Rainwater Harvesting Infrastructure Management

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Abstract

As climate change impact is affecting all countries, water scarcity is continually a pressing issue to all countries in the world. The groundwater availability around the globe and locally such as in the ground of Papua New Guinea, Lae City, the garden city of the country, is also affected by the phenomenon. An alternative source such as the rainwater which across the globe is not equally shared thus harvesting it by creating an infrastructure for wider use needs management for sustainability. The study focuses on the management of a rainwater harvesting infrastructure (RHI) from its initial stage or conceptualization by designing using axiomatic design process and creating a model prototype to show the features of the infrastructure. The axiomatic design process in the design of the rainwater harvesting infrastructure shows the customer needs and functionality of the infrastructure for cost-wise management. The chapter provides information for a broader and more significant impact of providing and designing infrastructure for massive use.

Keywords: rainwater harvesting, infrastructure management, natural resource, a renewable resource, climate change, sustainability

1. Introduction to rainwater harvesting

This chapter discusses the rainwater harvesting infrastructure (RHI) management. Similar to any harvesting strategy such as in the farm, infrastructure is important to keep your harvest sustainable until the next harvest. Rainwater, like any other renewable resource, needs to be sustainable because, with human activities, the regular hydrologic cycle is affected by climate change (**Figure 1**). There are five processes at work in the hydrologic cycle: condensation, precipitation, infiltration, runoff, and evatranspiration [1]. These occur simultaneously and, result in precipitation when the conditions are suitable. Precipitation is a product of condensation of atmospheric water vapor and fall under gravity to the land surface as rain and infiltrates the soil or flows to the ocean as runoff, or surface water (e.g., lakes, streams, oceans, etc.), evaporates, returning moisture to the atmosphere, while vegetation returns water to the atmosphere by transpiration and the cycle continuous. For more understanding, necessary information on rainwater harvesting is discussed below.

1.1 What is rainwater harvesting?

Rainwater harvesting [2] is the capturing of rain from rooftops, catchments, local streams, seasonal floodwaters, and watershed management to conserve water; to provide drinking water, irrigation water, and groundwater recharge; and to
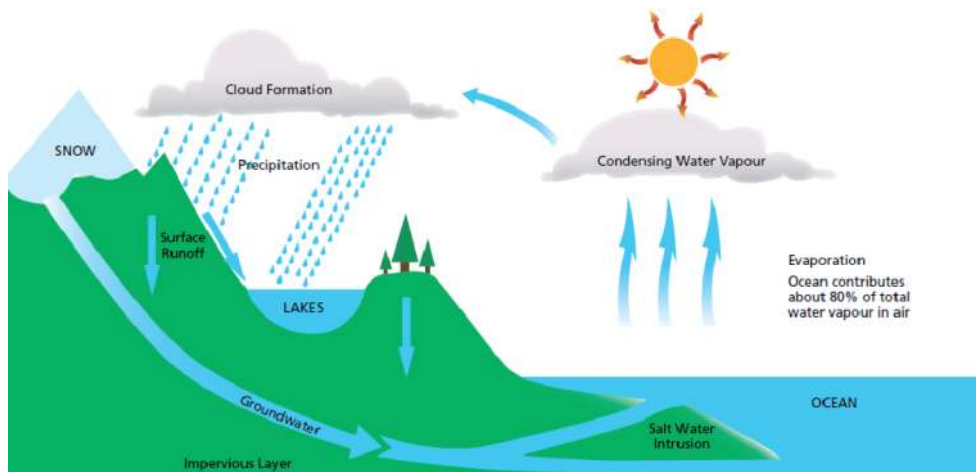
Figure 1.
Hydrologic cycle. (Adapted from NASA.)

reduce stormwater discharges, urban flood, water overloading in sewage treatment plants, and seawater ingress in coastal areas. It is an activity of direct or indirect collection of rainwater (**Table 1**).

The rainwater harvesting is a promising alternative infrastructure in the imminence of increasing water scarcity and escalating demand for water supply [3]. It maximizes water efficiency by capturing it rather than letting it run off. By doing so, it minimizes the increase in environmental impact from a large project in which the pressure on water supplies occurs. Allowing the rain to fall anywhere also allow deteriorating water quality and constrain the ability to meet the demand for fresh water from traditional sources as it goes to the drainage system instead of utilizing it for multiple functions. Therefore, rainwater harvesting augments availability of water, self-reliance, and sustainability.

1.2 What is a rainwater harvesting system?

For better understanding of the term rainwater harvesting system, we will define it here as a technology used to collect; convey rain for future use from relatively clean surfaces such as a roof, land surface, or rock catchment; and store it [4]. There are two classified practices in collecting rainwater from rainfall events. The two broad categories are land-based and roof-based. Land-based rainwater harvesting when runoff comes from land surfaces is collected in furrow dikes, ponds, tanks, and reservoirs. Roof-based rainwater harvesting comes from collecting rainwater runoff through roof surfaces which usually provides a much cleaner source of water for drinking purposes [5].

Due to the impact on climate change, a need for sustainable rainwater harvesting is a necessity. Thus, a sustainable rainwater harvesting system (SRHS) had been studied and is defined as the collection and storage of rainwater for human use in a manner that preserves and protects the environment and for the preservation of the natural resource (rainwater) for continuous supply today and in the future [6].

1.3 What is the rainwater harvesting infrastructure?

Rainwater harvesting was well defined above as collection and storage of rainwater for sustainability. Infrastructure is a fundamental physical and organizational structure and facilities that provide services to communities with high-cost

Type of tests		Locations of sample tested						
Test parameter		Erap	Boystown (Erap)	40 Mile	Balob T/C	Ampo	Martin Luther Seminary	WHO recommended
	BOD	3.95 mg/L	3.95 mg/L	4.30 mg/L	3.8 mg/L	3.8 mg/L	3.1 mg/L	1 mg/L
	Hardness ($CaCO_3$)	250.5 mg/L	180.5 mg/L	238 mg/L	180 mg/L	214 mg/L	187 mg/L	100–500 mg/L
	Turbidity	3.54 NTU	13.13 NTU	2.0 NTU	0.21 NTU	0.27 NTU	0.21 NTU	1 NTU
	Calcium	25 mg/L	75 mg/L	63 mg/L	57 mg/L	68 mg/L	61 mg/L	75–200 mg/L
	Magnesium	4.55 mg/L	20 mg/L	47 mg/L	8.9 mg/L	11 mg/L	8.6 mg/L	30–150 mg/L

Table 1.
Table of pollution of groundwater taken from wells in Lae City.

investments or capital equipment such as the communal rainwater harvesting that are vital to the country's economic development and prosperity. The infrastructure is essential for any faster economic growth and alleviation of poverty in the country. The presence of an infrastructure (such as water supply, sewerage, roads, public space, electricity, bridges, tunnels, railways, canals, dams, building, airports, etc.) helps in increasing the overall productivity of the country's economy. In this chapter, the infrastructure is rainwater harvesting infrastructure.

The image shows an example of a rainwater harvesting infrastructure in Elisabeth, Jamaica (one of the author's home country, as shown in **Figure 2**). This method of harvesting rainwater is through a public infrastructure that can cater to the growing population of the city.

1.4 Rainwater harvesting technologies

For an understanding of this section, technologies used in rainwater harvesting are discussed here. There are several rainwater harvesting technologies such as rooftop, in situ, surface water, and groundwater recharge.

1.4.1 Rooftop

Rooftop rainwater harvesting technologies, according to the UNFCCC, are rainwater harvesting system that is a simple technology that promotes sustainable rainwater management and uses the roof as a catchment. The system comprises of three (3) basic elements such as catchment area (represented by the roof), conveyance system (gutters), and storage (tank). An example of a rooftop rainwater harvesting system is shown in **Figure 3**.

1.4.2 In situ

The in situ technology is a method where the storage of collected rainwater in a direct way is utilized immediately. For example, in arid and semiarid regions, the storage for the maximum amount of rainwater during the wet season is made for use at a later time when rain is low during the dry season, especially for agricultural

Figure 2.
(a) An elevated rainwater concrete catchment of Elisabeth, Jamaica; (b) the surface runoff and the storage tank of Elisabeth, Jamaica RHI. (Adapted from Betasolo and Smith, 2017.)

Figure 3.
Rainwater harvesting system (RWHS) via rooftop at Papua New Guinea University of Technology. (Adapted from Betasolo and Smith, 2017.)

and domestic water supply. This technique as other rainfall harvesting systems has three components: a collection, a conveyance system, and a storage area.

An example of in situ rainwater harvesting used in the arid and semiarid regions of Northeastern Brazil and Paraguay is primarily for irrigation purposes. The rainwater harvesting in situ in Brazil includes site preparation of agricultural areas which uses Topographic Depressions as Rainfall Harvesting Areas. *Tajamares* are constructed in areas of low topography used for rainwater storage with clay soils at least 3 m deep that served as distribution canals that convey water from the storage area to the areas of use which is the practice in Paraguay [5].

1.4.3 Surface water

Surface water is water on the surface found on wetlands that is nonsaline and is replenished by one of the processes in the hydrologic cycle—precipitation. The surface water supports the replenishment of groundwater aquifer supply if it is channeled efficiently. In most urban areas, the surface water is wasted and polluted. The wasting can be mitigated with proper utilization of surface water from rain via rainwater harvesting and storing it into the aquifer. An example is shown in **Figure 4**.

1.4.4 Groundwater recharge

Groundwater recharge is a process where groundwater is supported by several techniques to add or bring back the health of the groundwater for sustainability. It can be upstream or downstream discharge such as areas close to mountain peaks because the precipitation is higher than in the adjacent lowlands. The shallow groundwater discharges directly to the valleys, and too low-lying zones and the deep groundwater discharge directly to the oceans through return flow on irrigation, leakage from runoff, and wastewater collection system [6, 7].

The pollution of groundwater is inevitable by an impairment of water quality by chemicals, heat, or bacteria that may not necessarily create public health hazards

Figure 4.
Surface water found in Papua New Guinea University of Technology.

but does adversely affect the quality of water for domestic, farm, municipal, or industrial use [8]. The human body of an average adult contains up to 55-60% water [9]. Therefore people's health is dependent on a clean supply of water and safe sanitation. It is estimated that 50% of the people living in developing countries are suffering from water-related diseases caused directly by infection or indirectly by disease-carrying organisms that breed in water, such as mosquitoes causing malaria, diarrhea, infections by parasites, and river blindness that are among the most widespread diseases. Study of Betasolo et al. is an example of groundwater pollution where BOD and turbidity level exceeds the standard. The study area is the industrial hub of Papua New Guinea (PNG), and for the most urbanized country, the pollution is much higher than that of PNG. The tabulated data comes from the result of a test in a National Analytical and Testing Service Laboratory (NATSL) of the Papua New Guinea University of Technology, and the result is compared to the World Health Organization (WHO) standards.

1.4.5 Fog and dew

The highlands of Papua New Guinea experience for (cloud that is at the ground) as temperature ranges from 18 to 23°C such that the dew can be collected (became tiny droplets of water) similar to rainwater harvesting for drinking. An example of such method is the one used by a Canadian nonprofit organization supporting safe drinking water at the region such as FogQuest who collect fog at 0.05 to 0.5 g of water from an instrument that looks like tall volleyball nets (made of polypropylene or polyethylene mesh) hanged to capture the water droplets [10].

Other regions (desert) similar to PNG may have the opportunity to collect rainwater produced from fog during winter period. I have lived sometime in those regions and experienced the dampness of some items left outside (balcony).

2. Importance of rainwater harvesting infrastructure

Rainwater is a resource as a result of the hydrologic cycle. Humans need water for various uses such as drinking water and save high-quality drinking water sources. It is used as utility water (i.e., flushing) to reduce the potable water consumption

and minimize the volume of generated wastewater that can be utilized for irrigation water and groundwater recharge or replenishing groundwater levels. Rainwater harvesting will relieve the pressure on sewers, and it reduces stormwater discharges and water overloading in sewage treatment plants. It acts as an environmental measure to mitigate floods by reducing urban flood and reduce seawater ingress, sediment transport, or soil erosions to coastal areas.

2.1 Water scarcity

Water supply scarcity is a pressing issue as population demand is increasing geometrically. In the overall earth's water supply, fresh water amounts only to 0.62%, and the amount of fresh water in the globe are decreasing as affected by climate change in its natural availability in lakes, rivers, and groundwater [11, 12]. A Ceres study [13] reported that water scarcity attributes to the following conditions: inadequate natural resources (physical water scarcity) and poor management of the sufficient available water resources (economic water scarcity).

For global identification of water scarcity, the reader can participate in an interactive map available in https://waterscarcityatlas.org/. A scenario on water scarcity can be derived and produced a map for the country's water scarcity condition. As of 2006 records PNG water scarcity status is "of no scarcity", but reports show that the sustainable access to improved drinking water and improved sanitation is still 45% (40–45%) which falls below the threshold to support the increasing populations of Papua New Guinea [14, 15]. Such population will be needing more access to water of which the PNG government's goal to provide by 2030 at least a 70% access to water is critiqued by the World Bank that they are not even on track to meet either the millennium goal or its national development targets [15]. The average monthly precipitation in mm is 260.37 summarized from 30-year records (1900–2012) of the World Bank on PNG's monthly average as it is an ideal measurement to assess climate patterns studied over a long time [16, 17].

2.2 Rainwater availability

Rainwater availability needs to be checked in assessing the feasibility of developing an infrastructure. To determine the factor to whether rainwater harvesting (RWH) is a viable water supply system is the rainfall pattern over the year. Tropical climate with short (1–4 months) dry seasons and multiple high-intensity rainstorms like in Lae City known for its name as Rainy Lae of Papua New Guinea is a most suitable condition for water harvesting. Also, rainwater harvesting is most valuable in wet tropical climates like PNG, where the water quantity of surface water varies and passes the general rule for precipitation of over 50 mm/month. Thus the discussion in most scenario used is of Papua New Guinea (PNG), a tropical country.

PNG has annual average rainfall is 3142 mm [19], an ideal water harvesting capability. However, the condition of most of the population have limited access to water supply. No access to water supply in settlement area as the water provider is unable to service them due to customary land issue. Ninety percent of the country's land is customary land which due to many ownership hinder the development of the property. Few others who can afford to dig and buy a pump have access to groundwater [18]. Other use the rooftop to harvest rainwater since Lae City has a rainfall that ranges from 4000 to 5800 annually [17].

However, the current strategies of rooftop rainwater harvesting on access to sustainable water and sanitation cannot keep pace with rapid population growth that needs to be addressed to meet the MDG targets. Unless an RWH system

infrastructure portfolio of significant investment is provided that can meet the increasing population demand to sustainable water supply and sanitation, the national goals to 2030 are also unlikely to be achieved. Therefore, proper management of rainwater resource for sustainability by creating an infrastructure is the aim of this chapter to mitigate the impact of water scarcity while there is an available untapped resource.

3. Types of rainwater harvesting

To further understand why rainwater harvesting infrastructure is important to sustain an increasing population, a discussion of the types of rainwater harvesting is presented in this section.

3.1 Rainwater harvesting via the roof

Rainwater harvesting via roof had been the source for domestic water supply in Papua New Guinea according to study of Betasolo et al. [17] by harvesting water through roof and collecting the rainwater with Tuffa tank [8] as shown in **Figure 3**. The roof is a collection area and the first contact to collect the rainwater. How effective and efficient the collection depends on the material of the roof, how the roof is build, and the quality of rainwater. From the roof, the rainwater is conveyed through gutters or conveyors or pipes for storage. The roof materials consists of inert material such as galvanized, wood, aluminum, plastic, glass, and fiberglass to maintain good quality of rainwater harvest.

The rainwater storage connecting the roof is made from an inert material such as corrugated galvanized iron, plastic, reinforced concrete, stainless steel, and fiberglass constructed as a separate unit from the building but connected via pipe systems.

3.2 Rainwater harvesting via catchments

The harvesting of rainwater is played by the catchments. A catchment is a collection of rainfall through a natural drainage area or natural landscape. A catchment area is a geographical area in which the river and its tributaries are drained or funneled. Papua New Guinea has large local streams (basins) such as Sepik River (the largest catchment of 78,000 km^2), Fly River (61,000 km^2), Purari River (33,670 km^2), Markham River (12,000 km^2), and Busu River. Markham River and Busu River are located closely to Lae City.

3.3 Rainwater harvesting via local streams seasonal floodwaters

Rainwater harvesting through local streams from floodwaters is harvesting rainwater that fall into the local streams, increasing the capacity of the streams and become floodwater affecting many of the vegetation. On the other hand, harvesting floodwater can support the needs of water on land irrigation as there are no irrigation facilities available in the country but rainfall to support the subsistence farming of most of the population. Rainwater harvesting through local streams also will provide groundwater recharge and decrease of salt water ingress on areas near the coastal line such as Lae City of Papua New Guinea that rely solely on groundwater as a water supply in the urban area.

3.4 Rainwater harvesting via watershed management to conserve water

Watershed development and management is a technique to conserve water. However, it does not directly provide the water supply of the people, but it supports a continuous supply of the resource. Thus, management of the watershed, which also involved a great sum of the fund, is as equally important as creating the infrastructure that caters to the direct supply of drinking water and service water. The requirement of a huge sum is because it requires an integration of technologies that captures the water supply.

A watershed is defined as an area from which rain runoff flows directly into a large stream, river, lake, or pond which has an independent hydrological unit because it provides an optimum use and conservation of soil and water resources. A development of an integrated watershed refers to the development and management of the water resources that achieve higher sustainable production without ecological imbalances because the proper management of watershed restores the ecosystem. One activity that achieves the reduction of surface runoff is by constructing a suitable structure or by changes in land management. Further, the reduction of surface runoff will increase infiltration and help in water conservation.

4. Design of rainwater harvesting using axiomatic design

Rainwater harvesting sustainability requires engineering the rainwater harvesting process and designing it to support demand of increasing population and the financing to enable the development of the infrastructure according to its demand. The design parameters of rainwater harvesting systems includes rain, catchment area (roof, pavement area, storm drains, etc.), conveyance system (gutters, downpipes), storage units or tanks (overground/underground), and distribution system (pipelines, pumps)with the addition of disinfection method such as chlorination and UV (**Table 2**).

The equation used to design based on the rational method is

$$\text{Rainwater Harvested} = \text{Rainfall (mm/year)} \times \text{Catchment area (m)} \times \text{Runoff Coefficient} \qquad (1)$$

A water conservation approach can increase the period of water availability and overcome water scarcity through agronomic and engineering procedures. Agronomics or the science that deals with field crop production and soil management has measures that include contour farming, off-season tillage, deep tillage, mulching, and providing vegetative barriers on the contour, which mainly prevent soil erosion and also help in improving soil moisture availability in the watershed.

Type of catchments	Coefficients
Ground surface coverings	0.6–0.8*
• Concrete	0.6–0.9
• The acrylic glass (PMMA)	0.7–0.8*
• Plastic sheeting	0.8–0.9*
Adapted from Roger S.	

Table 2.
Runoff coefficients.

4.1 What is axiomatic design (AD)?

Suh defines axiomatic design as a design that provides a clear basis to improve the technical design process based on logical and rational thought processes and tools [20]. The AD simplifies the complexity of the modeling and simulation as designers identify what they want to achieve. In the case of rainwater harvesting infrastructure, building a model is identified achievable than creating infrastructure as funding is a challenge with a difficult economy not only in PNG but to many developing countries. With the building of a model, it achieves how accurately it will simulate the design of the rainwater harvesting. The process Axiomatic Design (AD) on infrastructure development of rainwater harvesting is illustrated by Betasolo and Smith [15] in **Figures 5** and **6**.
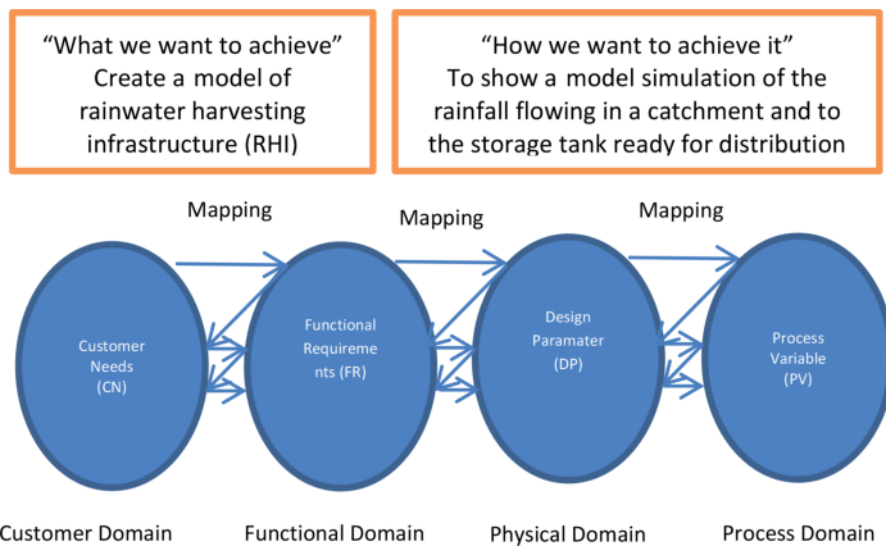

Figure 5.
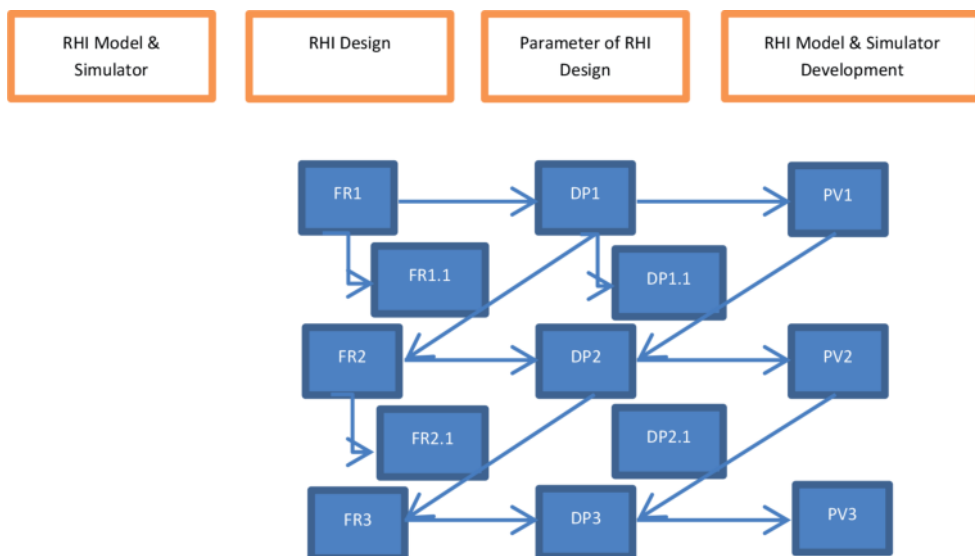*AD mapping from CN to FR to PD and PV. (Adapted from Betasolo and Smith).*

Figure 6.
AD decomposition of FR, PD, and PV. (Adapted from Betasolo and Smith.)

DPs	RHI system	Lightweight and transparent	Coefficient of runoff	Dimension of catchment	Shower or rain	Filter membrane	Tank	Clorination	Outlet
FRs	DP0	DP1	DP1.1	DP2	DP2.1	DP3	DP4	DP5	DP6
FR0	Fabricate an RHI model prototype	x	0	0	0	0	0	0	0	0
FR1	Determine the material to be used	0	x	0	0	0	0	0	0	0
FR1.1	Determine reliability of collecting surface	0	0	x	0	0	0	0	0	0
FR2	Estimate the water to be harvested	0	0	0	x	0	0	0	0	0
FR2.1	Simulate rain (dry and wet)	0	0	0	0	x	0	0	0	0
FR3	Remove dirt and other contamination	0	0	0	0	0	x	0	0	0
FR4	Contain water	0	0	0	0	0	0	x	0	0
FR5	Protect water quality	0	0	0	0	0	0	0	x	0
FR6	Provide point for distribution	0	0	0	0	0	0	0	0	x

Note: the DPs columns header row and the FRs/DPs descriptions are arranged in a rotated design matrix.

Table 3.
Rainwater harvesting infrastructure model prototype design matrix. (Adapted from Betasolo and Smith.)

4.1.1 FR and DP analysis

Table 3 shows the rainwater harvesting infrastructure model prototype design matrix. The design matrix shows a simplified decision where many alternatives and varying criteria are of importance for consideration.

The development of an RHI a requirements for its functionality such as the FR0: Fabricate a model prototype to showcase the RHI system (DP0) which is the design parameter because of the financial constraint to construct the infrastructure. The model prototype will show how the RHI system works and can be used to persuade investor to make the investment to the development of the infrastructure. The functional requirement FR1: Determine the material to be used. The material is affected by the collecting surface reliability (FR1.1). The quality of the surface affects the flow of the rainwater and the amount of rainwater collected. The process of functional requirement and design parameter continues (FR2–FR6 to DP2–DP6) until the requirements are satisfied.

4.2 RHI designing the model prototype

4.2.1 Factors affecting the model prototype

In the creation of a model, there are factors that a designer of RHI should consider. In modeling a rainwater harvesting system, first calculate the amount of rainwater to be collected by the catchment area affected by the nature surface as discussed in Section 3.2 as it relates to the material used in the catchment model prototype or even in actual site in which its slope, dimensions, the storage tank, and the water tightness of the reservoir are set up.

A rainfall catchment system design is composed of five (5) primary parameters such as rainfall pattern, water demand pattern, collection area, storage capacity, and system reliability. The rainfall amount is influenced by the rainfall amount that the area of the catchment is designed. For storage of water collected from the catchment, the size of the tank is based. Therefore, in creating a model prototype, the rainfall simulator included the catchment surface, an inlet canal, a filter compartment, circulation ports, storage tank, and a cleanout outlet as shown in **Figure** 7. To support the movement of the model prototype, an aluminum frame support is used.

A demonstration to final year students was carried out to test the water tightness of the unit and the simulation of rainfall pattern, as shown in **Figure 8**.

(a)   (b)

Figure 7.
(a) RHI model piping system on the making by Carl Smith; (b) the rainwater simulator represented by showerhead system placed at a distance from a rain tray, surface runoff, and the storage tank of RHI model.

Figure 8.
(a) Test on water tightness of tanks; (b) demonstration of rainwater simulating falling to the catchment area of RHI model.

5. Financing the rainwater harvesting infrastructure

In determining whether RWH is a viable water supply system, the rainfall pattern over the year plays a key role since economy and cost play important criteria in the infrastructure development. Tropical climate with short (1–4 months) dry seasons and high-intensity rainstorms provides the most suitable conditions for water harvesting in Lae City of Papua New Guinea. In addition, rainwater harvesting may also be valuable in wet tropical climates, where the water quantity varies greatly throughout the year. As a general rule, rainfall should be over 50 mm/month for at least half a year or 300 mm/year (unless other sources are extremely scarce) to make RWH environmentally feasible.

An example of an RHI with a catchment area of 3997.1 m^2 from Betasolo and Smith is estimated to cost for one (1) unit of $220,000.00 (0.6 M in Kina, Papua New Guinea's currency, $1 = K3) or about $50/m^2 (K150/m^2). The estimated household population to be served by the prototype is 5415 (the details of the calculation can be found in item 3.0 RHI designing the model of this paper). The infrastructure storage tank can hold about 11,320,500 liters (11.3 M m^3) annually or about 943,375 liters/day (943.4 m^3/day). It provides an approximate annual investment of K0.05/liter (K0.15/m^3). The current price for 1-liter bottled water is K3.5; if this amount is used to calculate for such investment, it will cost a total of $425,600 (K 1,276,800.00), a savings of about 47%. One of the authors pays $2/gal (K6/gal) or K1.5/liter for purified drinking water from a vendor.

Household infrastructure is not an ideal infrastructure system in rainwater harvesting due to the high-cost investment that only few can afford. However, for the majority of people, support from the government and private investment is necessary to make the infrastructure possible. Infrastructure finance from private investors and government or a public and private partnership (PPP) model creates opportunity for a design pitch of economically rational financing structures that has a better diversification of risks. The World Bank, ADB, and other similar institutions are some of the few institutions that support financing on such infrastructure.

6. Managing the rainwater harvesting infrastructure for sustainability

Because of the large sum of funds involved in the development of rainwater harvesting infrastructure, a management system should be in place for sustainability. A prototype or a model can be a method to assess performance and lessons learned. For example, rainwater harvesting infrastructure that supports farmers should involve farmers in planning and executing field programs. Ownership of the infrastructure should be channeled to the people who are the beneficiaries. As owners-beneficiaries, responsibility is also shared with the technical advice provider in the management as capabilities to run the rainwater harvesting infrastructure require an expert in handling issues associated to it.

7. Conclusion

The rainwater harvesting infrastructure management is essential especially when dealing with a facility that involves great cost. Understanding of the rainwater harvesting pros and cons is important in the selection of right infrastructure. The design of the infrastructure using an axiomatic design process saves the trial and error, but directly attending to the customer needs and designing it according to the functional requirement coupled with a model prototype show the possibility of the infrastructure to be implemented and investment to flow. Management should start at the beginning of the conceptualization of any infrastructure, to design and financing.

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