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Full Length Research Paper

Estimation of Storage Tank Capacities for Different Roofing Areas for Rainwater Harvesting in Dodoma Urban, Tanzania

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ABSTRACT

This study uses a mass balance model and economic analysis technique to present an estimation of roofing areas and storage tank capacity for Rainwater Harvesting (RWH) system. The water-saved benefits were estimated using the monthly rainfall of over 39 years from 1981 to 2020 and five roofing areas. The proposed roof-storage-ratio method presents the minimum requirement of roof area and storage tank size when the ratio value is closer to 1. The benefit-cost ratio and percentage of reliability indicated the optimal roofing areas ranging between 200 and 300 m2 for storage tank capacity between 20 and 25 m3, with a minimum discount rate of 5%. The increased capacity of storage tank and roofing area would also be a potential factor to increase the investment cost for installing the RWH system.

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INTRODUCTION

The semi-arid regions of the world are characterised by inadequate freshwater resources (Zaki, et al., 2019). Coupled with population growth and technological development, which affects consumption patterns and associated consequences like low rainfall and temperature (Zubaidi et al., 2020). According to Tulinave, et al. (2016), per capita demand for water ranges between 2 and 20 L per day for drinking and non-drinking during dry and wet seasons, respectively. This water demand is still unattainable during dry seasons, especially in developing countries featured with semi-arid areas (Rocha and Soares, 2015).

Rainwater Harvesting (RWH) has demonstrated benefits including clean water at the local points, relatively safe and sustained water demands (Terêncio, et al., 2018). It offers a low-cost alternative to water household water supply, especially in areas with water scarcity. One-third to two-thirds of the rainwater collected by the RWH system is available to a household each year, depending on the storage efficiency of the system (Thomas & Martinson, 2007). Apparently, RWH systems have been in use as an alternative source of water supply for many years in rural areas (Mayo & Mashauri, 1991). The design and performance of these systems largely depend on an insightful understanding of the nature of rainfall, water demand, roofing areas and storage facility (Taffere, et al., 2015). The threshold of rainfall intensity varies considerably from place to place over time or from one country to another leading to the complexity of having a universal classification (Llasat, 2001). Critchley et al (1991) indicated the rainfall in semi-arid areas was characterized by short duration, limited areal extent and relatively high intensity. De Paola et al (2014) indicated also there is an increase in frequency with irregular rainfall intensity.

According to the population census of 2012, the population of Dodoma city was 410,956 (URT, 2013). Following the shifting of the capital city from Dar es Salaam to the Dodoma region, the human population has increased, as well as associated human activities such as infrastructure development and urban agriculture, which have a bearing on water demand (Shemsanga, et al., 2018). Such a situation renders the only available groundwater resources allocated at the Makutupora sub-basin to be vulnerable. The boreholes drilled in the Makutopora sub-basin are the sole reliable source of freshwater supply in Dodoma urban. Successful RWH will therefore hinge on the need to assess the roof sizing and storage tank capacity; as well as water-saved benefits over the investment cost.

METHODS AND MATERIALS

Description of the Study area

This study was conducted in the Dodoma urban area, located in the central part of Tanzania (6.1584 °S; 35.7513 °E). The five buildings were identified for installation of the RWH system and located in different areas of the Dodoma urban as shown in Table 1. The roofing areas with the different materials required for five buildings had perimeters of 42, 46, 66, 74 and 92 m with roof areas of 110, 120, 269.4, 300 and 520 m^2, respectively as shown Table 2.

Table 1: Location for five surveyed buildings

S/N	Building size (m^2)	Location		Wards
		Latitude	Longitude	
1	110	6°08'06" S	35°43'44" E	Nkuhungu
2	120	6°10'02" S	35°47'35" E	Kisasa
3	269.4	6°13'46" S	35°45'52" E	Ntyuka chimalaa
4	300	6°11'45" S	35°49'57" E	Iyumbu
5	520	6°12'54" S	35°46'07" E	Ntyuka

Table 2: Estimation of RWH components for different roof areas

RWH components	Quantity required for different roofing areas				
	110, m^2	120, m^2	269.4, m^2	300, m^2	520, m^2
Gutter pipes 4"	7	8	11	12	15
Clamps 4"	28	31	44	49	61
Connectors, 4"	7	8	11	12	15
Corners, 4"	10	12	10	14	18
Downpipe, 3"	4	4	4	4	4
Poly pipe, 2" diameter ; m	30	30	30	30	30
Stopper, 4"	4	4	4	4	4
Elbow,4"	4	4	4	4	4
Downpipe Connector, 3"	4	4	4	4	4
Trenching and backfill, m	30	30	30	30	30

Estimation of water for RWH system

The average volume of the RWH system per one rainfall event collected is equal to the average flow rate times the average recorded time, as expressed in Equation 1 (Abdulla, 2020).

$$Q = C \times RI \times A \tag{1}$$

whereby (Q) is the estimated flow rate [m3/min], C is the runoff coefficient; A is the roof area [m^2] and RI is the rainfall intensity [mm/min]. According to Goel (2011), runoff coefficient is dependent on the type of surface features including the porosity of soil and degree of compactness, vegetation and the size of the area. This study used only the galvanized iron sheets roof with a runoff coefficient of 0.95 as adopted from Imteaz et al (2012). Estimation of tank size for these systems has been clearly described in different model concepts, including the mass balance model (Imteaz et al, (2012); Mun & Han, (2012); Mathur, (2013), Ward (2010) and Nguyen & Han (2017); as expressed in Equation (2).

$$W_t = W_{t-1} + QI_t - WD_t \tag{2}$$

$$Subject\ to: 0 \le W_t \le S_t$$

whereby S_t to be an intermediate storage tank that cannot exceed the maximum water-saved (W_{max}); W_t presents the water saved in the storage tank at end of time interval [m^3], t; QI_t presents the inflow during a time interval [m^3/min], WD_t presents the demand during a time interval, t [m].

The annual water supply using the RWH system divided by annual water saved in storage from the same source is called the roof-storage ratio (RSR). Three options are described from the RSR to define the minimum capacity of the storage tank and roof area relationship: (i) when the RSR is greater than 1, indicated water supplied by the RWH system is more than the storage tank capacity, (ii) when the RSR is less than 1, indicated rainwater was not available to fill the storage tank, so additional water was added to the system to save the water demand, (iii) when the RSR is equal or closer to 1 with an acceptable range of ±0.5, indicated the water-saved and rainwater harvested to meet the requirement.

A simple spreadsheet was adopted from (Jaber, et al., 2021) coded with the mass balance model expressed in Equation (2) used with the input data as shown in Table 5. The input data includes monthly rainfall, roof area, storage volume, water demand and loss factors.

Table 5: Initial parameters for sizing the storage tank

S/N	Items	Description
1	Roof area, m^2	110,120,269.36,300 and 520
2	Runoff coefficient, %	95
3	Initial tank volume, L	0
4	Tank size, L	5000, 10,000, 20,000 and 25,000
5	Monthly indoor Demand, L	20 L*7 people*30 days = 4200 L
6	Annual rainfall Reliability, %	80

Economic analysis of installing the RWH system

The economic analysis of the RWH system has utilized the payback period (PBP), net present value (NPV), and benefit-cost ratio (BCR). The payback period is defined as the number of years needed for an investment to pay for itself through water savings as expressed in Equation (3) (Abdulla, 2020).

$$PBP = \frac{IRWHC}{AWB} \tag{3}$$

whereby IRWHC stands for installation cost of RWH and AWB stands for annual water benefits, i.e., amount of water collected times price of water-saving. All the annual water benefits and costs are discounted over the running of the RWH system with the number of years as expressed in Equation (4) to get the Net-Present Value (Pinzon, 2012).

$$NPV = \sum_{t=0}^{n} \frac{AW_t \times P_t - IRWHC_t - AOC_t}{(1+i)^t} \tag{4}$$

where AW denotes the annual water saved in the time interval, *t*[min]; AOC is the annual operation cost in the time interval, *t*[min]; *i* is the interest rate of the RWH system in n year and P_t denotes the water price in the time interval, *t*[min].

The BCR compares the water-saved benefits with the investment cost. The RWH system is considered to be beneficial when the ratio is greater than 1 (Durodola, et al., 2020). The BCR is calculated using discounted rates as the sum of discounted benefits (SDB) divided by the sum of discounted costs (SDC) as occur at time t over the lifetime of the RWH system as expressed in Equation (5).

$$BCR = \frac{\sum_{t=0}^{N} \frac{SDB_t}{(1+i)^t}}{\sum_{t=0}^{N} \frac{SDC_t}{(1+i)^n}} \tag{5}$$

Some assumptions have been made as the input data to determine the economic analysis of the RWH system as stipulated below:

a) The average household size in Dodoma urban is 4.4 according to the census (URT, 2013), but this study used the surveyed average household size of 7 for five identified houses.
b) The lifetime of the RWH system is based on the material types of gutter 10-year warranty (CPS, 2021) and plastic storage facility with a lifespan of over 25 years (TopTank, 2021).
c) The interest rate of 5% can be used for the RWH system (Abdulla, 2020). Also, the interest rate ranged from 5 to 15 years with the RWH life cycle of 15 to 60 years (Christian, et al., 2016) or an interest rate of 10% as the opportunity cost of capital in Tanzania (Senkondo, et al., 2004).
d) Surveyed to the water bills payers indicated the water-saving price of TZS 1500 per 1 m^3 (1 USD = 2,328 TZS).
e) Three storage tanks were used, 5000, 10,000 and 20,000 litres with cost as described in Figure 2 surveyed data collected in the Dodoma urban shops.
f) Installation unit costs were collected during the survey in the Dodoma market, see Table 6.

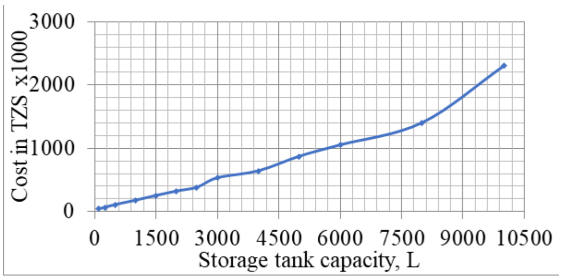

Figure 2: Variation of storage plastic tank capacity with market price

Table 6: Installation unit cost for several components of RWH system

S/N	Components	Quantity	Unit price, TZS
1	Gutter 4" diameter	6 m long	27,000
2	Downpipe 3"	6 m long class C	26,000
3	Poly Pipe 2"	per 1 m Class C	7,500
4	Corners 4"	1 pc	8,000
5	Connectors, 4"	1 pc	10,000
6	Stopper 4"	1 pc	4,500
7	Elbow 45° 3"	1 pc	6,000
8	Downpipe socket connector 3"	1 pc	9,000
9	Clamps 4"	25 pcs per 1.5 m	4,500
10	Nails and screws	0.5 kg	5,000
11	Pipe Trenching and backfill	per 1 m	10,000
12	Labour charges and transport	20% of total cost	

Performance evaluation of RWH System

The performance of the RWH system was evaluated using a time-based reliability. The annual rainfall with an exceedance probability of 0.8 is termed as the reliable rainfall (Rowntree, 1989). The time-based reliability ($R_e(t)$) used to identify the choice of RHW system over the other water supply as expressed in Equation (6), respectively.

$$\mathrm{Re}(t) = \frac{(X - Y)}{X} \times 100\% \tag{6}$$

where Y is the total number of days when harvested rainwater was unable to meet the daily water demand alone, and X denotes the total number of days (365 in a calendar year).

RESULTS AND DISCUSSION

Rainfall characteristics for the Dodoma region

The cumulative rainfall curves (Figure 3) for the Dodoma region from 1981 to 2012 were collected from (TMA, 2019) and 2017 to 2019 from (Hamisi, 2013). New installed gauge station at the College of Earth Sciences and Engineering, The University of Dodoma at the 6.17°S and 35.77°E, collected rainfall data for the year 2019/2020. The long-term from 1981 to

2010 and 2018/19 had less average monthly rainfall compared to the year 2017/18 (TMA, 2019). Typically, the rainfall starts from October to May whereby the wet season peaks in December and January.
The total annual rainfall over 39 years was compared with the NASA rainfall data from 1981 to 2017 (NASA, 2021) as shown in Figure 4. The result indicated the probability of equal or exceeded at 80%, the total annual rainfall is 480 mm. This amount of rainfall estimated at 80% defines the reliability to invest in the RWH system.

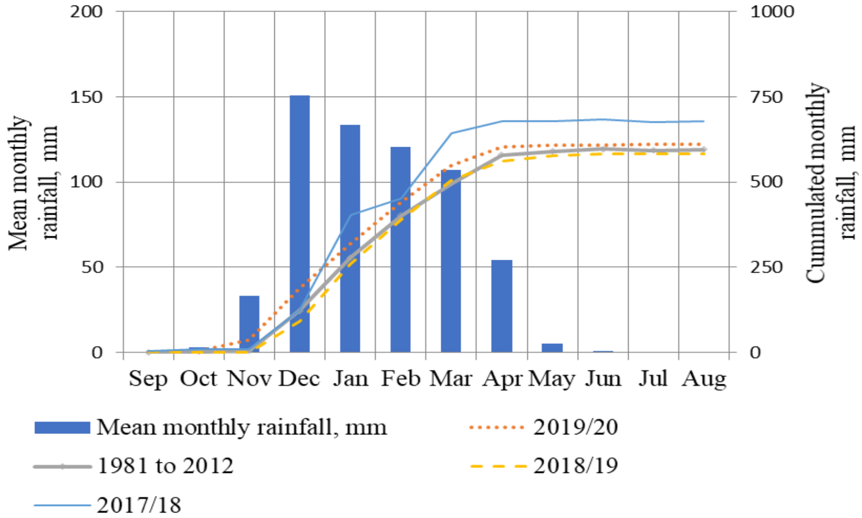

Figure 3: Cumulative rainfall curves for the Dodoma region from 1981 to 2012 and 2017 to 2020

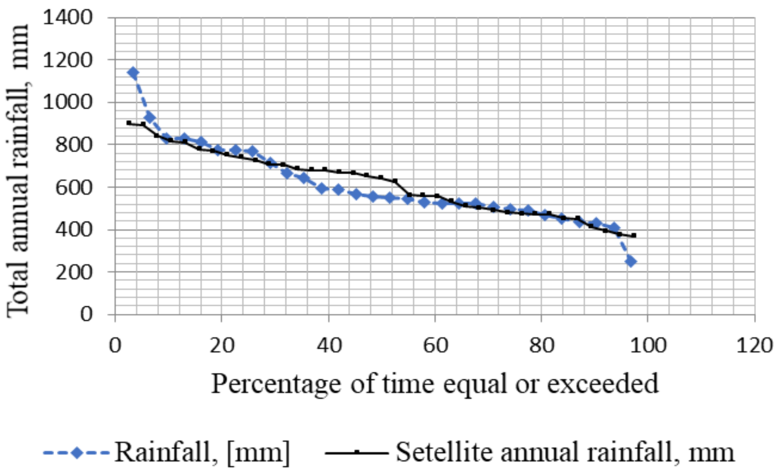

Figure 4: Comparison of measured and predicted rainfall data

Estimation of rainwater harvesting

Based on the mass balance model expressed in Equation (2), water-saved and water supply were calculated using monthly rainfall data. However, daily measurements or collection of rainwater from the RWH system would help to estimate the storage tank size (Hammes, et al., 2020). A larger amount of rainwater was harvested in the large roof area and storage tank than in small roof areas and storage tanks. An RSR value of equal or closer to one; indicates the roof area and

storage tank meet requirements. When the storage tank was 10 m^3 for the roof area of 110 m^2 and 120 m^2, the RSR was 1.04 and 1.26, respectively as shown in Table 7. Also, when storage tank capacity was above 20 m^3 for roof areas 269.36 m^2 and 300 m^2, the RSR was 1.25 and 1.14, respectively. But the storage tank of 25 m^3 for roof 520 m^2 indicated the RSR of 0.96. However, the RSR method would be used during the preliminary stage of the RWH system to estimate the roofing areas and storage tank capacity.

Table 7: Variation of rainwater supply and water-saved for different roof areas and tank sizes

Roof area, m^2	Tank size, L	Rainwater supply, L	Water-saved, L	RSR
	5000	50843	25605	0.50
	10000	50843	52770	1.04
	20000	50843	78344	1.54
110	25000	50843	78344	1.54
	5000	55465	26556	0.48
	10000	55465	69964	1.26
	20000	55465	97817	1.76
120	25000	55465	97817	1.76
	5000	124501	32030	0.26
	10000	124501	69964	0.56
	20000	124501	155218	1.25
269.36	25000	124501	206766	1.66
	5000	138663	32170	0.23
	10000	138663	70255	0.51
	20000	138663	157768	1.14
300	25000	138663	212479	1.53
	5000	240349	33174	0.14
	10000	240349	72425	0.30
	20000	240349	170643	0.71
520	25000	240349	229872	0.96

Economic analysis of RWH system

Cost variation of RWH components from different roofing areas

The total cost of installing RWH components for different roof areas was collected as outlined in section: *Economic analysis of installing the RWH system* and presented in Figure 5. The cost of purchasing gutters was high followed by the clamps compared to the other components. The annual water benefits were estimated as water-saved times the water price of TZS 1,500/= and total costs of installing a RWH system were 1.088; 1.152; 1.352;1.479 and 1.715 million (x10^6 TZS) for roofing areas of 110, 120, 269.36, 300 and 520 m^2, respectively. When the payback period evaluated for five buildings as shown in Figure 6; indicated roof area 269.36 m^2 had few numbers of years i.e., 4.4 years fixed with 5000 L for all four-tank sizes compared to the other roof areas.

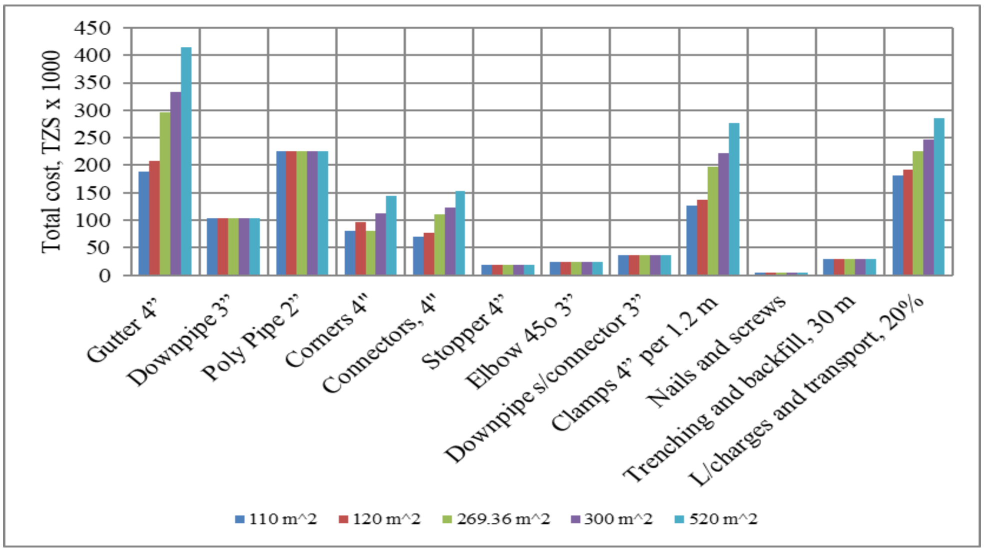

Figure 5: Different roofing areas with the total cost for several components of the RWH system

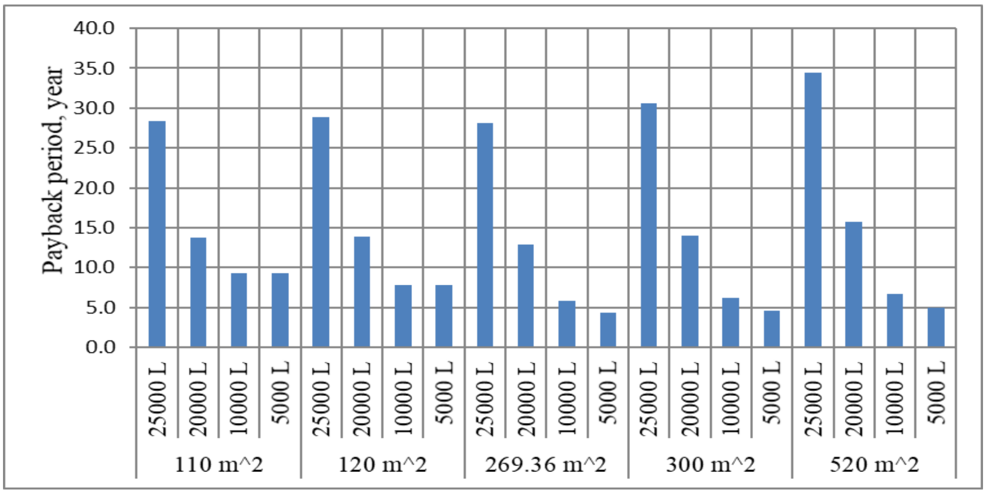

Figure 6: Evaluation of RWH system based on the payback period a for different roofing areas and tank sizes

Evaluation of NPV for RWH system

The NPV was estimated on the different storage tank sizes, roof areas and discounted rate of 5%, 10% and 20% as shown in Figure 7. All five roof areas have positive NPV at the discount rates of 5% and 10% for tank sizes of 20 m^3 and 25 m^3. Also, other roof areas had less NPV compared to roof area 520 m^2 at the discount rate of 5%, 10% and 20%. The percentage increase of NPV for roof area 520 m^2 was 9.82% higher than the roof area of 300 m^2 and 9.3% higher than the roof area 269.36 m^2 at the tank size of 25 m^3 and the discount rate of 5%. Again, the same roof area of 520 m^2 with the same tank size of 25 m^3 had a percentage increased of 8.29% and 5.20% at the discount rate of 10% for roof areas of 300 m^2 and 269.96 m^2, respectively. Assuming linear geometry, the gain was 8.64 dBi and 17 dBi, respectively.

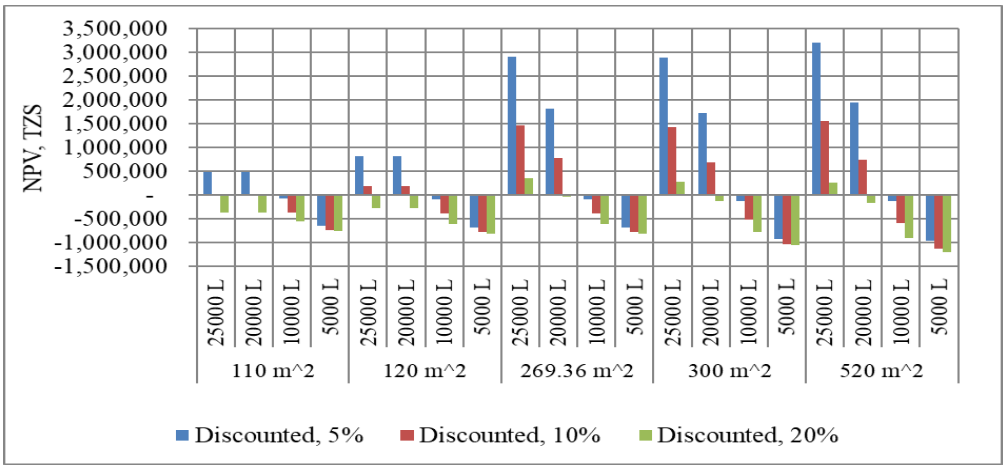

Figure 7: Estimated NPV for five roof areas and four tank sizes with three discount rates

Identification of optimal roof area and tank size using benefit-cost ratio

The BCR was used to identify the optimal roof area and tank size given the annual benefits for four storage tank sizes and five roof areas. Figure 8 shows the BCRs with three discount rates of 5%, 10% and 15%. Roof areas of 110 m^2 and 120 m^2 have annual benefits constant when the storage tank changed to 20 m^3 and 25 m^3, resulting to have the same BCRs. At the tank size of 25 m^3 and a discount rate of 5%, the roof area of 269.36 m^2 had a BCR of 2.83 which is higher compared to the roof area of 300 m^2 (BCR = 2.66) and 520 m^2 (BCR = 2.48). From this analysis, there is a point when the roof area and storage tank size are optimal considering the cost of installing the RWH system. A small storage tank indicated less BCR compared to the large storage tank with a curved relationship against the roof area.

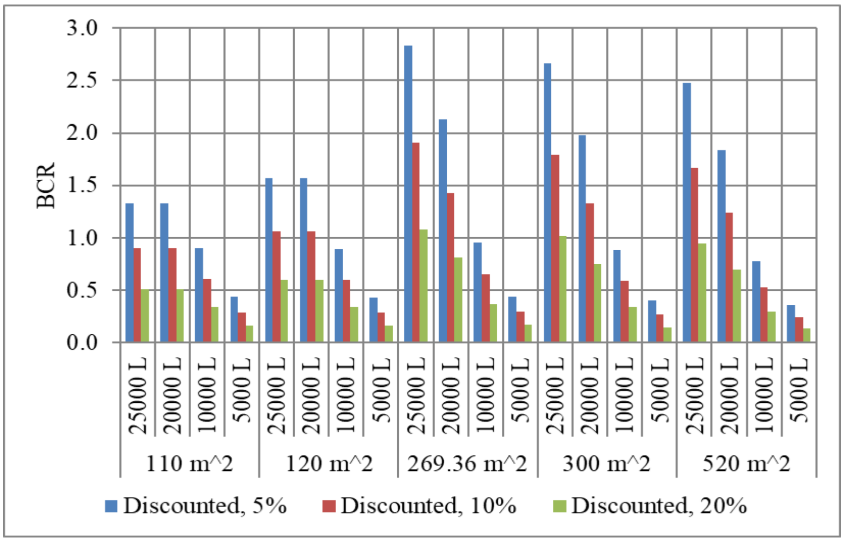

Figure 8: Comparison of BCR, roof area and storage tank for three discount rates

The time-based reliability used to identify the percentage of days that there is a need for a supplemental source of water. The time-based reliability of 100% means no need for a supplemental source of water throughout the year. Figure 9 shows the reliability of different roof areas. The time-based reliability was maximum for large storage tank (25 m^3) compared to the small storage tanks from roofing areas of 269.4 to 520 m^2. When the storage tank decreased to 20 m^3, the time-based reliability was less than 95% for all roofing areas, except for roofing areas of 520 m^2 which was about 98.5%, i.e., indicated only 5.5 days to supplement with other water sources. The curved shape indicated the optimal value of roof area and tank capacity for a particular house that lay between 200 and 300 m^2 and tank size between 20 and 25 m^3.

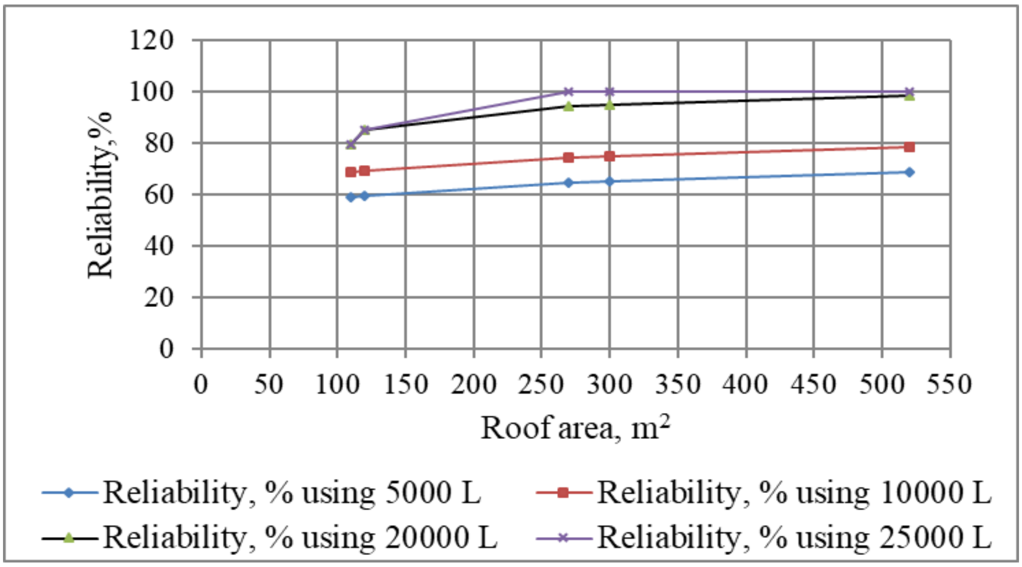

Figure 9: The time-based reliability of roof areas with different storage tank sizes

CONCLUSIONS

In this work, an overview of rainfall status in Dodoma urban was assessed, focusing on the timeline from early October and ending in early May with the maximum monthly rainfall in December and January. The total average annual rainfall of 480 mm was estimated at the probability of at least 80%. The proposed RSR method estimated the minimum roofing areas and storage tank using annual rainwater supply divided by annual water saved from the estimated data of the mass balance model. The RSR closer to 1, indicated the roof area is enough to fill the storage tank. With roofing areas of 110 and 120 [m^2], the minimum storage tank capacity is 10 [m^3] with the RSRs of 1.04 and 1.26, respectively.

In the roof areas of 269.4 and 300 [m^2], the storage tank capacity is 20 [m^3] with the RSRs of 1.25 and 1.14, respectively; also, in the roof area of 520 [m^2], the storage tank capacity is 25 [m^3] with the RSR of 0.96.

From the economic analysis performed to determine the profit of installing different sizing of the roof area for five buildings and four storage tanks of 5, 10, 20 and 25 [m^3], the cost of purchasing gutters and clamps are higher than the cost of purchasing connectors, pipes and fittings. Moreover, the payback period increased with the capacity of storage tanks for all five buildings. For 5000 L storage tank, the payback period was 4.4 years in the roofing area of 269.36 [m^2] and 5 years in the roofing area of 520 [m^2].

The study has established that large roofing areas and storage tanks earned more benefits than small roof areas and storage tanks. Decreasing the discount rate from 20% to 5%, increased the BCRs for different storage tank sizes. Based on the market local price, the roof area closer to 269.4 [m^2] showed higher BCRs and fewer payback periods. Increasing the roofing areas from 110 to 520 [m^2], indicated the

BCRs increased to the roofing areas of 269.4 [m^2] and started to decrease as the roofing areas reached 520 [m^2] for three discount rates. The time-based reliability used to determine the storage tank capacity at the constant water demand, i.e., indicates the percentage of days that the RWH system will save the water demand. The percentage of reliability indicated the storage tank sizes ranged between 20 and 25 [m^3] met requirements for five buildings with few days to be supplemented with other water sources.

Further work could evaluate the different types of storage tanks to be fixed with the RWH system to minimize investment costs. Additionally, rainfall intensity could also be evaluated using measured data and empirical models to develop the intensity duration frequency of rainfall in semi-arid areas.

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