



An Optimization Approach for Assessing the Reliability of Rainwater Harvesting

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Received: 30 March 2016 / Accepted: 14 March 2017 /

Published online: 24 March 2017

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Abstract This study was aimed at developing an optimization approach to rainwater harvesting (RWH) considering three (3) water consumption scenarios (WCS). These scenarios which include basic water need (BWN), pour flush (PF) and full plumbing connection (FPC) corresponding to 50 litres per capita per day (lpcd), 75(lpcd) and 150(lpcd) respectively were simulated for different categories of buildings. Reliability of supply was determined by first obtaining composite surplus/deficit of rainwater followed by optimizing the redistribution of surplus rainwater harvested to deficient buildings. Results showed that when total annual rainfall intercepted by roof exceeded total demand, 100% reliability of water supply was guaranteed. Reliability was found to be a linear function of storage. When reliability of supply is possible, the optimized storage bears an inverse exponential relationship to the roof plan area per capita. The relationship between surplus/deficit and roof plan area per capita follows a one-phase decay pattern. An optimal redistribution of surplus water from self-sufficient buildings to deficient ones gave an improvement in supply reliability from 64 to 87% for basic water need, 47 to 58% for pour flush and 28 to 29% for full plumbing connection.

Keywords Developing countries · Rainfall · Rainwater harvesting · Rainwater redistribution · Surplus/deficit

1 Introduction

Increasing surface runoff and subsequent contamination of water resources by runoff can be attributed to urbanization (Ryan et al. 2009). Increase in population invariably leads to an increase

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in water demand (Qadir et al. 2007; Villarreal et al. 2004). There has been progress in water conservation and management with more attention being given to rainwater harvesting (RWH) (Prinz 1996). Factors such as easy installation (Şen et al. 2013), low energy requirement and cheap maintenance (Nguyen et al. 2013) serves as motivation for urban and rural inhabitants to install rainwater harvesting systems (RWHS). Rainwater harvesting has been identified as one of the best means for promoting sustainable water supply in urban areas (Lye 2009; Kim et al. 2005). The long-term benefits of rainwater harvesting system is being overlooked and it is as a result of limited understanding of the cost of construction and maintenance over a long period of time (Rahman et al. 2012). In areas where domestic water source are contaminated, RWH has been proven to fill the gap as an alternative water source (Farreny et al. 2011; Islam et al. 2010; Fletcher et al. 2008). The installation of rainwater saving tanks have impacted positively on water management by reducing demand on municipal water supply (Butler et al. 2010; Jones and Hunt 2010; Abdulla and Al-Shareef 2009; Su et al. 2009). RWH should be encouraged in arid climates because it serves as an effective tool for solving drought and water shortage issues (Tabatabaee and Han 2010). Several considerations such as the environment and life cycle impact of RHW have ensured the development of a more accurate system design (Parkes et al. 2010). Gold et al. (2010) observed that the performance of RWHS needs to be redefined as a function of the runoff capture. Chiu et al. (2009) carried out a cost benefit analysis of water with respect to pumping energy cost for RWH. Imteaz et al. (2011) explored the daily water balance model to optimize the size of tanks to be used for residential buildings with large roof catchment. Further evaluation was carried out by Imteaz et al. (2011) on different climatic conditions and water rates which impacted on investment paybacks amounting up to 21 years.

Recent studies on field investigation of RWHS show that the overflow from stormwater cannot be prevented using RWHS alone (Campisano and Modica 2014; Petrucci et al. 2012). There have been many methods proposed to optimize multi – purpose reservoirs, most of which were analyzed using genetic algorithms, long term data set and fuzzy logic (Camnasio and Becciu 2011; Mehta and Jain 2009; Karamouz and Araghinejad 2008; Ahmed and Sarma 2005). Considering building with multi – use rain water tanks, the stochastic analysis of rainfall event processes needs to be relinquished in other to design a reliable rainfall facility because this will help in exploring new alternative potentials for the reduction of rainfall – runoff. This study sought to (i) ascertain the optimal reliability of water supply from RWH for various categories of residential buildings; (ii) establish the relationships between reliability and water demand; (iii) determine the relationship between optimal storage capacity and water demand; and (iv) investigate the possibility of redistributing excess roof runoff to deficient buildings.

2 Methodology

This research was pursued in two stages as outlined below.

(i) Determination of Composite Surplus/Deficit

First, a typical cluster of buildings consisting of different categories of buildings was simulated. Three water consumption scenarios (basic water need, pour flush and full plumbing connection) were adopted. The water consumption corresponding to the three scenarios are 50 litres per capita per day, 75 litres per capita per day and 150 litres per capita per day respectively. For the purpose of determining percentage of water demand that can be offset by rainfall as well as the resultant deficits and surpluses from each

category of building, the storage capacity required for optimal RWH was first determined by an optimization scheme. Generally, a storage tank is required if water spilled or wasted during peak rainfall would be needed in lean periods. If the sum of spills during rainfall peak is less than sum of deficit in lean periods, then the capacity of tank needed is equal to the sum of spills. If there are no surpluses, there would not be any need for a storage tank. If, however, the sum of spills exceeds the sum of deficit, then an optimization approach was adopted to determine the minimum capacity of storage tank that will yield 100% reliability of supply. The optimization scheme also computes the reliability of supply using inflow, demand and optimized RWH storage capacity. After satisfying monthly water demand, excess water was stored in the tank. If there is deficit in a particular month, the shortfall in water supply was satisfied using water previously stored in the tank. If the tank's capacity was reached, excess water was spilled. The objective function was formulated as follows:

$$\text{Minimize } \sum_{i=1}^{12} SP_i = \sum_{i=1}^{12} (S_{i-1} + I_i - D_i - C) \tag{1}$$

Subject to:

$$C \geq 0,$$

$$S_{i-1} + I_i - D_i \geq 0,$$

$$S_{i-1} + I_i - D_i \geq \sum_1^{12} (I_i - D_i)$$

$$C \leq \text{Max} \left(I_i - D_i + \sum_1^i CS_i \right)$$

I_i = inflow for i^{th} month, D_i = demand for i^{th} month, C = RWH storage capacity, S_i = water available for storage after satisfying monthly consumption, SP_i = spill for i^{th} month, CS_i = cumulative surplus up till the i^{th} month. The above optimization was implemented for each of the three income groups using six categories of dwellings viz.: bungalow, duplex, four flats, six flats, eight flats and ten flats, for the three water consumption scenarios. This resulted in the solving of thirty-six (36) optimization cases. The conceptual framework for optimal allocation of rainwater as outlined above is shown in Fig. 1. The results of the optimization scheme were used to obtain regression equation between percentage demand met as a function of roof area per capita and water demand per capita; optimal storage capacity and roof area per capita; and reliability as a function of RWH storage capacity and water demand per capita.

(ii) Optimal Redistribution of Surplus To Deficient Buildings

After computing the reliability of supply from the above technique, the values of surplus and deficit for each category of building was noted and recorded. The surpluses from self-sufficient buildings were used to offset the deficit in others. Instead of an arbitrary assignment of surpluses to deficient buildings, this study sought to adopt a systematic approach to ensure that sufficient water was assigned to the deficient building so that outstanding water demand is fully met (100% reliability of supply). The problem

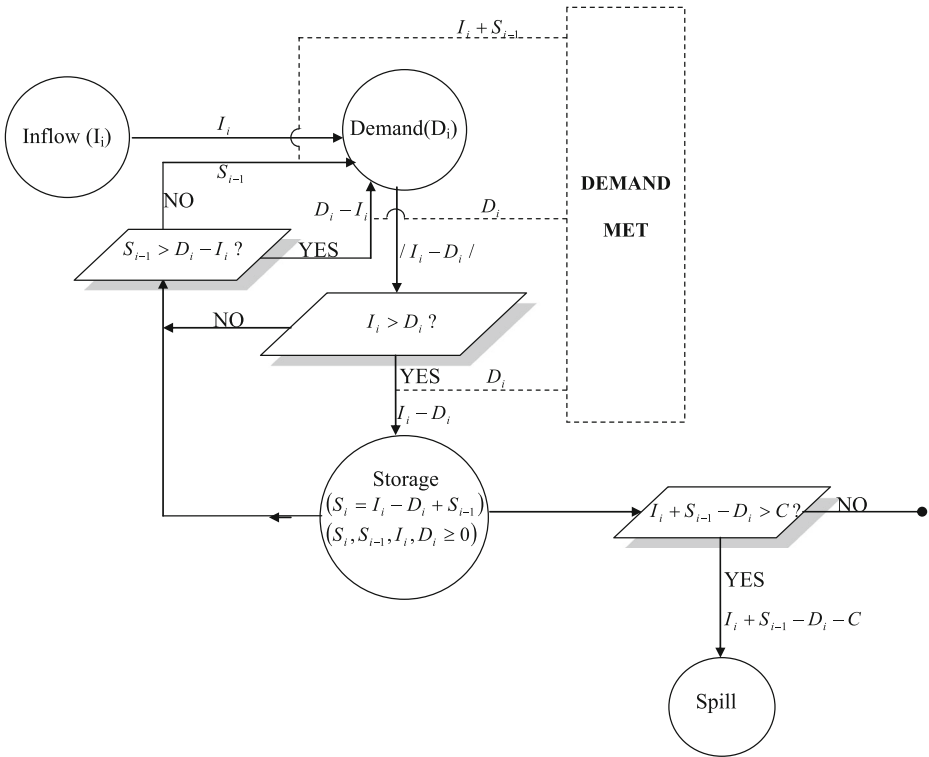
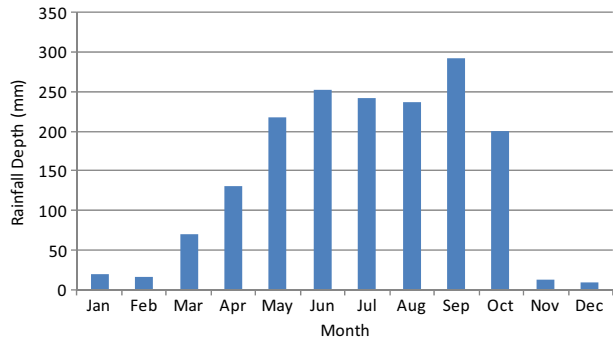


Fig. 1 Water allocation framework

of which deficient buildings are to be allocated water instead of the others can be solved by either a multi-criteria decision method or by an optimization approach. In this study, an optimization scheme was developed which sought the optimum combination of various building types whose deficit can be fully supplemented with surplus from self-sufficient buildings. The optimization problem was formulated as follows:

$$\begin{aligned}
 & \text{Min} \left(\sum_{i=1}^N S_i X_i \right), \text{ subject to the following constraints :} \\
 & X_i = B_i \text{ for } S_i > 0 \\
 & X_i \geq 0 \text{ for } S_i < 0 \\
 & X_i \leq B_i \text{ for } S_i < 0 \\
 & X_i = \text{integer} \\
 & \sum S_i X_i > 0
 \end{aligned} \tag{2}$$

S_i = surplus from each category of building, B_i = total number of buildings in category i , X_i = number of buildings in category i serviceable with surplus water, N = number of building categories. For the purpose of demonstrating the methodology developed in this work, the average monthly rainfall depth of Enugu, Nigeria was adopted (Fig. 2).

Fig. 2 Annual rainfall used for Enugu

3 Results and Discussion

3.1 Rainwater Harvesting Reliability and Storage Capacity

Table 1 shows that when total annual rainfall intercepted by the roof exceeds total annual demand of building occupants as in the case of bungalow and duplex, 100% reliability of water supply is guaranteed if an appropriately sized RWH storage tank is provided. When 100% reliability of supply is possible, the optimized storage tank bears an inverse exponential relationship to the roof area per capita. Roof area per capita refers to the roof area that supplies water to individual occupant if the roof is equally divided among occupants. For instance, for basic water need, when the roof area per capita is halved, the optimal RWH storage tank required for 100% supply quintuples. This is because the decrease in roof area is compensated for by a geometric increase in storage tank. However, if water demand is greater than inflow from rainfall, only a certain percentage of the demand will be met. Further analysis of the results presented in Table 1 shows that when total inflow from rainfall is less than water demand, percentage demand met (%DM) is linearly directly proportional to the roof area per capita and inversely proportional to water demand. The generalized and specific relationships for the rainfall data used are respectively given as Eqs. 3 and 4.

$$\%DM = \gamma \frac{A}{WD} \quad (3)$$

$$\%DM = 418.2 \frac{A}{WD} \quad (4)$$

Where A is the roof area per capita ($m^2/capita$) and WD is water demand ($lpcd$). These equations apply to situations where 100% reliability is not achievable due to inadequate rainfall or very small roof area. This suggests that high rise buildings do not favour optimal rainwater harvesting because of their extremely small roof area per capita. Generally, as water demand increases, the required storage capacity increases and the percentage demand met decreases and as roof area increases, demand met increases (Fig. 3). For a case where 100% reliability of supply is possible, the optimal reservoir capacity was found to bear an inverse power relationship to roof area per capita.

Table 1 Result of optimized rainwater harvesting for various building types

Type	Roof plan area	No of occupants	Roof plan area per capita (m ²)	Reservoir capacity(m ³)			Demand met (%)			Surplus			Deficit		
				BWN	PF	FPC	BWN	PF	FPC	BWN	PF	FPC	BWN	PF	FPC
Bungalow	270	6	45.00	23.36	41.2	106.67	100	100	100	302.45	247.73	83.56	-	-	-
Duplex	189	6	31.50	27.29	47.31	80.95	100	100	87.81	178.88	124.16	-	-	-	40
One storey (4 Flats)	343	24	14.29	144.2	116.52	0	100	79.69	39.84	85.49	-	-	133.39	790.03	-
Two storey (6 Flats)	343	36	9.53	116.52	8.06	0	79.69	53.12	26.5	-	-	-	133.39	461.71	1446.67
Three storey (8 Flats)	343	48	7.15	23.96	0	0	59.76	39.84	19.92	-	-	-	352.27	790.03	2103.31
Four storey (10 Flats)	343	60	5.72	0	0	0	47.8	31.87	15.94	-	-	-	571.15	1118.35	2759.95
Five storey (12 Flats)	343	72	4.76	0	0	0	39.84	26.56	13.28	-	-	-	790.03	1446.67	3416.59
Six storey (14 Flats)	343	84	4.08	0	0	0	34.15	22.77	11.383	-	-	-	1008.91	1774.99	4073.23
Total										566.82	371.89	83.56	2855.75	5725.14	14,629.78

BWN Basic water need (50lpcd), *PF* Pour flush (75lpcd), *FPC* Full plumbing connection

Fig. 3 Reliability of supply versus roof area

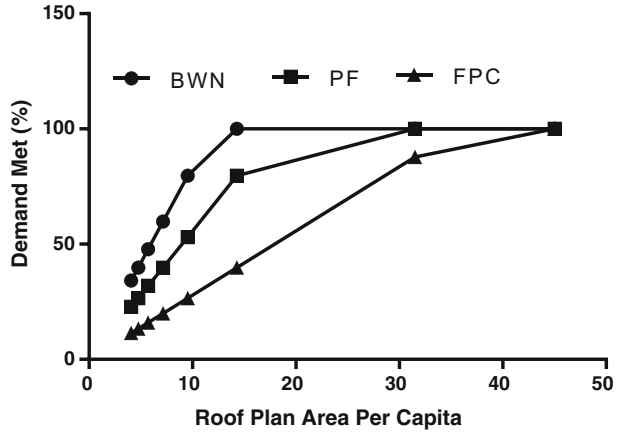


Figure 4 shows the plots of surplus/deficit versus roof area per capita and surplus/deficit per capita versus roof plan area. A deficit is equivalent to negative surplus as shown in the figure. As roof area per capita decreases, there is a transition from surplus to deficit. As roof area approaches zero, the surplus/deficit line tends to be asymptotic to the vertical axis. Further analyses of the plots show that they follow a one phase decay pattern of the general form shown below.

$$S = a \exp(-bA) + c \tag{6}$$

Where S is the surplus per capita per annum, while a , b , and c are coefficients of the equation. The coefficients were obtained as functions of water demand per capita per day (WD) using two-stage multiple regression analyses of the data. The coefficients a , b , and c are respectively given as Eqs. 7, 8 and 9

$$a = -53.97WD - 378.1, \quad R^2 = 0.999 \tag{7}$$

$$b = 0.45WD^{-0.17}, \quad R^2 = 0.973 \tag{8}$$

$$c = -2.5WD + 354.8, \quad R^2 = 0.999 \tag{9}$$

The coefficients above are specific to the rainfall data used in the study. However, similar expressions can be obtained for any geographical location of choice using available rainfall data.

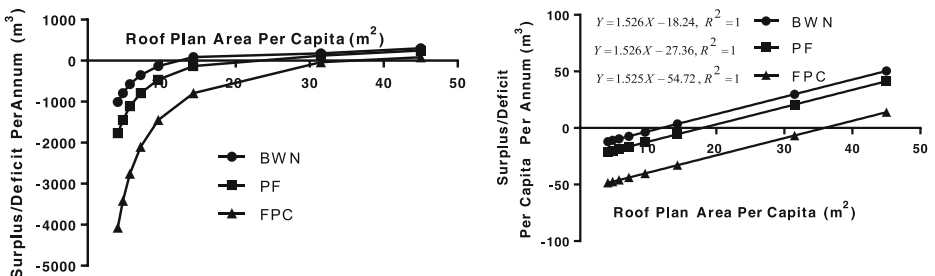


Fig. 4 Surplus and deficit versus roof area

In order to facilitate a rapid determination of RWH storage tank capacity for a desired reliability, a relationship between reliability and storage capacity was developed. Figure 5 shows that reliability of RWH is a linear function of capacity of RWH storage tank, given a specific building type and water demand. Figure 5 was generated by computing the reliability of supply for various values of storage capacity. The range of storage used was between zero (ie no storage) and the optimum storage capacity obtained by the optimization scheme presented in the methodology. The optimum storage capacity yields 100% reliability of RWH if total annual inflow from rainfall is greater than or equal to total annual water demand. If inflow is less than the total demand, then the reliability of RWH is the percentage ratio of inflow to demand. In this case, the required storage capacity is equal to the maximum deficit. Intermediate values of storage capacity were used to generate corresponding values of RWH reliability. Maximum possible reliability of supply can be expressed as follows.

$$R_{max} = 100 \times \frac{\begin{cases} D_i & D_i > I_i \\ I_i & D_i < I_i \end{cases}}{D_i} \tag{10}$$

Where R_{max} is the maximum possible reliability; D_i and I_i have been previously defined. The general linear relationship between storage and reliability is of the form given in Eq. 11.

$$R = aC + b \tag{11}$$

R is reliability (%) and C is the RWH storage tank capacity (m^3). The values of a and b were found to depend on water demand. A non linear regression analysis was performed for various values of a and b obtained for deifferent water demand options with R^2 values ranging

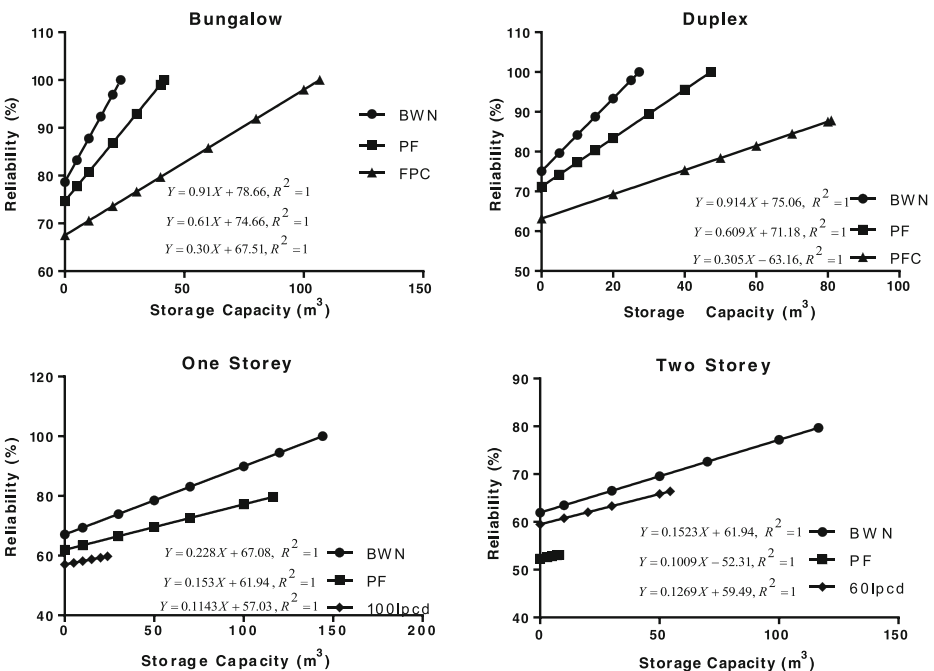


Fig. 5 Reliability of supply versus storage capacity

Table 2 Best fit equations for reliability-storage relationship

Category	Roof area per capita	<i>a</i>	<i>R</i> ²	<i>b</i>	<i>R</i> ²
Bungalow	45.0	$a = 47.78WD^{-1.01}$	0.999	$b = 136.1WD^{-0.14}$	0.999
Duplex	31.50	$a = 45.67WD^{-1}$	1	$b = 140.3WD^{-0.15}$	0.995
One storey	14.29	$a = 11.21WD^{-0.99}$	0.999	$b = 166.7WD^{-0.23}$	0.988
Two storey	9.53	$a = 8.11WD^{-1.01}$	1	$b = 327.8WD^{-0.42}$	0.945

between 0.945 and 1.0. Table 2 shows the expressions for *a* and *b* for various building types classified according to roof area per capita. It can be seen that the reliability-storage relationship can be generalized as follows.

$$R = \alpha(WD)^{-\beta}C + \gamma(WD)^{-\theta} \quad (0\% \leq R \leq 100\%) \quad (12)$$

Where α , β , γ and θ are constants that depend on building type and rainfall distribution of the location. *WD* is water demand in litres per capita per day. Equations 11 and 12 are the same except that the coefficients *a* and *b* have been expressed in terms of water demand (*WD*) in Eq. 12.

The reliability-storage relationship was verified using values of RWH storage capacity other than those used in calibrating the model. For various values of storage capacity (different from those used in calibration), the RWH reliability was determined as outlined in the methodology. The values of reliability for the same range of values of storage capacity were also determined using Eq. 12 and then plotted as shown in Fig. 6. Figure 6 shows a striking degree of agreement between actual values of reliability versus storage and values obtained using

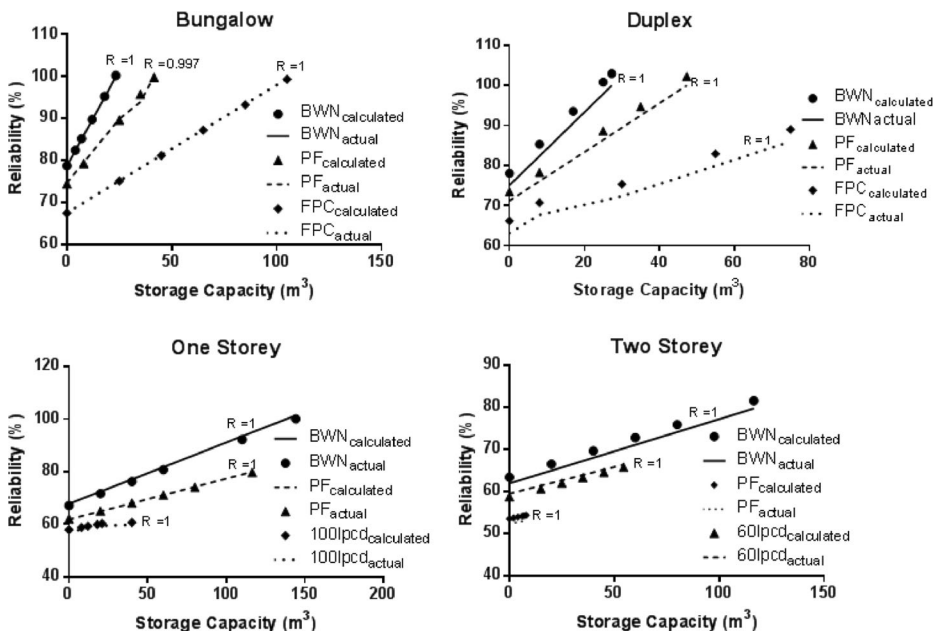


Fig. 6 Verification of reliability-storage relationship

Table 3 Table for optimal redistribution of surplus water (basic water need)

Type	Total number of buildings (B _i)	Number of buildings serviceable (X _i)	Total demand	Surplus per building type (S _i)	Overall surplus	Initial deficit	Additional demand met	Demand previously met	Total demand met	Outstanding deficit	Outstanding buildings
Bungalow	15	15	1641.6	302.45	4536.75	0	0	1641.60	1641.60	0	0
Duplex	10	10	1094.4	178.88	1788.8	0	0	1094.40	1094.40	0	0
One storey (4 Flats)	10	10	4377.6	85.49	854.9	0	0	4377.60	4377.60	0	0
Two storey (6 Flats)	7	6	4596.48	-133.39	-800.34	933.73	800.34	3662.93	4463.27	133.39	1
Three storey (8 Flats)	8	3	7004.16	-352.27	-1056.81	2818.16	1056.81	4185.69	5242.50	1761.35	5
Four storey (10 Flats)	2	2	2188.8	-571.15	-1142.3	1142.3	1142.3	1046.25	2188.55	0	0
Five storey (12 Flats)	4	4	5253.12	-790.03	-3160.12	3160.12	3160.12	2092.84	5252.96	0	0
Six storey (14 Flats)	3	1	4596.48	-1008.91	-1008.91	3026.73	1008.91	1569.70	2578.61	2017.82	2
SubTotal			30,752.6		11.97	11,081.04	7168.48	19,671.01	26,839.49	3912.56	
Percent						36%	23%	64%	87%	13%	

Table 4 Table for optimal redistribution of surplus water (pour flush)

Type	Total number of buildings (B _i)	Number of buildings serviceable (X _i)	Total demand	Surplus per building type (S _i)	Overall surplus	Initial deficit	Additional demand met	Demand previously met	Total demand met	Outstanding deficit	Outstanding buildings
Bungalow	15	15	2462.4	247.73	3715.95	0	0	2462.40	2462.40	0	0
Duplex	10	10	1641.6	124.16	1241.6	0	0	1641.60	1641.60	0	0
One storey (4 Flats)	10	10	6566.4	-133.39	-1333.9	1333.9	1333.9	5232.76	6566.66	0	0
Two storey (6 Flats)	7	3	6894.72	-461.71	-1385.13	3231.97	1385.13	3662.48	5047.61	1846.84	4
Three storey (8 Flats)	8	1	10,506.2	-790.03	-790.03	6320.24	790.03	4185.69	4975.72	5530.21	7
Four storey (10 Flats)	2	0	3283.2	-1118.35	0	2236.7	0	1046.36	1046.36	2236.7	2
Five storey (12 Flats)	4	1	7879.68	-1446.67	-1446.67	5786.68	1446.67	2092.84	3539.51	4340.01	3
Six storey (14 Flats)	3	0	6894.72	-1774.99	0	5324.97	0	1569.93	1569.93	5324.97	3
Sub Total			46,129		1.82	24,234.46	4955.73	21,894.05	26,849.78	19,278.73	
Percent						53%	11%	47%	58%	42%	

Table 5 Table for optimal redistribution of surplus water (full plumbing connection)

Type	Total number of buildings (B_i)	Number of buildings serviceable (X_i)	Total demand	Surplus per building type (S_i)	Overall surplus	Initial deficit	Additional demand met	Demand previously met	Total demand met	Outstanding deficit	Outstanding buildings
Bungalow	15	15	4924.8	83.56	1253.4	0	0	4924.80	4924.80	0	0
Duplex	10	10	3283.2	-40	-400	-400	400	2882.98	3282.98	0	0
One storey (4 Flats)	10	1	13,132.8	-790.03	-790.03	-7900.3	790.03	5232.11	6022.14	7110.27	9
Two storey (6 Flats)	7	0	13,789.4	-1446.67	0	-10,126.69	0	3654.20	3654.20	10,126.69	7
Three storey (8 Flats)	8	0	21,012.5	-2103.31	0	-16,826.48	0	4185.69	4185.69	16,826.48	8
Four storey (10 Flats)	2	0	6566.4	-2759.95	0	-5519.9	0	1046.68	1046.68	5519.9	2
Five storey (12 Flats)	4	0	15,759.4	-3416.59	0	-13,666.36	0	2092.84	2092.84	13,666.36	4
Six Storey (14 Flats)	3	0	13,789.4	-4073.23	0	-12,219.69	0	1569.65	1569.65	12,219.69	3
SubTotal			92,257.9		63.37	-66,659.42	1190.03	25,588.95	26,778.98	65,469.39	
Percent						72%	1%	28%	29%	71%	

Eq. 12. The coefficient of correlation between actual and calculated values ranged between 0.997 and 1.0. However, in some cases, Eq. 12 overestimated the values of RWH reliability for a given RWH storage capacity. It should be noted that storage-reliability relationship has an upper bound of 100% and a lower bound of 0% for reliability. The model is meaningless outside this range. For cases where inflow is less than demand, the upper bound is the percentage ratio of inflow to demand.

3.2 Rainwater Redistribution

Tables 3, 4 and 5 show that water supply from RWH can be significantly improved by channeling the surplus from self-sufficient buildings to deficient ones. Generally, low rise buildings tend to have more self-sufficiency with respect to RWH than tall buildings. This is because tall residential buildings with several floors have lower roof area per capita. Hence, for optimal integrated RWH, there is need to convey surplus water from self-sufficient to deficient buildings. The feasibility of this approach was demonstrated by assuming a settlement with an arbitrary mix of different building types. The case used for this demonstration consisted of 15 bungalows, 10 duplexes and so on as shown in Tables 3, 4 and 5. For basic water need (50 lpcd), the overall proportion of water demand met by RWH improved from 64 to 87% after surplus was optimally redistributed to deficient buildings. The improvement in reliability of supply for pour flush water demand (75 lpcd) and full plumbing connection (150 lpcd) improved from 47 to 58% and 28 to 29% respectively. The results of this study show that the proportion of domestic water demand that can be met by RWH depends on water demand and consumption. At low water demand and large roof area per capita, RWH can satisfy domestic water demand if sufficient storage is provided. However, as water demand increases and roof area per capita decreases, as is the case with tall residential buildings, the proportion of demand that can be met by RWH declines significantly. This shows that RWH can significantly reduce water stress in developing countries with very low per capita water demand and a large proportion of low rise buildings. With proper planning and implementation, surplus from self-sufficient buildings can be harnessed and redistributed to deficient ones in close proximity.

4 Conclusion

RWH has become imperative for developing countries as it can serve as a flood mitigation measure while also meeting water needs. In this study, an optimization approach to integrated rainwater (RWH) for different building categories under three (3) water consumption scenarios was proposed. The study outlined two important stages required for this process and they include determination of composite surplus/deficit and optimal redistribution of surplus to deficient buildings. The optimization approach used showed that there is high reliability of water supply from RWH especially for low rise buildings as they tend to have large roof area per capita compared to high rise buildings. In addition, the study also shows that adequate redistribution of surplus RW in aggregated buildings consisting of varying categories is feasible as long as they are not far apart. Finally, there is need for adequate planning and effective implementation of the findings of this research to reap good benefits from RWH.

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