O 77. ROOFTOP RAINWATER HARVESTING OPTIMIZATION IN ANTALYA, TURKEY

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ABSTRACT: The water resources of the world are consuming rapidly due to the population increases and growing industrializing world. Sustainable water resources management seems a solution for managing the scarce water resources. Rainwater harvesting can reduce water shortage problems, especially in countries which suffer from water scarcity. Saving of freshwater resources is essential for water conservation. In domestic uses, the non-potable water demand especially in toilets flushing can be changed with rainwater harvesting. In this study, Water Balance Model (WBM) and Rippl Method (RM) are used to investigate the optimization of rooftop rainwater harvesting in Antalya province of Turkey. The reliability analysis of the rooftop rainwater harvesting and optimal storage estimation analysis have done for system optimization. Comparisons among annual, eight, seven and six months regularizations are made in order to make the rainwater harvesting system feasible and cost-effective. For Antalya rooftop rainwater harvesting system, individual houses (a 6 household family water demand for toilets flushing 24 L/ca/day) are assessed by using the WBM and RM. For optimal rainwater storage tanks estimation 60, 40 and 35 m^2 rooftop areas are selected for annual, eight, and seven/six months regularizations respectively for supplying the water demand of toilets flushing with 90-100% reliability. Comparisons between two methods for optimal rainwater harvesting storage tanks are made in order to recommend a suitable method for storage tanks estimation. For annual regularizations, 21 m^3 and 17 m^3 storage tanks are estimated with RM and WBM respectively. Thus, WBM is recommended for Antalya province. For eight, seven and six months regularizations with RM; 9, 7, and 4 m^3 storage tanks are estimated respectively. The storage cost and payback period for annual regularization is 3600 TL and 24 years respectively. Storage, costs about 50% of the rooftop rainwater harvesting. Hence, twofold of storage cost might give the cost of the rooftop rainwater harvesting system.

Keywords: Alternative water resources, Rainwater harvesting, Rainwater harvesting optimizations, Sustainable water resources management, Water saving.

1. INTRODUCTION

Rainwater harvesting is one of the ancient water harvesting technique which is most common in dry regions of the world. Nowadays, rainwater harvesting is using for sustainable water resources management especially in developed countries. For none-developed countries, rooftop rainwater harvesting system is using for water supply and irrigation purposes. However, in developed countries, rainwater harvesting uses for saving the main water use. Water resources becoming scarce day by day. Turkey is among water-stressed countries and is expected to become water-poor country in the coming decade. In Turkey, the rainwater harvesting might be used for saving the main water use. Using the harvested rainwater in domestic non-potable demands can save a big amount of main water use. For rainwater harvesting system feasibility study is crucial, a feasibility study should be made prior to the system design. The most expensive part of the system is a storage tank. For rainwater harvesting system, the storage tank is the biggest factor of total installation cost (Chilton et al., 2000). For becoming the system more feasible and applicable prior to the design of the system optimizations should be made especially for optimal storage tanks design.

For water scarcity problems, investment in rainwater harvesting system seems to reduce the potable water consumption and reduce the upcoming water scarcity situations (EEA, 2012). For potable water savings, some studies about rainwater harvesting conducted worldwide. In Sweden using the collected rainwater in toilets flushing in a residential area could save about 60% of the urban water supply (Villarreal and Dixon, 2005). In the United Kingdom,rooftop rainwater harvesting system can fulfil 36% to 46% of toilets flushing water demand with 23 and 7 years payback periods respectively (Ward et al., 2010). Using of collected rainwater in residential buildings might supply about 40% of potable water demand (Muthukumaran et al., 2011).

In this study, for rainwater harvesting optimizations in Antalya province; annual, eight months, seven months and six months regularizations are made in order to design the system more feasible and reliable for future rainwater harvesting projects in the mentioned province. In this study, a 6 household family (water consumption in 6 household family toilets flushing demand 24 L/ca/day) is selected in order to design the optimal storage tanks for the various regularizations, the most suitable regularization can be recommended for an optimal storage tank.

2. MATERIALS AND METHODS

Daily and monthly rainfall data are used for most rainwater harvesting studies around the world. In this study, the average total monthly rainfall data of Antalya province is used. For hydro-meteorological studies, reliable data has a great importance. For rainwater harvesting analysis long-term rainfall data should be used. One of the reasons for the use of long-term precipitation data is that the average data to be obtained is more reliable (Turoğlu, 2014). It has been proposed that rainfall data should be longer than 10 years for the rainwater harvesting studies (Martin and Watkins, 2010). The average annual rainfall in Antalya is 1082 mm which most of the rainfall occurs during the winter season of December and January months.

In this study, for rainfall regime analysis, total annual precipitation data were used for Precipitation Concentration Index (PCI). For optimum storage tanks estimation, WBM and RM are used. For optimal storage tanks estimation average total monthly precipitation data is used. The most expensive part of the rooftop rainwater harvesting system is storage tanks. For system reliability and cost-effectiveness, rainfall regime analysis and optimization are conducted. PCI is used for rainfall regime analysis. A conceptual model of the study is given in Figure 1.

2.1 Precipitation Concentration Index (PCI)

Precipitation Concentration Index (PCI) (Oliver, 1980), an indicator of the concentration of rainfall in Antalya province was calculated for each year. Then, the average PCI values of annual PCI were calculated for obtaining the temporal PCI.

Temporal PCI was calculated using eq. (1):

$$\mathrm{PCI\ annual} = \frac{\sum_{i=1}^{12} \mathrm{Pi}^2}{(\sum_{i=1}^{12} \mathrm{Pi})^2} * 100 \tag{1}$$

Where Pi, represents the monthly precipitation in the i.*th* month.

The PCI values under 10 indicate the uniform distribution of rainfall throughout the year. The values between10-20 indicate seasonality and the values greater than 20 indicate that the precipitation is irregular throughout the year (Table 1). Many methods for concentration analysis of precipitation data are used worldwide. A study conducted in Turkey for reflecting the concentration of rainfall concentration, the PCI was estimated to be more appropriate than Modified Fournier Index (MFI) (Apaydin et al., 2006). The classification of PCI is given in Table 1.

Table 1. Classification of precipitation concentration index (Oliver, 1980)

Precipitation Concentration Index	Temporal PCI Concentration
<10	Uniform
11-15	Moderate
16-20	Concentrated
>20	Very Concentrated

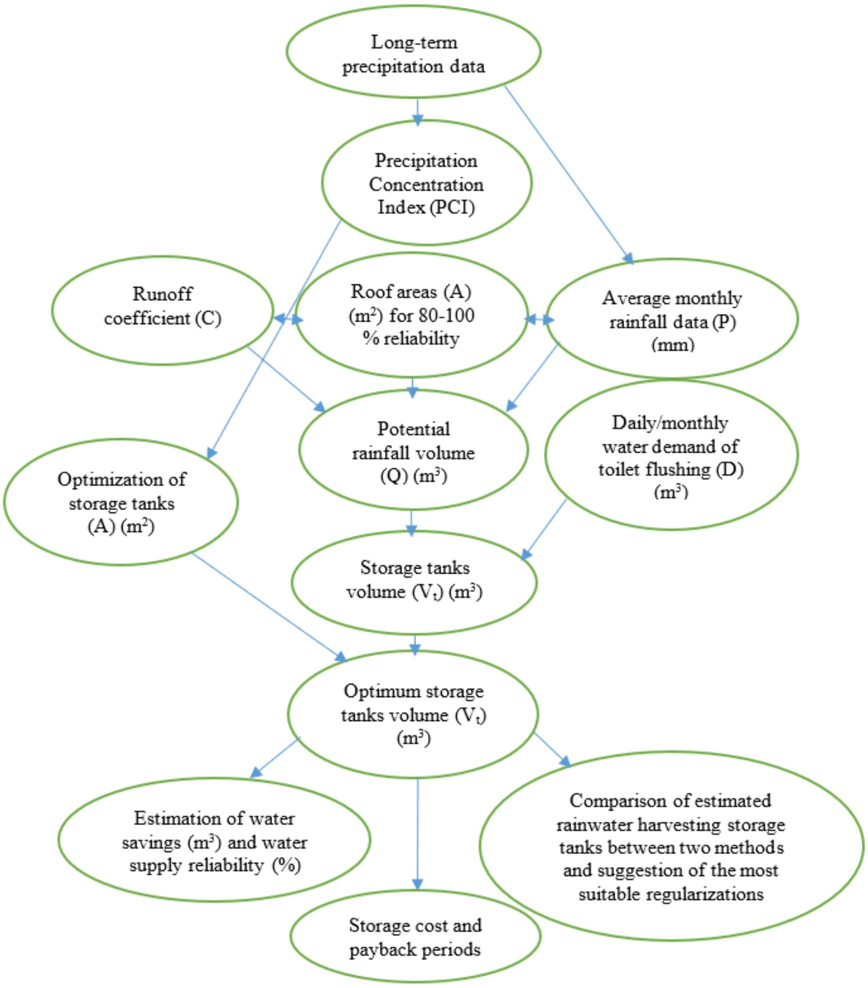

Figure 1. Conceptual model of the study

2.2 Water Balance Model

The most commonly used method to estimate the volume of optimum rainwater storage tanks is WBM. In this study monthly WBM was used by taking into account the monthly rainfall, water collection area, leakage and evaporation-related losses, storage volume and water usage (Imteaz et al., 2012). With this model, monthly rainwater usage, monthly volume of stored water in the tank can be calculated. The list of the data required for the estimation of the storage tank with the WBM is given in Table 2.

Table 2. WBM and necessary data for the estimation of the storage tank

Column 1	**Column 2**	**Column 3**	**Column 4**	**Column 5**	**Column 6**	**Column 7**	**Column 8**
Months	Average monthly rainfall (mm)	Monthly demand (m^3)	Collecting area (m^2)	Volume of monthly rainfall (m^3)	$V_{i\ month-1}$ (m^3)	(Column 5– Column 3) (m^3)	$V_{i\ month\ later}$ (m^3)
Jan … Dec							
	Storage tank capacity (m^3)= X(The biggest value)						

To better describe the WBM, the required data for the estimating of the storage tanks is presented in Table 2:

Column 1: time (month),

Column 2: average monthly rainfall is obtained based on the average monthly rainfall of time series (mm), time series in this study for Antalya is between 1929-2017 years,

Column 3: Monthly consumption refers to the volume of drinking water that can be changed with rainwater (m^3). In this study the daily water consumption in the toilets flusing for a family of 6 members for individual houses is 24 L/ca/day considered (DIN, 1989), a daily water demand 144 L/day, monthly water demand 4.32 m^3/month and annual water demand of 53 m^3/year,

Column 4: total collection area (m^2), in this study for 6 household family 60, 40 and 35 m^2 collection areas are selected due to the amount of precipitation and obtaining the volumetric reliability of (80-100%),

Column 5: it was obtained by multiplying column 2 by column 4 and according to (DIN, 1989), with the coefficient of flow required for impermeable areas (C) being taken as 0.8. Volume of monthly rainfall (m^3) is calculated by using eq. (2):

$$Q(m3) = \frac{(P - EL) * C * A}{1000} \quad (2)$$

P: average annual rainfall,

EL: precipitation losses (2mm/month, 24 mm/year) (Martin, 1980),

C: flow coefficient of (80-85%) recommended by (DIN, 1989) for impermeable areas in this study 80% value is selected,

A: roof area (m^2),

Column 6: corresponds to the volume of water in the tank at the beginning of a month (m^3),

Column 7: is calculated by the difference between monthly precipitation amount (column 5) and the monthly consumption (column 3) (m^3),

Column 8: The cumulative maximum positive difference corresponds to the optimal volume of the storage tank (m^3).

In the WBM, the volume of the water in the tank at the beginning of a certain month ($V_{i\ month\ -1}$) was initially assuming the tank is empty. The largest positive value from column 8 gives the minimum storage volume.

Mathematically, the model is expressed as follow:

$$V_{i\ month\ later} = V_{i\ month\ -1} + (V_{i\ month} - D_{i\ month}) \quad (3)$$

$$V_{i\ month\ later} = 0, \text{ if } V_{i\ month\ later} < 0 \quad (4)$$

$$V_{i\ month\ later} = C_{i\ month}, \text{ if } V_{i\ month\ later} > C_{i\ month} \quad (5)$$

$V_{i\ month\ later}$: The volume of accumulated water stored in a tank after a certain month (m^3),

$V_{i\ month}$: Volume of rainwater stored in a given month (m^3),

$V_{i\ month\ -1}$: The volume of water in the tank at the beginning of a given month (m^3),

$D_{i\ month}$: Water demand in a given month (m^3),

$C_{i\ month}$: Capacity of rainwater storage tank (m^3).

Volumetric reliability can be calculated by using eq. (6):

$$R_v = \frac{\text{Water Supply}}{\text{Water Demand}} * 100 \quad (6)$$

For optimization of rainwater harvesting storage tanks of Antalya province by using the WBM and RM an individual house of (a 6 member family toilets flushing water use 24 L/ca/day) annual water demand of 53 m^3/year is selected.

2.3 Rippl Method

In order to determine storage tanks for rooftop rainwater harvesting, it can be determine with RM which provides the storage volume required to ensure a regular flow during the longest drought period (Quadros, 2010). Among the most suitable methods to determine the storage volume for rainwater harvesting are the daily simulation using the 80% efficiency criteria, which is the most appropriate rate of economic saving/installation cost and the RM (Santos and Taveira-Pinto, 2013). The RM corresponds to the maximum (positive) accumulated difference between the water demand and the collected rainwater. The list of data required for the estimation of the storage tanks by RM is given in Table 3.

Table 3. Data required for estimation of the storage tank by RM (Tomaz, 2003)

Column 1 Months	**Column 2** Average monthly rainfall (mm)	**Column 3** Monthly demand (m^3)	**Column 4** Collecting area (m^2)	**Column 5** The volume of monthly rainfall (m^3)	**Column 6** (Column 3– Column 5) (m^3)	**Column 7** Cumulative differences from column 6 (m^3)
Jan						
…						
Dec						
Storage tank capacity (m^3)= X(The biggest value)						

The procedure of estimation of optimum rainwater storage tanks with RM is similar to WBM from column 1 to column 5. In RM the procedure of calculation for column 6 and column 7 is different from the WBM. For a better understanding of RM column 6 and 7 are described as below:
Column 6: is obtained by the difference between the monthly consumption (column 3) and the monthly precipitation amount (column 5) (m^3),
Column 7: Cumulative differences are calculated by ignoring the negative values obtained from column 6 in the first months. The cumulative maximum positive difference corresponds to the minimum volume of the storage tank (m^3).

3. RESULTS AND DISCUSSIONS

As the result of rainfall regime analyses, Antalya has very concentrated precipitation with 21.15 PCI value (Himat, 2019). For the desired demand of water supplying by rainwater, the biggest storage tanks among Turkey provinces are required in Antalya province due to the very concentrated precipitation patterns. In this study, the daily water consumption in the toilets flushing for a 6 household family of individual houses is 24 L/ca/day considered (DIN, 1989), a daily water demand 144 L/day, monthly water demand 4.32 m^3/month and annual water demand of 53 m^3/year family is selected. Accordingly, a comparison for Antalya province will be made between the WBM and the RM used for optimal rainwater harvesting storage tanks estimation.
Provinces which require big storage tanks for rainwater harvesting system feasibility and economically design optimizations should be made prior to the projects implementation. WBM and RM, annual, 8, 7 and 6 months regularizations for Antalya province are given in (Table 4, Table 5, and Table 6). It was estimated by RM that 21 m^3 of the storage tank and 60 m^2 roof area are required in order to obtain 53 m^3/year of water supply with 96% volumetric reliability (Table 4). Furthermore, for 8 months regularization, it was estimated by RM that 9 m^3 of the storage tank and 40 m^2 roof area are required in order to obtain 35 m^3/8 months of water supply with 94% volumetric reliability (Table 5). With the 8 month regularization for Antalya province, it is possible to estimate 42% smaller storage tanks with the RM. Estimation of the storage tanks for individual houses by the RM with annual regularizations for Antalya province (water consumption in 6 household family toilets flushing demand 24 L/ca/day) is given in Table 4.

Table 4. Estimation of the storage tanks for individual houses by the RM with annual regularization for Antalya

Method	Average annual rainfall(mm)	Roof area (m^2)	Demand (m^3)	Supply (m^3)	Volumetric Reliability (%)	Selected storage tank (m^3)
RM	**1082**	**60**	**53**	**51**	**96**	**21**

Long-term monthly average rainfall distribution and a number of average rainy days in Antalya (1929-2017) is illustrated in Figure 2. As shown in Figure 2, the average monthly precipitation distribution of Antalya has very big fluctuations. The fluctuations in the rainfall distribution might increase the storage requirements of the rainwater harvesting system. Summer season in Antalya is very dry. In June, July and August there is an average monthly rainfall of less than 10 mm (Figure 2). Rainwater harvesting is not effective in summer due to the very low rainfall during the season. Rainwater harvesting is more effective in autumn, winter and spring seasons of the year. In Antalya, the average number of rainy days show 12 rainy days in December and January, 11 rainy days in February and less than 10 rainy days in other months (Figure 2). July and August are the driest months of the year with the average monthly precipitation of 2.5 mm and 0.5 rainy days. During the year, there are only 74 rainy days the rest of the year is dry. Thus, it is mentioned as 20% wet season and 80% dry season in Antalya.

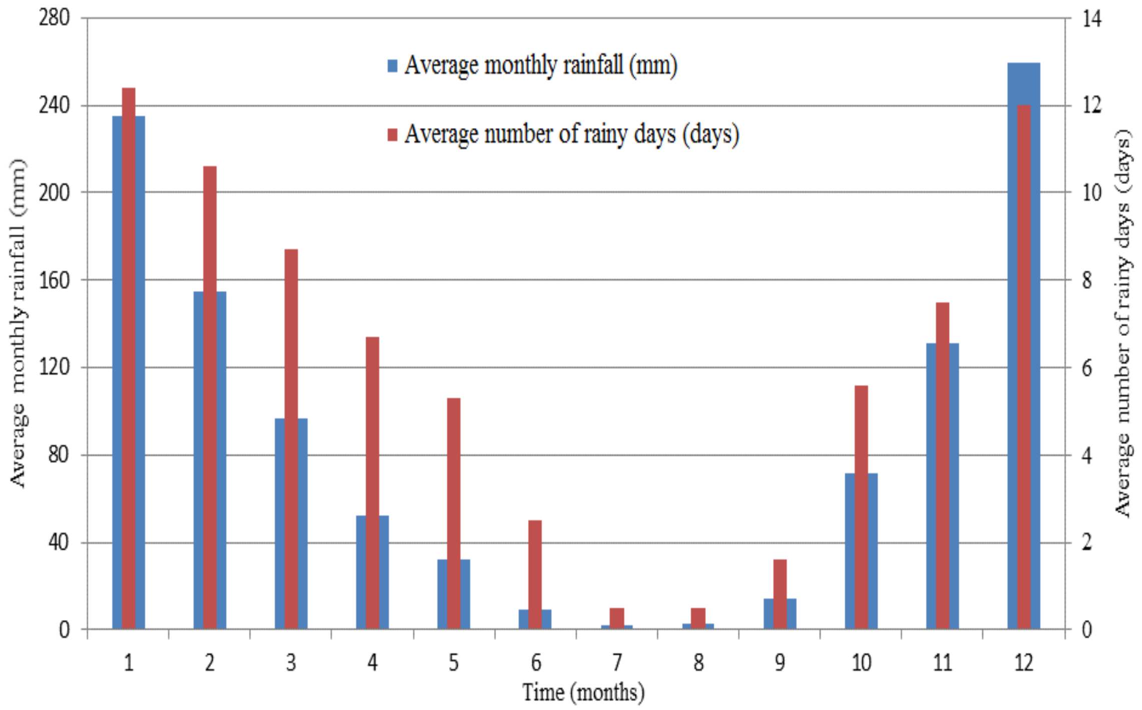

Figure 2. Monthly average rainfall distribution and number of average rainy days in Antalya (1929-2017)

Annual regularization for the differences between monthly water demand and monthly rainfall volume of Antalya is illustrated in Figure 3.

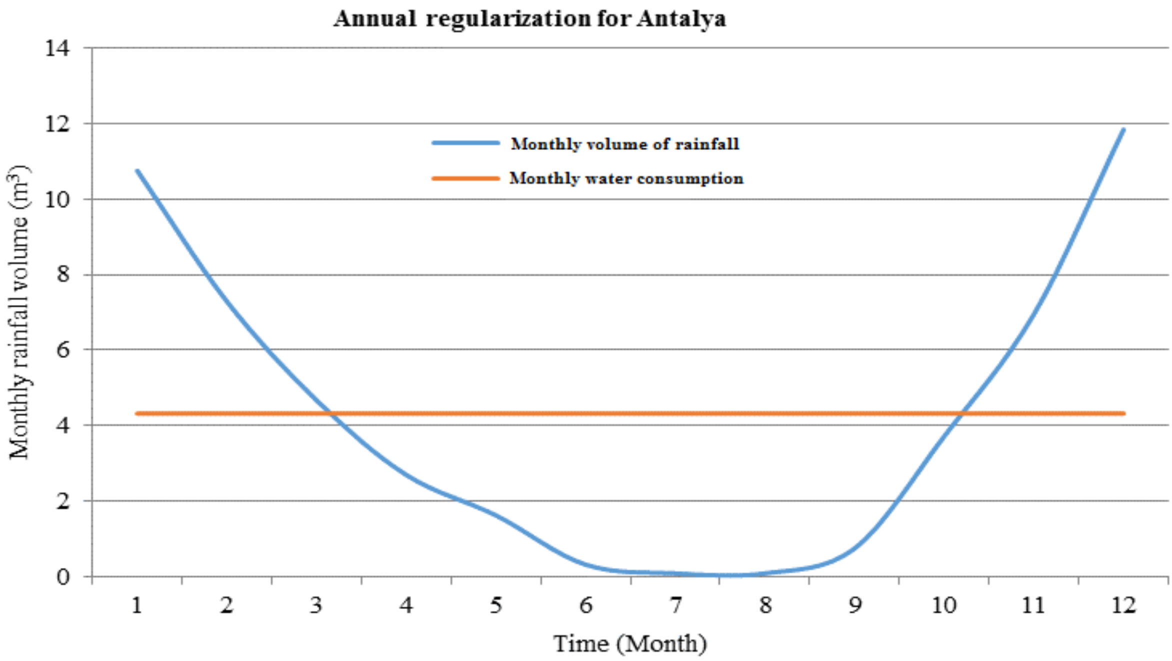

Figure 3. Annual regularization for the differences between water demand and rainfall volume of Antalya

As seen in Figure 3, the difference between monthly water volume and monthly water consumption is enormous. This is the reason for the big storage requirement. Hence, by using some regularizations it can be possible to decrease the difference between water supply and water demand. Regularizations of different months should be used to select the most appropriate time periods of the year for rainwater harvesting with a small storage tanks.
Estimation of the storage tanks for individual houses by the RM with 8 months regularizations for Antalya province is given in Table 5.

Table 5. Estimation of storage tanks for individual houses by the RM with 8 months regularizations for Antalya

Method	Average 8 months rainfall(mm)	Roof area (m^2)	Demand (m^3)	Supply (m^3)	Volumetric Reliability (%)	Selected storage tank (m^3)
RM	**1048**	**40**	**35**	**33**	**94**	**9**

Eight months regularization for the differences between monthly water demand and monthly rainfall volume of Antalya is illustrated in Figure 4. The difference between water demand and volume of rainfall is smaller than annual regularization. So, it can be possible to supply the water demand by smaller storage tank.

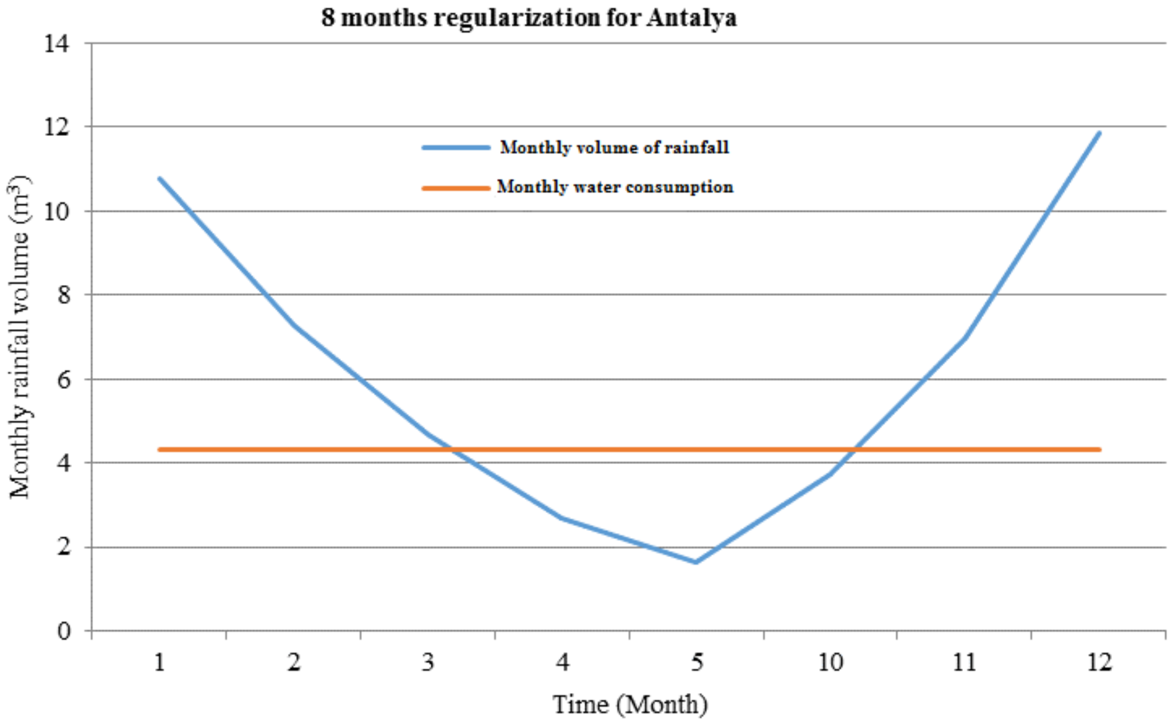

Figure 4. Eight months regularization for the differences between water demand and rainfall volume of Antalya

It was estimated that 17 m^3 of the storage tank is required by the WBM in order to supply 53 m^3/year of water with 96% volumetric reliability in Antalya (Table 6). However, for 8 months regularization by the RM, it was estimated that 9 m^3 of the storage tank is required in order to supply 35 m^3/8 months of water with 94% volumetric reliability in Antalya (Table 5). Furthermore, it was found that for annual regularization 30% smaller storage tanks can be estimated by the WBM than RM. It is recommended to use the WBM for the estimation of storage tanks of rainwater harvesting, as the WBM gives better results than the RM. Estimation of the storage tanks for individual houses by the WBM with annual regularizations for Antalya province is given in Table 6.

Table 6. Estimation of storage tanks for individual houses by the WBM with annual regularization for Antalya

Method	Average annual rainfall(mm)	Roof area (m^2)	Demand (m^3)	Supply (m^3)	Volumetric Reliability (%)	Selected storage tank (m^3)
WBM	**1082**	**80**	**53**	**51**	**97**	**17**

Estimation of the storage tanks for individual houses by the RM with 7 months regularizations for Antalya province is given in Table 7. For seven months, 28 m^3 water can be supplied from the rainwater using a 35 m^2 roof area with 7 m^3 storage tank (Table 7).

Table 7. Estimation of storage tanks for individual houses by the RM with 7 months regularizations for Antalya

Method	Average 7 months rainfall (mm)	Roof area (m^2)	Demand (m^3)	Suppl y (m^3)	Volumetric Reliability (%)	Selected storage tank (m^3)
RM	**1012**	**35**	**31**	**28**	**92**	**7**

Seven months regularization for the differences between monthly water demand and monthly rainfall volume of Antalya is illustrated in Figure 5. The difference between water demand and volume of rainfall is smaller than 8 months regularization. Hence, smaller storage tank can supply the demand.

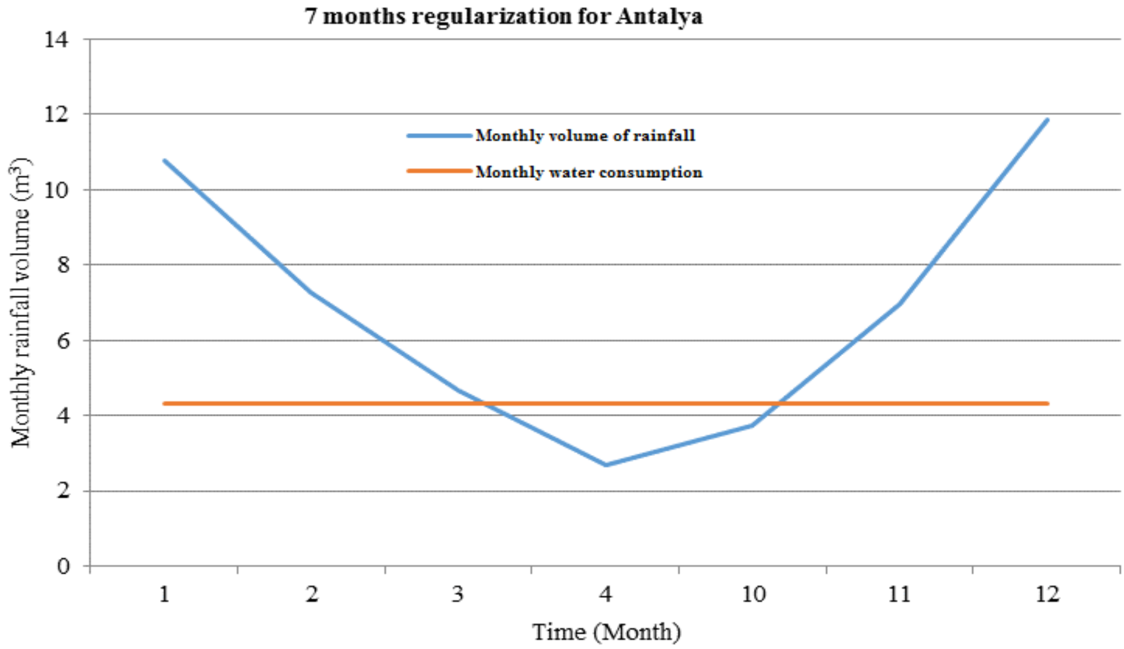

Figure 5. Seven months regularization for the differences between water demand and rainfall volume of Antalya

Six months regularization for the differences between monthly water demand and monthly rainfall volume of Antalya is shown in Figure 6. The difference between water demand and volume of rainfall is smaller than 7 months regularization. So, it is possible to supply the demand of water from rainwater with smaller storage tank. For the rainwater harvesting in Antalya, we can make the system more economical by 6 months regularizations (January, February, March, October, November, and December) (Table 8).

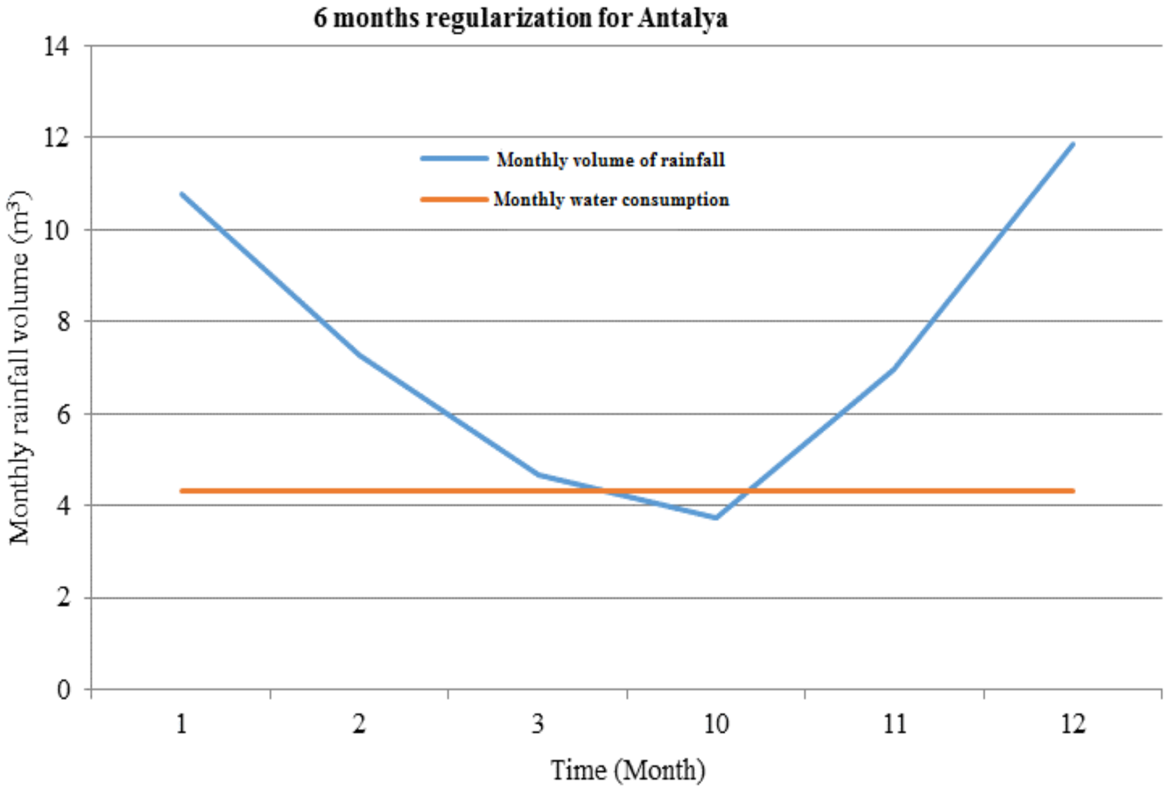

Figure 6. Six months regularization for the differences between water demand and rainfall volume of Antalya

Estimation of the storage tanks for individual houses by the RM with 6 months regularizations for Antalya province is given in Table 8. For six months, 26 m^3 water can be supplied from the rainwater using a 35 m^2 roof with 4 m^3 storage tank (Table 8).

Table 8. Estimation of storage tanks for individual houses by the RM with 6 months regularizations for Antalya

Method	Average 6 months rainfall (mm)	Roof area (m^2)	Demand (m^3)	Supply (m^3)	Volumetric Reliability (%)	Selected storage tank (m^3)
RM	**954**	**35**	**26**	**26**	**100**	**4**

In Antalya province by installing a 4 m^3 storage for rooftop rainwater harvesting it will be possible to supply the demand of 6 family toilets flushing in a six rainy months of the year. By installing the rooftop rainwater harvesing system in public/commercial buildings, it is possible to harvest a big amount of water and supply most of the toilets flushing water demand.

4. CONCLUSION

For rainwater harvesting, feasibility studies are crucial, so prior to the design of the system feasibility and optimization studies should be made in order to make the system applicable and cost-effective. Comparisons among two methods and regularizations for the rainwater harvesting in Antalya province are made in order to make the system more feasible and applicable for the mentioned province. For annual regularizations, 21 m^3 and 17 m^3 storage tanks are estimated with RM and WBM respectively. Thus, WBM is recommended for Antalya province. For eight, seven and six months regularizations with RM; 9, 7, and 4 m^3 storage tanks are estimated respectively. The storage cost and payback period for annual regularization is 3600 TL and 24 years respectively. Storage, costs about 50% of the rooftop rainwater harvesting. Hence, twofold of storage cost might give the cost of the rooftop rainwater harvesting system. For Antalya province, according to the comparisons between RM and WBM it was found that WBM estimated smaller storage tanks than RM. In Antalya, it is possible to harvest rainwater by installing 5-20 m^3 storage tanks from the roof areas of 30-60 m^2 for supplying the demand of toilets flushing of 6 member family houses. It was estimated that for annual regularization there is a need for 17 m^3 storage tank. The obtained results for regularizations show that 4 m^3 storage tank is required for half year supplying the desired demand of toilets flushing. Thus, for Antalya porovince six months regularization is recommended. In public/commercial buildings by installing the rooftop rainwater harvesting system it is possible to harvest a big amount of water and supply most of the toilets flushing water demand. According to the obtained results, it is possible to harvest rainwater even in Antalya province which has very concentrated precipitation. Regions which has concentrated and very concentrated PCI, optimization studies are essential for cost-effective system design.

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