Arab Gulf Journal of Scientific Research, 26 (1/2): 9- 18 (2008)

Research Paper **Ref. No 2460**

Rainfall and Runoff Characteristics of Namman Basin in the Kingdom of Saudi Arabia

خصائص الأمطار والسيول لوادي نعمان في المملكة العربية السعودية

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Abstract: Namman Basin is an arid mountainous basin located in the western region of Saudi Arabia and has a drainage area of about 650 km^2. Namman unconfined groundwater aquifer is the source of water to the historic underground galleries known as Ain Zubaidah. The galleries became dry due to the fall of groundwater levels dramatically in the last few decades. The galleries can be restored only if a proper water resources management is utilized in the basin. The aim of this research is to investigate two major hydrological components, namely rainfall and runoff, which are essential for a proper management of the water resources of the basin. Rainfall and runoff records for ten rain gauge stations and one runoff gauge station are used to investigate major characteristics of rainfall and runoff in Namman basin. Rainfall records are analyzed to derive conclusion about rainfall occurrence, depth, duration, temporal distribution and extreme values. The relation between rainfall depth and elevation is also investigated. Runoff records are utilized to investigate seasonal variation of runoff. Values of runoff coefficient for all runoff events are computed and the relation between rainfall and runoff for the basin are discussed. The results show that there are more than 30 rainstorms per year and only about two runoff events are usually observed. The temporal analysis of rainfall and runoff indicates that there are two rainy seasons, one is during fall and winter season and the other is during spring seasons while runoff is mainly observed in the winter season. Values of runoff coefficient were very low with mean value of 0.013, which indicate that most rainfall infiltrate through the alluvial channels of the basin.

Keywords: *rainfall, runoff, Namman basin, arid regions, mountainous basins, Saudi Arabia.*

المستخلص: وادي نعمان هو أحد الأودية الجبلية الجافة الواقعة بغرب المملكة العربية السعودية وتبلغ مساحته حوالي 650 كيلومترا مربعا. وقد كان الخزان الجوفي غير المحصور للوادي مصدر إمداد عين زبيدة التاريخية بالمياه لعدة قرون. وخلال العقود الأخيرة هبط مستوى الماء الجوفي بالوادى مما أدى لجفاف تلك العين. ويتطلب إحياء العين رفع مستوى الماء الجوفي بالوادي والذي يمكن الوصول إليه عن طريق وضع خطة مناسبة لإدارة مصادر المياه بالوادي. وتقوم الدرسة الحالية بالتركيز على عنصري المطر والسيل بالوادي وهما عنصران هيدرولوجيان هامان لإدارة المياه بالوادي. وقد استخدمت بيانات عشر محطات لقياس المطر ومحطة واحدة لقياس السيل لتحديد أهم خصائص المطر والسيل بالوادي. و تم تحليل بيانات المطر لتقدير عمق ومدة العواصف المطيرة والتوزيع الزماني للأمطار وكذلك قيم الأمطار العظمى. كما تم تسليط الضوء على العلاقة بين عمق المطر والارتفاع بمنطقة الوادي. وقد استخدمت بيانات السيول لتحديد التوزيع الزماني للسيول. كما تم حساب قيم معامل السيل ومناقشة العلاقة بين المطر والسيل بمنطقة الوادي. أظهرت النتائج أن معدل العواصف المطيرة يزيد على ثلاثين حالة سنويا بينما لا يزيد معدل حدوث السيل بالودي على حالتين سنويا. و تبين من دراسة التوزيع الزماني للأمطار والسيول وجود فصلين مطيرين أحدهما يشمل فصلي الخريف والشتاء والأخر خلال فصل الربيع بينما

كان الغالب على السيول الكبيرة أنها تحدث خلال فصل الشتاء. وقدكانت قيم معامل السيل منخفضة بمتوسط قدره 0.013، مما يدل على أن معظم مياه الأمطار تتسرب خلال الطبقة السطحية للرواسب الوديانية التي تغطي المجاري المائية للوادي.

كلمات مدخلية : *تساقط مطري، جريان سطحي ، وادي نعمان، مناطق جافة،أحواض جبلية ، المملكة العربية السعودية.*

INTRODUCTION

A large area on the surface of the Earth can be considered arid or semiarid. In fact, 47% of the surface of the Earth can be classified as dry lands (UNEP, 1992). In such regions, proper management of water resources is essential for the life and activities of their inhabitants. Availability of hydrologic data is the main constraint challenging proper water resources planning and management in arid regions (Michaud and Sorooshian, 1992). Namman basin, in western Saudi Arabia, is a mountainous arid basin which has rainfall and runoff records for more than twenty years. This advantage is not available for many arid basins around the Globe. Investigation of rainfall spatial and temporal characteristics is particularly important for the estimation of effective rainfall and groundwater recharge. Groundwater of Namman basin was utilized to provide pilgrims with water for several centuries through underground galleries of Ain Zubaidah which was constructed about 12 centuries ago. In the last decades, groundwater levels have substantially dropped below the level of the galleries which collect the water and they became dry and began to demolish. Ain Zubaidah may be restored if the grandwater levels rise back to the level of the underground galleries. This objective can only be achieved through proper management of the groundwater and surface water of the basin. In this study, the main characteristics of rainfall and runoff of Namman basin are determined. These information are expected to be valuable for the management of water resources of Namman basin, as well as for researchers interested in arid land hydrology particularly when studying hydrological processes at ungauged arid basins.

In comparison to humid regions researches in the field of arid land hydrology are limited due to the complex hydrological processes regarded to spatial and temporal variability and also data limitation and coverage. This is particularly true for surface water studies in the Middle East region in which few studies are available, such as Allam and Al-Wagdani (1989), Wheater, *et al.* (1991), Michaud and Sorooshian, (1992), Sorman and Abdulrazzak (1993), El-Hames and Richards (1994), Al-Qurashi and Herberston (1995), Twomlow and Bruneau (1998), Meirrovich, *et al.* (1998) and Zhu, *et al.* (1999). The current study is an addition to the previous studies in arid mountains land hydrology as it focuses on an important arid basin in western Saudi Arabia. In this study, rainfall and runoff data were analyzed to derive conclusions about the temporal and spatial characteristics of rainfall and runoff of the basin.

STUDY AREA

Namman basin has an important location for it is located between two major cities of western region of the Kingdom of Saudi Arabia, namely Makkah and Taif, as shown in Figure 1. The basin extends between longitudes 40° 00\` and 40° 20\`E, and latitudes 21° 07\` and 21° 30\`N. The region is characterized by frequent rainfall events, when compared to most of the other regions of the country. In particular, annual rainfall depth in the region is usually between 200 and 300 mm, while the mean annual rainfall depth in the country is about 100 mm. The boundary and channel network of the basin which were extracted from 1:50,000 scale topographic maps are presented in Figure 1. The total drainage area of the basin is about 650 km^2. Most of the area of the basin is mountainous and only about 10% of its drainage area is covered by alluvial deposits. The basin has six major tributaries; these are Majareesh, Alshara, Rahjan, Arar, Yarej and Alaq. The basin contains the historical groundwater galleries known as Ain Zubaidah which were a major source of water to the city of Makkah and its surrounding areas for several centuries. The basin contains ten rainfall stations and one runoff gauge station. Unfortunately, currently most of these stations are not functioning due to lack of maintenance.

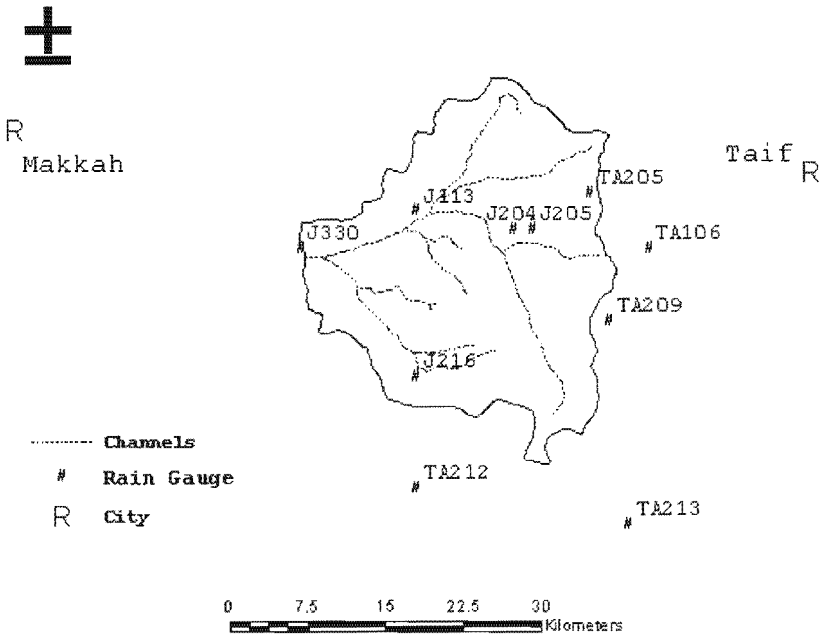

Fig. 1. Drainage and Rainfall Gauges Network of Namman Basin.

RAINFALL CHARACTERISTICS

The occurrence of rainfall and its spatial and temporal distributions on the western region of Saudi Arabia, in which the study area is located, are strongly influenced by topography and wind direction. Rainfall during the wet season (October – May) in the study region is associated with the Red Sea trough, which transports the southwesterly warm moist air towards the high western mountains. On the other hand, rainfall events are rare during summer and caused by thunderstorms affected by southwestern monsoons. In the study area, rainfall is usually initiated in the mid-afternoon and is characterized in general by high intensity and short duration (typically 1-2 hours) with extreme spatial variability. Rainfall data were collected from reports produced by the Ministry of Agriculture and Water (MAW), currently the Ministry of Water and Electricity (MWE). The reports provide data for 24 years (1963-1986) for ten rain gauges located within and around Namman basin. Rainfall data for the period 1987-2004 were obtained from unpublished data sheets prepared by the ministry since they stopped publishing the reports in 1987. In Fact, only three (J113, J204, J205) of the ten rain gauges were still working in 2004. Seven of these stations are recording gauges which provide information on rainfall depth and duration. One of the rain gauges is a totalizing station (J330) which provides only monthly rainfall depth values. The remaining two gauges (J113 and TA106) provide only daily rainfall depth values. The locations of the rain gauges are shown in Figure 1. Elevations of rain gauges above mean sea level as well as period of available records are shown in Table 1. The elevation of these gauges ranges from 520 to 2190 m above sea level.

The available rainfall records for the ten rain gauges were used to compute mean annual as well as mean monthly rainfall depths using the Thiessen polygons method. Values of mean annual rainfall depths for the ten rain gauges are presented in Table 1. The mean annual rainfall depth was 220 mm and the mean annual rainfall volume in the basin is about 143 million cubic meters (MCM). Rainfall depth values exhibit significant spatial variation due to the variation of elevation of the gauges location. Mean annual rainfall depth values vary from around 100 mm for low altitude gauges to more than 300 mm for the high altitude gauges. However, values of annual rainfall depth for station J330 are very low when compared to the depths of other stations on the region. This can be attributed to low altitude of the station and to the fact that it is a totalizing station located at a remote area and its rainfall depth is measured once a month. Therefore, the measured rainfall depth probably underestimates the actual value due to evaporation which may occur during the month.

Table 1. Altitude, Period of Records and Mean Annual Depth of Rainfall Gauges.

Station (ID)	Period of records (years)	Altitude (m)	Mean Annual rainfall depth (mm)
J113	1966-2005	520	217.9
J204	1966-2004	720	169.5
J205	1966-2004	910	206.1
J216	1967-1995	540	202.4
J330	1967-1988	380	106.1
TA106	1966-1999	1870	213.5
TA205	1966-1992	1940	244.8
TA209	1966-1994	1890	239.1
TA212	1966-1995	2130	306.9
TA213	1966-1995	2190	320.7

Values of rainfall depths vary significantly from month to month and from season to another. The monthly variations of mean rainfall depth are shown in Figure 2. The figure shows that rainfall is high during fall, winter and spring seasons and very low during summer. In fact, two rainy seasons can be distinguished, one during spring and the other during fall and it extends until the middle of the winter. An example rainfall annual temporal variation is presented in Figure 3 for rain gauge TA106. The figure indicates that no clear trend is obvious for the temporal variation of annual rainfall. In addition, the variation was very dramatic since the station recorded its minimum annual rainfall depth in 1980 and its maximum annual rainfall depth in 1982. The rainfall records of the six recording gauge stations (the rest of the stations are non-recording gauges) were used to determine values of mean rainfall duration and depth, as well as the number of rainy days per year and the mean time between storms for each rain gauge. The mean values of rainstorm duration vary from 0.90 to 2.6 hours. Mean values for rainstorm depth were found in the range between 6.5 to 8.5 mm. Number of rainy days per year was found to vary from 26 to 44 days. In other words, gauge stations in the basin receive between two to three rain storms per month. The values of mean time between storms are between 8 and 14 days. Values of mean rainfall depth, duration, number of rainy storms, and mean time between storms are presented in Table 3. In the year 1972, station TA213 received 73 rain storms. This means that there was one rainy day in every five days of that year. This large number of rain storms was the largest number of storms observed in any of the ten rain stations of the study area.

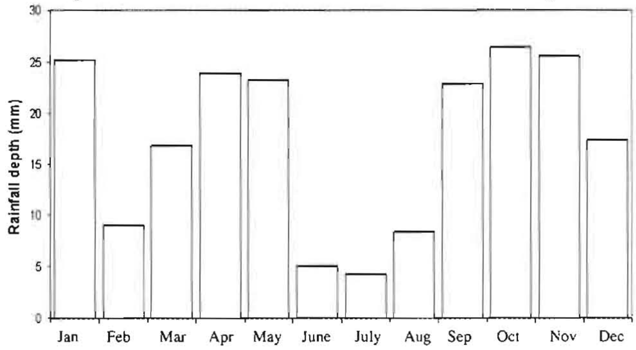

Fig. 2. Mean Monthly Rainfall Depth.

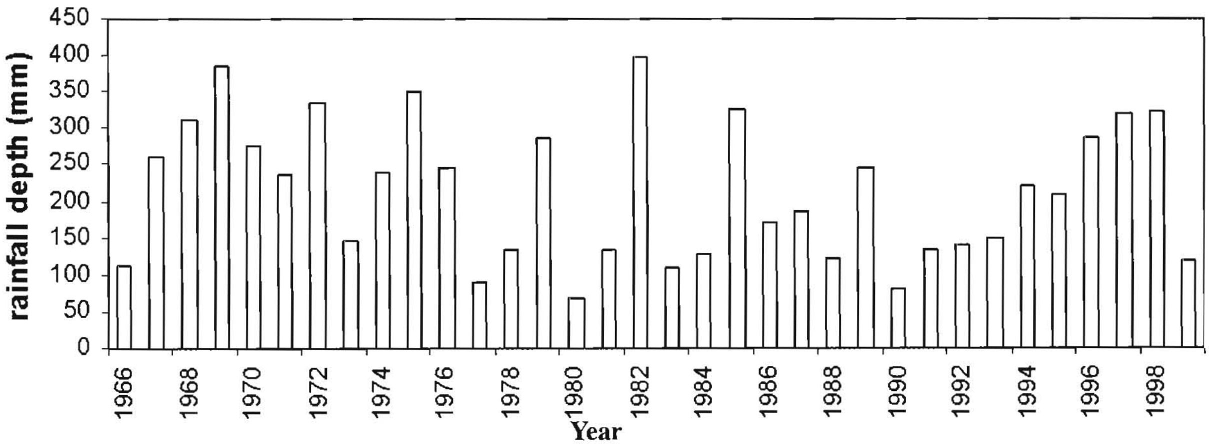

Fig. 3. Annual Rainfall Depth for Station TA106.

Rainfall records were examined and the maximum daily, monthly and annual rainfall depths were extracted. The largest annual rainfall depth was 600 mm recorded by station TA212 in 1969. In fact, the maximum annual rainfall depth occurred in the year 1969 for eight of the ten rain gauges used in this study. On the other hand, the largest value of monthly rainfall depth was recorded during the month of April, 1975, by station TA209. A historical maximum daily rainfall depth (190.5 mm) was recoded by station J113 on the seventh of March, 1998. Table 4 presents the values of maximum recorded annual, monthly and daily rainfall depths.

The existence of relation between altitude and rainfall depth especially for the mountainous basin is well known. Figure 4 shows a plot of altitude of rain gauges against their corresponding mean annual rainfall depth. The plotted data points suggest that there is a linear direct proportional relation between the two variables. Therefore, regression analysis technique was utilized to investigate the relation between elevations and mean annual rainfall depths. The resulted regression line is plotted in the same figure. The correlation coefficient value is not high (R^2=0.65). However, the regression line indicates the direct proportional relation between the two variables and the error in the predicted values of annual rainfall depth was less than 10% for five of the ten points. Hence, such error can be tolerated in rainfall studies due to the fact that error in measuring rainfall using rain gauges can be significant due to problems of turbulence and the gauge itself (Ward, 1975). The error in prediction was only high for the data of station J330, which is suspected to underestimate rainfall depth values as discussed above.

Table 2. Storms Characteristics.

Station	Mean number of storms	Mean storm depth (mm)	Mean storm duration (hrs)	Mean time between storms (days)
J204	28.6	7.2	2.6	12.8
J205	40.0	8.5	0.9	9.1
J216	26.3	8.0	1.7	13.9
TA209	30.1	7.9	2.1	12.1
TA212	31.9	8.2	2.0	11.4
TA213	44.5	6.5	2.1	8.2
Mean	33.6	7.7	1.9	11.3

Table 3. Maximum Annual, Monthly and Daily Rainfall Depth.

Station	Maximum annual rainfall depth (mm)	Year of Occurrence	Maximum Monthly rainfall depth (mm)	Month of Occurrence	Maximum Daily rainfall depth (mm)	Date of Occurrence
J113	469.7	1969	191.8	Mar.-1998	190.5	07/03/1998
J204	474.8	1969	268.4	Apr.-1975	110.0	07/03/1998
J205	492.0	1969	240.0	Apr.-1975	117.4	07/03/1998
J216	410.4	1968	143.2	Jan.-1969	63.4	13/03/1991
J330	307.4	1969	211.0	Jan.-1969	-	-
TA106	396.4	1982	245.3	Apr.-1975	151.5	07/03/1998
TA205	531.6	1969	251.6	Apr.-1975	87.4	28/01/1985
TA209	411.2	1969	277.2	Apr.-1975	102.6	17/04/1968
TA212	600.0	1969	214.0	Apr.-1975	100.8	14/03/1983
TA213	542.6	1968	193.8	Jan.-1969	87.2	13/05/1971

Determination of probability distribution of extreme rainfall is essential for designing hydraulic structures such as culverts, bridges and dams in the study area. Information of maximum daily rainfall depth of the rain gauges in the region was used to determine the return period of daily rainfall depth. The data was fitted to extreme value probability distribution. An example of that is shown in Figure 5 where Gumbel extreme distribution (Gumbel, 1958) was used to fit quite well the data of station J205. The fitted distribution shows that for return period of 100 years the expected maximum daily rainfall depth is about 136 mm.

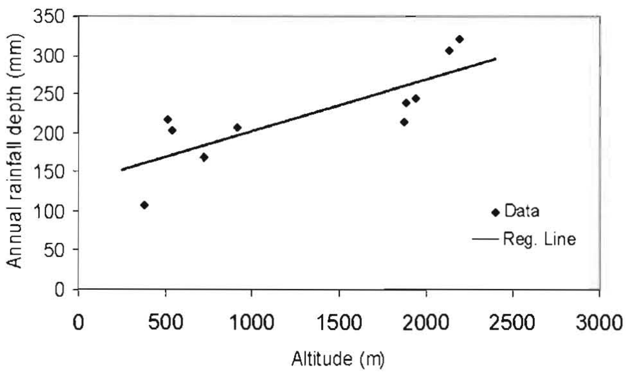

Fig. 4. Relation Between Altitude and Mean Annual Rainfall Depth.

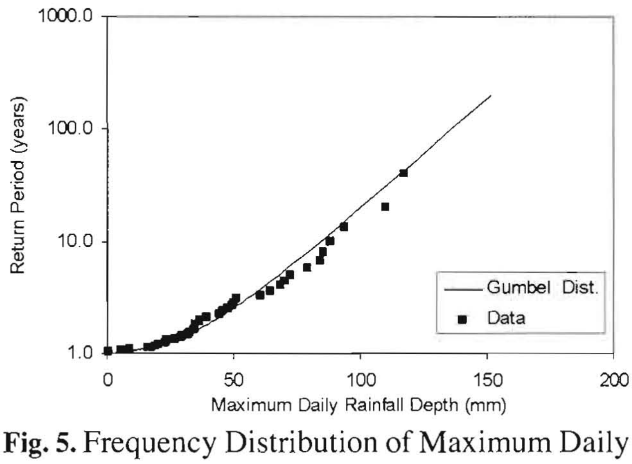

Fig. 5. Frequency Distribution of Maximum Daily Rainfall for Station J205.

RUNOFF CHARACTERISTICS

Runoff in Namman basin has usually flash flood characteristics due to the high slope of the upstream catchments and due to the characteristics of rainfall in the region which are usually of short duration and high intensity. There is only one runoff gauge station (J402) located within the basin at the down stream of the intersection of three major tributaries of the basin. The total drainage area of the tributaries which contribute to runoff at the location of the runoff gauge is 383 km^2, representing about 57% of the total drainage area of Namman basin.

The runoff gauge was operating for 22 years during the period 1977 to 1998. According to the record of the runoff gauge station, there were 54 days in which runoff were observed. Unfortunately, the records provide information of mean runoff discharge but no information about runoff hydrographs are available. Figure 6 shows values of mean monthly runoff volume which were computed from the 22 years records of the runoff station. The figure indicates that runoff occurs mainly during fall season and it is very rare during the summer. Values of runoff volume are high in the months of October, November and December, while values of rainfall depth (as shown in Figure 2) are high during these three months and also in the months of April and May. i.e., values of runoff coefficients are higher in the fall season compared to the spring season, and they can be partially attributed to the fact that rainfall events tend to occur in consecutive days in late fall and early winter while it is more temporally scattered during the rest of the year. Consecutive rainfall events keep soil moisture high and hence increase the probability of runoff occurrence with relatively large discharges. On the other hand, runoff discharges resulted from temporally scattered rainfall events, for which time between storms is large, are expected to be small even for events with relatively large rainfall depth. Values of runoff volumes presented in Figure 6 and their corresponding values of monthly rainfall depths suggest that runoff events which occur during the months of April and May have larger hydrologic abstractions due to evaporation compared to runoff events which occur in November and December.

The runoff records indicate that values of many runoff volumes were low. Out of the fifty four runoff events, twenty of them have runoff volume below 5000 cubic meters. In fact, runoff volumes were less than 1000 cubic meters for five of these events. Therefore, during 22 years only 34 runoff events produced runoff volume greater than 5000 cubic meters which means less than two events per year. Indeed, the ratio between the number of runoff events (less than 2) and the number of rainfall events (about 29 per year) is about 5%. Therefore, most of rainfall events did not produce surface runoff which can reach the location of the runoff gauge station. However, they may produce local and relatively small runoff at the up-stream locations of the basin. Moreover, the runoff gauge is located almost in the middle of the basin which means that runoff need to travel an extra 15 km to reach the outlet of the basin, during which significant hydrologic abstractions are expected due to infiltration and evaporation. Hence, runoff which may reach the outlet of the basin is expected to be very rare and it may occur only once in every several years. In conclusion, most, if not all, water which flows as surface runoff stay within the boundary of the basin and infiltrate within few hours of the occurrence of the runoff process.

The runoff records show that runoff was a single day event for 32 of the recoded events but it continues for two or three successive days for the rest of the events. Many of the multiple days runoff events resulted from single rainfall event and the recorded flow in the second and third days can be considered as base flow. For the purpose of computing runoff coefficient, runoff events which continue for multiple successive days were counted as a single runoff event and runoff volume of this event was computed as the sum of runoff volumes recoded in these successive days. Runoffs in successive days were considered as separate events only if they were resulted from significant successive rainfalls. Using this criterion, the number of runoff events was found to be 39 events.

Runoff coefficients for the 39 runoff events recoded by station J402 were computed. Since the runoff is produced by the eastern part of the basin, values of rainfall depths recorded by six rainfall stations which best represent rainfall on that part of the basin were used to compute average rainfall depths for the days at which runoff was recorded by the runoff gauge station. These stations were TA205, TA209, TA106, J205, J204 and J113. Values of rainfall depth, runoff volume and runoff coefficients for the 39 observed runoff events are presented in Table 4. The computed values of runoff coefficient vary from 0.0003 to 0.0623 with mean value of 0.013. Hence, on the average less than 2% of rainfall depth contributes to runoff and the rest infiltrate through the alluvial deposits of the basin. The average value of rainfall depths which produced runoff was found to be about 15 mm.

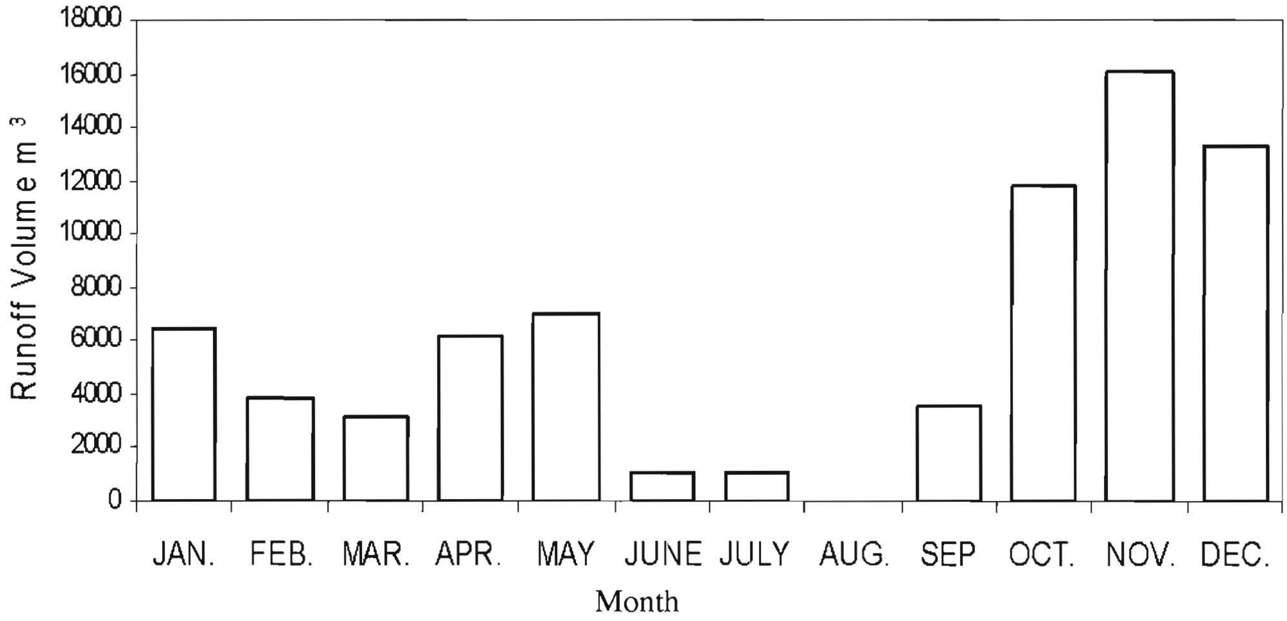

Fig. 6. Mean Monthly Runoff Volume.

Table 4. Characteristics of Runoff Events.

Storm Date	average rainfall depth (mm)	Runoff Volume (m3)	Runoff coefficient	Storm Date	Average rainfall depth (mm)	Runoff Volume (m3)	Runoff coefficient
31/07/1977	11.3	230000	0.0532	03/11/1985	7.2	4147	0.0015
15/02/1978	8.5	185000	0.0568	18/12/1985	55.3	6739	0.0003
17/02/1978	18.6	390000	0.0547	21/02/1986	2.6	394	0.0004
28/10/1979	10.0	42768	0.0111	02/03/1986	6.3	149472	0.0623
09/02/1980	16.2	82896	0.0134	13/04/1987	22.1	27606	0.0033
27/05/1982	7.6	2592	0.0009	24/05/1987	7.9	15552	0.0052
24/09/1982	5.9	34128	0.0152	28/05/1987	15.2	57024	0.0098
25/09/1982	4.1	7517	0.0048	16/10/1988	5.0	3456	0.0018
27/09/1982	2.5	5098	0.0054	11/01/1992	55.0	159840	0.0076
11/10/1982	5.5	3197	0.0015	15/05/1994	6.7	112320	0.0440
12/10/1982	9.3	7517	0.0021	03/01/1996	16.1	73440	0.0119
13/10/1982	8.8	4147	0.0012	25/11/1996	7.0	95040	0.0353
14/03/1983	15.7	15545	0.0026	06/12/1996	5.4	30240	0.0147
26/03/1983	15.8	15552	0.0026	08/01/1997	5.5	5184	0.0025
24/01/1984	1.1	2805	0.0053	16/10/1997	6.6	25920	0.0103
16/12/1984	1.0	1379	0.0035	18/10/1997	7.8	25920	0.0087
17/12/1984	3.4	1834	0.0014	28/10/1997	8.8	17280	0.0051
28/01/1985	34.3	13478	0.0010	04/05/1998	11.6	73440	0.0166
01/11/1985	10.6	4579	0.0011	08/03/1998	142.4	34560	0.0006
02/11/1985	10.9	156643	0.0377				

CONCLUSION AND RECOMMENDATIONS

Namman basin has a strategic location between Makkah and Taif cities in western Saudi Arabia. The results of the study indicated that mean annual rainfall volume of Namman basin is about 143 MCM. Therefore, a proper management of water recourses of Namman basin can contribute to satisfy part of the water demand of these two major cities in the country. Nammn basin has a quite dense rain gauge network and one runoff gauge station. however, most of these rain gauges have been stopped in the last decade. In addition, publications of hydrological data by the Ministry of Water and Electricity have been stopped since 1986. Therefore, it is recommended to pay more attention to rainfall and runoff data measurements and to establish databases for rainfall and runoff data in the region.

The results of the study show that surface runoff rarely reach the downstream of the basin since it infiltrates through the alluvial deposits. Due to the small volume of runoff and its spread over large area of the alluvial, infiltrated water stay in the top layer of the deposits and a large portion of it evaporates as a result of the arid hot climate of the region. It is recommended to keep (or slow down the movement) of the surface runoff in the upstream of the basin so it has the chance to deeply percolate and participate in the recharge of the groundwater aquifer of the basin. This objective may be achieved through constructing small dams in the upstream of the basin to prevent the surface runoff from traveling for long distances in the main channels of the basin.

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Ref, No, (2460)
Received 11/ 10/ 2007
In-revised form: 21/ 02/ 2008