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Spatial Analysis of Rainfall in Southwest of Saudi Arabia using GIS

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A Geographic Information System was used to study the characteristics and distribution of precipitation in southwest of Saudi Arabia based on a number of influencing factors including elevation, mountain slope and orientation, distance from moisture source and equator, wind direction, and geographic location. Results indicate that elevation explains about 25% of variability in precipitation in most of the seasons. Other factors such as aspect, slope, distance from moisture source have different effects but less than the effect of elevation. Finally a polynomial trend surface has been generated to correlate geographic location with precipitation and has shown a coefficient of determination of 70%.

Introduction

Studying precipitation amount and distribution is essential for the design of different engineering projects such as storm-water sewer systems and flood and drought control. Globally, rainfall varies in amount over space from almost zero mean annual value in some very extreme arid regions to a value of 11,680 mm in Mt. Waialeale, Hawaii, USA, with average land surface annual value of about 800 mm (Chow *et al.* 1988). The geographic distribution of rainfall depends on two main categories of factors: topographic factors and climatic factors. The first category includes elevation, mountain orientation, slope of mountain side, leeward and windward positions, and distance from source of moisture. The second one includes atmospheric conditions, storm types, seasonal patterns and wind speed and direction.

Among all the above-mentioned factors, it is believed that elevation is the most important one affecting both the quantity and distribution of precipitation specially in the mountainous regions (Lee 1911; Donley and Mitchell 1939; Bonacina 1945; Peck and Brown 1962; Chang 1973; Wolfson 1975). Annual and monthly orographic rainfall have been found to increase with altitude in different mountainous areas, however, the type of that increase changes from place to another and from time to time where other topographic and climatic factors determine such relation. According to Bonacina (1945), the amount of rainfall generally increases with increasing elevation up to a certain level approximately below 3,000 m.

Taylor (1980) applied multiple regression analysis to the state of California, USA using precipitation as the dependent variable and latitude and distance from sea line as the independent variables. A high regression coefficient (R^2) of 0.94 was produced. Dhar and Rakhencha (1981) found that relation between rainfall and elevation in Himalayas, India, can be expressed as a polynomial model of fourth degree. The orographic effect on mean annual rainfall in New Hampshire and Vermont, USA, was studied by Dingman *et al.* (1988) and a simple linear relation was developed between mean annual rainfall and geographic location with (R^2) of 0.694. Loukas and Quick (1993) conducted a study of a mountainous watershed in Southwest British Columbia, Canada. It was found that storm rainfall for each event increases up to a mid-elevation of the study watershed, and then decreases at higher elevations. In orographic precipitation, slopes may have a considerable effect on the lifting mechanism of air over mountain barriers. A study by Pockels (1981) concluded that the angle of slope is more important than elevation in determining the amount of orographic precipitation in the considered study area.

The southwest of Saudi Arabia, which is the area of concern in this study, has been studied by Alehaideb (1985). Several relationships between rainfall and topography using isohyetal method, harmonic analysis, and regression techniques were generated. Alehaideb concluded that the first harmonic analysis was the best technique to describe rainfall distribution in the study area. Relationships between mean annual rainfall and elevation in the mountainous and plateau stations and Red Sea coast stations were significant with (R^2) equal to 0.53 and 0.65 respectively. The same area was also investigated by Nouh (1987). Different distribution functions were fitted for point rainfall records of 71 stations. The study revealed that the amount of rainfall at a given location in the region is of seasonal nature and is greatly associated with the altitude and the slope of land at that location.

Design rainfall characteristics for southwest of Saudi Arabia were analyzed by Wheater *et al.* (1989). Considering intensity-duration-frequency and point to areal rainfall relationships, a complex regional pattern of rainfall intensity characteristics was identified based on short-term rainfall data and obtained from raingauges available in the area.

The complex nature of the above mentioned factors affecting precipitation requires an effective and efficient tool for handling the tremendous volume of data and providing spatial modeling capabilities. Geographic Information Systems, GIS, have recently been used by some researchers as a powerful technique for storing, analyzing, and displaying spatial data. Shih (1990), as an example, used GIS and remote sensing to monitor rainfall in Florida, USA, where eleven convective clouds that covered 26 raingauge stations were analyzed.

The main objective of this paper was to investigate the capability of GIS in studying the spatial variation of precipitation in southwest Saudi Arabia. The analysis aimed to develop relationships between rainfall and number of influencing factors including elevation, mountain orientation and slope, distance from moisture source and equator, and wind direction. The temporal variation has also been investigated since these relationships are expected to vary not just from one place to another but also from time to time.

Site Description

The southwest of Saudi Arabia is mostly mountainous. This region receives the highest amount of precipitation in the country with an average annual amount of about 400 mm on the mountains and 200 mm on the whole area. The area (220 km × 600 km) lies approximately between latitude 16°N on the south and latitude 22°N on

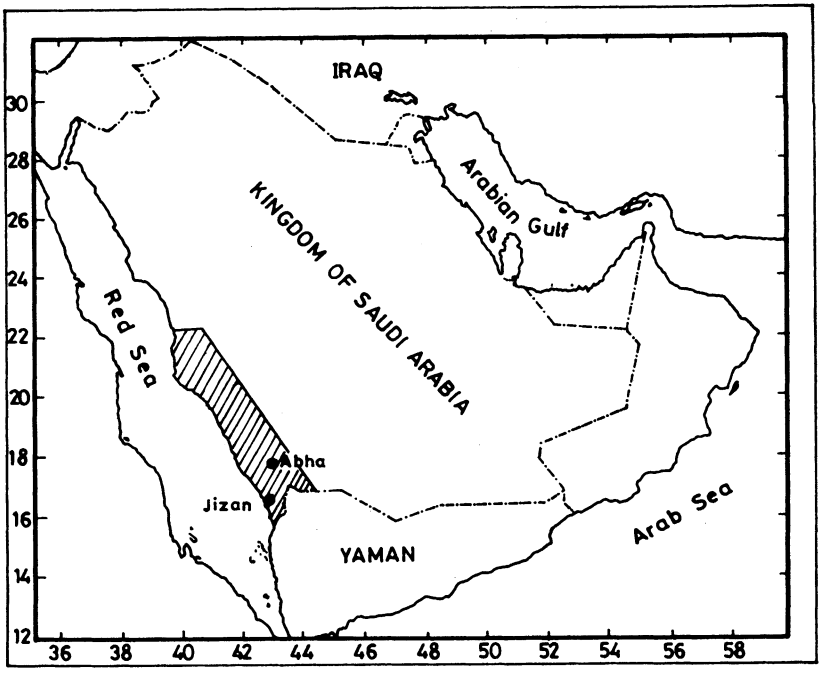

Fig. 1. Study Area (after Alehaideb 1985).

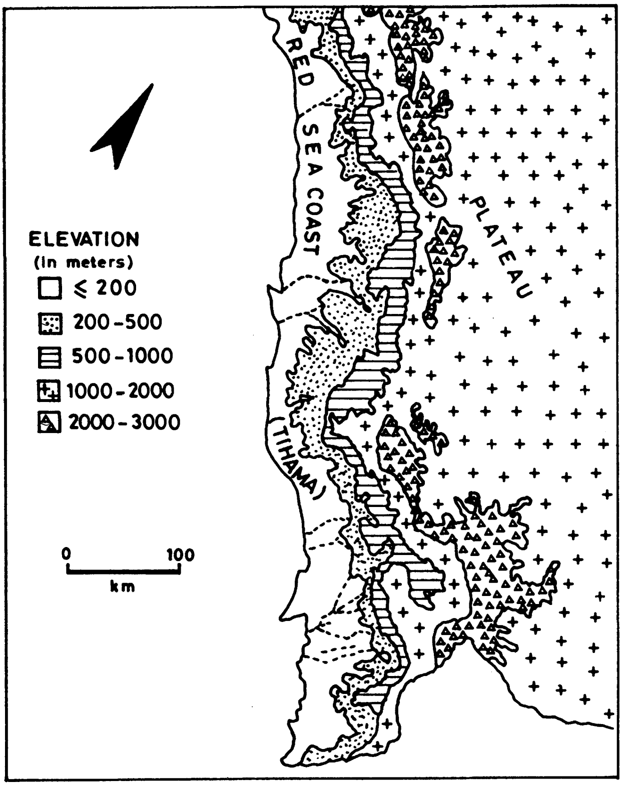

Fig. 2. Topography of the southwest region of Saudi Arabia (after Alehaideb 1985).

the north, while it is bounded by the Red Sea on the west (39°E) and longitude 45°E on the East as shown in Fig. 1. The terrain of the region can be divided into three zones as described by Alehaideb (1985): the Red Sea coastal plain, the Hijaz and Asir escarpment, and the Hijaz plateau, Fig. 2.

1) The Red Sea coastal plain (Tihama) is a narrow coastal strip. The width of the Tihama zone varies from zero in the north to about 40 km in the south near Jizan. In general, the climate in this zone near the Red Sea is hot and humidity is high.
2) The Scarp-Hijaz mountains extend from north to south parallel to the Red Sea. The width of the Scarp mountains ranges between 30 km to 140 km toward south and ranges from about 1,600 to 3,000 m in height. The climate of this zone is temperate and gets cooler with elevation.
3) The Hijaz plateau is relatively flat. Its elevation varies from 200 m to 1,800 m. The area is characterized by moderate climate that becomes warmer towards east and far away from the Scarp mountain. Compared to the other two zones, Hijaz plateau generally receives less rain which as well decreases further towards east.

Table 1 – Statistical Description of rainfall time-series data (mm)

Month	Mean	St. Error	Median	Mode	St. Deviation	Range	Minimum	Maximum	Number of records
Jan	19.15	1.23	13.85	11.50	16.86	94.60	0.20	94.80	188
Feb	16.38	1.17	10.80	8.40	16.11	86.90	0.00	86.90	188
Mar	20.83	1.31	16.15	34.60	18.00	117.50	0.00	117.50	188
Apr	28.15	2.44	20.10	14.90	33.44	251.50	0.00	251.50	188
May	25.01	1.57	19.65	0.00	21.56	91.70	0.00	91.70	188
Jun	6.82	0.72	3.10	0.00	9.84	52.10	0.00	52.10	188
Jul	13.20	1.16	7.90	0.00	15.84	125.00	0.00	125.00	188
Aug	17.91	1.63	8.75	0.00	22.35	122.00	0.00	122.00	188
Sep	13.52	1.41	4.80	0.00	19.32	104.40	0.00	104.40	188
Oct	14.51	1.22	9.75	0.00	16.68	117.50	0.00	117.50	188
Nov	10.72	0.92	7.25	0.00	12.59	95.00	0.00	95.00	188
Dec	12.67	0.96	8.20	0.00	13.20	99.00	0.00	99.00	188
Annual	198.87	9.99	166.90	442.30	136.94	693.60	17.90	711.50	188

Data Description

The study area is covered by 188 raingauges installed by the Ministry of Agriculture and Water (MOAW), Saudi Arabia. The monthly and annual rainfall data for these raingauges for the years 1975 to 1984 are published by MOAW in its hydrologic report 113. Statistical descriptions of these data are shown in Table 1 presenting 10-year average values for each month. Statistics show that the spring season (March, April and May) has the highest precipitation over the year in which a maximum average value of 251 mm was recorded in April. The average and standard deviation of the annual precipitation of 198.9 and 136.9 mm (coefficient of variation, $Cv = 0.69$) respectively indicate a high spatial variation over the region. The average monthly precipitation, on the other hand, is also highly variable as indicated by the high Cv values (0.86-1.44). This high variation can be explained by the wide extent and rugged terrain of the region varying from mountainous to coastal areas.

The GIS Approach

In this project it is intended to fully utilize GIS, that is data capturing, editing and analyzing as well as presenting results to be all performed within the GIS environment. In other words, the capabilities of GIS, represented by a commercial raster GIS package know as IDRISI, in analyzing rainfall is to be investigated through this case study. More elegant software might be available but IDRISI has the advantage of providing a wide range of modeling functions offered at an affordable price.

Building the Data-base

Building the data-base was the most critical and the most time-consuming part of the project. This stems from the fact that the completeness and accuracy of the data-base determine the quality of the analysis and final products. Developing the digital data-base for the area under investigation required three phases:

1) *A design phase:* It involved first determining the boundary of study area, which is described in the previous section. Second step was selecting a coordinate system compatible with the one used on the paper maps. The system selected was the latitude/longitude coordinates. Finally, it involved determining the data layers needed for the analysis, which was the most tedious part of the project. Twenty 600 × 800 base maps of 367m × 750m resolution covering 188 rain stations for the years 1975 to 1984 were required as follows: a contour map with contour interval of 100m; Red Sea shore line map; a raingauge reference map; twelve monthly rainfall maps representing the ten year records; four seasonal precipitation maps – Summer (June-August), Fall (September-November), Winter (December-February) and Spring (March-May); and finally an annual precipitation map.
2) *An automation phase:* This phase involved getting the spatial and attribute information into the data-base. Base maps were digitized using Autocad. Attribute data, on the other hand, were prepared in a spread sheet program (Excel) then exported to IDRISI in which they were linked to the geographic features on the base maps. The automation phase also involved data verification, editing and building topology.
3) *A management phase:* This was accomplished by georeferencing the spatial data so it represents real world coordinates.

Having the GIS data-base developed, the analytical tasks, which are otherwise extremely time consuming or even impossible if done manually, were undertaken.

Estimating the Areal Distribution of Precipitation

An attempt to estimate the areal distribution of precipitation depth over the study area, both Thiessen method and grid-point technique were used. Thiessen method was first applied to generate distributed values on a polygon basis. The raingauge map "XY" was processed and 188 polygons were drawn one around each gauge. Each produced polygon was linked to an attribute table in the GIS data-base summarizing the average monthly, seasonal and annual precipitation in that particular polygon.

Grid-point technique, which is more advantageous than Thiessen method, simply estimates precipitation at all points of a superimposed grid based on given measured values. The method might be impractical unless performed with the aid of powerful computing technology such as GIS. A reliable interpolation procedure (Potential model using a weight equal to the reciprocal of the distance squared) for the 188 station values over a 600 × 800 superimposed grid was performed resulting in an annual precipitation surface. The surface consists of 480,000 values each of which represents the average annual precipitation fallen on that particular grid point. Same procedures were also applied to calculate the average monthly and seasonal precipitation for each grid.

Analyzing the Spatial and Temporal Variation of Precipitation

Literature has revealed that a number of topographic and climatic factors affect rainfall distribution. In this study elevation, slope, aspect, distance from moisture source, and proximity to the equator (expressed in terms of latitude lines) were the topographic factors analyzed. As far as the climatic factors are concerned, wind direction was the only element analyzed since it was found to be the most dominating parameter in the study area (Alehiadeb 1985).

In light of the above, several relationships have been developed using the statistical capabilities of GIS mainly regression analysis and trend surface techniques.

1) Precipitation-Elevation Relationship

Previous studies have shown that elevation is the reason for most of the variation in precipitation in mountainous areas. Accordingly, a digital elevation model (DEM) for the southwestern region of Saudi Arabia was developed. Having the DEM constructed several precipitation-elevation relationships were generated using linear regression applied to the annual and seasonal precipitation for the entire area. Regression results have shown insignificant correlation (< 0.1) between elevation and both annual and seasonal precipitation. This might be justified by the strong interfering effect of the other topographic and climatic factors on these relations.

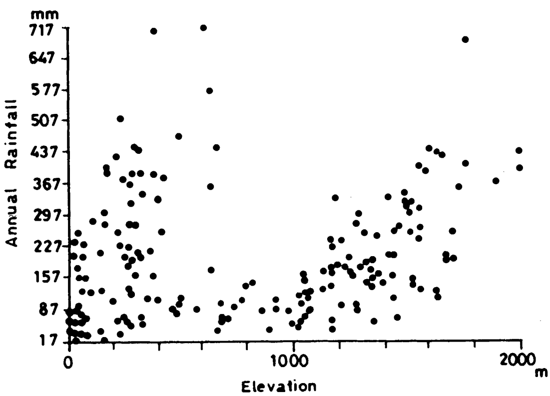

Fig. 3. Elevation *vs.* annual rainfall.

Table 2 – Regression results for the Red Sea coast and foothill (72 stations)

Independent variable	Dependent variable	Correlation coeff.	Goodness of fit	Regression Equation (mm)
Elev. 1	Annual prec.	0.53	28.29	$Y = 117.498 + 0.322x$
Elev. 1	Summer prec.	0.45	20.37	$Y = 33.589 + 0.548x$
Elev. 1	Fall prec.	0.08	0.1	$Y = 45.156 - 0.005x$
Elev. 1	Winter prec.	0.34	11.98	$Y = 37.726 + 0.022x$
Elev. 1	Spring prec.	0.49	24.61	$Y = 1.587 + 0.398x$

* Significant at 95% confidence level

Table 3 – Regression results for the Mountain and plateau (92 stations)

Independent variable	Dependent variable	Correlation coeff.	Goodness of fit	Regression Equation (mm)
Elev. 2	Annual prec.	0.70	49.44	$Y = 175.363 + 0.205x$
Elev. 2	Summer prec.	0.50	25.34	$Y = 46.566 + 0.0438x$
Elev. 2	Fall prec.	0.38	14.95	$Y = -12.952 + 0.020x$
Elev. 2	Winter prec.	0.48	23.42	$Y = -44.558 + 0.0528x$
Elev. 2	Spring prec.	0.58	34.03	$Y = -52.279 + 0.081x$

* Significant at 95% confidence level

Visual observation of Fig. 3 supports the suggestion by Alehiadeb (1985) that the interfering effect can be overcome by dividing the records into two groups: one for the Red Sea coast and foothill stations and another for the mountain and plateau. Repeating the regression analysis based on the suggested divisions, a noticeable improvement has been gained as shown in Tables 2 and 3.

2) Precipitation – Aspect Relationship

An aspect defines the direction that a slope faces (0, 90, 180 and 270 represent north, east, south and west respectively). It is determined as the direction someone would be facing if looking downhill along the line of steepest descent. Relating aspects to precipitation required first, computing the aspect for the 480,000 pixels in the study area. This aspect image which usually require a heavy computational effort was easily produced by the aid of the surface module of IDRISI.

Second, assuming a constant wind direction for each season (Alehaideb 1985), the average spring precipitation, as an example, was regressed against the calculated aspects. Results showed a significant inverse correlation of 0.25. This can be explained by the effect of the northeastern monsoon which causes spring precipitation to be higher on the eastern slopes. A similar relation was also developed for the Red Sea coast and foothill stations but against winter precipitation. The relationship with correlation coefficient of 0.25 has confirmed the argument that stations facing north should receive more precipitation than others since winter winds are northerly to northeasterly over the region.

As an attempt to eliminate the effect of elevation on the developed aspect-precipitation relationship, stations having an elevation of about 1,000 m were only reconsidered. For these selected stations, a line was then fitted relating winter precipitation to locational aspects. A 0.25 correlation coefficient similar to the one obtained above was achieved which indicates that the variation in precipitation was mainly due to the aspect thus explaining about 6% of the variation.

3) Precipitation – Slope Relationship

In orographic precipitation, slopes have a considerable effect on the lifting mechanism of air over the mountain barriers. A study by Pockels (1981) has concluded that the angle of slope is more important than the elevation in determining the amount of orographic precipitation. Accordingly, slope was studied to determine the extent of its effect in the area under investigation. A slope image for the 480,000 cells was generated, using IDRISI slope module, yet it just shows the general trend in slope rather than the exact pattern, which is due to the medium image resolution used.

Similar to the other factors, regression was applied to correlate slope with the annual and seasonal precipitation as shown in Table 4. Results indicate that the steep western slopes have more influence on precipitation distribution than do the mild slopes on the east. In addition, slope might explain up to 8% of precipitation variability (up to 49% can be explained by elevation) , which disagrees with Pockel's claim.

Table 4 – Correlation between slope and both annual and seasonal precipitation

	Correlation			Coefficient	
Stations	Annual	Summer	Fall	Winter	Spring
All stations	0.19	0.22	0.24	0	0.05
West slope stations	0.29	0.20	0.01	0.19	0.18
East slope stations	0.05	0.09	0.19	-0.17	0.03

4) Precipitation – Distance from Moisture Source Relationship

For precipitation to form, moisture must exist. The proximity of the source of this moisture, therefore, is assumed to have some sort of influence on the distribution of precipitation. This assumption was verified by correlating the annual precipitation with the distance to the Red Sea. A positive correlation coefficient of 0.29 was obtained for the western slopes which indicates an increase in precipitation as we get away from the moisture source where elevation increases. In contrast, the eastern slopes showed an opposite trend with a strong negative correlation of 58%.

5) Precipitation – Latitude Relationship

During winter, the Asir mountains are exposed to the northwesterly flow caused by the Mediterranean depression. This might lead to a larger amount of precipitation occurring along the northern section of the mountains. This assumption was tested by correlating the latitudes with the winter precipitation. Results showed about 50% correlation which confirm the proposed assumption.

6) Precipitation – Wind Direction Relationship

As pointed out by Alehaideb (1985), the climate of the southwest of Saudi Arabia is an interaction of local circulation due to the topography of the region and the universal circulation. Therefore wind direction varies from one season to another. In winter, the winds are northerly to northeasterly, while in summer, the winds are northwesterly to southwesterly. In spring, it is dominated by the southeast flow and northeast monsoon while in fall the area is under the influence of the southwest flow and Mediterranean depressions. Studying the effect of this diverse wind directions in a particular location requires defining the locational aspect of that point. Generally, locations perpendicular to the direction of wind receive more precipitation than others. The correlation between precipitation and wind is reflected in the aspect relationships discussed earlier.

Fitting a Polynomial Trend Surface

As a departure from linear regression, trend surface analysis has been conducted. This technique was first used by Unwin (1969) and it was proved to give better results than the conventional regression approach. This is due to the fact that the trend method uses polynomials rather than lines fitted by the linear regression.

Accordingly, two types of polynomials were fitted to correlate geographic locations with the average annual and average seasonal precipitation amounts using the IDRISI trend module. The polynomial equations are

$$Z = b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 \qquad \text{(Quadratic form)}$$

$$Z = b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 + b_6x^3 + b_7x^2y + b_8xy^2 + b_9y^3 \qquad \text{(Cubic form)}$$

where

Z – Estimated precipitation
x, y – Geographic coordinates.

Table 5 summarizes the results of the trend analysis in terms of surface coefficients and goodnesses of fit. Although results indicate that trend approach is superior to linear regression, the method unfortunately doesn't reveal the factors responsible for the variation.

Table 5 – Trend surface analysis results

Variables	Type of Poly-nomial	R^2	b0	b1	b2	b3	b4	b5	b6	b7	b8	b9
Annual on western slope	Quad ratic	50.41	106.01	1.12	-0.62	-0.011	0.018	-0.006	0	0	0	0
Summer on western slope	Quad-ratic	33.57	3.64	0.4	0.22	0.0026	0.003	0.0008	0	0	0	0
Winter on western slope	Cubic	73.19	-97.56	5.56	-2.04	-0.07	0.06	-0.13	0.0003	-0.0002	0.0001	0
Spring on western slope	Quad-ratic	41.82	42.35	-0.87	-0.82	0.0043	-0.0035	0.0002	0	0	0	0
Fall on western slope	Cubic	37.17	-37.49	1.82	-0.60	-0.0041	-0.0004	0.0029	0	0.0001	-0.0001	0
Annual on eastern slope	Quad-ratic	61.98	-1664.71	13.98	5.62	-0.036	-0.026	0.0005	0	0	0	0
Summer on eastern slope	Quad-ratic	69.19	-618.37	6.18	0.82	-0.02	-0.004	-0.0002	0	0	0	0
Winter on eastern slope	Quad-ratic	28.01	-112.78	12.73	-1.008	-0.046	0.013	-0.0021	0	0	0	0
Spring on eastern slope	Quad-ratic	56.15	-1103.53	10.58	1.9	-0.035	-0.0052	-0.0011	0	0	0	0
Fall on eastern slope	Quad-ratic	65.29	-462.19	2.13	3.4	0.0015	-0.03	0.003	0	0	0	0

* Polynomials listed are those of the highest R^2

Conclusions

Several conclusions and recommendations could be drawn from this study. Major findings are presented in the following:

1) The use of GIS in analyzing the spatial distribution of precipitation has facilitated the consideration of spatially distributed parameters, such as slope angle; elevation; aspect and others, over an area rather than the conventional lumped representative values. This with no doubt will provide more accurate results.
2) Due to the complicated and conflicting nature of the explanatory factors, the precipitation distribution over southwest of Saudi Arabia is not uniform. A wide variation can be noticed among seasons and locations.

3) Due to the irregularity of the topography of the area and diversity of moist air flow, the region was divided into two areas as suggested by Alehaideb 1) stations located west of Asir mountains along the Red Sea coast and foothills and 2) stations located on the east slope situated along the mountains and plateau. This study has also shown an improved relationship between elevation and precipitation based on this division.
4) As excepted, elevation explains most of the precipitation variation among the seasons. A coefficient of correlation of about 0.5 has been obtained in most of the seasons. This indicates that about 25% of the precipitation distribution is caused by the influence of elevation alone.
5) Other factors such as aspect, slope, distance from moisture source have different effects varying from 6%, 8% and 8% respectively, which are of less influence as compared to elevation.
6) Among the climatic factors, wind direction is considered the determining element in precipitation distribution. However, this factor depends on mountain orientation. Stations lying on the slope sides perpendicular to the direction of flow receive more precipitation than stations lying on the other sides.
7) The polynomial trend approach has shown results superior to linear regression. However, this technique correlates geographic locations with precipitation amount without indicating which factor is responsible for the variation.

Recommendations

1) GIS possess great capabilities that were partially used in this study. It is strongly recommended to conduct similar studies on different water resources problems to further explore this technology.
2) Software limitation and lack of reliable data have restricted this study to a great extent. The study can be extended to include more data and different statistical techniques such as multiple linear and non-linear regression. Multiple regression is valuable to eliminate the effect of the suppressing variables – variables acting in opposite directions. Non-linear regression on the other hand, allows for a better representation of curved relationships.

References

Alehaideb, S. (1985) Precipitation distribution in the southwest of Saudi Arabia, Ph. D. dissertation, Arizona State University.

Bonacina, L. (1945) Orographic rainfall and its place in the hydrology of the globe, *Quart. J. Ref. Met. Society, vol. 71*, pp. 41-52

Chang, M. (1973) Effect of topography and site exposure on precipitation distribution in mountainous areas, Ph.D. dissertation, Dept. of Hydrology, West Virginia University, Morgantown.

Chow, V., Maidment, D., and Mays, L. (1988) *Applied Hydrology,* McGraw-Hill Pub., New York.

Dhar, O., and Rakhecha, P. (1981) The effect of elevation on monsoon rainfall distribution in the central Himalayas, International Symposium on Monsoon Dynamics, ed. J. J. Lighthill and R. Pearce, Cambridge, Cambridge University Press, pp. 230-260.

Dingman, S., Seely-Reynolds, D., and Reynolds III, R. (1988) Application of kriging to estimating mean annual precipitation in a region of orographic influence, *Water Resources Bulletin, Vol. 25(2),* pp. 330-339.

Donley, D., and Mitchell, R. (1939) The relation of rainfall to elevation in the southern Appalachian Region, *Trans. Am. Geophys. Union, Vol. 20(4),* pp. 711-721.

Lee, C. H. (1911) Precipitation and Altitude in the Sierra, *Mon Weath Rev., Vol. 29(7),* pp. 1092-1099.

Loukas, A., and Quick, M. (1993) Rain distribution in a mountainous watershed, *Nordic Hydrology,Vol. 24*, pp. 223-242.

Nouh, M. (1987) Analysis of rainfall in the southwest region of Saudi Arabia, Proc. Inst. Civil Eng., Part 2, 83, pp. 339-349.

Peck, E. L., and Brown, M. (1962) An approach to the development of isohyetal maps for mountainous areas, *J. Geophys. Res., Vol. 67(2),* pp. 681-694.

Pockels, F. (1981) The theory of the formation of Precipitation on mountain slopes, *Mon. Weath.Rev.*

Shih, S. (1990) Satellite data and geographic information system for rainfall estimation, *J. of Irrigation and Drainage Eng., Vol. 116*(3), pp. 319-331.

Taylor, P. (1980) A Pedagogic application of multiple regression analysis, *J. Geography, Vol. 65(3)*, pp. 203-212.

Unwin, D. (1969) The areal extension of rainfall records: An alternative model, *J. of Hydrology, Vol. 7*, pp. 404-413.

Wheater, H. S., Larentis, P., and Hamilton, G. S. (1989) Design rainfall characteristics for south-west of Saudi Arabia, Proc. Instn. Civ. Engrs., Part 2, pp. 517-538.

Wolfson, N. (1975) Topographical effects on standard normal of rainfall over Israel, *Weather, Vol. 30(5),* pp. 138-145.

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