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A Reliability Analysis of Rainwater Catchment System

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Abstract—This article examines the reliability of rainwater harvesting (RWH) systems in subcatchment area. Using water balance simulation and two definitions of this value (time-based and volumetric ones), the reliability of rainwater harvesting systems for 25 locations in Medenine's dryland agricultural areas in south-eastern Tunisia is assessed. Extensive computer software was created using modelling idea for daily water balance, and three meteorological extremes, i.e. wet, average and dry years, were selected by analysing historical 20-year daily rainfall data to assess RWH system performance. Results stated that for wet climatic conditions, volumetric reliability of around 30–70% can be attained, whereas for these circumstances, only 10–24% time-based reliability can be accomplished. The method described in this article can also be applied to other arid and semi-arid areas by using daily rainfall data to predict water savings and the reliability of RWH systems.

Keywords: rainwater harvesting, reliability, catchment system, Tunisia

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INTRODUCTION

Water scarcity is one of the biggest problems in drought-prone regions, particularly in developing countries, due to increasing water demand, rising population and urban and industrial development [1]. It will therefore be critical to develop policies and technologies to identify alternative water resources, as well as to improve the management and planning water resources. The Rainwater Harvesting System (RWH) is presently getting enhanced attention as alternative water source and is regarded to be promising techniques that can save rainwater for domestic or agricultural use [1, 9, 16].

Available water supply can be calculated by water balance simulation based on catchment size, dam volume, rainfall, water demand, and evaporation losses [2, 4]. Modeling the water balance is also helpful in estimating the reliability of RWH, which can be described as the likelihood that the system will provide the necessary water requirement over a specified period of time [6]. Defining the reliability of rainwater harvesting scheme is an important factor in determining the reliability of demand that can lead to underestimation or overestimation of production efficiency and reliability, especially in dry environments [11]. Consequently, determining reliability will be a critical factor in the design of water supplies.

Male and Kennedy [13] assessed the potential rainwater use in Portland Oregon for domestic purposes, paying particular attention to the reliability of rainwater collection. They outlined the procedure based on the quantity of rainfall gathered, household demand, and storage tank capability using water balance. Results showed that the storage tank capacity, together with the size of the catchment area, is critical in determining the system's reliability. Imteaz [8] created tank tool using the modelling idea for the daily water balance. For several Australian towns including Melbourne, the advanced tool was widely used to analyse the reliability of rainwater tanks. Karim [10] examined how reliable certain size of rainwater tank is in terms of annual quantity and meeting the daily expected requirement in Bangladesh megacity. Lawrence and Lopes [12] performed reliability analyses of rainwater harvesting tanks for three Texas towns under various rainfall circumstances and various scenarios. Rainwater harvesting system's reliability is essential because citizens want to understand that water source can be dependent on it [14]. However, to explore the applicability and reliability of the rainwater harvesting scheme in the small sub-catchment, no in-depth research has yet been performed.

The main objective of this research was to use the water balance simulation strategy to evaluate the reli-

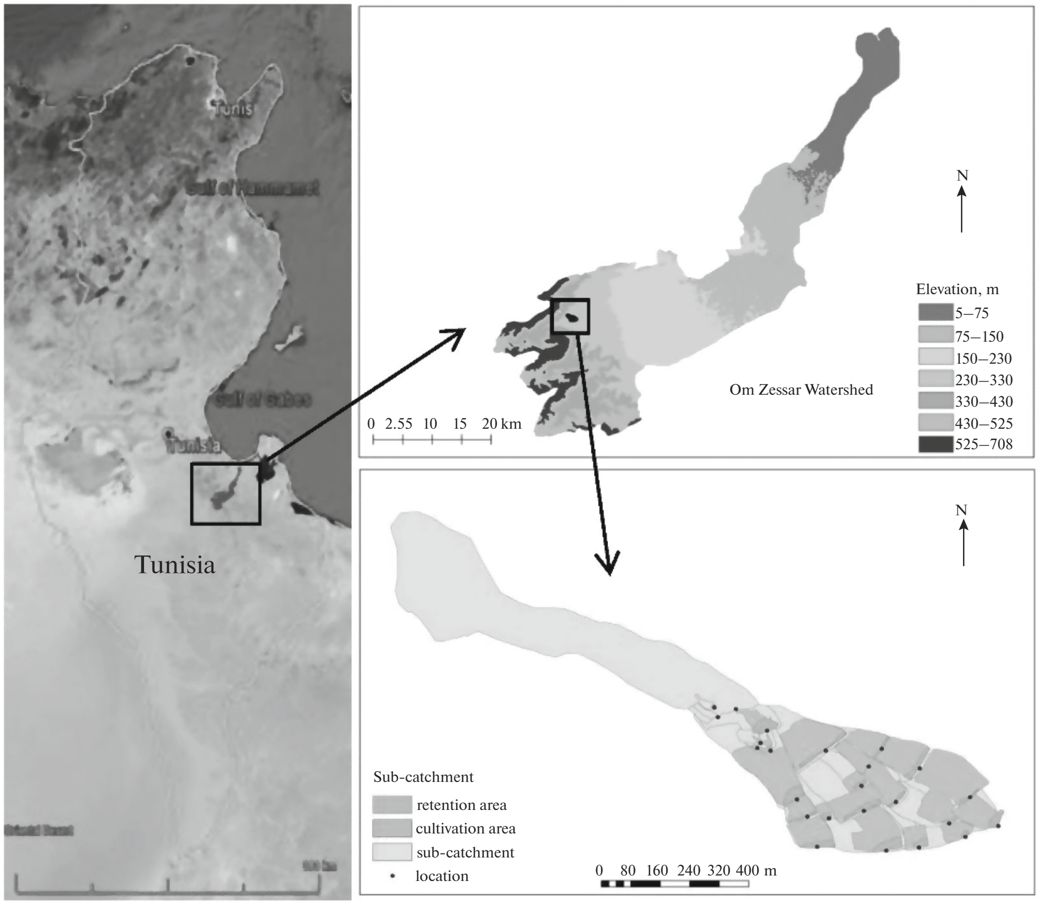

Fig. 1. Location of wadi Oum Zessar watershed and the test sub-catchment.

ability of RWH systems in small sub-catchment. This research therefore has the following goals:

(a) assess the performance of rainwater systems using the water balance model;

(b) determine the volumetric and time-based reliability of RWH systems in small sub-catchment.

MATERIALS AND METHODS

Study Area

The watershed of Oum Zessar in south-eastern Tunisia's Medenine province includes area of 367 km^2. For this case research, 50-ha catchment was chosen in the upstream watershed region. There are 25 sub-catchments in this catchment (Fig. 1). The area is characterised by arid Mediterranean climate with 150–230 mm/y rainfall, 19–22°C annual temperature and 1450 mm/y potential evapotranspiration [5].

Two main types of RWH structures have been built by local farmers to cope with water scarcity and to harvest rainfall/runoff to meet the water requirements of rainfed crops and trees: jessour (in moderate to steep slopes) and tabias (in gentle slopes). Each jessr (singular of jessour) or tabia consists of three components: impluvium or catchment area that provides runoff water; the terrace or cultivation area where runoff water is gathered and plants or trees are grown; and the dyke, which is a barrier to capture water and sediment. The dyke's shape and size are distinct, they have no specified layout. Each dyke has a spillway to regulate water flow between dykes (menfes if the spillway is on one or both sides and masref if the spillway is in the middle of the dyke) [3].

Data Collection

Daily precipitation as well as maximum and minimum temperature data were collected from two nearby meteorological stations at the Institute des Régions Arides (IRA) and Medenine/Tunisia. In order to investigate the reliability, the rainfall information for 20 years was evaluated to determine the three contrasting meteorological years, i.e. wet, dry, and average years. The respective years with annual maximum and minimum rainfall were correspondingly regarded to be wet and dry year. The year with an average annual rainfall of nearly 20 years was regarded as average year.

Each sub-catchment's physical features were evaluated. The soil texture was acquired by gathering samples, and the area slope was determined using field observation, digital elevation model (DEM) and geographic information system (GIS) in each sub-catchment. Infiltration rates were tested in the field using double-ring infiltrometer and the runoff coefficients were measured at several places in each sub-catchment using rainfall simulator. These data types were used as input for the model of water harvesting (WHCatch) [5].

Water Harvesting Model

The water balance of the 25 sub-catchments was evaluated based on the crop water requirements (demand), the rainfall-runoff relationship (supply) and the design of the RWH (storage) structures. The difference between total input and output was calculated as the change in water storage within the volume. There are usually two primary components in catchment: runoff area and reservoir area. We analysed the water balance of these two elements, among other sub-catchments, and evaluated RWH's performance throughout the system to improve the RWH system's actual storage.

According to Boers [7] the water-balance equation of the area can be written in units of volume (m^3) as:

$$\Delta S = I - Q, \quad (1)$$

where ΔS is change of storage over specified period of time, I is the inflow, and Q is the outflow, all in m^3.

Recognition of the different kinds of in- and outflow permits more comprehensive water balance equation:

$$\Delta S = Q_{\text{runoff}} + Q_{\text{rainfall}} + Q_{\text{in}} - Q_{\text{out}} - \text{Inf} - ET_{\text{c}}, \quad (2)$$

where Q_{in} is the volume of inflow from upstream catchmen t(s), Q_{out} is the volume of overflow from the retention basin to the next catchment (s), Inf is the infiltration loss from the retention basin obtained from the measured infiltration rate in each sub-catchment using the double-ring infiltrometer, ET_{c} is the maximum crop evapotranspiration, Q_{runoff} is the volume of runoff into the retention basin from the impluvium (runoff area) calculated as:

$$Q_{\text{runoff}} = 0.001CPA_r, \quad (3)$$

where C is the mean annual runoff coefficient measured in the field with the rain simulator, P is the mean annual precipitation (mm), and A_r is the impluvium or runoff area (m^2), and where Q_{rainfall} is the rainfall in the retention basin, calculated as:

$$Q_{\text{rainfall}} = 0.001PA_b, \quad (4)$$

where A_b is the area of the retention basin (m^2).

ET_{c} was calculated from the field measurements as described by Schiettecatte et al. (2005) for the same watershed. These authors used data from the Medenine meteorological station to calculate the average annual potential for evapotranspiration using the Penman-Monteith technique (PET) for 1985–1995.

Table 1. Rainfall, potential evapotranspiration (PET), maximum crop evapotranspiration (ET_{c}), and olive crop coefficient k_{c} (after [5])

Month	Rainfall, mm	PET, mm	ET_{c}, mm	k_{c}, for olive
Jan	37.5	69.6	27.8	0.40
Feb	30.6	88.6	35.4	0.40
Mar	40.0	121.2	66.7	0.55
Apr	16.3	159.3	79.6	0.50
May	11.2	198.4	89.3	0.45
Jun	1.00	213.5	85.4	0.40
Jul	0.00	234.8	82.2	0.35
Aug	2.00	220.9	77.3	0.35
Sep	17.1	166.6	75.0	0.45
Oct	23.0	126.8	63.4	0.50
Nov	19.9	91.1	41.0	0.45
Dec	36.7	67.4	26.9	0.40

The maximum ET_{c} was calculated by:

$$ET_{\text{c}} = PET\,k_{\text{c}}, \quad (5)$$

where k_{c} is the crop coefficient. The values for PET, ET_{c}, and k_{c} for olive trees are presented in Table 1.

The Water Harvesting at Catchment Level (WHCatch) Model

All input data had already been stored and made accessible in Excel, so in Excel we developed straightforward Visual Basic for Applications (VBA) macro. This macro conducted the above calculations and stored in the respective cells the resulting values. The code consisted of module for WHCatch and module for Sub-catchment Class. The latter contained all sub-catchment's characteristics and routines for carrying out some fundamental computations. There were some private subroutines and three public subroutines in the WHCatch module. The VBA macro will not be seen by common consumers of the Excel workbook. It will only be essential to enter the coding region if new functionality is needed. In the same Excel workbook, all output is stored and displayed, and the data obtained with this program can be read into GIS application. In most cases, the shape file with the area layout and the sub-catchment identification numbers (IDs) are available. This allows the sub-catchment ID in the shape file being combined with the Excel workbook ID.

Reliability Analysis

Two kinds of reliability have been calculated in this study. Time based reliability is calculated using the following equation of Imteaz [9]:

$$R_t = \frac{T_d - U_d}{T_d} \times 100, \tag{6}$$

where R_t is the timebased reliability (%), U_d is the total number of days when harvested rainwater was unable to meet the daily water demand alone and T_d denotes the total number of days (365 or 366) in a calendar year.

Where the volumetric reliability, R_v is given by:

$$R_v = \frac{\sum((VW)_d - VD_d)}{\sum VW_d}, \tag{7}$$

where VW_d is the total volume of water demand in a year and VD_d is the total water deficiency for year.

Sensitivity Analysis

Sensitivity analyses were conducted to evaluate the impacts of the runoff coefficient on the effectiveness of rainwater storage (volumetric reliability). Several sensitivity graphs illustrating effectiveness relationships with demand fraction and storage fraction were provided. The demand fraction (D/Q) is defined as follows:

$$\frac{D}{Q} = \frac{VW_d}{VW_s}, \tag{8}$$

where VW_s is the volume of rainwater supply in year and VW_d is the total volume of water demand in year.

The storage fraction (S/Q) is defined as:

$$\frac{S}{Q} = \frac{\text{Storage capacity (m}^3\text{)}}{VW_s}. \tag{9}$$

RESULTS AND DISCUSSION

The preliminary assessment was performed to examine the impact of storage capacity on daily reliability and to define the storage capacity that provides the optimum average reliability value for each unit. Simulations of water balance were performed on daily scale; the daily average reliability of each site was calculated over the entire period of analysis. Then, the related percentiles values were estimated.

Reliability Analysis

The time-based reliability relationships for various catchment sizes with storage capacity were shown in Fig. 2. For three scenarios (wet, average and dry), cases reliability increases up to storage volume of 112 m^3 (threshold), therefore becoming stable. The threshold value presents the point when reliability becomes independent of increases in storage capacity. It seems logical to suppose that wet year would be more reliable than the average and dry years because more rainfall would keep a full storage.

Volumetric reliability, i.e. the percentage of water savings for several catchment sizes with variable storage volume, was shown in Fig. 3. It is evident from this figure that the impact of storage size on volumetric reliability shows comparable trend as the time based reliability. The value of volumetric reliability can be observed to be higher than the time-based reliability considered for the catchment.

Sensitivity Analysis

For the runoff coefficient, which varies from 0.2 to 0.5 (C in Fig. 4), sensitivity analysis was carried out. Water efficiency vs. demand fraction curves with regard to runoff coefficients shows that under the wet climatic condition the runoff coefficient has negligible impact on water efficiency (Fig. 4).

Figure 5 illustrates the impact of the runoff coefficient on water efficiency. Results indicate that efficiency tends to increase with increasing storage fraction. Analysis shows that decrease of the runoff coefficient from 0.5 to 0.2 leads to decrease in effectiveness approximately of 2–3%.

CONCLUSIONS

This study examines how reliable certain size of rainwater storage is in terms of annual volume and meeting the expected daily requirement. The reliability of rainwater harvesting systems for the outlet of 25 locations situated in Medenine's dryland agricultural fields in south-eastern Tunisia is assessed using water balance simulation and two reliability definitions (time-based and volumetric reliabilities).

The reliability relationships with the different storage capacity have shown that both time base and volumetric reliabilities are increasing for the wet year up to storage volume of 112 m^3 (threshold). The application of the concept of thresholds allows property owners to achieve most system's reliability while minimizing installation costs. Consequently, reliability does not increase as the storage volume tries to increase. Volumetric reliability was found to be 10–35% higher than the time-based reliability for all cases. With the growing demand for water, both time-based and volumetric reliabilities reduced.

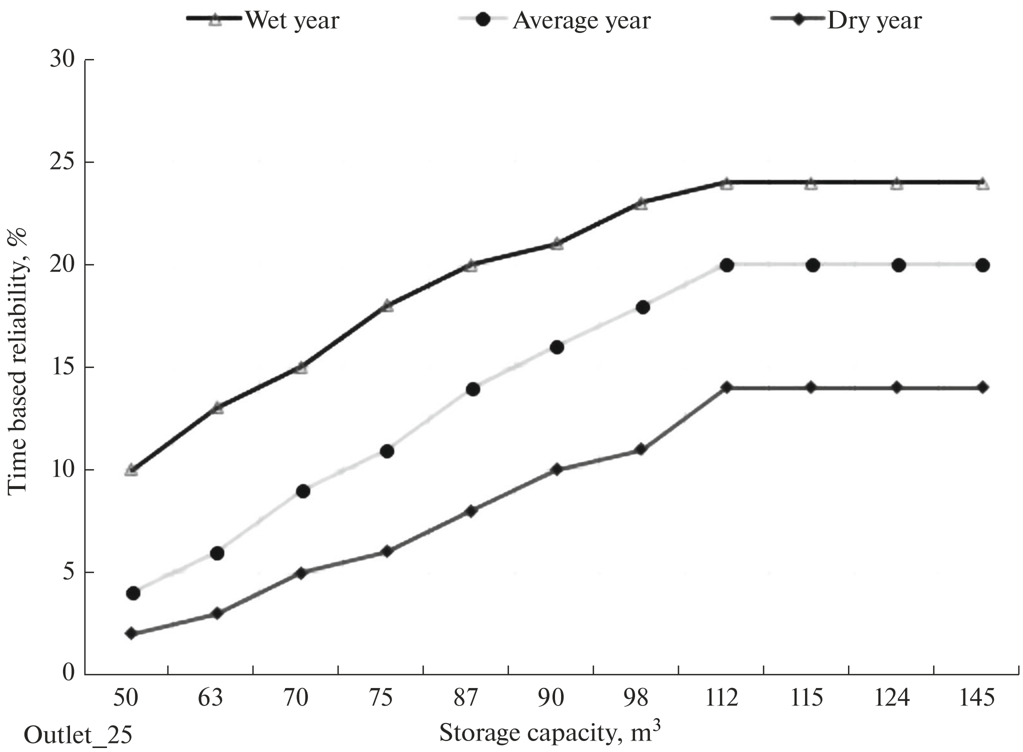

Fig. 2. Time based reliability relationships against storage capacity for different meteorological/climatic scenarios.

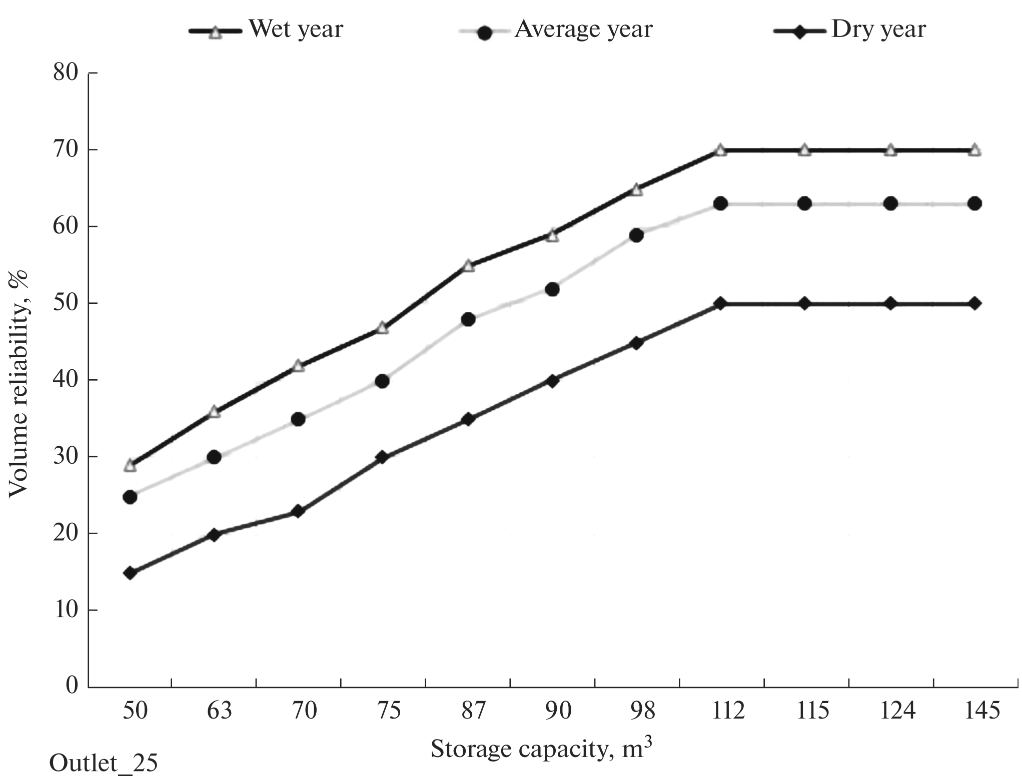

Fig. 3. Volumetric reliability relationships versus storage capacity for different meteorological/climatic scenarios.

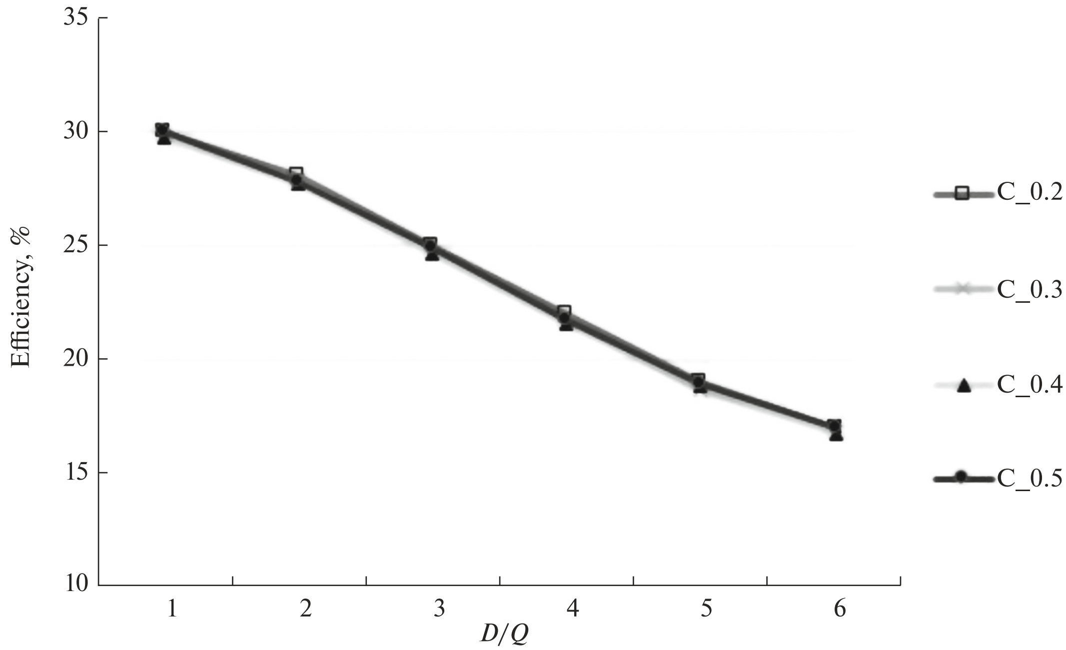

Fig. 4. Water saving efficiency relationships versus demand fraction (D/Q) for different runoff coefficients.

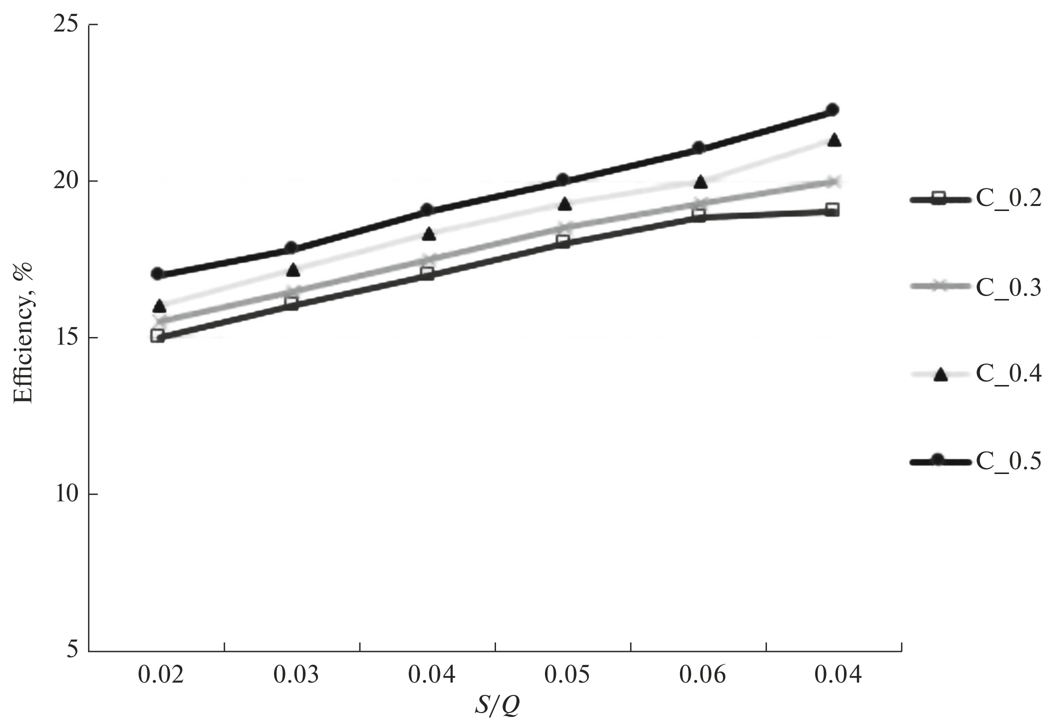

Fig. 5. Water saving efficiency relationships with the storage fraction (S/Q) for different runoff coefficients.

Finally, it is essential to understand reliability because it tells decision-makers and families how many days the rainwater collection scheme can meet their water requirements throughout the year.

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