Statistical analysis of flash flood events for designing water harvesting systems in an extremely arid environment

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Abstract

A water harvesting system for research purposes has been established in the Lisan Peninsula of the Dead Sea in the middle of the Jordan Rift Valley, where no authorized guideline is available for designing water harvesting systems. Rainfall and runoff, which occurs as flash floods, are being observed at the downstream end of a gorge having a 1.12 km^2 barren catchment area since September 30, 2014. Due to the extremely arid environment, water current as the runoff from the catchment is ephemeral, and the flash flood events can be clearly distinguishable from each other. Thirteen flash flood events with total runoff volume more than 100 m^3 have been successfully recorded during five rainy seasons. The duration, the total rainfall depths at two points, the total runoff volume, the maximum runoff discharge, and the bulk runoff coefficient of each flash flood event are considered as the random variables to be analyzed. Correlation analysis among the variables is conducted in terms of the classical methods of Pearson's correlation and Spearman's rank correlation, revealing that there is no straightforward relationship between rainfall and runoff. The performance of the conventional SCS runoff curve number method is also deficient in reproducing any rainfall-runoff relationship. Therefore, probability distributions are fitted to the empirical distribution of each variable. The lognormal distribution with three parameters and the generalized extreme value distribution serve well. The results support the design of the water harvesting system and provide quantitative information for designing similar systems in the future.

KEYWORDS

Jordan Rift Valley; Water harvesting; Flash flood; Statistical analysis; Probability distribution;

1. INTRODUCTION

The Jordan Rift Valley (JRV) refers to the depression below the sea level extending over the range of latitudes 30-33 N and longitudes 35-36 E, including Lake Tiberias to the north and the Dead Sea in the middle, surrounded by Jordanian Highlands and Judaean Mountains. Due to the arid environment as compared with the other parts of Jordan, as mentioned in Tarawneh and Kadıoğlu (2003), the management of irrigation water is vital in JRV (Al-Weshah 2000). However, available data of precipitation and streamflows in JRV are limited to monthly resolution, significantly hindering efficiency in modeling with widely used hydrological methodologies (Rumman et al. 2009). An innovative water harvesting (WH) system has been established for research purposes in the Lisan Peninsula of the Dead Sea (Unami et al. 2015). The geology of the Lisan Peninsula is detailed in Closson et al. (2007). A barren catchment area of = 1.12 km^2, as shown in Figure 1, yields flash floods several times a year, and hydraulic structures have been constructed at the outlet to harvest them as designed in Sharifi et al. (2015). The water current is fully collected at a gutter cutting across a 16 m wide valley bottom and then guided to an open-air reservoir of 1,000 m^3 capacity through a conveyance channel of 60 m long (Unami and Mohawesh 2018). The conveyance channel is equipped with a spillway to release excess backwater from the reservoir. As there is no authorized guideline in Jordan, an arbitrary flood discharge of 1,000 L/s is used in the hydraulic design of the spillway. A solar-driven desalination plant, having a blackish water reservoir of 300 m^3 capacity in a modified greenhouse, treats the harvested water to be used for irrigation (Unami et al. 2020), and year-round farming is performed under optimal water management policy (Unami et al. 2019). The available lands somewhat constrain the capacities of the reservoirs, but the open-air reservoir is large enough to buffer the brackish water to be sent to the desalination plant after siltation. An observation system is operating since September 30, 2014, so that time series data of rainfall and runoff in flash flood events are minutely acquired (Figure 2). Due to the extremely arid environment, water current as the runoff from the catchment is ephemeral, and the flash flood events are clearly distinguishable from each other.

Figure 1. Photo of the gorge in the barren catchment area

Figure 2. Photo of the observation system including VAISALA WXT536 weather transmitter and SR50A acoustic distance sensor for measurement of runoff discharge

This Scientific Briefing presents a statistical analysis of flash flood events observed at the observation system, in order to provide basic knowledge of hydrology in JRV to be utilized for designing WH systems. The duration, the rainfall depth, and the runoff coefficient of each flash flood event are standard hydrological parameters, but the most critical parameters for designing WH systems are the spillway design discharge and the reservoir capacity (Walsh et al. 2014). The correlations among those parameters as random variables are firstly analyzed in terms of the classical methods of Pearson's correlation (Pearson 1896) and Spearman's rank correlation (Spearman 1910). Then, probability distribution fitting is performed for each variable, focusing on the lognormal distribution with three parameters (LN3) (Levy and Kroll 1976) and the generalized extreme value distribution (GEV) (Jenkinson 1955) in particular. Fundamentals and recent developments in estimating the probability of extreme events from independent observation are presented in Makkonen and Tikanmäki (2019). The results support the design of the WH system, which has been already constructed with arbitrary hydrological parameters, providing quantitative information for designing and operating WH systems in the future as well.

2. METHODOLOGIES

2.1. Data Acquisition

The observation system has been set up over the conveyance channel of m wide rectangular cross-section, at the coordinates 31 15 33.2 N 35 29 20.2 E which falls on the point 2.4 m upstream from the downstream end, operating with a Campbell data logger connected to a VAISALA multi-weather sensor and a Campbell water level sensor. The data logging interval usually is 10 minutes, but it switches to 1 minute if the rainfall depth in the last 10 minutes is equal to or greater than 0.2 mm. If there is no rainfall for 12 hours, then the logging interval returns back to 10 minutes. As a result of the numerical experiment using the finite volume model for the two-dimensional shallow water equations (Unami et al. 2009), a functional relationship between the observed water depth and runoff discharge is determined as

where is the cross-sectional area, and is the hydraulic radius. This formula differs from the standard uniform flow formulae due to the curving alignment and non-uniform channel bed slopes of the conveyance channel. An auxiliary raingauge of a tipping-bucket type is located at the coordinates 31 15 41.2 N 35 29 39.5 E, 566 m apart from the observation system.

2.2. Statistical Methods

Rainfall depths or runoff discharges in prescribed time durations are statistically analyzed in the conventional hydrological studies. However, the statistical analysis here is conducted for the clearly distinguishable flash flood events, considering the duration as another variable. Namely, the duration , the total rainfall depth at the observation system, the total rainfall depth at the auxiliary raingauge, the total runoff volume , the maximum runoff discharge , and the bulk runoff coefficient of each flash flood event are considered as six variables to be analyzed. The duration of a flash flood event is defined as the length of the uninterrupted period, where both rainfall and runoff do not become zero simultaneously. A threshold of the total runoff volumes is set as 100 m^3, and flash flood events yielding less than that threshold are discarded.

Firstly, Pearson's correlation coefficients and Spearman's rank correlation coefficients are calculated for all combinations of the six variables. Then, probability distribution fitting is performed for each variable, using EasyFit software, which deals with 23 types of probability distributions. However, we focus on LN3 and GEV, both of which are well fit to variables taking positive values to represent extreme phenomena like flash floods. The cumulative distribution function (CDF) of the LN3 is given by

with three parameters , , and for the generic random variable , where erf represents the Gauss error function, while that of the GEV is given by

with three parameters , , and for the generic random variable . The Kolmogorov-Smirnov (K-S) test is applied to examining whether each of the six variables fits to each of the two probability distributions or not. The empirical cumulative distribution function (ECDF) for data set$E$ of the observed values of a generic variable, sorted in ascending order, is given by

where is the number of observations in the data set E , and is the indicator function, which is equal to 1 if and equal to 0 otherwise. The K-S statistic for the ECDF of a data sets and a given CDF is calculated as

which must satisfy the inequality

for a criterion , to reject, at a significance level , the null hypothesis that the observed values in the data set are drawn from the given distribution. The criterion solves the equation

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Note that there is a bug in EasyFit software in calculating the K-S statistic , and therefore another program is developed for that purpose using C++ language (Vetterling et al. 1999).

3. RESULTS AND DISCUSSION

3.1. Acquired Data

The rainy season in JRV is from October to May, with torrential rain sometimes causing disastrous flash floods. Table 1 summarizes the primary meteorological data obtained from the observation system, in terms of the rainfall depth (mm) for each month from October 2014 through July 2019, the total rainfall depth for each water year, the monthly and annual maximum, mean, and minimum values of air temperature ().

Table 1. Basic meteorological data of rainfall depth (mm) and air temperature () obtained from the observation system for each water year

		AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	Annua
D (mm)	2014-2015			6.58	10.51	21.11	29.35	21.80	4.30	10.59	0.00	0.00	0.00	104.71
	2015-2016	0.00	1.09	27.47	2.82	6.99	13.09	26.18	10.35	21.81	0.02	0.00	0.16	109.98
	2016-2017	0.00	0.00	3.79	0.47	11.41	4.63	26.27	14.50	1.65	0.37	0.30	0.00	63.39
	2017-2018	0.03	0.04	0.03	1.22	3.65	19.19	25.98	0.17	23.79	4.60	0.89	0.06	79.65
	2018-2019	0.06	0.18	3.60	9.70	1.20	1.53	15.07	29.21	5.8	0.00	0.00	0.00	66.35
T ()	Maximum	46.3	42.7	39.4	33.7	27.7	25.6	30.8	35.3	42.3	45.0	43.8	47.1	47.1
	Mean	34.4	32.5	28.3	22.7	17.8	15.9	18.0	21.6	25.4	29.6	32.1	34.3	26.1
	Minimum	25.9	21.6	17.4	9.1	6.4	4.2	4.5	10.4	12.0	18.3	21.2	23.6	4.2

Thirteen flash flood events with total runoff volume more than the threshold 100 m^3 have been successfully recorded during the five rainy seasons, though the observation system failed to record the other two significant events on April 12, 2015, and on February 22, 2016, due to technical problems. Therefore, the average occurrence of flash flood events is estimated at 3.0 times in a rainy season. The largest event occurred on April 13, 2016, as shown in Figure 3. Table 2 summarizes the date of occurrence, the starting time, the ending time, , , , , , and for each flash flood event.

Figure 3. Photos shot during the flash flood event on April 13, 2016, with an interval of 1 hour

Table 2. Observed rainfall-runoff events with total runoff volume more than 100 m^3

Date	Start	End	T (min)	D^o (mm)	D^a (mm)	V (m^3)	Q_{max} (L/s)	C (%)
12DEC2014	19:15	04:38+	564	13.81	12.0	307.49	66	1.99
11JAN2015	01:15	08:32	390	8.52	10.5	289.23	54	3.03
14JAN2015	22:52	03:18+	267	8.59	8.4	309.39	93	3.22
26OCT2015	08:08	10:42	155	10.28	7.8	593.02	243	5.15
09JAN2016	02:39	04:36	118	6.79	2.7	191.19	141	2.51
13APR2016	15:32	16:40	69	8.47	3.4	917.84	1816	9.68
16FEB2017	10:46	20:34	589	16.97	10.4	323.32	87	1.70
10MAR2017	21:33	01:14+	222	10.85	5.4	316.78	153	2.61
17FEB2018	07:48	09:53	126	6.38	4.4	290.12	169	4.06
26APR2018	16:58	04:55+	718	23.40	14.7	865.60	283	3.30
07FEB2019	05:41	11:27	347	6.00	6.0	174.38	55	2.59
25MAR2019	01:30	03:58	149	8.86	6.0	365.69	263	3.69
25MAR2019	09:59	12:03	125	3.36	3.6	135.90	55	3.61

3.2. Statistical Analysis

Table 3 shows the results of correlation analysis among the six variables in terms of the Pearson's correlation coefficients and the Spearman's rank correlation coefficients. There are moderate correlations among the duration and the total rainfall depths. The maximum discharge is correlated with the total runoff volume and with the bulk runoff coefficient, respectively. Correlation cannot be found in the other combinations of two variables. The difference between the two total rainfall depths in each event implicates spatial variability of rainfall distribution within the catchment area. As the absolute values of the Spearman's rank correlation coefficients are small in general, the six variables are considered independent and separately fitted to probability distributions. The weak correlation between the total rainfall depth at the observation system and the total runoff volume also implies a significant limitation of the conventional SCS runoff curve number method

where with the curve number represents the potential maximum soil moisture retention, and the parameter determines the initial abstraction (Zakaria et al. 2012). Figure 4 compares the observed total runoff depth () for each flash flood event with the estimations by of different and . The sum of the absolute errors, the sum of the square errors, and the maximum absolute error are minimized with = , , and , respectively. With the commonly used value of , those are minimized with = 76.8, 77.1, and 77.1, respectively. The incapability of the SCS runoff method to reproduce the total runoff volumes from the total rainfall depths is evident. To sum, we recommend direct monitoring of runoff discharges rather than rainfall depths.

Table 3. Results of correlation analysis among the six variables

	Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients
	T (min)	D^o (mm)	D^a (mm)	V (m^3)	Q_{max} (L/s)	C (%)

		Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients	Pearson's correlation coefficients
Spearman's rank correlation coefficients	T (min)		0.832758	0.916418	0.154390	-0.325066	-0.510888
	D^o (mm)	0.677849		0.826541	0.547776	-0.023423	-0.202675
	D^a (mm)	0.908907	0.710430		0.286360	-0.294580	-0.379325
	V (m^3)	0.157441	0.672747	0.293120		0.729663	0.691049
	$Q_{\max}$ (L/s)	-0.187542	0.320560	-0.039618	0.788810		0.924509
	C (%)	-0.459906	-0.199702	-0.241241	0.432951	0.614462	

Figure 4. Comparison of the observed total runoff depths with the estimations by the SCS runoff curve number method

Table 4 shows the results of probability distribution fitting. The high values of the significance level indicate that the null hypothesis is difficult to reject in all the cases. Figures 5-10 depict the empirical and the two fitted distributions for each variable. The duration T , the total rainfall depth at the observation system, the total rainfall depth at the auxiliary raingauge, and the bulk runoff coefficient well fit to the LN3. Fitting of to GEV is even better. However, the total runoff volume and the maximum runoff discharge , which determine the two critical parameters of the spillway design discharge and the reservoir capacity, do not fit very well to any of the two distributions though the LN3 for and GEV for are still acceptable. The remarkable concentration of the observed values around 300 (m^3) causes the irregular shape of the empirical distribution of .

Table 4. Results of probability distribution fitting

Distribution	Parameter	T (min)	D^o (mm)	D^a (mm)	V (m^3)	$Q_{\max}$ (L/s)	C (%)
Lognormal with three parameters		5.163	2.209	1.707	5.413	2.750	0.597
		0.91611	0.47110	0.59408	0.78628	5.84680	0.71192
		42.150	0.0091700	0.83274	89.607	54.000	1.2746
		0.14484	0.13983	0.13088	0.21045	0.25118	0.14033
		0.94792	0.96121	0.97915	0.61238	0.38501	0.96000
Generalized extreme value		182.32	7.4580	5.5326	261.92	86.243	2.6380
		138.38	3.1773	3.1142	126.04	54.482	0.84637
		0.19693	0.22196	0.0001940	0.31400	0.73851	0.37855
		0.16722	0.17177	0.11863	0.21369	0.16250	0.15698
		0.86042	0.83772	0.99309	0.59282	0.88238	0.90585

Figure 5. Empirical and fitted probability distributions for the duration

Figure 6. Empirical and fitted probability distributions for the total rainfall depth at the observation system

Figure 7. Empirical and fitted probability distributions for the total rainfall depth at the auxiliary raingauge

Figure 8. Empirical and fitted probability distributions for the total runoff volume

Figure 9. Empirical and fitted probability distributions for the maximum runoff discharge

Figure 10. Empirical and fitted probability distributions for the bulk runoff coefficient

3.3 Verification of the Existing WH System

The arbitrary design parameters of the existing WH system are verified with the results of the hydrological analysis.

We assume a Poisson distribution with a parameter for the number of flash flood events occurring in a rainy season; the probability that flash flood events occur times in a rainy season is equal to . The parameter is equal to the mean as well as to the variance. As presented in subsection 3.1, flash flood events occurred 4, 4, 2, 2, and 3 times in the rainy seasons 2014-2015, 2015-2016, 2016-2017, 2017-2018, and 2018-2019, respectively. The sample mean of these numbers of occurrence is 3.0, and their unbiased sample variance is 1.0. The K-S test to examine their goodness-of-fit to the Poisson distribution with parameter results in the significance level to justify the fitting.

Firstly, the reservoir capacity of the desalination plant, which is 300 m^3, is discussed. The CDF of the fitted LN3 to the total runoff volume is equal to 0.46770 at = 300 m^3. The probability that the reservoir in an empty state cannot be filled up with a single flash flood event in a rainy season is evaluated as = 0.20253 = 1/4.9375, implying that this likely happens once in five years. Indeed, a carry-over operation is implemented in the existing WH system to reduce the risk of shortage in the freshwater from the desalination plant.

Secondly, the maximum runoff discharge is discussed to evaluate the performance of the spillway. The CDF of the fitted GEV to is equal to 0.97063 at the design = 1,000 L/s and to 0.98690 at the historical = 1,816 L/s. The probabilities that the maximum runoff discharge exceeds those in a rainy season are evaluated as = 0.084351 [?] 1/12 and = 0.038546 [?] 1/26, respectively. As there is no substantial human activity in the downstream area of the WH system, that return period of 12 years might be acceptable. The historical event with that = 1,816 L/s on April 13, 2016, did not damage the hydraulic structures and the observation system. On the other hand, the Japanese guideline recommends that the design flood discharges for spillways of WH irrigation dams should be of 200 years return period with the safety factor 1.2 (Rural Development Bureau 2015). The maximum runoff discharge achieving the 200 years return period is estimated at 8,302 L/s, using the fitted GEV. This value implies that, according to the Froude number similitude, the spillway must be $(8{,}3021.2/1{,}000)^{2/5}$ [?] 2.508 times larger than the existing one if based on that guideline.

4. CONCLUSIONS

The hydrological data of flash flood events were obtained from the WH system developed in JRV. The statistical analysis quantified the correlations among the variables and their probability distributions. A strong correlation was not found among the variables, implicating that the spatial rainfall distribution was uneven and that the runoff process was nonlinear and highly stochastic. Researches on those physical phenomena shall be conducted in the follow-up studies, but we recommend direct monitoring of runoff discharges rather than rainfall depths for practical desing of WH systems. Probability distribution fitting was successful with LN3 or GEV, and the design of the WH system was verified. The spillway was designed with a return period of about 12 years but well functioned for the historical flash flood event with a return period of about 26 years. The design of a spillway based on the 200 years return period might be excessive in the context of cost-benefit analysis if the failure of the hydraulic structures would not give rise to significant consequences. The obtained knowledge of hydrology in JRV will be useful for designing and operating WH systems in the future.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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