Conceptual Design of a Sustainable Rainwater Harvesting and Treatment System

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Abstract. In Nigeria, corrugated sheets make up more than 60% of rooftop catchments, indicating the tremendous potential of rainwater harvesting and treatment as a dependable source of drinking water. Rain Water Harvesting and Treatment is a sustainable approach that should be incorporated in urban water cycle management. It has the potential to reduce the external water demand in urban areas, alleviate water stress, lessen non-point source pollution, decrease the volume of treatable urban runoff, stop flooding, and aid in the mitigation of climate change. However due to the fears, concerns and misconceptions of people concerning rainwater and its cleanliness, it has become imperative to design a treatment system that ensure rainwater after contact with contaminants in the atmosphere and on catchment areas is still suitable and most preferred for drinking purposes. The Rainwater treatment system used in this study comprises of an Aluminum catchment, a first flush and conveyance system, storage system, a treatment system, a Rain gauge, an Electronic water level indicator and a nozzle controller. This treatment system which is made up of ceramic disinfector pellets of various particle sizes such that as rainwater goes through the pellets it serves as a filter and also a disinfector to ensure the Rainwater comes out drinkable. This system is cost effective, it is easy to install and maintain and can be operated with little or no training and as such it is suitable for use in rural areas.

Keywords: Rainwater harvesting · Roof · Contamination · Water supply · Treatment

1 Introduction

Rainwater harvesting and treatment is a water conservation strategy that is particularly helpful in regions where other water resources are limited or challenging to access. This approach could be crucial in the future management of water resources in the rural areas of Nigeria and may offer a feasible solution to the problem of urban water stress. In addition to reducing the demand for primary water supply, rainwater source control can also provide a chance to reduce energy consumption and associated emissions (and wastewater to be treated) [1].

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The need for water is growing as a result of growing population, changing lifestyles, and the effect of climate change is becoming more vivid by the day. Water is more scarce and demand is typically higher in arid climates where many people live and work. An effective RWH&T system will significantly reduce the dependency on the mains water supply. Reducing the amount of mains water supplied will therefore result in less water being drawn from lakes, rivers, and aquifers, leaving more water available to improve the ecosystem and support the aquatic environment [2].

RWH&T systems can lessen the chance of floods and pollution by releasing less rainwater into drains, sewers, and ultimately rivers. When there is a high flow of water, they can help to slow it down and relieve the strain on the drainage systems. Rainwater harvesting is frequently used in sustainable drainage systems (SUDS). SUDS increase the retention and control of surface/storm water, which lowers the danger of flooding [3].

2 Literature Review

Since corrugated sheets make up more than 60% of rooftop catchments in Nigeria, RWH has a significant potential for being a dependable source of potable water. The community streams in Akufo, a hamlet in Ibadan, Nigeria, where rainwater exploitation was explored as a water source, were extremely filthy and sick; as a result, rainwater was viewed as a practical option in the construction of a community water supply network [4].

Moreover, [5] has researched the difficulties with RWH in Nigeria and determined that storage facilities were inadequate. In six rural villages in Nigeria, samples of rainwater were taken from thatch, aluminum, asbestos, corrugated iron roofing sheets, and open surfaces from catchment roofs. The potability of these samples was evaluated. In the rural areas, they discovered rainwater characteristics that were less than ideal, as the majority of the physicochemical and biological traits of the rainwater samples fell below the WHO criterion.

Therefore, this study is aimed at developing (designing and constructing) a sustainable, cost effective and portable rainwater harvesting and treatment system/technology that guarantees domestic water supply in the rural areas and urban areas of Nigeria with a view to reducing the water shortage problem.

3 Materials and Methods

3.1 Rain Water Harvesting and Treatment System Components

The RWH&T System collects roof runoff, provides water quality treatment and uses enough head to send the water to the secondary storage/distribution system.

The RWH&T system is comprised of five key components:

Catchment Surface – The roof of the mode RWH&T system provides the surface area for rainwater collection.

Conveyance System – This consists of gutters, downspouts, and piping that transport water from the roof to the primary storage, through the ceramic disinfector, and finally to secondary storage.

First Flush Device - This mechanism prevents the "initial flush" of rain from entering the storage tank. It is a quality control mechanism designed to keep pollutants that have accumulated on the roof from entering the system.

Water Storage – For the purpose of this design two storage tanks will be used above ground. The first storage, acting as the primary storage will be used to store the rainwater from the roof and it will be fitted with a water level indicator. The second storage acting as the secondary storage will be used to store the treated water.

Ceramic Disinfector – The filtration and treatment system is made up of clay mixed with rice husk and grog and infused with silver nitrate. The Ceramic disinfector pellets are installed in the disinfector compartment, just after the primary storage.

Recording Rain Gauge - The Tipping bucket rain gauge is used to automatically record the amount of rainfall received in the proposed area for a given time period (Fig. 1).

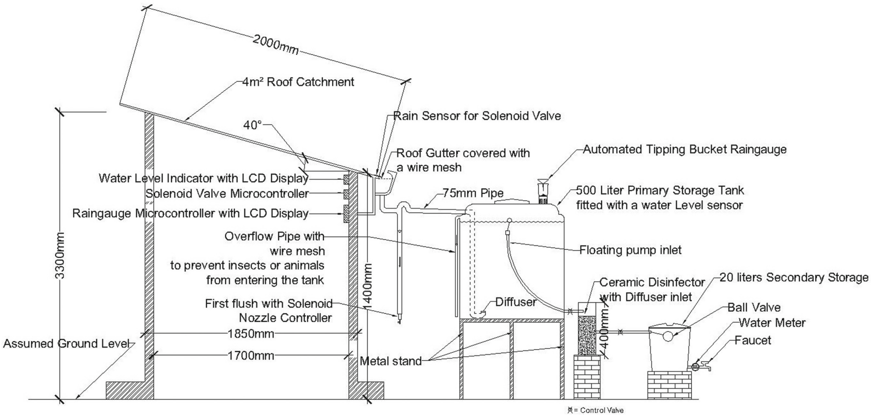

Fig. 1. Cross section through the RWH&T model system

3.2 The Catchment Surface

For the purpose of this design, the model catchment was constructed with aluminum roofing sheets. A Catchment area of 4 m^2 was used for this design model. This catchment was designed to meet the daily water demands for a family of 1 person for a year. According to [6] annual rainfall in the South Eastern part of Nigeria ranges from 1400 to 2700 mm. Hence, the catchment was designed with the maximum value of annual rainfall. The Catchment was designed to have a slope of 2:1, pitch of 7:12 and a slope factor of 1.1577.

The Runoff Coefficient (RC) is a dimensionless number that calculates the amount of rainfall that actually turns into runoff after accounting for spillage, leakage, surface wetting, and evaporation losses [7]. The RC is therefore helpful for estimating the potential water that may run off a surface and be transferred to a rainwater storage system (Table 1).

3.3 Interception and Conveyance System

This is the network of pipes, gutters, and downspouts that is used to transfer water from the roof to the primary storage, through the ceramic disinfector and then the secondary cistern. A PVC gutter covered with a screen was used to channel rainwater from the roof to the primary cistern. In order for the Interception and Conveyance System to function effectively, it was essential to be able to intercept the maximum quantity of water from the catchment, minimize transmission losses from the gutter to the cistern, and get rid of standing water, which may easily turn into a mosquito breeding ground.

Table 1. Runoff coefficients for different roof materials

Roof	Runoff coefficient (RC)	References
Roofs (in general)	0.7–0.95	[8]
Sloping roofs		
Concrete/asphalt	0.9	[9]
Metal	0.95	[9]
	0.81–0.84	[10]
Aluminum	0.7	[11]
Flat roofs		
Bituminous	0.7	[11]
Gravel	0.8–0.85	[9]
Level cement	s0.81	[10]

3.4 First Flush Device

The First flush system in this study was completely automated with a nozzle controller. It was designed to temporarily store and then automatically expel the first water that flowed off the roof following each rainstorm occurrence. Since the catchment surface may gather bird droppings, garbage, and other contaminants, the "initial flush" of water was directed to an area outside of the storage system.

A first-flush diverter is a necessary component of a RWH system for drinkable water. The first flush can be separated primarily using one of four techniques: manual, fixed volume, fixed mass, and flow rate. But for the purpose of this design, a fixed volume first flush device controlled by a solenoid nozzle sensor was used. The first flush was bent upwards along the pipe length to ensure the raw water does not escape into the primary tank. The size and length of the downpipe utilized were used to calculate how much water was directed to the first flush device. The first 1mm of rain on your roof is a “rule of thumb” on how much of the initial water to divert. Therefore:

i. Since the roof area is 4 m^2.
ii. One liter of water is produced by 1 mm of rain on 1 m^2 of roof.
iii. So, the first flush for the roof catchment should be 4 L + 10% factor of safety = 4.4 L = 0.0044 m^3
iv. Therefore, for a 3 in. pipe, the depth of the pipe should be 0.96 m (Fig. 2).

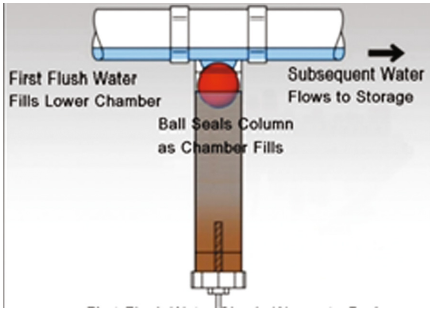

Fig. 2. Cross section through a fixed volume first flush device

3.5 Water Storage/Cistern

The most crucial and expensive part of the rain harvesting system is the storage cistern. For the sake of this design, Polyvinyl Chloride (PVC), a non-corrosive cistern material designed for longevity, was utilized since it will not rust or experience corrosion during its service life as will metal and concrete. PVC storage tanks are portable and simple to handle. They are often produced as a single unit. They do not have any sealants used to bind any component of the cistern together, nor do they have any joints or seams where pieces of the cistern have been welded together. Additionally, PVC storage tanks can be recycled once their useful lives are over.

The rainwater cistern used for this study was carefully placed and covered to prevent leaves, dust, insects, vermin, and other agricultural or industrial contaminants from contaminating the water. Diffusers/Strainers were installed at the inlet and outlet of the primary storage tank so as to screen the incoming and outgoing water. When given some time to sit inside the cistern, relatively clean water will typically get cleaner. When the water is reasonably clean, bacteria that enter the cistern will quickly die off. Algae growth was avoided by using a black cistern and keeping the cistern sited in a shady spot so as to keep the water cool. Additionally, a water level sensor was employed to provide a real-time reading of the water level in the main storage tank.

3.6 Cistern Design

The main calculation carried out was to accurately size the water tank to provide enough storage space. Several interconnected aspects that were considered together led to the storage capacity. They consist of:

i. The amount of rainfall available for use, as well as local rainfall data and meteorological patterns.
ii. The roof size.
iii. Runoff coefficient (value varies from 0.5 to 0.9 depending on the type of roof and slope).
iv. The number of users, consumption rates, or the daily water needs of the household.

All but the first of these factors can be controlled to some extent. The method of capturing rainwater, i.e. whether the system will give a full or partial supply, also influences the components and the sizes of the system. The tank is sized using a number of different techniques. The sophistication and complexity of these techniques varies. Others require computer software and expert engineers who are familiar with the software, while some can be easily completed by relatively novice, first-time operators. The following factors will play a significant role in determining the method used to design system components:

i. The complexity and scale of the system and its parts.
ii. the accessibility of the equipment needed to use a specific method (e.g. computers).
iii. The expertise and the level of education of the operator/designer.

It is also important to size the reservoir correctly in regions with low rainfall or variable rainfall distribution. There will be a surplus of water during some months of the year and a deficiency at other times. If there is insufficient water available all year to meet the demand, then enough catchment and storage will be needed to get through the dry spells. This will be done carefully to prevent unforeseen expense because storage is pricey. However, the following is a condensed method.

Supply Side Approach

i. Number of expected users: 1 person
ii. Consumption per day: 50 lpcd
iii. Total Demand: 50 L per day
iv. For a year the total water demand $= 50 \times 365 = 18{,}250$ L per year
v. Supply:
vi. Roof area: 4 m^2
vii. Runoff coefficient (aluminum roof): 0.7
viii. Average annual rainfall: 2700 mm per year = 2.7 m per year
ix. Water available annually (assuming all is collected) $= 4\ m^2 \times 2.7\ m \times 0.9 = 9.27\ m^3$
x. Daily available water $= 9.27/365 = 0.0267\ m^3$/day or 26.7 L per day. This amount of water is only about 50% of the basic water demand of 50 lpcd. Hence, the roof area needs to be increased to meet the basic water demand. The minimum roof

area per capita (person) required to harvest enough water to meet basic demand is 7.51 m^2 per capita. The implicit assumption is that there is uniform distribution of rainfall all year round, which is far from reality. If that was the case, a minimum storage of 50 L would have been adequate. Since this is not the case, a storage system is needed.

Demand Side Approach

The demand side approach will be utilized to calculate the maximum storage needed based on consumption rates and building occupancy.

i. Consumption per capita per day, lpcd – 50 L
ii. Number of persons, n = 1
iii. Longest average dry period – Assume a period of 15days
iv. Annual consumption = lpcd × n × 365 = 18,250 L.

Storage requirement, T = (18,250 × 15)/365 = 750 L. This storage should be enough to hold water for the length of dry days specified but will not be able to serve during the dry season which lasts for about four months. Besides, there will be water spill any day the rainfall amount exceeds 0.74 cm. An optimization approach with cost-benefit analysis is the most preferred method for the purpose of sustainability and cost minimization.

3.7 Ceramic Disinfector

For the purpose of this design, ceramic pellets were employed for filtration and water treatment. The ceramic pellets were manufactured with a mixture of good plastic clay, sawdust, grog, silver nitrate and water. The Ceramic disinfector compartment was located just after the primary storage. First, the dry clay sample was obtained from the Ceramic Studio, Department of Fine and Applied Arts, Faculty of Arts, University of Nigeria, and passed through a 22-mesh sieve. Grog was also utilized to increase the flow rate of water through the final filter and avoid shrinking of the ceramic disinfector during drying and firing. When clay bricks that were broken or rejected after primary production are ground, grog—which is clay that has already been fired—is produced. The ceramic disinfector was manufactured by combining 5.89 kg (73.7%) plastic clay, 1.90 kg (23.8%) rice husk, 196.8 g (2.46%) of grog and 0.11 g (0.001045%) of $AgNO_3$. Silver nitrate is a known bactericide. Once the clay, rice husk, and grog were thoroughly combined and thoroughly mixed with the hands, silver nitrate was prepared by combining it with a small amount of water and adding to the mixture. Water was then added gradually until the mixture had a consistent paste. Rubber gloves were worn during this mixture to avoid the black coloration of the hands by $AgNO_3$. Mixing silver nanoparticles into the clay mixture prior to firing has been found to increase silver retention in the ceramic disc filter and may result in a longer lifespan when compared to filters made using the silver microparticle approach, which release silver at high levels immediately during early use [12]. The amount of silver in the ceramic also affects how well the filter works.

After reading multiple articles where ceramic filters were made with various ratios of clay, sawdust, and grog, this combination of materials were chosen. Higher clay content fired ceramic filters displayed a comparatively low value of hydraulic conductivity and, as a result, an intolerably low flow rate, whereas higher rice husk content fired ceramic filters were brittle and readily shattered.

After mixing, the mix was then separated into 90 small portions, molded by hand, left to air dry for more than 24 h and then fired in the Kiln at a temperature of 900 °C for another 4 days. The rice husk in the filter is burned during this process, creating a porous, water-permeable ceramic substance.

Firing the Clay mixture at such high temperatures will allow for:

(1) the complete dehydration of the clay and
(2) the vitrification (chemical alteration) of the clay to create the final disinfector component.

After firing, the ceramic disinfectors were then cooled, crushed and sieved with sieve numbers 12 and 6. A normal filter lifespan is two to three years; to preserve the specified flow rate, it will be frequently cleaned with a brush. Next, the ceramic disinfector pellets will be inserted into the disinfector compartment which is inclined at 90° to enable flow by gravity, also one-way valves will be installed just before and after the ceramic disinfector to ensure there is no backflow.

3.8 Recording Rain Gauge

One of the major problems associated with water supply in developing countries is lack of adequate data for planning and implementation. Since the annual rainfall used here is a generalized value for Southeastern Nigeria, there is need to determine the actual amount of rainfall in the proposed location of the setup in order to validate the assumptions made. Hence, a tipping bucket rain gauge was built from scratch using locally sourced materials, electronic components and sensors, it was used to automatically record the amount of rainfall received in the proposed area for a given time period. It provides a continuous reading of rainfall depth and time (Table 2). To avoid interference from the surrounding the rain gauge was kept twice the distance away from the height of the nearest obstruction. It was placed 250mm off the top of the tank to prevent splash back. The tipping bucket rain gauge was designed and used alongside the RWH&T system so as to produce a unit hydrograph.

4 Results and Discussion

The rainfall recording of the rain gauge was compared with the standard gauge at the Department of Geography and the result is presented in Fig. 3. Although there are differences in the results of the two instruments, analysis of variance reveals that there is no appreciable difference between the recorded rainfall values of the standard gauge and the one produced in this study [$F\ (2.3) < F_{cr}\ (3.9)$]. However, the total volume of rainfall recorded by the test gauge over the period of comparison was about twice that recorded by the standard gauge. Hence, there is need for further validation before deployment of the unit.

Table 2. Component of the recording rain gauge

S/N	Materials	Function
1	Arduino Uno	It is an open-source electronic hardware board designed to read input and turn it into output. This is accomplished by instructing the board by delivering a set of instructions (a program) to the microcontroller on the board. Programs are designed using the Arduino programming language and the Arduino software or IDE (Integrated Development Environment). In the rain gauge it reads each bucket tip and converts the tips to rainfall amount (in millimeters) according to the calibration employed
2	16 × 2 LCD display	For displaying rainfall reading
3	Plastic box	–
4	LED's (red 2, yellow 2, green 2)	Switch, current and battery indicators
5	RTC module	Real Time Clock module is a time electronic system that timestamps all recorded data so that we know the exact day, hour, minute and second each data record took place
6	Bread board	Plastic board with tiny holes for holding electronic components to build an electronic circuit
7	Hot glue gun	Alternative to soldering iron
8	Data logger shield	Electronic system that receives and saves data (rainfall data in this case) on an SD card
9	Memory card 4Gb	For storage of rain data later to be retrieved via computer
10	PCB	Printed Circuit Board electrically connects electronic components and holds them fast to the board
11	Resistor – 220 Ω	To control electric current
12	Screw	–
13	Toggle switch - 1 no	For breaking or connecting circuit
14	Variable resistor - 10 kΩ	Current control
15	Connecting wires	For connecting electronic components

5 Conclusion

Following the need to design a sustainable rainwater harvesting and treatment system that is durable, affordable, efficient and easy to maintain this system was fabricated. It is self-sufficient and it requires little or no training to operate this system. It is the future

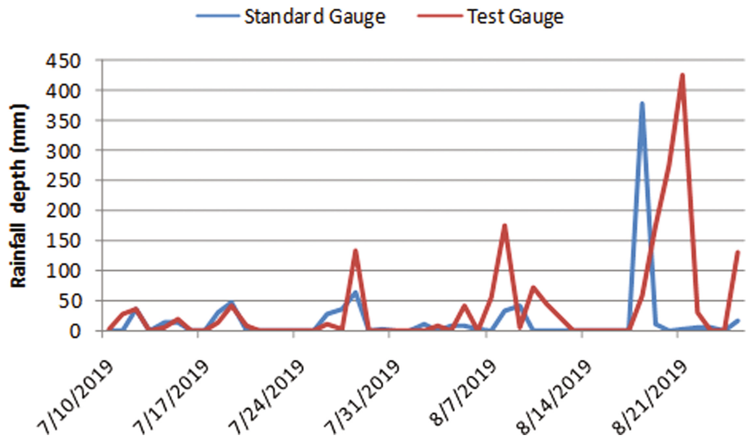

Fig. 3. Rainfall comparison chart between standard RG and designed TBRG

of water conservation in both Rural and Urban areas. The rainwater that will be treated by this system is expected to meet WHO's drinking standard and be as clean as nature originally intended it to be. The incorporation of a locally fabricated rain gauge is an innovative idea which requires fine-tuning and further validation before deployment.

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