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DESIGN OF RAINWATER HARVESTING SYSTEM: BASIC ENGINEERING AND ECONOMICS

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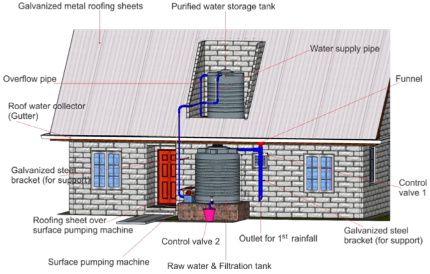
Graphical abstract



Abstract

Residents at the Universal Primary Education (UPE) sand-filled of Borokiri town in Port Harcourt city, Nigeria are facing challenges in obtaining potable water due to numerous factors. Consequently, most residents could not meet the minimum daily per capita water demand set by the United Nations (50 – 100L). The rainfall in Port Harcourt is quite high enough to augment the water scarcity however, the poor quality of the rainwater makes it unsafe. Hence, rainwater harvesting (RWH) system incorporated with treatment facility was designed for an average household of six inhabitants at a daily per capita water demand of 75L. Results showed that the treated water obtained from the designed RWH system was highly potable and the reliability of the designed RWH system for water supply is 75% at a safety factor of 1.22. It was also found that the optimal dimensions of the rectangular rooftop gutters are 170mm width by 100mm depth (including freeboard space) at a bed slope of 1inch in every 10feet. The research further revealed that the designed RWH system is highly economically viable as the net present value (NPV), profitability index (PI) and payback period (PBP) are 747, 439.21Naira, 3.4 and 1.72years respectively, at a discount rate of 15% and lifespan of 15years. Necessary recommendations were made for the inhabitants of the study area, government and non-governmental organizations.

Keywords: Borokiri, Design, Economics, RWH, Sand-filled.

1.0 INTRODUCTION

Rainfall has been identified as a good source of water since the beginning of human existence but modern technologies in abstracting and treatment of both groundwater and surface water have limited its domestic usefulness. Notwithstanding, certain regions of the world still face difficulties in accessing potable water despite the available technologies. For instance, in arid regions, surface water is scarce and adequate groundwater is not guaranteed despite the high cost of drilling in such regions. On the other hand, in the coastal regions, surface water is abundant but saline, and the seawater intrusion adversely affects the water quality in most drilled wells.

About 97% of the world's total water resources are found in ocean and sea, which limits its usage due to the associated high salinity. The remaining 3% that is freshwater, appears as groundwater and surface water in rivers, streams as well as lakes. Rainfall being the major form of precipitation is also freshwater in nature however, about 80 – 85% of it falls directly into seas and oceans. A major proportion of the remaining 15 – 20% of the rainwater that falls on land ends up as surface runoff into streams and rivers which finally flow to seas and oceans. Yet, the little quantity of rain that falls directly on rooftops is not fully harvested as a greater percentage of it also joins the surface runoff that drains to seas and oceans.

Borokiri is a town located in Port Harcourt Local Government Area of Rivers state, Nigeria. Several researchers including Arimieari *et al*. (2014) have shown that the surface water surrounding Borokiri town is not potable due to the saline nature. Also, the groundwater within the town has been reported to have poor quality in most areas especially UPE sand-filled due to geogenic factors and seawater intrusion during pumping (Ogbozige and Toko, 2022; Ogbozige and Toko, 2020). This has limited borehole owners to drill their wells within confined spaces identified to have less chloride content (Figure 1) since there is no functional municipal water supply in the entire Port Harcourt city. Consequently, buying water in jerry-cans from water vendors becomes an alternative for most residents of Borokiri town, supplemented with sachet water.

Figure 1 Drilled boreholes at close range within UPE sand-filled, Borokiri town

Water supply from vendors is not reliable and the cost per jerry-can of water is fast increasing due to the high demand hence, most residents have reduced their daily per capita water demand to as low as 20L as against the quantity recommended by the United Nations (50 – 100L). The situation used to improve during the rainy season as residents augment the vended water with rainwater though, the rainwater harvesting (RWH) potential of the rooftops have not been fully maximized since over 80% of water from the rooftops are not harvested but get infiltrated or flow as surface runoff. However, the recent atmospheric pollution of Port Harcourt city and its environs with black-soot, possibly emanating from incomplete combustion of petroleum products during illegal refining has drastically affected the rainwater quality thus, discouraging rainwater harvesting. In other words, some residents still do not have adequate water supply for basic domestic uses during the rainy season despite the heavy rainfall and long period of rainy season experienced in the area. Hence, this research aimed at designing a suitable rainwater harvesting (RWH) system that would treat the raw rainwater safely for domestic use and ensuring adequate supply throughout the rainy period, at a minimal cost for a household especially for residents at UPE sand-filled in Borokiri town of Port Harcourt city.

2.0 DESCRIPTION OF STUDY AREA

Borokiri is a well-known town in the humid Port Harcourt city of Rivers State (Nigeria) as it is the host community of major institutions such as Enitonna High School being the oldest secondary school in the entire Rivers State, as well as the Nigerian Navy Secondary School, Port Harcourt. However, the study area being UPE sand-filled is an area within the Borokiri town that lies within Latitude 4^0 44' 37.21'' to 4^0 45' 2.44'' North and Longitude 7^0 2' 2.04'' to 7^0 2' 23.77'' East. The place is called UPE sand-filled because it was initially a swampy area opposite the UPE School but was reclaimed by filling of sand by the Rivers State Government under the administration of Chief Melford Obiene Okilo about four decades ago. Some notable landmarks within the study area (UPE sand-filled) as could be seen in Figure 2 include St. Mark's Anglican Church, Borokiri; Church of God Mission International, Borokiri; New Era Brilliant College, Borokiri and Great Grace Global Reconciliation Ministries (GGGRM), Borokiri.

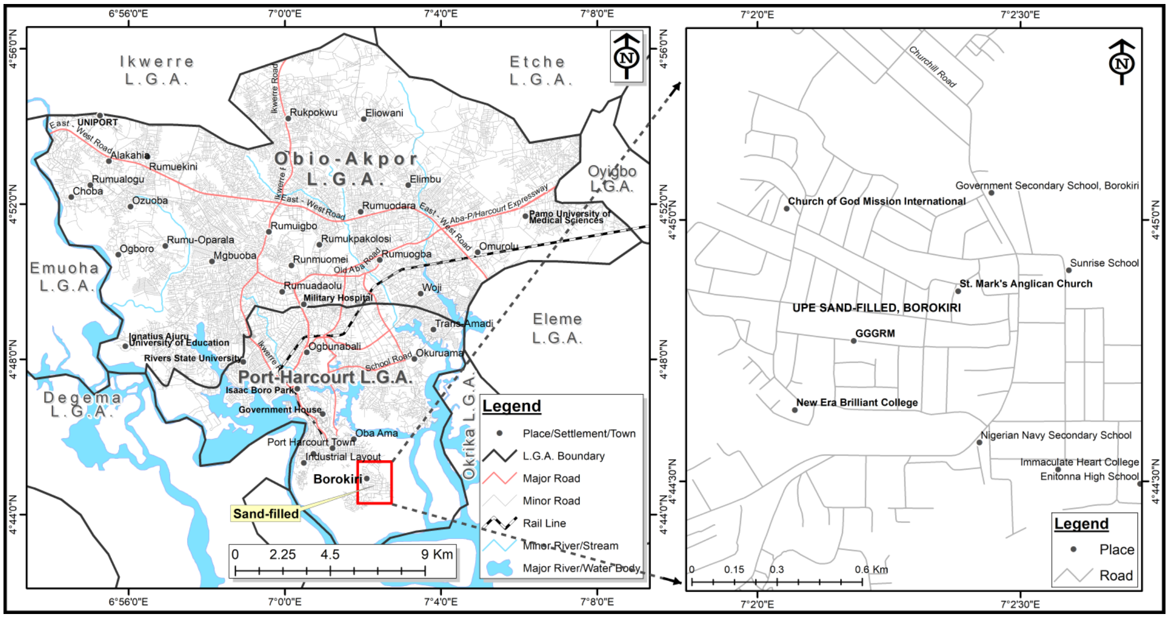


Figure 2 Map of study area (modified from the administrative map of Port Harcourt, Nigeria)

3.0 METHODOLOGY

The house proposed for the design of RWH system was identified and the per capita water demand was estimated thereafter, the estimated value was used in determining the water demand needed by the entire household after considering *Factor of Safety*. The monthly rainfall data of the catchment (study area) for the past 30years, beginning from January 1992 to December 2021 were obtained from the headquarters of the Nigerian Meteorological Agency (NIMET), Abuja. Afterward, the mean monthly rainfall was determined. The quantity of rainwater that could be effectively harvested from the rooftop which is called rainwater harvesting potentials of the rooftop was calculated using Equation (1).

$$Rainfwater\ harvesting\ potential\ (m^3) = R \times A_r \times C \qquad (1)$$

Where; R is the rainfall depth in metres (m), A_r is the total area of rooftop contributing harvested rainwater in m^2 and C is the runoff coefficient of the roof material (given in Table 1).

Table 1 Standard runoff coefficients for rooftop materials

Roof Type	Runoff Coefficient (C)
Galvanized iron sheet	0.90
Asbestos	0.80
Tiled roof	0.75
Concrete roof	0.70

Source: AFPRO-UNICEF, 2006

The capacity of the rainwater storage tank was determined with several considerations such as availability of space for storage tank or cistern, minimizing financial implications as well as minimizing water quality deterioration during storage. Thereafter, the dimensions of the rooftop gutter were designed and the entire rainwater harvesting system was modeled using SketchUp 2020 and CorelDraw 17 software. The reliability (Re) of the designed RWH system in meeting the daily water demand was calculated using Equation (2) and was interpreted as Excellent ($1.0 \geq Re \geq 0.90$), Good ($0.89 \geq Re \geq 0.80$), Acceptable ($0.79 \geq Re \geq 0.70$), Questionable ($0.69 \geq Re \geq 0.60$), Poor ($0.59 \geq Re \geq 0.50$) and Unacceptable ($Re < 0.50$) as reported in Suresh (2018).

$$Re = \frac{(X - Y)}{X} \times 100\% \qquad (2)$$

Where X is the total number of months in a year (i.e., 12) while Y is the total number of months the RWH system could not adequately provide the daily water demand for the entire household.

Prior to the estimation of the capacity of the rainwater storage tank and dimensioning of the rooftop gutters, the rainwater was sampled and analyzed for basic water quality parameters using standard methods, to identify the appropriate technique of treating the raw harvested rainwater at a minimal cost. Thereafter, the identified treatment technique was tested on small scale to confirm its suitability. The parameters examined were colour, turbidity, pH, iron (Fe), lead (Pb), cadmium (Cd) and heterotrophic plate count (HPC).

The economic viability of the designed RWH system was determined using three capital budgeting techniques viz: net present value (NPV), profitability index (PI) and payback period (PBP) through Equations (3), (4) and (5) respectively.

NPV is the difference between present value of future cash inflows and present value of cash outflows. Thus,

$$NPV = \sum_{t=1}^{t=N}\left[\frac{(AB)_t}{(1+r)^t}\right] - \sum_{t=1}^{t=N}\left[\frac{(AMOC)_t}{(1+r)^t}\right] - IC \qquad (3)$$

$$PI = \frac{Present\ value\ of\ future\ cash\ inflows}{Initial\ cash\ outflow} = \frac{\sum_{t=1}^{t=N}[(AB)_t/(1+r)^t]}{IC} \qquad (4)$$

$$PBP = \frac{Initial\ cash\ outflow}{Anuual\ cash\ inflow} = \frac{IC}{AB} \qquad (5)$$

Where: AB is the annual benefit of rainwater harvesting (i.e. amount of rainwater stored annually multiplied by price of water), $AMOC$ is the annual maintenance and operating cost, IC is the installation cost of RWH system, r is discount rate, t is time in years and N is the lifespan of the RWH system.

4.0 RESULTS AND DISCUSSION

4.1 Water Demand

The proposed building for the design of the RWH system was a 3-bedroom flat apartment and the water demand for the inhabitants of the apartment was estimated as follows,

$$Number\ of\ inhabitants = 6$$

$Average\ daily\ per\ capita\ water\ demand = 75L$ (UN, 2010 recommends between 50 to 100L). The per capita water demand is usually increased by 20 – 25% ($Singh, 2020$) to cater for miscellaneous water demands hence 22% increment was assumed thus, a factor of safety of 1.22.

$$It\ implies\ daily\ per\ capita\ water\ demand = 1.22 \times 75L = 91.5L = 0.0915m^3$$

$$Daily\ water\ demand\ for\ entire\ household = 6 \times 91.5L = 549L = 0.549m^3$$

$$Weekly\ water\ demand\ for\ entire\ houshold = 7 \times 549L = 3843L = 3.843m^3$$

$$Max.monthly\ water\ demand\ for\ entire\ household = 31 \times 549L = 17019L = 17.019m^3$$

$Max.annual\ water\ demand\ for\ entire\ household = 366 \times 549L$ (Leap year consideration) $= 200934L = 200.934m^3$

4.2 Rainwater Harvesting (RWH) Potential

The mean monthly rainfall of the study area for the past 30years (January 19922 to December 2021) based on the records obtained from NIMET headquarters, Abuja are presented in Figure 3.

The 3-bedroom flat apartment was roofed with galvanized iron sheet and the area of roof was determined from the house plan as $232.12m^2$. In other words, the parameters A_r and C in Equation (1) were substituted with $232.12m^2$ and 0.9 respectively while parameter R was substituted with the mean monthly rainfall depths given in

Figure 3 (after converting to metres) thus, generating the rainwater harvesting potential of the rooftop as shown in Table 2.

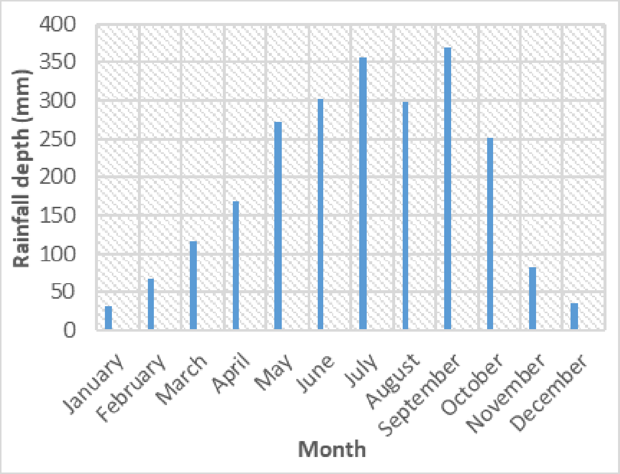


Figure 3 Mean monthly rainfall of study area (1992 – 2021)

4.3 Storage Tank Capacity

The information in Table 2 revealed that during the months of March – November inclusive, the daily RWH potential of the rooftop can successfully meet the 549L (0.549m^3) daily water demand for the entire household with excess. In other words, there would be constant rainwater supply for the entire household for nine (9) consecutive months of the year. In fact, the excess daily RWH potential for the said period (March – November) is high enough to cater for the water demand of the entire household during the non-raining period of December, January and February if stored. However, to achieve this all-round water supply, the storage of the excess water must commence during the month of October, which implies that the rainwater will be stored for over three months as against the maximum period of three (3) weeks for storing potable water (Ogbozige *et al.,* 2018). In other words, storing the rainwater for such long duration will render it non-potable with its associated effects. Also, the total volume of water needed for storage per day for augmenting the water shortage during the months of December, January and February is 702L (i.e., 307L + 332L + 63L) while the maximum number days during December, January and February is 91 (i.e. 31 + 31 + 29).

Table 2 Estimated (approximated) RWH potential of rooftop

Month	Maximum No. of days (a)	Monthly harvesting potential (b)	Weekly harvesting potential $(c) = [(b)/(a)] \times 7$	Daily harvesting potential $(d) = (c)/7 = (b)/(a)$	Daily harvested rainfall excess of daily demand $(e) = (d) - 0.549m^3$
January	31	6.716m^3 = 6716L	1.517m^3 = 1517L	0.217m^3 = 217L	– 0.332m^3 = – 332L
February	29	14.082m^3 = 14082L	3.399m^3 = 3399L	0.486m^3 = 486L	– 0.063m^3 = – 63L
March	31	24.240m^3 = 24240L	5.474m^3 = 5474L	0.782m^3 = 782L	0.233m^3 = 233L
April	30	35.362m^3 = 35362L	8.251m^3 = 8251L	1.179m^3 = 1179L	0.630m^3 = 630L
May	31	56.785m^3 = 56785L	12.822m^3 = 12822L	1.832m^3 = 1832L	1.283m^3 = 1283L
June	30	63.184m^3 = 63184L	14.742m^3 = 14742L	2.106m^3 = 2106L	1.557m^3 = 1557L
July	31	74.599m^3 = 74599L	16.844m^3 = 16844L	2.406m^3 = 2406L	1.857m^3 = 1857L
August	31	62.388m^3 = 62388L	14.088m^3 = 14088L	2.013m^3 = 2013L	1.464m^3 = 1464L
September	30	77.039m^3 = 77039L	17.976m^3 = 17976L	2.568m^3 = 2568L	2.019m^3 = 2019L
October	31	52.453m^3 = 52453L	11.844m^3 = 11844L	1.692m^3 = 1692L	1.143m^3 = 1143L
November	30	17.201m^3 = 17201L	4.014m^3 = 4014L	0.573m^3 = 573L	0.024m^3 = 24L
December	31	7.491m^3 = 7491L	1.692m^3 = 1692L	0.242m^3 = 242L	– 0.307m^3 = – 307L

Note: Column (b) was calculated using Equation (1) by substituting R with the monthly rainfall in Figure 3 (in meters) while A_r and C were substituted with 232.12m^2 and 0.9 respectively. The $0.549m^3$ been subtracted in the last column represent the daily water demand for the entire household.

It implies,

Volume of stored water needed for augmenting water shortage

$$= \frac{702L}{day} \times 91day = 63{,}882L = 63.882m^3$$

The cost of building a cistern tank of capacity 63,882L (63.882m^3) for an average household in a developing country like Nigeria will be too high. Besides, the groundwater table of the study area is very shallow (0.6 – 1.2m) as earlier reported by Nwankwoala and Omunguye (2013) thus, implying that storing the rainwater in a cistern being underground will not be suitable while space for storing such volume of water in GeePee tanks will hardly be available. Due to these setbacks (water quality deterioration, cost implication and availability of space) associated with rainwater storage for the non-rainy period, the RWH system was designed solely for the rainy period that could meet the daily water demand of the entire household.

The daily RWH potential during the month of August is excessively higher than the daily water demand of the entire household (Table 2) however, the information in Figure 3 revealed that the rainfall pattern, which tend to follow Normal Distribution was distorted during August. The sudden drop in rainfall during August could be attributed to the usual short dry season popularly known as 'August break' which last for about 2weeks. Hence, the capacity of the rainwater storage tank was designed to ensure water supply during the 2weeks 'August break' as follows:

$$Volume\ of\ storage\ tank\ (V) = volume\ of\ 2weeks\ water\ demand\ for\ entire\ household$$
$$= 2(3843L) = 7686L \cong 7700L = 7.7m^3$$

The 2weeks storage period is within the range recommended by Ogbozige *et al.* (2018) for storing potable water in plastic and galvanized tanks (≤ 3weeks). Also, Ogbozige *et al.* (2018) recommends black plastic tank as the best storage reservoir for potable water compared to galvanized metal and coloured plastic tanks since black colour absorbs maximum sunlight and thus minimize it penetration to the stored water consequently, algal growth becomes difficult in water stored in black plastic tanks as it requires sunlight to grow. In other words, the use of black plastic tanks in storing the harvested rainwater will eliminate algal growth in the tank. Hence, the storage tanks selected for this research are black coloured plastic tanks (GeePee tanks) of total capacity not less than 7700L.

The designed treatment method for the raw harvested rainwater was slow-sand filtration, with the filter media arranged as shown in Table 3.

Table 3 Arrangement of filter media for water treatment

Type of Layer	Depth	Material (Grade Size)
Top layer	20cm	Sand (0.2 – 0.4mm)
1st Intermediate layer	10cm	Granulated activated carbon (2mm)
2nd Intermediate layer	10cm	Gravel (10mm)
Bottom layer	10cm	Limestone (20mm)

Total depth of filter media (H_f) = 50cm = 0.5m

The filtration tank which also contains the raw rainwater (supernatant) has the following dimensions.

$$Volume\ (V_{rf}) = 5000L = 5m^3$$

$$Hight\ (H) = 2180mm = 218cm = 2.18m$$

$$Diameter\ (D) = 1700mm = 170cm = 1.7m$$

Since the total depth of filter media (H_f) is 50cm (i.e. 0.5m), it implies the volume occupied by the filter media (V_f) is:

$$(V_f) = \frac{\pi D^2}{4}(H_f) = \frac{3.142 \times 1.7^2}{4}(0.5) = 1.135m^3 = 1135L$$

In other words, the volume of the raw harvested rainwater (V_r) above the filter media (also known as supernatant) is the difference between the entire volume of the tank and volume occupied by filter media. i.e.

$$V_r = V_{rf} - V_f = 5 - 1.135 = 3.865m^3 = 3865L$$

Since the estimated volume of storage tank (V) is $7700L$ while volume of stored raw water above filter media (supernatant) is already $3865L$, it implies an additional $3835L$ tank is needed however, there is no storage tank of such capacity in the market hence the closest available capacity being $4000L$ was provided. The $4000L$ tank was installed overhead to store the treated or purified water after being lifted by surface pumping machine. Thus, the total volume of stored water (V) is the sum of the raw water above the filter media (V_r) and volume of purified water overhead (V_p). Consequently, the maximum volume of stored water is $7865L$ which is a little bit greater than the $7700L$ water demand during the 2weeks 'August break' (safe).

4.4 Design of Rooftop Gutter

A rectangular gutter made with galvanized iron sheet was designed using Manning's model shown in Equation (6), to channel the rainwater from the rooftop to the treatment tank through a pipe.

$$Q = \frac{AR^{2/3}S^{1/2}}{n} \tag{6}$$

Where:

$$Q = expected\ peak\ discharge\ (m^3/s) = \left(\frac{1}{3.6}\right)Cia$$

$C =$ runoff coefficient of the roof material $= 0.9$ (for galvanized iron roofing sheet)

$i =$ max. rainfall intensity of catchment in mm/hr $= 337.8$ (Ogbozige, 2021)

$a =$ catchment (rooftop) area contributing to gutter in km^2.

The designed roof type is double-pitched, and each pitch of the roof has a gutter that received the rainwater. However, both pitches did not have equal area occupied by galvanized metal roofing sheet, as part of the first pitch was designed to accommodate an overhead water storage tank. The total area of the roof occupied by galvanized roofing sheet is 232.12m^2 while the area occupied by the individual pitch of the roof are 109.48m^2 (the part containing overheat tank) and 122.64m^2. Hence, the gutters' dimensions were designed based on the side of roof that has more flow of rainwater into a gutter, which is the pitch with an area of 122.64m^2. i.e.

$$a = 122.64m^2 = 0.00012264km^2$$

It implies,

$$Q = \left(\frac{1}{3.6}\right) \times 0.9 \times 337.8 \times 0.00012264 = 1.0357 \times 10^{-2}\ m^3/s$$

$A = cross\ sectional\ area\ of\ gutter\ (m^2) = by$

$b = channel\ width\ (m)$

$y = depth\ of\ flow\ (m)$

$$R = hydraulic\ radius\ (m) = \frac{cross\ sectional\ area}{wetted\ perimeter} = \frac{by}{b+2y}$$

$S =$ bed slope of gutter $=$ 1inch to 10feet (conventional) $= 0.008$

$n =$ Manning's roughness coefficient of material (galvanised iron sheet)) $= 0.016$

To minimize the cost of materials needed for construction, the rectangular rooftop gutter was designed for *most economic* *section*. However, for a rectangular channel to have *most economic section*, the depth of flow (y) must be equal to half of the channel width (b), i.e. $y = \frac{b}{2}$ hence, the cross sectional area of gutter (A) could be expressed as shown in Equation (7).

$$A = by = b\left(\frac{b}{2}\right) = \frac{b^2}{2} \tag{7}$$

Also, for most economic section of rectangular channel to occur, the hydraulic radius R must be equal to half of the depth of flow y, (i.e. $R = \frac{y}{2}$). Thus, by combining these two conditions for *most economic section* of rectangular channel, the hydraulic radius (R) could be expressed as shown in Equation (8).

$$R = \frac{y}{2} = \frac{b/2}{2} = \frac{b}{4} \tag{8}$$

By substituting Equations (7) and (8) as well as the estimated values of discharge Q, bed slope S and Manning's coefficient n into Equation (6), it becomes,

$$1.0357 \times 10^{-2} = \frac{{}^{b^2}/_{2}\left({}^{b}/_{4}\right)^{2/3}(0.008)^{1/2}}{0.016}$$

$$\frac{1.0357\times10^{-2}(0.016)}{(0.008)^{1/2}} = \frac{b^2}{2}\left(\frac{b}{4}\right)^{2/3}$$

$$1.8527 \times 10^{-3} = \frac{b^{8/3}}{5.04}$$

$$1.8527 \times 10^{-3}(5.04) = b^{8/3}$$

$$9.3376 \times 10^{-3} = b^{8/3}$$

$$\therefore b = \left(\sqrt[8]{9.3376 \times 10^{-3}}\right)^3 = 0.17$$

In other words, the width of the rectangular rooftop gutter, $b = 0.17m = 17cm = 170mm$.

Since the depth of flow for most economic section of rectangular channel is half of the channel width, it implies the depth of flow (y) is estimated as:

$y = \frac{b}{2} = \frac{0.17m}{2} = 0.085m$ however, by adding a freeboard space of $0.015m$ the total depth of flow becomes $0.085m + 0.015m = 0.1m = 10cm = 100mm$.

Hence, the width and depth of the rooftop gutter were designed as $170mm$ and $100mm$ respectively while the bed slope is 1inch drop in every 10feet.

4.5 Operation of RWH System

The front and aerial views of the designed RWH system are presented in Figure 4 and Figure 5 respectively. At the commencement of rainfall, *the control valve 1* is kept opened to enable the first harvested rainwater entering at the *funnel* to flow out through the pipe labelled "*outlet for 1st rainfall*". This is because the first rainfall usually washed dusts and fecal materials of birds and lizards, from both the roof and gutters hence, such rainwater is been eliminated from entering the storage tank by opening the *control valve 1*. After ensuring proper washing of the rooftop and gutters, the *control vale 1* is closed to enable the harvested rainwater to enter the lower storage tank where treatment by filtration occurs at the bottom of the tank. In other words, the lower storage tank contains series of filter media at the bottom and raw harvested rainwater above the filter media. The treated or purified water (i.e., after filtration) is lifted to an overhead storage tank by means of a one-Horsepower (1hp) surface pumping machine, which finally flows to the kitchen, bathrooms and toilets through internally arranged pipe network. Once the overhead tank is filled as indicated by water flowing out through the *overflow pipe*, the pumping machine is switched off while the excess water flows out through the *overflow pipe* is removed through a *floor drain* (Figure 5). Similarly, once the lower storage tank is filled, the *control vale 1* is opened again to allow the excess untreated water flow out to a drainage through the first rainfall outlet pipe thus, the pipe serves dual purposes.

The constructed roof gutters as well as all the polyvinyl chloride (PVC) pipes used were supported firmly by means of galvanized steel brackets (i.e. hangers and pipe brackets respectively) while the pumping machine was protected from rainfall by providing a roofing sheet over it. Outdoor fetching of the treated rainwater was made possible by providing a *control valve 2* since opening the valve will enable outflow of the treated rainwater through the fitted tap.

The actual flow rate of the newly designed slow-rate sand filter could be determined by opening the *control valve 2* and recording the time taken to fill a known volume of bucket since flow rate is volume per unit time. During filtration process, most impurities in the raw water are retained at the pore spaces of the topmost filter media layer, which consequently reduces the flow rate of the filtration gradually. Therefore, after operating the system for some times and the flow rate noticed at the opening of *control valve 2* is considerably lower than the actual flow rate earlier determined, then it signifies that about 2 – 3cm of the topmost layer of the filter media needs replacement with fresh one. In other words, the treatment process being slow-rate sand filtration does not need backwashing of filter media. Likewise, the granulated activated carbon (GAC) should be replaced when due, usually between 6 – 12 months (Woodard, 2019).
Based on the information in Equation (2) and Table 2, the reliability (Re) of the RWH system in meeting daily water demand of the entire household is calculated as:

$$Re = \frac{(X-Y)}{X} \times 100\% = \frac{(12-3)}{12} \times 100\% = 75\% = 0.75$$

[Note: Y = December to February = 3 months]
Hence, the designed RWH system has an acceptable reliability coefficient.

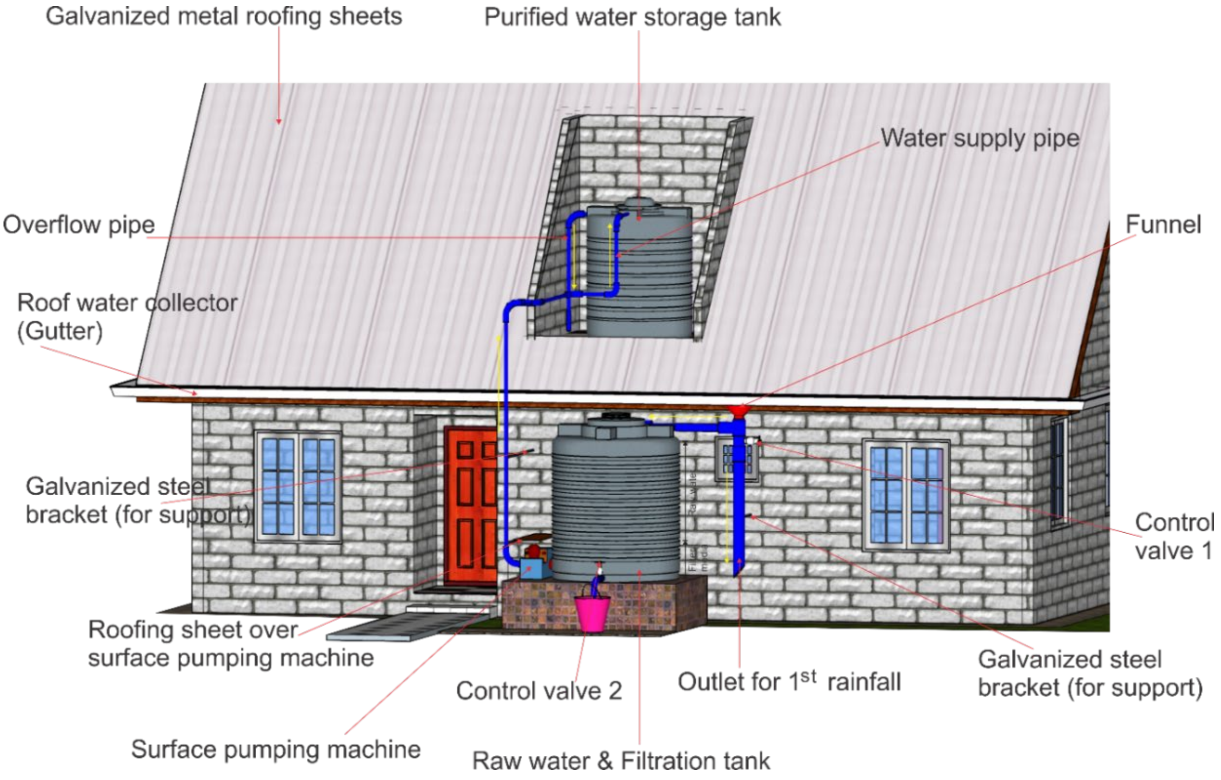


Figure 4 Front view of designed rainwater harvesting system

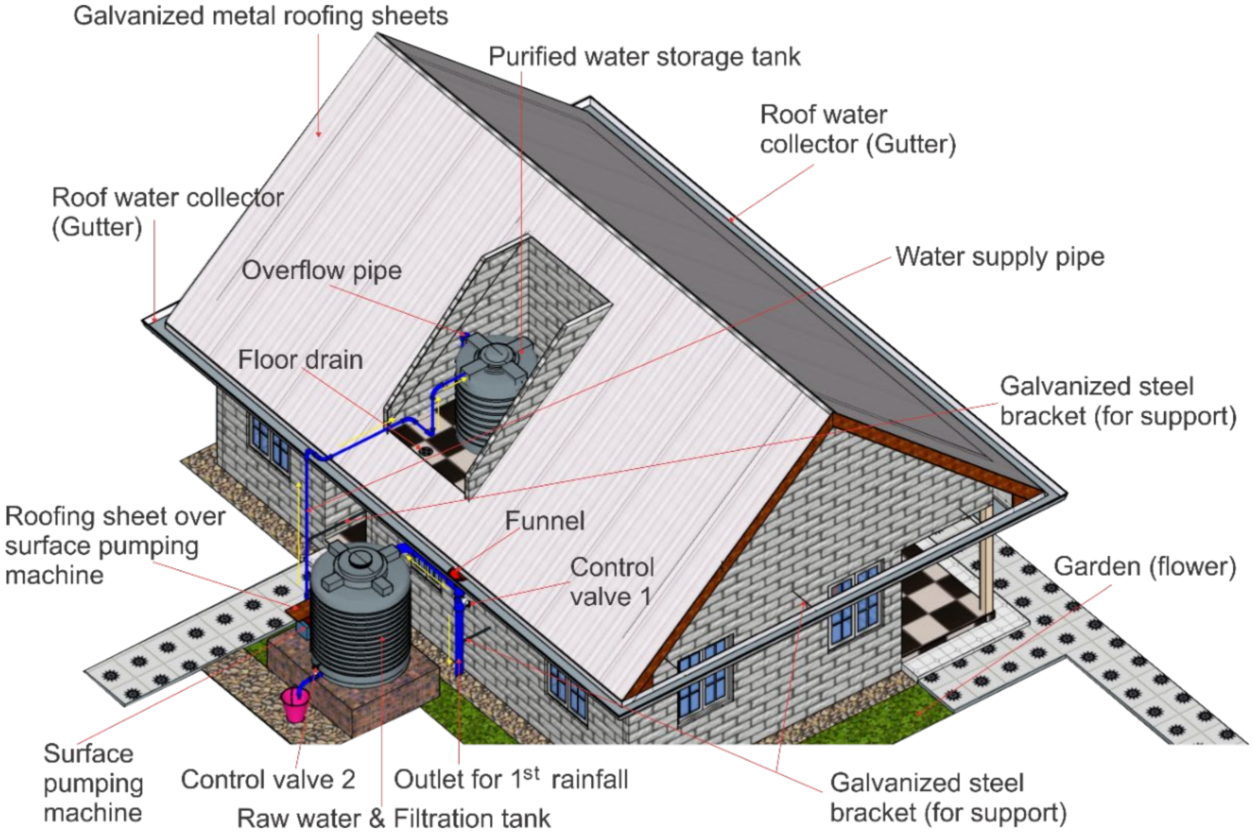


Figure 5 Aerial view of designed rainwater harvesting system on double-pitch roof

4.6 Water Quality

The quality of the rainwater before and after treatment with slow-rate sand filter on small scale but same depth of filter media is presented in Table 4. The information in Table 4 revealed that the quality of the rainwater in terms of colour, turbidity, pH, Pb and Cd are poor prior to treatment since these parameters exceeded their corresponding permissible limits set by WHO standard, unlike Fe and heterotrophic plate count (HPC) which were within the permissible limits. It is also revealed that the galvanized iron-roofing sheet imparted some metallic iron and heterotrophic bacteria in the rainwater though, their concentrations were within the WHO acceptable limits. This is because the concentrations of metallic iron (Fe) and heterotrophic bacteria (HPC) in the rainwater obtained directly from the atmosphere were 0.207mg/l and 5CFU/ml respectively while the values correspondingly increased to 0.211mg/l and 7CFU/ml in the harvested rainwater before treatment.

Table 4 Quality of untreated and treated rainwater

Parameter	Direct from Atmosphere	From Roofing Sheet (Before Treatment)	From Roofing Sheet (After Treatment)	WHO Limit
Colour (TCU)	20	20	10	15
Turbidity (NTU)	13.072	13.072	0.737	5.00
pH	5.8	5.8	6.7	6.5 – 8.5
Fe (mg/l)	0.207	0.211	0.153	0.3
Pb (mg/l)	0.024	0.024	0.006	0.01
Cd (mg/l)	0.005	0.005	0.002	0.003
HPC (CFU/ml)	5	7	2	100

TCU = True Colour Unit, NTU = Naphelometric Turbidity Unit, HPC = Heterotrophic Plate Count, CFU = Colony Forming Unit

The poor colour and turbidity noticed in the raw rainwater could be attributed to the black soot usually experienced in Port Harcourt atmosphere, caused by incomplete combustion of petroleum products. The low pH of the raw rainwater (5.8) was caused by the anthropogenic emissions of sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) into the atmosphere by industrial activities, which eventually reacted with water, oxygen and other chemicals in the atmosphere to form sulphuric acid (H_2SO_4) and nitric acids (HNO_3) then precipitated as acid rain. In other words, the low pH in the raw rainwater was caused by the acidic nature of the rain. Similarly, the presence of metals (Fe, Pb and Cd) in the raw rainwater was as a result of pollutants emitted into the atmosphere by the various industries in Port Harcourt and were washed down by the rain. However, the increase in metallic iron (Fe) in the raw rainwater obtained from the galvanized iron-roofing sheet (although little) compared to the rainwater obtained directly from the atmosphere could be credited to corrosion of the iron-roofing sheet due to the years of acid rains, which consequently eroded additional metallic irons into the harvested rainwater. Actually, the presence of heterotrophic bacteria in water did not pose a health risk especially when the concentration is lower than 100CFU/ml however, higher concentrations of HPC is an indication for ideal environments for the growth of other bacteria that could be pathogenic. Heterotrophic bacteria (though very small) were found in the raw rainwater acquired directly from the atmosphere. This is because the atmosphere also contains some airborne bacteria due to particle resuspension or based on aerosolization of surfaces exposed to air current. The little increase of HPC in the raw rainwater gotten from the roof (7CFU/ml) compared to the rainwater obtained directly from the atmosphere (5CFU/ml) despite washing of roof and gutters by the early rain before sampling, could be attributed to the effect of meteorological parameters such as wind speed and direction. This is because wind speed and direction during rainfall could cause uplift of bacteria from different sources to land on the roof.

The reduction or improvement in colour of the harvested rainwater from 20TCU to 10TCU after treatment was because of adsorption by the granulated activated carbon (GAC) used as intermediate filter media. The turbidity causing materials in the rainwater during treatment were removed by the topmost layer of fine sand filter media (0.2 – 0.4mm) as the water percolates down the filter media thus, enabling the filtrate or treated rainwater to have a tolerable level of turbidity (0.737NTU). The pH of the raw rainwater was raised from 5.8 to a permissible value of 6.7 after treatment. This was caused by the limestones used as filter media at the bottom layer of the tank since limestones are alkaline in nature. The reduction in metals (Fe, Pb and Cd) in the treated rainwater was caused by the adsorption of the metallic ions into the binding sites in the granulated activated carbon. In other words, the activated carbon which was used as intermediate filter media served as an adsorbent for metals and colour during the treatment process. The heterotrophic plate count (HPC) in the treated water was reduced from 7CFU/ml to 2CFU/ml, which is about 71.43% reduction. The reason why the heterotrophic bacteria were not totally (100%) removed in the treated water was because the biofilm layer (schmutzdecke) had not been fully developed at the surface of the topmost filter media at the time the treatment was done. Notwithstanding, the heterotrophic plate count (HPC) recorded in both the raw and treated water were highly permissible based on WHO standard.

4.7 Economic Analysis of RWH System

The cost of installing the newly designed RWH system is presented in Table 5. The installation cost excluded the building itself. The capital budgeting techniques used in determining the economic viability of the designed RWH system (NPV, PI and PBP) were calculated based on the following assumptions.

i. The discount rate (r) is 15%.

ii. The lifespan of the entire RWH system (N) is assumed to be same as the lifespan of the rainwater storage tanks which is 15years (GeePee, 2022).

iii. The annual cash inflow of the RWH system, also known as annual water benefit (i.e., amount of rainwater stored annually multiplied by price of water), as well as the annual maintenance cost are assumed to be constant throughout the lifespan of the designed RWH system.

iv. The operating cost of lifting water from lower storage tank to overhead storage tank by means of surface pumping machine is negligible.

v. The cost of buying water from vendors within the study area is thirty Nigerian Naira per 20L Jerry-can (NGN30/20L) and assumed to be constant during the 15years lifespan of the RWH system.

vi. The entire filter media are replaced twice a year (i.e., every six months).

Table 5 Installation cost of RWH system

S/No.	Description	Rate (NGN)	Quantity	Amount (NGN)
1	5000L capacity GeePee tank (victory)	150,000	1	150,000
2	4000L capacity GeePee tank (Platinum)	110,000	1	110,000
3	Galvanized iron coil for gutters	750/metre	10 metres	7,500
4	Galvanized gutter support brackets (hangers)	150	16	2,400
5	Funnel	350	1	350
6	1'' pressure PVC pipe	1,000	2	2,000
7	1½'' pressure PVC pipe	1,500	1	1,500
8	1'' PVC elbow joint	100	7	700
9	1½'' PVC T-joint	400	1	400
10	1½'' control valve	800	1	800
11	3/4'' PVC tap	400	1	400
12	Galvanized bracket for pipe support	150	4	600
13	Sand for filter media (0.2 – 0.4mm)	500/wheelbarrow	4 wheelbarrows	2,000
14	Granulated Activated Carbon (2mm)	5,000/bag	2 bags	10,000
15	Gravel (10mm)	1,000/wheelbarrow	2 wheelbarrows	2,000
16	Limestone (20mm)	1,000/wheelbarrow	2 wheelbarrows	2,000
17	One-Horsepower surface pumping machine	25,000	1	25,000
18	6'' concrete block (hollow)	100	40	4,000
19	Cement	4,000/bag	3 bags	12,000
20	Coarse sand	500/wheelbarrow	9 wheelbarrows	4,500
21	Tiles (12'' × 12'')	2,000/carton	3 cartons	6,000
22	Overall labour	–	–	10,000
23	Total			354,150
24	Add 10% for contingency			35,415
25	**Grand total**			**NGN389,565**

NGN = Nigerian Naira

Based on the above assumptions, the annual cash inflow or annual water benefit (AB), being the product of amount of rainwater stored annually and price of water, is therefore calculated as follows:

$$Daily\ water\ demand\ of\ entire\ houshold\ (DWD_H) = 549L$$

$$Months\ of\ adequate\ rainwater\ storage\ to\ meet\ DWD_H = March\ to\ November$$

$$Number\ of\ days\ from\ March\ to\ November = 275$$

$$Amount\ of\ rainwater\ stored\ annually\ to\ meet\ DWD_H = 549L \times 275 = 150{,}975L$$

$$Annual\ cash\ inflow\ or\ water\ benefit\ (\boldsymbol{AB}) = 150{,}975L \times \frac{\boldsymbol{NGN30}}{\boldsymbol{20L}} = \boldsymbol{NGN226,462.5}$$

Similarly, the annual maintenance and operation cost ($AMOC$) is calculated as follows:

$$Cost\ of\ filter\ media = NGN(2{,}000 + 10{,}000 + 2{,}000 + 2{,}000) = NGN16{,}000$$

$$Frequency\ of\ replacing\ filter\ media\ per\ annum = 2$$ (i.e. every six months)

$$Annual\ maintenance\ and\ operation\ cost\ (\boldsymbol{AMOC}) = 2 \times NGN16{,}000 = \boldsymbol{NGN32,000}$$

Hence, the present values of future annual water benefit as well as future annual maintenance and operation cost are calculated as shown in Table 6.

Table 6 Present values of future annual inflows and outflows

Year (t)	FV of annual water benefit $(AB) = (AB)_t$	Present annual water benefit $(AB)_t/(1+0.15)^t$	FV of annual maintenance and operation cost $(AMOC) = (AMOC)_t$	Present annual maintenance and operation cost $(AMOC)_t/(1+0.15)^t$
1	226,462.5	196,923.91	32,000	27,826.09
2	226,462.5	171,238.19	32,000	24,196.60
3	226,462.5	148,902.77	32,000	21,040.52
4	226,462.5	129,480.67	32,000	18,296.10
5	226,462.5	112,591.89	32,000	15,909.66
6	226,462.5	97,905.99	32,000	13,834.48
7	226,462.5	85,135.64	32,000	12,029.99
8	226,462.5	74,030.99	32,000	10,460.86
9	226,462.5	64,374.78	32,000	9,096.40
10	226,462.5	55,978.07	32,000	7,909.91
11	226,462.5	48,676.58	32,000	6,878.18
12	226,462.5	42,327.46	32,000	5,981.03
13	226,462.5	36,806.49	32,000	5,200.89
14	226,462.5	32,005.64	32,000	4,522.52
15	226,462.5	27,830.99	32,000	3,932.62
		$\sum = \mathbf{1,324,210.06}$		$\sum = \mathbf{187,115.85}$

Note: FV = Future value. In columns 2 and 4, $(AB) = (AB)_t$ and $(AMOC) = (AMOC)_t$ because both AB and $AMOC$ were assumed to be constant while $r = 0.15$ because discount rate was assumed to be $15\% = 0.15$. All calculated amounts are in Nigerian Naira (NGN).

In other words, the net present value (NPV), profitability index (PI) and payback period (PBP) as respectively expressed in Equations (3), (4) and (5) becomes,

$$NPV = NGN1{,}324{,}210.06 - NGN187{,}115.85 - NGN389{,}565 = NGN747{,}439.21$$

$$PI = \frac{\boldsymbol{NGN1,324,210.06}}{\boldsymbol{NGN389,565}} = 3.4$$

$$PBP = \frac{\boldsymbol{NGN389,565}}{\boldsymbol{NGN226,462.5\ per\ year}} = 1.72years \cong 1year\ and\ 9months$$

The economic analysis of the designed RWH system have revealed that the net present value (NPV) is much greater than zero. Likewise, the profitability index (PI) is substantially greater than unity (one), and quite a short payback period (PBP) of approximately $1year\ and\ 9months$. It obviously implies that the designed RWH system is highly economically viable. This affirmed the report of Jing *et al.* (2017) who claimed that economic viability of RWH system could be achieved if properly designed in humid and semi-humid regions.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Untreated rainwater within Port Harcourt city including UPE Sand-filled of Borokiri town is not potable however, it becomes highly potable when treated with series of filter media such as sand, granulated activate carbon (GAC) and limestone. Rainwater harvesting (RWH) potential from rooftops within UPE Sand-filled of Borokiri town in Port Harcourt city, is high enough to meet the water demand of an average household throughout a year. However, the financial implications for large storage tanks and available space for installation makes the reliability of RWH within the study area to be 0.75 (i.e. 9months in a year). Venturing into RWH cum treatment within Borokiri town of Port Harcourt city (especially at UPE Sand-filled) is highly profitable as it has a net present value (NPV) very much greater than zero, as well as profitability index (PI) substantially greater than unity (one) with a payback period of less than two years.

Rainwater in the entire Port Harcourt city should not be drank unless treated and ascertained. Wastage of harvested rainwater in storage tanks should be avoided in order not to reduce the reliability of the RWH system. Residents in UPE Sand-filled of Borokiri town (Port Harcourt) as well as other settlements who patronized water vendors due to challenges in obtaining potable groundwater~~,~~ are advised to go into RWH cum treatment since it is highly economically viable. However, the State or Federal Government as well as Non-Governmental Organizations (NGOs) are advised to provide a functional municipal water supply in the entire Port Harcourt city to ensure affordable and more reliable (constant) potable water supply for even the low-income earners as well as people who may not have the initial investment cost.

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