Geostatistical study of annual and seasonal mean rainfall patterns in southwest Saudi Arabia

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Abstract The spatial and temporal variability of rainfall is a major problem in its description and prediction. Saudi Arabia has an extremely dry climate, but in the southwest region comparatively more rainfall events occur within the effects of topography and seasonality. Sixty-three representative stations were selected for a 21-year period covering different micro-climate conditions. Geostatistical methods were used to reflect the regional and seasonal rainfall patterns throughout the southwest region. The results indicate that high variations in regional rainfall estimation occur in the mountainous areas, while the variance decreases in shadow areas in all seasons. The variation of the rainfall estimation accuracy decreases from winter to autumn.

Key words precipitation; geostatistics; variogram; kriging; mapping; seasonality; Saudi Arabia

Distribution géostatistique de la pluie moyenne annuelle et saisonnière dans le Sud-Ouest de l'Arabie Saoudite

Résumé La description et la prévision de la variabilité spatiale et temporelle de la pluie sont des problèmes majeurs. L'Arabie Saoudite a un climat extrêmement sec; mais, comparativement, les événements pluvieux sont plus nombreux dans la région Sud-Ouest, sous influence de la topographie et de la saisonnalité. Soixante trois stations représentatives, couvrant différentes conditions micro-climatiques, et une période de 21 ans, ont été sélectionnées. Des méthodes géostatistiques ont été utilisées pour caractériser la distribution de la pluie régionale saisonnière au sein de la région Sud-Ouest. Les résultats indiquent de grandes variations dans l'estimation régionale de la pluie dans les zones montagneuses, tandis que la variance décroît dans les zones abritées, pour toutes les saisons. La variation de la précision de l'estimation de la pluie décroît de l'hiver à l'automne.

Mots clefs précipitation; géostatistique; variogramme; krigeage; cartographie; saisonnalité; Arabie Saoudite

INTRODUCTION

Capturing the spatial and temporal distribution of rainfall is of key importance for the description and prediction of rainfall phenomena. Local seasonal (Mediterranean and monsoonal air mass movements, moisture, temperature and pressure) and topographical (altitude, distance from the sea) factors affect the magnitude and distribution of rainfall, which vary from place to place, and from time to time, even in small areas. The description and prediction of rainfall variability in space and/or time are fundamental requirements for a wide variety of human activities and water project designs.

There is a wide choice of interpolation techniques for rainfall mapping. These range from simple approaches, such as Thiessen polygons, the inverse distance and polynomial fitting to more complex approaches such as kriging (Tabios & Salas, 1985; Rouhani, 1986; Ahmed & Marsily, 1987; Hevesi *et al*., 1992; Bogaert, 1996).

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The kriging method has seen many applications, especially in the mining industry and, more recently, in hydrology and meteorology. The kriging method is based on the theory of regionalized variables (ReV) and, consequently, it has become and essential element in the area of geostatistics (Journel & Huijbregts, 1978).

In Saudi Arabia, rainfall has very low total magnitude during a specific time interval and is unpredictable with irregular but very intense local storms. The southwest region lies within the subtropical climate zone of Saudi Arabia and receives the highest amount of rainfall in comparison to other regions, because it is mountainous with elevations reaching to over 2000 m a.m.s.l. The study area lies between latitudes 17°00′ and 22°00′N and longitudes 40°00′ and 43°00′E (see Fig. 1). The average annual rainfall can reach more than 600 mm in the mountains, and decreases towards the coast in the west to 120 mm, and on the leeward side of the mountains

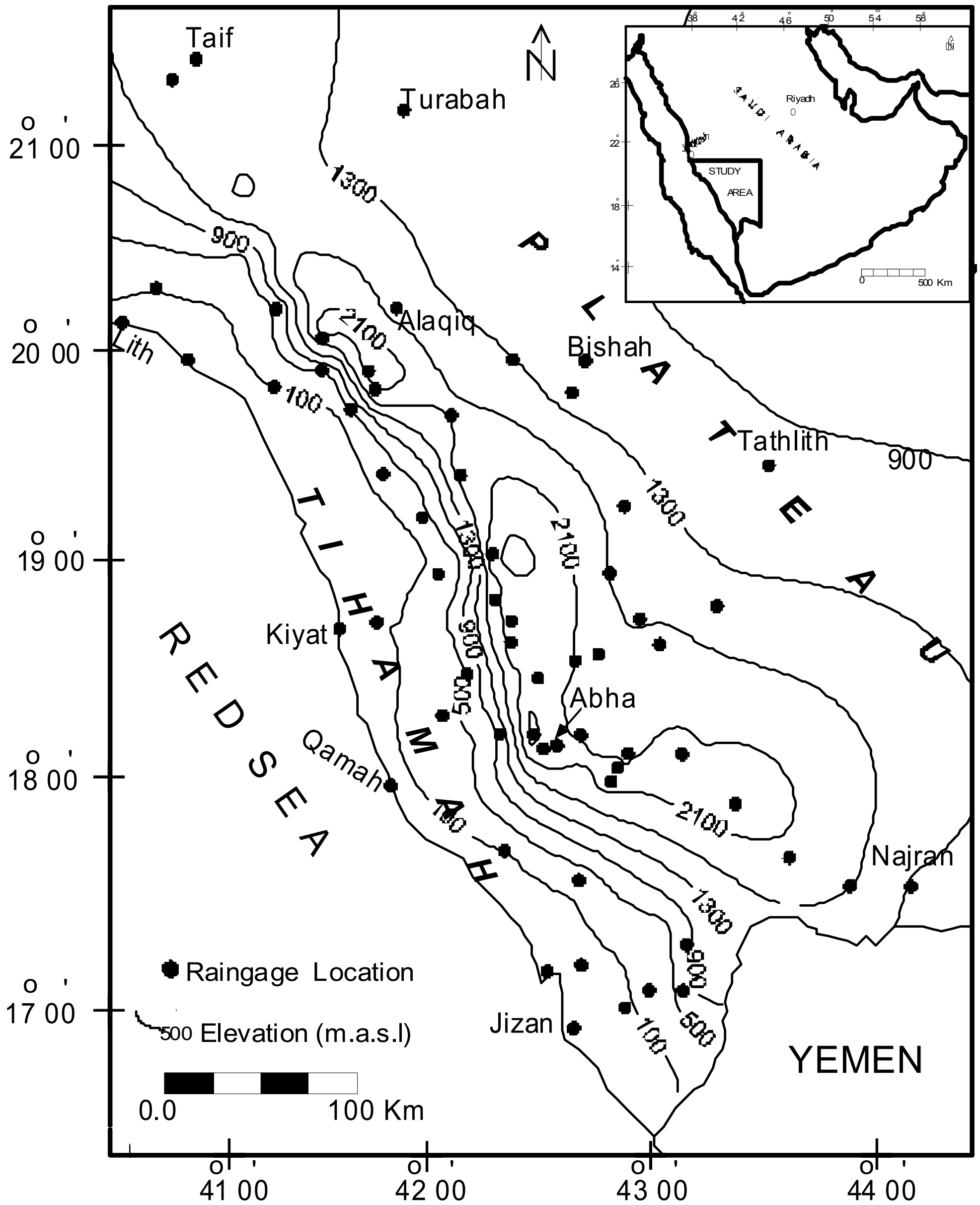

Fig. 1 Topographical map of study area in southwest Saudi Arabia.

to the east to 100 mm. The network of rainfall measuring stations in the southwest is sparse and available data are insufficient to characterize the highly variable spatial distribution of rainfall. Therefore, in areas where data are not available, it is necessary to develop methods to estimate rainfall using data from surrounding weather stations.

The major goal of this study is to characterize the spatial variability of annual and seasonal rainfall patterns by suitable variogram models, which are then used in the kriging process for assigning values to ungauged locations leading to mean and variance maps.

MECHANISM OF RAINFALL IN THE SOUTHWEST REGION

Rainfall generally occurs when an air mass rises and cools. Beside the orographic effects, large-scale flows of air are the main centres that make the air rise and hence produce rainfall. The southwest region comes under the influence of subtropical and orographic conditions. Thus, rainfall in different seasons results from different mechanisms.

During winter (December–February), rainfall is usually associated with weak influxes of moist and cold air of westerly Mediterranean origin that is coupled with the local effects of the Red Sea and Scarp Mountains with orographic rainfall occurrence. However, during spring (March–May), the intertropical front starts to move northwards and the region comes under the influence of a relatively moist southeasterly stream of monsoon air and the Red Sea convergence zone, which give rise to rainfall along the leeward side of the mountains and the Red Sea coast. During summer (June–August), monsoon conditions are predominant, creating thunderstorms along the escarpment and the southern part of the Red Sea coast (Tihamah). During autumn (September–November), the southeasterly air stream weakens as a result of increasing northwesterly air streams. In the case of strong convergence, the phenomenon causes tropical conditions and widespread rainfall. Finally, rainfall occurs over the escarpment and the Red Sea coast (Taha *et al.*, 1981; Şen, 1983; Alehaideb, 1985; Nouh, 1987; Alyamani & Şen, 1997).

In general, rainfall in the southwest region occurs in every season of the year. Autumn rainfall is related to local diurnal circulation, summer rainfalls to the monsoons, and winter and spring rainfalls to the interaction between African-Mediterranean air flows (Table 1).

GEOSTATISTICAL ESTIMATION

Geostatistics, or the study of regionalized variables (ReV), was developed for the statistical study of natural phenomena, which have spatially varying properties with an apparent continuity in structure. The first step in geostatistics involves analysing the spatial structure of the variable from the historical characteristics by deriving a sample variogram. A functional model is fitted to the sample variogram which contains information that can be used for interpolation to estimate the characteristics at unsampled locations and to extend findings for the regional behaviour of the natural phenomena. This interpolation method is known as the kriging technique. More detailed information about geostatistics may be found in the literature (Matheron, 1963, 1971; David, 1977; Journel & Huijbregts, 1978; Isaaks & Srivastava, 1989; Cressie, 1993; Clark & Harper, 2000).

Table 1 Summary statistics for seasonal and annual rainfall data.

Region	Number of stations	Winter (mm)	Spring (mm)	Summer (mm)	Autumn (mm)	Annual (mm)
Coast (Tihamah)	25	141[a]	199	238	152	684
		13[b]	6	5	3	55
		53.5[c]	51.4	58.6	53.7	217.2
		33.4[d]	51.3	58.2	40.5	160.3
Mountains	24	169	264	148	69	527
		20	80	16	10	150
		78.5	155.3	57.1	30.8	321.8
		47	53.5	35.4	18.8	120.4
Leeward side of mountains (desert)	14	28	99	30	37	150
		7	29	3	3	44
		17.4	64.4	11.9	9.6	103.3
		6.6	17.8	8.22	8.3	27.7

[a] Sample maximum.
[b] Sample minimum.
[c] Sample mean.
[d] Sample standard deviation.

A variogram is a graph or formula describing the expected squared difference in values between pairs of samples with a given orientation. It is estimated as:

$$\hat{\gamma}(h) = \frac{1}{2N}\sum_{i=1}^{N}[Z(x+h)-Z(x)]^2 \tag{1}$$

where N is a number of pairs that have separation distance of h, which means that $\hat{\gamma}(h)$ is the mean squared difference between pairs of points. A plot of $\hat{\gamma}(h)$ versus h is referred to as the sample variogram.

The sample variogram is determined having assumed a suitable variogram model, such as the Gaussian, spherical, exponential, or linear types. The adequacy of the chosen model is to be tested using cross-validation, where an acceptable fit appears by a mean estimation error (*MEE*) between measured and estimated values of approximately zero (Cressie, 1992; Clark & Harper, 2000):

$$MEE = \frac{1}{n}\sum_{i=1}^{n}\left\{\left[Z(x_i)-\hat{Z}(x_i)\right]/\sigma_i\right\} \approx 0 \tag{2}$$

where $Z(x_i)$ is the measured value of ReV at location x_i, $\hat{Z}(x_i)$ is the estimated value of ReV at location x_i, σ_i is the calculated kriging estimation error variance for $\hat{Z}(x_i)$, and n is the number of estimated values.

On the other hand, the root mean square error (*RMSE*) is close to one as follows:

$$RMSE = \left\{\frac{1}{n}\sum_{i=1}^{n}\left[\left(Z(x_i)-\hat{Z}(x_i)\right)/\sigma_i\right]^2\right\}^{1/2} \approx 1 \tag{3}$$

In addition, another procedure to check the validity of the model is to plot the residuals against the estimated values. The first step in modelling the variogram is the computation of an experimental variogram. The small sample size and the irregularity of the sample location lead to the assumption of isotropy. An omnidirectional, or average, variogram is computed for the natural logarithm of the average annual and seasonal data using equation (1) (Cooper & Istok, 1988). After a suitable variogram model fitting and its parameter estimations, the kriging technique is applied to estimate the value of a variable $Z(x_0)$ at every grid point x_0, where no observation is available. The kriging estimate has the linear form (Journel & Huijbregts, 1978):

$$\hat{Z}(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \qquad i = 1, 2, \ldots, n \tag{4}$$

where $\hat{Z}(x_0)$ is an estimator of unknown true value of $Z(x_0)$; λ_i are the kriging weights accorded to each sample; and n is the number of samples to be included in the estimation. The problem is to find the set of weight coefficients in such a way that the kriging estimator should satisfy the following conditions of unbiasedness and the minimum estimation variance, respectively:

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{5}$$

and

$$\sigma^2 = E\left\{\left[\hat{Z}(x_0) - Z(x_0)\right]^2\right\} \text{Minimum} \tag{6}$$

These two constrains make kriging a good interpolator compared to other interpolation techniques.

DATA PREPARATION

The mean annual and seasonal rainfall records for the southwest of Saudi Arabia were adapted from reports published by the Hydrology Division, Ministry of Agriculture and Water in Saudi Arabia and Al-Jerash (1989). Rainfall records from 63 stations between 1971 and 1990 were selected for this study (Fig. 1). These stations were chosen based on four criteria : (a) they represent the best spatial coverage of the region; (b) they maximize the same monthly rainfall records; (c) they have continuous monthly rainfall; and (d) they reflect the wide variety of environments within the study area covering the coast (Tihamah), the mountains and the leeward side of the mountains (desert). Descriptive statistics for the 63 stations are listed in Table 1, grouped according to these three regions: 25 stations located within the coast; 24 within the mountains and 14 within the leeward side (Fig. 1 and Table 1).

Problems in data, such as non-normality, trend and outliers, should be fixed before developing any kind of model. Normality of the sample data distribution is known to improve the results from kriging. Transformation is very important to make the data more symmetrical, linear and constant in variance. Given that this research deals with annual and seasonal rainfall data, it is pragmatic to find one transformation which works reasonably well for all. The Box-Cox transformation is widely used and can be easily managed so that the skewness of transformed data $Z(x,t)$ becomes close to zero (Salas, 1993).

However, as stated by Hevesi *et al*. (1992), rainfall histograms for arid regions behave like lognormal distribution. Hence, the transformation $Y = \ln(Z(x))$ was applied

Table 2 Descriptive statistics and normality test for annual and seasonal data.

	Mean (mm)	Median (mm)	SD (mm)	Skewness	CV (%)	K-S* (D_{max})
Annual	232	178	151	0.8	0.65	0.18
Winter	55.0	41.0	43.1	1.15	0.78	0.20
Spring	94.0	81.0	68.0	0.72	0.72	0.14
Summer	47.6	32.0	47.3	1.84	0.99	0.17
Autumn	35.2	21.0	33.2	1.44	0.95	0.19
ln-Annual	5.22	5.18	0.7	-0.7	0.13	0.10
ln-Winter	3.71	3.71	0.79	-0.051	0.21	0.07
ln-Spring	4.21	4.39	0.92	-0.65	0.22	0.11
ln-Summer	3.38	3.46	1.06	-0.24	0.31	0.08
ln-Autumn	3.1	3.04	1.02	-0.15	0.33	0.08

* K-S: Kolmogorov-Smirnov statistic.

for determining approximately normal annual and seasonal data. Data were accepted as normally distributed if the computed Kolmogorov-Smirnov statistic (D_{max}) was less than the corresponding critical value for the 5% level of significance (see Table 2.). Thus the null hypothesis of the transformed data normality cannot be rejected at the 0.05 level of significance. Further investigation can be done by visual inspection of the normal probability plots: most of the data lie on a straight line for the transformed rainfall values. In addition, the skewness coefficients are reduced close to zero (Subyani, 1997). Table 2 shows the statistics and normality test for original and transformed annual and seasonal data.

The back-transformed value, i.e. exp(Y(x)) is a biased predictor. However, the unbiased expression for the kriging estimates Z(x) is given as (Gilbert, 1987):

$$Z^*(x) = \exp\left\{Y^*(x) + \sigma_y^2/2\right\} \tag{7}$$

where $Z^*(x)$ is the original data in mm, $Y^*(x)$ is the natural logarithm and σ_y^2 is the lognormal kriging variance. The estimation variance is given as:

$$\sigma_{Z^*}^2 = \left(Z^*\right)^2\left[\exp(\sigma_y^2) - 1\right] \tag{8}$$

These two last expressions were used for constructing the rainfall isohyets and their variances.

RESULTS

Variogram models of annual and seasonal rainfall

Figure 2 shows the sample and fitted variograms for the natural logarithm of average annual rainfall (ln AAR). An isotropic spherical model with no nugget, but with a sill equal to the sample variance of 0.48 and a range of 110 km, is selected as the best representation of the spatial structure.

Cross-validation was applied to check whether the spherical model is adequate to describe the spatial correlation of the annual rainfall. For a diagnostic check, the mean estimation and the root mean square errors for ln AAR are 0.067 and 0.94, respectively, which suggests the validity of the spherical model and its parameters (see Table 3).

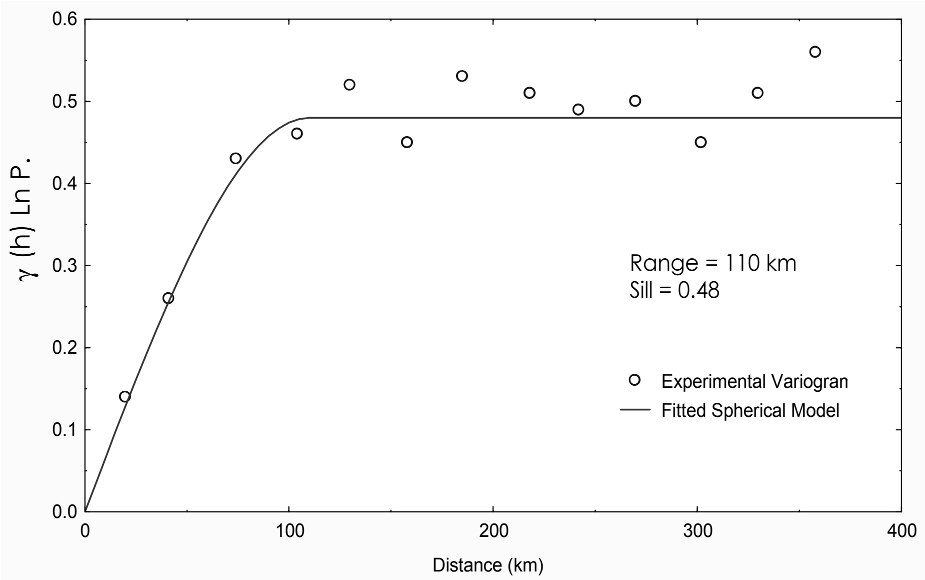

Fig. 2 Experimental and fitted variogram model for ln-annual rainfall.

Table 3 Variogram cross-validation in the study area.

Season	Model	*N*	*MEE*	*RMSE*
ln-Annual	Spherical	60	0.067	0.94
ln-Winter	Exponential	60	0.027	0.84
ln-Spring	Exponential	61	0.08	0.71
ln-Summer	Spherical	62	0.07	0.91
ln-Autumn	Spherical	62	0.04	1.08

N: number of gauges

Figure 3(a)–(d) presents the sampled and modelled variograms and their parameters for winter, spring, summer and autumn, respectively. In winter, the exponential variogram model is fitted with the small nugget of 0.05. The sill is 0.67 and the practical range of dependency, i.e. radius of influence, is 70 km (Fig. 3(a)). The spring sample variogram behaved as an exponential model with a nugget of 0.1, sill of 0.95 and radius of influence equal to 90 km (Fig. 3(b)). For the summer and autumn, the sample variograms behave as spherical models, with sill around 1.0 and the ranges of influence of the order of 140 and 110 km, respectively (Fig. 3(c) and (d)).

Cross-validation was applied to check the validity of these variogram model parameters. The models that satisfied unbiased and consistent estimation are shown in Table 3. The mean error estimation (*MEE*) and root mean square error (*RMSE*) are approximately 0 and 1, respectively, except for the spring where the rainfall data are highly variable compared to the other seasons.

Kriging of annual and seasonal rainfall

Kriging estimates were computed for the average annual and seasonal rainfall amounts. The sample variogram represents the continuity structure quite well. The cross-valida-

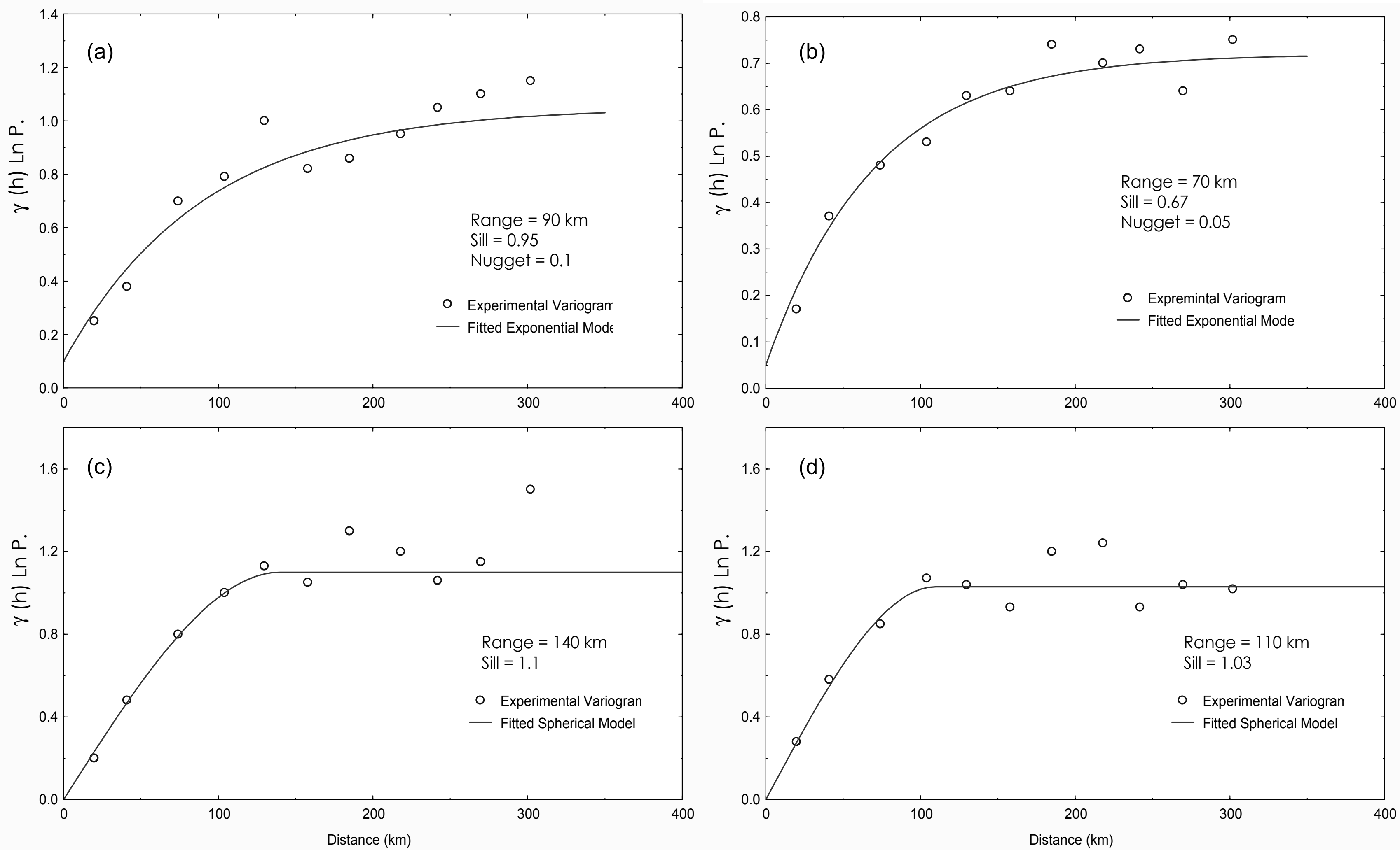

Fig. 3 Experimental and fitted variogram models for ln-seasonal rainfall: (a) winter, (b) spring, (c) summer, and (d) autumn.

tion supports the selection of models and their parameters. For kriging estimation and variance, the back-transformed values were applied.

The kriged isohyets for annual rainfall show a rapid increase in average values from the Red Sea coast up to the mountains and a gradual decrease to the northern and eastern parts of the study area (Fig. 4(a)). Orographic effects are produced toward the mountain area with the maximum kriged estimate exceeding 350 mm year^{-1}. In the eastern and northeastern parts of the study area, kriging estimates are around 100 mm year^{-1}. In the northern part, with a moderate elevation reaching more than 1000 m, kriging estimates also exceed 100 mm year^{-1}. This figure reflects the topographical variation (see Fig. 1) with annual rainfall that generally increases with elevation.

Kriging variances indicate similar behaviour to the average annual rainfall estimates. Small values near the clusters of stations in the mountain area (Fig. 4(b)) indicate high estimation accuracy, whereas large values were obtained in the north, east and northeast, which are low estimation accuracy areas owing to the scarcity of sampling locations. Generally, high estimation variances occur for areas lacking in data.

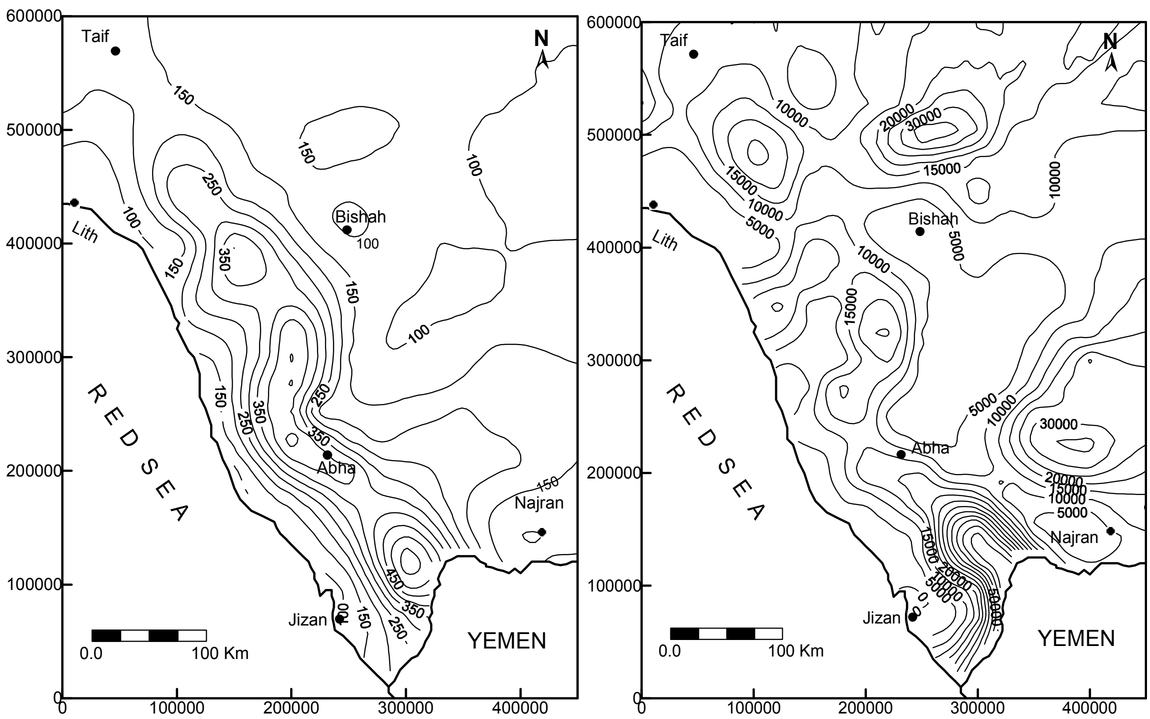

Fig. 4 (a) Isohyetal map of kriging for annual rainfall (mm), and (b) kriging variances for annual rainfall (mm^2).

In winter (December–February), rainfall is associated most of the time with moist and cold air of northerly Mediterranean origin, which is coupled with the local effects of the Red Sea convergence zone, the Scarp Mountains, as well as orographic rainfall occurrences. Figure 5(a) shows that the kriging estimates exceed 120 mm in the middle and northern sections of the mountainous areas. However, they do not exceed 30 mm in the south of Tihamah, because there is no Mediterranean or Red Sea effect, and the

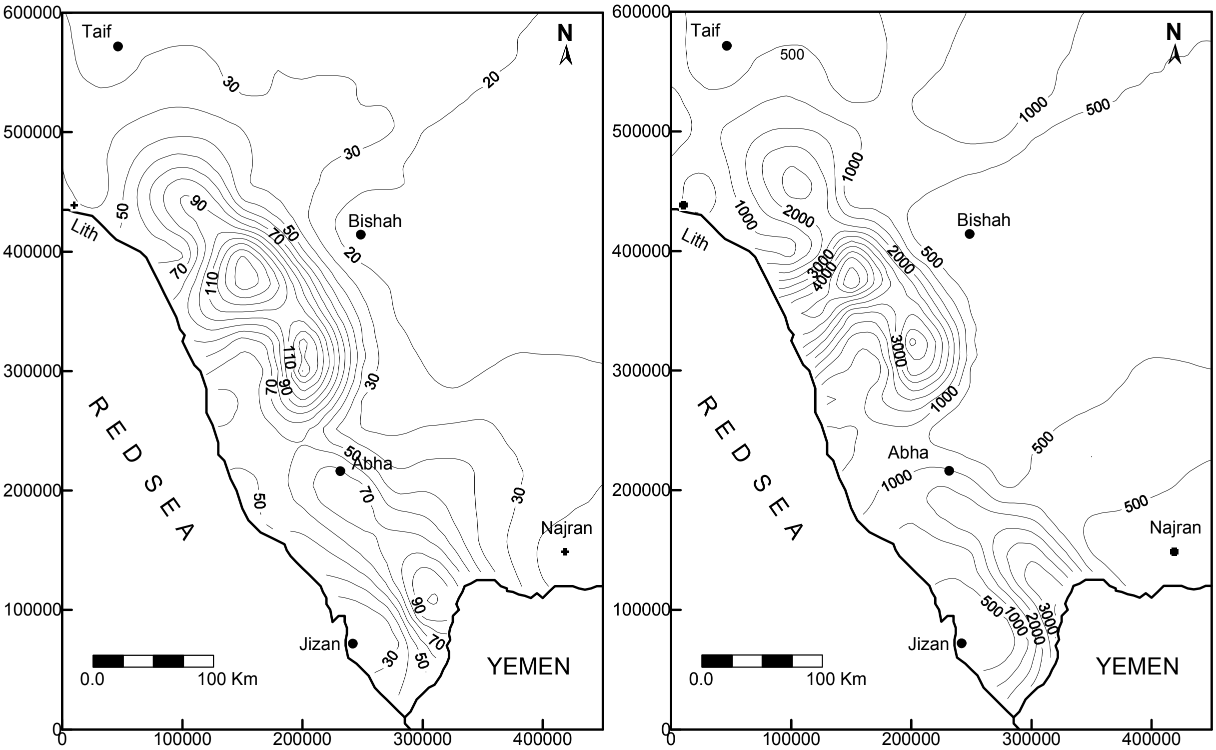

Fig. 5 (a) Isohyetal map of kriging for winter rainfall (mm) and (b) kriging variances for winter rainfall (mm^2).

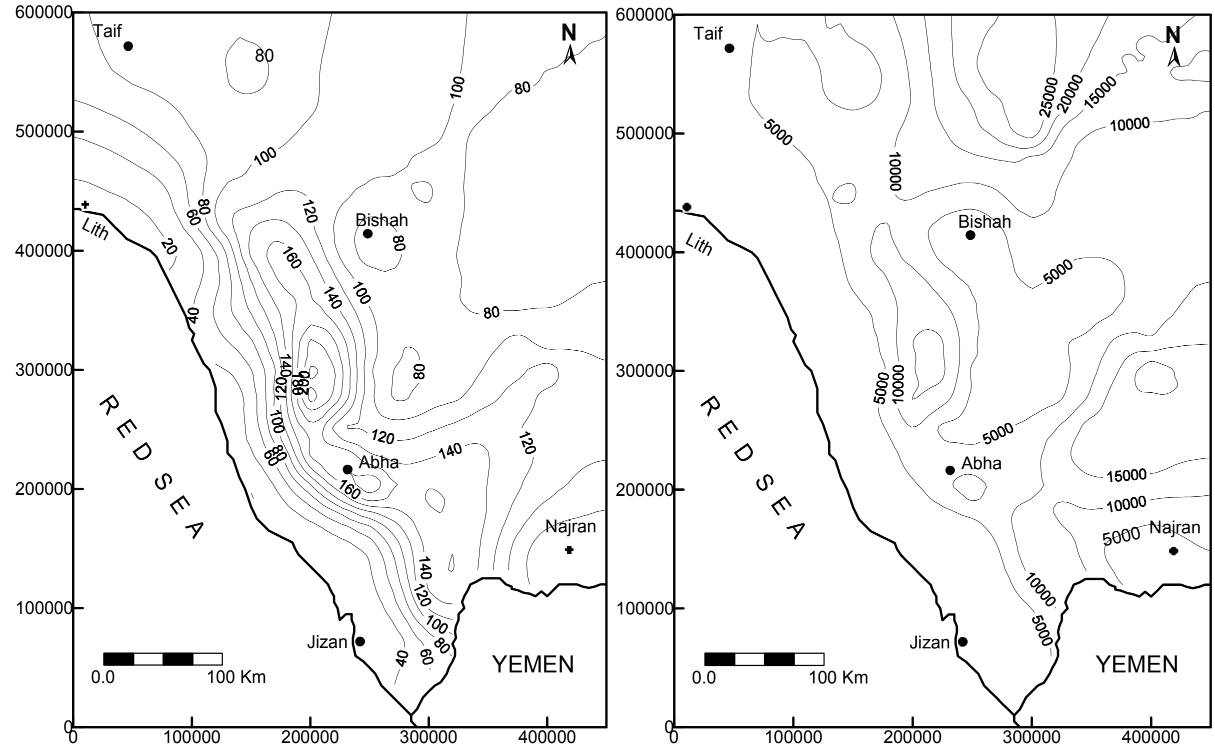

Fig. 6 (a) Isohyetal map of kriging for spring rainfall (mm) and (b) kriging variances for spring rainfall (mm^2).

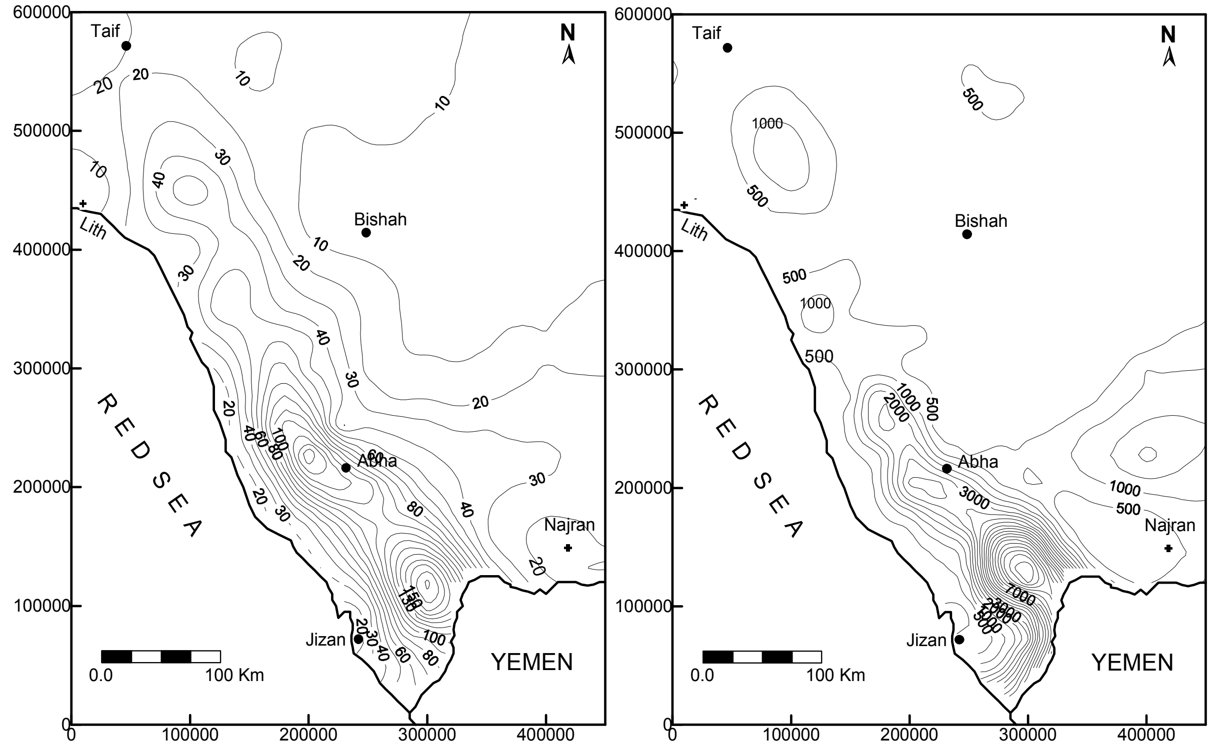

Fig. 7 (a) Isohyetal map of kriging for summer rainfall (mm) and (b) kriging variances for summer rainfall (mm^2).

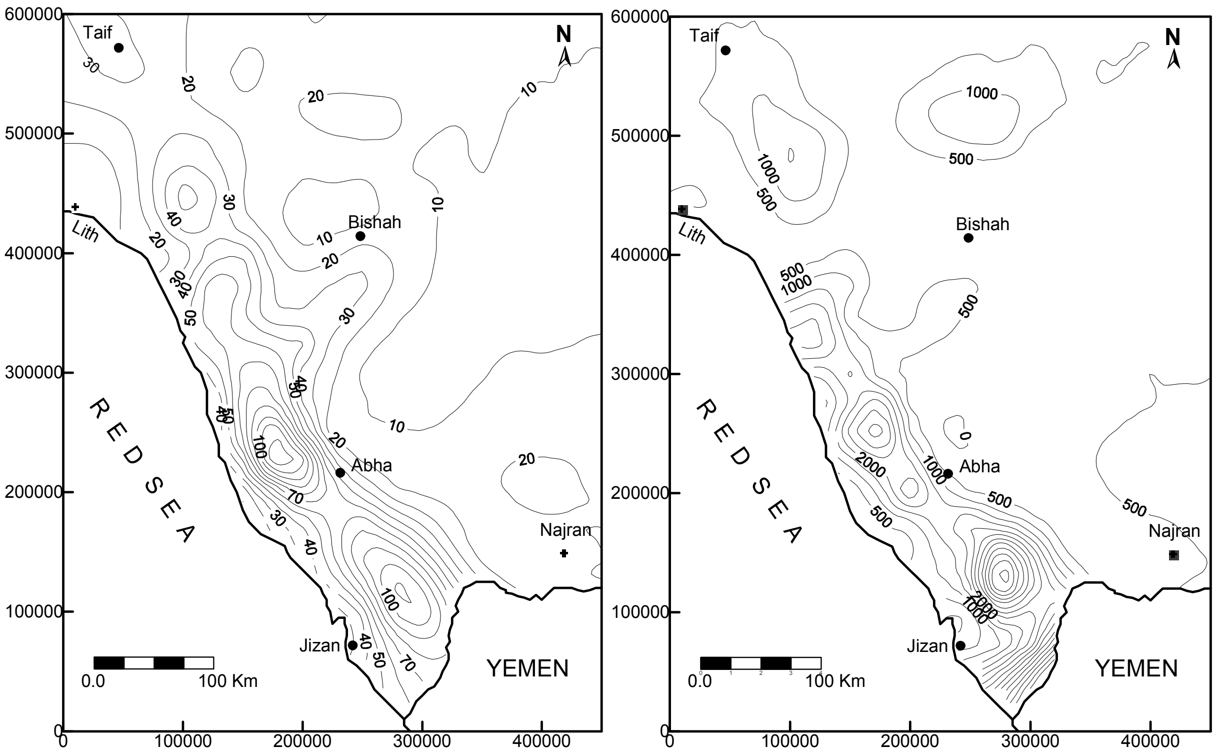

Fig. 8 (a) Isohyetal map of kriging for autumn rainfall (mm) and (b) kriging variances for autumn rainfall (mm^2).

elevation is not high enough for orographic rainfall occurrence. On the other hand, the southern part of the study area receives less than 100 mm of rainfall due to the absence of monsoons. The Plateau area (eastern and northeastern parts of the study area) receives less than 20 mm, because it is located in the shadow (leeward side) area of the mountains. The kriging estimation variance map has a similar trend throughout the study area as shown in Fig. 5(b).

In spring (March–May), the whole region comes under the influence of the south-east monsoon airstream, the Red Sea convergence zone and the Mediterranean depression, which distribute rainfall in all regions. The kriging estimates give more detailed information about the rainfall distribution as shown in Fig. 6(a). Rainfall in this figure increases gradually from the Red Sea coast (40 mm) to the mountains where the highest amount of rain falls (more than 160 mm), and decreases to the plateau area, which receives about 100 mm. Generally, the southwest region of Saudi Arabia receives the highest amount of rainfall during the spring compared with other seasons. This high amount of rainfall is due to the effects of increasing African-Mediterranean interaction, where rainfall occurs orographically in the mountains, and the southeast monsoon effect where the Plateau and eastern slope receive more rainfall than the Red Sea coast. Kriging variances show an increase in estimation accuracy in the mountains region, as shown in Fig. 6(b).

In summer (June–August), the southwest monsoon flow from the Indian Ocean and the Arabian Sea is the predominant factor, which increases the rainfall along the Scarp Mountains and low elevation areas in the south of the study area. Kriging estimates for the summer season exceed 120 mm in the mountains and 160 mm in the foothills near the Yemen border (Fig. 7(a)). Rainfall decreases toward the northern part of the study area, even though this area has a high elevation. This is because it is far away from the monsoon effect. Moreover, the kriging variances show no change in estimation accuracy in the foothills and mountains, but in the plateau area the variances are greater because there is not enough information (Fig. 7(b)).

In autumn (September–November), the local diurnal circulation and the southern air stream weakens. In other words, it is a transition period from summer to winter and, in general, the area receives little rainfall. The kriging estimation in the foothills and the mountains in the southern part of the study area shows that they receive higher amounts of rainfall than the northern areas, similar to the autumn monsoon flow effects, as shown in Fig. 8(a). The kriging variances show an increase in estimation accuracy in the northern part of the study area, whereas there is no clear change in the southern part (Fig. 8(b)).

Generally, rainfall is predominant in the northern mountain areas during winter due to the Mediterranean effect, and it is widespread in all regions during spring because of the local diurnal circulation effects. Orographic conditions are clear in winter and spring. This orographic factor is also clear for the appearance of the nugget effect in the exponential models in both winter and spring. During summer, rainfall moves towards the south due to the monsoon flow effect with its southwesterly wind. However, during autumn, being a transition season, the area comes under the influence of the monsoon as well as the local diurnal circulations. Figure 9 illustrates these spatio-seasonal variations of rainfall in the southwest of Saudi Arabia.

The kriging estimation variances were also investigated with regard to the spatial and temporal variations in rainfall in the study area. In spatial variation, the small

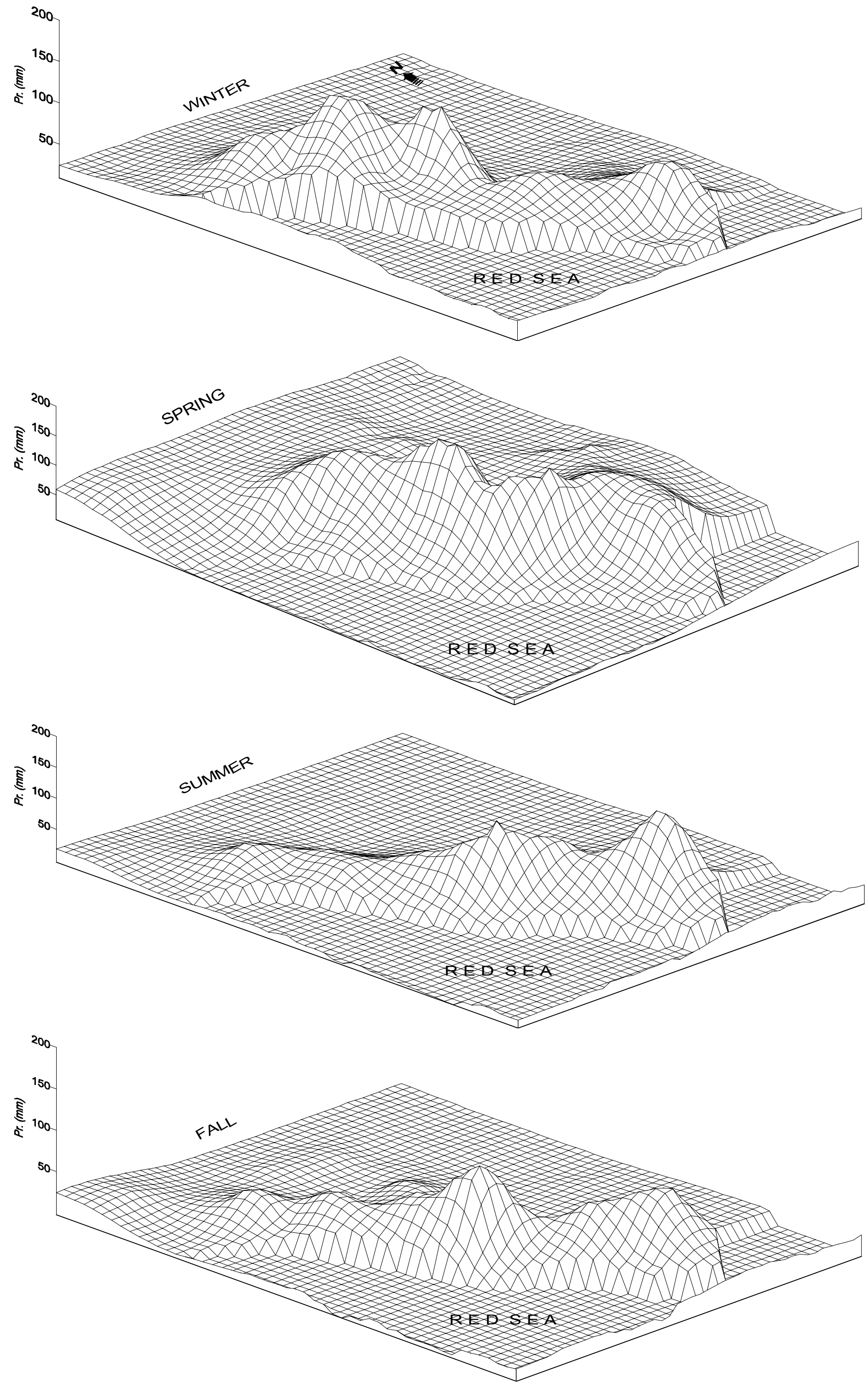

Fig. 9 Spatio-temporal kriging maps for rainfall in Southwest Saudi Arabia.

value or high estimation accuracy of kriging variances occurs in the mountainous areas in all seasons. Towards the east, north and northeast of the study area, there is a consistent increase in variances implying low estimation accuracy. In time variation, kriging variance increases from winter to autumn. These variations in space and time are due to several factors such as (a) clusters of stations in the mountain areas reflecting higher estimation accuracy; (b) scarcity of stations in the north, east and northeastern areas reflecting lower estimation accuracy; and (c) high variability in summer and autumn rainfall giving rise to low accuracy estimation compared with the somewhat lower variability in rainfall during winter and spring.

CONCLUSIONS

The description of the rainfall variability in space and/or in time is among the fundamental requirements for a wide variety of human activities as well as water resources project design, management and operation. Geostatistical methods were applied to develop new maps for the prediction of rainfall in different seasons. The assigned objectives of this study were to predict the magnitude and variation of rainfall in space as well as during different time periods. These techniques were applied to rainfall data gathered from a meteorological station network covering the southwest region of Saudi Arabia. Rainfall in this area is characterized by high variations in spatial and temporal distributions. The major conclusions of this study can be summarized as follows:

1. The spatial structure and continuity of the rainfall data were modelled at different time scales. Cross-validation procedures were applied to test the validity of different structural models. The results show that (a) a nugget effect and exponential structure variogram best fit winter and spring data where orographic influence is dominant, and (b) spherical structures with no nugget effect best fit summer and autumn data, which assume greater influence of the monsoon flow effect.
2. From the kriging contour maps, rainfall is predominant in the mountainous area during winter as a result of the Mediterranean effect, and is widespread in all areas during the spring. Orographic conditions are clear in the winter and spring. Monsoon conditions are predominant in summer in the south of the study area, where autumn rainfall is in a transitional phase between summer and winter conditions. It is concluded that the kriging technique lends itself well to represent rainfall behaviour in the different seasons.
3. The preliminary analysis of annual rainfall showed that the maximum amount of rainfall does not necessarily occur at high elevations. The direct conclusion is that other factors are responsible for rainfall occurrence at different locations within the study area. Among these factors one can list the distance from the source of moisture, temperature, pressure and topography. Another possible reason is that each season is characterized by specific climate conditions. Spring and autumn rainfalls are related to local diurnal circulation, summer rainfall to monsoon, and winter rainfall to the African-Mediterranean interaction. Hence, the rainfall–elevation relationship can be better evaluated by seasonality due to different climate conditions.
4. The kriging variances were also calculated in the study area for all four seasons. There are space and time variations in the kriging estimation variances. These variations are the result of several factors, such as (a) clusters of stations in the mountainous areas indicating high estimation accuracy; (b) scarcity of stations in the north, east and northeastern areas indicating low estimation accuracy; and (c) high variability in summer and autumn rainfall yields with low accuracy estimation compared to somewhat low variability in rainfall during winter and spring.

These facts are very helpful for redesigning raingauge networks, seasonal agriculture and rangeland management, flood control, and water resources design, operation, management and maintenance.

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