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Rainfall-Runoff Relation for Three Mountainous Arid Basins

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Abstract. Regression analysis was utilized to investigate the rainfall-runoff relations of three mountainous basins in the western and southwestern regions of Saudi Arabia. Areal mean rainfall depth was computed using Thiessen polygons method for different combination of rainfall stations to investigate which one produced the best result. Regression analysis was performed for four different combinations of soil moisture conditions and rainfall locations. Spatial distribution of rainfall is found to be the most important factor affecting values of runoff coefficients for the study basins.

Key Words: Rainfall-runoff, Prediction, Arid Regions, Mountainous Basins, Regression Analysis.

Introduction

Management of water resources in arid and semiarid regions of the world is essential for meeting all sectors of water requirement. This is particularly true for an arid country such as Saudi Arabia, where no reliable source of fresh water exists, other than groundwater and desalination. Surface runoff, if properly managed, could contribute significantly to the longevity of groundwater supplies in the renewable shallow aquifers. Proper and effective utilization of surface water requires the formulation of appropriate management schemes that can be accomplished through investigating the relationship between rainfall and runoff of the major contributing drainage basins. This is particularly true for the southwest region of the country, where a majority of rainfall-runoff events take place. Large volumes of surface runoff are available in this area and can be utilized through the use of properly designed storage dams and recharge scheme.

Researches in the field of arid land hydrology are limited in comparison to humid regions due to the complex hydrological processes regarded to spatial and time variability and also data limitation and coverage. This is particularly true for the region of Arabian Peninsula in which few studies are available such as (Allam & Al-Wagdany, 1989; Wheater *et al.,* 1991; Michaud & Sorooshian, 1992; Sorman & Abdulrazzak, 1993; El-Hames & Richards, 1994; Al-Qurashi & Herberton, 1995; Twomlow & Bruneau, 1998 and Zhu *et al.,* 1999).

Rainfall-runoff relation is usually complex and influenced by various storm patterns, antecedent soil and basin characteristics. Due to the complexity of these and the frequent paucity of adequate data, many approximate formulas have been developed to relate rainfall to runoff. Depending on data availability, various analytical, statistical and numerical models have been applied to investigate the relation of many hydrological processes. Regression analysis is one of these techniques that has been applied to establish relationship between dependent and independent variables, and is widely used in hydrology to investigate relations between different hydrologic variables. This technique has the advantages that it does not required detailed information of hydrologic and soil parameters. Therefore, it is selected and applied in the current study to investigate rainfall-runoff relations influencing variables for three basins in the southwestern region of Saudi Arabia.

Study Area

The selected three basins for the current study are located in the southwestern region of the Kingdom of Saudi Arabia. The locations of the basins are presented in Fig. 1. They are selected mainly for two reasons. First: They are located in a region characterized with frequent rainfall events compared to other regions of Saudi Arabia. Second: They are among five representative basins identified by the Ministry of Agriculture and Water during the period 1984 through 1987. The basins were instrumented and monitored during that period through an extensive hydrological network. Therefore, rainfall and runoff data are available for the basins during that period. Unfortunately, the process of data collection for the three basins had been stopped since 1988. The outcome of analysis can be used to extrapolate their finding to basins with similar hydrological and morphological characteristics. The morphological and hydrological characteristics of the basins are shown in Table 1.

The three selected basins are Al-Alyah, Dhara and Al-Jawf. They are characterized by a mountainous nature with spare vegetation coverage and steeply channels. The density of the rainfall network in the selected basins is estimated to be one gauge per 60 square kilometers. This density complies with the standard of the World Meteorological Organization (WMO) that is 100-250 km^2 for mountainous areas and 1500-10000 km^2 for arid zones.

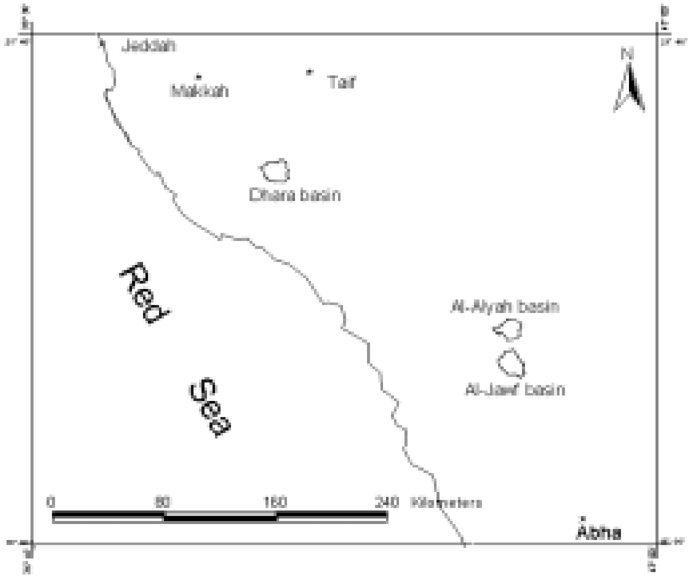

FIG. 1. Locations of the study basins.

TABLE 1. Geomorphologic and hydrological characteristics of the study basins.

Characteristic	Al-Alayh	Dhara	Al-Jawf
Drainage area (km^2)	170	274	305
Mean slope of main channel (m/m)	0.012	0.011	0.033
Length of main channel (km)	20	19	23
Mean width of the basin (km)	10	13	20
Alluvium area (km^2)	4	12	33
Elevation range (m)	2000 - 1800	650 - 350	740 - 551
Mean annual temperature ºC	24	31	31
Maximum temperature ºC	42	49	45
Minimum temperature ºC	– 1	15	13
Mean annual relative humidity %	31	54	47
Average annual solar radiation Ly/day	468	448	454
Average daily pan evaporation (mm)	5.6	6.5	6.2
Mean annual rainfall depth (mm)	184	185	485
Number of rainy days per year	60	36	120
Mean annual runoff discharge m^3/s)	14	13	41

The first selected basin with an area of 170 km^2 is Al-Alyah, which is located at the upstream of Wadi Tabalah. It is located between longitude 41º49′ & 42º03′ east and latitudes 19º29′ & 19º39′north. It has three rainfall and one run-off stations as shown in Fig. 2. The second basin is Dhara, which is located in the northwest of Wadi Alith between longitudes 40º12′ & 40º25′ east and latitudes 20º39′ & 20º50′ north. It has a drainage area of 274 km^2 and equipped with five rainfall and one runoff gauge stations. The map of the basins is presented in Fig. 3. The third basin is Al-Jawf, which is a sub-catchment of Wadi Yiba and located between longitude 41º53′ & 42º04′ east and latitudes 19º13′ & 19º26′ north. It has a drainage area of 305 km^2 and equipped by four rainfall and one runoff gauge stations. The drainage network and locations of stations in the basin are shown in Fig. 4.

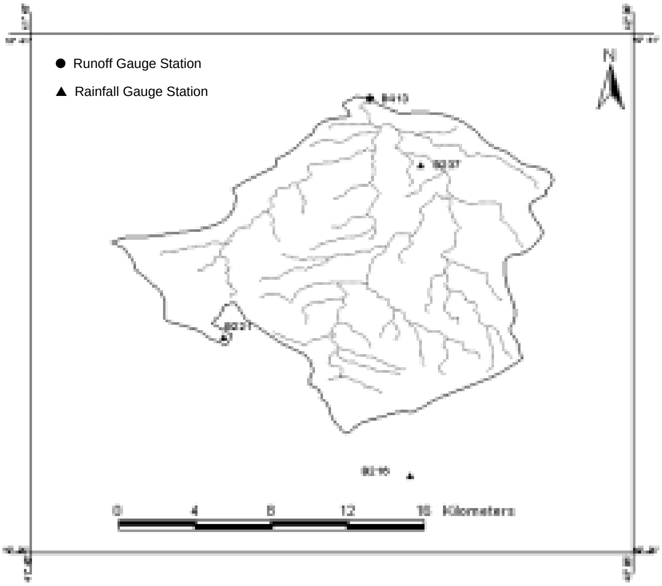

FIG. 2. Drainage network of Al-Alyah basin.

Hydrological Data

The rainfall and runoff data utilized in this study were collected from reports obtained from the Ministry of Agriculture and Water (MAW). The general climate of Saudi Arabia is hot and dry. In some climate classification studies, the country is classified as arid with some areas of hyper-aridity and semi-aridity (MAW, F12, 1988). Two of the study basins (Dahra and Al-Jawf) are located on western side of the Asir escarpment, while the third (Al-Alyah) is located on the eastern side of the escarpment. The Asir escarpment is a mountain range that runs parallel to the Red Sea in the southwestern region of Saudi Arabia.

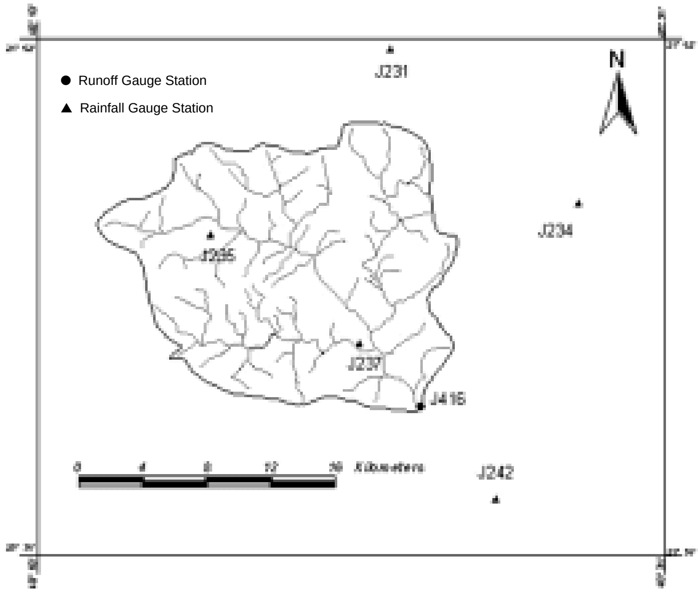

FIG. 3. Drainage network of Dhara basin.

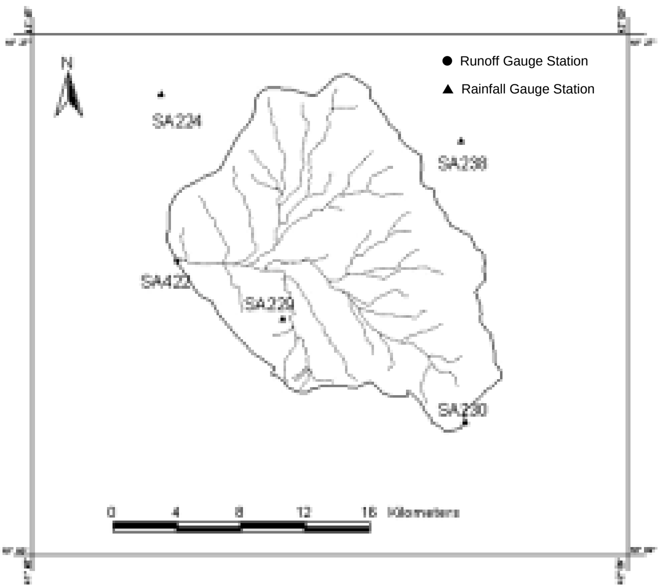

FIG. 4. Drainage network of Al-Jawf basin.

The climate of the western side of the escarpment ridge is hot with little seasonal variation. The mean annual temperature is 31ºC. Due to the availability of moisture from the Red Sea, the climate is humid, where the average relative humidity is 60% on an annual basis. The climate of the eastern side of the escarpment ridge is also hot but dry and has more seasonal variation than the western side. The mean annual temperature is 24ºC with a mean annual relative humidity of 25%. Climatic data were collected from reports of MAW and summarized in Table 1 for the study basins.

The occurrence of rainfall on the study area is strongly influenced by topography. Rainfall is usually initiated in the mid-afternoon and characterized in general by high intensity and short duration (typically 1-2 hours) with extreme spatial variability. Rainfall data which was collected from MAW reports (1984-87) shows that rainfall varies from season to season and from year to another, and rainy days occur more frequently in spring and fall. Values of mean annual rainfall and number of rainy days for the study basins are shown in Table 1 .

Surface runoff occurs in the wadi system and mainly generated by intense rainstorms of relatively localized spatial extent. As a result of the spatial characteristics of rainfall, runoff is generated to a random and localized pattern in a form of spate of flash flood flows. The flows are characterized by hydrographs with steep rising limbs (10-30 minute duration) and rapid recession to zero baseflow. High infiltration rate is the major factor affecting hydrograph shapes since they decrease significantly in magnitude downstream, unless augmented by subsequent tributary inflows. Values of mean annual runoff discharges are presented Table 1.

Rainfall-Runoff Relations for the Study Basins

Al-Alyah basin has three rainfall gauge stations, two of them (B216 and B221) are located on the upstream of the basin, while the third station (B237) is on the down stream of the basin. Rainfall data are available for 39 rainfall-runoff events over the basin. Regression analysis were performed to obtain relationship between runoff and areal rainfall depths (computed by using Thiessen polygons method) for different combinations of rainfall gauge stations. These combinations were selected to account for upstream and downstream rainfall events. Results of the regression analysis are presented in Table 2. Similar procedures were carried out for the other two basins and the results are summarized in Table 2. Rainfall and runoff data are available for 37 events over Dhara basin and 98 events over Al-Jawf basin during the period 1984 to 1987.

Table 2 shows that the best correlation coefficients equal 0.79 for Alyah basin, 0.78 for Dhara basin and 0.48 for Al-Jawf basin. The table also indicates that rainfall-runoff relations are significantly affected by the combination of rainfall stations used in the study. This suggested that considering spatial distribution of rainfall might improve results of regression analysis. Therefore, rainfall events on the three basins were reclassified as upstream and downstream events. It is well known that soil moisture content plays a major role in the mechanism of runoff generation, especially, in arid regions. Two rainfall events with similar characteristics that occur over the same watershed can produce completely different runoff hydrographs depending on the antecedent soil moisture content of the watershed. In order to account for this extremely important factor, rainfall events were classified to wet event if there was rainfall event over the region on the previous day, otherwise they are regarded as dry events. Using the two above classifications, rainfall events over the basins were divided into four groups as, up-dry, up-wet, down-dry and down-wet events. Regression analysis is applied to rainfall-runoff data for each of the four groups and for the three basins. Results are presented in Table 3. Regression lines and data points are presented in Fig. 5 and 6 for two cases out of the 15 cases presented in Table 3.

TABLE 2. Results of regression analysis for the study basins.

Alyah	Source of rainfall data	All stations	B237	B237 & B216	B237 & B216	B221 & B216	B221	B216
	R^2	0.64	0.79	0.56	0.43	0.04	0.047	0.005
Dhara	Source of rainfall data	J235 & J237	J237, J235 & J231	J237, J235, J231 & J234	J235, J237 & J234	J235, J237 & J242	J235	J237
	R^2	0.78	0.76	0.75	0.60	0.65	0.51	0.57
Al-Jawf	Source of rainfall data	SA229	B238, SA230, SA229 & SA224	B238, SA229 & SA230	SA229, B238 & SA224	SA230 & SA229	SA238 & SA229	
	R^2	0.42	0.42	0.39	0.48	0.31	0.34	

Discussion

The application of regression analysis to investigate rainfall-runoff relation for 20 different combination of rainfall gauge stations provided values of R^2 between 0.005 to 0.79 for the three study basins. After reclassifying rainfall events to four groups depending on location of the rainfall storm and antecedent soil moisture content, results of regression analysis were notably improved. Values of R^2 were ranging between 0.78 and 0.97. These results suggest that for arid region spatial distribution of rainfall and antecedent soil moisture conditions are very important factors, and should be considered even if the utilized technique is not a physically based hydrologic model.

Results for regression analysis are best for rainfall records of the nearest rainfall gauge stations to runoff gauge stations. This may indicate that most of runoff produced in the upstream of the study basins infiltrates and evaporates before it reaches a runoff gauge station. Therefore, the runoff coefficient is expected to change dramatically depending on the extent of the rainfall event producing it. This conclusion is in agreement with the values of runoff coefficients presented in Table 3, where the values for the three basins are much higher for downstream storms compared to upstream ones. Moreover, the runoff coefficient for downstream storms and dry soil is much higher than that for upstream storms on a wet soil. In fact, the effect of soil moisture content on values of runoff coefficient is less than that of spatial distribution of rainfall.

TABLE 3. Results of regression analysis for the four classifications.

Case	Alayh			Dhara			Al-Jawf		
	No. of events	R^2	Runoff coef. (%)	No. of events	R^2	Runoff coef. (%)	No. of events	R^2	Runoff coef. (%)
All	39	0.64	9.6	37	0.78	4.4	98	0.42	2.6
Up-dry	12	0.96	2.4	11	0.93	0.13	31	0.81	0.08
Up-wet	8	0.93	5.1	7	0.91	2.1	27	0.89	1.6
Down-dry	10	0.97	15.9	10	0.86	5.3	23	0.84	2.3
Down-wet	9	0.97	17.3	9	0.78	5.7	17	0.82	4.5

The three basins that were investigated in the current study are characterized with having only one runoff gauge station. It should be noticed that availability of additional runoff gauges might affect the result of the study due to the change of the scale of the drainage basin, which will become smaller. However, it is common in hydrology to consider the scale and its effect on results of the study. Therefore, results should be utilized mainly for applications suitable to the scale at which the study were carried out.

Investigation of rainfall-runoff relationship in arid regions is very difficult task due to the complexity of the hydrological flow processes and scarcity of data. Most of the simulation models that are used to compute or predict runoff in humid regions are not applicable for arid regions. It is recommended to pay more attentions to studies in this direction, since it is noted that researches in the field of surface water are very limited for arid regions. It is also advisable to provide series efforts toward collecting hydrological data with enough quantity and acceptable quality for such regions.

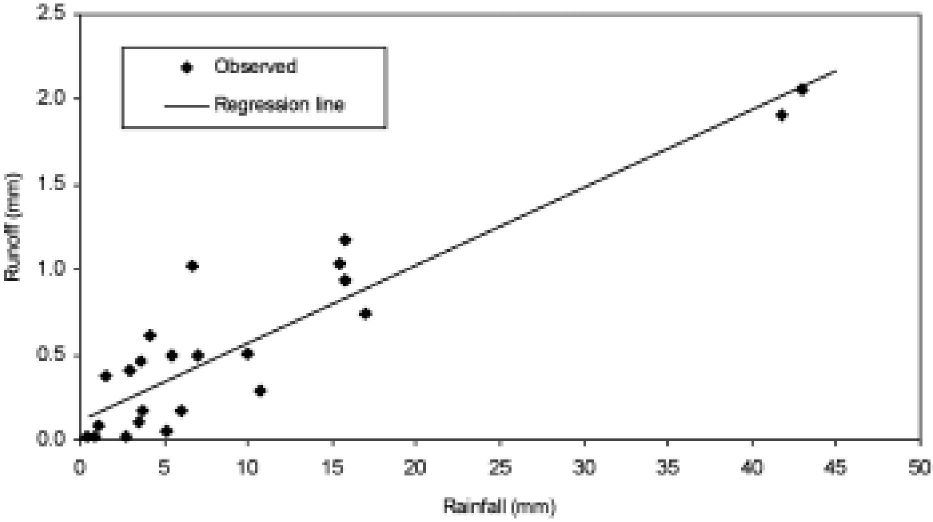

FIG. 5. Rainfall-runoff relationship of the down-wet case in wadi Al-Jawf.

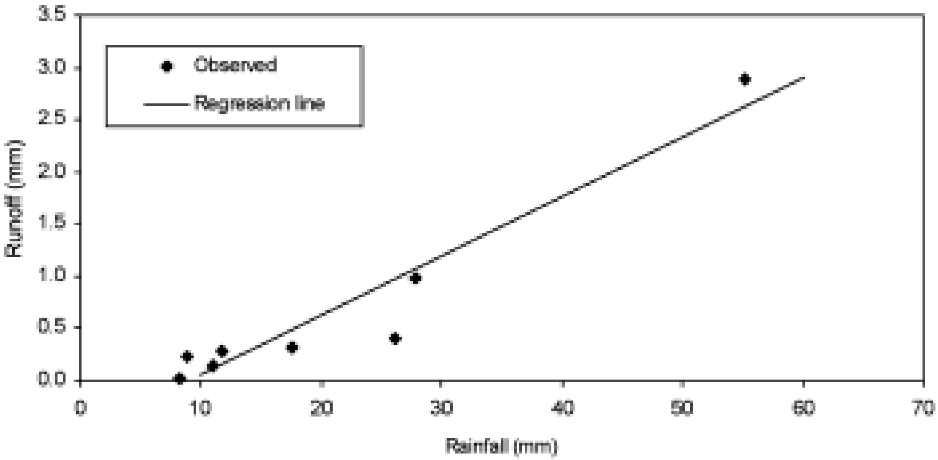

FIG. 6. Rainfall-runoff relationship of the down-wet case in wadi Dhara.

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العلاقـة بين المطر والسيل لثلاثـة أوديـة بمنطقـة جبليـة

عبدالله بن سعد الوقداني و محي بن عبدالرحمن الشهري*
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*و *وزارة الزراعة والمياه - المملكة العربية السعودية*

المستخلص. تم استخدام التحليل التراجعي في هذه الدراسة لتحديد العلاقـة بين عمق المطر الهاطل وعمق السيل الناتج عنه ، وذلك لثلاثة أودية ذات طبيعـة جبلية تقع في كل من غـرب وجنوب غرب المملكة العربية السعودية . وبالنسبـة لحساب عمق الأمطار المتوسطة ، فقد استخدمت طريقـة مضلعـات ثيسن ، حيث حسبت تلك الأعمـاق لمجموعات مختلفة (تشكيلات متغيرة) من محطات قياس الأمطار بغرض التعرف على المجموعة التي تعطي أفضل النتائج . فقد تم إجراء التحليل التراجعي لأربع مجموعات مختلفة من المحتوى الرطوبي للتربة ومواقع هطول المطر . وخلصت الدراسة إلى أن التوزيع المكاني لهطول الأمطار كان العامل الرئيس من حيث التأثير على قيمة معامل السيل بالأودية المدروسة .