Determination of Rainfall-Runoff Relationship for Wadi Dayqah Catchment

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Abstract. The aim of this study is to investigate the rainfall-runoff relationship for the Wadi Dayqah catchment, Oman. HEC-GeoHMS software was used to delineate catchment boundaries and to determine the sub-catchment areas and their centroids, while HEC-HMS and Excel sheets were used for event modeling and calibration. Three storm events from eight different rain gauge stations, with one Wadi gauge, were used in the study. Phi-index and Green-Ampt infiltration methods were used to model the losses, while the SCS unit hydrograph method, Snyder (Tulsa) unit hydrograph method, and a derived unit hydrograph were used for modeling the transformation process. The inverse-distance method was used for modeling meteorological processes. The developed models using the standard methods did not give reasonable results. Therefore, an empirical relationship between rainfall and runoff volume was developed. The data showed that there is a reasonable exponential relationship between the rainfall depth and the runoff volume of the Wadi Dayqah Catchment. The new relationship was verified by analyzing two storm events and using the observed water level and volume of water in the reservoir, and good agreement was found between the observed and computed runoff volumes. The results of this study will be useful for reservoir management during storm events.

Keywords: Rainfall-runoff relationship, HEC-GeoHMS, Wadi Dayqah, Hydrologic modeling

Presenter or Main Author Biography: Prof. Sana is a hydraulics, hydrology, and coastal engineering specialist with more than 30 years of teaching, research, and consultancy experience. He has published 50 papers in Scopus-listed international journals, 13 in other journals, and 72 papers in international conferences, including 5 keynote lectures. Currently, he is a professor of Hydraulics and Water Resources Engineering at the PNG University of Technology, Lae, Papua New Guinea.

1. INTRODUCTION

1.1 Flash Flooding in Arid Countries

Oman is an arid country with limited natural water resources. Most of the surface runoffs take place as flash floods passing through ephemeral streams (called *Wadi* in Arabic language). To protect from flooding and utilize the runoff, public authorities in Oman have constructed several dams at suitable locations in the streams. Many of these dams serve to recharge groundwater aquifers or to store water for domestic and agricultural usage. Wadi Dayqah Dam located in Quriyat, Oman, is one of these dams meant for flood protection and storage.

According to the Ministry of Regional Municipalities, Oman (2012) Wadi Dayqah Dam has a storage capacity of approximately 100 million m^3 and a comprehensive potable water supply system to supply the country's capital, Muscat urban area. The system includes a treatment plant and a pump station with several reservoirs. However, the dam experienced several overflow events where the flood water wasted to the sea, especially during heavy rain events like Phet Cyclone in 2010, in addition to losing 2.5 m depth of stored water annually by evaporation (Ministry of Regional Municipalities and Water Resources, 2012). This amount is about 9 million m^3 per year, which is almost equal to 25 percent of the planned supply to Muscat urban area. Figure 1 shows the spillway of Dayqah Dam during Phet Cyclone in 2010.

During the rainfall, especially extreme rainfall events like cyclones, the dam operation team releases the water from the reservoir to provide space for the incoming flood. However, this water release activity is based on the experience of the operation team only and without actual calculations or simulations. Consequently, there is a possibility of wasting precious freshwater during a rainfall event if the amount of water released is overestimated. On the other hand, a risk of flooding is there if the released water is underestimated. Hence, a rainfall-runoff relationship should be established, and based on that, an estimation method should be implemented to determine the amount of water to be released from the reservoir to accommodate the expected flood.

In the present study a rainfall-runoff relationship has been established for Wadi Dayqah watershed. Using the relationship between the volume of water and water surface in the reservoir and rainfall-runoff relationship, a simple Excel sheet is developed that may be used to estimate the amount of water to be released prior to the stormflow reaching the reservoir.

1.2 Study Area

Wadi Dayqah is located in Northern part of Eastern Al Hajar mountains approximately 60 km from Muscat. The wadi passes through Daghmar Village to discharge to the Sea of Oman near Quriyat (Fig. 1). Wadi Dayqah drains a catchment area of about 2,000 km^2. However, the catchment area upstream of the dam is 1,688 km^2 only (Ministry of Regional Municipalities and Water Resources, 2012).

According to the Ministry of Regional Municipalities and Water Resources [1], two dams (main and saddle dams) were constructed on Wadi Dayqah in 2006 and officially opened in 2012. The main dam is built at the main flow stream of the wadi and the saddle dam on the depression to close the gap in the mountains to prevent water from escaping while the water rises in the reservoir. The main characteristics of the dam are shown in Table 1. The levels shown in Table 1 are from the dam foundation, which is at 105 meters above sea level.

Rainfall events mainly occur during January, March, April, and December based on the previous recorded data. Annual rainfall varies extremely between years. Also, the total annual rainfall volume mainly results from high-intensity rainfall events that last for a few hours in a few days, distributed unevenly throughout the year. For example, in 2007, the annual rainfall depth was 371.8 mm, and the daily rainfall of 6th June 2007 was 322.0 mm (about 87% of the annual rainfall in 2007). Similar events used to cause rapid and huge floods. In general, average annual rainfall in this area ranges from 70mm to 150mm as per rainfall records. The average recorded minimum, mean and maximum temperature from 2004 to 2015 in the surrounding meteorological stations in Muscat, Sur and Qalhat were 13.9℃, 28.5℃ and 42.4℃, respectively. The average monthly potential evaporation values of the study area range between 4.58 cm/month and 47.35 cm/month as calculated by Thornthwaite method using the above temperatures.

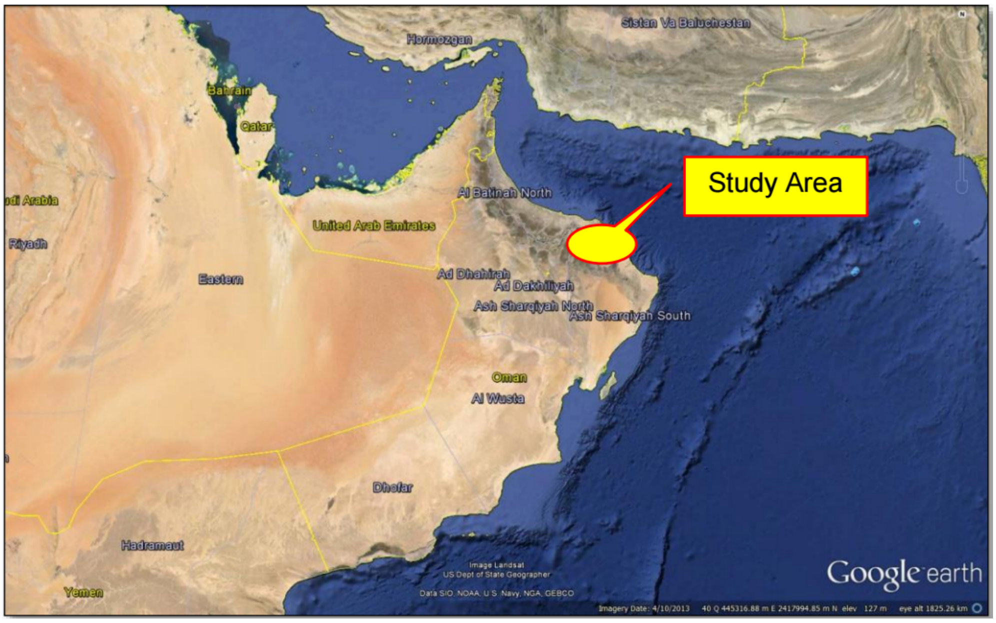

Fig. 1. Location of the study area in Oman (Wadi Dayqah)

Table 1. Wadi Dayqah Dam Characteristics.

Dam characteristic	Dimension
Length (m)	410
Dam height (m)	75.43
Crest width (m)	5
Base width (m)	55.4
Volume of RCC (m^3)	590,000
Design flood (m3)	18,398
Spillway crest length (m)	201.74
Spillway height (m)	67.5
Number of outlets (No.)	11
Outlet diameters (m)	1.0 o 1.60

2. RELEVANT LITERATURE

HEC-HMS is one of the popular software for rainfall-runoff modeling globally. Several studies have utilized this model, a few of them are Yener et al. [2], Han [3], Abushandi [4], Choudhari et al. [5] and Jin et al. [6]. Using other models or methods, some studies have been conducted regarding Oman, dealing with the use of tank model to study rainfall-runoff process (Al-Housni et al. [7]), flash floods (Al-Rawas et al. [8]), development of intensity-duration-frequency (IDF) curves (Chitrakar et al. [9]) and analysis of remote sensing data of rainfall in Oman (Al-Quashi et al. [10]). The studies on rainfall-runoff modeling are scarce in the Arabian Peninsula due to the complexity of the inherent processes in arid zones. The present study will help enhance the understanding of the rainfall-runoff process in the Wadi Dayqah watershed.

3. METHODOLOGY

Here HEC-HMS software is used to simulate watersheds using different data sets. The software offers several methods for processing meteorological data. Additionally, it provides flexibility in simulating storm events, infiltration, runoff, and evaporation processes by allowing the selection of multiple methods for each. The software is capable of using GIS to delineate basins and subbasins from terrain data. The geometric characteristics, like basin areas, centroids, longest flow length, stream slope, and average basin slopes, can be estimated. Additional Basin characteristics like curve numbers can be obtained if land use and soil type data are available in GIS format. The level of accuracy of streams and sub-basins delineations depends on the accuracy of the raw DEM data used in terrain processing.

Terrain data of the Wadi Dayqah Catchment of 5 × 5 meter resolution were obtained from the National Survey Authority (NSA), Oman. These data were used for delineating catchment boundaries and stream flow by the HEC-HMS software. It was found that the total area of Wadi Dayqah Catchment upstream of the wadi gauge is 1873 km^2 as shown in Figure 2. The catchment was divided into 19 sub-catchments, and the centroid of each was determined using the center of gravity method. Rainfall data from 1977 to 2015 of five five-minute time intervals were obtained from public authorities from different rain gauges that are located within or around Wadi Dayqah Catchment. Also, the daily recorded wadi flow rates of the three main wadis, Wadi Dayqah, Wadi Tayein, and Wadi Khabbah were obtained from 1984 to 2011. However, the records of five-minute intervals from Wadi Dayqah gauge were available for March 1997, only. Three distinct rainfall events were selected for the modeling. One of these events is shown in Fig. 3 and Fig. 4.

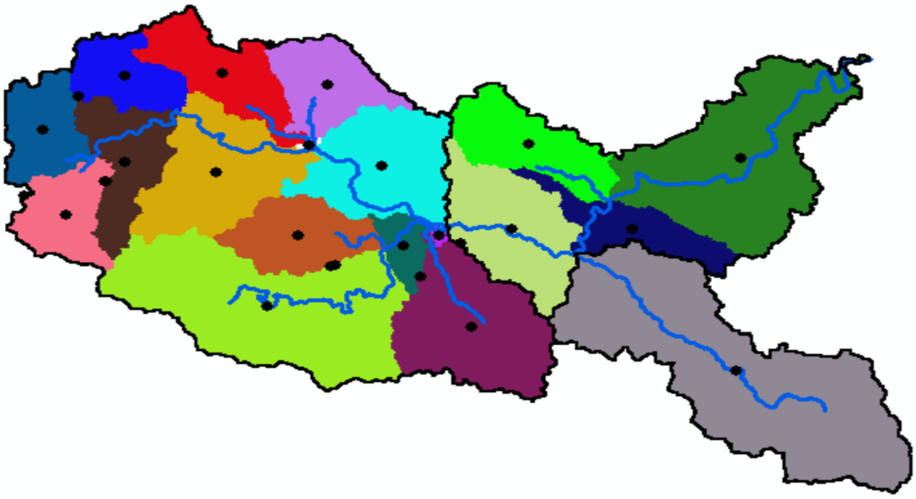

Fig. 2. Subcatchments in Wadi Dayqah Watershed developed using HEC-HMS

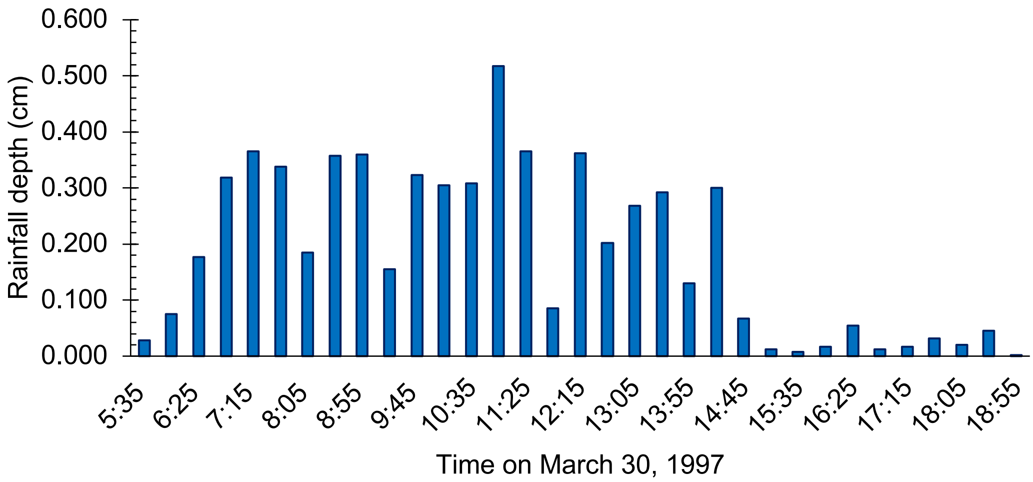

Fig. 3. One of the rainfall events selected for modeling (Event 3).

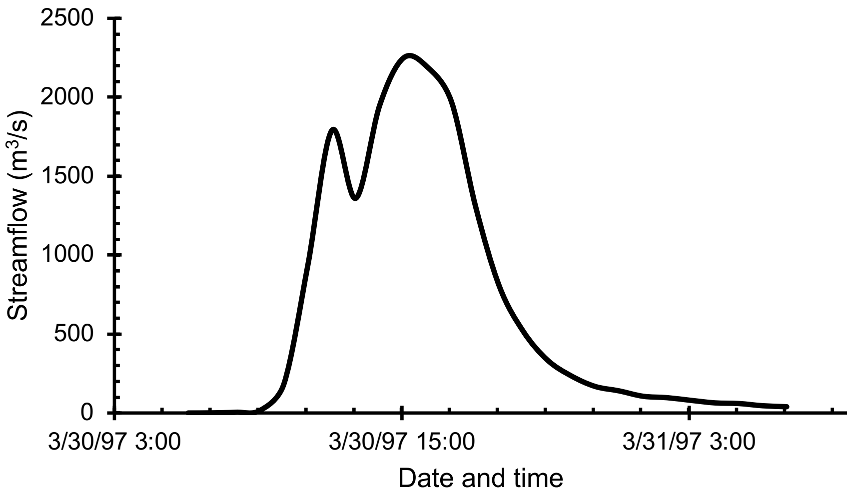

Fig. 4. Streamflow corresponding to Event 3.

In order to establish the rainfall-runoff relationship for Wadi Dayqah Catchment, the following three methods were used: (1) SCS Unit Hydrograph transform method with Green & Ampt loss method (2) Snyder Unit Hydrograph transform method with Green & Ampt loss method, and (3) Unit Hydrograph transform method with a constant (Φ index) loss method. The transform method defines the calculation method of actual surface runoff in each sub-basin, while the loss method defines the calculation method of the actual infiltration process. The evaporation process is ignored in this study, as its impact is minor for a short simulation period. No base flow method was selected as its values were deducted from the wadi observed values before being inserted into the model.

In the UH SCS transform method, the percentage of runoff that occurs before the peak flow is counted by peak rate factor (PRF). For example, the standard SCS UH curve (PRF 484) corresponds to 37.5% of flow occurs before the peak flow. The steeper watersheds typically have higher PRF than flatter watersheds. The peak rate factors for watersheds from flatter to steeper are PRF200 to PRF600, respectively. For Wadi Dayqah Watershed, different PRFs were tried and examined by running the model and comparing the observed and computed runoff hydrographs. It was found that the PRF600 gives the best fit between the hydrographs. Moreover, it was found that the calibrated parameters were affecting the runoff response in the following sequence: percentage imperviousness, lag time, hydraulic conductivity, and then suction head and the saturated content.

4. RESULTS

The summary of the results obtained from the three methods is shown in Table 2. The calibration of the model parameters was done manually in HEC-HMS for Method 1 and Method 2. Whereas, for Method 3 the unit hydrographs were derived from each event. An average UH was then obtained and used to compute the streamflow from the excess rainfall. A reasonable agreement was found between the observed and computed values as depicted by high Nash coefficient values in Table 2.

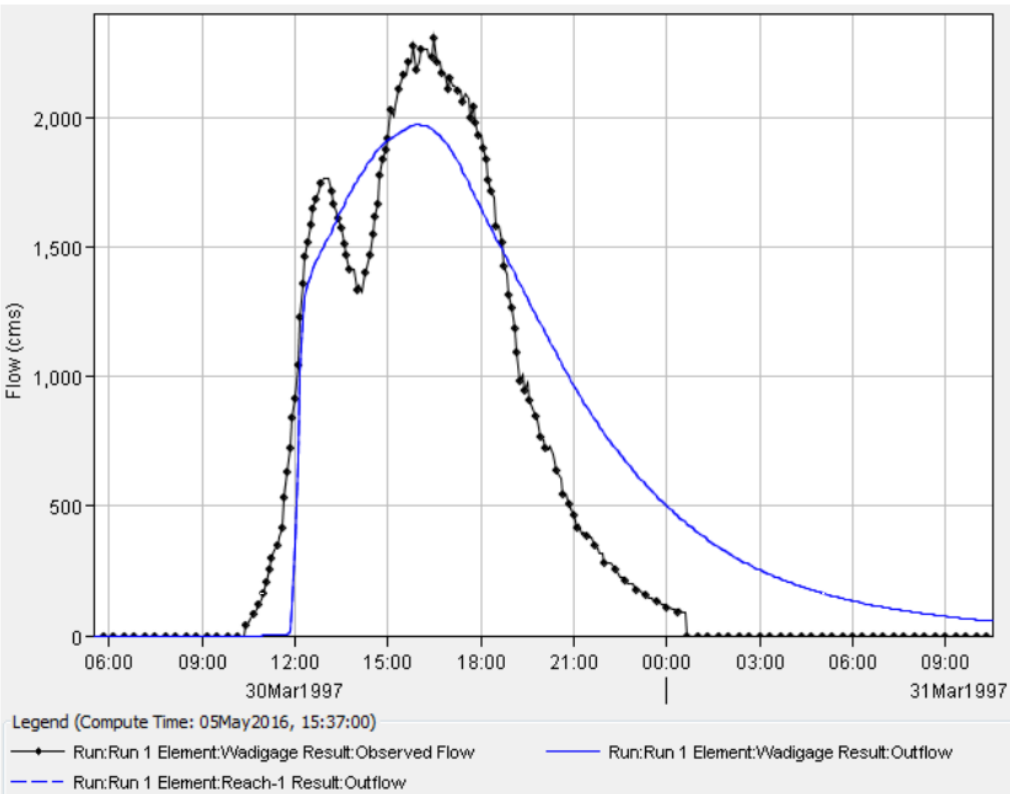

Fig. 5. Streamflow hydrograph from Snyder UH method with Green-Ampt for infiltration (Event 3)

An empirical relationship between the rainfall and runoff volumes was also derived as shown in Eq. (1):

$$\text{Runoff} = 3.4027\exp(0.0412 \times \text{Rainfall depth}) \quad (1)$$

Where Runoff is in million m^3/s and Rainfall depth is in mm.

The relationship between storage volume and water level in the reservoir of Wadi Dayqah Dam was developed using the collected water level and volume data from MRMWR (Eq. 2). The validity of the relationship depends on the accuracy of the field measurements of water level and the contour map of the reservoir area.

$$\Delta = 0.0374h^2 - 9.0958h + 556.02 \quad (2)$$

Where Δ is the water storage volume in million m^3 and h is the water level in meters.

Table 2. Calibrated model parameters and summary of results.

Parameter	Event-1	Event-2	Event-3
SCS Unit Hydrograph Transform Method			
Imperviousness (%)	22.4	22.4	22.4
Lag time (min)	315	370	285
Nash	0.44	0.86	0.43
RMSE	0.46	0.33	0.55
Snyder Unit Hydrograph Transform Method			
Imperviousness (%)	20.0	22.4	52.0
Nash	0.23	0.91	0.88
RMSE	0.53	0.27	0.25
Number of outlets (No.)	11		
Outlet diameters (m)	1.00 to 1.60		
Unit Hydrograph Transform Method with Φ index			
Nash	0.87	0.79	0.80

Equation (1) was validated using two rainfall events (Nov. 2 and Nov. 9, 2011) for which the water surface elevation in the Wadi Dayqah reservoir was available. Using the observed water surface elevation the volume of runoff was calculated from Eq. (2). A comparison between Eq. (1) and the data from the rainfall events in 2011 is shown in Fig. 6.

An excellent agreement is found between Eq. (1) and the observed runoff volume, which shows the validity of Eq. (1). However, more observations are required to prove the validity of the equation for a wide range of rainfall depths.

Both Eq. (1) and Eq. (2) were used to develop a simple Excel sheet to determine the amount of water to be released from the reservoir before a storm to ensure the safety of the dam.

5. CONCLUSIONS

For a proper operation of the Wadi Dayqah Dam a hydrologic study is carried out using HEC-HMS model to establish a rainfall-runoff relationship. Three different methods were utilized and varying performance of the estimations was observed. Finally, an empirical relationship between rainfall depth and runoff volume was developed using the available data and validated using another set of data. This relationship along with the existing empirical relationship between the water surface elevation in the reservoir and the volume of water in the reservoir, will be used to release an appropriate amount of water to make room for incoming stormwater. The biggest challenge is the availability of recent data on hydrologic parameters. More data is required to validate the methods proposed in this study.

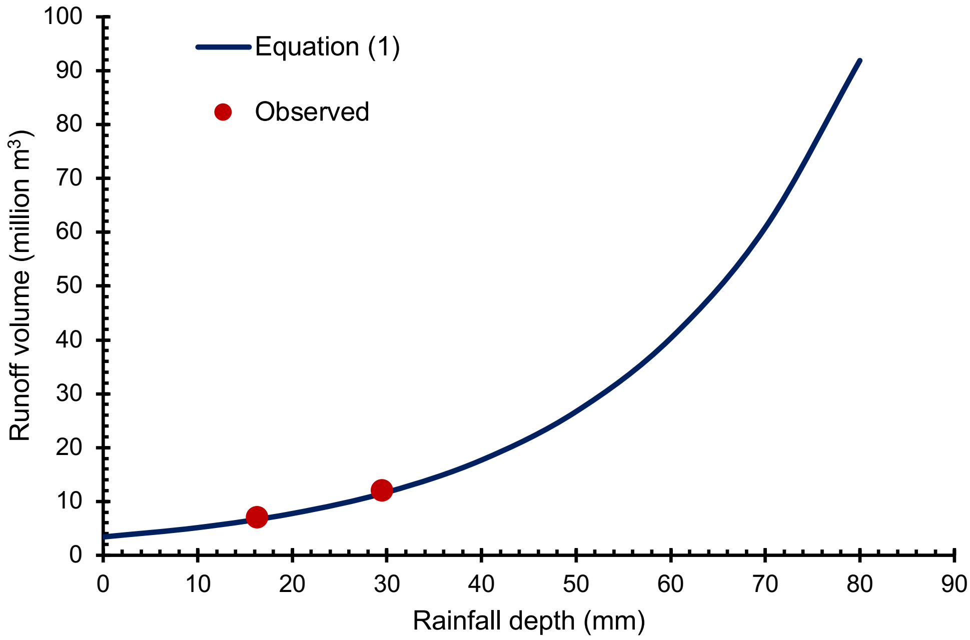

Fig. 6. Empirical Rainfall-Runoff relationship (Eq. 1)

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