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TOPOGRAPHIC, SEASONAL AND ARIDITY INFLUENCES ON RAINFALL VARIABILITY IN WESTERN SAUDI ARABIA

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In the Western region of Saudi Arabia, rainfall is characterized by variability in space and time. The mean annual and seasonal rainfall are investigated on the basis of the records of 30 stations over the course of 35 years revealing a positive relationship with elevation. Four representative stations with complete records are selected to determine the aridity index of the area. The results show that the spatial variation of annual rainfall moderately reflects the effect of topography. Seasonal isohyet maps are more practical than annual ones in arid regions due to the interaction between different sources of moisture. Seasonal maps can also be helpful in identifying recharge and flood estimation. The aridity index classifies the study area as having desert conditions and a water deficit except the mountainous areas which can be described as semi arid. The results are important for future climate and water studies in Western Saudi Arabia.

INTRODUCTION

Climate is the fundamental factor shaping the natural environment for it sets the stage upon which all physical, chemical and biological processes operate. This becomes especially evident in the climate changes of the earth. Great environmental contrasts occur within short distances as a result of the diverse topography and the highly variable nature of the energy and moisture fluxes within the system. This is especially true in the western part of the Kingdom of Saudi Arabia and along the Red Sea coastal areas, where adjacent to the Tihamah, the rather flat coastal area about 50 km in width, there is a sharply rising mountain chain that reaches elevations greater than 1500 m, especially to the north where the Hijaz Mountains lie.

One of the main targets in studying the hydrological and environmental characteristics of any area is to identify the major factors affecting the magnitude and distribution of climate parameters, such as rainfall, air mass movement, the distance from the source of moisture, temperature, pressure, and topography of watersheds. In arid and extremely-arid regions, the magnitude and distribution of these parameters vary spatially and temporally affecting the hydrological cycle of the area. Description and prediction of the rainfall variability in space and/or in time are fundamental requirements for a wide variety of human activities and water project designs.

In Saudi Arabia, rainfall can be described as very scarce and unpredictable as well as irregular, but very extensive during local storms. In addition, the rate of evaporation is very high. In Western Saudi Arabia rainfall occurs sporadically in space and time due to the climate being affected by tropical air masses from the Atlantic Ocean and by maritime polar air masses coming from the Mediterranean Sea in addition to monsoon effects from the Indian Ocean during late summer and fall seasons (Sen, 1983; Aljerash, 1989; Subyani et al., 2009).

The main purpose of this study is to find out the pattern of rainfall variability in Western Saudi Arabia. This includes the relative importance of both spatial topographic and temporal variability on an annual and seasonal basis, in addition to determination of simple aridity indices for the study area.

GEOGRAPHIC SETTING

The study area is located in the Western part of Saudi Arabia and is bounded by latitudes 21^{O} 15' and 25^{O} 00' N and longitudes 37^{O} 45' and 41^{O} 00' E (Figure 1) and it is a part of the Arabian Shield that covers one third of the Arabian Peninsula. This area extends from Jeddah city in the South to Yanbu city in the North along the Red Sea coast. It is characterized by a flat coastal plain with high land value, rapid population growth, and fast growing urbanization. From a topographic point of view, the study area can be classified into three regions, the Red Sea coastal plain (Tihamah), the hills (Pediments), and the mountains and basalt plateau (Harrat Rahat). The Tihamah is low in elevation and ranges from zero to 200 m a.s.l. and extends eastward from the coastal plain to medium elevation hills or pediments. The Hijaz mountains seldom exceed 1500 m elevation in the north of study area, and the elevation gradually decreases toward the south of the study area reaching about 600 m around the Holy city of Makkah. The basaltic plateau is characterized by a uniform elevation ranging from 1000 m in the north to less than 700 m in the south.

Climate condition

The climate pattern of the Western province of Saudi Arabia can best be described by looking at the various air masses that affect the rainfall distribution over the area under study. It is a

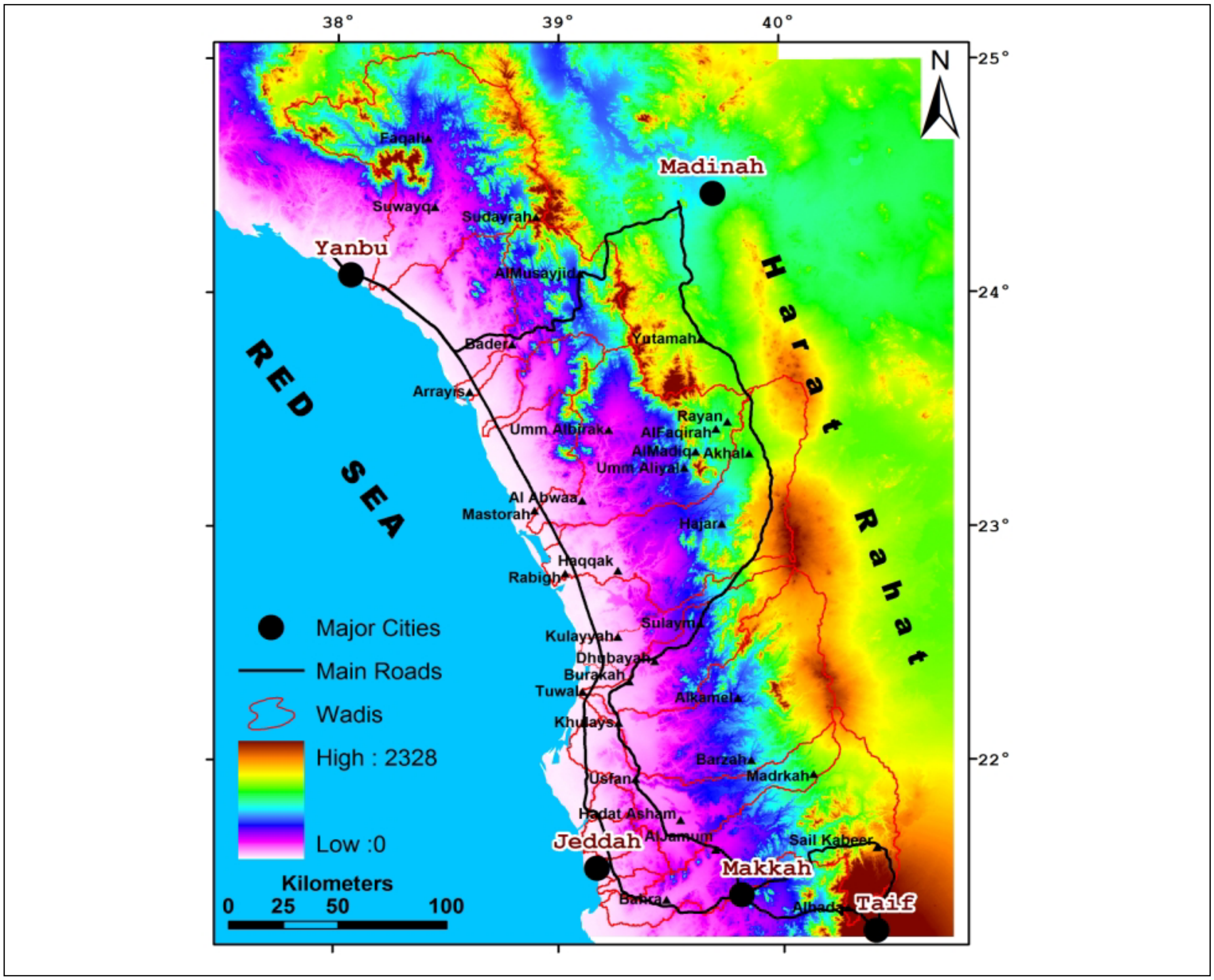

Figure 1. Location map of the study area.

combination of Mediterranean and monsoonal weather patterns, modified by theHijaz Escarpment. (Sen, 1983; Alyamani and Sen, 1992; Subyani, 2004).

Air masses influencing the Kingdom's climate stem from three major fronts of moisture. The monsoon front during the late fall and summer (maritime tropical air mass) that reaches the area from south, southwest, and southeast. This front originates from the Indian Ocean and the Arabian Sea and brings warm and moist air. Outbreaks of westerly air become more frequent and are characterized by medium to high intensity rainfall in the south and southwest of the country. This front often picks up further moisture while moving through the Red Sea trough. In addition to these three major fronts, modification of air mass by topographic effects of the Hijaz Escarpments and the presence of the Red Sea also affect climate conditions.

The study area with different physiographic and topographic features is predominantly arid and very hot in summer in Harrat, to semi arid with hot summers in the coast, cooler winters in mountains and from high to moderate seasonal air temperatures, high incident radiation, and high wind speeds that often cause dust storms, especially in the coast.

Mean annual rainfall

The climate data used in this research are collected from the Hydrology Division of the Ministry of Water and Electricity (2007). The available rainfall records cover a period of 25-35 years

(1970-2005). Some of these stations do not cover the same time intervals and there are gaps in some records. However, the rainfall stations are chosen based on the following criteria that: 1) they provide a good spatial coverage of the region; 2) they provide data for similar periods; 3) they have continuous monthly rainfall records; and 4) they represent all different climatic and topographic conditions.

Due to the different morphological units in the study area, Tihamah, foothills, and mountains, the climate recording stations were lumped according to their location and related to one of these three morphological units. Table 1 summarizes average rainfall and temperature data. This table shows high variation in the mean rainfall from coastal areas to mountains (5 times). On the other hand, the temperatures in the foothills are little different from coastal areas, whereas the differences are greater between foothills and the mountains.

The mean annual rainfall distribution in Figure 2 shows the spatial variation of rainfall strongly reflecting the effect of topography, where the annual rainfall generally increases with elevation (Orographic effect). Generally, the eastern part of the area receives a considerably higher amount of rainfall with an average of about 220 mm/year near the Hijaz Escarpment as compared to the western part having an average of less than 100 mm/year near the Red Sea coast (low lying areas, Tihamah). The general tendency for the rainfall is to be more regular in the highlands than the coastal plain. During the late morning the sun warms up the sea surface causing the evaporation of sea water, followed by the condensation and the formation of clouds. The winds take over these clouds from the sea towards the escarpment crossing over the coastal plane and the foot hills. As the clouds rise and reach the escarpment with low temperature, rain starts to fall.

Rainfall-elevation relation

The variation of annual rainfall with elevation is investigated in the study area. Figure 3 shows the plotting of the mean annual rainfall of the available stations versus the elevation in the study area with a general regression relation indicating a positive relation between rainfall and elevation ($r^2 = 0.5828$). However, the strength of the relationship is affected by some outliers as can be seen in Figure 3 which shows that some low elevation stations receive higher amount of rainfall while some high elevation stations receive low amounts. The Pearson correlation coefficient has a value of $r = 0.75$ for the whole area. The result shows a strong and significant correlation and reflects the variation of rainfall in the study area.

Generally, in these three regions, the maximum amount of annual rainfall does not always occur at the highest elevation. This indicates that the elevation is not the only factor in rainfall distribution. Other geographic factors, such as distance from the source moisture, temperature and pressure, and topography are also important. Another main factor as found in this analysis is the time factor (i.e. seasonality). Hence, the rainfall distribution is not uniform in time or in space, it should be treated and analyzed as spatiotemporal phenomena.

Table 1. Average rainfall and temperature for main morphological units in the study area.

Topographical Units	Rainfall (mm/year)			Temperature (ºC)		
	Min.	Mean	Max.	Min.	Mean	Max.
Coastal Area	17	50	100	24	32	39
Foothill Area	103	170	230	22	29	34
Mountain Area	70	325	650	16	22	28

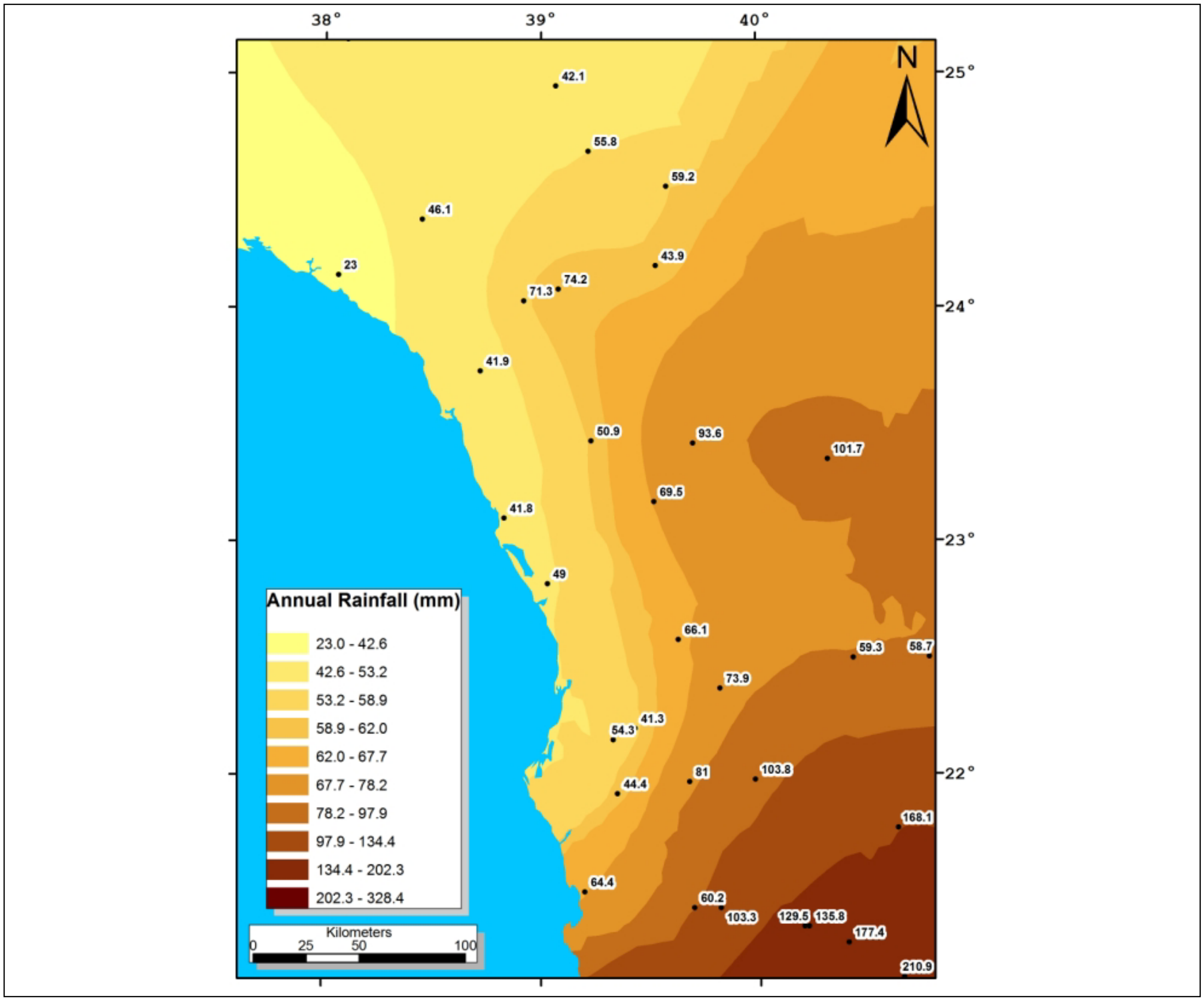

Figure 2. Mean annual isohyetal map.

Mean Seasonal rainfall

Due to the spatial and temporal variations in rainfall, especially in arid and semi arid regions, the mean annual rainfall distribution cannot give a clear idea about the different mechanism of climate conditions. Isohyet maps are prepared on a seasonal basis since seasonal figures are more practical than annual ones. The seasonal isohyet maps can be interpreted as follows:

· During winter (December-February): Rainfall amounts increase towards the south due to the topography (Figure 4). The highest rainfall (47 mm) is near the high mountains close to Taif City over the Escarpment in the south and decreases gradually towards the north. Rainfall is usually associated with weak influxes of moist cold air of westerly Mediterranean origin, which is coupled with the local effects of the Red Sea and Escarpment with orographic rainfall occurrences. In addition, the Red Sea coastal area receives a significant amount of rainfall that decreases from south to north (form 24 mm to 10 mm). Areas within more than 20 mm isohyet are relevant for groundwater recharge. The study area receives the highest amount of rainfall during winter and the basins are subject to floods.

· During spring (March-May): Figure 5 shows a different rainfall pattern. The maximum rainfall (100 mm) is in the high mountains near Taif City and decreases gradually from the west

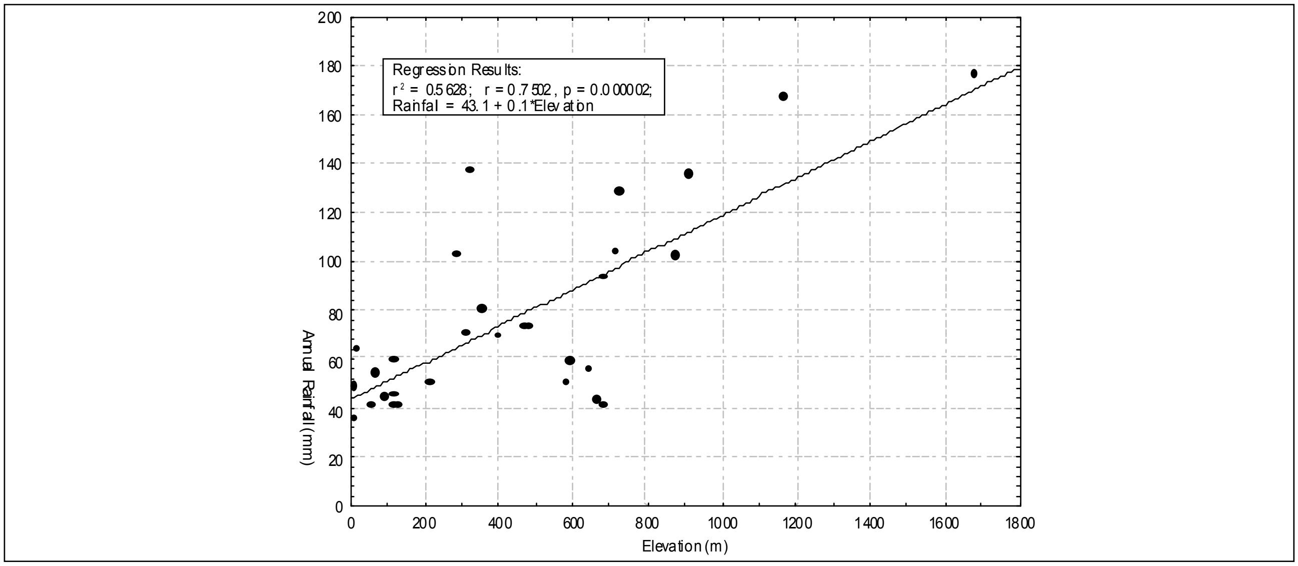

Figure 3. Rainfall-elevation relation in the study area.

towards the east. The equal spacing of the isohyets indicates that the spatial variation in rainfall is less than in the winter season. This is due to the Red Sea convergence zone and the Mediterranean depression, which distribute rainfall all over the region with good potential for groundwater recharge.

· During summer (June-August): Figure 6 shows that during the summer season there is very little rainfall with the exception of the Taif scarp mountains where rainfall is about 30 mm due to monsoon conditions, which create thunderstorms along the escarpment and the southern part of the Red Sea coast. There is no significant impact of rainfall on the recharge mechanism.

· During fall (September-November): Figure 7 shows that the fall pattern of rainfall is similar to that of winter, because the southeasterly air stream weakens as a result of increasing outbreaks of northwesterly air streams. The highest rainfall (50 mm) is in the scarp mountain areas of the Taif area and decreases gradually towards the north. The Red Sea coastal area receives a good amount of rainfall decreasing from south to north (form 30 mm to 10 mm). Areas within more than 20 mm isohyet are relevant for less groundwater recharge due to the previous dry summer season. However, the area is also subject to floods.

Aridity index in the Study Area

Arid and semiarid regions are subject to rainfall deficiencies. An aridity index is a numerical indicator of the degree of dryness of the climate at a given location. A number of aridity indices have been proposed, these indicators serve to identify, locate, or delimit regions that suffer from a deficit of available water (UNEP, 1997). In this report, the simple aridity index (AI) is used. It is the ratio of the average monthly rainfall to the average monthly potential evapotranspiration. In general, the boundaries that define various degrees of aridity and the approximate areal classifications are presented in Table 2.

Table 2. Climate classification and aridity indices.

Classification	Aridity Index
Hyperarid	$AI < 0.05$
Arid	$0.05 < AI < 0.20$
Semi-arid	$0.20 < AI < 0.50$
Dry sub-humid	$0.50 < AI < 0.65$

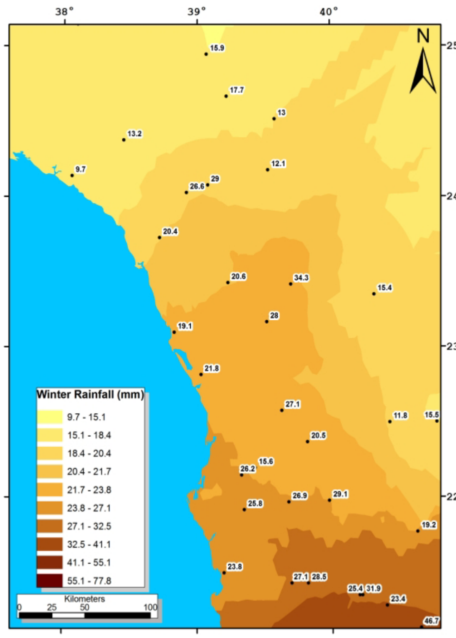

Figure 4. Isohyetal map for winter rainfall.

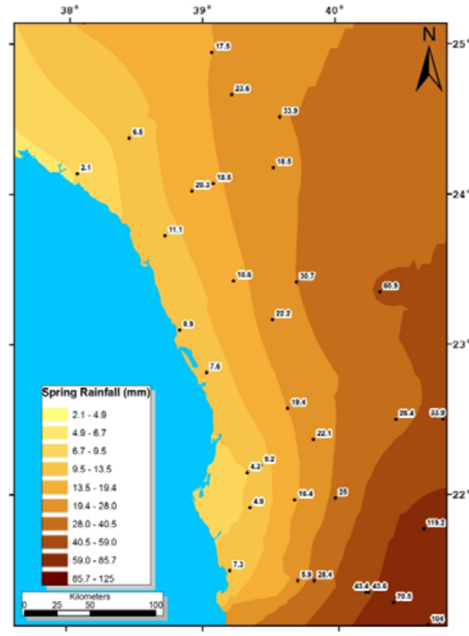

Figure 5. Isohyetal map for spring rainfall.

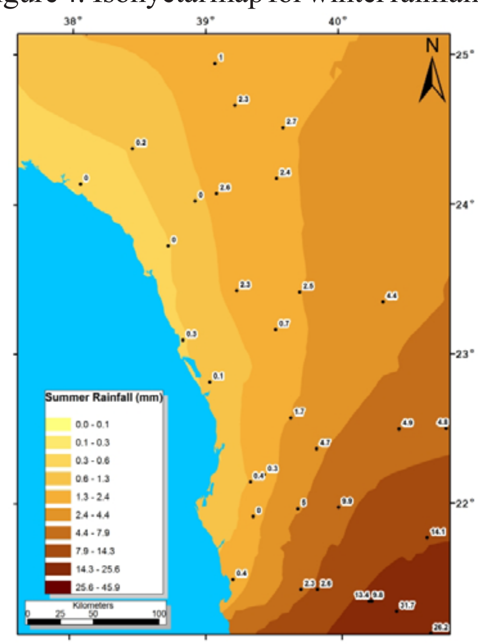

Figure 6. Isohyetal map for summer rainfall.

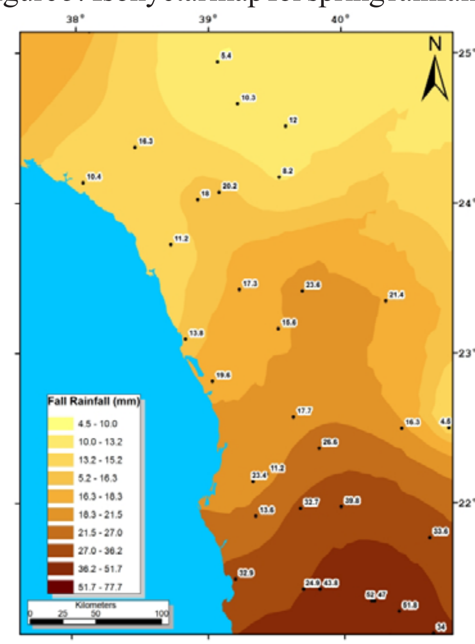

Figure 7. Isohyetal map for fall rainfall.

In the study area, four main meteorological stations are selected for average monthly rainfall and temperature for the period 1970-2004. The Jeddah and Yanbu stations are located on the coast (Tihamah), the Taif station is located in the mountain area (1500 m a s l) and the Madinah station is located in Harrat Rahat (600 m a s l).

Figure 8a shows the average monthly rainfall at Jeddah station, which indicates that the maximum rainfall occurs mainly in the winter but winter rainfall is heavier than spring rainfall. In addition, November rainstorms are the strongest and usually in the form of floods. Figure 8b shows the average monthly temperature which ranges from 25 ^{O}C in winter to around 30 ^{O}C. Potential Evapotranspiration (PE) is also shown in Figure 8c indicating a high rate in summer (200 mm) and about 100 mm in winter.

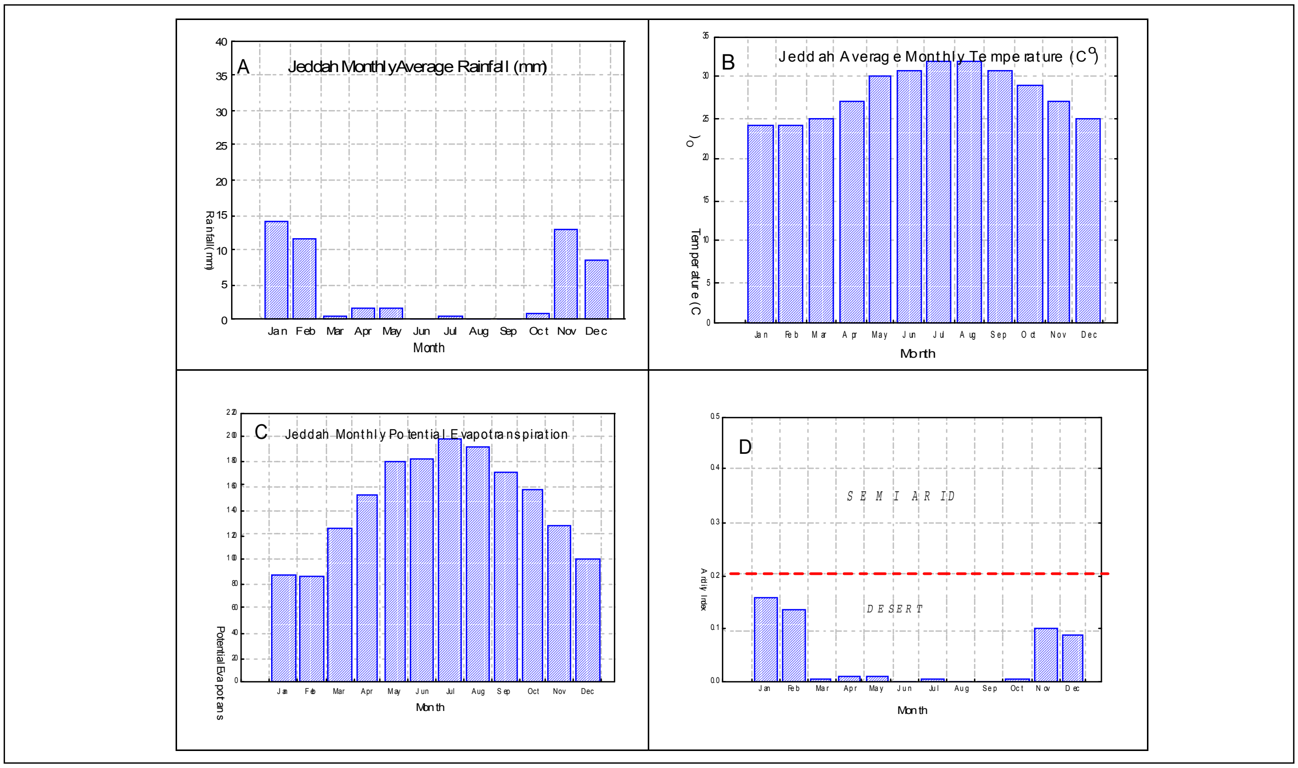

Figure 8. Meteorological data from Jeddah station: (a) rainfall; (b) temperature; (c) potential evapotranspiration; (d) Aridity index (1970-2004).

Figure 8d gives the monthly aridity index at the Jeddah station; it is between 0.0 and 0.2, which indicates that the area is subject hyper-arid to arid conditions all the year.

Rainfall at the Taif station occurs throughout the year, with the highest values in the spring season (Figure 9a). Figure 9b shows the average monthly temperature, which has summer highs between 25-27 ^{O}C. In winter, it ranges from 15 to 18 ^{O}C. Dividing precipitation by potential evapotranspiration (Figure 9c) one can get the aridity index as in Figure 9d which indicates that the Taif area aridity feature ranges from desert conditions in summer to semi-arid conditions in spring and winter.

Towards the northern part of the study area, the Yanbu meteorological station near the Red Sea coast has very little monthly rainfall in winter and spring, and no rain in summer (Figure 10a). This is due to the Yanbu city location in the shadow zone of Mountains in the east, which has an impact on the winter and spring rainfall seasons with air masses from the Mediterranean towards north and northwestern parts of the Arabian Peninsula. In summer, Yanbu does not benefit from the summer monsoon rainfall season due to its location. Figure 10b shows the average monthly temperature, which has summer highs of 28-33 ^{O}C. In winter, it is exposed to temperature variations between 20-25 ^{O}C. Dividing precipitation by potential evapotranspiration (Figure 10c) one can get the aridity index as shown in Figure 10d, indicates that Yanbu area is under hyper-arid condition.

The Medinah station is located in the north eastern part of the study area, in Harrat Rahat (600 m a s l). Figure 11a shows that precipitation occurs mainly in spring and comparatively in lesser amounts during winter. It can be seen from Figure 11b that the average monthly temperature maxima in summer varies between 32-35 ^{O}C in winter from 17 to 20 ^{O}C. Division of precipitation by potential evapotranspiration as given in Figure 11c leads to the aridity index as in Figure 11d, which indicates that Madinah area aridity classification ranges between hyper-arid conditions in summer and arid conditions in spring and winter.

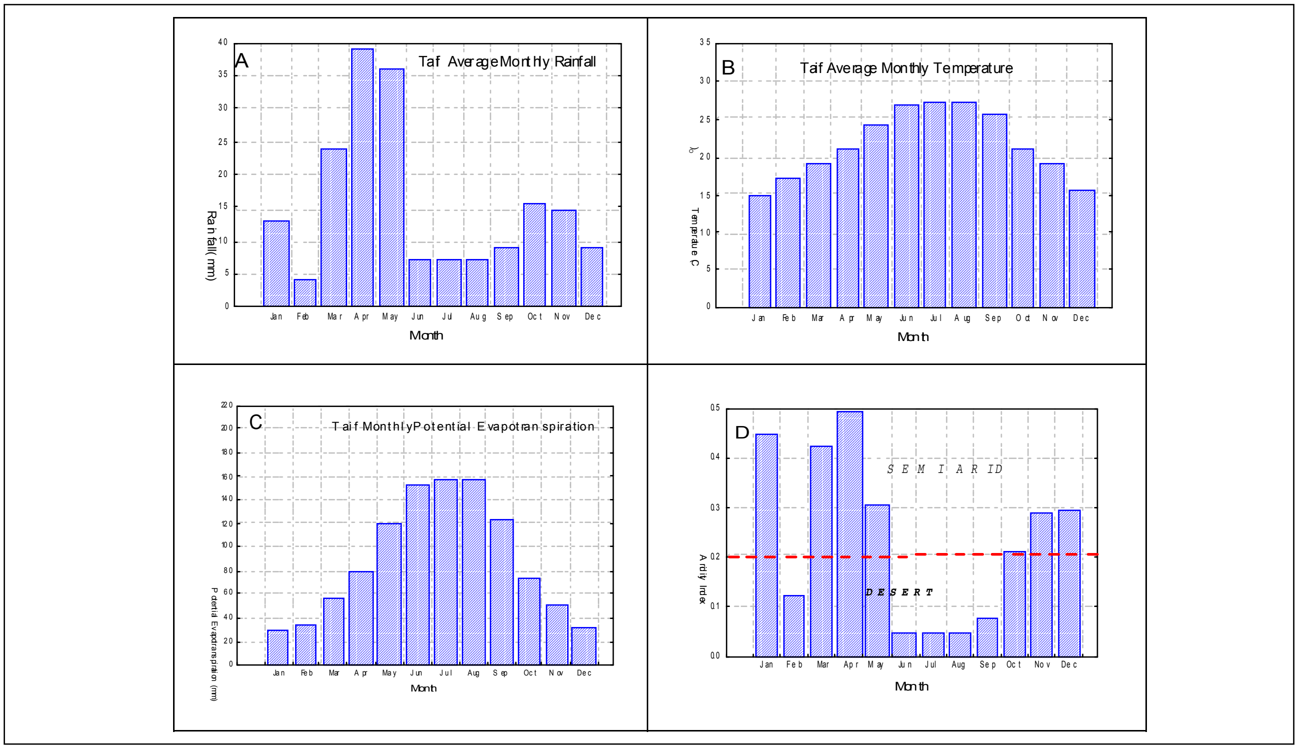

Figure 9. Meteorological data from Taif station: (a) rainfall; (b) temperature;

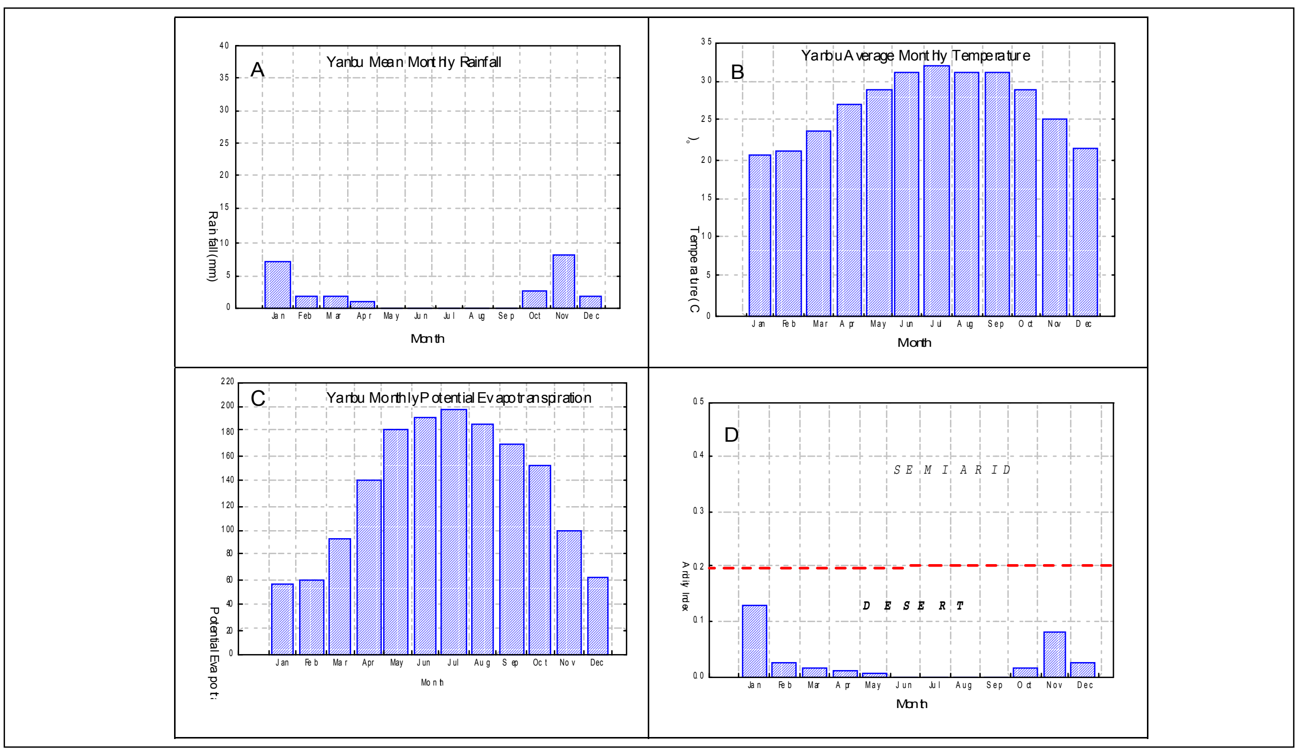

Figure 10. Meteorological data from Yanbu station: (a) rainfall; (b) temperature; (c) potential

CONCLUSION

Rainfall is one of the most important factors for hydrologic assessment in arid regions. Hydrological assessment is concerned with floods, evaporation, infiltration, stream flow and sediment transport. In western Saudi Arabia, available rainfall records at a set of meteorological stations cover periods of 25-35 years (1970-2005) and they are utilized to produce mean annual

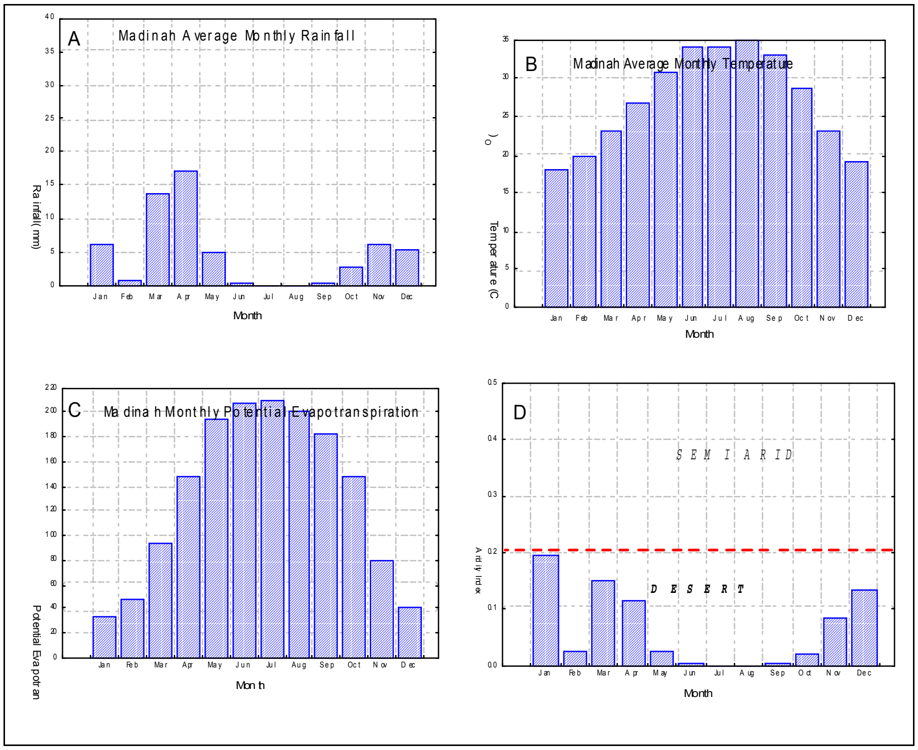

Figure 11. Meteorological data from Madinah station: (a) rainfall; (b) temperature; (c) potential evapotranspiration; (d) Aridity index (1970-2004).

and seasonal rainfall maps for the study area. In addition, the simple aridity index (AI) is used for some data in order to identify, locate or delimit regions that suffer from a deficit of available rainfall. The amount of annual rainfall changes considerably from year to year, which indicates the sporadic and haphazard nature of rainfall events. In general, rainfall is predominant in the mountain areas during winter due to the Mediterranean effect, and it is widespread in all areas during spring because of the local diurnal circulation effects. Summer and fall season rainfall amounts are insignificant except for the local orographic rain storms. In order to identify in greater detail the regional rainfall features in the study area, it is necessary to establish additional daily rainfall stations.

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