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Rainwater Harvesting in Residential Areas of Arid and Semi-Arid Regions (Case Study: Torbat-E Jam, Iran)

S. H. Hoseini[a*], V. Attarzadeh Hosseini[b]

[a] *Department of Natural Resources, Torbat-e Jam Branch, Islamic Azad University, Torbat-e Jam, Razavi Khorasan, Iran*
[b] *Young Researcher's Club Torbat-e Jam Branch, Islamic Azad University, Torbat-e Jam, Razavi Khorasan, Iran*

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Abstract

Nowadays, rainwater harvesting systems, particularly on the roof of the buildings in residential areas could be considered as a managerial procedure to reduce water crisis. This efficient method is being investigated and implemented in different countries all around the world. This study was conducted on the estimation of rainfall, runoff coefficient, and the calculation of the optimized tank volume and the total harvested amount of rainwater on the roofs of the residential areas in Torbat-e Jam. It is noteworthy to mention that the roofs' surfaces are covered by waterproofing. This study aimed to estimate the amount of the harvested rainwater in the study area, and to apply this method in different areas of Torbat-e Jam, Razavi Khorasan Province, Iran. According to the results, the values of the roofs' runoff coefficient and average rainfall were 0.9 and 154 mm, respectively. The results of the tank volume sensitivity analysis showed that the average peak 24-hour rainfall is the best rainfall index to calculate the tank volume. The total harvested amount of rainwater was 5,606 m^3 considering the total surface of the roofs and the annual rainfall in the study area. Applying this procedure in other areas of Torbat-e Jam, the harvested rainwater was estimated as 772,806 m^3. This amount of harvest resulted in 15.5% water saving.

Key words: Arid and Semi-Arid Regions; Rainwater; Water demand; Sustainability

1. Introduction

Several studies have reported the potential of rainwater harvesting as a useful method for saving potable water. According to these publications, this system has a potential of 12% to 100% in saving potable water under specific environmental conditions (Herrmann and Schmida, 1999; Ghisi *et al*., 2007; Sazakli *et al*., 2007; Abdulla and Al-Shareef, 2009; Zhang *et al*, 2009: Terêncio *et al*., 2018). Rainwater harvesting systems reuse runoff, increasing the sustainability of water supplies and they may also reduce runoff discharges and thus help water quality management (Alamdari *et al*., 2018; Musayev *et al*., 2018). The rainwater harvesting is believed to be a suitable method for effective urban runoff management and better water resources management. This method would provide an alternative source of water to tackle the drought phenomenon in semi-arid regions (Wifag *et al*., 2014; Adham *et al*., 2018). In addition, using higher runoff coefficient of roofs results in higher amounts of harvested rainwater from the roof of the buildings (Ramier *et al*., 2004; Yan Li *et al*., 2004; Farreny *et al*., 2011; Young Lee *et al*., 2012). Moreover, certain studies have shown the influence of sloping roof on water quality and quantity (Farreny *et al*., 2011; Vargas-Parra *et al*., 2019). A study on green roofs demonstrated that these roofs could be effective in the runoff output. Therefore, constructing green roofs can be considered as a solution for decreasing runoff in residential areas (Mentens *et al*., 2006). The presence of appropriate tanks is necessary for gathering and storing rainwater (Imteaz *et al*., 2017; Imteaz and Moniruzzaman, 2018; Kisakye and vander bruggen, 2018). The volume of the tanks in the study area is dependent on hydrologic conditions (Imteaz *et al*., 2017) and demands for water usage (Ghisi *et al*., 2007; Su *et al*., 2009;

* Corresponding author. Tel.: +98 915 1058593
Fax: +98 51 35251080
E-mail address: s.h.hosseini@iautj.ac.ir

Campisano and Modica, 2012; Zhang *et al*., 2017). Many researchers have suggested the application of computer models, such as SWMM[1] (Villarreal and Dixon, 2005; Walsh *et al.*, 2014). Recently, SWMM model has been suggested to calculate rainwater harvesting tank volume in some cities, for instance Sydney. Additionally, new methods have been suggested for designing the water tank, which can save to 85 % of the rainwater (Hashim *et al*., 2013). Recently, researchers have investigated the optimum function of the rainwater harvesting systems and different models, which consider inflow, outflow, and storage variations, which have been presented for water tank design (Palla *et al*., 2011; Tamaddun *et al*., 2018). In the present study, we represented a method to determine the optimum tanks volume, reduce the costs of water harvesting system, and gain the highest efficiency. In this work, the volume of the tanks was calculated considering the climatic, hydrologic, hydraulic, and physical parameters of the study area and then the tank volume was improved with actual water demand and sensitivity analysis. Quantitative investigation of harvesting runoff from rainwater harvesting systems is an important step for establishing these systems. Herein, we aimed to investigate rainwater harvesting in the residential areas of arid and semi-arid regions and estimate the real amount of available water.

2. Materials and Methods

2.1. Study area

Torbat-e Jam, with an area of 14 km^2, is located in Razavi Khorasan, Iran. This city is of a dry and cold climate based on Amberje climate classification. The average rainfall in the study area was recorded as 154 mm. The average annual evaporation was measured at 1,875-mm. The study area is located southwest of Torbat-e Jam.

2.2. Calculation of runoff coefficient

In order to calculate the runoff coefficient, the following steps were taken:

1. Amount of average annual rainfall: for the estimation of this factor, we utilized data from synoptic station of Torbat-e Jam for a time series from 2001 to 2013.

2. Determining runoff height: For this purpose, the runoff generated from each rainfall event on the roofs was directed into a 38-liter water tank using PVC pipes (Farreny *et al*., 2011) (Fig. 1). Afterwards, the runoff height was calculated as follows:

$$R=V/A \quad (1)$$

where V is the volume of gathered water in the tank (m^3), A shows the area of the roof (97.46 square meter), and R depicts the runoff height (m).

Fig. 1. A view of collecting rainwater by PVC pipes

[1] - Storm Water Management Model

3. Calculation of the runoff coefficient: The runoff coefficient could be calculated by:

$$C=R/P \quad (2)$$

where *C* is the runoff coefficient, *P* is the average annual rainfall (mm) and *R* shows the runoff (mm).

2.3. Calculation of the collected water volume

The rainwater harvested volume was calculated employing the following equation (Palla *et al*., 2011; Worm and Hattum, 2006):

$$Q = \varphi \times R \times A \quad (3)$$

In which *Q* is the average annual rainfall volume (m^2), *R* is the average annual rainfall (m), *A* is the roof's area (m^2), and φ represents the runoff coefficient.

2.4. Determination of water demand

Water demand was calculated by (Worm and Hattum, 2006 ; Palla *et al*., 2011):

Annual water demand = 365 × water usage × number of family members (4)

2.5. Domestic consumption per capita

Domestic consumption is predicted to be in the range of 75 to 150 liters per day for each person (www.waterstandard.wrm.ir). In this study, we considered a domestic consumption of 150 liters.

2.6. Calculation of the optimized volume for the pipes

Optimized volume for the pipes was calculated as follows:

$$V = \varphi \times Rp \times A \quad (5)$$

where *V* is the optimized volume of the tank (m^3), *Rp* depicts the average peak of annual rainfall (m), *A* is the area of roof, and φ depicts the runoff coefficient.

2.7. Sensitivity analysis of the tank volume

Tank volume was investigated using different parameters in order to have a better and more accurate assessment. These parameters included the average annual rainfall, average monthly rainfall, average ten-day rainfall, average weekly rainfall and average of 24-hour rainfall peak from 2001-2013. Using Equation (6), the optimized volume of the tank could be calculated (Fewkes and Butler, 2000; Mitchell, 2007; Palla *et al*., 2012).

$$Vmax = It + Vt\text{-}1 - Yt - SPt \quad (6)$$
$$It = \varphi \times Rt \times A$$

in which *Rt* is the daily rainfall (m), *It* is the volume of harvested rainwater (m^3), *Vt-1* is the volume of water in the tank from previous days, *Vmax* depicts tank volume, *SPt* is the outflow volume of the tank, *Yt* represents the outflow volume from the tank for providing non-drinking water demands, φ is the runoff coefficient, and *A* shows the area of rainwater harvesting surface (m^2).

3. Results

3.1. The average of rainfall

The average annual rainfall was estimated to be 154mm utilizing synoptic station data in a time series of 2001-2013. Figure 2 represents the average monthly rainfall and Figure 3 depicts the average accumulative monthly rainfall values.

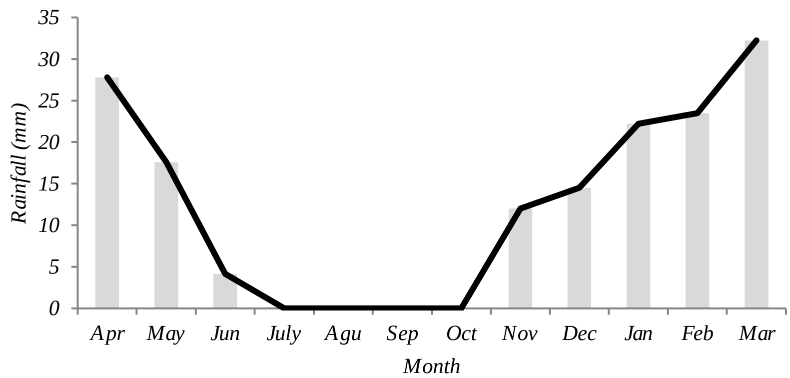

Fig. 2. The average monthly rainfall

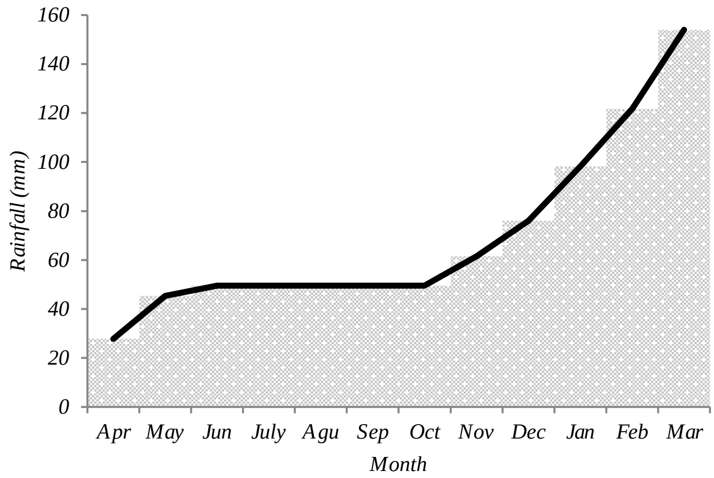

Fig. 3. The average accumulative monthly rainfall

3.2. The runoff coefficient (C)

The runoff coefficient was determined measuring the roof's surface, average rainfall of the area in a 13-year period, and calculating the generated runoff gathered by the tanks and implementing the ratio of the runoff and rainfall height (Table 1).

Table 1. The runoff coefficient parameters

A (m^2)	V(m^3)	R=V/A	P(m^3)	C = R/P
97.4600	2.4890	0.0250	0.0278	0.9000

The runoff coefficient was considered at 0.9 for the roofs of the buildings (Lancaster, 2006). It needs to be clarified that the roofs of all of the buildings were covered with isolated insulation.

3.3. Calculation of the harvested rainwater volume and water demand for the study area

It is noteworthy that, based on the gathered information, the average number of the family members in the study area are considered as 4 people. The average number of the students and stuff in the self-service and security buildings are 15020 people. Table 2 presents the calculation of the harvested rainwater and water demands in the study area. The volume of harvested rainwater and annual water demand can be calculated using Equations 3 and 4, respectively.

Table 2. Calculation of the harvested rainwater volume and water demand

Buildings	Area (m^2)	Building number	Annual harvested water (lit)	Daily harvested water (lit)	Annual water demand (lit)	Monthly water demand (lit)	Daily water demand (lit / head)
Payame Noor training	597	1	82740	226.69	547500	45625	1500
Payame Noor self-services	468	1	64860	177.71	73000	6083.33	200
Payame Noor Security building	13.70	1	1890	5.20	7300	608.33	20
Building N.1	486	18	67350	184.54	525600	43800	1440
Building N.2	466	8	64580	176.95	233600	19466.66	640
Building N.3	606.50	10	84060	230.30	292000	24333.33	800
Building N.4	502	18	69570	190.62	525600	43800	1440
Building N.5	321	12	44490	121.89	350400	29200	960
Building N.6	150	6	20790	56.95	175200	14600	480
Building N.7	256.50	9	35550	97.39	262800	21900	720
Building N.8	118.50	2	16420	44.99	58400	4866.66	160

3.5. Investigating the linear regression between harvested rainwater and area of the roofs

In the present study, the relationship between two variables of harvested rainwater from roof of the buildings and the area related to them was determined (Fig. 4). Using the obtained Equation, the total volume of the harvested water was calculated to be 772800 m^3.

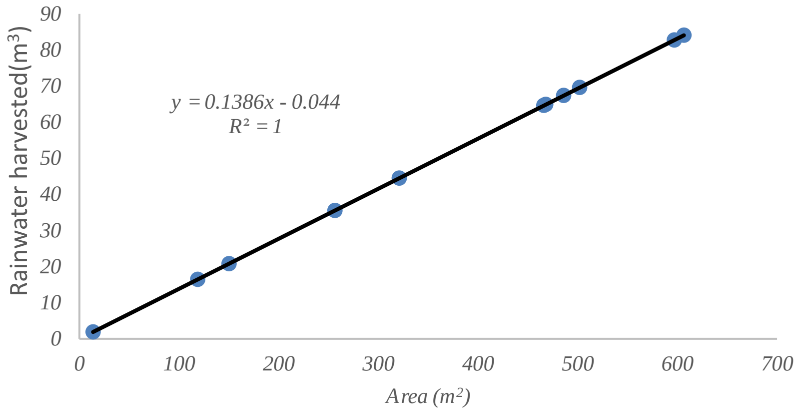

Fig. 4. Linear regression between two variables of harvested rainwater (m^3) and their area (m^2)

3.6. Calculation of the tank volume and harvested rainwater volume in the study area

Table 3 illustrates the calculation of the tank volume and harvested rainwater volume in the study area. The tank volume for each building was calculated by implementing Equation 5. The harvested rainwater volume was obtained by considering the number of the buildings in that area.

Table 3. Calculation of the tank volume and harvested rainwater volume in the study area

Buildings	Roof Area (m^2)	Annually harvested rainwater (m^3)	Tank volume (lit)	Corrected tank volume (lit)	The number of buildings	Annually harvested rainwater volume in the study area (m^3)
Payame Noor training	597	82.74	10746	10000	1	82.74
Payame Noor self-services	468	64.86	8424	9000	1	64.86
Payeme Noor Security building	13.70	1.89	246.6	500	1	1.899
Building N.1	486	67.35	8748	9000	4	269.44
Building N.2	466	64.58	8388	9000	1	64.59
Building N.3	606.50	84.06	10917	10000	1	84.06
Building N.4	502	69.57	9036	9000	7	487.04
Building N.5	321	44.49	5778	6000	66	2936.38
Building N.6	150	20.79	2700	3000	59	1226.61
Building N.7	256.50	35.55	4617	5000	4	142.20
Building N.8	118.50	16.42	2133	2000	15	246.36
Total						5606.19

3.7. The results of the tank volume sensitivity analysis

In order to calculate the optimized volume of tanks, we took different parameters into consideration. These parameters include the average annual rainfall, average monthly rainfall, average 10-day rainfall, average weekly rainfall, and average 24-hour rainfall peak in the period of 2001-2013. Using the above-mentioned parameters and Equation 5, different volumes were obtained and ultimately, the optimum volume was achieved. Table 4 shows the results of the sensitivity analysis. According to these results, using different Equations and the parameters, the optimum tank volume was calculated. Based on Table 4, the self-service of Payame Noor needs a tank volume of 65 m^3 to provide its demand for 324 days. This volume, considering the rainfall statistics, will be mostly empty, which is not economically justifiable. Therefore, considering the average 24-hour rainfall peak, a tank volume of 9 m^3 was calculated to provide water demands for 42 days. Considerint the average rainfall in the study area, which could be up to to 20 mm, a volume tank of 9 m^3 seems to make sense. By taking other parameters into account, such as average monthly rainfall, average 10-day rainfall, and average weekly rainfall in Equation 5, different volumes were calculated. However, these tanks cannot respond to the unexpected rainfall events.

Table 4. The results of the sensitivity analysis

Buildings	Roof Area (m^2)	water demand (Liter)	Average annual rainfall (154 mm)		Average monthly rainfall (12.8 mm)		Average 10-day rainfall (4.27 mm)		Average weekly rainfall (3 mm)		Average peak 24-hour rainfall (20 mm)	
			Tank volume (m^3)	Water demand (day)	Tank volume (m^3)	Water demand (day)	Tank volume (m^3)	Water demand (day)	Tank volume (m^3)	Water demand (day)	Tank volume (m^3)	Water demand (day)
Payame Noor training	597	1500	83	55	7	4.5	2.5	1.5	2	1	10	7
Payame Noor self-services	468	200	65	324	5.5	27	2	9	2	6	9	42
Payame Noor Security building	13.7	20	2	90	0.2	8	0.05	2.5	0.03	2	0.5	12.5
Building N.1	486	1440	70	47	6	4	2	1.5	1.5	1	9	6
Building N.2	466	640	65	100	6	9	2	3	1.5	2	9	13
Building N.3	606.5	800	84	105	7	9	2.5	3	2	2	10	13
Building N.4	502	1440	7	48	6	4	2	1	1.5	0.5	9	6
Building N.5	321	960	44	46	4	4	1.5	1	0.8	1	6	6
Building N.6	150	480	20	43	2	3.5	0.6	1	0.4	<1	3	5.5
Building N.7	256.5	720	35	49	3	4	1	>1	0.7	<1	5	6.5
Building N.8	118.5	160	17	102	1.5	8.5	0.5	3	0.3	2	2	13

4. Discussion

Based on the calculations, the runoff coefficient of the roofs was computed at 0.9. In rainwater harvesting, the presence of surfaces with high runoff coefficients is appropriate (Farreny *et al*., 2011; Ramier *et al*., 2004; Yan Li *et al*., 2004; Young Lee *et al*., 2012). The results exhibited a direct and significant relationship among these factors. The more the rainfall amount is, the more runoff we would have. In addition, considering the linear regression between the harvested rainwater and the roof area with a correlation coefficient of 1, it could be inferred that there is a direct and strong relationship between these two factors. More roof surface area means more harvested rainwater. Considering the total water demand and harvested rainwater volume, (for example, in two buildings: self-service of Payame Noor, and B.7), it could be concluded that self-service can respond to water demand since it has a large roof area and low density of the people.

In building B.7, due to the small area and high density of the people, water demands could not be satisfied. Therefore, rainwater harvesting systems are better to be established in places in which on top of considerable rainfall, the area of roof surface is large and the number of people in the building is low.

The results of the tank volume sensitivity analysis and solving the Equations showed that the average peak 24-hour rainfall is the best rainfall index to calculate the tank volume.

The optimum volume demonstrates the volume which is economically justifiable and can provide water demands of the residents. Regarding the types of tanks, Polyethylene tanks were selected owing to their high resistance against acids and, bases, and other anti-metals, low heat transfer, easy transformation, easy production in different sizes, high resistance against cracking, and leaking, corrosion resistance even in high temperatures, and easy and low-cost installation (Rashidi Mehrabadi, 2011).

In terms of rainwater harvesting, tanks cost the most. For example, 10,000 liter vertical tanks, three-layer 5,000 liter horizontal tanks, and 5,000 liter vertical tanks cost 39,6$, 27,00$, 21,00 $, respectively. Additionally, each aluminum sheet and each PVC rainspout respectively cost 7.6$, and 4$.

The costs of the pipes and connections, workers' payment, and so forth were predicted to be 0.009 of the total cost of the building. The total volume of the harvested rainwater in all the buildings of the study area was calculated as 5,605 m^3.

5. Conclusion

Considering the information on roofs' area in Torbat-e Jam, a volume of 772,800 m^3 rainwater can be harvested. This volume can provide water equal to a groundwater well with a discharge of 24.5 liter per second. This means that utilization of rainwater harvesting would stop using the groundwater wells with the mentioned discharge and reduce the costs and energy consumption. The average consumption of water in Torbat-e Jam was measured to be 5 million m^3 (in residential areas); therefore, 15% of this volume can be obtained by rainwater harvesting. This is a significant volume and can be considered as a contingency plan for the managers to provide water resources and resolve water crisis. Accordingly, it is of great necessity to identify and control pollutions ahead of executing rainwater harvesting projects since the costs of the filtrations are high. In old buildings, rainwater harvesting could be done applying iron foundation and sloping aluminum plates on them. Employing certain efficient methods, the tanks can be filled and the water can be used for dry seasons to satisfy water demands of a building. One of these methods could be secondary sink which is connected to the rainwater harvesting system (outflow waters from this sink include clean waters such as waters from washing fruits, vegetables, and rice) and filtering light waters from washing machine. Another method which can be suggested is putting a tank in bathroom and kitchen, connected to the roof rainwater harvesting tanks which can transport clean water to the mentioned packages.

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