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Spatial regression approach to estimate synthetic unit hydrograph by geomorphic characteristics of watersheds in arid regions (Postprint)

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Abstract

Rainfall-runoff relationship in arid regions is unique and challenging to study. Studies for bridging the hydro-meteorological knowledge gap for planning, designing and managing water resources is therefore vitally important. The objective of this study is to develop a method for estimating unit hydrograph at reasonably finer time resolutions (10-min and 1-h) which can be easily adaptable by practitioners at sub-catchment levels, especially when the focus area is ungauged. Observed wadi-flow at 5-min interval and tipping bucket rainfall measurements at 1-min interval were obtained to cover 10 major watersheds in Oman. The deconvolution method was applied to derive the unit hydrographs (UHs) from wadi-flow and excess rainfall. Key catchment characteristics such as the watershed area, length of the main wadi and the length to the centroid of the catchment area were derived from digital elevation model (DEM) data. The whole study area was then divided into 515 sub-catchments with various shapes and sizes. A strong relationship was found between the wadi length and the length to the centroid of the catchment area (R2>0.89). This relationship was then adopted to simplify the classical Snyder method to determine UHs. Moreover, several parameters of the Snyder method were calibrated to the arid environment by matching the peak-flow, lag-time and three time-widths (75%, 50% and 30% of the peak-flow) of 10-min and 1-h UHs with physical characteristics of the watersheds. All developed relationships were validated with independent rainfall and wadi-flow events. Results indicate that the calibrated parameters in these arid watersheds are quite distinct from those suggested for other regions of the world. A marked difference was found between the 10-min UHs estimated by the S-hydrograph method and the deconvolution method. Therefore, it is concluded that a method depends on natural hydro-meteorological conditions would be more practical in arid region. The proposed methodology can be

used for water resources management in arid regions having similar climate and geographical settings.

Full Text

Spatial Regression Approach to Estimate Synthetic Unit Hydrograph by Geomorphic Characteristics of Watersheds in Arid Regions

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Abstract

The rainfall-runoff relationship in arid regions is unique and challenging to study, making research to bridge the hydro-meteorological knowledge gap vitally important for planning, designing, and managing water resources. The objective of this study is to develop a method for estimating unit hydrographs at reasonably fine time resolutions (10-min and 1-h) that can be easily adapted by practitioners at sub-catchment levels, especially for ungauged areas. Observed wadi-flow at 5-min intervals and tipping bucket rainfall measurements at 1-min intervals were obtained for 10 major watersheds in Oman. The deconvolution method was applied to derive unit hydrographs (UHs) from wadi-flow and excess rainfall. Key catchment characteristics such as watershed area, length of the main wadi, and the length to the centroid of the catchment area were derived from digital elevation model (DEM) data. The entire study area was then divided into 515 sub-catchments with various shapes and sizes. A strong relationship was found between the wadi length and the length to the centroid of the catchment area ($R^2 > 0.89$), which was adopted to simplify the classical Snyder method for determining UHs.

Moreover, several parameters of the Snyder method were calibrated to the arid environment by matching the peak-flow, lag-time, and three time-widths (75%, 50%, and 30% of the peak-flow) of 10-min and 1-h UHs with physical characteristics of the watersheds. All developed relationships were validated with independent rainfall and wadi-flow events. Results indicate that the calibrated parameters in these arid watersheds are quite distinct from those suggested for other regions worldwide. A marked difference was found between the 10-min UHs estimated by the S-hydrograph method and the deconvolution method. Therefore, it is concluded that a method dependent on natural hydro-meteorological conditions would be more practical in arid regions. The proposed methodology can be used for water resources management in arid regions with similar climate and geographical settings.

Keywords: deconvolution method; S-hydrograph method; Snyder method; DEM data; river length

1 Introduction

Floods are perhaps the most concerning natural phenomenon in arid regions, proving to have both positive and negative impacts. Moderate floods that spread over large areas and are regulated by wide-opened channels, successive dikes, and retention basins can significantly replenish groundwater aquifers (Abdalla et al., 2013, 2014; Mayaud et al., 2019). Young et al. (2004) discovered freshwater lenses in Central Oman shallow aquifers claimed to be formed by recharge water from infrequent cyclonic rainfall. In contrast, flash floods are rare but potentially catastrophic hazards in many parts of the world (Badrzadeh et al., 2015; Ahmadalipour and Moradkhani, 2019), including arid regions. For example, Cyclone Gonu in 2007 is considered the worst natural disaster in recorded Omani history, causing approximately 4.6 billion USD in damage and 69 deaths.

Flash floods are affected by various hydro-meteorological characteristics, most notably triggered by extremely heavy rainfall but also intensified by steep slopes, poor vegetation cover, soils with low permeability, and ephemeral streams (locally known as wadi) attributed to long dry periods (Ghoneim and Foody, 2013; Parsons, 2018). Damages caused by flash floods are exacerbated as population growth and assets progressively expand in flood-prone areas (Hering et al., 2004; Kazama et al., 2009; Merz et al., 2010). Most areas categorized as arid climate zones in the Middle East receive annual total rainfall of less than 130 mm with occasional high-intensity, short-duration storms that can cause river flows to rise from zero to peak within a few minutes to a few hours (Greenbaum et al., 1998).

In addition to difficulties arising from lack of gauging stations, river-flow simulation in arid regions presents unique challenges due to the rare occurrence of rainfall events and their greater spatial variability (Pilgrim et al., 1988). In response to these issues, hydro-meteorological data networks have been expanded and updated in various countries (Sen, 2008). Consequently, many large watersheds in Oman have been equipped with river-gauge stations at their outlets, providing an important opportunity to understand complex rainfall-runoff relationships in arid regions and eventually enhance water management and adaptation measures. Owing to population growth and industrialization, urbanization gradually expands from coastal valley areas to upstream catchment areas in Oman. Planning and designing various infrastructures such as roads, bridges, culverts, and recharge dams warrant wadi-flow data, which are not yet available for many small and medium-scale watersheds.

Traditional runoff simulation methods such as Sherman' s unit hydrograph (UH) technique (Sherman, 1932) and Tank model (Sugawara, 1995) use concurrent rainfall and wadi-flow data to develop complete flood hydrographs at the catchment outlet resulting from arbitrary storms. In the absence of river-flow and rainfall data in ungauged catchments, synthetic UH methods are widely used for hydrologic/hydraulic designs (Bhuyan et al., 2015; Tomirotti and Mignosa, 2017). As explained by Chow et al. (1988), there are three types of synthetic unit hydrographs: (1) those using geomorphological properties of the watershed to develop theoretical or empirical relationships for UH characteristics such as peak-flow rate and timing (Snyder, 1938; Gray, 1961); (2) those based on dimensionless UH (Soil Conservation Service, 1972); and (3) those based on models of watershed storage (Clark, 1943).

Synthetic UH methods do not depend on hydrological observations and are widely used in ungauged watersheds. However, parameters appearing in empirical relations are subject to great uncertainty when original equations are applied under radically different hydro-meteorological conditions. For example, Snyder (1938) developed a set of empirical equations for time-lag and peak-flow of his proposed synthetic UH by analyzing runoff characteristics in numerous drainage areas (26–26,000 km^2) in the Appalachian Highlands of the eastern United States.

Since then, many studies have regionalized model parameters worldwide. Borga et al. (1991) used the Snyder method for developing a real-time flood forecasting system in Italy. Usul and Tezcan (1995) developed UHs from runoff data for four catchment areas in Turkey, matching their characteristics with Snyder' s synthetic UH to obtain parameters best-fit for local conditions. Jena and Tiwari (2006) applied similar methodology in two medium-sized agricultural watersheds, proposing model parameters applicable for West Bengal state in India. El Hassan et al. (2013) used the Snyder method embedded in HEC-HMS software to simulate rainfall-runoff relationships in a semi-urbanized catchment in Texas, United States.

The main objective of this study was to develop an easily adaptable methodology for designing hydraulic structures in ungauged catchment areas. A set of type curves was presented to develop the UH based on three simple but important catchment characteristics: watershed area, length of the main wadi, and length to the centroid of the watershed along the main wadi from its outlet. This relationship was developed based on Snyder' s UH method but was made easily operationalizable for practical designs in ungauged catchment areas. Most past studies selected coarse time durations (e.g., 1-h or 2-h) when developing UHs due to the absence of rainfall and wadi-flow data at finer time resolutions. UHs with coarse time resolutions might not be accurately convertible to finer time durations to match the intense, short-duration rainfall events common in arid regions. This study used wadi-flow data accumulated at 10-min intervals at the outlets of 12 watersheds with catchment areas ranging from 45 to 1660 km^2 in Oman. Concurrent rainfall data at 1-min intervals collected using tipping bucket rain gauges at 37 stations were also obtained. These fine-resolution data provided a unique opportunity to understand complex hydrological responses in arid regions (1-h and 10-min UHs).

2 Study Area

Oman is located on the southeast strip of the Arabian Peninsula [Figure 1: see original paper]. Densely populated urban cities such as Sohar, Muscat (the capital), Sur, and Salalah are located along the 3165 km long coastal plain. A series of rugged mountains (with the highest peak of 3075 m above sea level) and Ophiolite hills run parallel to most of the coastline. The interior region accounts for nearly 82% of the country and mainly consists of sandy deserts. The climate in Oman varies from semi-arid to hyper-arid. According to records from 49 gauge stations over the 1985–2004 period, total annual rainfall ranges from 31 mm in the interior desert to 330 mm in the northern Oman mountain region, with a station average of 129 mm/a. The number of wet days (rainfall > 1 mm) over the same period varies from 2 to 32 days per year, with a station average of 12 days (Gunawardhana et al., 2018).

AlSarmi and Washington (2013) analyzed rainfall records at 23 stations covering 6 countries in the Arabian Peninsula, including Oman, for the period 1970–2008 and showed that the number of wet days with rainfall exceeding 10 mm significantly decreased. Gunawardhana and Al-Rawas (2016) studied rainfall records during 1990–2010 in three major coastal cities in Oman and found that the contribution from extreme rainfall to annual totals steadily increased. Moreover, Gunawardhana et al. (2018) predicted enhanced tropical cyclone activities in the northeast coastal region during 2040–2059 and 2080–2099 periods, along with decreases in the number of rainy days and increases in rainfall intensity in many regions. These findings highlight the necessity of rainfall-runoff modeling to cope with potential changes in rainfall regime.

3 Methodology

The research methodology consists of three major steps: (1) delineation of catchment areas and river networks using digital elevation model (DEM) data and extraction of watershed characteristics; (2) derivation of UHs at different time durations from observed river-flow and rainfall records; and (3) matching physical characteristics of watersheds with corresponding UH features to develop hydro-morphological relations.

In the first stage, paired rainfall and river-flow data were collected for 12 major watersheds [Figure 1: see original paper]. Observed river-flow at 5-min intervals and tipping bucket rainfall measurements at 1-min intervals were obtained from the Ministry of Regional Municipalities and Water Resources of Oman. Selected hydrographs cover a large extent of river-flow rates, including the highest ever recorded during Hurricane Gonu in 2007. Key catchment characteristics such as watershed area, length of the main river, and length to the centroid of the watershed along the main river from its outlet were derived from 40-m resolution DEM data using the HEC-GeoHMS (Geospatial Hydrologic Modeling Extension) tool. The selected watersheds have a wide range of areas (45–1660 km^2) and river lengths (13–92 km), which is essential for generalizing results from small to large ungauged basins. In general, catchment shape affects the magnitude and timing of peak-flow (Nouh, 1990). The entire study area, comprising 12 major watersheds, was divided into 515 sub-catchments with various shapes and sizes. The basin shape factor, computed by dividing the square of river length by watershed area (Al-Rawas and Valeo, 2010), ranges from 0.5 (very circular) to 19.5 (extremely elongated). Similarly, sub-catchment areas extend over a wide range of 0.01 to 42.00 km^2.

In the second stage, river-flow observations were aggregated to 10-min and 1-h durations when generating river-flow hydrographs. Similarly, 10-min and 1-h total rainfalls were calculated from tipping bucket rain gauge records to match river-flow durations. When multiple rain gauge stations corresponded to a catchment area, the Thiessen Polygon method was used for averaging rainfall time series. For example, the Thiessen Polygons developed for the Aday catchment area are shown in Figure 1b. There are no perennial river flows in these watersheds; most watersheds in arid regions have ephemeral-type rivers that produce flow temporarily during rainfall and dry up immediately due to extremely high evaporation demand and infiltration rates. Therefore, base-flow is essentially negligible and excess rainfall volume equals the integrated area under the hydrograph. The reverse process of the discrete UH convolution technique, known as the deconvolution method (Chow et al., 1988), was applied to derive a UH from river-flow and excess rainfall. Excess rainfall was calculated using the constant fraction loss model (McCune, 1998; Dingman, 2015), where a certain percentage of rainfall becomes runoff. The corresponding mathematical equation can be expressed as:

$$i(t) = C_r \cdot p(t) = \frac{\int Q(t)dt}{A \int p(t)dt} \cdot p(t)$$

where $i(t)$ is the excess rainfall rate (m/h), $p(t)$ is the observed rainfall rate (m/h), C_r is the fraction of rainfall that converts to runoff, $A \int p(t)dt$ is the rainfall volume (m^3), A is the watershed area (m^2), and $\int Q(t)dt$ is the cumulative wadi-flow volume (m^3).

In the third stage, Snyder' s empirical relationships were followed to relate UH features with watershed physical characteristics. According to Snyder (1938), lag-time (t_p), defined as the time from the center of mass of excess rainfall to the peak-flow rate, is given by:

$$t_p = C_t \left(L \cdot L_c\right)^n$$

where L is the main wadi length from the most upstream point of the watershed to the catchment outlet (km), L_c is the distance from the catchment outlet to the point along the main wadi closest to the watershed centroid (km), and C_t and n are parameters dependent on particular catchment characteristics. Snyder (1938) calibrated $n = 0.3$ by analyzing numerous hydrographs in the

Appalachian Highlands of the eastern United States. Since then, many studies have used this value without proper calibration to local conditions, including in arid regions (Sen, 2008; Sudhakar et al., 2015). In this study, parameters n and C_t were calibrated by matching properties of derived UHs.

Also according to Snyder (1938), the peak-flow rate is given by:

$$Q_p = \frac{C_p \cdot A}{t_p}$$

where Q_p is the peak-flow rate (m^3/s), C_p is a parameter dependent on watershed storage and retention characteristics, and A is the catchment area (km^2). In this study, a relationship between L and L_c was developed using the 515 sub-catchments delineated in the first step. Because C_p and C_t depend on particular catchment characteristics, they were combined into a single parameter (C in Eq. 4) and calibrated by matching properties of derived UHs. Accordingly, the relationship between L and L_c simplifies Equation 3, allowing Q_p to be estimated in terms of two physical watershed features: L and A as in Equation 4:

$$Q_p = C \cdot \frac{A}{L^m}$$

where the exponent m can be calculated based on the relationship between L and L_c.

4.1 Extraction of Catchment Characteristics from DEM Data

Until recently, basic catchment characteristics such as watershed area and wadi length were derived manually from topographic map sheets. Some watershed parameters, such as slope and area centroid, are not readily available through manual delineation and must be calculated, making accurate estimation difficult. As DEM data and automatic catchment delineation have become widely available, parameter estimation reliability has significantly improved. However, this requires certain expertise and sophisticated software that may not be available to designers and practitioners at local government levels. Therefore, this study aimed to reduce the number of parameters required to estimate flood hydrographs and present them based on easily achievable parameters. Accordingly, a relationship between L and L_c was developed. Out of 515 sub-catchments delineated, half were used to develop the relationship [Figure 2a: see original paper] and the rest for model validation [Figure 2b: see original paper]. This relationship was further validated with information from 12 major watersheds [Figure 2c: see original paper]. All three relationships included various catchment areas with different shapes and produced high coefficients of determination ($R^2 > 0.89$). This relationship can therefore be successfully applied in Equation 3 to simplify Qp estimations (Eq. 4).

4.2 Derivation of UHs at Different Time Durations

Eight of the 12 major watersheds studied were used to develop relationships for calculating lag-time and peak-flow rate of the UH (Eqs. 2 and 4), while the remaining four watersheds were used for verification. Observed wadi-flow rates at 10-min and 1-h intervals along with calculated excess rainfall (Eq. 1) at the same durations were used with the deconvolution method to estimate corresponding UHs. In the verification stage, these UHs were applied with different rainfall events to calculate resultant wadi-flow. Figure 3 presents observed and simulated wadi-flows for calibration and verification of 1-h UHs. The UHs were calibrated using short-duration rainfall events, yielding well-defined single-peaked hydrographs with short time bases, and verified using events with the highest observed peak-flow. Four of the eight major watersheds were verified with observed wadi-flows during Cyclone Gonu in 2007.

When multiple hydrographs were available for a catchment area, they were all used for verifying the calibrated UHs. Coefficients of determination ($R^2 > 0.89$) indicated good agreement between observed and simulated wadi-flows. Some differences between observed and simulated wadi-flows can be attributed not only to model limitations but also to various issues such as observational errors in wadi-flow and rainfall measurements, and inadequacy of meteorological stations to capture spatial distribution of rainfall events.

When a UH of a given excess-rainfall duration is available, the principle of superposition (S-hydrograph method) can derive UHs of any required duration (Chow et al., 1988). Accordingly, 1-h UHs developed in the previous stage were used to calculate 10-min UHs. Another set of 10-min UHs was derived using 10-min rainfall and wadi-flow data with the deconvolution method. Figure 4 depicts a marked difference between the 10-min UHs developed by these two methods for the Aday watershed. Similar phenomena of different magnitudes were observed in all watersheds, where the 10-min UH developed from 10-min rainfall and wadi-flow data produced greater peak-flow. This difference can be attributed to assumptions made in deriving UHs. For example, it is assumed that excess rainfall is uniformly distributed over the entire watershed at a constant rate for the selected duration—an assumption rarely satisfied under natural conditions in arid regions. Arid regions experience occasional rainfall events with intensity varying significantly over time (Greenbaum et al., 1998). Therefore, such differences between the theoretical S-hydrograph method and the deconvolution method with real data can be expected. Figure 5 shows peak-flow simulated by these two methods and their match with observed 10-min averaged peak-flow. The UH derived from the S-hydrograph method underestimated peak-flow by up to 30%, while the deconvolution method with short-term real data produced promising results. This difference between observed and simulated peak-flows by the S-hydrograph method increased with catchment area. These results therefore demand appropriate modifications to existing methods for wadi-flow estimation in arid regions.

4.3.1 Peak-Flow

According to Snyder (1938), peak-flow (Q_p) can be expressed as a function of three physical watershed characteristics: area (A), length of the main wadi (L), and length to the centroid of the watershed (L_c) (Eq. 3). Based on the relationship developed between L and L_c in Figure 2a, Equation 4 can estimate Q_p as a function of A and L. Accordingly, peak-flows from derived UHs and delineated catchment characteristics (Table 1) were used with the least-square method to obtain parameters C and m. Figure 6a compares peak-flows from derived UHs with those derived using estimated C and m. Because this study aims to develop an easily adaptable methodology for design, it is important to keep calibrated parameters unified across different time durations. Accordingly, the calibrated m value of 0.7 was applied to peak-flows from derived 10-min UHs. Figure 6b shows that peak-flow matches the $A/L^{0.7}$ ratio reasonably well ($R^2 = 0.98$). Hence, $m = 0.7$ can be used in estimating peak-flow of UHs at 1-h and 10-min durations and might be applicable for other durations as well. Differences between 1-h and 10-min UHs for various features such as peak-flow and lag-time can be accounted for by markedly different gradients of the two graphs (1.89 and 3.01 $\mathrm{m}^3/(\mathrm{s} \cdot \mathrm{km}^1 \cdot {}^3)$) for 1-h and 10-min UHs, respectively).

4.3.2 Lag-Time

Lag-time (t_p) is defined as the time from the center of mass of excess rainfall to the peak-flow rate, which according to Equation 2 can be expressed as a function of the length of the main wadi (L) and length to the centroid of the watershed from its outlet (L_c). Theoretically, lag-time of the 10-min UH should be smaller than that of the 1-h UH (Fig. 4). When the n parameter of Equation 2 is calibrated ($n = 0.35$) and fixed for any time duration, the remaining parameter C_t should vary to account for differences between 10-min and 1-h UHs. Figure 7 shows calibrated C_t for estimating lag-time for 1-h and 10-min UHs. The relationship between t_p and $(L \times L_c)^{0.35}$ for the 1-h UH produces only moderate agreement with a coefficient of determination equal to 0.74. This is because lag-time for 1-h UHs can only be estimated with $±$0.5 h accuracy. When actual lag-time for different catchments varies within a smaller range (1.0–3.5 h as in Fig. 7), such uncertainty in estimating t_p can be significant. Due to finer time resolution, the relationship between t_p and $(L \times L_c)^{0.35}$ for the 10-min UH produces good agreement with a coefficient of determination equal to 0.98.

4.3.3 Time-Widths

Sections 4.3.1 and 4.3.2 present quantitative analyses to estimate peak-flow and lag-time. However, to determine UH shape, additional ordinates must be known. Snyder (1938) expressed the time-width of the UH at a discharge equal to a certain percent of peak-flow as a function of peak-flow rate per unit watershed area, assuming one-third of this width is distributed before the UH peak time and two-thirds after the peak (Chow et al., 1988; Angelidis et al., 2010). Accordingly, three relationships were developed for time-width at 75%, 50%, and 30% of peak-flow based on derived UHs [Figure 8: see original paper]. Time-width is inversely proportional to peak-flow per unit watershed area. All six graphs produced relatively acceptable relationships with determination coefficients exceeding 0.87. These empirical equations provide six additional points on the UH, bringing the total to eight ordinates for determining the probable UH shape.

Rainfall-runoff hydrographs in arid regions can be quite distinct from those in humid regions. Attributed to steep slopes, flow is faster in arid regions, resulting in shorter rising limbs and greater peak-flow. Total discharge decreases significantly within short periods due to high evaporation and transmission loss rates. Wadi-beds in these regions are generally composed of alluvial sediments dominated by highly permeable coarser grain sizes. Therefore, the 1:2 width-ratio suggested by Snyder (1938) may not be applicable in arid regions. A series of UHs was developed for 1-h and 10-min durations for all study areas based on empirical relationships from previous steps (Figs. 2, 6, 7, and 8). When comparing these UHs with those derived from observed wadi-flow, the 3:4 width-ratio produced better results than the 1:2 width-ratio. For example, Figure 9 shows a comparison of 10-min UHs developed for the Afi watershed with two different width-ratios. The 3:4 width-ratio formed a shorter rising limb than the 1:2 width-ratio and matched better with the UH derived from observed wadi-flow.

The applicability of the proposed empirical equations to develop UHs at 1-h and 10-min durations was tested by simulating wadi-flows in four additional watersheds different from those used for calibrating and verifying UHs in Figure 3. Catchment characteristics for these watersheds are shown in Table 1. Figure 10 shows observed and simulated hydrographs based on the proposed empirical equations. Simulations by the 1-h UHs agree better with observations than results from 10-min UHs. When simulating wadi-flows at finer time resolutions, uncertainty arises due to temporal and spatial variations of rainfall events, especially in arid regions. However, time-averaged 1-h wadi-flows smooth abrupt variations at 10-min intervals and therefore produce better agreements. All simulations reasonably capture different hydrograph features such as general trend, peak-flow, and time-lag when matched with observations. This indicates that the developed empirical relationships can be applied in deriving UHs particularly for arid regions in Oman. These results can be further improved by applying them in different countries with similar climate and geographical settings.

5 Conclusions

Rainfall-runoff relationships in arid regions are unique and challenging to understand properly. This study aimed to develop a simple but reliable procedure for estimating UHs at reasonably fine time resolutions (10-min and 1-h) that can be easily adapted by practitioners at sub-catchment levels, especially when ungauged. For example, wadi length can be easily estimated by automatic delineation from DEM data or even by manual methods, while calculation of the catchment centroid is rather difficult, especially when paper-based topographic maps are used. Results indicate that the strong relationship found between wadi length and length to the centroid of the catchment area can be adopted to simplify existing methods for determining UHs. Moreover, it was found that the principle of superposition with the assumption of uniform excess rainfall distribution is not applicable in arid regions. A marked difference was found between 10-min UHs estimated by the S-hydrograph method and the deconvolution method. Therefore, it is concluded that a method dependent on natural hydro-meteorological conditions would be more practical in arid regions.

A set of empirical equations was developed for estimating peak-flow, lag-time, and time-widths at 75%, 50%, and 30% of peak-flow for 10-min and 1-h UHs by analyzing wadi-flows in eight watersheds. Developed relationships were successfully validated with observed wadi-flows in four independent watersheds. When calibrated parameters are concerned, developed empirical relationships are quite distinct from those suggested for other regions. For example, the 3:4 width-ratio was found more suitable for arid regions than the 1:2 width-ratio suggested in numerous past studies. The proposed methodology is expected to be useful for water resources management in arid regions, especially for planning countermeasures to cope with future climate change.

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Note: Figure translations are in progress. See original paper for figures.

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