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Rainwater harvesting in Jordan: a case of Royal Pavilion at Amman Airport

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ABSTRACT

Volumes of rainwater harvested on-site are estimated by short-term storage capacity by two methods: graphical method and analytical method. The first method considers the difference between demand and supply over a specified period of time. The second uses random events to determine analytically, the storage capacity required to guarantee the draft. The comparison between the two methods indicates that there are minor differences. Based on the volume of water harvested after applying these methods, run-off coefficient for impervious surface in arid and semi-arid area was estimated. New analytical approach for long-term storage capacity is utilized to estimate the detention pond capacity off-site for the local natural streams. To apply this method, it is necessary to estimate the overall mean storage capacity in which the soil conservation service method is utilized. This technique is confirmed with graphical method.

Keywords: Rainwater harvesting; Long-term storage; Short-term storage; Mass curve; Random events; Jordan

1. Introduction

Water is one of the most vital requirements for economic and social development. People's survival is compromised when the annual water availability per capita drops below 500 m^3 [1]. In 1948, the average water availability in Jordan was 3,000 m^3 per capita per year. By the late 1990s, it had fallen to 200 m^3. By 2050, it is projected to fall to 90 m^3. This decline resulted mainly from population growth in addition to very limited availability and poor management of water resources. The increasing population continues to place enormous pressure on decision-makers to find new water supplies and develop an updated water conservation policy [2].

Jordan has increasingly faced drought periods, and with the current water privatization the cost of water supplied to such huge institutions is rising annually, and at some point the administration of the Royal Pavilion at the Amman Airport with its growing demand for water will find itself forced to design and implement water harvesting systems. Moreover, having these huge institutions harvest water using systems will result in more water-saving that could be used in other industrial and agricultural areas, eventually enhancing

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This article was originally published with an error in the units in Table 6. This version has been corrected. Please see Corrigendum (DOI: 10.1080/19443994.2013.832023) the development of the Jordanian economy. New building codes considering installments for efficient and suitable rainwater harvesting systems, particularly in areas with feasible annual precipitation, should be adopted.

Rainwater harvesting as defined in this study includes run-off from both rooftops and other catchment surfaces including storm water from roads, parking lots, and other open space areas. Rainwater harvesting is an effective water conservation tool, since it provides "free" water that is not from municipal supply. It is a means to meet the current water needs adequately and sustainably [3]. Water harvesting is the process of concentrating rainfall as run-off from a larger area for use to a smaller target area aiming to capture as much water as possible and store it into a reservoir or soil profile to facilitate using it by human activities such as agriculture. There are many benefits to harvesting rainwater, especially in arid and semi-arid countries like Jordan. Water harvesting not only reduces dependence on groundwater, but also reduces off-site flooding and erosion by holding rainwater on the site. Water harvesting is the process of concentrating rainfall as run-off from a larger area for use in a smaller target area aiming to capture as much water as possible and store it into a reservoir or soil profile to facilitate using it for human activities such as agriculture. It is appropriate for large-scale engineered landscapes such as parks, airports, parking lots, and apartment complexes, as well as small scale residential landscapes. Water harvesting is mostly practiced in the dry areas with 100–300 mm annual rainfall, where crops cannot grow depending only on rainfall.

Prior to establishing rainwater harvesting schemes, it is of utmost important to ensure optimal and sustainable storage and use of this water. Storage tank could be one of the water-harvesting schemes. Storage tank can be located above (surface) or below ground. Storage capacity and storage location are the main factors to be considered in the design of surface storage. Storage capacity is influenced by the accessible run-off volume, its distribution, and the pattern of water withdrawal from it. Storage location is affected by topography, land value, and type of withdrawal [4]. The best catchments, from which water can be harvested, can have hard, smooth surfaces, such as concrete or metal roofing material. The amount of water harvested depends on the size, surface texture, and slope of the catchment area.

In arid and semi-arid areas, rainfalls are unpredictable, sporadic, and intense storms creating high run-off and floods. The floodwater flows to flat and impermeable areas and is mostly lost by evaporation. It is estimated that the volume of water lost in this manner exceeds all the utilized sources of water in the country. Harvesting this water and using it for food and feed production in arid regions is a priority for the country, as well as for many other countries in the Middle East.

All concepts to mitigate water shortage should be applied in Jordan. The research of (Hochstrat et al.) presented a summary of drought planning activities of some water scarce regions. These activities include the intention to combine the various elements of water savings, water reuse, and exploring new water resources [5].

Arid zones are characterized by a low average annual rainfall. However, very high rainfall intensities can occur causing run-off and erosion on the hill slopes. The soil conservation service (SCS) method for determining the unit hydrograph is an easy method that can be used for estimating stream discharge. Developed by the SCS [6] for ungauged streams, this method requires topographic, soil characteristic, and land cover maps of the basin of interest along with precipitation data for a given maximum rain event. Additional requirements such as a reasonable homogenous basin, consisting of several main branches and large storage reservoirs, having a time of concentration (t_c) of less than 0.1 h or greater than 10 h should be entailed.

The SCS method uses the run-off curve number. This number is a function of soil type and land use. The potential abstraction S can be obtained by Eq. (1).

$$S = \frac{1,000}{CN} - 10 \tag{1}$$

where S is the potential abstraction in inches or millimeters and CN is the averaged curve number.

The run-off can be obtained from Eq. (2).

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{2}$$

where Q is the accumulated run-off (rainfall excess) in inches, P is the rainfall depth in inches, and I_a is the initial potential abstraction in inches and approximated by $I_a = 0.2\ S$. Note that I_a includes surface storage, interception, and infiltration prior to run-off.

When the run-off and the time of concentration are known, the maximum discharge using the graphical peak discharge method can be calculated. This is done by first determining the SCS type that best describes the maximum precipitation event in the concerned basin. Fig. 1 shows a graphical representation of the SCS types, with type IA being the least intense, while type III being the most intense. Once the SCS type is determined for the basin, the next step is to calculate the unit peak discharge q_u.

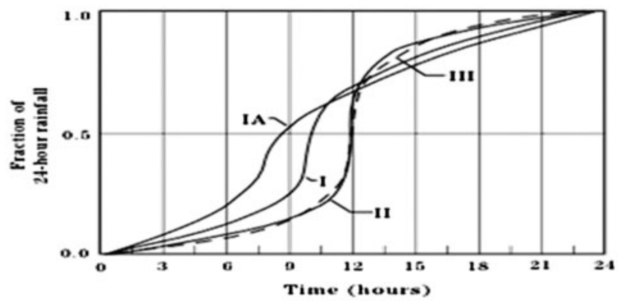

Fig. 1. SCS 24 h rainfall distributions [7].

$$\log(q_u) = C_0 + C_1 \times \log(t_c) + C_2[\log(t_c)]^2 \tag{3}$$

where q_u is the unit peak discharge, t_c is the time of concentration in hours, and C_0, C_1, and C_2 are coefficients.

Swamp and pond adjustment factor F_p depends on a percentage of pond and swamp areas. The value of this coefficient ranges between 0.72 and 1.0.

Once q_u, F_p, Q, and the basin area are found, the peak discharge q_p can be calculated with the following equation:

$$q_p = q_u \times F_p \times Q \times A \tag{4}$$

where q_p is the peak discharge in cfs, q_u is the unit peak discharge, F_p is the pond and swamp adjustment factor, Q is the run-off in inches, and A is the basin area in square miles. Kirpich empirical formula can be used to determine the time of concentration in hours [8].

$$t_c = \left(\frac{0.87L^3}{\Delta H}\right)^{0.385} \times 60 \tag{5}$$

where t_c is the time of concentration in (min) (the time required for water to flow from the most remote point of the basin to the location being analyzed), L denotes the length of the basin area in km measured along the watercourse from the upper end of the watercourse to the farthest point on the drainage area, and ΔH is the difference in elevation between the farthest point on the watersheds to the structure location in (m).

Long-term storage capacity of reservoirs was studied by Hurst et al. [9]. The study was based on the superposition of run-off, rainfall, and temperature (natural phenomena), subject to annual or seasonal variations that might be treated as random events which is subjected to the probability law. On this superposition, Hurst established a mathematical relation that was established between the range of cumulative departures from the mean and the standard deviation for a series of purely random events and he estimated that the storage needed to guarantee a draft less than the mean by the following empirical relations:

$$R = 1.25\sigma\sqrt{N} \tag{6}$$

$$\frac{S}{R} = 0.97 - 0.95\sqrt{\frac{M - B}{\sigma}} \tag{7}$$

where R is the random event, σ is the standard deviation, N is the number of the observations, S is the storage capacity required to guarantee the draft, M is the overall mean, and B is the draft [9].

Fathy [10] proposed a new approach to the problem of long-term storage. He proposed the following relations:

$$\frac{S}{M} = N_d\delta_d - N_d\beta \tag{8}$$

where N_d is the length of the maximum deficit period, M is the mean for that period, and δ_d is the maximum deviation in the sub-ordinate period from the overall mean.

$$\delta d = \frac{a}{N^m} \tag{9}$$

where β is the coefficient which is equal to $(1-B)$, B is the draft, a, and m are empirical coefficients determined analytically.

2. Materials and methods

2.1. Study area

The study area lies in the arid regions of Jordan where the rainfall is scarce and evapotranspiration rates are high. Since the largest need for irrigation water in the target area occurs during the time of lowest rainfall and highest temperature, a rainwater harvesting system should be designed to meet this need via capturing water prior to the summer season.

This research was carried out on the Wadi Sahab watershed. According to the Palestine Grid, the coordinates of the study area are (N 147 to N 125 and E 257 to E 236) with a catchment area of 171 km^2. The main stream length is 31.9 km and the highest and lowest elevation in the catchment are 961 m and 709 m above mean sea level, respectively. The Royal Pavilion at the Amman Airport has a surface area of 375,000 m^2 that includes buildings, service roads, and airport aprons at the southeastern part of Amman. Figs. 2 and 3 show the catchment area for the major natural stream that hit the study area and the plan of the buildings and aprons for the Royal Pavilion Airport.

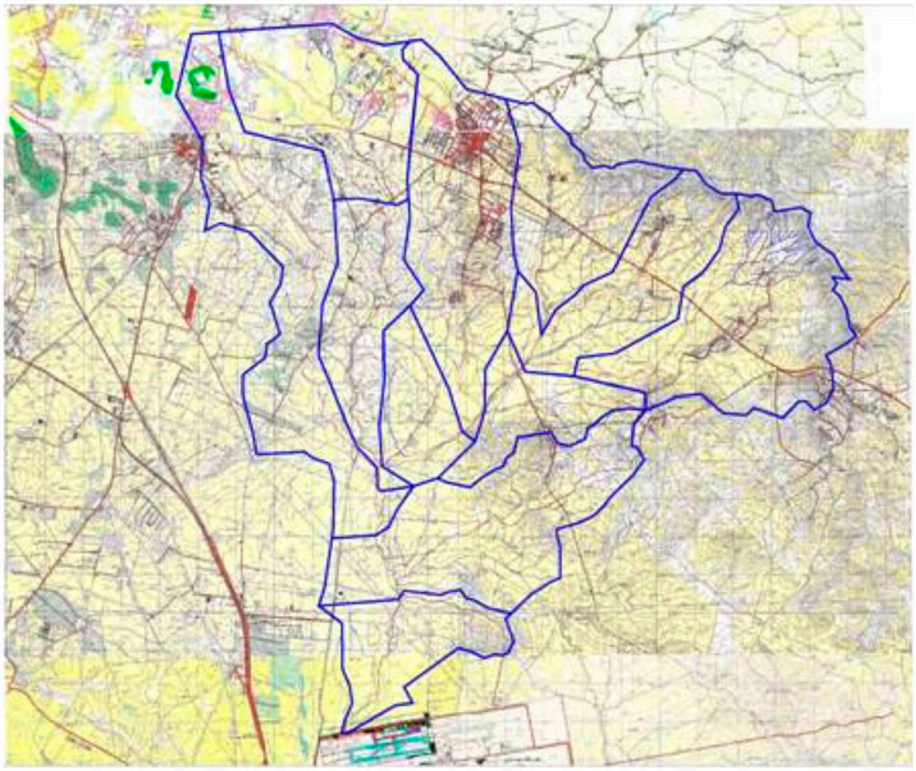

Fig. 2. Catchment of the study area.

2.2. Data available

Daily precipitation data for the targeted area (water years 1976–1980) was obtained from the Zeituna Rainfall Station operated by the Water Authority of Jordan. The water year starts at October and ends at May. The water year 1977/1978 was selected (rainfall is 190.7 mm) as it is approximately around the average annual rainfall for the Zeituna Rainfall Station [11]. The average annual rainfall at the study area is 178 mm, with most of the rainfall concentrated in the winter period and most rainfall events have a short duration with a high intensity.

The annual maximum rainfall depths (mm) for a specified duration for the Zeituna Rainfall Station and intensity duration frequency (IDF) curves are shown in Table 1 and Fig. 4, respectively. The daily rainfall depth for the average water year for the Zeituna Rainfall Station is shown in Fig. 5. The relation between rainfall intensity and time of concentration and return period in years is given by Eq. (10) [12].

$$i_t^T = \left(\frac{106.897 \log 10^{0.480} T^{0.519}}{(t_c + 0.75)^{0.49}} \right) \tag{10}$$

where i is the rainfall intensity, t_c is the time of concentration, and T is the return period in years.

Table 1
Annual maximum rainfall depths (mm) for specified duration for the Zeituna rainfall station

Year	Duration (min)						
	20	30	60	120	180	360	1,440
1968/1969	6.6	9.8	14.6	16.4	18.5	19.9	37.2
1969/1970	4.2	4.4	6.4	7.7	10.1	18.2	30.2
1970/1971	5.0	8.3	9.4	15.3	19.5	34.0	66.0
1971/1972	5.0	7.4	12.4	15.0	15.9	25.7	45.4
1972/1973	2.4	3.4	5.3	9.3	10.8	13.7	22.0
1973/1974	5.9	8.0	10.3	13.5	16.7	22.4	57.4
1974/1975	5.4	7.4	9.8	10.0	12.8	16.5	31.9
1975/1976	2.4	4.8	6.4	8.7	10.5	14.5	26.2
1976/1977	2.2	3.6	4.9	8.3	11.5	15.0	25.6
1977/1978	4.0	5.0	6.6	10.1	11.5	15.5	26.8
1978/1979	2.2	2.8	4.2	7.0	9.4	13.3	24.1
1979/1980	4.2	5.6	7.8	13.8	20.8	37.8	88.9
1980/1981	3.8	4.6	8.0	13.2	15.2	24.4	49.6
1981/1982	5.4	10.3	10.5	10.7	11.3	15.9	27.7
1982/1983	7.0	7.6	10.9	11.9	12.6	17.5	35.5
1983/1984	3.0	4.3	4.3	8.2	10.6	17.9	26.5
CLOSED							
Average	4.3	6.1	8.2	11.2	13.6	20.1	38.8

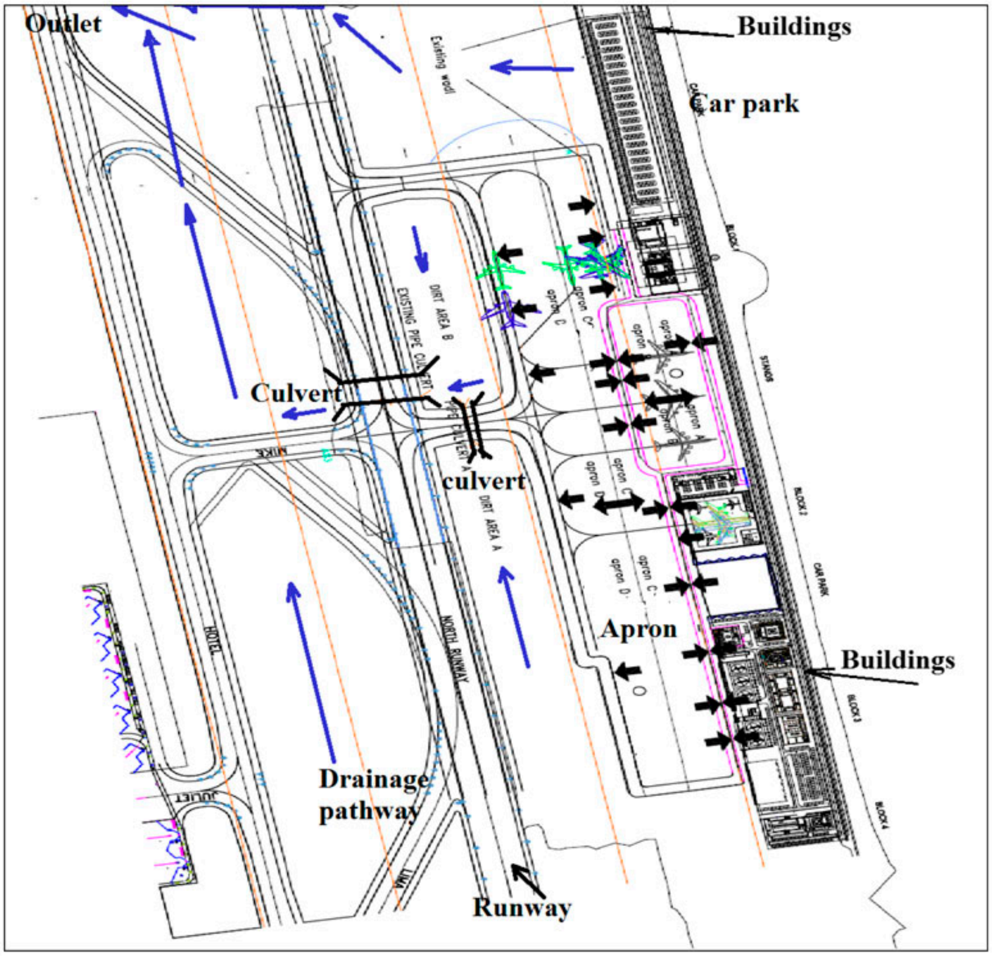

Fig. 3. Plan of the Royal Pavilion at Amman Airport.

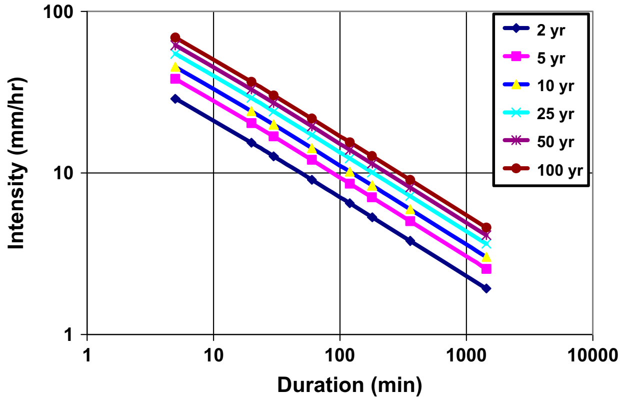

Fig. 4. IDF curves for the Zeituna rainfall station [12].

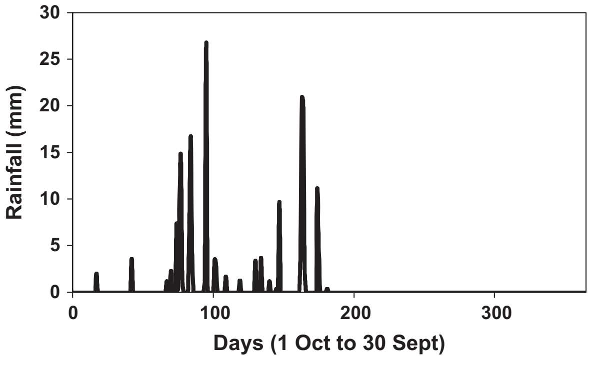

Fig. 5. Daily rainfall depth for the average water year for the Zeituna rainfall station.

3. Results and analysis

3.1. On-site

3.1.1. Mass-curve short-term storage

This method considers the difference between the demand and supply over studied period of time. To find out this difference, cumulative run-off is plotted against time. Cumulative demand is plotted and then superimposed on this graph starting from the peak of the dry period. If more peaks are available, the cumulative demand line may be started from each peak. Maximum difference between the supply and demand over the period of time is the capacity of the harvesting structure. This method maintains two main assumptions:

(1) If 12 months of data are available, the inflow and demands are assumed to repeat in cyclic progression of N-average year cycles; and
(2) The reservoir is assumed to be full at the beginning of a dry season.

The procedure outlines are as follows:

- Yield = catchment area (m^2) × rainfall (m) × run-off coefficient.
- Demand = the demand equation tells you how much water is required for a given landscaped area.
- Demand = monthly average of water supply = sum of water supply divided by 12.
- Reservoir capacity = summation of deficits or summation of surplus.

The calculations for reservoir capacity are shown in Table 2.

Graphically, Fig. 6 shows the accumulation demand and surplus for one water year based on the rainfall records from the Zeituna Rainfall Station. Tank (reservoir) size that could be used to store harvested water equals 36460m^3. Four tanks with dimension of (35 m × 35 m × 7.5 m), with daily consumption of 159 m^3 could be used.

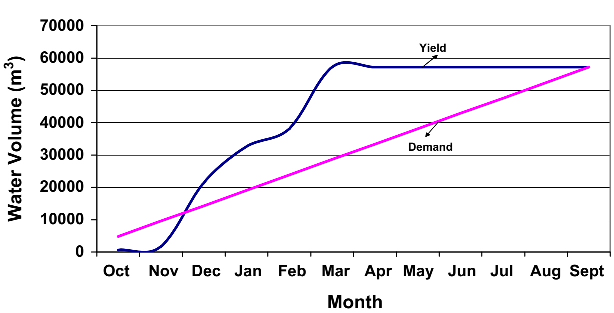

Fig. 6. Short-term storage accumulated demand and surplus.

3.1.2. Analytical method

Hurst [9] suggested using relationships between R, the random events and S, the storage capacity required to guarantee the draft, the overall mean M, and the draft B, and these were previously presented in introduction as:

$$R = 1.25\sigma\sqrt{N} \tag{11}$$

$$\frac{S}{R} = 0.97 - 0.95\sqrt{\frac{M-B}{\sigma}} \tag{12}$$

Random empirical relations (Eqs. 11 and 12) are used to estimate the storage capacity required to guarantee the draft, the results are: $R = 32{,}900$ m^3 and $S = 24{,}900$ m^3. It is assumed that the draft $B = 0.92$ from the overall mean, and (standard deviation = 7601.1, Mean yield $M = 4767.5$, and number of events $N = 12$) which inserted in the relations are obtained from Table 2. Evidently, the numerical term in the random event's relations ought to be unity, if the overall mean flow is equal to the demand ($M = B$) and $S = 32{,}900$ m^3 can be obtained, that should have the same value as R.

3.1.3. On-site retention pond

The potential volume of harvested rainwater can be very easily determined if the average annual rainfall, area of the catchments, and its coefficient of run-off is known. Mathematically it can be written as

$$V = C \times P \times A \tag{13}$$

where V is the volume of rainwater harvested, A is the catchments area contributing run-off, P is the average annual rainfall depth, and C is the coefficient of run-off.

The conversion of rainfall into run-off is inversely dependent on hydraulic conductivity of the surface. Ward and Trimble used run-off coefficient C equal to 0.8 to estimate the water harvesting [13]. The run-off coefficient tells what percent of the rainfall can be harvested from specific surfaces.

If Eq. (12) is applied to find the reservoir volume by inserting the catchment area ($A = 375{,}000$ m^2), average rainfall per year ($p = 178$ mm), and the value 0.8 for C, the volume of rainwater harvested will be equal to 53,400 m^3. This value is much larger than the values

Table 2
Reservoir capacity for water year 1977/1978 for the Zeituna rainfall station

Month	Rainfall (mm)	C	A (m^2)	Yield (m^3)	Demand (m^3)	Yield—demand (m^3)	Note
Oct	2	0.8	375,000	600	4767.5	−4167.5	Deficit
Nov	3.6	0.8	375,000	1,080	4767.5	−3687.5	Deficit
Dec	65.6	0.8	375,000	19,680	4767.5	14912.5	Surplus
Jan	37.5	0.8	375,000	11,250	4767.5	6482.5	Surplus
Feb	18.6	0.8	375,000	5,580	4767.5	812.5	Surplus
Mar	63.4	0.8	375,000	19,020	4767.5	14252.5	Surplus
April	0	0.8	375,000	0	4767.5	−4767.5	Deficit
May	0	0.8	375,000	0	4767.5	−4767.5	Deficit
Jun	0	0.8	375,000	0	4767.5	−4767.5	Deficit
Jul	0	0.8	375,000	0	4767.5	−4767.5	Deficit
Aug	0	0.8	375,000	0	4767.5	−4767.5	Deficit
Sept	0	0.8	375,000	0	4767.5	−4767.5	Deficit
			Mean	4767.5			
			Standard deviation	7601.1			

that are obtained from the previous two methods. This difference is due to the large value used for C, so, it is recommended to use $C = 0.50$ in arid and semi-arid area to estimate the water harvested based on the average rainfall depth. Cooombes developed a model Probabilistic Urban Rainwater and Wastewater Reuse Simulator used for event based on storm water peak discharge calculations [14]. However, this model was not used in this study due to lack of short duration data.

3. 2. Major stream (Off-site discharge)

3.2.1. The SCS curve number method for storm water harvesting

Various run-off models are available in the literature. Each of these models has their own merits and demerits. The SCS curve number method is simple, well acclaimed, and produces better results [15,16].

The SCS curve number method was used to calculate the abstraction from the storm rainfall and the flood volume as follows:

(1) Estimate the value of CN for the catchment area,
(2) Use Eq. (1) to estimate S,
(3) Calculate the initial abstraction via $I_a = 0.2\ S$,
(4) Compute the run-off depth from Eq. (2),
(5) Calculate the unit peak discharge q_u from Eq. (3),
(6) Estimate the adjustment factor F_p (ranges between 0.72 and 1.0 and depends on the percentage of pond and swamp areas), and
(7) Find peak discharge q_p using Eq. (4).

The results of calculations are presented in Table 3 for the average rainfall year of the target area. Note that only three days produce a direct run-off. It is worth mentioning that when P is less than 0.2S the direct run-off should be equal to zero. Table 4 shows the maximum storage capacity for maximum rainfall depth for the period 1969 to 1984.

3.2.2. Long-term storage-analytical method

Starting from Eq. (8) that was previously presented in introduction as:

Table 3
Reservoir capacity for water year 1977/1978 for the Zeituna rainfall station

Date	P_{max} (in)	CN	S (in)	I_a (in)	$P–I_a$ (in)	Q (in)	A (mi2)	t_c (h)	C_0	C_1	C_2	log (q_u)	q_u	F_p	q_p cfs	q_p m^3/s	Volume (MCM)
2-Jan	1.06	75	3	0.67	0.39	0.0405	66.05	5.5333	2.235	−0.5039	−0.089	1.8117	64.8	0.75	130.19	3.69	0.176
11-Mar	0.82	75	3	0.67	0.16	0.0070	66.05	5.5333	2.235	−0.5039	−0.089	1.8117	64.8	0.75	22.443	0.64	0.030
12-Mar	0.80	75	3	0.67	0.13	0.0051	66.05	5.5333	2.235	−0.5039	−0.089	1.8117	64.8	0.75	16.277	0.46	0.022

Table 4
Reservoir capacity for maximum rainfall depth for the Zeituna rainfall station

Date	P_{max} (in)	CN	S (in)	I_a (in)	$P-I_a$ (in)	Q(in) (in)	A (mi^2)	t_c (h)	C_0	C_1	C_2	log (q_u)	Q_u	F_P	q_P cfs	q_i m^3/s	Volume (MCM)
1968/1969	1.46	75	3.3	0.67	0.8	0.1541	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	494.8	14.0	0.669
1969/1970	1.19	75	3.3	0.67	0.5	0.0708	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	227.2	6.4	0.307
1970/1971	2.60	75	3.3	0.67	1.9	0.7088	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	2275.9	64.4	3.078
1971/1972	1.79	75	3.3	0.67	1.1	0.2820	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	905.5	25.6	1.225
1972/1973	0.87	75	3.3	0.67	0.2	0.0113	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	36.2	1.0	0.049
1973/1974	2.26	75	3.3	0.67	1.6	0.5152	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	1654.4	46.8	2.238
1974/1975	1.26	75	3.3	0.67	0.6	0.0885	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	284.2	8.0	0.384
1975/1976	1.03	75	3.3	0.67	0.4	0.0360	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	115.6	3.3	0.156
1976/1977	1.01	75	3.3	0.67	0.3	0.0317	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	101.7	2.9	0.138
1977/1978	1.06	75	3.3	0.67	0.4	0.0405	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	130.2	3.7	0.176
1978/1979	0.95	75	3.3	0.67	0.3	0.0220	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	70.7	2.0	0.096
1979/1980	3.50	75	3.3	0.67	2.8	1.3018	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	4180.2	118.4	5.654
1980/1981	1.95	75	3.3	0.67	1.3	0.3581	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	1149.8	32.6	1.555
1981/1982	1.09	75	3.3	0.67	0.4	0.0478	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	153.6	4.3	0.208
1982/1983	1.40	75	3.3	0.67	0.7	0.1315	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	422.2	12.0	0.571
1983/1984	1.04	75	3.3	0.67	0.4	0.0382	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	122.8	3.5	0.166
Avg.	1.53	75	3.3	0.67	0.9	0.1342	66.1	5.53	2.235	−0.5039	−0.089	1.812	64.8	0.75	431.0	12.2	0.583
																Overall mean	1.015

$$\frac{S}{M} = N_d\delta_d - N_d\beta$$

$$\text{for } \frac{S}{M} = \text{maximum}, \frac{d\frac{S}{M}}{dN_d} = 0 \text{ or } \frac{d(aN_d^{1-m} - N_d \times \beta)}{dN_d} = 0$$

$$(1 - m) \times a \times N_d^{-m} - \beta = 0 \tag{14}$$

in which:

$$\frac{S}{M} = N_d \times \frac{a}{N_d^m} - N_d \times \beta \tag{15}$$

The reservoir capacity is 1.015 MCM for maximum storage capacity using overall mean (Table 4). Value of δ can be determined from the maximum deficit for 4 and 8 years (Table 5) and the reservoir capacity as follows:

$$\delta = \frac{0.874}{1.015} = 0.86 = \frac{a}{N^m} \text{ For 4 years} \tag{16}$$

$$\delta = \frac{0.457}{1.015} = 0.45 = \frac{a}{N^m} \text{ For 8 years} \tag{17}$$

The following procedure was followed for determination the storage capacity:

STEP 1:
Solving Eqs. (15) and (16)
You get $m = 0.94$ and $a = 3.16$.

STEP 2:

Table 5
Deviations in the 4-years and 8-years from the overall mean

Mean flow 4 years (MCM)	Mean flow 8 years (MCM)	Deviation 4 years (MCM)	Deviation 8 years (MCM)
1.320	1.013	0.305	−0.002
1.165	0.947	0.150	−0.068
1.647	0.931	0.633	−0.084
0.974	0.558	−0.041	−0.457
0.707	1.111	−0.308	0.096
0.729	1.300	−0.286	0.285
0.214	1.046	−0.801	0.031
0.141	1.069	−0.874	0.054
1.516	1.070	0.501	0.056
1.870	1.126	0.855	0.111
1.878	Non	0.863	Non
1.997	Non	0.982	Non
0.625	Non	−0.390	Non
0.382	Non	−0.633	Non

Table 6
Reservoir capacity for long-term storage for the Zeituna rainfall station

Date	Yield (Mm^3)	Demand (Mm^3)	Yield—demand (Mm^3)	Note
1968/1969	0.669	0.93334	−0.26434	Deficit
1969/1970	0.307	0.93334	−0.62634	Deficit
1970/1971	3.078	0.93334	2.14466	Surplus
1971/1972	1.225	0.93334	0.29166	Surplus
1972/1973	0.049	0.93334	−0.88434	Deficit
1973/1974	2.235	0.93334	1.30166	Surplus
1974/1975	0.384	0.93334	−0.54934	Deficit
1975/1976	0.156	0.93334	−0.77734	Deficit
1976/1977	0.138	0.93334	−0.79534	Deficit
1977/1978	0.176	0.93334	−0.75734	Deficit
1978/1979	0.096	0.93334	−0.83734	Deficit
1979/1980	5.654	0.93334	4.72066	Surplus
1980/1981	1.555	0.93334	0.62166	Surplus
1981/1982	0.205	0.93334	−0.72834	Deficit
1982/1983	0.571	0.93334	−0.36234	Deficit
1983/1984	0.166	0.93334	−0.76734	Deficit

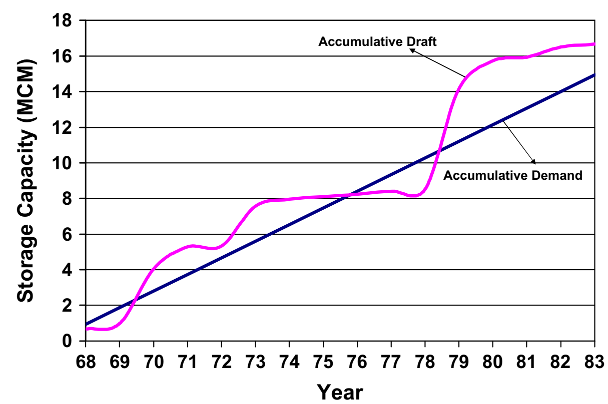

Fig. 7. Long-term storage accumulated demand and surplus.

Assume $\beta = 0.08$ where β is the coefficient which is equal to $(1-B)$, where B is the draft.

STEP 3:
Substitute (m and a) in Eq. (13) to get $N_d = 2.5$ years for $\beta = 0.08$.

STEP 4:
Apply Eq. (14) to find $\frac{S}{M} = 3.138$ and compute the storage capacity $S = 3.18$ MCM, where M is the mean for that period = 1.015 (Table 4).

This method is compared with the results from mass curve for a long period as shown in Table 6 and Fig. 7 which was 3.7 MCM.

4. Discussion

In this research, different methods were utilized to compute the amount of the harvested water. These methods use both short-term and long-term storage. For the short-term storage, the analytical method for random event can be used to estimate the storage capacity, and the result obtained by this method is close to the mass curve graphical method. It is recommended to use run-off coefficient equals to 0.50 in arid and semi-arid area to estimate the rainwater harvested based on the average rainfall depth.

The new approach is derived to estimate the storage capacity for long-term storage and when compared with other techniques, the analytical method for this approach can be utilized to estimate the volume of rainwater harvested for natural streams. The results show that it is vital to harvest rainwater in Jordan; the fourth poorest country in the world in terms of water resources. The main finding drawn from the research is that the potential volume for water harvested in the targeted area is around 3 MCM for the main stream considering the mean deviations for 25 and 50% of the number of events from the overall mean of the available data-set.

5. Conclusions

Due to rapid development, Jordan should rely on the desalination of sea water to satisfy its need for distilled water. Harvesting of rainwater is an additional valuable water resource supply, which should be assessed for its viability. The problem of rainwater in arid zones is considered one of low annual rainfall rates with a non-uniform distribution of rainfall throughout the year. Jordan, as in other arid countries experiences sudden heavy rainfall for short-hour durations as shown in Table 1.

Dirt, debris, and other materials from the roof surface of the pavilion may contaminate the rainwater. The best strategy to use this water is to filter and screen out the contaminants *before* they enter the reservoirs. For potable purposes water should pass through an inline purification system. It is highly recommended to present the requirements for first flush devices to divert the highly polluted initial portion of roof run-off [17]. It shall be noted that harvested rainwater captured from roof tops provided water of acceptable quality for non-drinking purposes and did not pose any health hazards.

Remote areas in Jordan could be benefited from rainwater harvesting which reflected positively on other sectors that contributed in increasing livestock, reducing groundwater depletion, increasing sources of fresh water, mitigating drought, and increasing groundwater recharge. It is evident that rainwater harvesting is one of the promising potential approaches to increase water availability in Jordan. Therefore, promotion of water harvesting should be acknowledged by governmental institutions and become an integral part of water development policies.

Symbols

a and m	—	empirical coefficients determined analytically
A	—	the basin area in (mi^2, km^2)
B	—	draft
C_0, C_1, and C_2	—	coefficients
CN	—	curve number
F_p	—	swamp and pond adjustment factor
i	—	rainfall intensity (mm/hr, in/hr)
I_a	—	initial potential abstraction in inches
L	—	length of the basin area in (mi, km)
M	—	overall mean
N	—	number of the observations
N_d	—	length of the maximum deficit period in years
P	—	rainfall depth in inches
Q	—	accumulated run-off (rainfall excess) in inches
q_u	—	unit peak discharge
R	—	random event
S	—	storage capacity required to guarantee the draft
T	—	return period in years
t_c	—	time of concentration (min)
V	—	volume of rainwater harvested (m^3)
ΔH	—	difference in elevation in (m)
β	—	coefficient which is equal to $(1-B)$
δ_d	—	maximum deviation from the overall mean
σ	—	standard deviation

Abbreviations

SCS	—	Soil Conservation Service
USDA	—	United States Department of Agriculture

References

[1] J.F. Brennan, The China, India, Pakistan water crises: Prospects for interstate conflict, Naval postgraduate school Monterey, California, unpublished thesis, 2008.

[2] D. Hummel, The interaction of population dynamics and transformations in water supply systems in the Jordan River Basin, in: F. Zereini, H. Hötzl (Eds.), Climae Changes and Water Resources in the Middle East and North Africa, Berlin, 2008.

[3] J. Baca, L. Blair, J. Stomp, J. Witherspoon M. Brasher, A. Armijo, B. Winter, T. Kline, H. Yntema, M. McEntee, G. Payne, M. Brasher, Rainfall harvesting: Supply from the sky, Publication of the city of Albuquerque, 1995. Available from http://www.cabq.gov/resources

[4] M.J. Khanjani, J.R. Busch, Optimal irrigation water use from probability and cost-benefit analyses, Trans. ASAE 25(4) (1982) 961–965.

[5] R. Hochstrat, T. Wintgens, C. Kazner, T. Melinb, J. Gebel, Options for water scarcity and drought management—The role of desalination, Desalin. Water Treat. 18 (2010) 96–102.

[6] Soil Conservation Service (SCS), National Engineering Handbook, Section 4, Hydrology, US Department of Agriculture, Washington, DC, 1972.

[7] USDA, Hydrology for Small Watersheds United States Department of Agriculture, Natural Resources Conservation Service, Engineering Division, Technical Release 55, 1988.

[8] Z.P. Kirpich, Time of concentration of small agricultural watersheds. Civil Eng. 30(6) (1940) 361.

[9] H.E. Hurst, R.P. Black, Y.M. Simaika, Long-term Storage and Experimental Study, Constable, Central London, 1965.

[10] A. Fathy, River Hydraulics and Long-term Storage, Professional Notes, Faculty of Engineering, University of Alexandria, Alexandria, 1955.

[11] Technical Paper No. 50, Water Year. Rainfall in Jordan, Water Authority Resources Department, Surface Water Division, 1976–1980.

[12] N. Hadadin, Rainfall intensity duration—frequency relationship in the Mujib Basin in Jordan, J. Appl. Sci. 8(10) (2005) 1777–1784.

[13] A.D. Ward, S.W. Trimble, Environmental Hydrology, 2nd ed., CRC Press, New York, 2004.

[14] P. Coombes, On-site Water Balance Modeling using PURRS, Workshop on Rainwater Tank and Wastewater Reuse Modelling - Key Elements in Water Cycle Analysis and Sustainable Development, Melbourne, Australia, June 19–20, 2003.

[15] M.M. Stuebe, D.M. Johnston, Runoff volume estimation using GIS techniques, Water Resour. Bull. 26(4) (1990) 611–620.

[16] R.K. Sahu, S.K. Mishra, T. I. Eldho, M.K. Jain, An advanced soil moisture accounting procedure for SCS curve number method, Hydrol. Process. 21 (2007) 2872–2881.

[17] N.S. Miguntanna, P. Egodawatta, A. Goonetilleke, Pollutant characteristics on roof surfaces for evaluation as a stormwater harvesting catchment, Desalin. Water Treat. 19 (2010) 205–211.