonas spp., Hepatitis A virus, Pseudomonas spp, Shigella spp.,* and *Vibrio parahaemolyticus*(Simmons 1999). The most common diaherreal diseases found in Rwanda are: cholera, typhoid, paratyphoid, salmonella, giardiasis, and cryptosporidiosis (Gasana et al. 2002). Studies have also found chemical contamination to be a problem in some rainwater systems, particularly with the persistence of lead resulting from lead flashing and lead-based paints used in the roof construction (Meera and Ahammed 2006). In some studies, heightened levels of zinc and magnesium were also found, likely resulting from other parts of the roof or gutter construction.

Gould (1999) makes special note of the lowered microbial drinking water standards for developing countries, a move that increases the likelihood that water will meet the standard. The rural areas of many developing countries cannot meet the stringent regulations set out by the EPA and World Health Organization of 0 colonies/100mL water for thermotolerant bacteria (EPA 2008). Gould discusses two proposals to allow the standards for *E. coli* to be raised to 10 colonies/100mL for rural water supplies in developing countries (Gould 1999).

Within the context of a microbial risk assessment for a drinking water source there are four main steps applicable to rainwater harvesting: 1. hazard identification; 2. exposure assessment; 3. dose-response estimation; and 4. risk characterization (Simmons 1999). Hazard identification involves the characterization of the pathogens including their prevalence and virility; exposure assessment is based on the level of contamination in addition to the mode of exposure, typically ingestion or inhalation. The amount of infective agent, the pathogenicity of the pollutant and the vulnerability of the host all contribute to the dose-response estimation while a combination of the first three factors develops the final risk characterization (Simmons 1999). These factors are an important aspect of decision making in regards to tank operation and maintenance. The more vulnerable the end users are, the more care needs to be taken to ensure their safety. Being overly-cautious comes at the risk of costing too much time and money and not being viable in the long term. The 2008 fieldwork, discussed in Chapter 3, makes a first-attempt at a risk assessment for the drinking water supply in Bisate Village. Certainly a more comprehensive study is desirable, but the preliminary assessment is sufficient to understand the magnitude of the contamination.

2.3.5. First Flush Diversion Options

As rainwater harvesting gains popularity in developed nations, first flush diversion options are becoming more abundant and commonplace. There are many options available on the market that can be easily installed as part of a home rainwater collection system. Alternatively, a device could be designed on site using available local materials such as PVC pipes or plastic containers. The following presents some design options for first flush devices, but it is not meant to be an all-inclusive list.

It is important to note that there are several genres of first flush devices: automatic, manual, constant volume, and intensity-dependent. Automatic devices do not require the user to attend to the system during a rain event, although regular maintenance is required. By contrast, manual devices must be operated by the user during each rain event. Each provides advantages and disadvantages, which are discussed below. Within the automatic device genre, options for the diversion chambers include constant volume and intensity-dependent. Intensity-dependent chambers operate under the notion that the first flush will not necessarily occur at the very beginning of the rain event but rather after the intensity has increased to sufficiently wash the contaminants from the roof. Constant volume devices collect a set volume of water, regardless of the intensity of the rain or contamination on the roof.

2.3.5.1. Manual Diverters

Manual diversion is the lowest cost option for dealing with the first flush but requires the most attention. The downspout coming from the gutter is allowed to swivel, giving the user an opportunity to waste the first few minutes of the rainstorm if the person feels that the water coming from the roof is dirty. Figure 2-4 illustrates a standard manual diverter with the swiveling mechanism.

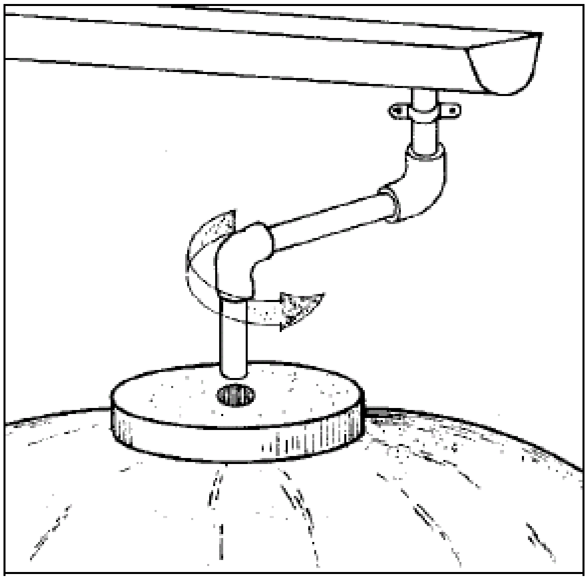


Figure 2-4: Manual first flush diverter (Martinson 2007)

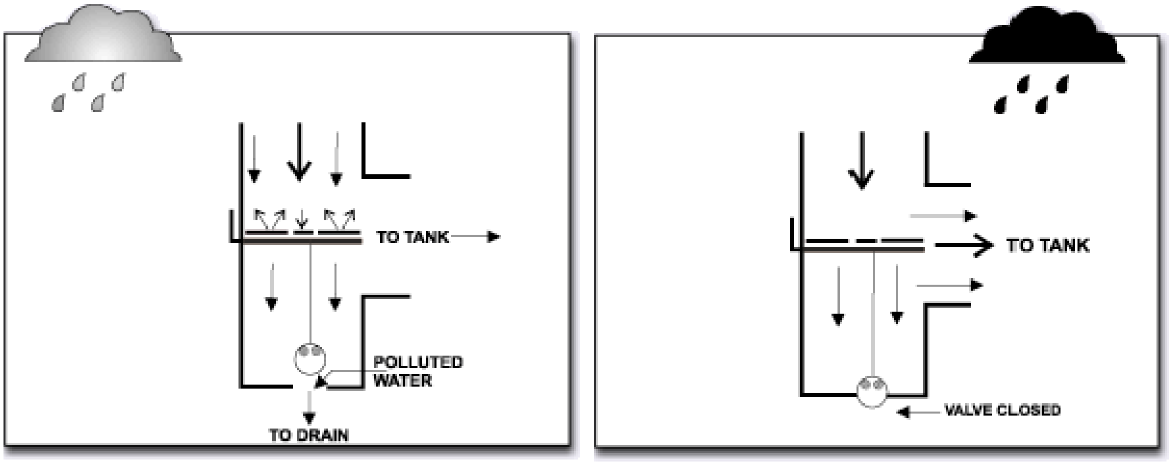
There are several issues related to manual diverters that make them undesirable for use in Rwanda. Perhaps the most obvious drawback to the manual diverter is that the user must be present at the beginning of each rainstorm. If the rain begins while the person is out of the home or at night, then either the rainwater is all wasted because the pipe is disengaged, or the contaminated water enters the tank untreated. Additionally, the user must be educated in how much water to waste; as discussed previously, some authors recommend wasting the first ten minutes of the storm, but that requires the user to keep track of the time and again be present to turn the pipe back to the correct position.

The benefit to using a manual diverter is the simplicity of the system. There are no complicated setups required and additional parts are not required to make it work. It would not be appropriate for a community-size system to employ a manual diverter, because it is up to the user to decide how much water to divert.

2.3.5.2. Intensity-Dependent Diverters

The main thought behind the design of intensity-dependent diverters is that low-intensity drizzles do not have enough flow to wash contaminants from the roof. Once the intensity of the rain increases it is much more likely that the particulate matter will be carried off the roof. There are several designs available that wait until the intensity has reached a certain level to allow the clean water to flow into the tank. These designs do not consider the contamination that may come directly from the atmosphere at the beginning of a rain event nor do they consider the implications of sediment build-up in the valve.

One such device utilizes a valve located in the downpipe from the roof (Figure 2-5). The valve consists of a hollow plastic ball, an extendible elastic cord, and a perforated baffle plate. The plastic ball has holes in the top and a small drainage hole in the bottom. The valve divides the flow between a dirty-water drain for diverted water and a clean-water pipe into the storage tank. When it begins raining, water flowing from the roof and down the pipe hits the baffle plate which attenuates the flow. The water falls through the perforations in the baffle plate and some of it enters the hollow ball. The remainder flows out of the valve to the ground. Water is directed into the tank only when the intensity of rain is high enough to fill the ball faster than it drains. There is a lag between when that minimum intensity is reached and when the valve actually closes to allow the high intensity rain to properly clean the surface. The baffle serves to slow the flow into the device, so the lag is increased and sudden surges of water will not prematurely close the value. Even as it is raining, the water slowly leaks out of the ball, eventually opening the valve and resetting the device (Vidacovich 2004). There are alternate configurations that rely on elastics, pulleys, or tipping flaps, but the concept is the same for all. Two stages of operation are shown in Figure 2-5.



Low-intensity rain High-intensity rain

Figure 2-5: Flow-rate diversion (Church 2001)

The intensity- and flow-dependent diverters are not appropriate for Bisate Village due to the complexity of design and the numerous moving parts. The elastic band used to close the valve in Figure 2-5 is supposed to have a lifespan of 7+ years, but finding replacement parts for the device would be near impossible in rural Rwanda. The device is too specialized to be used in such a remote area and is thus not recommended.

2.3.5.3. Constant Volume Options

Constant volume containers are the most straightforward of the automatic designs and hence the most appropriate for Rwanda. They provide a reliable option for removing the first flush that requires relatively little maintenance yet is also durable. As with many of the diversion options, a diversion chamber is installed on the conveyance pipe between the gutter and storage tank. The premise behind the design is very simple; the dirty water will flow into the chamber before filling into the tank; once the chamber is filled by diverted water, the cleaner water will bypass the chamber and flow into the tank. This process is illustrated in Figure 2-6. After the rain event the chamber must then be emptied before the next storm. This is typically accomplished by installing a removable cap or stopper at the end of the diversion pipe that is easily removed and replaced. The chamber can be something as simple as a length of PVC pipe of the correct volume to adequately improve the water quality.

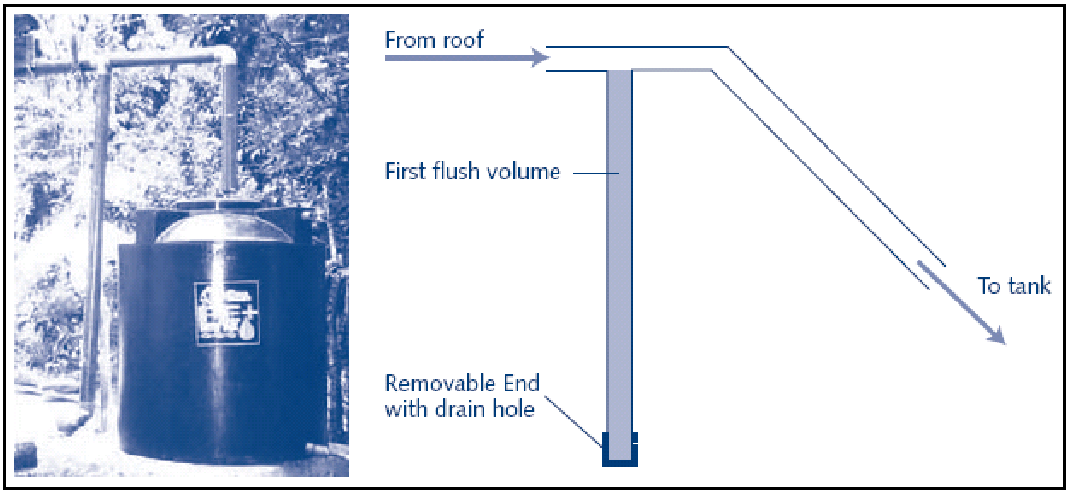


Figure 2-6: First flush diversion option with drain hole (Thomas and Martinson 2007)

There is some concern regarding mixing between the diverted water and the clean water flowing into the tank. There are a variety of options available to prevent the clean water from entraining the separated dirty water. In some designs a floating ball in the diversion chamber rises as the water fills, eventually reaching the top and blocking additional water from entering the chamber. Figure 2-7 illustrates one such example. Michaelides (1987) completed a comprehensive study on mixing through several different diverters and found that having a pipe diverter with a horizontal pipe leading into the main diversion chamber (as in Figure 2-6 and Figure 2-7) was effective at preventing mixing of contaminated water while designs with the rainwater falling directly into a diverter (from the gutter) were not as effective (Michaelides 1987).

If properly designed, the amount of mixing between the diverted water and the clean water is minimal. One design in use in Kenya does not incorporate a floating ball but rather employs an L-shaped pipe to allow the sediment to collect at the bottom (Figure 2-8). Clear fluid stays at the top while particles settle, minimizing mixing. Note the removable end cap.

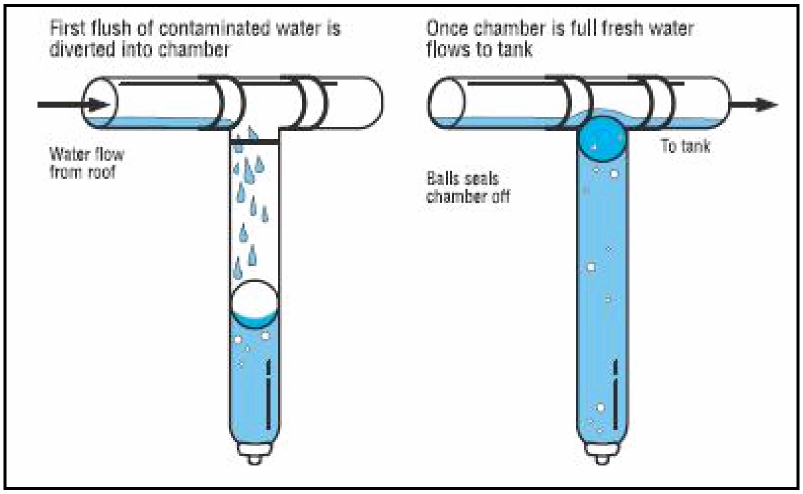


Figure 2-7: First flush diverter with floating ball (Rain Harvesting)

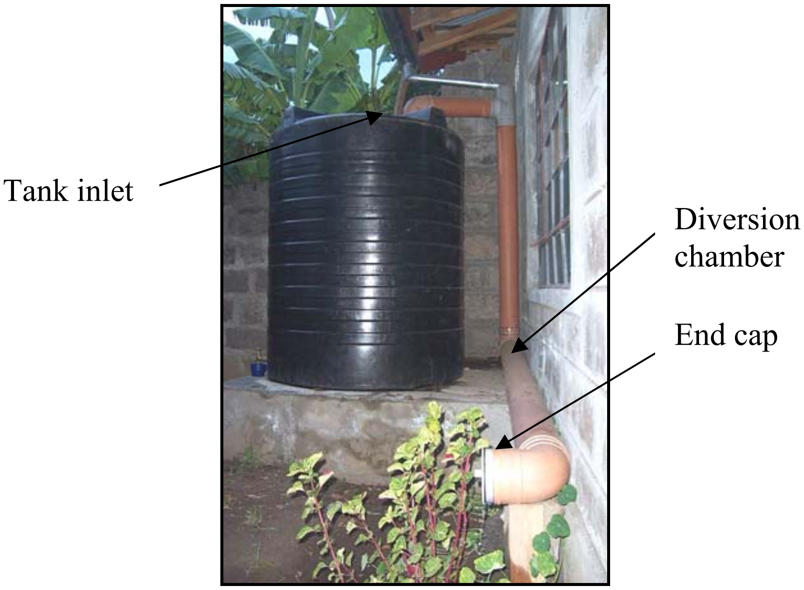


Figure 2-8: First flush design in use in Kenya (Stevenson 2007)

Many variations on pipe diverter designs are available, some of which include a drip valve at the bottom of the pipe; the valve allows water to slowly drip from the pipe, resetting the system for the next rain. Other systems have only a removable cap, requiring the homeowner to empty the pipe after each storm. Even if slow-drip end caps are used, the pipe must still be cleaned out regularly to remove dirt and debris. In both designs, the diverted water can be used for other household purposes such as cleaning and irrigation which do not require potable water.

Particularly for rural areas in developing counties it is important to minimize the number of parts that can be lost, broken, stolen, or misused. While most of the designs involve a removable end cap for the diversion pipe, it is important to ensure that the cap is not lost or misplaced. Without it the water will not be able to reach the tank at all and the system will fail. A chain or similar should connect the cap to the pipe.

Many variations on the constant volume diverter are available, including a tipping-bucket configuration, sometimes referred to as a see-saw diverter. A hose conveys water to a bucket which, once full, tips the see-saw to a position that allows water to flow into the collection tank. These devices are complicated to set up and are prone to breaking, making them less desirable than some of the aforementioned designs. Experience has shown that users often disable these systems because of their complexity (Martinson 2007). One such design of a tipping bucket device is shown in Figure 2-9.

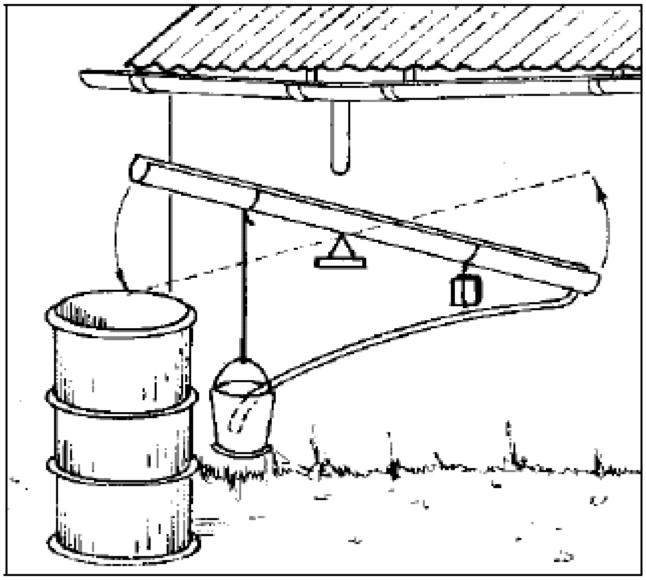


Figure 2-9: See-saw diverter (Martinson 2007)

2.4. Implementation Considerations

2.4.1. Obstacles

Although there are many benefits to community rainwater collection systems, there are also barriers to its use. Many people, rich and poor alike, have a negative image of rainwater (Thomas 2005). During fieldwork in Rwanda, several professionals indicated that rainwater is not potable due to the lack of minerals. Their concerns were based on the taste of rainwater, rather than the health effects. Despite the lack of minerals, rainwater is certainly potable if it is filtered and disinfected before consumption; if the collection system is well maintained the water is potable directly from the storage vessel. Others recognize that rainfall is unreliable during different seasons or on a year-by-year basis—an issue addressed later in this report.

Because of the unreliability of rainfall and tank-size restrictions due to financial constraints, rooftop rainwater harvesting should not be relied on as the sole source of water for a community. There should be alternate sources of water available for periods when the stored rainwater is not sufficient. Potential alternatives include water from protected wells, springs, or individual family reservoirs.

Otherwise good designs can fail when professionals and governments overlook the cultural values of the local people. As quoted by Pacey (1986), "poor villagers...have their own clear perception of basic human needs... Earning enough from employment or land to buy more and better food for the family and to build a more durable house is considered fundamental. Sanitation and even health are not." Before outsiders can come into a region and make recommendations about what technologies should be implemented, or about what changes should be made, the existing culture and society need to be examined and the people themselves asked what they are looking for in a water system.

It is important to consider future water use as a result of system implementation. When computing the initial system size, the community's daily water consumption is one of the main design considerations. Thought must be given to how much water the community will use *after* the tank has been installed. Having clean water held in a tank in close proximity to the house will inevitably lead to increased consumption. Increased consumption could potentially leave the existing problems unresolved; women will still walk to get water, perhaps from unsafe sources (Pacey 1986). Therefore, future consumption should be considered in the original design to allow for a small increase in use and still have enough volume to maintain water levels during the dry seasons. Proper management of community water supplies will ensure that water use rates remain at the appropriate level for the system.

Those who are in the most desperate need for water should not be neglected because of their poverty. Families living in thatched-roof homes or those living in temporary shelters need to be considered even though their housing situations do not easily facilitate the implementation of a rainwater collection system (Pacey 1986). Particularly in community projects equity is a major concern. If a water system is given to one village, but a neighboring village gets none, the unsupplied community may feel cheated, which has the potential to cause hostility between the villages. One method of fairly dividing resources is based on need and community interest. Those villages with the poorest people having the least available water should be considered first *only* if they are interested. Providing water to a village that has no interest in outside technology is futile. Options must be presented along with an explanation of long-term benefits and responsibilities associated with an increase in safe water.

2.4.2. Education and Management

As presented previously, there are many options for catchment system construction; the most significant challenge comes from tank construction. It is particularly important in developing countries to employ local labor, rather than solely rely on outside aid. For this reason, brick and masonry tanks are beneficial to local community dynamic. Even if plastic or metal tanks are installed, local labor can still be used to construct the foundations and install the tanks. It is important to involve the community in all aspects of a collection system, to help them understand the mechanics of the system and the importance of regular maintenance.

Maintenance issues are often overlooked, and broken system components can interrupt water collection. If donors supply the infrastructure and cover the initial costs, serious issues arise when parts of the system break or when periodic maintenance is needed. It can be particularly problematic if the local people are not trained in the operation of their system.

As mentioned previously, it is absolutely necessary that new technologies introduced to a community are appropriate for that specific area. Technologies designed for the developed world cannot be transferred directly to the developing world. It is crucial for the community members to be well-educated in the technology being introduced to their village. In addition to the implementation of a community rainwater harvesting system, an education program must be introduced simultaneously to teach users about water management and water quality. Because the long dry season in Rwanda generally lasts three months, water management is a necessary aspect of a community system. Residents of Bisate Village have access to several different water sources of various qualities. Some sources are unmanaged, such as the main tap in Bisate, others have set hours of operation and are managed by a designated person, still others are kept under lock and key for only specialized uses, such as the health clinic tanks. The current management strategies are an improvement over the former strategy of allowing people to take as much as they wanted until the taps went dry. While it is important that people be able to use water freely, it is more important that the water be managed to ensure supply during periods lacking rain for as many people as possible.

Although not expressly considered in this report, a hygiene system that includes educational programs to teach about the importance of hand washing and latrine use should be continued in Bisate. As of January 2008, some educational programs were in progress related to hygiene and sanitation. For a detailed guide to hygiene improvements, the World Bank's "Handwashing Handbook: A guide for developing a hygiene promotion program to increase handwashing with soap" should be referenced (World Bank undated).

One of the most important aspects of an education program is an understanding of the target audience. For the program to be effective, the social dynamic of the community should be determined, and an appropriate approach be developed (World Bank undated). Education programs are integral to the implementation of a community system and programs in the primary schools are excellent ways to teach the community. The Bisate Health Clinic is also a common gathering place for people in the community. During our fieldwork, short presentations were given to decision-makers in the village about the importance of properly maintaining the water tanks. Those people then disseminated the information to other community members. Adult education programs at the clinic would be a great way to teach people about the appropriate use of community tanks and the need for better hygiene and sanitation.

Based on personal experience with other appropriate water technologies in Kibera, a slum in Nairobi, Kenya, education programs should be engaging and involve colorful figures and visual tools to engage the audience. Visual tools are particularly important for illiterate villagers. The incorporation of traditional song and dance may also encourage community participation.

Community rainwater harvesting is an attractive water-supply option for Bisate, the benefits of which can be maximized by an appropriate management plan and careful design. The implementation of a first flush devise is a low-cost method of improving the quality of water stored in the rain tanks.

CHAPTER 3: Fieldwork

IMVURA IZAGWA RYARI? [When is it going to rain?]
SIMBEZE! [I don't know!]. –The eternal question during fieldwork.

Chapter 3: Fieldwork

3.1. Fieldwork Specifics

3.1.1. Location: Bisate Village, Rwanda

The main focus of this project is Bisate Village in the Northern Province, Musanze district, Kinigi sector of Rwanda. Bisate Village is comprised of two cells, Kaguhu and Bisoke, with a total population of approximately 8,500, broken down by cell in Table 3-1. The village exhibits a very high population density of approximately 300 people per square kilometer. The total area of the village is only 28 square kilometers, the majority of which is agricultural (Nshimyimana 2007a). For comparison, New Jersey, the most densely populated state in the U.S., had a density of 370 people per square kilometer as of the 2000 Census (State of New Jersey Department of Labor and Workforce Development 2007).

Table 3-1: Population breakdown of Bisate Village (Nshimyimana 2007a)

Names of Cells	Number of people	Number of households
Kaguhu	4,664	1,048
Bisoke	3,700	812
Total for Bisate Village	**8,364**	**1,860**

One of the main fieldwork goals of 2007 was to understand the existing water conditions in the village to develop a plan for water supply. Bisate is a rural village that sits at the base of Bisoke volcano. Figure 3-1 is a map of the Northern Province with Musanze District and all of its sectors marked; Bisate Village is also labeled.

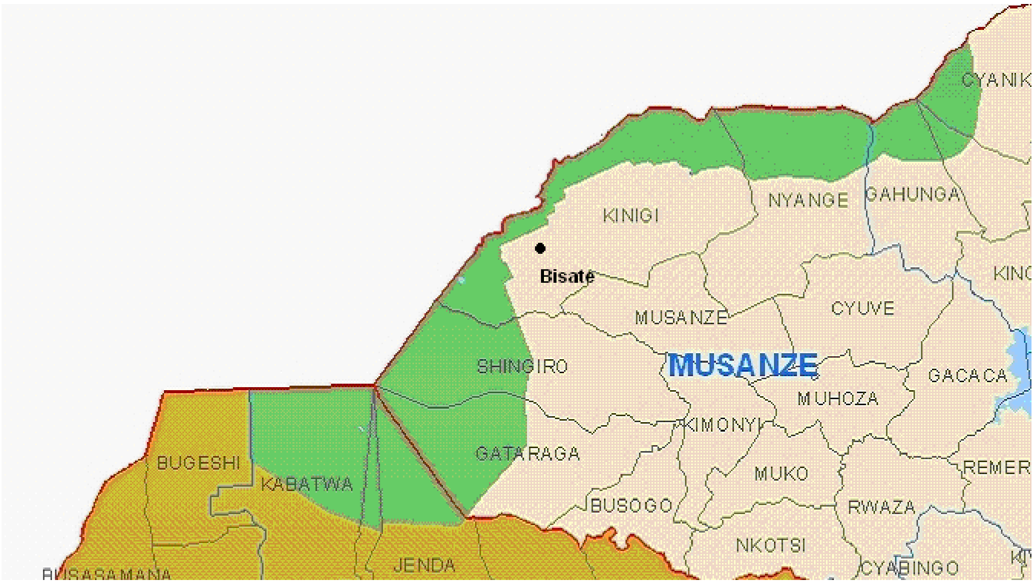


Figure 3-1: Cells of Musanze District, Northern Province (Ildephonse 2006)

The village is comprised of a small town center with approximately fifty small buildings used to buy and sell goods. There is a large primary school near the center of town that serves approximately 1,700 students. The Bisate health clinic is centrally located and is comprised of two main buildings. A new pavilion and roof structure for the rain tanks were constructed in 2007. Figure 3-2 shows the clinic in 2008.

Figure 3-2: Bisate health clinic

3.1.2. 2006-2007 Fieldwork Team

Fieldwork in January 2007 was completed by a team of three engineers: Ms. Kelly Doyle, Ms. Daria Cresti, and Ms. Christian Zoghbi with the supervision of Dr. Peter Shanahan and assistance from Mr. Jean Pierre Nshimyimana. Temporary field assistance was given by Ms. Katie Shanahan. The group is pictured in Figure 3-3. The reader is referred to the individual theses (Cresti 2007; Zoghbi 2007) or group report (Cresti et al. 2007) produced by the team members for additional information.

Figure 3-3: 2007 Team: (L to R) Dr. Peter Shanahan, Kelly Doyle, Jean Pierre Nshimyimana, Christian Zoghbi, Daria Cresti, Katie Shanahan

3.1.3. 2007-2008 Fieldwork Team

The majority of the field data presented in this chapter were collected in late December 2007 and January 2008 by Ms. Kelly Doyle, Mr. Bernard Isaacson, and Mr. Jean Pierre Nshimyimana, with U.S.-based supervision from Dr. Peter Shanahan. Preparatory work in the U.S. was assisted by two MIT undergraduate students, Ms. Yan Huang and Mr. Charles Agoos. The Rwanda field team is pictured in Figure 3-4.

Figure 3-4: 2007-2008 Fieldwork Team (L to R): Kelly Doyle, Jean Pierre Nshimyimana, Bernard Isaacson

3.2. Methods: Water Testing

In order to understand the current water situation in Bisate, the existing rainwater collection tanks and natural sources were visually surveyed and water samples drawn. The team completed basic water tests as a general measure of the water quality of the existing supply. The water was generally found to be contaminated with total coliform, some *E. coli*, and high levels of suspended solids (measured as turbidity) as would be expected with untreated water. The water test methods used in 2007 include 3M Petrifilm for microbiological testing, test strips for hardness, alkalinity, and pH, and nephelometer readings for turbidity. Based on the results of the 2007 fieldwork, the water tests were modified for 2008 work to include more accurate pH and conductivity measurements, microbiological enumeration by membrane filtration, and color quantification; hardness and alkalinity were not measured in 2008.

Samples collected in 2008 followed the Standard Methods procedure as accurately as possible given the field conditions (Eaton 2005). Samples were tested for total coliform and *E. coli* using the membrane filtration method and m-coliBlue 24 broth; turbidity, pH, conductivity, and color were also measured for each water sample. Duplicates, blanks, and standards were used as a means of quality assurance and quality control.

3.2.1. Sample Preparation and Storage

Following Standard Methods section 9060 (Eaton 2005), samples should be collected in non-reactive, sterile bottles that have been rinsed with distilled or de-ionized water. All water samples were collected in either pre-sterilized one-time-use Whirl-pak bags or locally obtained plastic water bottles. For lack of available resources, the bottles were reused and cleaned with a household bleach dilution (125mL bleach per 5L water). The bottles and caps were first pre-rinsed with tap water to remove particulate matter, thoroughly rinsed via shaking with the bleach solution and then vigorously rinsed with sterilized water to remove excess bleach. Water was removed from the bottle by rapid movement while the bottle was upside-down; it was then capped immediately and stored upright in a box. During each rinse cycle the bottles were capped loosely and the water was allowed to spill over the threads.

As per Standard Methods 9060 B (Eaton 2005), samples were stored in a cooler with ice packs for transport when possible. Samples were run as soon as possible but no longer than three hours after collection. Samples not being tested immediately were stored in the refrigerator.

3.2.2. Significance of Microbial Testing

According to the World Health Organization (WHO 2004) "Infectious diseases caused by pathogenic bacteria, viruses, protozoa and helminthes are the most common and widespread health risk associated with drinking water." The presence of coliform in drinking water does not absolutely guarantee that pathogenic organisms are contaminating the water. Instead, coliform and *E. coli* are indicator organisms; their presence suggests that fecal matter and pathogenic bacteria are likely in the water.

There are four main classifications of water-related diseases based on the type of transmission: water-borne, water-washed, water-based, and insect-vector (House et al. 2004). Water-borne are those diseases transmitted by the direct consumption of contaminated food or drink. Cholera is one such water-borne disease that causes severe diarrhea often leading to death, particularly in children.

Although everyone in a population is affected by contaminated water supplies, children under five years are the most vulnerable to water related diseases, particularly diarrhea. The most common method of disease transmission is through the fecal-oral route, illustrated in Figure 3-5. As depicted, when diseased hosts defecate, the fecal matter is transmitted to a new host via water, unwashed hands, insects or direct contact, and subsequently ingested through contaminated water, direct person-to-person contact or via food preparation and consumption. There are a variety of water-borne pathogens that affect the quality of life of those afflicted. A partial list of waterborne pathogens and their significance in water supplies is provided in Table 3-2 (WHO 2004).

The second classification is water-washed or water-scarce diseases, which primarily occur due to insufficient washing often resulting from water shortages. The transmission of these diseases can be reduced by increasing the volume of water available to the affected person, both to increase their daily water intake, and to improve their sanitation and hygiene practices. Amoebic dysentery, trachoma (eye infection), and scabies are all examples of water-washed diseases.

Water-based diseases result from contact with water containing parasitic organisms such as guinea worm or schistosomiasis. The last classification is insect-vector diseases that are transmitted by an insect that breeds or bites near water; these include malaria and river blindness (House et al. 2004). The latter two classifications of disease are less of a concern in Bisate Village than water-borne and water-washed; guinea worm is not present in Rwanda and malaria is not a strong concern because the cool climate is not suitable for malaria-transmitting mosquitoes.

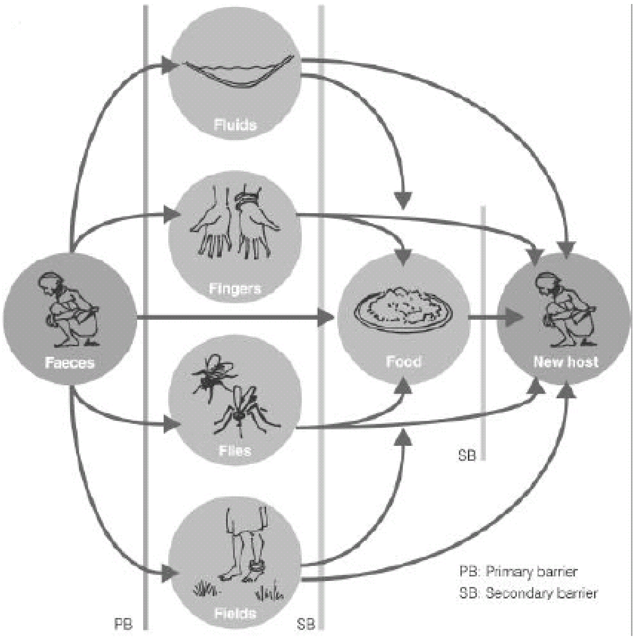


Figure 3-5: Fecal Oral Route ***(Howard and Bartram 2003)***

Table 3-2: Waterborne pathogens and their significance in water supplies (WHO 2004)

Pathogen	Health significance	Persistence in water supplies[a]	Resistance to chlorine[b]	Relative infectivity[c]	Important animal source
Bacteria					
Burkholderia pseudomallei	Low	May multiply	Low	Low	No
Campylobacter jejuni, C. coli	High	Moderate	Low	Moderate	Yes
Escherichia coli – Pathogenic[d]	High	Moderate	Low	Low	Yes
E. coli – Enterohaemorrhagic	High	Moderate	Low	High	Yes
Legionella spp.	High	Multiply	Low	Moderate	No
Non-tuberculous mycobacteria	Low	Multiply	High	Low	No
Pseudomonas aeruginosa[e]	Moderate	May multiply	Moderate	Low	No
Salmonella typhi	High	Moderate	Low	Low	No
Other salmonellae	High	May multiply	Low	Low	Yes
Shigella spp.	High	Short	Low	Moderate	No
Vibrio cholerae	High	Short	Low	Low	No
Yersinia enterocolitica	High	Long	Low	Low	Yes

WHO sets its guideline level for thermotolerant coliform (*E. coli*) at zero colonies per 100 mL sample. It is not always feasible for a developing region to achieve such a stringent threshold so a thermotolerant coliform guide was originally created by Ockwell in 1986 for emergency situations and adapted by Waterlines (2004) in Table 3-3.

Table 3-3: Thermotolerant Coliform (*E. coli*) Guide *(House et al. 2004)*

Level of fecal pollution (*E. coli* colonies per 100 mL sample)	Inference
1 – 10	Reasonable Quality
10 – 100	Polluted
100 – 1,000	Dangerous
> 1,000	Very Dangerous

3.2.3. Membrane Filtration

Water samples were tested for microbial contamination using the membrane filtration (MF) method, a common method used to enumerate indicator organisms of fecal bacteria. The Hach Company produces m-ColiBlue 24 broth, capable of growing and distinguishing total coliform and *E. coli* colonies on the same Petri dish. Testing procedure followed Standard Methods section 9222 (Eaton 2005); lack of a high-end laboratory space necessitated the use of boiled tap water in place of distilled or de-ionized water in all tests.

A Millipore metal filter stand was used in conjunction with sterile disposable filter cups and a 140cc. syringe to strain the water sample through 45µm filter paper (see Figure 3-6 for MF setup). The filter stand was sterilized by flaming for 3-5 seconds with a standard lighter; all other laboratory equipment was sterilized with 95% isopropyl alcohol after each sample; beakers and graduated cylinders were then rinsed twice with sterilized water to remove the alcohol residue. Duplicates, blanks, and dilutions were run each day for quality control. Samples were placed in Petri dishes bacteria-side down in a 35ºC incubator for 24 hours ±2 hours. Power failures required improvisation to keep the incubator at the appropriate temperature; the temperature did not fluctuate more than ±3º from the set level.

Figure 3-6: Membrane Filtration Equipment

Colonies were counted 24 hours after placement in the incubator by two different analysts and the numbers compared for accuracy. If the counts varied by more than 10% the colonies were recounted; if they varied by less than 10%, the average was used. All results were converted to units of colonies per 100 mL sample based on Standard Methods section 9222 B (Eaton 2005).

As per section 6 of Standard Methods 9222 B, coliform density was calculated using:

Equation 3-1

$$TotalColiforms/100mL = \frac{coliform\_colonies\_counted * 100}{mL\_sample\_filtered}$$

If no colonies were observed, results are reported based on the sample dilution. Raw water samples without colonies are reported as "<1 colonies per 100 mL" while 1:100 dilutions are reported as "<100 colonies per 100 mL." For plotting, results with no observed colonies were entered as 1. Samples that did not have the target range of 20 to 200 colonies per Petri dish were reported based on Part b of Section 6 of Standard Methods 9222 B (Eaton 2005) which uses a weighted average to report results as colonies per 100 mL. Samples with greater than 200 colonies per dish are officially considered as too numerous to count (TNTC), but the colonies were counted and reported anyway, to provide an approximate colony quantification for scale comparison.

3.2.4. Turbidity

According to the U.S. Environmental Protection Agency (EPA) (2008):

> Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness. Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.

Turbidity is quantified by measuring the amount of light passing through a sample and comparing it to a standard scale of Nephelometric turbidity units. Turbidity is often used as a surrogate for total suspended solids (TSS) and is a common water quality parameter (Davis-Colley and Smith 2001). Turbid drinking water is problematic for a variety of reasons. Bacteria can attach themselves to the sediment particles, creating breeding grounds for disease-causing organisms. Additionally, if the water is treated using chlorination, the particles in the water can inhibit the efficacy of the chlorine while at the same time producing chlorine byproducts known as trihalomethanes which have been under scrutiny for many years as a potential carcinogen (Gilkey and Williams 1998). The U.S. Environmental Protection Agency regulates the quantities of disinfection byproducts allowed in the drinking water supply partly through regulation of turbidity. Turbidity may never exceed 5 NTU, and as of 2002 it must be below 1 NTU and be less than 0.3 NTU in 95% of daily samples in a month (U.S. Environmental Protection Agency (EPA) 2008).

A LaMotte 2020e turbidity meter (Figure 3-7) measured turbidity of all samples and reported results in nephelometric turbidity units (NTUs). The meter was calibrated with a supplied blank, and 0.1 NTU, 1.0 NTU, and 10 NTU standards each day. All calibration runs were within 5% of the standard value. The unit was set to average two readings per sample, which reduces error from settling particles.

Figure 3-7: Turbidimeter setup

3.2.5. Conductivity

Just as turbidity is taken as a surrogate for total suspended solids, conductivity is a metric for total dissolved solids (TDS). Regulated by the EPA under the secondary drinking water standards, high or low levels of TDS do not pose a health threat to consumers of the water, but are regulated because of their aesthetic properties. The EPA sets the upper limit for TDS at 500 mg/L (USEPA 2008). Conductivity is a measure of the electrical charge that can pass through the water. Groundwater tends to have a much higher conductivity than rainwater since it has dissolved minerals from the ground. Rainwater typically has very low conductivity because it has very little contact with mineral-rich surfaces. Stored rainwater with high conductivity likely acquired its dissolved ions from the collection surface and/or storage tank.

Water low in dissolved minerals may taste bland to a user accustomed to drinking spring or well water. From personal conversations in Rwanda, some local officials are concerned that rainwater does not provide the users with the necessary minerals that they require, yet local villagers explained that they were willing to drink the rainwater in the absence of better alternatives.

For field testing, a Hanna Model HI9812 pH/EC/TDS meter was used to measure pH and electrical conductivity (EC) (Figure 3-8). The unit was calibrated using the supplied solutions. The probe was rinsed with sterilized water after each use and submerged into the water sample. To obtain an accurate reading the probe was swirled in the sample until a constant value displayed on the screen. Conductivity and pH values were recorded in succession for each sample.

3.2.6. pH

The U.S. Environmental Protection Agency regulates pH levels with secondary standards, indicating that high or low levels do not pose a health threat, but may cause corrosion and staining in pipes (EPA 2006). pH is a measure of hydrogen ion concentration in the water. The scale for pH ranges from 1 to 14, where pH = 7 is neutral. The standards are set between 6.5 and 8.5. Water with a pH lower than 6.5 (acidic) might have a bitter metallic taste and cause corrosion; water with pH greater than 8.5 (basic) may have a slippery feel, soda taste and leave deposits (EPA 2006). pH levels were measured in this study to gain a better understanding of the water chemistry using the same meter as for conductivity, shown in Figure 3-8.

Figure 3-8: pH/conductivity meter

3.2.7. Color

The U.S. EPA mandates that color be kept lower than 15 color units, regulated as a secondary drinking water standard. According to the EPA, high color counts in water are an aesthetic concern for end users instead of a health concern, but may be indicative of dissolved organic material, inorganic contaminants, and high disinfectant demand (USEPA 2006). In the U.S., users typically complain about the water color when it reaches a level of 5-30 color units (USEPA 2006). Samples in Rwanda were measured for color as an additional water quality indicator using a Hach Apha-Platinum-Cobalt Standard color wheel (0-100 units). Laboratory sterilized water was used as the "zero" to compare to other water samples. The color wheel is shown in Figure 3-9 with a close-up of the color scale. Some of the samples had different shades of color than those on the wheel; these samples were given the closest value.

Figure 3-9: Color wheel

3.2.8. Total Hardness, Total Alkalinity, and pH Test Strips

As a general analysis of water quality, Hach 5-in-1 test strips (Product # 27552-50) were employed to measure the total hardness, total alkalinity and pH of water samples. The strips are very easy to use; the strip is dipped into the water sample for one second, removed and held horizontally for 30 seconds. The indicators on the strip change color reflecting the water chemistry. To get a concentration reading, the indicator colors are compared to the color chart supplied on the bottle.

The color scales supplied on each bottle convert a qualitative color into a quantitative measurement. Unfortunately, the supplied color charts are not very precise. Colors must often be interpolated and results may vary from person-to-person. Consequently, the results of the Hach test strips are meant only as a general indication of water quality.

3.2.8.1. Total Hardness

Water hardness is related to the concentration of multivalent cations dissolved in the water (Wilkes University undated). Hard water is characterized by high levels of dissolved calcium and magnesium. Because water often becomes harder as it dissolves minerals in the ground, hardness was sampled in order to differentiate waters of different geologic or hydrologic origin (Zoghbi 2007). Results are reported in parts per million (ppm) as $CaCO_3$.

In the U.S. there are no primary or secondary drinking water standards for hardness, but a classification scale for hardness has been adopted by the U.S. Department of the Interior and is provided in Table 3-4.

Table 3-4: Hardness Scale *(Wilkes University undated)*

Classification	mg/L (ppm)
Soft	0 – 17
Slightly hard	17 – 60
Moderately hard	60 – 120
Hard	120 -180
Very hard	> 180

3.2.8.2. Total Alkalinity

Alkalinity is a measure of water's ability to neutralize acids and is measured as the amount of bicarbonate in a water sample. Bicarbonate is the major anion in water and alkalinity is related to pH and corrosion. Typically alkalinity levels are similar to hardness levels because of their relationship to calcium carbonate. Large differences in hardness and alkalinity levels of the same sample could result from high sodium, chloride, nitrate, or sulfate concentrations (U. of Wisconsin undated). Similar to hardness, there are no indications in the literature that alkalinity has any adverse health consequences, but it was also used to evaluate the origin of different waters.

3.3. Methods: First Flush Capture

The main goals of the 2008 fieldwork were to understand the first flush phenomenon as it relates to the site location and storm characteristics and to quantify the first flush to provide recommendations for water quality improvements in the areas practicing rooftop rainwater harvesting. In order to better understand the phenomenon, rainwater samples were collected sequentially, separating the first few millimeters of first flush water from the remaining storm runoff. Each sample in the series was tested for microbial contamination, turbidity, pH, conductivity, and color to understand how the quality improved with depth of runoff.

Theoretically, the wash-off process associated with the first flush should cause exponentially decreasing concentrations of contaminants. To test the efficacy of the wash-off process, a plot was generated of normalized contaminant concentration (quantified as cumulative contaminant reduction) versus volume flushed. Based on the results, recommendations were made for an appropriate depth of runoff to be diverted from the main tank.

3.3.1. The GIZMOs

Based on the work of (Martinson and Thomas 2005), several bottle arrays were constructed to collect rainwater from a small section of roof. I describe the collection apparatus as a Graduated Inflow-collector for Zero Mixing with Overflow, or hereafter "GIZMO."

Originally four GIZMOs were constructed, each with a four-bottle array capable of holding either 0.56-liter or 1.5-liter bottles. In the field they were modified into three units, one of which had eight places for bottles. The basic concept is simple: prior to the rain event the bottles are clean and empty; the first rain that falls on the roof, presumed to be the most contaminated, fills the first bottle. Once the first bottle is full, the water bypasses it and continues into the second bottle in the series, and so on. When all the bottles are full, the rest of the runoff spills out the end, which theoretically represents the storage tank.

All GIZMOs were constructed from ¾" PVC piping using 90º elbows, tee joints, and threaded male adaptors. All threaded connections were wrapped with Teflon tape to prevent leaks; corner connections were affixed with PVC glue; tee connections were not glued, allowing for disassembly. The entire array was installed on a slope, with the overflow end more elevated than the first bottle; this prevented heavy rain from washing water into a bottle before the preceding one was full. Yaziz et al. (1989) recommend a 5% slope, but this recommendation was often not followed in the field due to construction constraints.

A total of three arrays were installed in Bisate Village: one at the local health clinic (CL array), one on a local house (HS array), and a third on a building used to store potatoes (PT array). Each location was selected for its site characteristics and assigned a two-letter abbreviation for labeling use. Descriptions of each site and the reasons for selection follow. The GPS points for each sampling location are in Appendix B.

3.3.1.1. Clinic Array-CL

One array was assembled at the health clinic, on a new iron roof approximately two meters away from the main dirt road (Figure 3-10). There were several tall bushes near the structure, between the road and the roof, but no overhanging trees. The roof area which collected water was 3.4 m^2. The setup consisted of four bottles, originally all 0.56-L in volume. After the first two storms the array was changed to include two 1.5-L bottles followed by two 0.56-L bottles in order to capture more of the first flush. The first arrangement captured 0.66 mm of runoff while the final setup captured 1.34 mm of runoff.

Figure 3-10: CL array on new iron roof

3.3.1.2. House Array-HS

A second GIZMO was installed on the roof of a local store/home in the commercial section of the village near the clinic (Figure 3-11). There were dirt roads in close proximity to the building, but none that were used by vehicles, only pedestrians. The roof was approximately 8.5 meters from crest to gutter, thus a very short length of gutter was used to assure the capture of an appropriate volume of water. The HS-GIZMO was equipped with eight bottles; two 1.5-L bottles and six 0.56-L bottles; the system collected a total depth of 1.45 mm of runoff. The GIZMO was so long that the pipe had a slight bend in it, which may have contributed to unexpected turbidity values, discussed later in this chapter.

Figure 3-11: HS array on rusty iron roof

3.3.1.3. Potato-storage house Array-PT

The third GIZMO (Figure 3-12) was installed at the potato-storage house, 1.3 kilometers from the health clinic, down-slope from the volcanoes. The roof was made of old clay tiles and was approximately 10 meters from the main roadway. The building beneath the roof was constructed of wooden slats and was used to store potatoes before planting. The area collecting water was 1.58 m^2, capturing a total runoff depth of 1.61 mm.

Because of the localized weather patterns, even though only 1.3 km apart, weather differed slightly between the clinic and the potato-storage house. On several occasions the CL and HS locations received rain and the PT location did not. Considering that runoff is a function of the roof type it is also possible that some of the rain that fell on the clay roof was absorbed by the clay, leaked into cracks in the roof, or collected in small depressions on the roof and evaporated.

Figure 3-12: PT array on old clay-tile roof

3.3.2. Sample Collection Methodology

The main goal of the first flush fieldwork was to understand how water quality changes as a storm progresses. The bottle arrays allow analysis of discrete volumes of runoff as the storm passes. The GIZMOs were installed during fair weather; the last rainfall was 4.5 days before the first collected storm and the last storm greater than 1.5 mm had been 9.5 days earlier.

The antecedent dry weather period (ADWP) is one factor in the magnitude of the first flush. It is believed that the longer the dry weather before a storm, the more dust and dirt will accumulate on the roof and thus the greater the flushing effect from the rain. Field and travel conditions prohibited use of an electronic rain gauge capable of taking small, incremental readings, so a standard plastic rain gauge was used to collect rainfall data (Figure 3-13). The gauge was already in place at the DFGFI Trackers' house and the trackers record the rainfall depth at 6 am and 6 pm everyday. Since rainfall was measured only every 12 hours, it was not possible to measure the intensity of each rain event, but the total depth of each storm was determined from the rainfall data and matched with samples collected that day. Samples were typically collected around 10:00 am, so any precipitation after collection time was considered part of the following storm. For collection purposes, the storms were numbered sequentially; the storm number, date, total rain depth, and ADWP are listed in Table 3-5. The 12-hour rainfall values for January 2008 are in Appendix D.

Figure 3-13: Rain gauge at trackers' house

Table 3-5: Storm characteristics

Storm #	Date of sample collection	Total storm depth (mm)	Antecedent Dry Weather Period (days)
S1	01/06/2008	6.0	4.5
S2	01/07/2008	1.2	0.5
S3	01/09/2008	25.8	1.5
S4	01/13/2008	9.8	3.0
S5	01/14/2008	4.6	0.5
S6	01/16/2008	12.9	0.5

3.4. Results: Fieldwork 2007: Water Supply

3.4.1. Existing Water Sources

3.4.1.1. Tank Descriptions and Locations

The following is a list with some of the rainwater tanks used in Bisate Village. Water supply analysis was completed in January 2007, but significant changes were made between then and our subsequent visit in January 2008; descriptions reflect the January 2008 configuration. For a list of the newest improvements to the village, see the supplemental reading in Appendix A. The GPS locations are found in Appendix B.

	**System Description:** – Painted metal tank – Corrugated metal roof (new) – Metal gutters – Storage capacity ~10 m^3 – Matching ~10 m^3 tank on adjacent school building – Two new 10 m^3 tanks were added – (When observed in January 2008, the gutter to one old tank was no longer functional)

Figure 3-14: Metal tank at primary school (photograph by D. Cresti)

	**System Description:** – Masonry tank – Reinforced concrete cover – Corrugated metal roof (new) – Plastic gutters – Storage capacity ~40 m^3 – Collects water from ~218 m^2 (half of the roof) – (When observed in January 2008, the downspout was no longer functional)

Figure 3-15: Masonry tank at Catholic Church

System Description:

- Brick tank
- Uncovered opening in cover
- Asbestos roof (old)
- Plastic gutters
- Storage capacity ~6 m^3
- Collects water from roof and from Bushokoro source

Figure 3-16: Brick tank at clinic director's house

System Description:

- Plastic tank
- Partially covered opening in top
- Corrugated metal roof (old)
- Plastic gutters
- Storage capacity ~1 m^3
- Outlet spigot in disuse or broken

Figure 3-17: Plastic tank at ORTPN trackers' house

System Description:

- Metal tank
- Corrugated metal roof (old)
- Plastic gutters
- Storage capacity ~0.8 m^3
- Water not consumed because of quality concerns
- Tank had been removed as of January 2008

Figure 3-18: Metal tank at DFGFI trackers' house (photograph by D. Cresti)

3.4.1.2. Bushokoro Water Supply

Bushokoro is a forest spring that supplies water to Bisate Village via buried pipes and gravity flow. As of January 2008 the source was unprotected in the forest and open to contamination by animals and people.

	**System Description:** – Water from surface water or shallow perched spring – Three semi-covered concrete chambers collect water

Figure 3-19: Water source at Bushokoro

	**System Description:** – Removable chamber covers – Unprotected system – Evidence of human and animal traffic

Figure 3-20: Inside of Bushokoro collection chamber

	**System Description**: – Holding tank with concrete cap and manhole cover – Concrete overflow box – Unprotected area – Evidence of human and animal traffic

Figure 3-21: Second holding tank for Bushokoro water in the forest

	**System Description:** – Masonry tank – Locked maintenance hatch – Nearby public tap serves >1,000 people – Collects water from Bushokoro – Supplies water to Bisate tap

Figure 3-22: Large masonry holding tank outside forest

	**System Description:** – No management plan – Broken spigot – Water flows at constant rate of ~11 m^3/day – Runs dry after several days without precipitation – New spigot and foundation in place as of January 2008

Figure 3-23: Tap in Bisate (photograph by D. Cresti)

3.4.2. Microbial and Turbidity Tests on Current Water Supply

Existing rainwater tanks in Bisate Village were sampled in 2007 and tested for a variety of water quality parameters, as previously discussed. The results from the existing rainwater tanks are presented in Table 3-6. Although there is some inherent inaccuracy in the turbidimeter, all values are reported with three significant figures (when available) recognizing that the values can vary ± 2%. Samples with no colonies detected are reported as <100 colonies per 100 mL based on the 1 mL sample-size used in the Petrifilm test.

One control sample was taken from a private tap in Musanze (Laura Clauson's house). The water there is supplied by Electrogaz, the supplier of piped water in Rwanda. There was no microbial contamination present and turbidity was 0.45 NTU.

Table 3-6: Water Quality Results- Existing Rainwater Tanks

	Coliform (colonies/100mL)	***E. coli* (colonies/100mL)**	**Turbidity (NTU)**
WHO Standard	***0***	***0***	***<5 for chlorination***
Primary School (large metal)	**100**	<100	3.96
Catholic Church (stone)	<100	<100	1.55
Director's House (brick)	**700**	<100	1.01
ORTPN Trackers' House (plastic)	**200**	<100	**8.96**
DFGFI Trackers' House (small metal)	**800**	<100	**5.23**
*****Samples that exceed the WHO standard are shown in bold type			

Since none of the water entering the rainwater tanks is diverted to a first flush device, filtered, or disinfected prior to consumption, it is not surprising that most of the samples had coliform contamination. By the time of sampling, the DFGFI trackers had already ceased drinking the water from their small metal tank because of concerns about quality. It appeared unlikely that the roof or gutters had been cleaned since the tank was installed.

The ORTPN Trackers' tank in January 2007 was a small plastic one, shown in Figure 3-17. It was fitted with a cover, but the cover was broken and only partially shielded the opening. As a result of overuse, inefficient gutters, or lack of rain, the tank was almost empty at the time it was sampled and had substantial sediment buildup at the bottom. The sample was collected by a local man who sat on the edge of the tank and dipped the sample bottle into the remaining water. The water level was below the spigot, so his extraction method demonstrated how water is typically retrieved from the tank. Based on the condition of the cover, it appeared that the spigot was not typically used, even when the tank was full.

Both the primary school (Figure 3-14) and Catholic Church (Figure 3-15) yielded relatively clean water samples. Both of these buildings had new iron roofs that were set back from the main dirt road and did not have trees nearby, explaining the better quality water collected from their roofs. Although the sample results indicate that the water from the church roof was free of microbial contamination, it is still recommended that the water be treated prior to consumption since water quality can vary over time.

There were several samples taken from the system of the clinic director, shown in Figure 3-16. The results, presented in Table 3-7, indicate that the tank contamination likely came from both the old asbestos roof and contamination in the Bushokoro water supply line. The presence of *E. coli* in the overflow pipe, but not in the roof sample or tank samples, emphasized the variability of the water quality. Rainwater tanks were generally sampled only once, so the quality of the water in the tank on one particular day was not necessarily indicative of the typical water quality. Additionally, the Petrifilm testing method used only one milliliter of water, which may not have been an accurate representation of the entire tank volume. This limitation was particularly applicable to samples taken from rain storage tanks that were not actively being filled. The water within the tank was likely stratified and the microbial contamination may not have been uniform throughout the entire volume.

Table 3-7: Water Quality Results-Clinic Director's House

	Total Coliform (colonies/100mL)	***E. coli* (colonies/100mL)**	**Turbidity (NTU)**
WHO Standard	***0***	***0***	***<5 for chlorination***
Director's House-brick$_1$	**700**	<100	1.01
Director's House-brick$_2$	**800**	<100	NA
Director's House-overflow pipe	**700**	**300**	3.19
Director's House-direct roof runoff	**400**	<100	**33.8**
Clinic Roof-direct roof runoff	<100	<100	**23.1**
*****Samples that exceed the WHO standard are shown in bold type			

Results from the Bushokoro water system originating in Volcanoes National Park (VNP) are presented in Table 3-8. As discussed in section 3.4.1.2., the water is drawn from a source in the forest, flows through a holding tank in the forest (not sampled) into another holding tank with a tap, to finally end at the Bisate tap. Since the source in the park is unprotected, it was expected that bacterial contamination would be present. *E. coli* was not detected in any of the samples and turbidity levels were low, but the high coliform count at the forest source was high, as expected. It is important to note that the samples were not all collected on the same day. Bisate tap, the holding tank, and the holding tank tap were all collected on January 8, 2007, while Bushokoro Source was sampled on January 11. However, the microbial contamination could have varied by day, depending on weather conditions or animal visitors to the source, so it is possible that either the low values for the tanks or the high value at the source were not indicative of the typical coliform count.

Table 3-8: Water Quality Results-VNP Water Sources

	Total Coliform (colonies/100mL)	*E. coli* (colonies/100mL)	Turbidity (NTU)
WHO Standard	***0***	***0***	***<5 for chlorination***
Bushokoro Source	**2200**	<100	2.06
Tap at Holding Tank	**300**	<100	4.22
Holding Tank	**300**	<100	2.34
Bisate Tap	**300**	<100	1.09
Bunyenyeri Holding Tank	<100	<100	0.23
Bunyenyeri Tap	**600**	<100	0.35
***Samples that exceed the WHO standard are shown in bold type**			

Included in Table 3-8 are the results from the Bunyenyeri supply, which is another water source in the forest. Similar to Bushokoro, the water from the forest is piped to a large holding tank on a hill, which then feeds into another pipe terminating at a tap. The Bunyenyeri tap is controlled by a valve, although it is unclear who manages the supply. During personal communication in the village several people expressed their preference for Bunyenyeri water, recognizing its superior water quality over other water in the area. Since no colonies were found in the Bunyenyeri holding tank water, the coliform contamination at the Bunyenyeri tap was likely from unclean hands touching the tap. During sample collection, local girls were observed putting their mouths on the tap spout and sucking to draw some of the water from the pipe (Figure 3-24). It was not obvious how the water at the tap was managed at the time of this report, but it is evident that a more effective strategy is needed.

Figure 3-24: Girl draws water from Bunyenyeri tap (photograph by D. Cresti)

The results of the biological tests on the Bushokoro and Bunyenyeri supplies indicate the presence of bacteria in the stored water supplies. Some duplicate samples were run on selected locations, but no duplicates were run from the same location on the same day. Results from duplicate samples run on different days on the same source had a range no greater than 600 colonies/100mL, which as noted above reflects variability of the quality of the water source. Three duplicate turbidity tests were run from the same sample locations on the same day. The difference in values was no higher than 30% of the largest value.

3.4.3. Hardness, Alkalinity and pH Tests on Current Water Supply

All of the sampled rainwater collection tanks exhibited acceptable levels of hardness, alkalinity, and pH. The hardness in all tanks ranged from 30 to 50 parts per million (ppm) as $CaCO_3$ which is in the range of "slightly hard" as classified in Table 3-4.

Samples taken from several springs far from Bisate (Mpenge, Amakera, Kigome and Irwaniro) had very hard water (425 ppm), which was expected, as water traveling through underground springs tends to dissolve minerals, increasing hardness. Although the hardness levels were high, there are no known health concerns related to high levels. Similar to the rainwater collected, the forest sources supplying water to Bisate (Bushokoro and Bunyenyeri) had hardness levels between 30 and 80 ppm, which indicated that the water is coming from either shallow perched springs or surface water, rather than from deep groundwater.

The U.S. EPA lists pH as a secondary drinking water standard with the preferred range between 6.5 and 8.5 (USEPA 2006). All samples taken from tanks and groundwater sources yielded pH values within the EPA suggested range.

3.5. Results: Fieldwork 2008: First Flush Water Quality

Tables of coliform, *E. coli*, turbidity, and conductivity values for each site and storm are found in Appendix C.

3.5.1. Microbial Testing

3.5.1.1. Total Coliform

Coliform results are reported as colonies per 100 mL of sample. Microbial data are plotted on a semi-log scale because the results span many orders of magnitude. Unlike the turbidity and other water quality data discussed below, most of the coliform counts do not exhibit clear exponential decay trends and thus trendlines were not applied. Samples without enumerable colonies are plotted with a base value of 1 colony/ 100 mL regardless of the dilution on that sample. Coliform results are plotted in Figure 3-25, Figure 3-26, and Figure 3-27.

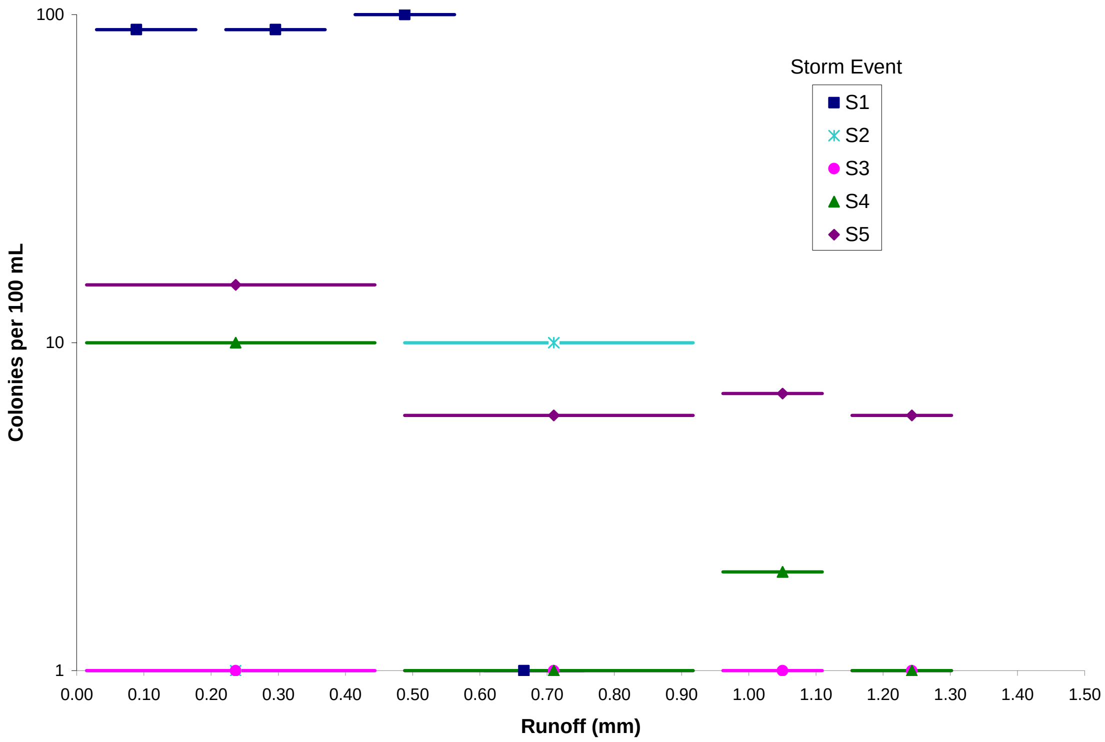


Figure 3-25: Total Coliform results for CL

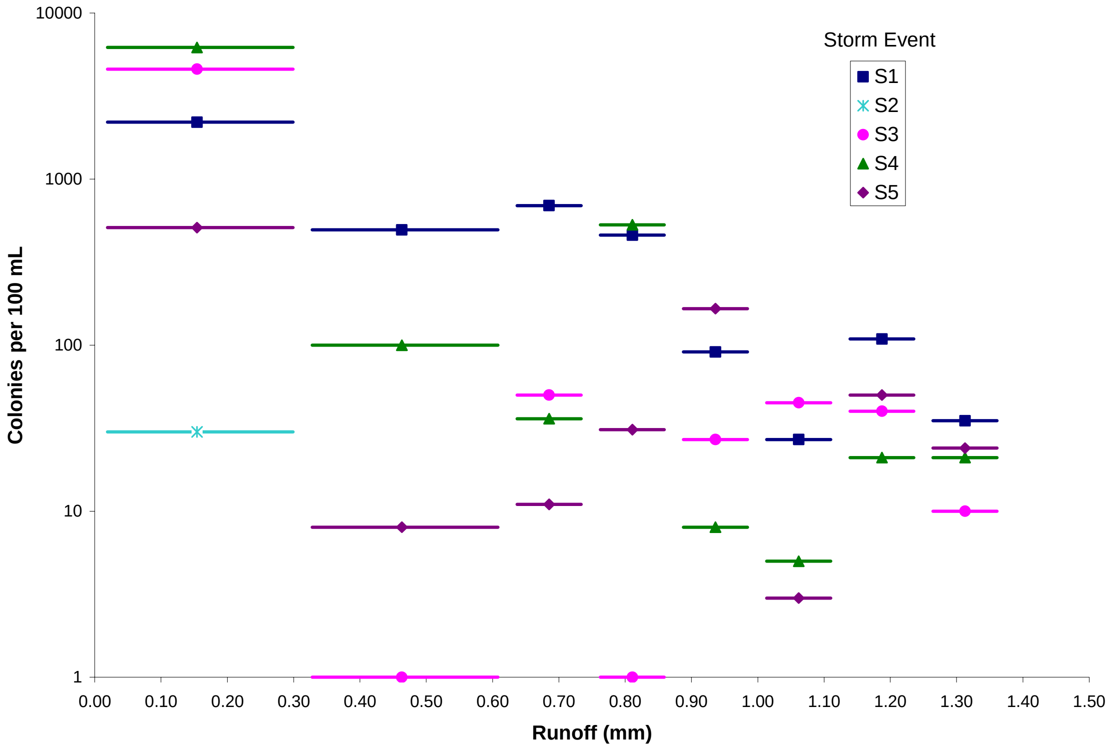


Figure 3-26: Total Coliform results for HS

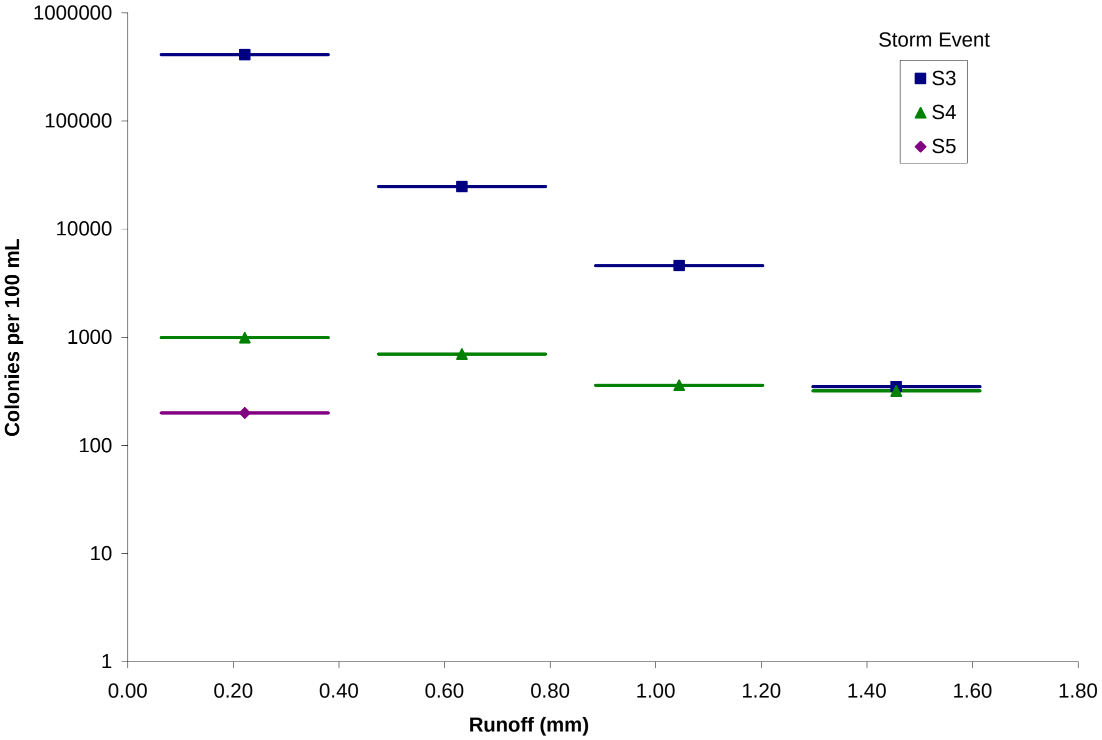


Figure 3-27: Total Coliform results for PT

3.5.1.2. E. coli

Most of the samples revealed no *E. coli* colonies, and are reported based on their original sample dilution (i.e. 1:100 dilution = <100 colonies/100 mL). Because so few colonies were found, a graphical representation of the data is not suitable. The *E. coli* results are presented below in Table 3-9, Table 3-10, and Table 3-11 for each storm event (S1-S6) against the cumulative runoff depth over the aliquots. As discussed previously, the array configuration for the CL location was altered after storm S2; the runoff depth increments were adjusted for storms S3-S6 in Table 3-9. Samples with enumerable colonies are shown in bold type.

Table 3-9: *E. coli* results for CL (colonies per 100 mL)

Runoff Depth	S1	S2	Runoff Depth	S3	S4	S5	S6
0.03 – 0.18 mm	<100	<10	**0.03 – 0.46 mm**	<10	**10**	**5**	NS
0.22 – 0.37 mm	<100	<10	**0.50 – 0.93 mm**	<10	<1	<1	NS
0.41 – 0.56 mm	<100	NS	**0.98 – 1.12 mm**	<10	<1	**1**	NS
0.61 – 0.75 mm	<10	NS	**1.17 – 1.32 mm**	<1	<1	<1	NS

NS indicates that no samples were collected
Values in bold type indicate enumerable colonies were present on sample
Samples reporting "<#" indicate no colonies were enumerated

Table 3-10: ***E. coli*** **results for HS (colonies per 100 mL)**

Runoff Depth	S1	S2	S3	S4	S5	S6
0.02 – 0.30 mm	<100	**10**	<100	**200**	**3**	NS
0.33 – 0.61 mm	<100	NS	<100	**10**	<1	NS
0.64 – 0.73 mm	<100	NS	<10	**70**	<1	NS
0.76 – 0.86 mm	<10	NS	<100	**20**	<1	NS
0.89 – 0.98 mm	<10	NS	<10	<1	**1**	NS
1.01 – 1.11 mm	<10	NS	<10	**1**	<1	NS
1.14 – 1.24 mm	<10	NS	<10	<1	**1**	NS
1.26 – 1.36 mm	<1	NS	<1	<1	<1	NS

Table 3-11: ***E. coli*** **results for PT (colonies per 100 mL)**

Runoff Depth	S1	S2	S3	S4	S5	S6
0.06 – 0.38 mm	NS	NS	<10	<100	<1	NS
0.47 – 0.79 mm	NS	NS	<10	**100**	NS	NS
0.89 – 1.20 mm	NS	NS	<10	<10	NS	NS
1.30 – 1.61 mm	NS	NS	<10	<10	NS	NS

3.5.2. Turbidity Results

Turbidity was measured at each location (HS, CL, PT) and each sample bottle (A-D, or A-H), and for each storm (S1-S6) but only if the bottles were full. Plots were generated based on the analysis completed by Martinson and Thomas (2005) in Uganda who undertook a similar study. Owing to the roofing constraints in Rwanda, not all of the bottles collected the same depth of runoff. For comparability, the turbidity results are presented as normalized values based on the turbidity of the initial sample for each storm. The turbidity value of the first bottle in each series was divided into all the subsequent turbidities for that storm to calculate the cumulative reduction in turbidity for each storm; thus, the first aliquot automatically has a value of unity.

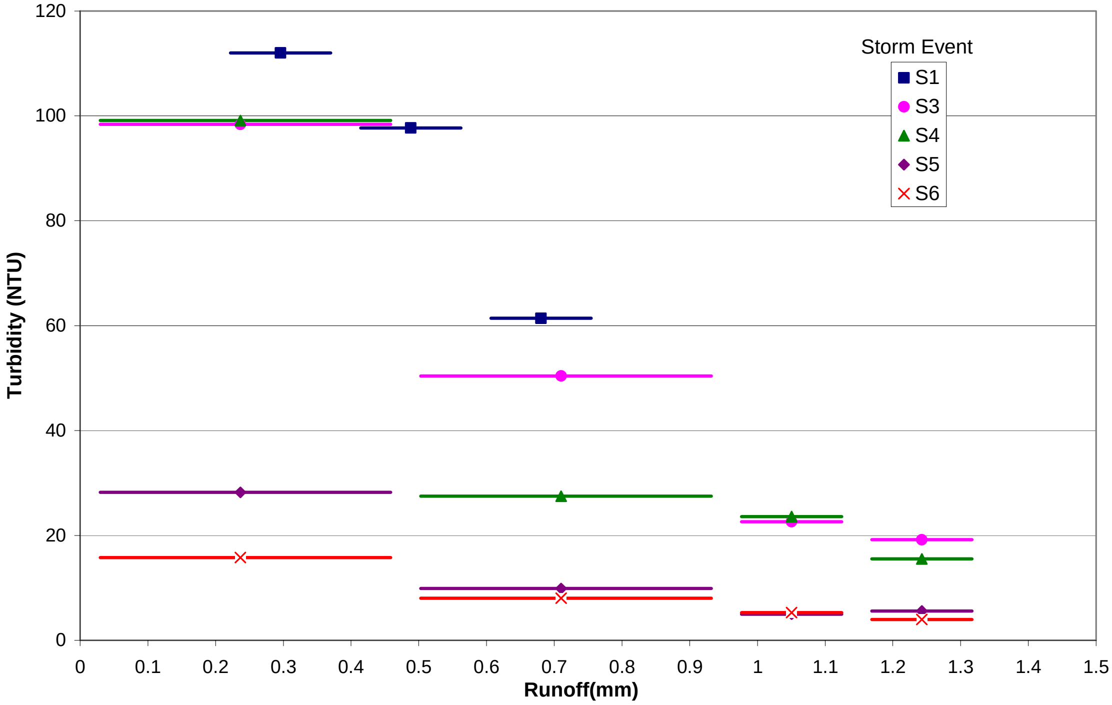
Following the procedure of Martinson and Thomas (2005), exponential trendlines fitting the Sartor and Boyd formula (Equation 3-2) were fit to each set of data and R^2 values were determined. The cumulative volume corresponding to half of the aliquot volume was used as the x-coordinate in the curve-fitting procedure. The width of each bar represents the depth of runoff captured by a particular bottle. There is a gap between each bar that accounts for the water stored in the array apparatus between sampling bottles which was measured using a graduated cylinder. Since the arrays were constructed on a slope, all pipes except the last segment are full when the preceding bottle is full. Raw turbidity values (NTU) are also presented for each sample, plotted against the runoff depth. Results are shown in Figure 3-28 through Figure 3-33.

The Sartor and Boyd equation (introduced in Chapter 2) was fit to the cumulative turbidity reduction results. It states:

Equation 3-2

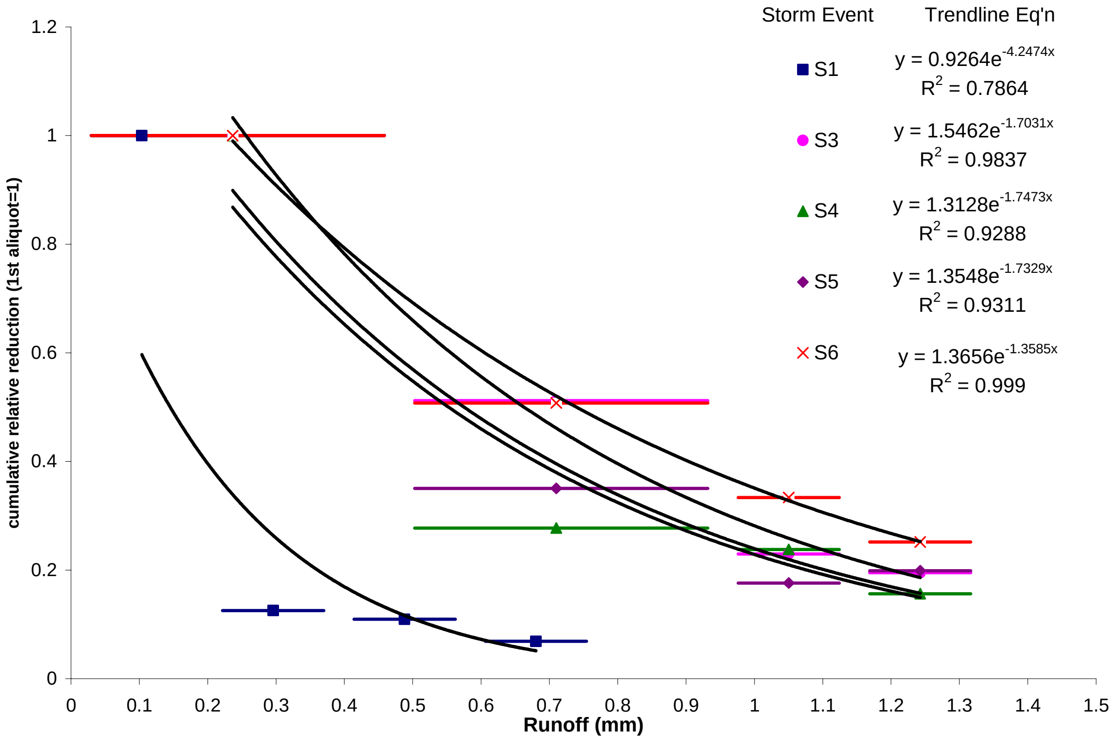
$$N = N_0 e^{-krt}$$

Where: N = turbidity of current runoff; N_0 = initial turbidity of first aliquot (initial sediment load available to wash off); k = constant (mm^{-1}); r = rainfall intensity (mm/hr); t = rain duration (hr).



**Note: To make the graph more readable, the first turbidity measurement during storm S1 was removed. It collected 0.03 - 0.18 mm of runoff and had a turbidity of 893 NTU, which is off the chart.

Figure 3-28: Measured raw turbidity at CL



** Note: Storm S1 had a different array setup than subsequent storms

Figure 3-29: Normalized measured turbidity at CL

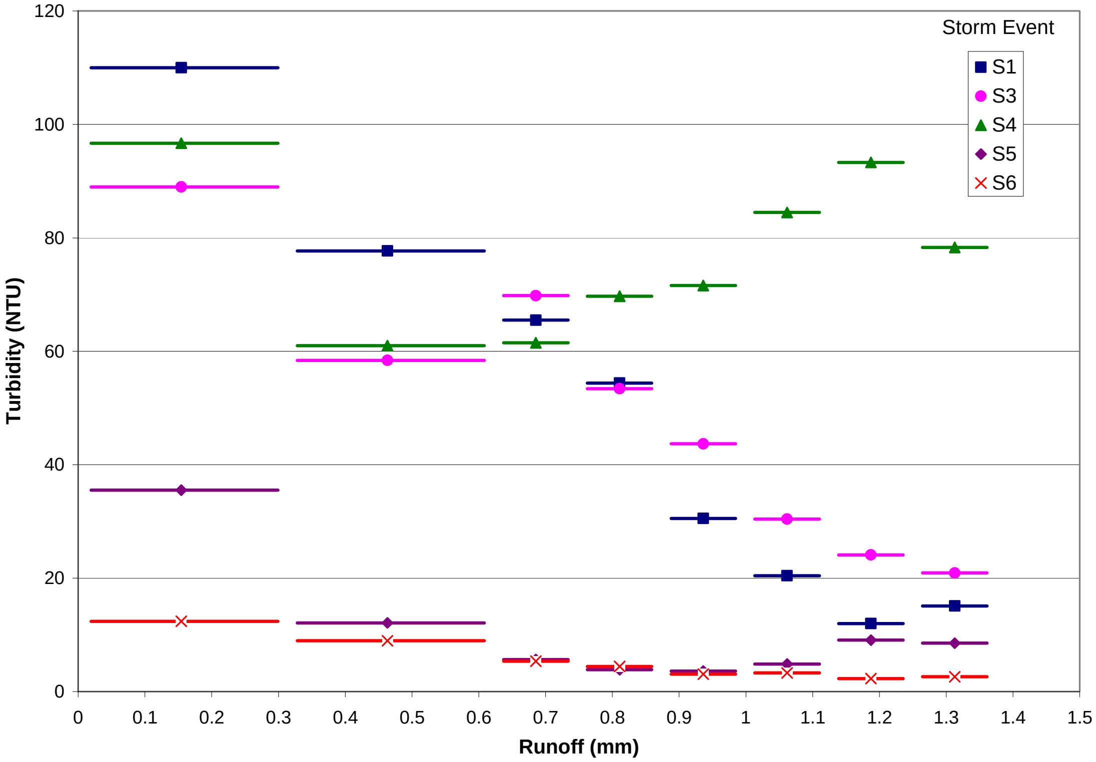
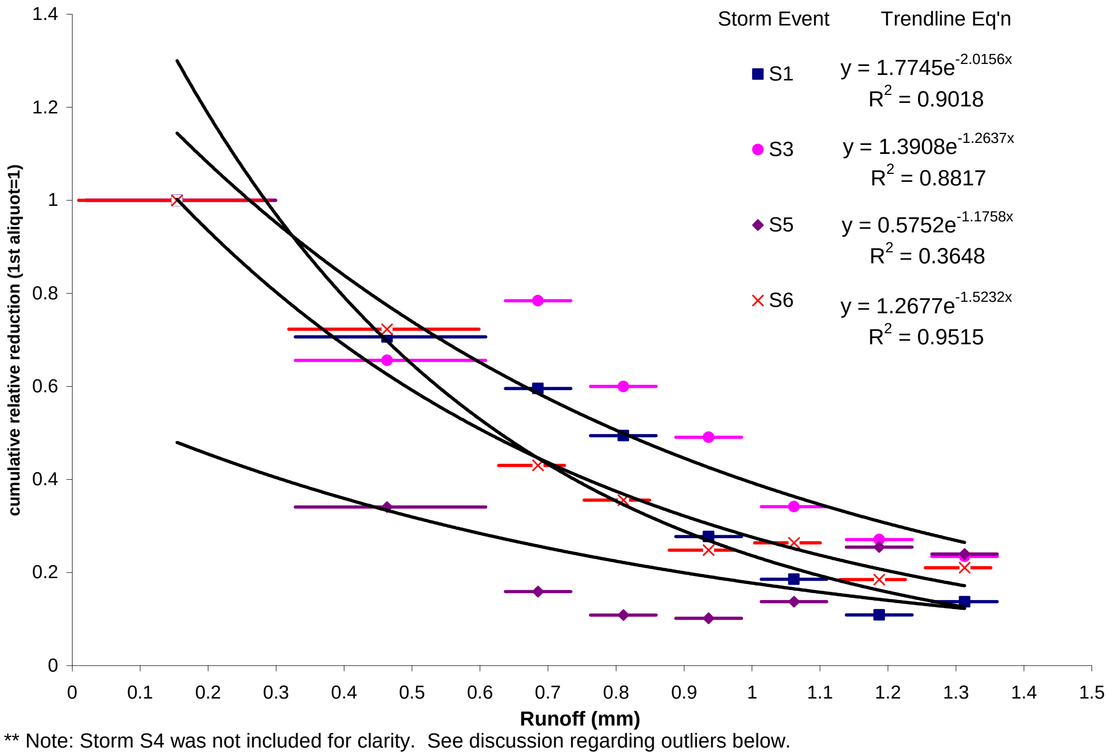


Figure 3-30: Measured raw turbidity at HS



** Note: Storm S4 was not included for clarity. See discussion regarding outliers below.

Figure 3-31: Normalized measured turbidity at HS

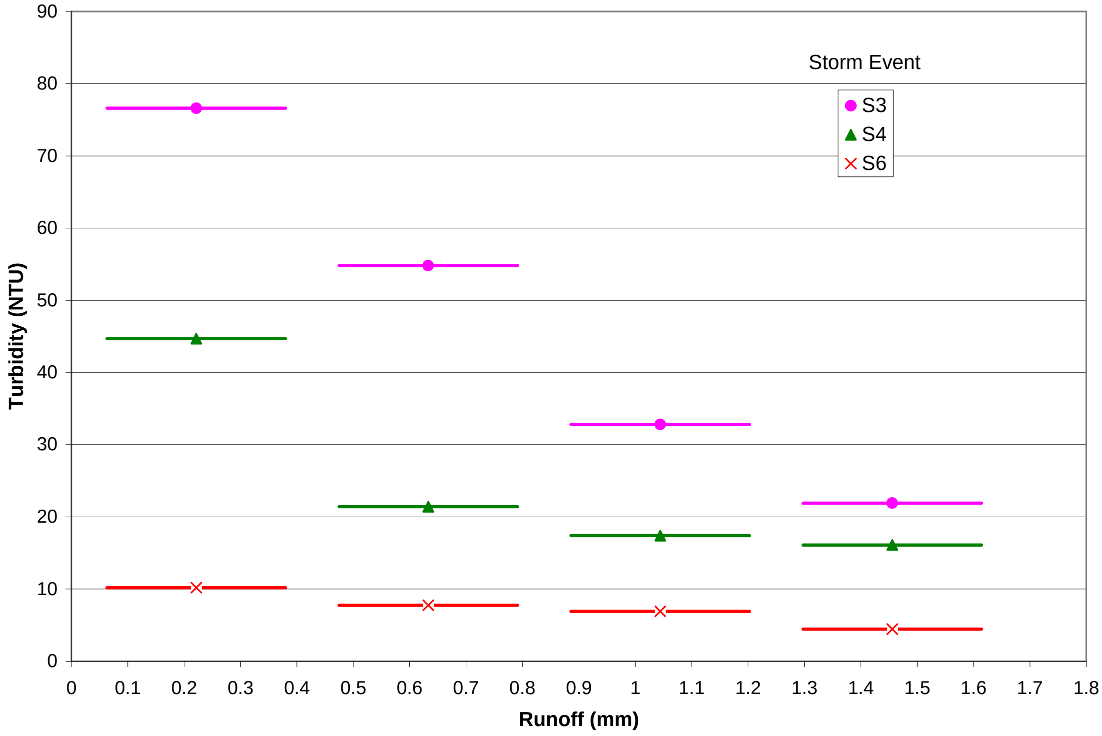


Figure 3-32: Measured raw turbidity at PT

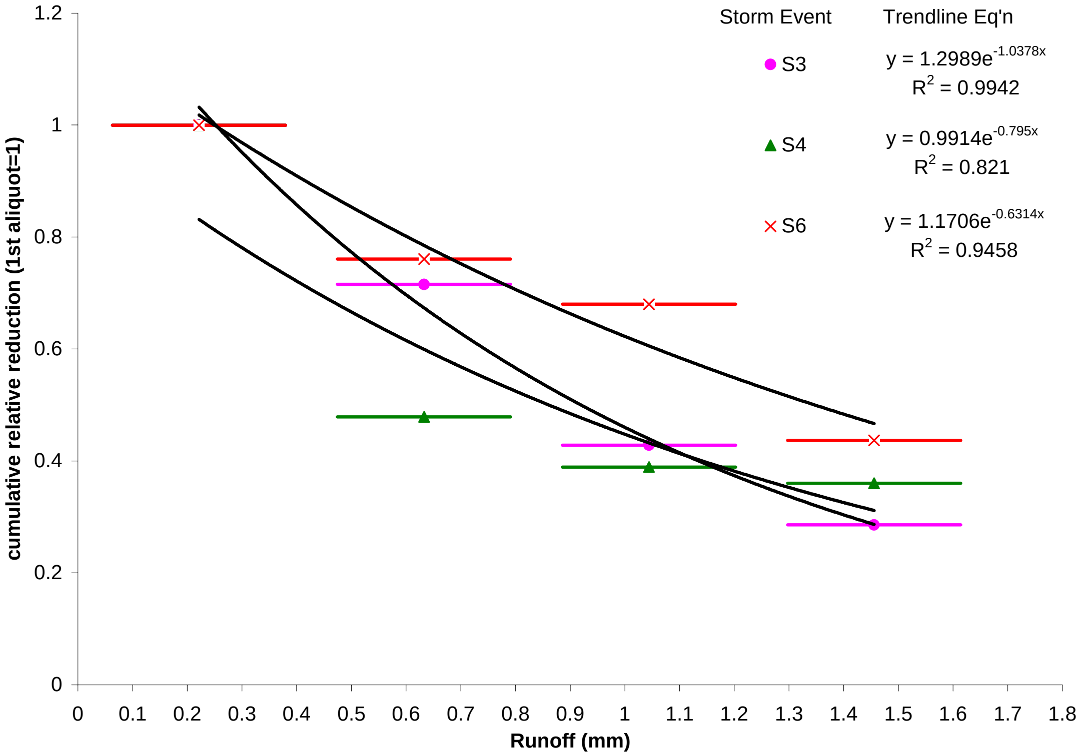


Figure 3-33: Normalized measured turbidity at PT

3.5.3. pH and Conductivity

pH and conductivity were measured at each location (HS, CL, PT) and sample bottle (A-D, or A-H) for each storm (S1-S6) but only if the bottles were full.

The U.S. EPA recommends that water not fall outside of the 6.5 to 8.5 range (USEPA 2006); the rainwater sampled from the GIZMO setups ranged from 6.4 to 7.7, indicating that pH is not a concern. The slightly acidic values were all from the clay tiled roof. The slightly acidic water could have resulted from the tiles themselves or from organic matter decomposing on the roof. The pH and conductivity results are summarized in Table 3-12 and Table 3-13.

Table 3-12: pH and conductivity ranges

	pH	Conductivity
Max	7.7	110
Min	6.4	0

Table 3-13: pH and conductivity comparisons based on roof type

Roof location and type	pH (average)	Conductivity (average) (µs/sec)	Conductivity (maximum) (µs/sec)
CL-new iron roof	7.4	39	110
HS-old iron roof	7.2	22	70
PT-old clay tiled roof	6.7	14	40

The normalized conductivity results are plotted in Figure 3-34, Figure 3-35, and Figure 3-36. Exponential curves were fit to the data and R^2 values were determined. Storms with samples containing zero-value conductivity readings were not assigned decay curves (PT-S6 and HS-S6).

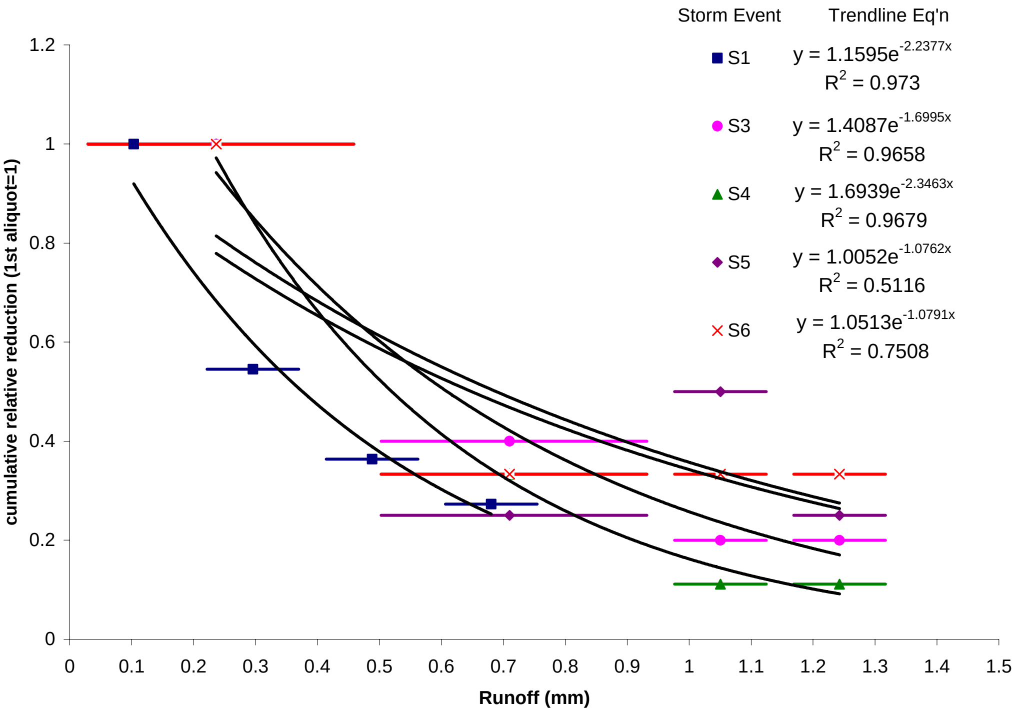


Figure 3-34: Normalized measured conductivity at CL

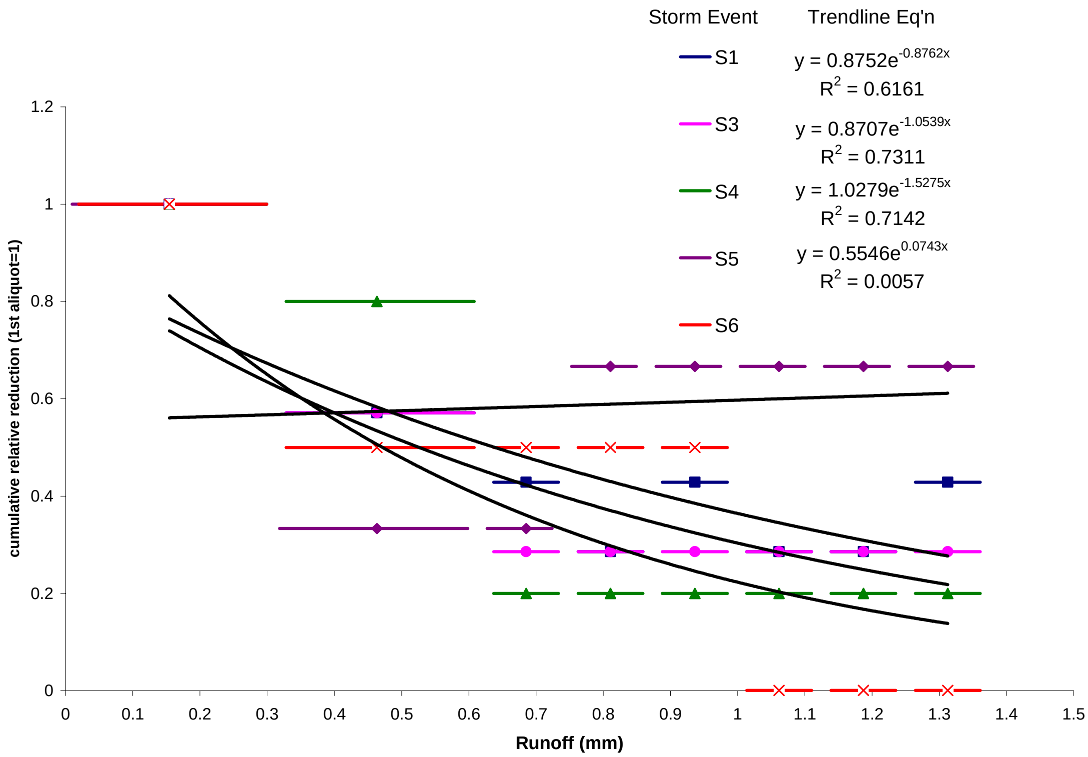


Figure 3-35: Normalized measured conductivity at HS

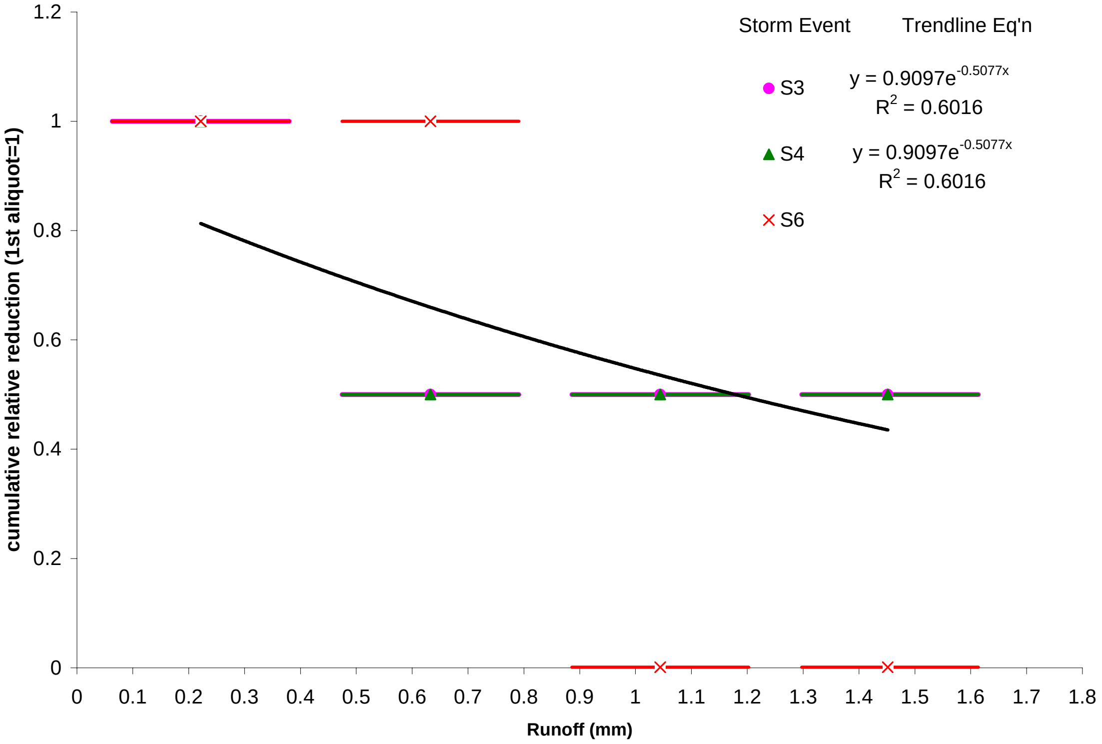


Figure 3-36: Normalized measured conductivity at PT

3.6. Discussion: First Flush Trends

3.6.1. Microbial Results

3.6.1.1. Total Coliform

The trends of coliform reduction over runoff depth are exponential for PT storm events S3 and S4 (Figure 3-27), having an R^2 value of 0.99 and 0.94 respectively, yet the results from the CL and HS locations do not follow such clear trends. Although some of the trends in Figure 3-25, Figure 3-26, and Figure 3-27 do indicate exponential reductions in coliform over runoff depth, the exponents (k) range from 0.84 to 6.7 with R^2 values as low as 0.12. For visual clarity the trendlines were not shown on the graphs, but the respective k and R^2 values for each storm are listed in Table 3-14. Although not all of the results indicate clear exponential trends, there is a distinct overall decrease in coliform contamination with runoff depth. The order-of-magnitude differences in coliform counts are due to the testing procedure where dilutions of the raw water varied between 1:10, 1:100, and 1:1,000. There is inherent error in the sampling procedure because a dilution may miss the intended target range of 20-200 colonies per Petri dish. There were also some issues with enumeration because the water was often too heavily laden with particulate matter to use a low dilution, but did not contain enough microbial contamination to merit using the higher dilution.

Coliform counts for CL were markedly lower than at the other two locations, perhaps owing to the newness of the roof and its lack of organic matter. Even though only two full storms were captured from PT, the high levels of contamination in those samples indicate that the tile roof is promoting bacterial growth. The clay tiles have a rough surface and the overlapping fashion with which they were installed creates a very high surface area, excellent for trapping and holding particulate matter and encouraging the growth of moss and mildew which could shelter bacteria from disinfecting sunlight.

Table 3-14: Results of exponential trendlines for coliform results

Location	Storm	k value	R^2
PT	S3	5.6	0.99
	S4	0.98	0.94
CL	S1	6.7	0.55
	S4	2.0	0.64
	S5	0.84	0.71
HS	S1	3.6	0.81
	S3	2.4	0.12
	S4	4.7	0.61
	S5	1.5	0.12

3.6.1.2. E. coli

The low colony counts for *E. coli* are promising, indicating that the rooftop runoff is not typically contaminated with fecal bacteria. The highest *E. coli* counts were from the HS location during storm S4, where a high of 200 colonies per 100 mL was enumerated. Based on Table 3-3, counts above 100 colonies per 100 mL are considered dangerous levels and those above 10 colonies per 100 mL are considered polluted. It is important to notice that although there were several samples containing *E. coli* in high quantities, all samples at runoff depths greater than 0.89 mm did not have more than 1 colony per 100 mL, a level considered "reasonable quality" from Table 3-3. This again confirms the benefit of the first flush diverter in removing harmful bacteria from the runoff and supports the diversion of the first one millimeter of runoff.

3.6.1.3. Sources of Error

Several sources of error may affect the microbial results, some of which have already been discussed. Every day when microbial samples were run, blanks were also run using the sterilized, boiled water that was used for dilutions. Total coliform colonies were found in blanks on 01/07/2008 (1 colony per 100 mL) and on 01/14/2008 (9 colonies per 100 mL) which correspond to storms S2 and S5. The colonies found in the blank samples indicate that the results of storm S2 and S5 could be slightly elevated as a result of the contaminated water.

In some instances where no colonies were found, it is possible that the sample was over-diluted and colonies that were actually present were missed. The limited equipment supply, lack of proper sterilization equipment, and meager laboratory space prevented a more comprehensive analysis of all the samples.

On several occasions power failures affected the temperature of the incubator. To maintain the temperature at 35ºC, warm water bottles were placed inside the incubator for thermal mass. The temperature was monitored every few minutes to adjust the bottles, but it is possible that error was introduced owing to loss of power.

3.6.2. Turbidity

The turbidity measurements presented in Figure 3-28 through Figure 3-33 are shown as both actual measured values (raw data) and values normalized on the initial reading for each location and each storm event.

3.6.2.1. Raw Data

The raw data graphs (Figure 3-28, Figure 3-30, and Figure 3-32) are useful for illustrating the general reduction in turbidity during each storm event.

The highest turbidity value was measured in the first aliquot at the CL location during the first measured storm, representing only the initial 0.18 mm of rain. It has a turbidity value of 893 NTU, but was not displayed in Figure 3-28 for visual clarity. No other readings exceeded 110 NTU; however, no others captured such a small runoff depth at the beginning of a storm.

It is also interesting to note that the initial turbidity readings decreased towards the end of our fieldwork, most likely because the rain events occurred more frequently at the end of the month than at the beginning. By comparing the antecedent dry weather period (ADWP) to the initial turbidity reading at HS, there is an indication that there is less of a need to divert water during the rainy season, but that diversion is important after a long period without rain. Table 3-15 compares the antecedent dry weather period (ADWP) to the turbidity values at the HS location.

The CL and PT locations did not have a long enough record of initial turbidity readings to be useful in such a comparison since the CL array was re-designed and the PT array received less runoff than the other two.

Table 3-15: ADWP and Turbidity

Storm #	Antecedent Dry Weather Period (days)	Turbidity of first 0.29 mm of runoff at HS location (NTU)
S1	4.5	110
S4	3.0	96.7
S3	1.5	89.0
S2	0.5	75.2
S5	0.5	35.5
S6	0.5	12.4

3.6.2.2. Normalized Data

The normalized data show the rate of reduction in turbidity during the storm, thus indicating what fraction of the initial turbidity is reduced in subsequent samples (Figure 3-29, Figure 3-31, and Figure 3-33). It is worthwhile to compare the raw data for one storm and the normalized curve for the same storm. For example, the turbidity of the first sample of storm S6 at PT was only slightly over 10 NTU and the final sample was just under 4.5 NTU (Figure 3-32). The cumulative reduction of the turbidity of that sample was actually very small, as indicated by the low k value in Figure 3-33 and Table 3-16 (0.63). Ideally, if a foul flush system were in operation during that storm, it would not be engaged because the water is not contaminated enough to merit diversion.

The small number of data points makes conclusions difficult, but the exponents from the curves fit into a relatively small range, allowing general conclusions to be drawn from the data. Martinson and Thomas (2005) found k values that ranged from 0.65 to 2.2 for several different types of roofs in three different Ugandan towns, with varying proximities to roadways. The Rwandan turbidity data produced k values ranging from 0.05 to 4.25, but the two extreme values correspond to the anomalous S4 storm at the HS location and the first storm at the CL location which collected a much smaller runoff depth than all other samples. After removing those two outliers, the k values only range from 0.63 to 2.02, which is very similar to the results reported by Martinson and Thomas. The k values for each storm are listed in Table 3-16.

Table 3-16: k values from normalized turbidity trendlines

Location	Storm	k value
PT	S3	1.04
	S4	0.80
	S6	0.63
CL	**S1**	**4.25**
	S3	1.70
	S4	1.75
	S5	1.73
	S6	1.36
HS	S1	2.02
	S3	1.26
	S4	**0.05**
	S5	1.18
	S6	1.52
* Values shown in bold type are outliers		

3.6.2.3. Outliers

With an ideal first flush, turbidity should decrease exponentially with increasing cumulative runoff depth. All of the samples at the HS location exhibited anomalies in their turbidity measurements insofar as the turbidity increased with runoff depth in at least one of the bottles. The most obvious example is storm S4 which showed a marked increase in turbidity with depth in four of the eight bottles. Figure 3-37 shows each of the sample bottles from HS, storm S4. There is an obvious reduction in turbidity from the first bottle to the second and third, and then a more subtle darkening of the water in the sixth through eighth bottles.

Storm S5 also exhibited an increase in the last three collection bottles, resulting in a low R^2 value for that trendline (0.36 in Figure 3-31 and Table 3-16). The HS array was the only setup with eight sequential bottles (Figure 3-11); it is likely that the setup of the GIZMO is the reason for the incongruous turbidity values. In subsequent observations of the bottle array it was noted that debris often accumulated in the bend in the entry pipe to the GIZMO, which during a surge in flow in the middle of the storm may have been carried into bottles towards the end of the array. Prior to fieldwork in Rwanda an informal dye test in the laboratory confirmed that if the slope of the array was too shallow (estimated as < 5%) and the flow into the entry pipe approached the flow capacity into a bottle, that water could skip over one bottle before it was full and begin filling the next bottle.

The piping of the GIZMO was slightly bowed as a result of its length and the degree to which it was bowed changed each time the device was reset. The design slope for the setup is 5%, which the HS setup did not meet. Rainfall intensity was not measured for the storms, however it is possible that if the storm intensity were high enough, some water could have mixed between aliquots, or, more likely, if the intensity were low enough that some particulate matter could have settled in the bend in the entry pipe and been carried to later bottles when the rain intensity increased again. In either scenario, the increasing turbidity could well be the result of the GIZMO setup rather than the actual pollutant profile.

Figure 3-38 compares the excluded outlying data from storm S4 to the exponential data of storm S1 originally presented in Figure 3-31. Had rainfall intensity also been measured, it might have been possible to better hypothesize a cause of these increases, but the lack of more fine-scaled rainfall data prevents more than an educated guess as to the cause of the anomalies.

Figure 3-37: Turbidity at HS location, storm S4
(Bottles A through H are from left to right)

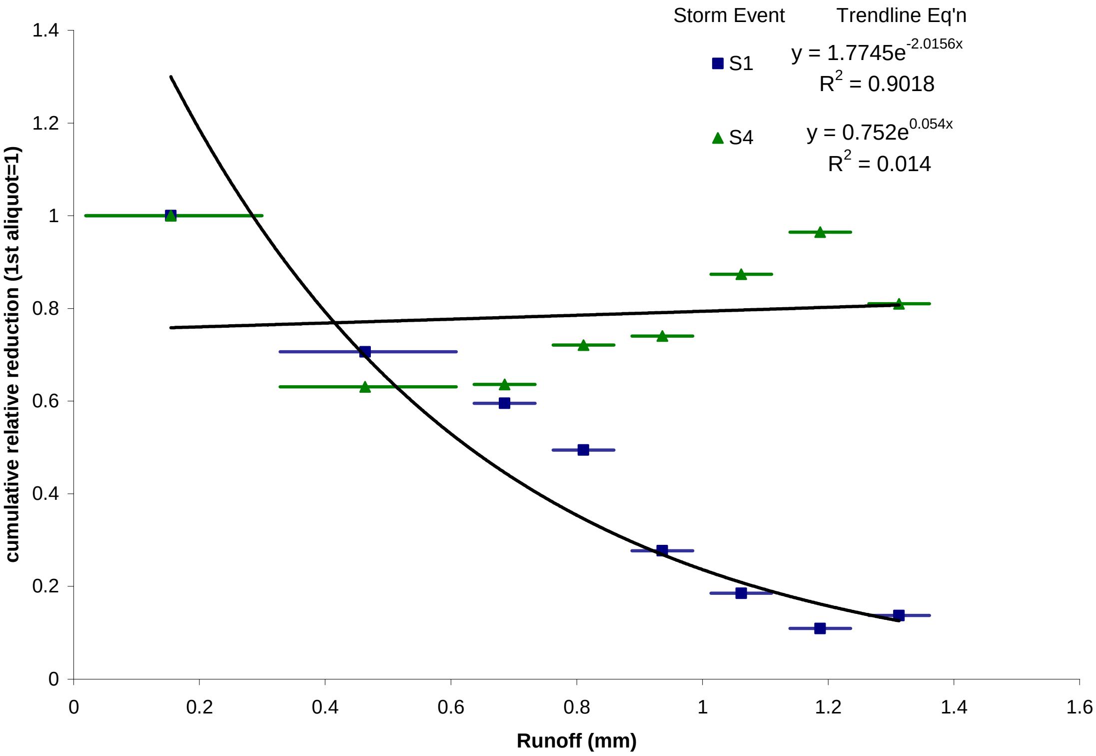


Figure 3-38: Outlier turbidity data at HS

It can be seen from Figure 3-29 that storm S1 at CL follows a different trend than the other four storms at the same location. This is because the original GIZMO setup consisted of four 0.56-L bottles but it was determined that not enough of the first flush was being captured by that volume, so the design was changed to have two 1.5-L bottles followed by two 0.56-L bottles. Storm S1 was the only storm which was completely captured with the smaller volume bottles. The turbidity in the fourth bottle was still relatively high, around 61 NTU, meaning that the tail of the exponential decay curve was not captured. The small runoff depth capture is the explanation for the atypical cumulative turbidity reduction for storm S1 at CL.

3.6.3. Conductivity

The complete set of conductivity results is found in Appendix C. The conductivity of the rainwater samples was typically low, around 20 μs/cm. Conductivity, which depends upon the dissolved solids carried from the roof, declines with rain volume similarly to other pollutants. The conductivity values tended to reach a minimum between 10 and 20 μs/cm, typically after the first 0.5 mm of runoff. The highest values of conductivity were recorded in the first bottle of the CL array, possibly due to its close proximity to the road or dissolved minerals from the roofing material. None of the samples had values significantly higher than is expected for rainwater, but the higher values likely reflected the amount of dirt in the water, a measurement better quantified with turbidity.

3.6.4. Color

Color was measured in every rainwater sample, yet the quantification of the color value is subjective and not a useful metric for understanding rainwater quality. Many of the samples had color values above the highest value measurable and other samples were a different shade than that available on the color wheel. The difficulty in determining accurate values for each sample necessitated significant approximations for color results. Some of the storms showed reductions in color with runoff depth, but turbidity measurements portrayed the improvement in water quality with runoff depth much more accurately. Since the color results were uninformative and inconclusive for water quality, the results are not presented.

3.7. Recommendations

Goals of the fieldwork were to understand the first flush phenomenon, gather water quality information, and use the data to quantify runoff diversion so as to improve the quality of water filling the main tank. It is important to specify the difference between the rainfall depth and the runoff depth. While seemingly the same, the runoff depth is the rainfall depth minus any losses due to evaporation, leaking, gutter overflow, etc. The losses can be most easily approximated by using the runoff coefficient for each roofing material presented in Table 3-17. Other authors recommend using a generic value for runoff capture such as 0.85, regardless of roofing material. The assumption is that 15% of the rain falling on the roof will not make it into the tank (Thomas 2002). Since calculations were completed for a generic roof, for the remainder of this thesis losses were assumed to be 15% and were accounted for prior to first flush diversion.

Table 3-17: Runoff coefficient for typical roofing materials (Warwick undated; Smet 2003)

Roof Material	Runoff Coefficient, c
Galvanized Iron Sheets and Plastic	0.8 – 0.9
Clay or Cement Tile	0.5 – 0.75
Asbestos Sheets	0.8 – 0.9
Thatch	0.2

3.7.1. Sizing of First Flush Devices

The amount of water diverted in a first flush unit is not only affected by the roof type and pollutant characteristics, but also by the relative importance of the water to the end users. While it is very unlikely that the first flush diversion will deliver completely pure water to the storage tank, it is meant to improve the quality of water. There will always be some risk in drinking RWH water unless it is chemically treated or disinfected, but the risk is decreased by diverting the first flush.

The ADWP affects the amount of particulate matter that settles on the roof and it is known that the first flush need not be diverted if it has recently rained. Thus, the first flush device needs to be of a size large enough to capture the majority of pollutants after a long dry spell, but not so large that clean water is captured after a rainy period. The literature recommends diverting anywhere between 0.2 and 2.0 mm of runoff, and based on the field results from Rwanda, I am recommending that the first 1 mm of runoff be diverted. The following discussion will analyze the compiled results from all of the water quality tests to understand the implications of diverting 1 mm of runoff.

3.7.1.1. Water Quality Results for All Locations

For the three locations in Bisate, a one-millimeter diversion of water would have resulted in a drastic decrease in total coliform counts. If the first millimeter of rain had been diverted and the remaining water sampled for coliform, all of the CL samples would have had coliform readings below 10 col/100 mL, the HS samples would have a maximum coliform count only slightly higher than 100 col/100 mL, but PT would still have counts as high as 4,600 col/100 mL, perhaps indicating that old clay tiles are not suitable for RWH for drinking water supply and that even iron roofs need to be kept clean as they age.

Figure 3-39 shows the total coliform results on a logarithmic scale for all of the sampled locations and storms. Any points to the right of the vertical line at 1 mm would be collected in the main tank after a 1-mm diversion. The four highest values are all from the PT location, but all other samples are low, with a maximum of 109 col/100 mL.

The real health concern with bacterial contamination is *E. coli*, rather than total coliform, but it is easier to understand the trend in pollutant decrease over time with total coliform because they are more prevalent. WHO recommends 0 *E. coli* colonies per 100mL, but Gould (1999) proposed the level be raised to 10 colonies/100 mL for developing countries, a level achieved by all of the samples before 1 mm of runoff (Table 3-9 through Table 3-11).

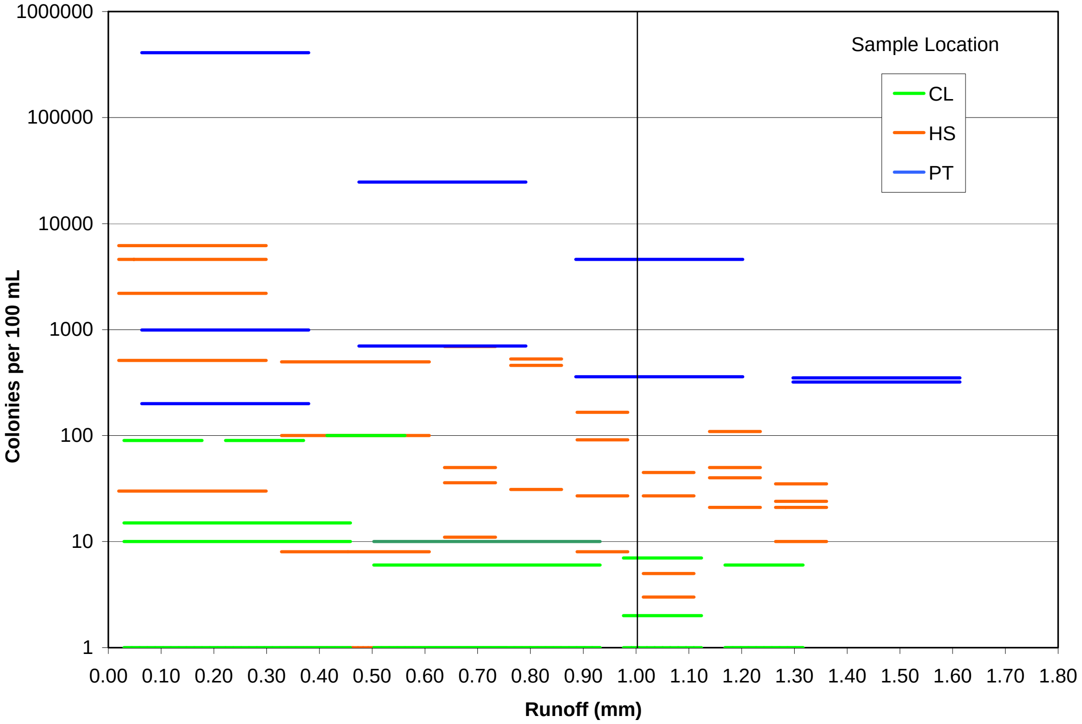
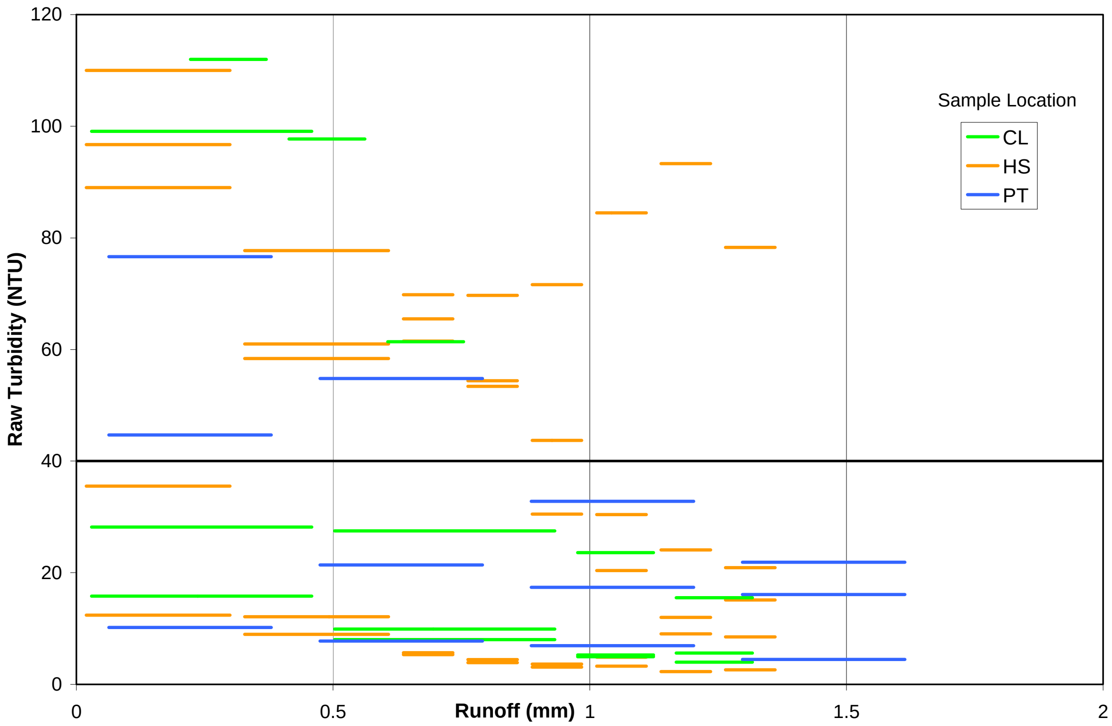


Figure 3-39: Coliform results for all locations

Raw turbidity results and normalized cumulative turbidity reduction results are presented for all sites on combined graphs in Figure 3-40 and Figure 3-41 respectively. Storm HS-S4, introduced previously as a strong outlier, is also included. Although WHO (2008) recommends that drinking water have turbidity less than 5 NTU for chlorination, this is an unrealistic expectation for a first flush diversion system. The presence of *E. coli* is the primary health concern for water quality (of the parameters studied). Total coliform and turbidity are used as metrics for contamination and turbidity standards are set in the context of chlorination. The *E. coli* results show that 1 mm runoff diversion is sufficient to reduce *E. coli* levels to 1 colony per 100 mL. One millimeter diversion corresponds to a maximum turbidity level for 40 NTU for all samples except HS-S4 (discussed previously). Since the rainwater will not be chlorinated immediately, if at all, turbidity will not significantly affect drinking water safety. However, it is most important to reduce the amount of sediment buildup in the tank. A targeted maximum turbidity of 40 NTU would not in itself be problematic and would result in turbidity much lower than 40 NTU most of the time. Thus, one millimeter of diversion corresponds to good drinking water quality (*E. coli* less than 1 colony/ 100 mL) and minimal tank sedimentation (turbidity < 40 NTU).

The normalized measured turbidity is also presented in Figure 3-41 to evaluate the applicability of Martinson and Thomas' "Rule of Thumb" for first flush diversion. They state, "for each mm flushed away the contaminant load will halve" (2005). The horizontal line at 50% reduction indicates that the turbidity results, in general, follow their rule of thumb. There are two sets of values that do not exhibit the 50% reduction; the first is HS-S4, as discussed, and the other is the last storm at the PT location (S6), which had an initial turbidity of only 12.4 NTU, meaning that there was very little potential for reducing the turbidity. It had rained only one day before the S6 sample collection, meaning that the water from that storm should not have been diverted at all.



** Note: The turbidity value at CL-S1 was removed to make the graph more readable; the value was 893

Figure 3-40: Measured raw turbidity at all sample locations

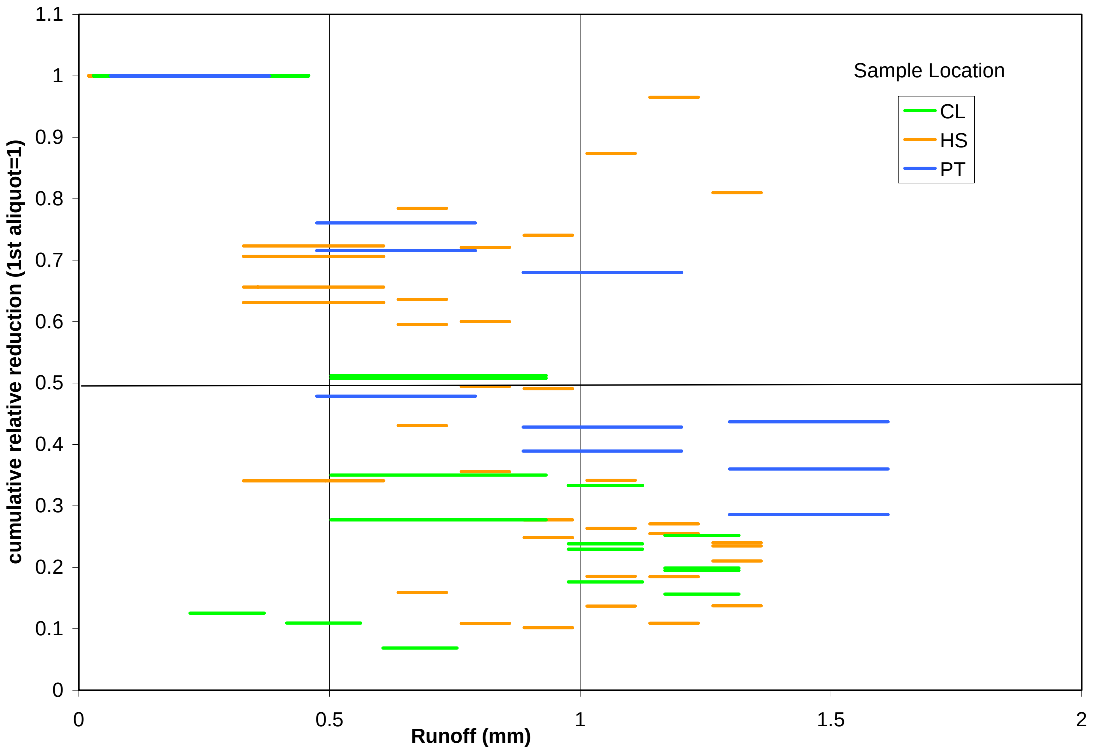


Figure 3-41: Normalized measured turbidity at all locations

For comparison, the normalized conductivity plots are shown in Figure 3-42. All of the samples show at least a 50% reduction in conductivity after the first one millimeter of runoff, except for storm HS-S5, which reached a stable conductivity of 20 µs/cm after the 0.75 mm and did not see a further reduction with runoff depth.

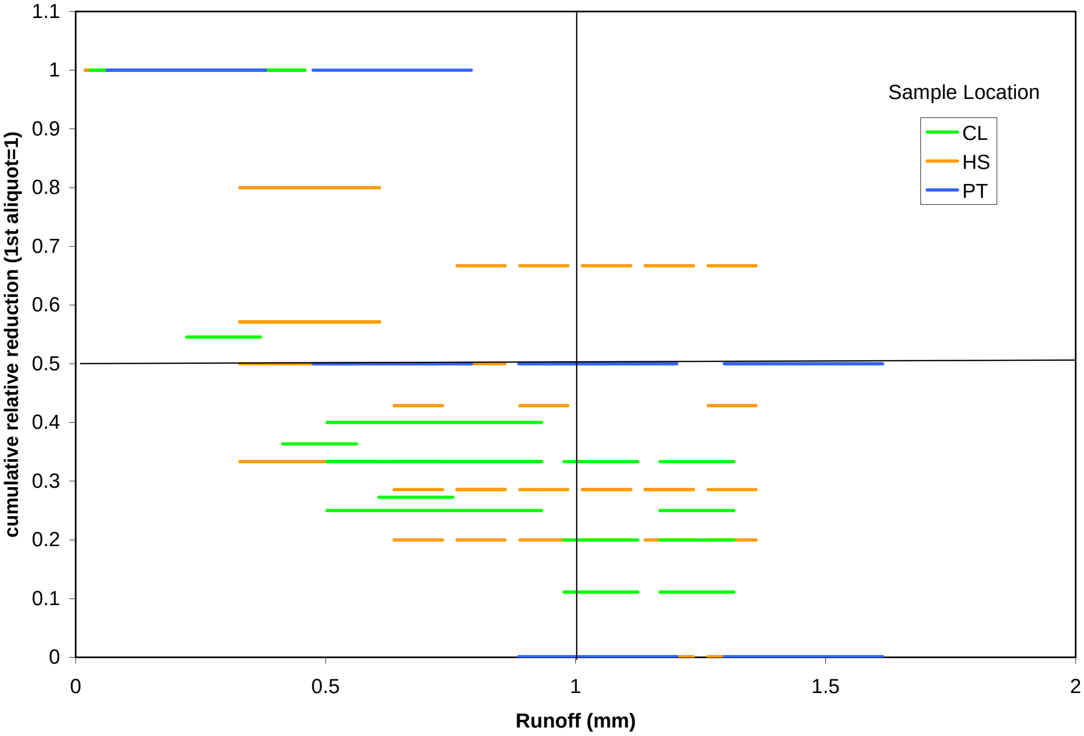


Figure 3-42: Cumulative conductivity reduction for all locations

In general, the roofs sampled in Rwanda follow the same trends in pollutant (turbidity and conductivity) reduction as the roofs tested in Uganda by Martinson and Thomas (2005). Exponential trendlines fit to normalized pollutant graphs produce the same range of k values as those in the Ugandan study and the rule-of-thumb proposed also holds true in this Rwandan study. The similarity of results from this study and the Ugandan work indicate that they are applicable in many places that practice rainwater harvesting.

3.7.1.2. Roofing Material

The results from Figure 3-39 through Figure 3-42 are categorized by sample location and therefore roof type. The CL roof was very new, well constructed corrugated iron; the HS roof was old, rusted corrugated iron with some debris on the roof; and the PT roof was constructed of old clay tiles in fairly poor condition with some mold and moss growing on it. The coliform results were lowest for the new roof and worst for the old clay roof. Similarly, the turbidity results are typically the most consistent and overall the lowest for the new iron roof and worst for the old clay roof. Even the conductivity reductions are most predictable for the new roof. These differences in performance of each roofing material strengthen the opinion that some roofs are less suitable for rainwater harvesting than others. Based on the coliform data, I would advise against an old clay tile roof for collecting water to be used for drinking, unless the water is treated. Buildings with clean corrugated iron roofs are the easiest to clean and least likely to collect and hold debris, making them the best option for rooftop rainwater harvesting. If cleaned by hand at the end of a long dry spell, diversion of the first flush should provide water of highly improved quality for future use.

The conductivity and turbidity results for the fieldwork completed in Rwanda in 2008 confirm the "Rule of Thumb" presented by Martinson and Thomas (2005) that the contaminant load halves with each millimeter diverted. The raw values also confirm that in most instances, diverting the first millimeter will drastically improve the water quality. Based on the results presented in this chapter, I maintain that it is most beneficial for the first millimeter to be diverted from the runoff stream after three days of no rain, or more frequently if the roof is in an area that is prone to high levels of pollution.

3.7.2. Diversion Device Design

The most straightforward, easy-to-operate and easy-to-install design for the first flush device is a standard pipe diverter, similar to ones in place in Kenya (shown in Figure 2-7). The design should be such that the water from the downpipe flows through a horizontal pipe before entering the diverter (as in Figure 2-6 and Figure 2-7), to reduce the velocity of the water and thus reduce mixing. A ball valve could be incorporated into the design, but is probably unnecessary and would add additional cost and maintenance issues. A simple first flush diverter design is illustrated in Figure 3-43.

A soak-away pit should be constructed beneath the diversion pipe to allow the absorption of the diverted water when the pipe is opened. The soak-away pit can be as simple as a hole in the ground with a slightly larger volume than the diversion pipe, filled with large gravel (~10 cm dimension). The gravel should be made of a stone that is locally available and thus should not add excessive cost to the project.

An alternate design could incorporate a small seep hole in the bottom of the pipe to allow the water to slowly drain, and thus reset itself automatically, but it is likely that the hole would easily clog and not be effective. Thus a manually removed end cap is recommended, but it should be secured to the diverter pipe with a chain to prevent it from being lost or misplaced.

To calculate the required diverter volume for a specific roof (m^3), simply multiply the projected roof area (m^2) by the depth to be diverted in meters (1 mm = 0.001 m as recommended above). The volume of the diverter is calculated by the geometric formula, $V = \pi r^2 h$, where V is the volume (m^3), r is the inside radius of the pipe (m), and h is the length of pipe (m). If an L-shaped pipe is used, the volume calculation can be done in two sections. Then, one can multiply by 1,000 to convert from cubic meters to liters if desired.

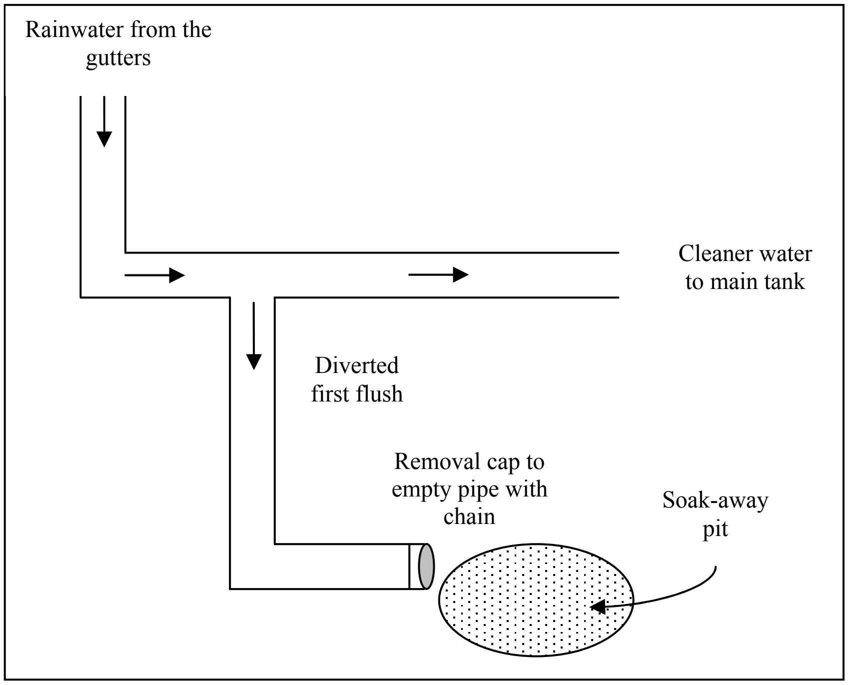


Figure 3-43: Basic pipe diverter design

3.7.3. System Management

All aspects of a rainwater harvesting system need to be properly managed in order to be effective. Neglect of any one part can cause failure of the entire system. The first flush diverter described above needs to be manually emptied before a rainstorm to make room for the new volume of dirty water. It is important that the diverter not be emptied immediately after a rainstorm because then clean water will be unnecessarily diverted into it. Instead, after three days without rain (or really whenever the user feels that the roof is dirty), it should be emptied. To be more effective, the roof should be well cleaned after extended periods without rain (such as the end of the dry season). The diverter cap can be removed completely and the roof scrubbed and rinsed, with all the dirty water being released immediately. This preemptive measure will improve the rainwater quality and reduce the amount of rainwater that needs to be removed when the rains begin.

3.7.4. Implications for Rainwater Harvesting

The implementation of an appropriately sized, well maintained first flush device as part of a rooftop rainwater catchment system has the potential to significantly improve the quality of stored rainwater without exorbitant expense. Although turbidity measurements from the existing tanks were typically below 10 NTU, some samples taken from the water tanks had *E. coli* values as high as 63 colonies/100 mL and total coliform counts as high at 31,000 col/100 mL in 2008. The people in Bisate were drinking this water directly, highlighting the need for quality improvements.

CHAPTER 4: Storage-Reliability-Yield Behavior

Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to water. People move when there is too little of it. People move when there is too much of it. People journey down it. People write and sing and dance and dream about it. People fight over it. And all people, everywhere and every day, need it. –Mikhail Gorbachev, President Green Cross International.

Chapter 4: Storage-Reliability-Yield Behavior

4.1. Introduction to Storage-Reliability-Yield (SRY)

A number of ways exist to evaluate the reliability of a rainwater harvesting system, one of which involves an analysis of the storage-reliability-yield behavior of a rainwater harvesting (RWH) system. As discussed previously, a RWH system involves collection of rainwater on a rooftop, conveyance to gutters, diversion of the first flush, storage in a tank, and finally, consumption. During design of a RWH system, often the most challenging task is selection of a suitable tank so as to optimize tank size based on rainfall, the length of the dry season, cost of materials, final use of the water, availability of materials and labor, maintenance needs, and many other site-specific considerations.

There are very simple "back-of-the-envelope" calculations and also complicated statistical methods to determine appropriate storage volume. Once a volume has been selected it is advantageous to calculate the anticipated reliability of the system based on known (or assumed) parameters such as daily demand and monthly rainfall.

The following sections describe several different methods for calculating the reliability of a RWH system and an evaluation of three sites in Bisate Village which currently implement rainwater harvesting technologies. To more comprehensively evaluate the storage-reliability-yield (SRY) behavior of the RWH systems, a simulation model was employed using generated pseudo-daily rainfall data for Bisate Village.

4.2. Rainfall Reliability: Three Simple Approaches

In sizing a rainwater harvesting system, there must be a balance between system performance and system cost, particularly in developing nations (Thomas 2005). Approaches to sizing a rainwater system should be based on both community water demand and available water supply, but in Rwanda, demand is generally not the limiting factor. One standard sizing method is to consider the reliability of rainfall in the region of interest. This process can take many forms, based on the availability of data for that geographic area. In Northwestern Rwanda at the time of this thesis there was very little methodology for the sizing of rainwater tanks. Workers that install plastic tanks were untrained in tank sizing and generally estimated size based on available land area (Clauson 2007). In instances where sizing calculations were attempted, the average annual value for rainfall was used (approximately 1,240 mm per year).

Since Rwanda has four distinct periods of characteristic precipitation, annual average rainfall is an inadequate indicator of supply reliability. It does not account for the variations in rainfall, particularly during the long dry and long wet seasons. As discussed later in this chapter, reservoir volumes based on average annual values do not necessarily indicate when the storage capacity is insufficient to last the duration of an abnormally long dry season. There are several simple methods available to calculate the necessary capacity for a collection system including demand-side calculations, supply-side calculations, and statistics-based computer models.

4.2.1. Demand-Side Approach

Demand-side calculations are a critical part of tank sizing, although it is important that they not be used alone. The concept is simple: calculate the average yearly demand on a water source based on the number of users and their daily (or monthly) consumption. If summed over a full year, this will yield a value for average annual consumption. This value is useful to compare to the results of supply-side calculations but should not be used as a tank volume estimator.

An equally simple yet more accurate calculation multiplies the rate of consumption by the average length of the longest dry season to obtain a value for required storage (Warwick undated). This calculation assumes that there is sufficient rainfall during the rainy seasons and a sufficient roof area for catchment. The calculated value is essentially the size of the tank assuming that it is completely full on the last day of the rainy season, completely dry on the last day of the dry season, and that the rainy season will start on time and have sufficient rainfall to meet daily demand. While these assumptions may not always hold true, the calculation is very easy to do and is a good way to make a first rough estimate of the necessary tank size.

4.2.2. Simple Supply-Side Approach (Rational Method)

One very simple way to size a rainwater collection system based on the supply of rainfall and the available roof area is by using a modified version of the rational equation. This method is used in much of the available literature as a method of tank sizing and is originally adapted from reservoir sizing calculations. The basic formula is symbolized in Equation 4-1.

Equation 4-1

$$Q=ciA$$

Where Q is the volume of water collected from the roof in a year [m^3], c is the runoff coefficient for the existing roof [dimensionless], i is the average rainfall per year [m/year], and A is the surface area of the roof [m^2] (Mays 2005).

The runoff coefficient is based on the type of construction material. Although most of the water falling on a roof will run off into the gutters, some will splash off the sides in heavy rain and some will be absorbed by the roofing material. The coefficient is a number between zero and one that expresses the approximate loss fraction of water over a year. A high coefficient indicates that most of the water is reaching the gutters, while a low number means that substantial amounts of rainwater will not be captured (Warwick undated). Introduced earlier as Table 3-17, the table below shows typical runoff coefficients to be used in the rational method calculation (Warwick undated, Smet 2003).

Roof Material	Runoff Coefficient, c
Galvanized Iron Sheets and Plastic	0.8 – 0.9
Clay or Cement Tile	0.5 – 0.75
Asbestos Sheets	0.8 – 0.9
Thatch	0.2

Although asbestos sheets have a high runoff coefficient, inhalation of asbestos dust is extremely harmful to health and old sheets have a tendency to grow mold and moss. For these reasons, it is not recommended that water be collected from asbestos roofs.

The results from the rational equation yield a volume of water that is collected from the roof in an average year. The calculation is simple and gives a good rough estimation for tank sizing but it does not factor into account seasonal variations in rainfall. Similarly, the rational equation does not account for the dry season, a time when extra reserves are needed to compensate for the lack of precipitation.

4.2.3. Rainwater Tank Performance Calculator

The University of Warwick, as part of their Domestic Roofwater Harvesting Research Program, developed an open-access rainwater harvesting system modeling service that calculates the reliability of a tank, based on historic rainfall and daily water demand. The model, called the Rainwater Tank Performance Calculator (Warwick 2007), is available at:

<www.eng.warwick.ac.uk/dtu/rwh/model>

The Warwick Calculator requires several inputs including the area of the collecting roof, the nominal daily water demand, ten years of monthly rainfall data, and selection of a water management strategy.

Warwick presents three water management strategies from which to choose:

1. **Constant Demand**: The user draws a set amount of water from the tank every day if there is enough available, otherwise the user withdraws what water is left in the tank.
2. **Varies with tank content**: The user draws off an amount dependent on the volume of water in the tank. If the tank is between one-third and two-thirds full, the user takes the specified nominal demand. If the tank is more than two thirds full, the user draws off more water than usual, but if the tank is less than one third full, the user takes less water than normal. This water conservation means that system reliability is improved for a given tank size.
3. **Varies with season**: The user takes more water from the tank if it has rained recently and less when it has not. This aids water conservation and increases system reliability for a given tank size.

The output displays a chart with the reliability, satisfaction and efficiency of the selected tank size in addition to three other possible tank sizes. The reliability of the tank is defined as the fraction of days the total demand will be met by the system; the satisfaction is the fraction of total water demand that can be met by the system; and the efficiency is the fraction of roof runoff captured by the system.

4.2.3.1. Design Efficiency

Since cost is such a strongly limiting factor, it is important to optimize tank design to maximize benefits while minimizing cost. There are several measures of system efficiency. Qualitatively, an inefficient system is one that is either too small and does not capture a large portion of the rainwater, or one that is too large and remains only partially filled for most of the year. An inefficient system can also be a faulty one, where water is lost through cracks or broken faucets. A basic calculation for storage efficiency is provided in Equation 4-2 (Warwick undated).

Equation 4-2

$$\text{Storage Efficiency} = (1 - \frac{Q_{\text{over}}}{Q_{\text{in}}}) * 100$$

Where efficiency is measured in percent, Q_{over} is the volume of water overflowing the tank per unit time (L/time) and Q_{in} is the volume of water flowing into the tank during the same time period (L/time). Similarly, Equation 4-3 was developed by the University of Warwick to calculate system efficiency.

Equation 4-3

$$\text{System Efficiency} = (1 - \frac{Q_{use}}{Q_{in}}) * 100$$

Again efficiency is measured in percent, and Q_{use} is the volume of water used by the household over the same time period.

The aforementioned model was used to assess the performance of the new rain tanks in Bisate at the health clinic, the primary school, and trackers' house. Descriptions of the new RWH systems are found in the supplemental reading in Appendix A. For the model to run, ten years of monthly rainfall are required. The data used were collected at the Karisoke Research Center in Musanze, which is approximately 18 kilometers southwest of Bisate Village. Although the rainfall totals are not exactly the same for both cities, the general patterns are the same, so the Musanze record was used as a surrogate for missing Bisate records. Monthly data for Musanze are available from 1977 until 1992 and also from 2002 through 2005. Rainfall totals are missing for several months throughout those years, likely a result of violence surrounding the genocide. For the performance calculations, only years with complete monthly records were used. The complete 20-year record highlighting the specific years used in the calculations can be found in Appendix E.

4.3. Reliability Calculations for Bisate Using Three Simple Approaches

As described, in 2007 thirteen new plastic tanks were installed in Bisate. Five tanks were installed at the health clinic; four each hold 10 m^3 and one holds 1.35 m^3. The primary school received two tanks of 10 m^3 each in addition to its existing two metal tanks each with a volume of 10 m^3. The trackers received four 10 m^3 tanks and one 2.5 m^3 tank but had their small metal tank removed (Figure 3-18). These values were used in several reliability calculations reported below as the volume of water storage. The total tank volumes are listed in Table 4-1.

Table 4-1: Total Tank Volumes

Location	Total Storage Volume for RWH (m^3)
Clinic	41.3
Primary School	40.0
Trackers' House	42.5

The goal of the following reliability calculations is to compare the various available methods for tank sizing and to judge the efficacy of the new collection tanks.

4.3.1. Demand-Side Calculations

The demand for water from the Bisate health clinic, primary school and DFGFI trackers' house was originally calculated by Jean Pierre Nshimyimana. The World Health Organization estimates that each pupil uses five liters of water per day, so the demand calculations were determined based on the assumption that the children have other sources of water at home and will use one liter at school for drinking and one liter for washing their hands each day. The breakdown of water demand for the health clinic, the primary school and the DFGFI trackers' house are tabulated in Table 4-2.

Table 4-2: Breakdown of Water Demand (Nshimyimana 2007c)

Clinic Water Demand		
Activity	**Volume of water per day**	**Total monthly usage (Liters)**
Cleaning the clinic	80L	2,400
Washing bed sheets	20L/bed * 15beds * 9times/month	2,700
Washing toilets	60L	1,800
Caring for patients	40L/person * 15beds (max)	18,000
Drinking water	20L	600
Hand washing	1L/person * 70people	2,100
Total	**920 L/day**	**27,600 L/month**
Annual Total		**336 m^3**

Primary School Water Demand		
Activity	**Volume of water per day (Liters)**	**Total monthly usage (Liters)**
Cleaning toilets	120	3,600
Washing hands	1,726	51,800
Drinking water	1,726	51,800
Cleaning classrooms	400	12,000
Total	**4,000 L/day**	**119,200 L/month**
Annual Total		**1,450 m^3**

Trackers' House Water Demand		
Activity	**Volume of water per day (Liters)**	**Total monthly usage (Liters)**
Toilets/Sanitation	180	5,400
Washing clothes	400	12,000
Cleaning the house	60	1,800
Cooking and washing utensils	120	3,600
Drinking water	40	1,200
Body washing	400	12,000
Total	**1,200 L/day**	**36,000 L/month**
Annual Total		**438 m^3**

The values from Table 4-2 are the quantities for annual consumption, which is assumed to remain constant all year. The dry season is conservatively assumed to be three months long (90 days) yielding large storage requirements for each location which are provided in Table 4-3.

Table 4-3: Comparison of required versus proposed storage

Storage Requirements assuming 90 day dry season			
	Daily Water Demand	Storage Requirement for Long Dry Season	Existing Storage for RWH
Health Clinic	950 L	85 m^3	**41 m^3**
Primary School	4,000 L	360 m^3	**40 m^3**
Trackers House	1,200 L	110 m^3	**43 m^3**
*Bold-type values indicate the storage volume is not sufficient to last a 90-day dry season			

The "Existing Storage for RWH" column in Table 4-3 is the total storage that is available to the end users for RWH as of January 2008. Theoretically, the storage volume should be higher than the dry season storage requirement to allow for continued water use during longer-than-average dry events and when there are insufficient rains during parts of the rainy season. Unfortunately, it is prohibitively expensive to create reservoirs large enough to hold that volume of water and also unrealistic to assume that there will be no rain at all during the dry season or that alternate supplies of water will not be available.

According to the calculations summarized in Table 4-3, the rainwater collected in the proposed and existing tanks at all three locations is insufficient to supply the specified water demand for the duration of a three-month dry season. To better manage the water during that time, water conservation measures could be enacted to reduce the per-person consumption. Conservation measures will not allow every person to have adequate water throughout the dry season, so alternate water supplies are needed.

4.3.2. Using the Supply Side Approach (Rational Method)

Based on the formula Q=ciA (Equation 4-1), the rational method considers the annual volume of runoff coming from a roof by multiplying the roof area by the average annual rainfall and applying a loss coefficient. All of the analyzed roofs are made of iron sheets and a loss coefficient of 0.85 was used for all calculations. The roof areas in Table 4-4 are based on measurements taken in January 2008. The annual consumption (demand) values in Table 4-5 are from Table 4-2 above. The rational method is based on average annual rainfall and is compared to the average annual water demand. For Bisate, it was assumed that the average rainfall is 1.24 meters per year based on the average of 20 years of data (data provided in Appendix E). The tabulated results for volume are listed in Table 4-5.

Table 4-4: Roof Collection Areas

Location	Roof Area (m^2)
Clinic	378
Primary School	535
Trackers' House	506

Table 4-5: Rational Method Results

Location	Consumption (m^3/year)	Volume running off roof each year (m^3/year)
Clinic	336	398
Primary School	1,450	**564**
Trackers' House	438	533
*Bold-type values indicate that minimum annual consumption is not met		

The results of the rational method indicate that the clinic and trackers' house both have sufficient roof area and subsequent runoff to accommodate the average yearly consumption at each location. Although there are several school buildings near to each other, only the two main buildings, much newer than the others, are being used to collect rainwater. Since there are so many students using the facility, the roof area of those two buildings is not sufficient to provide all of the daily water needs for all of the pupils at the school.

It is interesting to compare the results of the demand calculation with the rational method calculation. As discussed, Table 4-3 indicates that there is not sufficient tank volume to provide the specified demand for the clinic, trackers' house or primary school for the duration of the dry season. In contrast, Table 4-5 shows that there is sufficient annual rainfall to meet demand at two of three locations. It is important to look skeptically at the results of the rational method since they are based on average annual data, not monthly or daily data. In a region such as Rwanda with four distinct seasons, it is not appropriate to use annual averages. Conversely, it is advantageous to recognize the importance of simple calculations; the rational method provides a very quick and easy-to-understand method of determining an appropriate tank volume.

4.3.3. Warwick Calculator Method

The Warwick Calculator determined the reliability, satisfaction, and efficiency of a rainwater harvesting system based on user-supplied input values. The calculator requires ten years of monthly rainfall, collection surface area, daily demand, and a water management strategy. Unlike the demand- and supply-side calculations, the Warwick simulation considers annual and seasonal variation in rainfall patterns. Figure 4-1 is a bar chart displaying the breakdown of average monthly rainfall in Ruhengeri. It is shaded based on the season, with the main dry season lasting from June to August. Unlike other regions in Africa, Rwanda gets a significant amount of rain all year long, and even though there is less rain during the dry season, there is typically some. Figure 4-2 shows the monthly precipitation values that comprise the averaged bar chart in Figure 4-1. The goal of including Figure 4-2 is to illustrate the yearly variation in monthly trends. Twenty years of monthly rainfall data were averaged, but it is obvious that each year does not have the same rainfall pattern. Although the seasonal trends are similar, the yearly variations are substantial. The Rainwater Tank Performance Calculator, available through the University of Warwick, accounts for the monthly variation in rainfall by generating pseudo-daily rainfall records, a process discussed in depth later in this chapter. The complete rainfall data used in Figure 4-2 are listed in Appendix E.

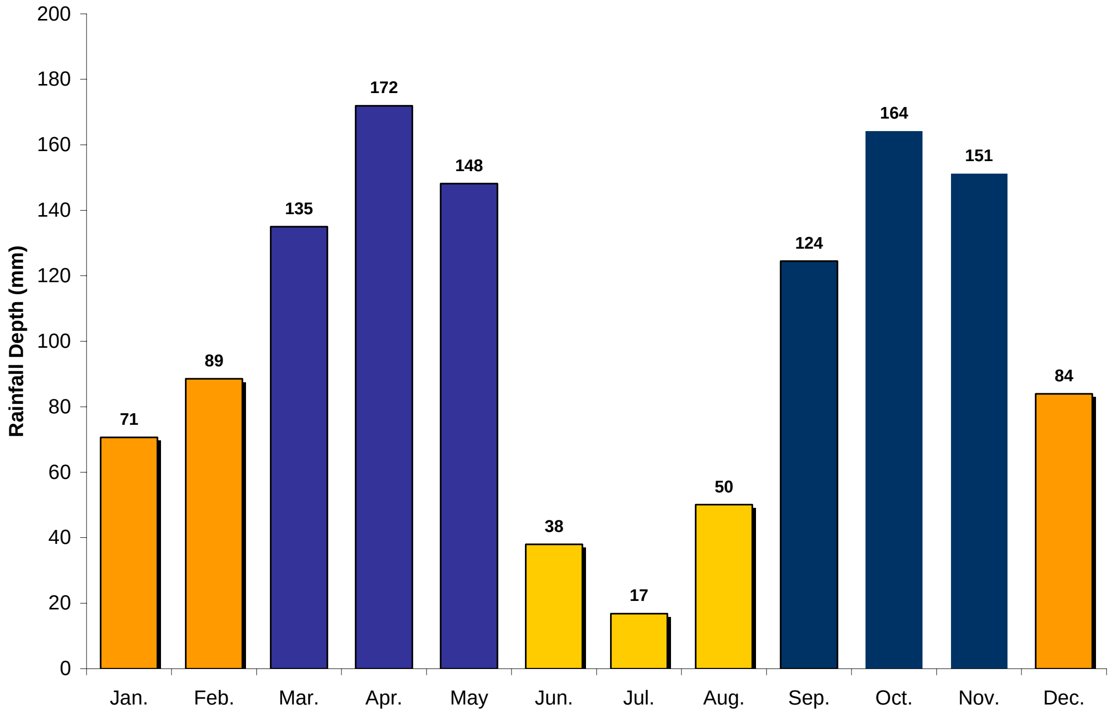


Figure 4-1 : Average Monthly Rainfall 1977-1992, 2002-2005, Musanze

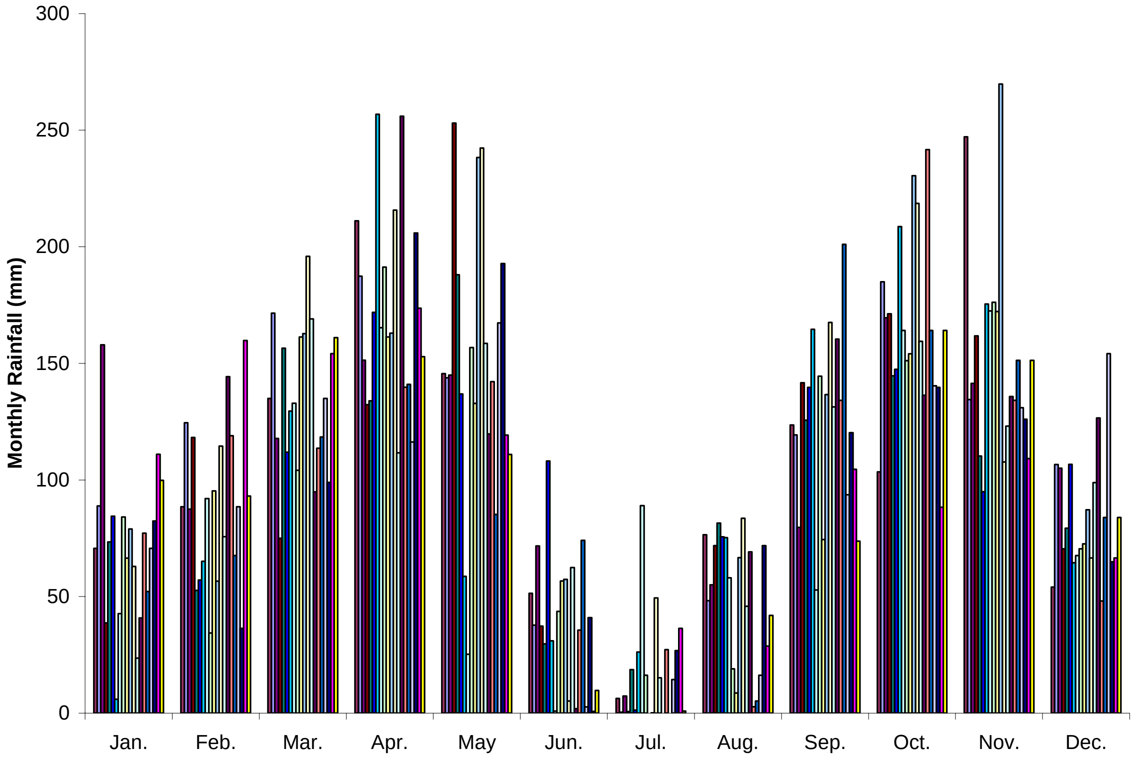


Figure 4-2: Monthly Rainfall 1977-1992, 2002-2005, Musanze

Table 4-6 provides the abbreviated results of the Warwick computer model for each of the three management options. Again, reliability is the percentage of days that water demand is met. The satisfaction value is the percentage of total demand met by the system. Lastly, efficiency is the percentage of water running off of the roof that is collected by the system. A system that is too small will have a low efficiency, since much of the water is lost to overflow.

Table 4-6: Reliability Calculation Results

Clinic			
	Constant	Varies	Seasonal
Reliability	85%	89%	83%
Satisfaction	86%	93%	87%
Efficiency	67%	74%	75%

Primary School			
	Constant	Varies	Seasonal
Reliability	30%	37%	24%
Satisfaction	38%	52%	35%
Efficiency	91%	94%	94%

Trackers' House			
	Constant	Varies	Seasonal
Reliability	82%	88%	80%
Satisfaction	84%	92%	85%
Efficiency	65%	73%	72%

The demand-side calculations showed that none of the locations have sufficient storage capacity to provide water for the duration of the dry season, so it is not surprising that the reliability values are below 100%. As also indicated by the demand-side calculations, the primary school has a much lower reliability when compared to the other two locations. The system at the primary school captures most of the rainfall that falls on its roof but meets demand less than half the time. It is not clear why the values for the seasonal management plan are lower than the values for both the varying water use and constant water use models. Unfortunately the Warwick Calculator is essentially a black-box and there is no way to determine the reason for unexpected results.

The reader should take note that even the highest reliability is only 89% (at the clinic with variable demand), meaning that the tank will be dry for approximately 40 days per average year. The school tanks will be dry for approximately 135 days per average year with variable demand. The tanks are absolutely an improvement to not having any, but it is imperative that they not be relied on as a sole source of water. A combination of water use from the tanks, Bushokoro and Bunyenyeri taps, future groundwater wells and individual family collection systems is necessary. Ideally, by combining multiple water sources and effectively managing them, the people of

Bisate will be able to have reliable supplies of water through the dry season and will not have to enter VNP to collect unclean surface water.

4.4. Simulation Models

While the three reliability-calculation methods presented above are often sufficient for analyzing system performance, a more technically rigorous method was desired to understand more fully the impact that losses (evaporation, etc.) and foul flush diversion have on the performance of the system. Following the work of Lars Hanson of Tufts University, a simulation model was developed to find SRY relationships for Bisate Village by varying the daily demand and storage volume. The work completed by Hanson (2007) considered 232 first-order stations in the contiguous United States and while very comprehensive it his analysis, losses and first flush diversion were not part of the scope of work. The following sections will describe the methods used to develop a simulation model. I include losses and the first flush in the calculations in an effort to understand the effects of losses and diversion on the system performance.

4.4.1. Simulation Parameters

Originally developed to study reservoir operation, SRY behavior is easily adapted to domestic rooftop RWH as rainwater systems are essentially just small reservoirs. A comprehensive discussion of the applications of SRY (sometimes referred to as Storage-Yield-Performance or SYP) to reservoir systems is not included here, so the reader is referred to (McMahon and Adeloye 2005) and other similar texts for further information.

The SRY method is a convenient way of accounting for all of the major design parameters in a single analysis. The roof collection area, volumetric tank capacity, daily demand (yield), and rooftop runoff coefficient are all parameters within the model that can be easily adjusted for different sites. For simplicity of calculations and for easy scaling at specific sites, a unit area of one square meter is used for the roof collection surface. Although rainfall is often available in millimeters, all calculations are completed in meters for convenience. The goal of the simulation is to develop curves of constant reliability based on daily yield and tank storage capacity.

While there are a variety of ways to consider the yield of a system, this method follows the work of Hanson (2007) in defining a dimensionless yield fraction (α), defined as:

Equation 4-4

$$\alpha = \frac{y}{\mu_{dp} A_c}$$

Where y is the daily yield (demand) [m^3/day]; μ_{dp} is the mean daily precipitation [m/day]; and A_c is the collection area [m^2]. μ_{dp} is determined by calculating the arithmetic average of daily precipitation for the entire rainfall record. For the remainder of these calculations A_c is taken as 1 m^2. All further calculations will consider a constant daily yield, although other rationing scenarios are possible, as discussed in the sections about the Warwick performance calculator.

Following Hanson (2007) the physical storage ratio (S_r) is used to quantify the storage capacity of the rain tank. It is normalized by the collection area to provide a more comprehensive analysis that is not dependent on roof size. The physical storage ratio is:

Equation 4-5

$$S_r = \frac{s}{A_c}$$

Where s is the storage capacity of the tank [m^3], A_c is the collection area [1 m^2], and S_r is measured in meters.

Hanson's work (2007) did not factor in a runoff coefficient to account for losses, nor did it consider the application of a first flush diversion system. Based on the fieldwork completed in Rwanda in 2008 and on the work of Martinson and Thomas (2002) it is recommended that the first 1 mm of runoff be diverted from the main supply into an alternate chamber if three or more days have passed without precipitation. Losses will vary depending on the roughness of the roofing material, the temperature of the roof, the number of holes or cracks in the roof or gutters, and the amount of water that splashes over the edge of the roof or sides of the gutters. From Thomas (2002) and for the purposes of these calculations it is useful to assume that the losses are around 15%, meaning that 85% of the rain hitting the roof reaches the first flush device. It is prudent to note that the first flush removal is considered independent of the other system losses.

As noted earlier in this chapter, there are a variety of ways to consider the reliability of a RWH system; reliability is typically based on either time or volume. Time-based reliability considers system "failure" to reflect the amount of time the system is not meeting demand, while volume-based reliability considers "failure" to reflect the volume of daily yield not being met by the system. For time-based reliability, if the daily demand is not satisfied for a given day, the system is considered to have failed. Time-based reliability is considered to be a more conservative method of determining system performance and will be the only type of reliability considered from here on.

Equation 4-6

$$q = 1 - \frac{d_f}{n}$$

Where q is the time-based reliability; d_f is the total number of days of failure of the system; and n is the number of days of the rainfall record (and thus the simulation). Reliability is reported as a number between 0 and 1, where 0 is a system that never meets demand and 1 represents a system that satisfies demand for the entire simulation duration.

There are two options for simulating the tank performance, a yield-after-storage (YAS) algorithm and a yield-before-storage (YBS) algorithm. While rarely a concern in the actual operation of the tank, it is important to distinguish the difference between them for the simulation. YAS, also called spill-before-yield (Hanson 2007), is considered a more conservative approach and assumes that when the tank is at capacity any additional water added to the tank will spill out and be wasted. Only at the end of the day will the user come to extract the full daily yield. By contrast, the YBS algorithm assumes that the user will extract her daily yield before the day's rain, meaning that today's supply does not rely on today's precipitation. The reader is referred to (Bogardi and Kundzewicz 2002; Dhillon 1999; Moran, Patrick Alfred Pierce 1959) for further discussion on spillage algorithms and reservoir reliability. Considered to be more conservative, the YAS approach is used in this simulation to determine how much water is in the tank at the end of each day.

The goal of the SRY analysis for this thesis is to understand the relationship between storage, reliability, and yield. To visualize this relationship a contour graph is used. The storage term, S_r, is taken as the y-coordinate; the dimensionless yield term, α, is used as the x-coordinate; and contour lines represent reliability in the z-direction. To generate the surfaces the simulation is run with a range of α and S_r values. The S_r values used by Hanson (2007) were converted from feet to meters while the α values remained the same. A full list of the α and S_r values used in the simulation can be found in Appendix F.

4.5. Pseudo-daily Rainfall Generation

In order to accurately simulate the dynamics of a RWH system on a daily basis, it is necessary to have a daily rainfall record. While relatively easy to find in the U.S. and other developed nations, long-record daily rainfall is often non-existent or prohibitively expensive to purchase in many developing nations (Thomas 2002). In the absence of advanced weather stations it is necessary to work with the available precipitation records and yet try to generate the most accurate results possible. Precipitation records from a location may be available as: an annual average, a set of typical monthly averages, actual monthly data, actual daily data, or in other smaller (hourly or by-the-minute) time increments. However, not all of these types of records are useful for system simulation. An annual average value is too general for the purposes of a simulation, and monthly values averaged over many years do not reflect the occurrence of extreme events. Records in time increments less than one day are hard to find. The most useful types of rainfall data for use in a simulation are daily records, but as in the case of Bisate Village and many other areas in developing countries, daily records were not available for a long enough record to be useful.

As mentioned earlier, monthly totals collected in a nearby town (Musanze) were available from 1977 until 2005, with 9 years missing from 1993 until 2001, likely interrupted by the violence surrounding the genocide. Within the available monthly data, there were several months with missing data. In order to maintain a long rainfall record, missing values were replaced with the 20-year average for that month, the same values as are presented in Figure 4-1.

These 20 years of monthly data were used to generate 20 years of pseudo-daily rainfall data to be used in the simulation. An approach developed by Terry Thomas (2002) at the University of Warwick and used in the Warwick performance calculator was employed. The reader is referred to (McMahon and Adeloye 2005) for a more comprehensive discussion on statistical rainfall generation. The method used in this thesis was developed expressly for the purpose of generating pseudo-daily rainfall records in the absence of adequate daily data.

In addition to the 20 years of monthly rainfall data, two years of daily precipitation values were available for Bisate Village from 2000 and 2001. Since those records were available, the generated pseudo-daily record was adjusted to mimic the wet-day average of the actual daily values using an iterative approach.

4.5.1. Rainfall Generation Process

Thomas (2002) compiled rainfall data from several different locations in the tropics and deduced trends in the data which he then used to generate pseudo-daily data for other locations. The concept behind pseudo-daily rainfall generation is that if the characteristics of daily rainfall are assumed, random numbers can be assigned to known probabilities to generate a synthetic set of daily precipitation values that are similar to the actual monthly data, yet have a daily distribution. Thomas (2002) illustrated that this method of data generation is much more accurate than the more crude method of dividing the monthly total by the number of days per month to assign the daily rainfall.

To begin, the probability of a day being wet is calculated from an empirical relationship originally calculated by Thomas (2002):

Equation 4-7

$$P_m = \sqrt{\frac{R_m}{A}}$$

Where P_m is the probability of a day being wet ($0 < P_m < 1$) in month *m* of each year; R_m is the actual monthly rainfall record [mm]; and A is an empirical coefficient with value 800 mm for the humid tropics, as specified by Thomas (2002). R_m and P_m both have unique values for every month of the simulation.

Following the example of Thomas (2002), who for simplicity assumed that there are 30 days in each month and thus 360 days in a year, the number of wet days in a standard 30-day month (n_{wm}) is calculated as:

Equation 4-8

$$n_{wm} = 30P_m$$

Where n_{wm} is measured in days (including fractions). To maintain correct monthly totals the mean wet-day rainfall (R_{wm}) in month *m* is calculated as:

Equation 4-9

$$R_{wm} = \frac{R_m}{n_{wm}}$$

There is some concern regarding the bunching of wet days in a month. It is more probable for today to be a wet day if yesterday was a wet day. So, the probability of a day being wet is partially related to the seasonality of the rainfall and the influence of the preceding day's weather, but following the procedure of Thomas (2002), the bunching of wet days is not considered and each day's rainfall is considered independent of the next. Instead, it is assumed that wet days are randomly spaced and can then be assigned a value using a random number generator. If X is a random number between 0 and 1, assigned each day, that day is considered wet if $X < P_m$.

To account for the probability of very high and very low precipitation in a given day Thomas (2002) uses a transformation function before generating the pseudo-daily rainfall value. The transformation function used is:

Equation 4-10 a & b

$$r' = -R_{wm} \ln(Z)$$

$$Z = aX + bX^2 + cX^3$$

Where r' is the generated pseudo-daily rainfall record, R_{wm} is the mean wet-day rainfall for each month in the series, a is a scaling factor, $b = 3 - 3a$, and $c = 2a - 2$. The scaling factor, *a*, determines the frequency of wet days and magnitude of rainfall on wet days. A low value of a will generate a rainfall record with only a few, but very wet days. A high value of a creates a rainfall record with fewer wet days and a lower wet-day average rainfall. The value of a cannot be larger than nine to prevent the generation of negative rainfall amounts. A guess-and-check method was utilized to determine the most appropriate value of a for this simulation so as to generate a series of daily rainfall with a wet-day average that matched that of the available daily data. A very high wet-day average was generated using $a = 1$, around 21 mm, while $a = 9$ generated a lower wet-day average, around 4 mm.

The generated rainfall values (r') are first scaled to match the correct monthly values (process described below), and then the average wet-day rainfall is calculated. From the two available years of daily rainfall values, the average wet-day rainfall for Bisate is around 9.2 mm. Using $a = 9$ for the transformation variable and scaling the record to fit the actual monthly totals yielded an average wet-day rainfall of around 10.1 mm, reasonably close to the actual wet-day average.

As mentioned, the generated daily rainfall (r') values in each month are re-scaled to generate r" values that sum correctly to the original monthly R_m total rainfall. The scaling factor is calculated by dividing the sum of the generated pseudo-daily rainfall values (r') for each month by the actual monthly rainfall for that month (R_m). Each generated pseudo-daily value within the month is then divided by the scaling factor for that month. The resulting generated daily rainfall record is in units of millimeters and will have the same monthly totals as the original monthly data, but have a more realistic wet-day distribution than would be found by evenly dividing the monthly total by 30 days.

By using Equation 4-7 through Equation 4-10 a & b, and applying an appropriate scaling factor, a set of pseudo-daily rainfall can be generated for as long a record as exists for monthly data. The generated pseudo-daily rainfall record (r") has a similar wet-day average and exact monthly totals to the actual rainfall records from the location of interest. It should be noted that the monthly data used in the rainfall generation was from Musanze, a town about 18 km from Bisate Village, but the two-year daily record was from Bisate Village itself. Musanze typically receives slightly less rain than the village. The precipitation record generated with this process was used to evaluate the storage-reliability-yield behavior of rainwater harvesting systems utilizing the methods introduced by Hanson (2007) and discussed previously in this chapter.

4.6. S-R-Y Behavior Results

Following the procedures outlined earlier in this chapter, 20 years of pseudo-daily rainfall were generated for Bisate Village. Those values were then used in the SRY simulation model programmed in a Visual Basic for Applications (VBA) script. The program simulates tank operation with a range of alpha and S_r values and computes the reliability based on the number of days demand is not met. The resulting matrix of alpha, S_r, and reliability was then plotted in MatLab. The plots show the yield term (alpha) on the x-axis and the storage term (S_r) on the y-axis with contours of constant reliability (Figure 4-3 - Figure 4-8). The SRY simulation was run with a variety of water management strategies to gage the sensitivity of the model. The first scenario does not consider losses or first flush diversion of any kind, but rather treats the entire pseudo-daily rainfall as available for storage and use (Figure 4-3). For the remaining five graphs, 85% retention of rainfall was assumed, accounting for various types of losses. Each of the four diversion scenarios uses a different combination of runoff depth diversion and ADWP criteria. Scenario 5 diverts the first flush every time it rains, regardless of whether or not it rained the day before, while scenarios 3, 4, and 6 specify a minimum runoff depth before diversion. A description of each scenario is found in Table 4-7.

Table 4-7: SRY simulation scenarios

Scenario	Figure number	Assumed loss	Diversion
Scenario 1	Figure 4-3	Zero loss	No diversion
Scenario 2	Figure 4-4	15% loss	No diversion
Scenario 3	Figure 4-5	15% loss	0.5-mm diversion after three consecutive days each with <0.5 mm total rainfall
Scenario 4	Figure 4-6	15% loss	1-mm diversion after three consecutive days each with <1 mm total rainfall
Scenario 5	Figure 4-7	15% loss	1-mm diversion on each day with rainfall
Scenario 6	Figure 4-8	15% loss	2-mm diversion after three consecutive days each with <2 mm total rainfall

The contour lines in the following figures are displayed at constant reliabilities of 99, 90 80, 70, 60, and 50%. The black sections of the graph represent reliabilities less than 50%.

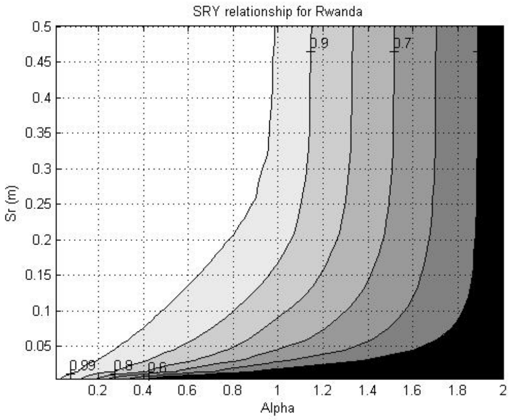


Figure 4-3: Base case, no losses, no diversion

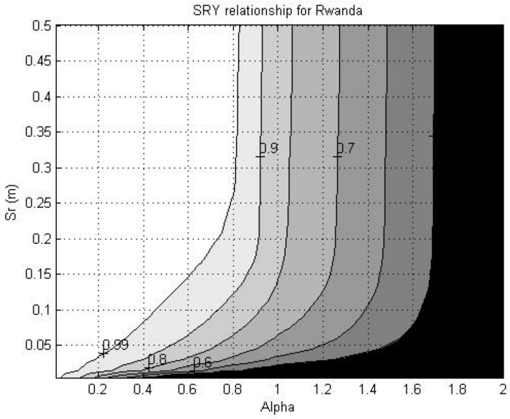


Figure 4-4: 15% losses, no diversion

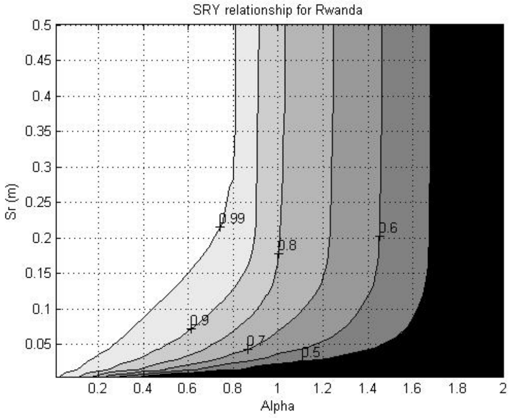


Figure 4-5:15% losses + 0.5mm diversion after 3 days low rain

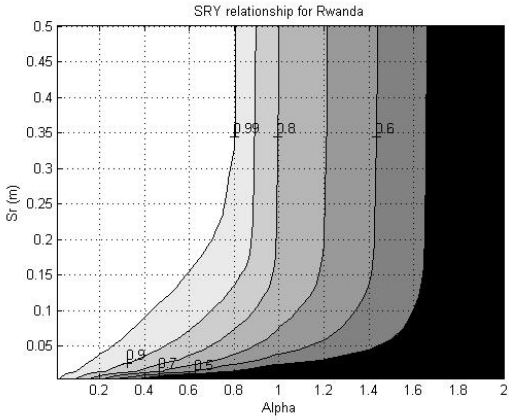


Figure 4-6: 15% losses + 1mm diversion after 3 days low rain

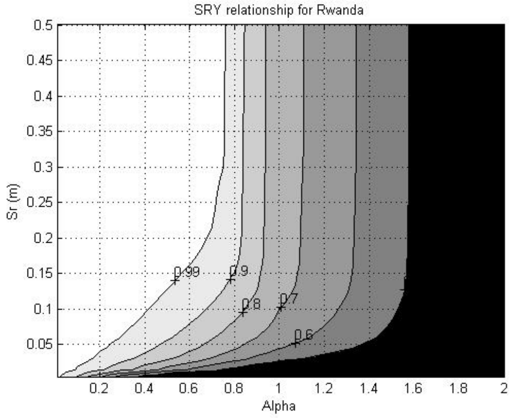


Figure 4-7: 15% losses + 1mm diversion on every day with rain

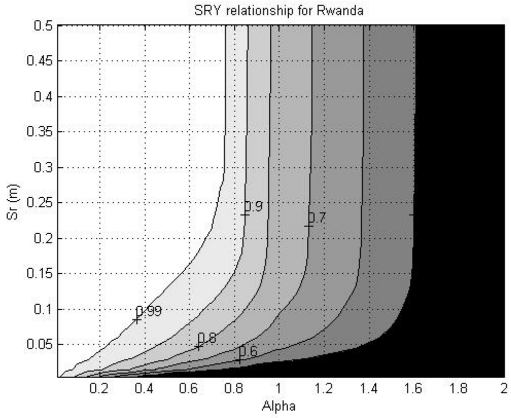


Figure 4-8: 15% losses + 2 mm diversion after 3 days of low rain

4.7. SRY Discussion

The goal of running multiple simulations is to understand how reliability is affected by first-flush diversion. All of the contour lines in each of the graphs eventually reach a constant alpha value. The vertical contour lines indicate that the daily yield of the system will not increase even if the tank volume is increased. At certain values of alpha and S_r, the tank volume is not the limiting factor, but instead system performance is restricted by the amount of runoff available. To attain a higher reliability, alpha may be improved either by increasing the size of the collection area (A_c) or reducing demand.

Surprisingly, the graphs do not vary much from one scenario to the next. An easy way to compare the plots is to note at what value of alpha the 99% reliability contour asymptotes. The scenario with the most available runoff for RWH is the base case (Figure 4-3) which reaches a maximum alpha of approximately one. Alpha equals one when the daily yield per unit area is equal to the mean daily rainfall. Scenario 6, with 2 mm diversion (Figure 4-8), has the least amount of runoff available for capture and has a maximum alpha value of approximately 0.75. Thus, alpha varies by no more than 25% throughout these scenarios.

To better understand the sensitivity of the model and to evaluate the performance of the existing tanks in Rwanda, the alpha and S_r values for each of the three RWH system locations are shown in Table 4-8. The values were calculated using Table 4-1, Table 4-2, Table 4-4, Equation 4-4, and Equation 4-5.

Table 4-8: Alpha and S_r values for three locations in Bisate

	Health Clinic	Primary School	Trackers' House
alpha	0.71	2.2	0.69
S_r	0.11	0.07	0.08

The simulation was re-run using the specific combination of alpha and S_r values for the three sites in order to calculate the exact reliability of each, as shown in Table 4-9. Because the water demand at the primary school is so high, the alpha value is above the maximum displayed on the chart, with also explains the very low reliabilities.

Table 4-9: Reliability values for each scenario at three locations in Bisate

		Reliability (%)		
Figure Number	**Scenario**	**Health Clinic**	**Primary School**	**Trackers' House**
Figure 4-3	Base case, no losses, no diversion	94.4 %	36.8 %	91.0 %
Figure 4-4	15% losses, no diversion	92.4 %	30.6 %	88.8 %
Figure 4-5	15% losses, 0.5 mm diversion after 3 consecutive days each with <0.5 mm rain	91.7 %	30.1 %	88.0 %
Figure 4-6	15% losses, 1 mm diversion after 3 consecutive days each with <1 mm rain	90.9 %	29.6 %	87.1 %
Figure 4-7	15% losses, 1 mm diversion on each day of rain	89.7 %	27.8 %	85.7 %
Figure 4-8	15% losses, 2 mm diversion after 3 consecutive days each with <2 mm rain	89.5 %	28.4 %	85.1 %

In Chapter 3, I recommend that systems in Bisate Village divert 1 mm of diversion after three consecutive days with less than 1 mm of precipitation. Any runoff depth less than 1 mm is not sufficient to effectively clean the roof of particulate matter and thus should not be considered a significant rain event. Diversion of a first-flush volume reduces reliability only slightly according to the simulation model. Table 4-10 compares the reduction in reliabilities and the increase in the number of days where demand is not met resulting from the 1-mm-diversion-after-3-dry-days scenario.

Table 4-10: Reduction in reliability from adoption of first flush diversion

	Health Clinic	Primary School	Trackers' House
Reduction in reliability from 1mm-3 day diversion scheme	1.5%	1.0%	1.7%
Additional days not meeting demand with first flush diversion	6 days	4 days	7 days

Table 4-10 illustrates that with the recommended 1-mm diversion of the first flush the reliability of the system is not drastically reduced. Theoretically there will be between four and seven additional days where the specified demand is not met, which is reasonable when one considers the variability in the rainfall and water use. Even though a constant demand is specified, it is very unlikely that the exact same amount of water will be used each day. For a slight reduction in performance, the end users should be able to enjoy 50% reduction in turbidity and conductivity, and a large reduction in microbial contamination. It is also relevant to consider the uses of the diverted first flush. While not suitable for drinking, the water can still be used for other purposes, such as irrigation.

4.7.1. Comparison to Warwick Computer Model

Section 4.3.3 of this chapter discusses the Warwick Performance Calculator (Warwick 2008) and its results for the clinic, primary school, and trackers' house. I used a similar method to the one used in the calculator to generate a pseudo-daily rainfall record and simulate tank performance. Thus, the results from the Warwick calculator and the simulation used in this thesis should be similar. The performance calculator also assumes 85% retention of rainfall, although it assumes the tank is half full on day one while the SRY simulation begins with an empty tank. Ten years of monthly rainfall record are used to generate ten years of pseudo-daily record in the calculator, which is the same process used in this thesis, although I used twenty years of data. Within the rainfall generation process, it is likely that the online software selected a different a value (Equation 4-10) than I used in my calculations, since there is no documentation within the software to determine what value of a was used. It is most appropriate to compare the constant-yield management strategy from the Warwick calculator for each location with the "15% losses, no diversion" simulation (Figure 4-4). The comparison of the two reliability models is shown in Table 4-11.

Table 4-11: Comparison of reliabilities (%) from Warwick calculator and SRY simulation for three locations

	Health Clinic	**Primary School**	**Trackers' House**
Warwick Calculator	85%	30%	82%
SRY simulation	92%	31%	89%

The SRY simulation produced reliabilities 7% higher than the Warwick calculator for both the health clinic and the trackers house, but the low reliabilities at the primary school differed by only 1%. The differences between the two simulations are possibly a result of the longer rainfall record used in the SRY simulation, the potentially different *a* values, or perhaps another parameter not visible within the "black box" of the performance calculator. The Warwick calculator has a 2% inherent variability in reliability values (Warwick 2008), so assuming the SRY simulation has a similar variability, the differences between the values is even smaller. A 3% difference in reliability values is acceptable given the variable nature of the RWH system and the limitations in the simulation itself.

4.8. SRY Conclusions

Overall, the results of the simulation indicate that the diversion of the first flush does not significantly reduce the reliability of the system. The 2008 fieldwork presented in Chapter 3 confirmed that diversion of the first millimeter of runoff is appropriate to see a 50% reduction in turbidity and conductivity, and a drastic reduction in bacterial contamination. It is unnecessary to divert runoff if heavy rain has recently fallen, so it is recommended that the first flush be diverted after three consecutive days each with precipitation amounts less than 1 mm. The simulation results suggest that the recommended first flush diversion will not drastically reduce the reliability of the system, strengthening the argument for first flush diversion. Although fieldwork was completed in Rwanda, the results of this study are applicable in most places utilizing rooftop rainwater harvesting technology, but may need to be adjusted on a case-by-case basis. With a simple PVC diversion pipe, water quality can be improved, meaning a supply of cleaner water to people with few alternatives.

CHAPTER 5: Conclusions

A good scientist is a person with original ideas. A good engineer is a person who makes a design that works with as few original ideas as possible. –Freeman Dyson.

Chapter 5: Conclusions

5.1. Research Needs

This thesis focused on the effect of first flush diversion on RWH system reliability in the context of a daily simulation model and water quality tests, an aspect of RWH not previously considered, yet there are many further research needs in this field. The impact of rainfall intensity on the first flush phenomenon is not well characterized in the literature and there is a need for a more fine-tuned understanding of the wash-off process. A longer-term study of the effect of ADWP on initial turbidity would be useful for making recommendations on how often the first flush should be diverted during the rainy season. It would also be useful to complete a study that more accurately calculates the loss fraction for different roofs. Much of the literature, including this thesis, just assumes a value for losses based on a generalized value, or from a range of values for a particular roofing material. One study could consider the effect of roof material, slope, and/or gutter design on losses.

More extensive studies on the effect of tree-proximity and distance-to-roadway on runoff quality should be completed in conjunction with a study on the effects of roof- and tank-cleaning on runoff quality. There are many questions regarding the stored water in the tank that need to be answered definitively. How significantly does scrubbing the roof affect the overall runoff water quality? Is proximity to trees a concern for fecal contamination from birds, and do the leaves on the roof negatively affect water quality? Is there any correlation between distance to a latrine and *E. coli* contamination in the tank?

There are also many optimization problems to be considered for a rainwater harvesting system. For example, finding an optimized first flush diversion scheme that maximizes pollutant removal and minimizes the amount of “clean” water wasted in the diverter.

There is also much work to be done to secure other sources of water and make them safe for consumption. There have been no studies to date on how to best protect the natural water sources in Bisate (such as Bushokoro and Bunyenyeri) from bacterial contamination. Since RWH cannot be relied on as a sole system for water provision, it is necessary to have an alternate supply with safe, reliable water. Future studies should also consider options for disinfection and/or filtration systems to be installed in tandem with a first flush diversion system.

There is no shortage of studies that could be completed related to rainwater harvesting, the first flush, or sanitation in Bisate, but the recommendations made above are areas in need of attention.

5.2. Thesis Summary and Conclusions

Rooftop rainwater harvesting (RWH) is a well-known technology used to supply water for domestic use in developing countries. In recent years it has also been adopted in developed nations to reduce runoff and to provide supplemental water for irrigation. While there are many ways to collect runoff for future use, RWH involves collection of rainwater runoff from a rooftop via a guttering system and storage in a cistern. Although not always implemented, there are a variety of technologies to improve the water quality prior to consumption.

Chapter 5: Conclusions

Design of an appropriate RWH system in developing countries involves the proper selection of roof and tank materials, sound gutter design and construction, selection of a suitable treatment technology, and appropriate tank sizing and construction. Beyond the main technical design components, a successful rainwater harvesting system will also be adequately protected from vandalism, have an official management plan, a regular maintenance schedule, and be operable by the local people. All parts for the system should be locally available and people must be trained in maintenance techniques. With proper design and management, a rainwater harvesting system can provide a significant portion of domestic water needs for a community, and with a simple treatment system the water quality can be quite good.

During dry weather, pollutants accumulate on the roof surface, typically in the form of dust, bird droppings, leaves, and dead insects. Without a treatment system, the first rainstorm after a dry period of several days carries the pollutants into the main tank, contaminating the entire supply. The portion of pollutant-laden water flowing from a roof at the beginning of a rainstorm is known as the first flush, and it has been shown that diverting that water so as to prevent it from entering the storage tank improves the water quality in the main storage tank. While there are many design options for a first flush diversion device, the simplest involves a long PVC pipe attached to the downspout with a removable plug or stopper at the end. The dirtiest water at the beginning of the storm fills the pipe; once full, the cleaner runoff then flows into the main tank. The diversion pipe should then be emptied several days after the rainstorm in preparation for the next rain event.

The literature defines under what criteria the first flush actually occurs. Some scholars maintain that a significant first flush exists when 80% of the total contaminant load is transported in the first 30% of the total storm volume (Saget et al. 1996; Bertrand-Krajewski 1998). Another definition states that the first flush phenomenon exists when the ratio of the fractional volume transported to fractional storm volume passed is greater than one (Helsel *et al.* 1979). For the purposes of this thesis it is assumed that the first flush exists if the contaminant concentration decreases with runoff depth.

Given the variety of first flush definitions and design options for the diverter, one of the goals of this thesis was to quantify the first flush for several RWH systems in rural Rwanda. Bisate, a village of approximately 8,500 people, is located in the foothills of the Virunga Volcanoes in northwestern Rwanda. This area of Rwanda is also home to the endangered mountain gorilla, and the Dian Fossey Gorilla Fund International. Although rain is plentiful in the region, access to reliable, safe drinking water sources is scarce due to geologic conditions and lack of infrastructure. In-country fieldwork in January 2007 evaluated the potential for rainwater harvesting and considered design options for new tank construction. During 2007, 13 new tanks were constructed and an interest in improved water quality was noted for the systems. To address water quality concerns, the author completed a second round of fieldwork in January 2008 aimed at testing the water quality of the first flush.

Sampling apparatuses named Graduated Inflow-collectors for Zero Mixing and Overflow (GIZMOs) were used to collect discrete time-sequenced volumes of runoff from three different roofs in the village. Constructed with PCV pipe and plastic water bottles, the GIZMOs captured up to the first 1.6 mm of runoff from a new iron roof, an old dirty rusty iron roof, and an old dirty clay tile roof. The water was retrieved from the bottles and tested for turbidity, pH, conductivity, color, total coliform, and *E. coli*.

Chapter 5: Conclusions

Analysis of the first flush measurements revealed generally exponential decreases in turbidity and conductivity with increasing cumulative runoff depth. For turbidity, exponents ranged from about 0.6 to 2.0, which matched the range of exponent values for a similar study conducted on roofs in Uganda (Martinson and Thomas 2005). Although the microbial results did not follow exponential trendlines as closely, there was a clear reduction with increased runoff depth, often of several orders of magnitude. None of the samples revealed *E. coli* values higher than 1 colony per 100 mL after 0.86 mm of runoff, which strongly supports first flush diversion. Based on the results of the water quality analysis and other first flush diversion recommendations in the literature, the author proposes that the first one millimeter of rain be diverted from the main supply after three consecutive days each with rainfall less than one millimeter. The three-day delay is to prevent water from being wasted when the roof is still clean from a recent heavy rain.

Because maintaining an adequate water supply is such a high priority, it is important to understand the impact of first flush diversion on the reliability of the system over a long time period. The reliability of a rainwater harvesting system is a measure of its ability to produce the water needed by the system users. Although there are several ways to measure reliability, this thesis used time-based reliability which divides the number of days demand is not met by the total number of days considered. The reliability of the RWH system is particularly important for tank sizing. There are several simple methods to calculate the required storage for a community tank. These include calculations based on dry-season demand or based on available annual supply, although these methods do not consider seasonal or yearly variations in rainfall. A free online performance calculator provided by the University of Warwick is one tool to evaluate the performance of an existing or proposed rainwater harvesting system (Warwick 2008), but it does not consider the impact of first flush removal on the reliability. There is no tool to evaluate the reliability of a rainwater harvesting system while accounting for water losses due to evaporation, leaks, and diversion of the first flush of runoff. This thesis developed such a tool based on a storage-reliability-yield simulation model from work completed by Hanson (2007).

Reliability is based on a variety of factors, but especially on: the rainfall distribution in the area, the size of the collection roof, the capacity of the storage tank, and the daily demand for the water. The storage-reliability-yield (SRY) behavior of a rainwater harvesting system indicates trends in reliability as storage and yield (demand) are varied. As in many developing countries, daily rainfall records of sufficient duration do not exist for Bisate Village. Fortunately, 20 years of monthly records are available from a nearby town, in addition to the two years of daily values available for Bisate. A rainfall disaggregation method was used to synthesize a 20-year sequence of pseudo-daily values based on the actual 20-year monthly series. The two years of available daily data were then used to fine-tune the wet-day rainfall average to make it closely match the actual average. The generated rainfall data has the exact monthly totals as the real monthly record, has a similar wet-day rainfall average, and similar distribution of daily rainfall totals as the actual two-year daily record. That pseudo-daily rainfall series was then input into the SRY simulation model to calculate the reliability trends for a variety of storage and yield (demand) combinations.

The SRY simulation model with first flush diversion was coded in Visual Basic for Applications (VBA) and run through a series of combinations of storage and yield terms to mimic the day-to-day functioning of the RWH system. For example, if the volume of water exceeded the volume of the tank, any excess water was spilled. Similarly, if the demand was greater than the remaining volume of water in the tank, the tank was emptied and the system was considered to have not met demand on that day. For simulation purposes it was assumed that the daily yield was removed from the tank after the day's rain had filled into the tank (or spilled over in excess). The simulation was run for the full 20-year pseudo-daily rainfall record and a matrix of storage, yield, and reliability values was generated.

The simulation was then run for a variety of first flush management scenarios to determine the effect of diversion on the reliability of the system. Based on the results of the SRY simulation, the adoption of a "1 mm diversion after 3 days" rule will lead to a decrease in reliability of between 1-2%, which means approximately an additional 4-8 days per year when demand is not met. Considering the limitations of the simulation itself, the seasonal and annual variability of rainfall, the uncertainty and variability of water demand, and the occurrence of unforeseen circumstances (i.e. vandalism), even a 5% decrease in reliability is relatively insignificant. Since the systems are never 100% reliable, RWH systems should not be relied on as the sole source of water for a community. By removing the first millimeter of runoff after three days with little rain, the water quality of the stored water will greatly improve. The simulations showed that the SRY behavior is not drastically affected by diversion of the first flush.

Both the water quality analysis of the first flush during in-country fieldwork and evaluation of the reliability of a rainwater harvesting system implementing first flush diversion lead to the recommendation that the first millimeter of runoff be diverted from the roof after three consecutive days of precipitation less than one millimeter. This recommendation is case-specific but should greatly improve the quality of water stored in the tanks, improving the health of the end users without severely compromising the reliability of the system.

While the first flush diversion is a simple way to improve water quality, like all other technologies, it must be properly managed and maintained. There are a variety of "automatic" diverters, but for long-term use a simple system with locally available parts is the best option. Care needs to be taken to empty the device at the appropriate times, to clean the pipe of debris, to wash the roof after an extended period without rain (at the end of the dry season), and to periodically clean the tanks. With proper operation and maintenance, rooftop rainwater harvesting in conjunction with first flush diversion has the potential to provide relatively clean, reliable water to people in need.

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APPENDICES

The test of progress is not whether we add more to the abundance of those who have much; it is whether we provide enough for those who have little. –FDR 1937

Appendix A: Supplemental Reading

A.1. Previous Project Work

This work is a continuation of research begun during the 2006-2007 academic year; three students conducted research related to water supply options for Bisate Village and produced a joint document, Design of a Sustainable Drinking Water System for Bisate Village, Rwanda (Cresti et al. 2007). Ms Daria Cresti completed a design and evaluation of individual family-sized rainwater collection ponds for Bisate Village. Ms. Christiane Zoghbi completed a preliminary evaluation of groundwater for extraction in the region of Volcanoes National Park (VNP) in Rwanda, which includes Bisate. The author completed a report entitled Rainwater Harvesting Design Considerations and Evaluation of Existing Water Supply System in Bisate Village, Rwanda which has been incorporated into this document. That report focused on the background information on Rwanda, water issues in the volcanoes region, the project location, and the local organizations that provided support for the project. The 2006-2007 academic year focused on water supply in Bisate Village, while the 2007-2008 academic year concentrated on water quality of harvested rainwater. The reader is referred to the theses produced by the other members of the team for more information on their work (Cresti 2007, Zoghbi 2007).

A.2. Rwanda Background

While the focus of this report is not on the history of Rwanda or the recent genocide, the events that took place in the last two decades have had such a drastic impact on the country and on its current welfare that it is important to introduce them. The genocide began on April 6, 1994 following the explosion of President Habyarimana's airplane (Percival 1995). The genocide killed an estimated 800,000 people during the 3 months of intense fighting, while twice that many were displaced to neighboring countries (DOS 2007). The genocide disrupted the entire country, leaving many without the basic necessities and destroying most of the infrastructure. Residents of the Northern Province told our team that the violence of the war continued for many years, particularly during a hostile time in 1997 and 1998. The genocide redefined the country and its goals; the Rwandan citizens are still recovering from war and trying to continue their lives. The effects of the genocide are apparent in most aspects of Rwandan society.

In an effort to recover from the war, the government has made many changes to give the country a new face. Once a month citizens participate in a day of service, working to plant flowers, remove trash, and fix roadways. Many of the war-torn buildings in Kigali have since been reconstructed and in 2005 sector boundaries were redrawn and many towns were renamed, a source of confusion for spatially-dependent data analysis.

The following statistics come from the U.S. Department of State’s Bureau of Africa Affairs, and help to illustrate the current cultural dynamic of the country. Eighty-five percent of the estimated 8.6 million inhabitants of Rwanda are Hutu, fourteen percent are Tutsi, and one percent Twa. Although the genocide in 1994 was primarily targeted at the Tutsi communities, revenge killings and a variety of other factors have kept the relative ratios similar both pre- and post-genocide. Official identity cards labeling a person as “Hutu” or “Tutsi” have been destroyed and there is no longer formal documentation of such a distinction. Approximately 94% of the population considers themselves to be Christian, a result of the Belgian colonization, which began in 1915. Another 4.6% of the population is Muslim and 1.7% claims no religion.

The primary language spoken in the country is Kinyarwanda, while most government work and professional meetings are carried out in either French or English. There are six years of mandatory primary education with a country-wide literacy rate of 70%. Sub-par sanitation and hygiene practices, water-borne disease, and the effects of sicknesses such as malaria are reflected in the low average life expectancy of only 47.3 years and an infant mortality rate of roughly 90 deaths per 1,000 births (DOS 2007). For comparison, in the United States literacy is 99%, life expectancy is approximately 75 years and 81 years for men and women respectively, and infant mortality is about 6 deaths per 1,000 live births (CIA 2007).

Rwanda has the highest population density of all the countries in Africa. As of an estimate in 2006, the density in the country is approximately 330 people per square kilometer. According to sources in Rwanda, the population density in some of the districts in the Northern Province is close to 580 people per square kilometer (Nshimyimana 2007b). By comparison, New Jersey, the most densely populated state in the U.S. has approximately 400 people per square kilometer (Phillips 2007). Considering that the majority of the population relies on subsistence agriculture, the demand so many people place on the land is enormous. Following the disruption during the genocide, many citizens fled from the cities, settling in the rural areas. The extreme poverty, high population, and erosion problems leading to poor soil conditions have forced people to continually clear land in the mountains. The reduction in vegetation, extensive farming, and soil degradation has exacerbated water scarcity problems in the northwest region of the country (Bangs 2006).

A.2.1. Economy/Tourism

Although Rwanda is a very poor sub-Saharan African country, in recent years the government has been trying to increase tourism in an effort to increase revenue and to protect and promote the culture and heritage of Rwanda. One of its economic strategies is to increase high-end eco-tourism, bringing in high profits while avoiding the negative consequences of tourism, such as habitat degradation in the parks.

Although about 90% of the population is engaged in subsistence agriculture, the country has export markets for tea, coffee and pyrethrum (used to make insecticide) . The economy is rebounding from the genocide, boasting a growth rate of around 6%. The government has specific plans to reform the economic system including placing an emphasis on human resource development, liberalizing trade, and privatizing public enterprises (REIPA 2007).

Tourism is also considered one of the most important resources to narrow the wide trade gap between imports and exports, currently at $260 million and $70 million, respectively (RDG undated). However, as a result of the genocide and recent instability in neighboring countries, the tourism industry is extremely sensitive to all safety-related events in Africa (UN 2006).

Rwandan tourism is managed by ORTPN (*Office Rwandais du Tourisme et des Parcs Nationaux*), which continues to be an important advocate of eco-tourism. Some of the most popular tourism activities include treks to view mountain gorillas in Volcanoes National Park, hikes to see golden monkeys in Nyungwe National Park, visits to Lake Kivu, and game drives in

Akagera National Park. One of the key strategies of ORTPN has been to endorse high-end tourism, as opposed to mass tourism, with the goal of attracting fewer individuals with more money and a higher sensitivity to environmental issues. By charging high prices for tourism activities, the government can benefit from the profits without sacrificing natural and cultural beauty for large crowds. For example, during the 2007 fieldwork, gorilla-tracking permits cost $375 US per person, yet increased to $500 US during the year. Only eight tourists are allowed to visit each gorilla group per day, to avoid adverse impacts on the gorilla population. Tourists may also hike the volcanoes with escorts from armed soldiers. Figure A-1 is a view of three Rwandan volcanoes from the slopes of Bisoke volcano. Protecting the environment as well as providing people who live around tourist areas with enough revenue for self-support has been a goal for the tourism industry in the nation (RDG undated).

Figure A-1: View of volcanoes from Bisoke

A.3. Collaboration in Rwanda

A.3.1. Dian Fossey Gorilla Fund International

The Dian Fossey Gorilla Fund International (DFGFI) is a non-profit organization created in 1978 dedicated to the conservation and protection of the endangered mountain gorillas (*Gorilla gorilla berengei*) and their habitat in Africa. Figure A-2 shows one of the silverback mountain gorillas in the VNP that the author visited in 2007. DFGFI is well-known to the public through the novel and motion picture both entitled “Gorillas in the Mist,” which documented the life of Dr. Dian Fossey and the struggles of the mountain gorillas. DFGFI promotes continued research on both the gorillas and the ecosystems in which they live (DFGFI 2007). The organization is committed to keeping Dr. Fossey’s passion and love of primates strong. In addition to supporting research, DFGFI also provides educational assistance to local communities and supports economic development initiatives. It has been instrumental in protecting the critically endangered mountain gorillas since Dr. Fossey’s tragic murder in 1984. Thanks to the efforts of DFGFI, the gorillas remained largely protected from the horrors of the 1994 genocide and 1997/1998 violence, although there are continued threats to their safety from poachers and rebels, particularly in DCR. The tourism industry relies heavily on the animals to attract wealthy foreign tourists to the poverty stricken region.

Appendix A: Supplemental Reading

Figure A-2: Silverback Mountain Gorilla

DFGFI supports many kinds of research in an effort to promote understanding and conservation. Their research includes monitoring and protection of the gorillas in Volcanoes National Park, dissemination of knowledge to promote common gorilla monitoring protocols, collection of demographic data in collaboration with 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 2007). Through their research efforts, scientists at DFGFI have discovered that many of the gorillas carry the same intestinal parasites as local people, indicating that human interaction with the gorillas has adverse effects on the gorillas' health (Lilly 2006). The primary reason for the unintended human-gorilla interaction is the scarcity of water in the region. When the local people enter the forest, they can spread human diseases to the gorillas, endangering the health of the population. Although it is possible for tourists to spread disease also, there are strict rules that must be obeyed to keep the gorillas safe.

Originally opened in 1967, the Karisoke Research Center is the main hub of gorilla research, where scientists study and track the 380 remaining mountain gorillas in Rwanda (DFGFI 2007). Although the original research center built and used by Dian Fossey was destroyed during the genocide, research continues from another facility in Musanze, about 18 km from the national park (Figure A-3).

Figure A-3: The main gate to Karisoke, displaying the DFGFI logo

A.3.2. Ecosystem Health Program

One of the many conservation and research initiatives undertaken by DFGFI is the Ecosystem Health Program (EHP). Fieldwork was partially sponsored by the EHP and our group worked closely with their team, particularly Jean Pierre Nshimyimana, who is an expert in environmental health and acted as a technical field guide and translator. The main purpose of the DFGFI Ecosystem Health Program is to provide a healthy environment for both the mountain gorillas and local people in order to better the lives of both groups.

In order to achieve their mission, the staff of the EHP diagnoses and treats intestinal parasites in both human and gorilla communities, educates local people about improved sanitation methods, trains health-care providers to treat parasitic diseases, and provides medication to local schools and health clinics (DFGFI 2007). The Bisate health clinic is one such facility receiving aid from the EHP. As of January 2008 the clinic had no electricity, no running water, and was staffed by only a handful of nurses, but many new projects were in progress to improve conditions.

The Ecosystem Health Program seeks to protect the gorillas and humans from parasitic diseases. For humans, having a reliable source of clean water is integral to healthy living, and thus it became mutually beneficial for MIT students to work in tandem with the Ecosystem Health Program to design alternatives for sustainable sources of domestic water.

A.4. Bisate Village

A.4.1. Water Sources for Bisate Village

The Bushokoro water system supplies water to the main tap in Bisate. Within the national park, the source is a small waterfall that appears to be derived from surface water or from a shallow perched spring. At the base of the waterfall a large concrete catch basin has been constructed. The basin consisted of three boxes with plan areas of approximately one square meter each with removable concrete covers. A wire screen partially covers an opening into the tank to prevent large debris from falling into the system. Still within the forest, the water piped from the collection basins is held in an underground concrete cistern. The area around the tank is not protected and there is evidence of heavy human and animal traffic in the area. The water from the tank flows to a large stone/masonry holding tank more than one kilometer away from town. The tank is sealed, accessible only with proper tools, and has a spigot that supplies water to about 1,000 people (Nshimyimana 2007a). The water then flows to the main tap in Bisate where it is collected by the local people in their personal jerrycans.

As mentioned in below, in 2008 a new tank was under construction to act as an additional intermediate tank for water flowing from Bushokoro.

Bisate also has a relatively new Catholic church with a large masonry tank collecting water from one-half of the roof. The tank holds roughly 40 m^3 of water and is owned by ORTPN, but a hail storm took down the gutters in mid-2007 and they are still pending replacement as of early 2008. The runoff from the other half of the roof is now directed into tanks for use by the DFGFI trackers.

A.4.2. Recommendations from 2007 and New Improvements

During and following fieldwork in 2007, the team made many recommendations for improvements to the water and sanitation infrastructure in Bisate, which were eventually documented and presented in the final versions of the reports. In response to the recommendations, many changes were made and are still underway in Bisate. There are three main focus areas: the local health clinic, primary school, and gorilla trackers' house. The sections below will outline what recommendations were suggested in 2007 and what has been accomplished at each location as of January 2008. Under the umbrella of DFGFI and the Ecosystem Health Program, Jean Pierre Nshimyimana is responsible for the majority of the work completed in Bisate in 2007.

A.4.2.1. Bisate Health Clinic

The focal point of Bisate is the health clinic, which has had the good fortune of receiving aid from several funding sources. According to Jean Pierre Nshimyimana, the clinic staff sees approximately 100 people per day and serves a total population of approximately 20,000, yet it only has 15 patient beds, does not have electricity or running water. Figure A-4 shows the health clinic, with a newly renovated grass and gravel driveway/walking path.

Figure A-4: Bisate Health Clinic

The water for the clinic was previously collected from Bushokoro source, the unprotected forest spring contaminated with bacteria. It is unclear how the clinic obtained water during the dry season when the spring ran dry, but there were no improved sources in close proximity to the clinic. Since January 2007 five new plastic water tanks have been installed: four 10 m^3 tanks and one 1.35 m^3 tank. To collect the water, gutters were installed along both of the existing buildings and a new roof was constructed above the tanks. The total collection area to the tanks is 378 m^2 with 81 meters of guttering. Some concern had been expressed in the past regarding security issues with plastic tanks. Plastic tanks have the potential to be easily vandalized and the water contaminated by dirty hands in the tank. To alleviate this concern the tanks were surrounded by a chain-linked fence and the gate secured with a lock, as seen in Figure A-5.

The tanks are connected to each other via 3-inch PVC pipes allowing overflow water from one tank to fill the next tank in sequence. There are also 1-inch galvanized steel pipes and valves at the bottom of each tank to control the flow of water to the fetching point outside the fence.

Figure A-5: New rain tanks and gutters at health clinic

The clinic health workers are responsible for operation and maintenance of the tanks and are also key-holders to the gate. The valves are only opened when the water is to be used for the clinic's needs. Other people needing water use Bushokoro source water from one of two nearby fetching points.

There was also a very small 0.250 m^3 tank installed on the roof of the nearby latrine. The water from this tank is reserved for handwashing only and is not protected or covered.

A.4.2.2. DFGFI Trackers' House

The team observed in 2007 that the trackers' only source of water was a small, elevated metal tank. The trackers doubted the quality of the water from it, and so were not using it for drinking water. Recommendations were made to clean the tank and improve water access to the house. In a similar design to the clinic tanks, five new plastic tanks were installed behind the trackers house. Four are 10 m^3 each and one is 2.5 m^3, collecting water from a total area of 506 m^2. The area includes: the trackers' house roof, the roof above the tanks, and a portion of the roof on the nearby Catholic Church. Now obsolete, the old metal tank was removed and sold to a local man for personal use. The new tanks, roof, and fetching point are visible in Figure A-6.

The trackers have a very high daily water demand compared to the majority of people in the village because they need to wash their uniforms everyday after returning from the forest; only 50 trackers use the water from the new tanks.

There is also a new station for washing dishes and utensils. The water from the area runs into a soak-away pit which allows it to percolate back into the soil. By draining away the water and food scraps there are less flies gathering in the area.

Figure A-6: New trackers' house tanks

A.4.2.3. Primary School

Approximately 1,700 pupils attend the local primary school; in 2007 the main water supply for the school consisted of two 10 m^3 metal tanks. Students also collected water from the public tap receiving water from Bushokoro Source. Two new 10 m^3 plastic Afri-tanks have been constructed adjacent to the existing tanks. As visible in Figure A-7, both tanks were outfitted with reinforced concrete bases and new gravity fed fetching points.

Figure A-7: New tank at primary school

Unfortunately, heavy storms and disrepair in 2007 resulted in a broken gutter connection feeding one of the existing tanks. Plans have been made to fix the broken pipe, but as of January 2008, no water was flowing to or from one of the metal tanks; the 1,700 students have a maximum storage volume of 30 m^3 instead of 40 m^3.

A.4.2.4. Community Water Tank

A new 25 cubic meter tank was constructed to collect water from Bunyenyeri Source, which is locally thought to have the best quality water of all available sources. The masonry construction utilizes local stones, steel rebar, and concrete. Water from the source located within VNP is piped into the tank without treatment or filtration; users can fetch water from one of two nearby spigots. Overflow water falls onto a concrete pad, across bare soil and under the stone wall surrounding the tank; plans are in place for a soak-away pit to manage the overflow water. Figure A-8 shows the new tank with its overflow pipe and the fetching point with children collecting water. It is estimated that the tank serves 3,000 people in the surrounding area who all have access to the tank in the morning until 2-3 pm, when the valves are closed for the remainder of the day.

The tank is locally managed and one man has primary responsibility for operation and maintenance. In the last several months the spigots have broken on more than one occasion; the community replaced the pieces themselves, without looking to donor support for help. This type of management is the model for all of the water tanks in Bisate.

Figure A-8: New community water tank from Bunyenyeri source

A.4.2.5. Bushokoro Water Storage Tank

Throughout the three weeks of fieldwork in 2008, significant progress was made on the construction of a new community water tank. The tank will collect water from Bushokoro Source, also in VNP, and supply it to the public tap located in the village. Water from Bushokoro source was sampled and tested in 2007; it was found to be contaminated with total coliform and E. coli likely due to the lack of protection around the source. Humans and other animals are able to access and potentially contaminate the water. Recommendations were made for the protection of the source; no changes have been made to date, but planning is underway.

The photo series in Figure A-9 illustrates the progress made on the community water tank in January 2008. The final construction will be similar to the Bunyenyeri tank described previously.

Figure A-9: Progress of Bushokoro community water tank

The water flows from this tank to a public tap approximately 100 meters away. In 2007 the author noticed that the tap was broken; as a result of the high pressure head on the faucet it was calculated that $11m^3$ of water flowed through the tap each day, the vast majority of it being wasted. The construction of this new tank will alleviate some of the pressure on the public tap and also provide an additional reservoir to store water during extended periods without rain.

A.4.2.6. Sanitation Activities

Thirty-two new latrines were installed at the primary school. Previously the ~1,700 students and teachers all shared six latrines, which equates to almost 300 students per toilet. Now 100 boys and 33 girls will share separate sets of toilets. The new toilets are seen next to the old latrine building in Figure A-10.

Figure A-10: New toilets at primary school

Several other sanitation projects were underway in January 2008 in the area around the clinic. New latrines were installed, equipped with an anaerobic digester to produce methane gas for energy, adjacent to a wash room for patients. The rather unsanitary placenta pit in the rear of the clinic will be replaced with a more hygienic concrete pit to keep rodents and insects away. Medical sharps, such as syringes, were formerly disposed of in an open, unprotected pit at the rear of the clinic. They are now collected in designated boxes and brought to the Musanze hospital for incineration.

The progress made in water and sanitation activities has been incredible during 2007. As of January 2008, many projects were in progress, with plans to be completed in the coming months. Significant improvements have been made, but without proper management and maintenance the projects will be for naught. Both the primary school and Catholic Church have broken gutters and hence unusable storage tanks. The spigots on the new Bushokoro fetching point are already broken and water spills out unused. Responsibility is now assigned to particular individuals who are in charge of maintenance.

A.5. Additional Information on RWH System Design

A.5.1. Tank Material Options

The following sections provide options for tank material selection, with a brief analysis on each material's suitability for Rwanda. The list is not meant to be exclusive, but discusses some of the most common tank materials.

A.5.1.1. Brick Tanks

The use of locally made bricks is one attractive option for tank construction in many rural areas. Bricks can be made of sandy-clay soils that are fired in an oven, from cut stone, or compacted earth stabilized with concrete (Warwick undated). Although bricks are heavy they are relatively easy to transport because of their size. Before construction of the tank walls, a reinforced concrete foundation should be laid that will form the base of the tank. Following construction of the main tank, the interior should be coated with a mortar or plaster mix to prevent leaks. The top of the tank should be covered with either concrete or iron sheets to protect the water from contamination.

Brick tanks offer a very solid construction capable of enduring adverse weather and protecting the contents from vandalism. Materials are typically available locally and construction can be completed by community members (SEARNET undated). Although clay is often locally available, it is time- and resource-intensive to construct a brick tank, so those in severe poverty may be unable to afford one. Additionally, because brick breaks relatively easily under pressure, the amount of brick needed to create a strong tank may surpass the amount of ferrocement (discussed later) or other material needed to build a tank of comparable size, making it resource intensive and costly.

Figure A-11a & b: Recently made compacted bricks and baked-brick water tank (photographs by D. Cresti and author)

Brick tanks have been used in areas of Rwanda—the Bisate clinic director maintains a brick tank in her yard—but the government of Rwanda is trying to avoid the widespread use of fired brick for construction. The country is suffering from severe deforestation and bricks require a woodfueled fire to bake the clay. There are other options for brick construction, including unbaked compacted earth bricks. Figure A-11a shows recently made compacted clay bricks while Figure A-11b shows the clinic director's baked-brick rainwater collection tank. Compacted clay bricks are currently in use for house construction throughout Rwanda, yet are prone to erosion from water. It is not recommended to use unbaked bricks for tank construction, but they could be used as a protective layer to cover a plastic or metal tank to prevent ultraviolet light damage or vandalism.

A.5.1.2. Concrete

Reinforced concrete tanks are very durable, but are susceptible to cracking if the foundation soil is not firm enough, or if located in areas with seismic concerns. Due to the inherent weight of concrete, the structure is cast-in-place and not movable once constructed. It is possible for the tank to be assembled of prefabricated segments, but Bisate Village is remote and transportation to the area is costly and difficult. It is extremely unlikely that pre-fabricated concrete tanks will be affordable in rural Rwanda. The concrete is a mixture of four main components: Portland cement, aggregate (gravel), sand and water. Typically gravel, sand, and water are locally available and relatively inexpensive. The cost is primarily dictated by the cement and reinforcing steel bars.

Reinforced concrete tanks are resource-intensive, and cement is expensive in Bisate Village. This option is not feasible for Bisate, but a combination of brick-concrete, masonry-concrete, or metal with a concrete base and/or cover are more viable options.

A.5.1.3. Ferrocement

Ferrocement is a simple combination of low cost steel and mortar. While similar to reinforced concrete, the inherent difference is in the reinforcing steel. Unlike concrete, ferrocement uses several layers of steel-mesh coated with a cement mortar. The result is a structure that can be as thin as 1 inch, allowing for less raw-material use than a similarly sized concrete tank. It is much less expensive than other options, such as galvanized iron, and construction can be completed by local people. This option is well suited for low-income regions due to the availability of materials, simple skills required, simple equipment needed, and the shared cost of formwork when multiple projects are undertaken (Watt 1978).

There are many innovative options for ferrocement use. Durable woven baskets used for grain storage may be used in place of wire mesh. These baskets are already used in Kenya, Burundi and Rwanda, so the use of existing materials makes them an attractive alternative to traditional materials (Pacey 1986).

Construction of ferrocement tanks can easily be completed using local labor. The construction of a pot-shaped tank is outlined in Figure A-12. The available literature suggests that pot-shaped tanks constructed with wire mesh have the capacity to provide storage for an individual family, not to an entire community.

Appendix A: Supplemental Reading

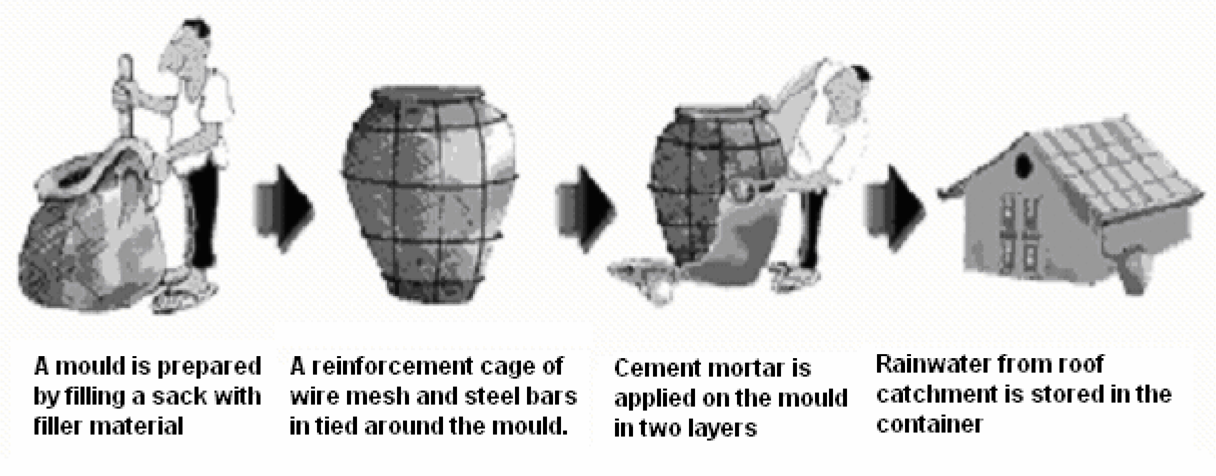


Figure A-12: Steps for ferrocement tank construction ***(UN-HABITAT 2005)***

Another variety of ferrocement construction implements a skeletal cage (Figure A-13). Very specific instructions for construction are provided by the Centre for Science and Environment (CSE). The construction steps are generally comparable to the construction phases of brick, masonry, and concrete tanks, and include:

1. Site selection
2. Marking for a circular foundation
3. Excavation of foundation
4. Compacting the excavated pit
5. Placing concrete in foundation
6. Erection of mould
7. Erection of skeletal elements
8. Plastering of outside wall
9. Plastering inside wall
10. Removal of mould
11. Casting of the tank floor
12. Curing the tank
13. Construction of roof

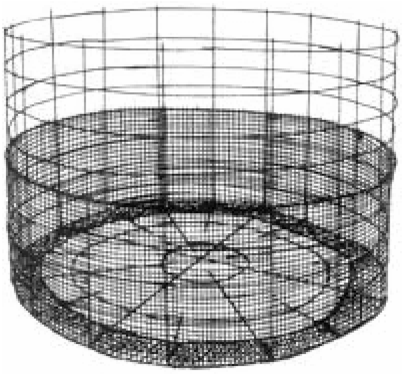


Figure A-13: Skeletal cage for ferrocement tank construction ***(CSE undated)***

The sizing charts for wire mesh selection and tank dimensions indicate that the maximum capacity of a skeletal reinforced ferrocement tank is 10,000 liters (10 m^3) which is perhaps sufficient for a few families to share, but not sufficient for a community tank (CSE undated). In Bisate, it is difficult for families to acquire construction supplies such as steel reinforcing bars or cement, so it is unlikely that any families would be able to afford such a tank without financial assistance. A more realistic use of ferrocement is in conjunction with another construction option; brick, masonry, or excavated pit.

A.5.1.4. Wood

Construction of wood holding tanks is commonplace throughout the world, but an unlikely option for Rwanda. New York City uses cedar tanks to hold water on top of high-rise buildings to provide water pressure to the building. Typical tanks use cedar planks because of their rot-resistant capabilities (McShane 2002). Other wood can also be used, including redwood, pine or cypress. The tank is then wrapped with steel tension cables and lined with a plastic (Pushard 2007).

Due to high rates of deforestation in Rwanda and the government restrictions on fired bricks because of wood shortages, it is not recommended that wood water tanks be considered for the Bisate region. Besides small-diameter bamboo and eucalyptus trees there are few trees available for timber harvesting.

A.5.1.5. Plastic

Perhaps the most easily installed option for rainwater collection is a pre-made plastic tank. There are a wide variety of companies with many different size tanks available for use. Typically, tanks are made of polyethylene, considered to be a durable plastic although fiberglass options are available (UN-HABITAT 2005). There is a concern that plastic tanks are less secure than other materials, as water thieves can puncture the plastic tank with a hot metal rod to steal water during the dry season (Clauson 2007). To avoid an issue like this, the tank could be buried, surrounded by a layer of brick (baked or unbaked), compacted earth, or ferrocement to protect the plastic shell. It is unlikely that individual families in Rwanda will be able to afford plastic tanks, but it is feasible that communities will be able to afford them with a simple financing plan or donor aid.

The following table lists prices in effect since September 2006 for tanks of various sizes. The prices include 18% tax but do not include transportation, installation of concrete foundations, pipes or connections. An average rate of 550 FRW to one U.S. dollar was used for conversion.

Table A-12: Afritank brand polyethylene water storage tank cost/size comparison (Clauson 2007)

Storage Volume	Price (FRW) (including 18% tax)	Price (USD) (including 18% tax)
100 L	18,000	$33
140 L	22,000	$40
250 L	36,000	$65
500 L	65,000	$120
1000 L	102,000	$185
1350 L	141,000	$260
2000 L	175,000	$320
2500 L	196,000	$360
3500 L	320,000	$580
5000 L	425,000	$770
10,000 L	818,000	$1500

A subsidiary of Kentainers Limited, AquaSAN S.A.R.L. sells food-grade polyethylene products for industrial, agricultural and domestic purposes. Kentainers originated in Nairobi, Kenya, and now has affiliated businesses in Uganda, Rwanda and Tanzania. AquaSAN is one of the suppliers of plastic water collection tanks. Their tanks are used either to directly collect rainwater from roof surfaces, or as a storage reservoir for piped water in urban areas.

AquaSAN water tanks are molded from polyethylene and contain 2.5% carbon black, a substance that reduces ultraviolet light degradation of the plastic. According to the product brochure, the tanks have a 30-year lifespan and do not change the taste of the stored water. Tanks are made by Afritank and range in size from 150 liters to 10,000 liters (Kentainers undated). A typical tank is shown below in Figure A-14 with a standard sand and stone foundation; a concrete or masonry foundation could also be installed. The foundation is a necessary component of a functioning system since it provides a level surface for the tank and protects the base from damage. The cost of constructing the base should be included in the financial planning for the collection system.

Figure A-14: Typical AFRITANK plastic water collection tank with foundation (Kentainers undated)

A.5.1.6. Metal

Metal collection tanks are also available, constructed from a range of metals. Tanks can be made from galvanized steel, aquaplate (a polymer coated steel), or other types of coated steel. They come in a variety of sizes, some as large as 22,500 liters (Government of South Australia 1999). These tanks may not be readily available to remote areas in developing countries, but the installation labor is reduced because they are pre-made. Frequent maintenance is needed to ensure that the metal is well protected from rust, but if deemed affordable, these tanks offer a fast, durable option for rainwater collection. To maintain tanks, existing rust should be scrubbed off and the tank painted with non-lead-based paint. Tank corrosion can be partially abated by building a concrete foundation, but even a solid foundation will not guarantee a rust-free system.

Tanks can also be fabricated on site from sheet metal. In many regions a variation on this idea has been used for years where old oil drums informally collect water. Larger tanks can be ordered and installed relatively easily.

A.5.1.7. Underground Cistern

In some regions, particularly those with a stable subsurface, it may be useful to construct an underground cistern. The concept is simple—an excavated hole is lined with mortar, covered and connected to the roof gutters. While the system is very simple, the main drawback to an underground storage tank is the need for a pump to safely extract the water. While above-ground tanks rely on gravity, either a hand pump or electrical pump is needed to remove the water from an underground tank, adding additional parts and expense. It is not recommended to leave an opening in the cover for bucket dipping because of the risk of microbial contamination from unclean hands or buckets. Although a bucket system is inexpensive it easily leads to contamination of the water and should be avoided. There are a variety of non-electrical pump options or covered bucket systems applicable for underground cisterns. Simple pumps used to extract groundwater at shallow depths using suction are useful for safe water extraction, although additional cost and maintenance concerns are added.

Another drawback is in tank repair. In underground cisterns, it is difficult to know if a tank is leaking, since it is almost completely buried. Leaking tanks pose a risk for both water loss and supply contamination. Even if a leak is identified, it can be difficult to repair. Although there are some drawbacks to underground tanks, they can provide a large capacity reservoir that requires fewer construction materials than an equivalently sized above-ground tank.

There are also very serious concerns regarding contamination of water stored underground. In heavy rain, overland flow could inundate the area, contaminating the entire supply. Additionally, cracks in the tank walls or holes in the cover are a pathway for pollutants, greatly increasing the dangers of using a buried tank.

Water stored in underground tanks is typically at a cooler temperature than water stored in above-ground cisterns, a benefit since cool water is typically more preferable to users than warm water. In northwestern Rwanda, the subsurface is primarily porous volcanic rock; an underground cistern would need to be well lined with either heavy-duty plastic or mortar to prevent rapid infiltration of water into the pore space. To construct an adequately sized tank excavation would likely be very expensive because of the rocky subsurface. An underground cistern could be a viable option for Bisate Village only if the pit could be adequately excavated, and protected from contamination. Although an option, this is not recommended based on the aforementioned risks.

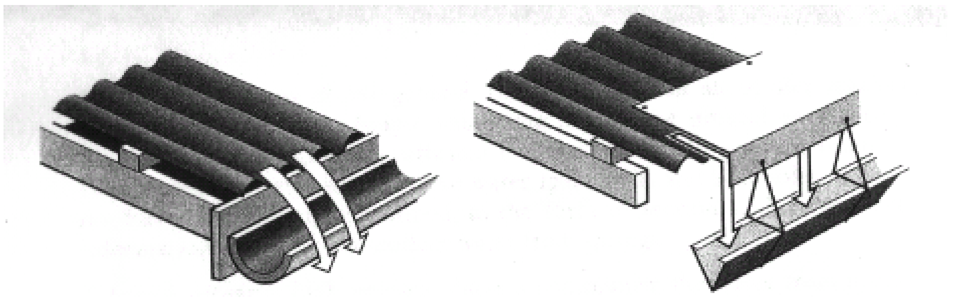
A.5.2. Gutters

For community rainwater harvesting tanks, water is collected from large roofs that are almost exclusively made from metal sheets. For large systems, gutters should be made from metal or durable plastic, such as polyvinyl chloride (PVC). Gutters can be easily constructed from sheet metal folded to create a V-shaped or simple rectangular channel, which is then mounted beneath the existing roof eaves using basic hangers. Gutters can also be constructed from halved PVC-piping or pre-made PVC gutters that are then secured to the eaves (UN-HABITAT 2005).

In more rural areas, bamboo or some tree trunks may be used in a similar fashion to PVC. Bamboo is readily available in Rwanda, although most of the bamboo plants used in construction have a very small diameter that is not sufficient for collecting water from a large roof. Bamboo also has a tendency to rot and harbor bacteria and so should be used with caution.

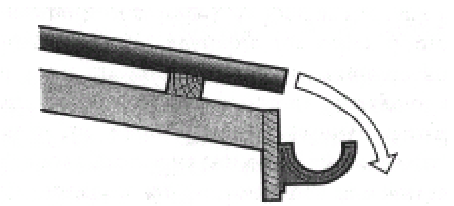
Plastic gutters are the easiest to install and maintain and are currently used at several of the collection systems in Bisate. During installation, sufficient slope should be given to the gutters to prevent water from ponding in flat areas (around 5%). Care should be taken to regularly clean the gutters to avoid debris build-up, particularly after a long period without rain. Debris left in the gutters can contribute to mold problems when it does rain.

Figure A-15 shows several different guttering options, including designs to prevent overspill (Skinner 2003). For guttering systems in Rwanda, option e. in Figure A-15 with a raised edge is the most suitable. It is a simple design that can be easily made with metal sheets but it still prevents the water from overshooting the trough. Metal braces can be used to support the gutter from below and cross braces attached at the top prevent the gutter from collapsing in heavy rain or hail. Metal gutters also need to be installed at a sufficient slope to prevent ponding. It is recommended that the gutter slope change by at least 0.08 cm per meter of gutter (Greenbuilder 2007). Additional care must be taken to ensure that they remain rust and corrosion-free.

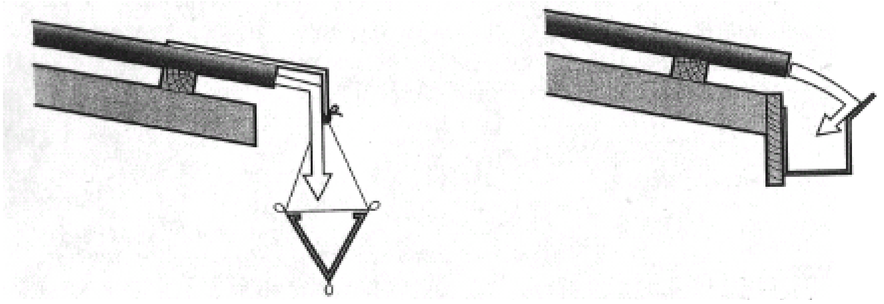


a. Un-covered traditional gutter

b. V-shaped gutter with splash guard



c. Profile view of runoff overshooting gutter



d. Profile of V-shaped gutter and guard

e. Alternate trough and splash-guard option

Figure A-15: Guttering Options ***(Skinner 2003)***

A.5.3. Collection Systems

The combination of catchment surface, gutters, and tank comprises the rooftop rainwater collection system. Each piece of the system is critically important; if one component fails, the entire system fails. It is easy for an engineer in the U.S. to design a system for Rwanda, but in reality the individuals that will reap the benefits of the catchments play a significant role in the system development. The dissemination of knowledge surrounding rainwater catchment depends heavily on village interaction and communication. It is incorrect to think of water problems purely as a technical issue. The problem, as well as the solution, encompasses technical knowledge, political corruption, culture, economic hardships, and environmental factors (Pacey 1986).

If a system design calls for construction of a brick tank, but the village cannot buy enough bricks to finish the job, then the design is faulty. Technically speaking, it would be a fine design, but there are other factors limiting the success of the catchment system. Similarly, if a sophisticated first-flush device is installed, but the owners do not understand or are not taught how to use it properly, then both the technology and the money spent on it were wasted. The system needs to be simple enough that the users will be able to fix it on their own when it breaks and straightforward enough that they can understand how to maintain it. They also need to understand the importance of having clean water and the ties between sickness and unhygienic water uses. A water tank meant for irrigation will have a much different setup than a tank for domestic drinking water. Before tank design can begin, there needs to be an understanding of the ultimate use of the water.

A.5.4. Financing

Cost is obviously one of the primary design limitations in the developing world. Community members are unable to front the cost of large systems and often cannot afford to pay for regular upkeep and maintenance even if the initial cost is subsidized. Access to water is a fundamental human need; as such, it should not be inhibited by poverty. However, clean, reliable water supplies are not cheap, so funding must come from somewhere.

In Bisate Village, much of the funding for water projects comes through the Dian Fossey Fund and their Ecosystem Health Program. The long-term sustainability of donor aid is volatile and there are real concerns about the burden of responsibility for maintenance and repairs. Microfinance loans have worked extremely well in developing countries in allowing the poor to finance their own water projects (Fonseca 2006).

Microfinance took root in Bangladesh in 1976 with the issuance of small loans to groups of women. Rather than having to supply collateral, the women form a solidarity group where the closeness of the group motivates them to make their scheduled payments. If one woman defaults, all are punished. Peer pressure and feelings of financial independence keep repayment rates greater than 90% in many instances (Fonseca 2006). The UN Year of Microcredit program called for "building inclusive financial sectors and strengthening the powerful, but often untapped, entrepreneurial spirit existing in communities around the world" (Year of Microcredit 2005).

Water projects are only recently coming into the spectrum of projects serviced by microfinance. Traditionally micro-scale loans are geared toward income-generating activities. One of the main reasons that the water sector has been slow to enter the microfinance trend is a lack of awareness of the viability of water supply projects as money-making businesses (Fonseca 2006). There is real potential for the successful implementation of micro-scale loans in Rwanda. The benefits over straight donor aid are significant; loan recipients are able to be more financially independent and can pay back the donated money at a reduced interest rate. Although microfinance loans are not always immediately profitable for money lenders, donors have the ability to make their money reach more people as the loan is typically paid back and can be re-loaned.

Microfinance alone is not enough to end poverty in Africa, but it is a possible financing option that is often overlooked for water projects. Nonetheless, large-scale rain harvesting projects, such as the 40 m^3 ORTPN tank next to the Catholic Church in Bisate, are projects that could not be funded only with microfinance loans. For such projects, outside intervention by NGOs or the government is needed. Moreover, even when such funds are obtained, plans need to be made in advance for the continued maintenance of the system.

Although there are no apparent microfinance options for the Bisate community, a microfinance institution, Agaseke Financial Centre for Entrepreneurs (CFE Agaseke) has been providing microfinance loans to the people of Rwanda since its inception in December 2003. Created with assistance from the Canadian International Development Agency (CIDA) and Développement International Desjardins, the institution supports three branches in Kigali and one each in Butare, Gitarama and Musanze. Forty percent of the loans offered by CFE Agaseke are given to women and the majority of their loans are made to entrepreneurs in the business and service sectors (CIDA 2007).

As with all outside interventions, financing options such as microcredit need to be understood and accepted by the community before implementation to increase the likelihood of success. Microcredit is a potential option for Rwanda that does not appear to have been explored in Bisate Village.

A.6. Impact of a Community Rainwater Collection System

Although there are significant investments in time and money required for the successful implementation of a rainwater harvesting system, the impact of a successful water supply on a community extends beyond the increase in available volume of water. There are a myriad of societal and environmental benefits resulting from a reliable, sustainable drinking water system.

A.6.1. Women and Children

The societal impacts of a drinking water system are often left out of a traditional cost-benefit analysis. Traditionally it is the work of women and children to collect water for the household that will be used for domestic purposes such as cooking, cleaning, and drinking. Women are also typically in charge of raising children, and even tending fields. Women can spend up to one third of their day walking to fetch water; in Bisate, during the dry season, women are forced to walk several hours into the VNP to retrieve often-unclean surface water because there is no water available in the village (Nshimyimana 2007b). By having a reliable supply of water in close proximity to their homes, women would have more time to devote to productive activities. Rather than fetch water, they can care for children, sells crafts and produce, or engage in other money-earning activities. As children often accompany their mothers in collecting water, having a reliable supply nearby will give them more time to spend in school, an investment yielding long-term benefits that will help the entire community.

Figure A-16: Women waiting for water (photograph by D. Cresti)

A.6.2. Health and Hygiene

Many water-related diseases are caused by a lack of access to water, rather than by contaminated water. These infections are considered to be “water-washed,” and typically depend on the quantity of water used rather than the quality. In some cases, water-washed diseases can be intestinal in nature, causing diarrhea and decreased productivity. Skin infections such as scabies and infestations of lice are also caused by a lack of water coupled with poor hygiene practices (Cairncross 1993). During fieldwork we observed that many of the children in Bisate suffered from acute skin infections and had poor hygiene practices. When more water is available for hygienic purposes, decreases in infection rates occur.

Water-borne diseases are those caused by microbially-contaminated water (Cairncross 1993). If the water supply system is properly maintained, water quality will improve, potentially reducing the risks of contracting water-borne diseases. Implementation of disinfection and safe storage options for families further reduces disease occurrence. A chart of diarrhea disease reduction as a result of various interventions is provided in Table A-13 (House et al. 2004). In addition to improving water infrastructure and resources, a health and hygiene education program should be implemented in the village to teach people the importance of maintaining clean supplies and the benefits of personal hygiene improvements.

To quantify the value of improvements in water resources to a community, Disability Adjusted Life Years (DALYS) can be used as a measure of the years lost from premature death and years lived with disabilities for a population. A DALY is an index that is commonly used to gauge the global burden of disease and can indicate the general health of a population. One DALY is essentially one lost year of healthy life (Murcott 2007). Water supply and hygiene improvements reduce DALYS for a community. The less people are sick, the more time there is for education, domestic work, and other meaningful or profitable activities. In Rwanda, the average life expectancy is only 47 years; ideally with an increase in safe, reliable water, that statistic will improve (DOS 2007).

Table A-13: Intervention effectiveness in reducing water-related disease (House et. al. 2004)

The Effect of Interventions on the Reduction of Diarrheal Diseases	
Intervention	**Reduction in Diarrhea (approx. %)**
Water Quality	15
Water Quantity	20
Hygiene	33
Sanitation	35

A.6.3. Erosion Mitigation

During a rain event, the turbidity of runoff water becomes extremely high (>1,000 NTU) as a result of erosion. Although rooftop area may be a small overall percentage of land area, reducing the contribution of rooftops to runoff can lead to improvements in flood control, erosion control, and sediment loading in surface water bodies (Pacey 1986). Most applicable to Bisate is reduction in topsoil erosion. During fieldwork, we witnessed several heavy rains in which large volumes of water flooded streets and inhibited travel, as shown in Figure A-17. Collecting some of that water before it has a chance to erode the fertile soil benefits both the farmers in Bisate and the people down-slope who receive sediment-laden floodwaters in the rivers. Reducing erosion protects the soil resources on which agricultural communities are built, providing benefits to all members of the community and is an additional reason to consider community collection tanks.

Figure A-17: Sediment-laden runoff impedes travel

A.6.4. Mountain Gorillas

Direct ties between community health and gorilla preservation have led to sponsorship of the Ecosystem Health Program by the Dian Fossey Gorilla Fund International. Historically, the people of Bisate have trekked into the national park during times of water scarcity to either collect water directly from the sources (Bushokoro and Bunyenyeri) or from any surface water they could find (Nshimyimana 2007b).

Partially due to their close genetic ties with humans, gorillas are at heightened risk of contracting diseases from humans. During the escalated violence in the northwest section of Rwanda in the late 1990s, more than half of the population of Musanze fled into the VNP. The feces of the refugees provided a source of contamination and disease for the population of gorillas (Rutagarama 2001). Close human interaction with the gorillas is still a source of concern, particularly when local people enter the forest in search of water. By reducing the need for alternative unimproved sources (i.e. surface water) there is less chance of physical interaction between the gorillas and villagers, and also less of a chance for microbial interaction in the form of fecal matter.

As well as posing a danger to gorillas, there is also a burden on other flora and fauna in the park when large groups of people enter. Large areas of vegetation become trampled and wildlife is disturbed by heavy human traffic, reducing habitat quality and availability. In addition to concerns for the biologic community of the VNP, it is unsafe for humans to enter without a military escort, as rebels, poachers, and buffalo all present serious threats to people. Minimizing the exposure of local people is beneficial to all parties.

A.6.5. Cost

Bisate is a relatively remove village, 18 km from Musanze, the nearest major city with piped water. The option of piping treated spring water to Bisate from another city is unrealistic due to the high cost of such an infrastructure project, which would need to address the high elevation of Bisate. Rooftop rainwater harvesting provides a localized solution that does not require extensive and complicated networks of pipes and pumps, nor does it require the large-scale maintenance of a traditional distribution system. Rainwater tanks are simple, accessible, and local enough for the end users to fix and maintain their own tanks if people are effectively trained. Since the tanks are often locally constructed, community labor can be employed, which increases the skill level of residents. Villages with reliable sources of community water are also found to be more politically stable and closely identified than those without water (Pacey 1986).

The primary cost associated with rainwater collection is in construction materials. Once the system is constructed, relatively little expenditure is needed to maintain the system (with routine maintenance). If an appropriate financing plan is adopted, or if loans are available, the system should be affordable to the community. Money does need to be set aside for maintenance and replacement of broken parts, although those costs should be low. With the use of disinfection or filtration, costs will increase, so the design should minimize costs through the use of local materials and labor whenever possible. There is no energy cost associated with rainwater harvesting; no fuel is needed and even if a pump is used for extraction, it can be hand-powered (Gould 1990). While many still cannot afford tanks, it is becoming increasingly possible for families and villages to use community-based revolving funds and micro-credits to finance small projects such as water collection systems (Gould 1990).

All of the costs and benefits of a rainwater system should be weighed and analyzed before construction begins. Attempts should be made to maximize the benefits of the system to the greatest number of people, particularly to the poorest who may not have an alternate source of water. Rainwater harvesting has already proven its potential as a reliable source of water all over the world, and Rwanda has the potential to truly benefit from this simple technology if it is appropriately implemented.

Appendix B: GPS Locations

Appendix B: GPS locations

The following table provides latitude, longitude, and elevation data for several locations in and around Bisate Village. Measurements were recorded with a Garmin eTrex Venture. The device measured position based on the WGS84 datum.

WGS 84 Datum	**Latitude**	**Longitude**	
Description	**S**	**E**	**elev(m)**
CL location	01d27.354'	029d31.499'	2509
HS location	01d27.305'	029d31.411'	2513
PT location	01d26.773'	029d31.864'	2499
Metal and plastic primary school tanks	01d27.264'	029d31.580'	2509
Brick tank at director’s house	01d27.304’	029d31.524’	2506
Plastic tank at ORTPN trackers’ house	01d27.304’	029d31.497’	2514
Plastic clinic tanks	01d27.361'	029d31.517'	2506
Masonry tank at Catholic church	01d27.472’	029d31.553’	2516
Plastic DFGFI trackers’ tanks	01d27.494'	029d31.573'	2510
Bushokoro holding tank in forest	01d27.425’	029d30.412’	2761
Bushokoro intermediate holding tank	01d27.202’	029d30.852’	2614
New Bushokoro tank under construction	01d27.324'	029d31.488'	2512
Bisate water tap (from Bushokoro)	01d27.312’	029d31.524’	2507
Bunyenyeri intermediate holding tank	01d27.703’	029d31.307’	2533
New Bunyenyeri community water tank	01d27.189'	029d30.627'	2619
Bunyenyeri water tap	01d27.728’	029d31.386’	2524
Rest area on Bisoke volcano	01d28.123'	029d29.988'	2964
Top of Bisoke volcano	01d27.657'	029d29.332'	3632
Bisate Village to Musanze	18.3 km		-665.3 m

Appendix C: 2008 Water Quality Results

C.1. Coliform Results

The following tables display the total coliform data for each location (CL, HS, and PT) for each of the six storms (S1-S6). Bold-type values indicate the presence of enumerable colonies. Samples without enumerable colonies were assigned a "<" value based on the sample dilution. For example, a 1:100 dilution with no enumerable colonies is assigned "<100 colonies per 100 mL." Values with an "x" indicate no sample was tested.

Coliform results for CL location (colonies per 100 mL)							
Runoff Depth	**S1**	**S2**	**Runoff Depth**	**S3**	**S4**	**S5**	**S6**
0.03 – 0.18 mm	**90**	<10	**0.03 – 0.46 mm**	<10	**10**	**15**	x
0.22 – 0.37 mm	**90**	**10**	**0.50 – 0.93 mm**	<10	<1	**6**	x
0.41 – 0.56 mm	**100**	x	**0.98 – 1.12 mm**	<10	**2**	**7**	x
0.61 – 0.75 mm	<10	x	**1.17 – 1.32 mm**	<1	<1	**6**	x

Coliform results for HS location (colonies per 100 mL)						
	S1	S2	S3	S4	S5	S6
0.02 – 0.30 mm	**2200**	**30**	**4600**	**6200**	**510**	x
0.33 – 0.61 mm	**495**	x	<100	**100**	**8**	x
0.64 – 0.73 mm	**693**	x	**50**	**36**	**11**	x
0.76 – 0.86 mm	**460**	x	<100	**530**	**31**	x
0.89 – 0.98 mm	**91**	x	**27**	**8**	**166**	x
1.01 – 1.11 mm	**27**	x	**45**	**5**	**3**	x
1.14 – 1.24 mm	**109**	x	**40**	**21**	**50**	x
1.26 – 1.36 mm	**35**	x	**10**	**21**	**24**	x

Coliform results for PT location (colonies per 100 mL)						
	S1	S2	S3	S4	S5	S6
0.06 – 0.38 mm	x	x	**410000**	**990**	**200**	x
0.47 – 0.79 mm	x	x	**24700**	**700**	x	x
0.89 – 1.20 mm	x	x	**4600**	**360**	x	x
1.30 – 1.61 mm	x	x	**350**	**320**	x	x

Appendix C: 2008 Water Quality Results

C.2. *E. coli* Results

The following tables display the *E. coli* data for each location (CL, HS, and PT) for each of the six storms (S1-S6). Bold-type values indicate the presence of enumerable colonies. Samples without enumerable colonies were assigned a "<" value based on the sample dilution. For example, a 1:100 dilution with no enumerable colonies is assigned "<100 colonies per 100 mL." Values with an "x" indicate no sample was tested.

***E.coli* results for CL location (colonies per 100 mL)**							
Runoff Depth	**S1**	**S2**	**Runoff Depth**	**S3**	**S4**	**S5**	**S6**
0.03 – 0.18 mm	<100	<10	**0.03 – 0.46 mm**	<10	**10**	**5**	x
0.22 – 0.37 mm	<100	<10	**0.50 – 0.93 mm**	<10	<1	<1	x
0.41 – 0.56 mm	<100	x	**0.98 – 1.12 mm**	<10	<1	**1**	x
0.61 – 0.75 mm	<10	x	**1.17 – 1.32 mm**	<1	<1	<1	x

***E.coli* results for HS location (colonies per 100 mL)**						
	S1	S2	S3	S4	S5	S6
0.02 – 0.30 mm	<100	**10**	<100	**200**	**3**	x
0.33 – 0.61 mm	<100	x	<100	**10**	<1	x
0.64 – 0.73 mm	<100	x	<10	**40**	<1	x
0.76 – 0.86 mm	<10	x	<100	**20**	<1	x
0.89 – 0.98 mm	<10	x	<10	<1	**1**	x
1.01 – 1.11 mm	<10	x	<10	**1**	<1	x
1.14 – 1.24 mm	<10	x	<10	<1	**1**	x
1.26 – 1.36 mm	<1	x	<1	<1	<1	x

***E.coli* results for PT location (colonies per 100 mL)**						
	S1	S2	S3	S4	S5	S6
0.06 – 0.38 mm	x	x	<10	<100	<1	x
0.47 – 0.79 mm	x	x	<10	**100**	x	x
0.89 – 1.20 mm	x	x	<10	<10	x	x
1.30 – 1.61 mm	x	x	<10	<10	x	x

Appendix C: 2008 Water Quality Results

C.3. Turbidity Results

The following tables display the turbidity data for each location (CL, HS, and PT) for each of the six storms (S1-S6). Values with an "x" indicate no sample was tested.

CL Turbidity (NTU)							
Runoff Depth	**S1**	**S2**	**Runoff Depth**	**S3**	**S4**	**S5**	**S6**
0.03 – 0.18 mm	893	62.2	**0.03 – 0.46 mm**	98.4	99.1	28.2	15.8
0.22 – 0.37 mm	112	40.0	**0.50 – 0.93 mm**	50.4	27.5	9.88	8.02
0.41 – 0.56 mm	97.7	x	**0.98 – 1.12 mm**	22.6	23.6	4.97	5.27
0.61 – 0.75 mm	61.4	x	**1.17 – 1.32 mm**	19.2	15.5	5.61	3.98

HS-Turbidity (NTU)						
Runoff Depth	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
0.02 – 0.30 mm	110	75.2	89.0	96.7	35.5	12.4
0.33 – 0.61 mm	77.7	x	58.4	61.0	12.1	8.97
0.64 – 0.73 mm	65.5	x	69.8	61.5	5.65	5.34
0.76 – 0.86 mm	54.4	x	53.4	69.7	3.86	4.41
0.89 – 0.98 mm	30.5	x	43.7	71.6	3.61	3.08
1.01 – 1.11 mm	20.4	x	30.4	84.5	4.87	3.27
1.14 – 1.24 mm	12.0	x	24.1	93.3	9.05	2.29
1.26 – 1.36 mm	15.1	x	20.9	78.3	8.52	2.61

PT-Turbidity (NTU)						
Runoff Depth	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
0.06 – 0.38 mm	x	x	76.6	44.7	8.21	10.19
0.47 – 0.79 mm	x	x	54.8	21.4	x	7.75
0.89 – 1.20 mm	x	x	32.8	17.4	x	6.93
1.30 – 1.61 mm	x	x	21.9	16.1	x	4.45

Appendix C: 2008 Water Quality Results

C.4. Conductivity Results

The following tables display the conductivity data for each location (CL, HS, and PT) for each of the six storms (S1-S6). Values with an "x" indicate no sample was tested.

CL Conductivity (μs/cm)							
Runoff Depth	**S1**	**S2**	**Runoff Depth**	**S3**	**S4**	**S5**	**S6**
0.03 – 0.18 mm	110	110	**0.03 – 0.46 mm**	100	90	40	30
0.22 – 0.37 mm	60	40	**0.50 – 0.93 mm**	40	30	10	10
0.41 – 0.56 mm	40	x	**0.98 – 1.12 mm**	20	10	20	10
0.61 – 0.75 mm	30	x	**1.17 – 1.32 mm**	20	10	10	10

HS Conductivity (μs/cm)						
Runoff Depth	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
0.02 – 0.30 mm	70	70	70	50	30	20
0.33 – 0.61 mm	40	x	40	40	10	10
0.64 – 0.73 mm	30	x	20	10	10	10
0.76 – 0.86 mm	20	x	20	10	20	10
0.89 – 0.98 mm	30	x	20	10	20	10
1.01 – 1.11 mm	20	x	20	10	20	0
1.14 – 1.24 mm	20	x	20	10	20	0
1.26 – 1.36 mm	30	x	20	10	20	0

PT Conductivity (μs/cm)						
Runoff Depth	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
0.06 – 0.38 mm	x	x	40	20	10	10
0.47 – 0.79 mm	x	x	20	10	x	10
0.89 – 1.20 mm	x	x	20	10	x	0
1.30 – 1.61 mm	x	x	20	10	x	0

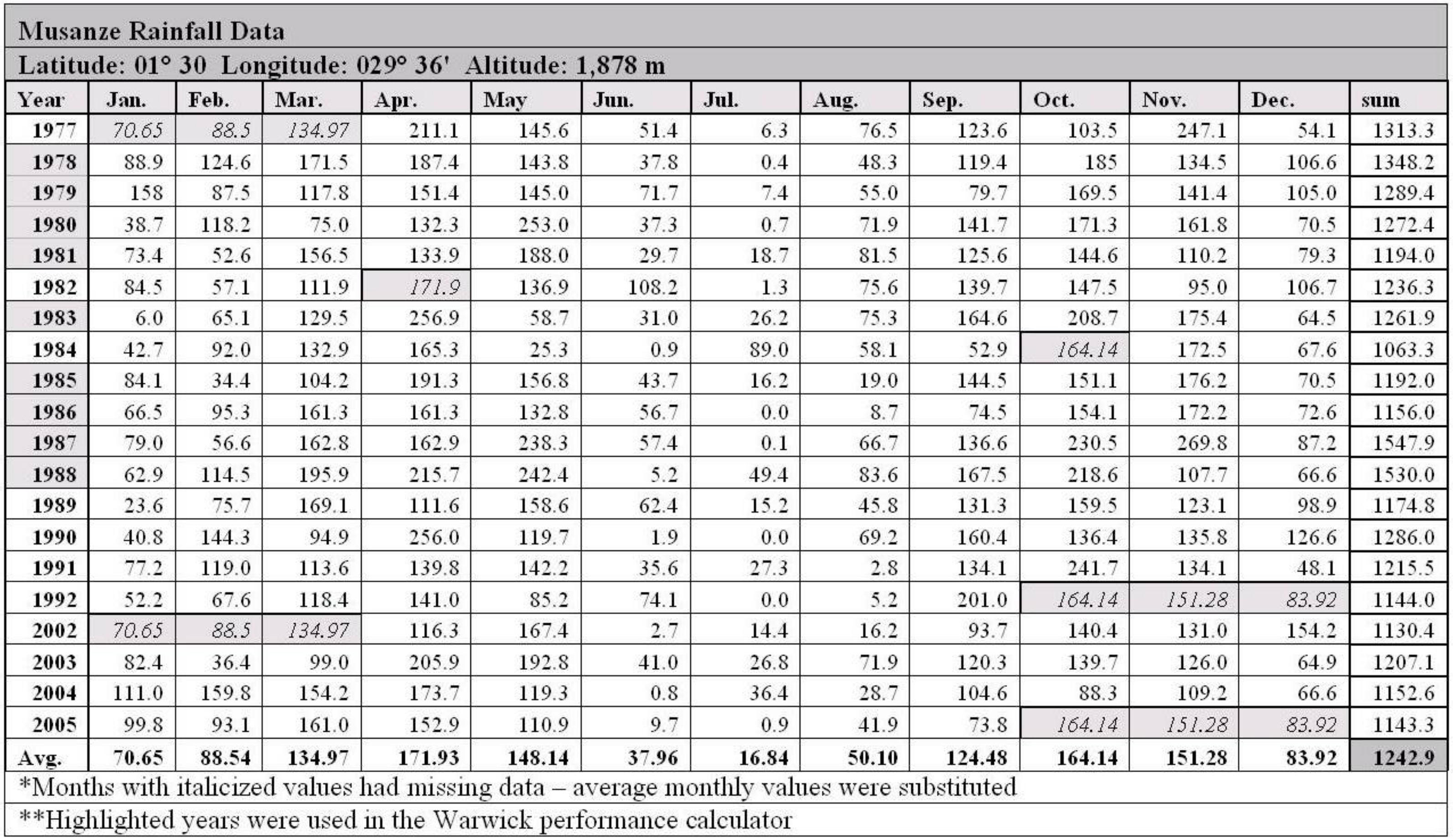
Appendix D: 12-hour Rainfall Record

The following table provides the 12-hour rainfall record collected at the DFGFI trackers' house used to determine the antecedent dry weather period and total runoff volume for each storm. The precipitation captured on each sample collection day is in bold type and the corresponding storm number is shown in parenthesis (S1-S6). "NP" indicates that no precipitation was recorded.

Date	6am (mm)	6pm (mm)	Daily Total (mm)
12/23/2007	NP	12	12
12/24/2007	4.2	1.2	5.6
12/25/2007	1.2	2.2	3.4
12/26/2007	1.2	6.4	7.6
12/27/2007	NP	NP	0
12/28/2007	NP	NP	0
12/29/2007	NP	NP	0
12/30/2007	1.2	NP	1.2
12/31/2007	NP	1.2	1.2
01/01/2008	NP	NP	0
01/02/2008	NP	NP	0
01/03/2008	NP	NP	0
01/04/2008	NP	NP	0
01/05/2008	NP	**3.6 (S1)**	3.6
01/06/2008	**2.4 (S1)**	NP	2.4
01/07/2008	**1.2 (S2)**	NP	1.2
01/08/2008	NP	NP	0
01/09/2008	**12.2 (S3)**	**13.6 (S3)**	25.8
01/10/2008	NP	NP	0
01/11/2008	NP	NP	0
01/12/2008	NP	**9.8 (S4)**	9.8
01/13/2008	NP	**4.6 (S5)**	3.6
01/14/2008	NP	3.6	3.6
01/15/2008	NP	**12.9 (S6)**	12.9
01/16/2008	TRACE	NP	0
01/17/2008	NP	10.6	10.6
01/18/2008	NP		3.2

Appendix E: Musanze Rainfall Record

Appendix E: Musanze Rainfall Record



Musanze Rainfall Data

Latitude: 01° 30 Longitude: 029° 36' Altitude: 1,878 m

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	sum
1977	*70.65*	*88.5*	*134.97*	211.1	145.6	51.4	6.3	76.5	123.6	103.5	247.1	54.1	1313.3
1978	88.9	124.6	171.5	187.4	143.8	37.8	0.4	48.3	119.4	185	134.5	106.6	1348.2
1979	158	87.5	117.8	151.4	145.0	71.7	7.4	55.0	79.7	169.5	141.4	105.0	1289.4
1980	38.7	118.2	75.0	132.3	253.0	37.3	0.7	71.9	141.7	171.3	161.8	70.5	1272.4
1981	73.4	52.6	156.5	133.9	188.0	29.7	18.7	81.5	125.6	144.6	110.2	79.3	1194.0
1982	84.5	57.1	111.9	*171.9*	136.9	108.2	1.3	75.6	139.7	147.5	95.0	106.7	1236.3
1983	6.0	65.1	129.5	256.9	58.7	31.0	26.2	75.3	164.6	208.7	175.4	64.5	1261.9
1984	42.7	92.0	132.9	165.3	25.3	0.9	89.0	58.1	52.9	*164.14*	172.5	67.6	1063.3
1985	84.1	34.4	104.2	191.3	156.8	43.7	16.2	19.0	144.5	151.1	176.2	70.5	1192.0
1986	66.5	95.3	161.3	161.3	132.8	56.7	0.0	8.7	74.5	154.1	172.2	72.6	1156.0
1987	79.0	56.6	162.8	162.9	238.3	57.4	0.1	66.7	136.6	230.5	269.8	87.2	1547.9
1988	62.9	114.5	195.9	215.7	242.4	5.2	49.4	83.6	167.5	218.6	107.7	66.6	1530.0
1989	23.6	75.7	169.1	111.6	158.6	62.4	15.2	45.8	131.3	159.5	123.1	98.9	1174.8
1990	40.8	144.3	94.9	256.0	119.7	1.9	0.0	69.2	160.4	136.4	135.8	126.6	1286.0
1991	77.2	119.0	113.6	139.8	142.2	35.6	27.3	2.8	134.1	241.7	134.1	48.1	1215.5
1992	52.2	67.6	118.4	141.0	85.2	74.1	0.0	5.2	201.0	*164.14*	*151.28*	*83.92*	1144.0
2002	*70.65*	*88.5*	*134.97*	116.3	167.4	2.7	14.4	16.2	93.7	140.4	131.0	154.2	1130.4
2003	82.4	36.4	99.0	205.9	192.8	41.0	26.8	71.9	120.3	139.7	126.0	64.9	1207.1
2004	111.0	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	161.0	152.9	110.9	9.7	0.9	41.9	73.8	*164.14*	*151.28*	*83.92*	1143.3
Avg.	**70.65**	**88.54**	**134.97**	**171.93**	**148.14**	**37.96**	**16.84**	**50.10**	**124.48**	**164.14**	**151.28**	**83.92**	**1242.9**

*Months with italicized values had missing data – average monthly values were substituted

**Highlighted years were used in the Warwick performance calculator

Appendix F: Alpha and S_r values

The following list of values were used in the SRY simulation model to generate reliability values. Alpha values were taken directly from (Hanson 2007). S_r values were converted from feet to meters and modified slightly.

alpha	S_r (m)
0.01	0.005
0.05	0.015
0.10	0.030
0.15	0.045
0.20	0.060
0.25	0.075
0.30	0.090
0.35	0.105
0.40	0.120
0.45	0.135
0.50	0.150
0.55	0.165
0.60	0.180
0.65	0.195
0.70	0.210
0.75	0.225
0.80	0.240
0.85	0.255
0.90	0.270
0.95	0.285
0.99	0.300
1.00	0.330
2.00	0.360
3.00	0.390
4.00	0.420
	0.450
	0.480
	0.500
	0.540
	0.570
	0.600
	0.680
	0.760
	0.840
	0.920
	1.000