Roof rainwater harvesting as an alternative to mitigate water scarcity in Rwanda

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Abstract- Water scarcity is a problem that affects all developmental aspects, including agriculture, health, education, peace, and economic activities.

The state of water scarcity problem is increasing due to the rise of water demand caused by population growth, urbanization, and increase of industrial water usage.

The millennium development goals had set targets that were not met, and the on-going sustainable development goals were set to realize the goals. Water is addressed on most of the SDGs goals: clean water and sanitation, life below water, zero hunger, etc.

There must be a consideration of investing in the community to harvest rainwater from rooftop to supplement the available water as this can reduce the problems of water scarcity and rainwater runoff that sometimes cause floods, erosion, and landslides. The majority of Rwandese have been experiencing water scarcity problems to the point of weekly or monthly water shortage, and the trend is expected to have an increase due to the projected rapid urbanization. There has been an effort to increase water supply and implementation of the roof rainwater harvesting system by the national government and private sector, trying to help in financial assistance.

Index Terms- Water scarcity, rainwater harvesting, water treatment, water demand and supply

I. INTRODUCTION

Water scarcity and stress are reaching worryingly high levels worldwide due to the intensive exploitation and pollution of water resources (Rojas, Prieto, et al. 2018).

The availability of safe drinking water, a vital natural resource, is still a distant dream to many around the world, especially in developing countries. Increasing human activity and industrialization has led to a wide range of physical, chemical, and biological pollutants entering water bodies and affecting human lives. Efforts to develop efficient, economical, and technologically sound methods to produce clean water for developing countries have increased worldwide. We focus on solar disinfection, filtration, hybrid filtration methods, treatment of harvested rainwater, herbal water disinfection, and arsenic removal technologies (Aniruddha B. Pandit 2015).

Rainwater harvesting and use were once a necessity. Systematic rainwater harvesting for domestic use has been practiced for thousands of years. Rainwater catchment systems can be found in most regions of the world, with adaptations suited to local climatic conditions. Despite its long history and ubiquitous use, rainwater harvesting is rarely practiced where public and private utilities supply safe, abundant, and reliable water. But this is changing—the potential for rainwater harvesting is being rediscovered as stress on conventional potable water supplies increases (Martin R. Yoklic 2005).

Rwanda covers an area of 26, 338 Km^2 with a population of 12,794,412 (NISR, 2018), which is among the countries with the highest population density in Africa.

Rwanda's location is within the equatorial belt. The rainfall characteristics for Rwanda are known to exhibit significant temporal and spatial variation due to varied topography and the existence of large water bodies near the country. However, two rainy seasons are generally distinguishable, one centered around March-May and the other around October – December.

Technically, a country is said to be experiencing water stress when the supply quantity per capita per year is below 1700 cubic meters. If this quantity falls below 1000 cubic meters, then the country is experiencing water scarcity. The worst cases are if the level is below 500 cubic meters, which are referred to as absolute water scarcity. Today Rwanda's water availability per capita is 670 cubic meters per capita per year, which classifies it as a water-scarce country (Ministry of Natural Resources, November 2016).

The purpose of this paper is to analyze the water scarcity problem in Rwanda and propose a Roof Rainwater Harvesting system as a reliable, safe source of water to the Rwandan community.

Roof rainwater harvesting is currently a globally recognized reliable water source for both non-potable usage (toilet flushing, irrigation, laundry) and potable use (drinking, cooking, showering) after proper treatment.

In recent years, over-exploitation of natural water sources by anthropogenic activities has led to negative environmental effects, and, consequently, to a growing need for developing new sources of water. Pressure on natural water sources can be relieved by using alternative sources for uses that do not necessarily require potable water. One of these alternative sources is onsite rooftop rainwater, which may be used for toilet flushing, garden irrigation, laundry, car washing, etc. Harvested rainwater is used not only in areas where water supply is limited by climate or infrastructure but recently also in well-developed, water-ample regions (Friedler, Gilboa, et al. 2017). Our study will include the theoretical treatment of harvested roof rainwater for portable use.

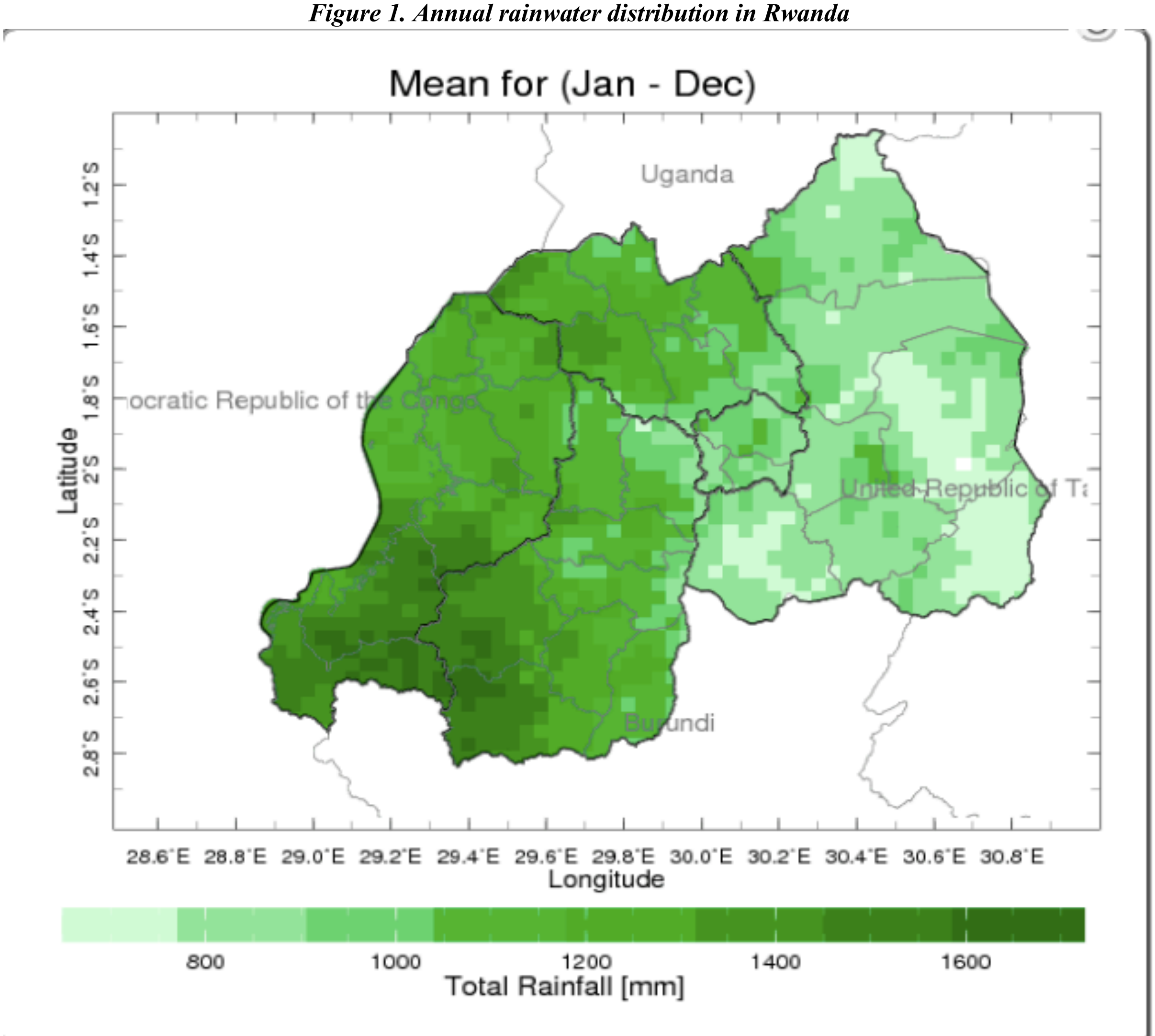
Rainwater harvesting has been used throughout history as a water conservation measure, particularly in regions where other water resources are scarce or difficult to access. In recent years, researchers and policymakers have shown renewed interest in water use strategies due to rising water demand, increased investment in conservation (both water and energy), and an elevated regulatory emphasis on reducing storm-water runoff volumes and associated pollutant loads. In the last decade, as interest in the practice has grown, numerous state, municipal, and regional agencies have adopted or amended codes and guidelines to encourage responsible and active rainwater harvesting practices. Besides, researchers from universities and non-government organizations, as well as industry consultants, have published papers and articles addressing a broad range of topics related to the installation, maintenance, costs, and performance of harvest and use systems (Chris Solloway 2013).

II. Climate and Precipitation in Rwanda

Rwanda is a country with a high altitude located in East Africa, where rainfall is an essential climate variable. The country experience two dry seasons and two rainy seasons, the two rainy seasons are September – December (locally known as Short rain season) and March-May (locally known as long or heavy rain season).

Roof op water harvesting is recommended in areas of high-intensity rainfalls, well distributed over the years (Kumar 2004). The warmest annual average temperatures are found in the low eastern lying (20 - 21°C) and Bugarama Valley (23 - 24°C), and cooler temperatures in higher elevations of the central plateau (17.5 - 19°C) and mountains (less than 17°C). Temperatures vary little throughout the year. Rwanda experiences a bimodal pattern of rainfall, which is driven primarily by the progression of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ follows the annual progress of the sun as it goes to the Northern Summer when the sun crosses the equator around March 21, and the Southern Summer around September 23 each year.

Figure 1. Annual rainwater distribution in Rwanda



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According to Rwanda Meteorology Agency, rainfall time series (1981-2017) reconstructed from station observations, remote sensing, and other proxies. The annual rainfall distribution is between 800mm – 1600 mm and above, depending on the geographic location.

The general climatic pattern reflects two rainy seasons and two dry seasons during the year. The annual rainfall per year stands at an average of 1200 mm. However, it varies from region to region as follows:
(a) 700 mm to 1400 mm in the eastern plateau and lowlands of the west;
(b) 1200 mm to 1400 mm in central plateau; and
(c) 1300 mm to 2000 mm in the high-altitude region.

The fact that Rwanda is endowed the above climatic patterns that show the abundance of rainwater, the country's households served with improved water supply with 500 meters of their home, and 49% spend more than 30 minutes fetching water. The situation is most acute in Kigali (the capital city), where the current production of about 90,000 m^3/day covers only three-quarters of the demand of about 120,000 m^3/day. This water scarcity problem shows that roof rainwater harvesting is a reliable source of water countrywide to mitigate water scarcity affecting the livelihood of the Rwandan population. Furthermore, considering the importance of RWH regarding its contribution to water scarcity, the Government of Rwanda set policy, legal and institutional framework to promote RRWH and to eradicate hydrological disasters (*article 11 of law no. 20/2011 of 21/06/2021*).

III. Water demand and supply in Rwanda

Rwanda, the country with a population of 12,794,412, as in 2017, the levels of necessary drinking water access stand at 49% in rural areas, compared to 77% in urban areas, of which 36% is safely managed. Rwandan national statistics present more optimistic data regarding current coverage for water supply: 86.4% for urban households and 72.4% for rural households in 2012. However, distance to and reliability of the water sources were not taken into account in these data. (**IRC 2019**)

Table 1. Water tariff per consumption in Rwanda

Tariff by consumption (tax exclusive)	**USD / m^3**
0-5 m^3	0.3 / m^3
6-20 m^3	0.36/ m^3
21-50 m^3	0.45 / m^3
51-100 m^3	0.80 /m^3
Above 100m^3	0.93
Industries	0.80

IV. Overall Design of Roof Rainwater Harvesting System

There are two sets of inquiries in this. First, how much water could be captured using roof water harvesting techniques in different types of housing stocks and typical rainfall years, or, in other words, what are the hydrological opportunities for roof water harvesting? Second, what is the scale at which this technique can be adopted in the urban and rural environments; or, in other words, what are the constraints in adopting this system in typical urban/ rural setting, if the water is available? How far is roof water harvesting systems economically viable, and what are the considerations involved in the economic evaluation of roof water harvesting systems? (Kumar 2004).

Rainwater systems, which collect rainfall from the roof surface, are an attractive alternative technology, and one of the cleanest water resources. Microorganisms can be treated by disinfection processes or by inducing a biofilm, but particulate matter can only be easily removed with effective storage tank design parameters (Kim, Park, et al. 2019).

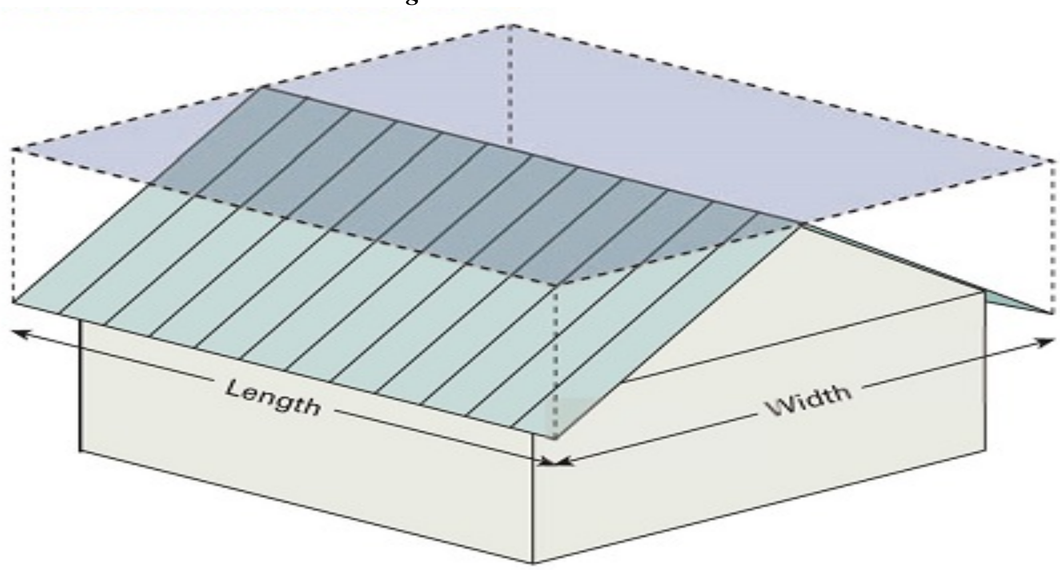
Rainwater harvesting systems consist of 7 major components: 1) catchment area, 2) roof wash (first flush/filter) system, 3) pre-storage filtration system. 4) rainwater conveyance (e.g., gutter), 5) cistern 6) water delivery, and 7) water treatment (disinfection/filtration) system (Malcolm Siegel 2008).

While designing the Roof Rainwater Harvesting System, consideration of household water demand and per capita rainwater distribution is a key before deciding on other components such as catchment area (roof), gutters, filters, pipes, water pump, water tank, and treatment system.

- *Household Water Demand per capita*= members of the household x 365 days x daily consumption per person
- Catchment area (roof): In our study context, the catchment area is the root surface. The general things to consider are household water demand, per capita rain distribution, collection efficiency, and roof materials and surrounding assessment.

The first thing to consider is whether enough rainfall can be collected to provide sufficient water for the intended use. This harvested rainwater depends on the rainfall rate, the catchment area, the efficiency of collection, and the water demand. Both the average annual rate of precipitation and the length of dry seasons must be considered in system design (Malcolm Siegel 2008).
The annual quantity of harvested rainwater from the roof depends on annual rainfall (R), and the area of the catchment (A). An estimate of mean annual runoff from a given catchment can be obtained using the equation:
$S = R * A$. Where S = Rainwater supply per annum, R = mean annual rainfall (R)
A = Area of the catchment (length (L) x width (B)

Figure 2 Rain catchment area



Example

For a building with a roof size of 10m x 12 m in a location with the average annual rainfall of 800 mm

A=10x12=120m^2

Average annual rainfall (R)=800=0.80 m

Total annual harvested rainwater=180 m^{2}x0.80m = 96,000 liters

Due to rain evaporation from the roof, if 70 % of annual rainfall is harvested, the volume of harvested water= 96,000 x 0.70 =67,200 liters

Average daily water for consumption = 67,200/365 = 184 liters per day.

- Gutters: The installation of gutters is to convey the rainwater from the roof to the pre-treatment tank. Gutters locally available are semi-circular (PVC materials) or rectangular (metal materials), semi-circular is recommended to avoid corrosion and for its long-lasting. Additionally, gutters need to be supported so that they cannot sag or fall off when loaded with rainwater and leakage, rain splash or overflow should be considered while choosing gutters size. However, the rule of thumb says that 1 cm^2 is required for every m^2 of the catchment area (roof).
- Filters: These are likely to be installed on both pre-treatment and post-treatment processes, depending on factors related to harvested water usage purposes.

This part of the system keeps large particulates and debris from entering the cisterns even after the roof wash system has done its job. It may consist of a domed stainless-steel screen placed over the inlets leading to the cistern. Pre-storage filters may include leaf guards where windblown debris or overhanging trees are significant (Malcolm Siegel 2008).

- First-flush system: Roof wash systems or first flush systems is a system for keeping dust and other pollutants (bird droppings, leaves) that have settled on the roof from reaching the cistern. It is not required for systems designed for non-potable water use, but it is required for potable use systems. It is designed to purge the initial water flowing off the roof during the rainfall (Malcolm Siegel 2008).

First-flush devices should be regarded as an additional barrier to reduce contamination, and it is estimated that 20-25 liters could be diverted.

- Pre-treatment water tank: This is the expensive main component of the system; the amount of harvested rainwater will ultimately depend on the volume of the storage tank. This paper recommends a polyethylene tank, which is the most available and durable in Rwanda; it is supposed to be installed above ground for future proper cleaning.
- Water pump: The purpose of this pump is to increase water pressure. It can be installed after the pre-treatment tank and post-treatment tank depending on the clean water installation and gravity-flow.
- Water treatment (disinfection/filtration) system: The treatment process depends on factors related to water demand, and water usage purpose (potable or non-potable). The suggested treatment process includes filtration, UV sterilize.

This is likely to be the most complicated part of the system and consists of several components. The design will depend on factors related to the intended use (potable or non-potable), water demand, and the relationship of the harvested water system to supplementary sources of water. Processes include filtration, disinfection, and polishing steps, as discussed in more detail later. Disinfection may include UV sterilization, ozonation, chlorination and filtration systems such as nanofiltration and reverse osmosis. Water treatment may take place at the point-of-entry into the house, at point-of-use taps, or a combination of both (Malcolm Siegel 2008).

- Post-treatment water tank: This is the reservoir installed after treatment process to store rainwater for potable use, its size always depends on water demand. This paper recommends a polyethylene tank, which is the most available and durable in Rwanda; it is supposed to be installed above ground for future proper cleaning.

The storage system (tank) choice in terms of quality and capacity will depend on available space, materials, annual rainfall, household water demand, and financial capability.

Feasible Roof Rainwater Harvesting system and cost in Rwanda

Numerous storage systems for roof rainwater harvesting such as Ferro-cement tank, brick/masonry tanks, artisanal tank with plastic liner, metal tank, fiberglass tanks, polyethylene tanks, and jerry cans of 20 litters are applicable in Rwanda. However, the following observation was made while conducting our study to come up with a conclusive recommendation

Table 2 Available Water tank comparison in Rwanda

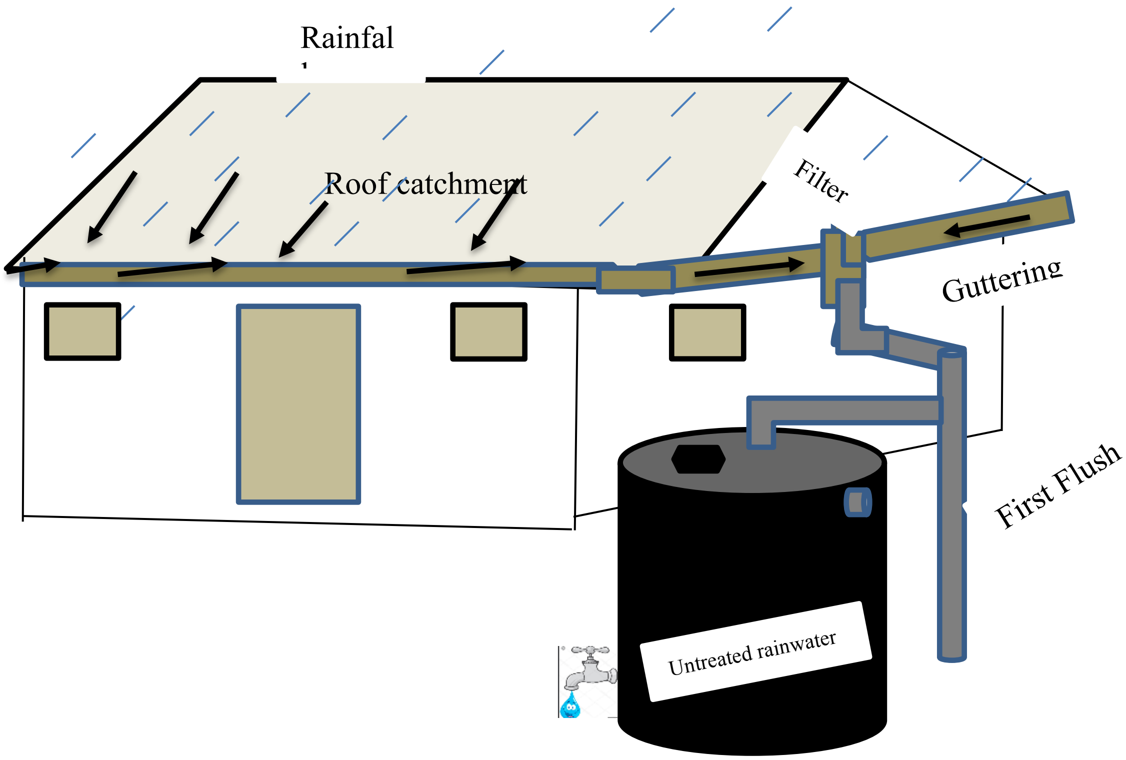
Description	Cost/USD	Observation
Ferro-cement tanks	220 / m^3	• Risk of cracking which may cause leakage • Known technology • A larger one will require excellent artisans • Not the cheapest and durable
Brick/Masonry tank	165/ m^3	• Long life • Known technology, used for larger and smaller tack • Risk of cracking • Expensive and not durable
metal tank	176/ m^3	• Exposed to corrosion • Expensive and not durable
fiberglass tanks	242/ m^3	• Long-lasting • A limited number of suppliers • The most expensive
polyethylene tanks	143/ m^3	• Widely available in Rwanda • Light and quick installation • Require foundation or other support construction • Long-lasting and affordable due to available installment payment • Easy to clean and available in many sizes.

After examining different Roof Rainwater Harvesting Systems based on available materials and affordability within the country

The researcher advised that material selection and size should be at the core of the purpose of water usage, quantity willing to capture, collection surface, estimate indoor and outdoor water demand, and the calculated volume of rainfall, etc. while designing Roof Rainwater Harvesting System. Additionally, considering available materials and affordability, the researcher recommended the following rainwater harvesting materials, cost, and design.

- Polyethylene tank: 143 USD/m3
- Iron sheet (roofing materials): 4.95 USD/m
- Plastic gutters: 6.6 USD/m
- Filter: 4.5 USD
- Water pump: 220 USD
- 300 ml Diluted bleach "Sodium hypochlorite solution (known as Sûr'Eau) = 0.33 USD
- Water tap = 2.75 USD
- Polyvinyl Chloride (PVC) Pipe= 8.8 USD/m

Figure 3 Proposed roof rainwater harvesting system



V. Roof Rainwater pollutants and treatment process

Physical, chemical, and bacteriological characteristics are likely to be found in roof rainwater. Concentrations of fecal coliforms deposited by animals on the catchment area (roof) are much unavoidable (Rojas, Prieto, et al. 2018).

Water may be contaminated by a variety of substances depending on the source of the water body, the environmental factors, and human activity. Physical contaminants lead to the turbidity of water owing to the presence of materials like clay, microorganisms, or soil runoff, and particles in water bodies may harbor microbes (pathogenic or nonpathogenic). Bacteria enter into water bodies mainly in the form of, e.g., animal and human wastes or runoff from farms.

The process of the Roof Rainwater harvesting system includes the collection, conveyance, and storage of rainwater for future use (Aniruddha B. Pandit 2015).

In our research, it was reported that the quality of harvested rainwater depends mostly on the materials used to construct the Rainwater Harvesting system and its environmental location. Before appropriate treatment, Roof Rainwater characteristics include microbes that affect the quality of harvested rainwater, metals, and nutrients.

The rainwater quality is relatively reasonable but not free from all impurities; numerous studies analyzed that roof cleanliness and storage system (tank) is critical in maintaining a tasty variety of rainwater. The storage system requires cleaning and disinfection when the tank is empty or at least once every year.

Roof Rainwater treatment for potable use will consist of several steps, including filtration, and disinfection.

Filtration can begin at the inlet to the cistern using a sand filter. Within the house, other cleaners can remove large particles such as parasites, while others can remove the smaller viruses.

Disinfection: There are three methods of disinfection commonly used: chlorination, ultraviolet light, and ozonation.

Chlorination is often used in combination with the other two technologies because a free chlorine residual can be maintained in the distribution system, providing on-going treatment for viruses. Chlorine is available via chlorine gas, liquid sodium hypochlorite bleach, or solid calcium hypochlorite. Chlorine gas is corrosive and dangerous and not recommended for home systems. The solid Ca-hypochlorite is stable and easy to dispense using in-line chlorinators, where solid pellets of tablets slowly dissolve. The solid form, however, is very concentrated and must be kept in tightly closed containers away from combustible materials like oils. Liquid bleach is more practical for most homeowners because it is safe and easy to dispense. It is crucial to use chlorine that is certified by ANSI/NSF as listed on the NSF website. Disinfectants for pools and spas may contain toxic compounds such as cyanide and shouldn't be used in drinking water systems (Malcolm Siegel 2008).

In our study, Diluted bleach "Sodium hypochlorite solution (branded as Sûr'Eau) is recommended because it is certified and available at the Rwandan Market. The general dosage recommended is 0.2 mg/L, water should be kept without use for about half an hour after adding diluted bleach.

Figure 4 Recommended diluted bleach for rainwater treatment

Diluted bleach "Sodium hypochlorite solution."

Microbes in harvested rainwater may originate from different locations depending on the conditions of climate. Rain may be affected by the type of wildlife that may come into contact with the collection surface. Additionally, it is recognized that birds act as a significant source of pathogens; other causes include dry deposition or by wet deposition (during rain events). Inappropriate design and material selection may promote contributions from avian sources and inhibit cleaning activities, thus resulting in lower microbial quality of harvested rainwater.

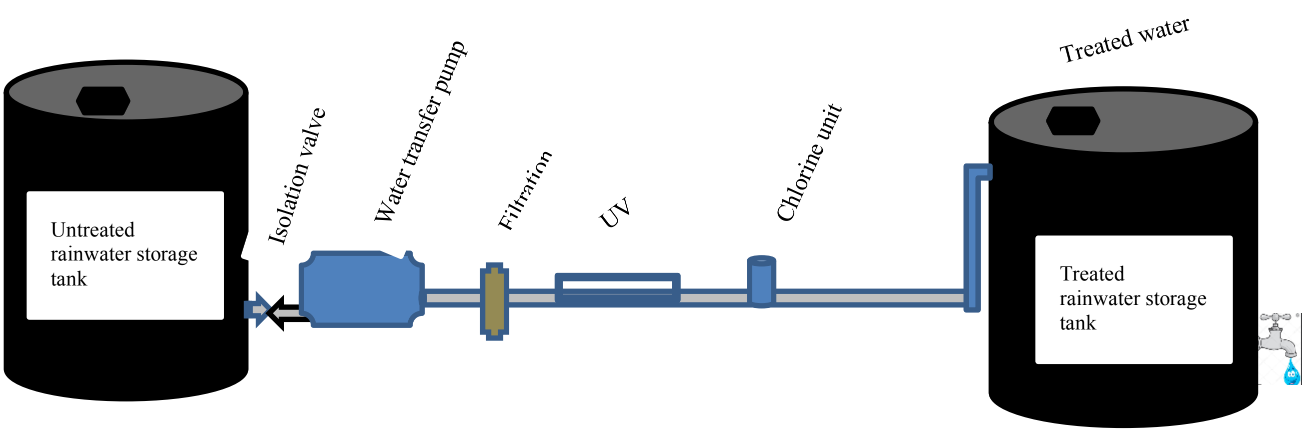
Our study has shown that rough roofing surfaces, such as asphalt shingles, trap and retain particles and pollutants more so than smooth materials and can have a detrimental effect on harvested water quality. In addition to the roofing materials, gutters have been identified as significant contributors of heavy metals to roof runoff, especially Zn and Al.

Pre-storage and post-storage treatment processes are most likely the cause of a generally better quality of stored water compared to roof runoff, and, in many cases, led to compliance with potable water guidelines and standards.

Numerous studies documented that roof rainwater contains a variety of pollutants, including sediment, heavy metals, nutrients, and bacteria. Potential treatment options for RWH systems include both pre-storage (debris screens, filters, and first-flush diversion) and post-storage measures (post-storage filtration, clariflocculation, and disinfection).

Harvested Roof Rainwater treatment system

Figure 5. Rainwater treatment design



VI. Benefits and Risks from the Use of Harvested Rainwater

Rainwater is an alternative water supply that offers several benefits, and in recent years has been promoted to improve the availability of water for different purposes, particularly in rural areas. Nevertheless, certain factors could favor the expansion of the Rainwater Harvesting System, and develop and maximize the adoption, use, and benefit of systems. When Rainwater Harvesting is promoted, the current water supply should be considered. Water availability and the supply service determine the purposes to which water will be put. In essence, non-potable uses are accepted in all localities, whereas potable applications are most accepted in areas with fewer supply alternatives (María L. Fuentes-Galván 2018).

In our case study, rainwater users perceive that due to water scarcity, they acknowledge Rainwater not only to be an alternative supply but also the primary water source for the community and a tool to decrease hydrological disasters that disrupt the environmental condition.

Numerous pieces of evidence significantly advise that it might be securer to drink rainwater when effectively harvested than water supplied from the public water system in many countries. Our research study with community health workers in Rwanda showed that drinking water from the municipal supply system reported a higher sickness rate than drinking harvested and treated roof rainwater.

The use of disinfectants such as chlorine has come under public health scrutiny in recent years because of the carcinogenic disinfection byproducts (DBPs) that are produced by the reaction between natural organic matter (NOM) in water and the chlorine oxidants. The NOM or Total Organic Content (TOC) of rainwater is very low (absent or limited contamination by animal and microbial sources); therefore, the risk of DBP formation is more moderate in the rain than in-ground or surface waters. The purity of properly harvested and treated rainwater, however, carries its health risks. The absence of essential nutrients in the rain has health implications: lack of calcium and magnesium increases the risk of cardiovascular diseases; the lack of fluoride increases the risk for dental caries. Care must be taken to include vitamin supplements in the diet if harvested rainwater is the sole source of drinking water (Malcolm Siegel 2008).

VII. Discussion

In many countries, the roof rainwater system is taken as a supplement to the public water supply. However, certain precautions are required to protect both the roof rainwater harvesting system and public water system:

- Corrosion control: pH should be less than 7.7 to prevent likely precipitation of carbonate salts in the pipes and pipes joints. This study recommends the use of polyvinyl chloride pipes and fittings in plumbing to mitigate corrosion.
- Filters and first flush should be installed to ensure turbidity control and prevent pollutants from reaching harvested water storage. Additionally, the chlorine unit must be installed efficiently to kill bacteria, viruses, and protozoans that commonly grow on the collection area (roof), water channels (pipes), and rainwater storage reservoir (tank).

Depending on financial capacity by rainwater harvesters, our study recommends two water tanks while designing the system; the first one is an untreated rainwater tank for non-potable use (laundry, toilet flushing, and irrigation). The second one is a treated water tank for potable use (cooking, drinking, cooking, bathing, etc.). Additionally, the researcher advises color-coding on both portable and non-potable systems to ensure successful, related harvested rainwater purposes.

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