Geostatistical analysis for estimation of mean rainfalls in Andhra Pradesh, India

Krishna Murthy B R and G Abbaiah

Abstract— Rainfall is a hydrological phenomenon that varies in magnitude in space as well as in time and requires suitable tools to predict mean values in space and time. Estimation of rainfall data is necessary in many natural resources and water resource studies. There are several methods to estimate rainfall among which interpolation is very useful approach. In this research, geostatistical interpolation methods are used to estimate monthly (June-December), seasonal (South-West and North-East Monsoon seasons) and annual rainfalls in Andhra Pradesh, India. Monthly rainfall data from a network of 23 meteorological stations for the period 1970-2003 has been in the study. The main objectives of this work are: (1) to analyze and model the spatial variability of rainfall, (2) to interpolate kriging maps for different months as well as seasons, (3) to analyze and model the structural cross correlation of rainfall with elevation for different seasons, (4) to investigate whether co-kriging would improve the accuracy of rainfall estimates by including elevation as a secondary variable, and (5) to compare prediction errors and prediction variances with those of kriging and cokriging methods for different seasons. Rainfall surfaces have been predicted using ordinary kriging method for these analyses. Co-kriging analysis has been done to improve the accuracy of prediction, by including the elevation as a co-variate. It has not resulted in significant improvement in the prediction. It was observed that the rainfall data is skewed and Box-cox transformation has been used for converting the skewed data to normal.

It is observed that the trend is present in all the cases, and is constant for November, North-East monsoon. The first order polynomial fits well for June, August, Sept, October, December, Annual period and South -West monsoon. The second order polynomial fits best for July. It has been observed that the directional effects are predominant in October, November, South-West Monsoon and Annual rainfall. Spherical model fits well for June, July, November, South-West and North-East monsoons, where as the Gaussian model fits well for August, September, October, December and annual rainfalls. Nugget effect is zero for June, November, and North-East monsoon. The cross-validation error statistics of OCK presented in terms of coefficient of determination (R2), kriged root mean square error (KRMSE), and kriged average error (KAE) are within the acceptable limits (KAE close to zero, R2 close to one, and KRMSE from 0.98 to 1.341). The exploratory data analysis, variogram model fitting, and generation of prediction map through kriging were accomplished by using ESRI'S ArcGIS and geostatistical analyst extension.

Keywords— Andhra Pradesh, annual rainfall, Geostatistical analysis, India, kriging, and seasonal rainfall.

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I. INTRODUCTION

Rainfall information is an important input in the hydrological modeling, predicting extreme precipitation events such as draughts and floods, estimating quantity and quality of surface water and groundwater. However, in most cases, the network of the precipitation measuring stations is sparse and available data are insufficient to characterize the highly variable precipitation and its spatial distribution. This is especially true in the case of developing countries like India, where the complexity of the rainfall distribution is combined with the measurement difficulties. Therefore, it is necessary to develop methods to estimate rainfall in areas where rainfall has not been measured, using data from the surrounding weather stations.

Deterministic interpolation techniques create surfaces from measured points, based on either the extent of similarity (e.g., Inverse Distance Weighted) or the degree of smoothing (e.g., Radial Basis Functions). These techniques do not use a model of random spatial processes. Deterministic interpolation techniques can be divided into two groups, global and local. Global techniques calculate predictions using the entire dataset. Local techniques calculate predictions from the measured points within neighborhoods, which are smaller spatial areas within the larger study area.

Geostatistics assumes that at least some of the spatial variations of natural phenomena can be modeled by random processes with spatial autocorrelation. Geostatistical techniques produce not only prediction surfaces but also error or uncertainty surfaces, giving an indication of how good the predictions are. Many methods are associated with geostatistics, but they are all in the Kriging family. Ordinary, Simple, Universal, probability, Indicator, and Disjunctive kriging, along with their counterparts in cokriging, are available in the geostatistical analysis. Kriging is divided into two distinct tasks: quantifying the spatial structure of the data and producing a prediction. Quantifying the structure, known as variography, is where a spatial dependence model is fit to the data. To make a prediction for an unknown value for a specific location, kriging will use the fitted model from variography, the spatial data configuration, and the values of the measured sample points around the prediction location. The geostatistical analysis provides many tools to help determine which parameters to use, and also provides reliable defaults that can be used to make a surface quickly.

The main objectives of this study are: (1) to analyze and model the spatial variability of rainfall, (2) to interpolate kriging maps for different months as well as seasons, (3) to analyze and model the structural cross correlation of rainfall with elevation for different seasons, (4) to investigate whether co-kriging would improve the accuracy of rainfall estimates by including elevation as a secondary variable, and (5) to compare prediction errors and prediction variances with those of kriging and cokriging methods for different seasons.

II. State of the Art Review

Geostatistical methods have been shown to be superior to several other estimation methods, such as Thiessen polygon, polynomial interpolation, and inverse distance method by Creutin and Obled [1], Tabios and Salas [2] . Geostatistical methods were successfully used to study spatial distributions of precipitation by Dingman et. al.,[3], Hevesi et. al,[4], extreme precipitation events by Chang [5] and contaminant distribution with rainfall by Eynon [6]; Venkatram [7]. One of the advantages of the geostatistical methods is to use available additional information to improve precipitation estimations. Precipitation highly depends upon geographical and topographical land features. Incorporating this information in the geostatistical procedure can significantly improve precipitation estimations. Elevation is the most widely used additional information in the geostatistical analysis of precipitation distribution by Chua and Bras [8], and Phillips et. al.,[9]. Subyami Ali M [10] investigated the feasibility of applying the Theory of Regionalized Variables, Univariate and Multivariate Geostatistics, to precipitation in the southwest region of Saudi Arabia. Sh. Rahmatizadeh et. al [11] have applied geostatistics in air-quality management in metropolitan area, Tehran. They have included the pollutants such as CO, NO2, SO2 and PM10 which are emitted from stationary and mobile sources. They have presented optimum interpolation methods for each pollutant. Detailed information about geostatistical procedures can be found in literature Journel and Huijbregs, [12] Isaaks and Srivastava, [13] 1989, ESRI, 2001[14], Deutsch, C.V. and Journel, A.G. [15]

III. METHODS AND MATERIALS

Kriging is a spatial interpolation method which is widely used in meteorology, geology, environmental sciences, agriculture etc.. It incorporates models of spatial correlation, which can be formulated in terms of covariance or semivariogram functions. Parameters of the model viz., partial sill, nugget, range were estimated by minimizin g the squared differences between empirical semivariogram values and theoretical model.

The first step in statistical data analysis is to verify three data features: dependency, stationarity and distribution. If the data are independent, it makes little sense to analyze them geostatistically. If data are not stationary, they need to be made so, usually by data detrending and data transformation. Geostatistics works best when input data are Gaussian. If not, data have to be made close to Gaussian distribution.

Preliminary analysis of the data will help in selecting the optimum geostatistical model. Preliminary analysis includes identifying the distribution of the data, looking for global and local outlier, global trends and examining the spatial correlation and covariance among the multiple datasets. Exploratory data analysis will help in accomplishing these tasks. With information on dependency, stationarity and distribution, one can proceed to the modeling step of geostatistical analysis, kriging.

A. Ordinary Kriging

The ordinary kriging model is

$$Z(s) = \mu + \varepsilon(s) \quad (1)$$

Where s = (X, Y) is a location and Z(s) is the value at that location. The model is based on a constant mean μ for the data (no trend) and random errors ε(s) with spatial dependence. It is assumed that the random process ε(s) is intrinsically stationary. The predictor is formed as a weighted sum of the data.

$$Z(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \quad (2)$$

Where $Z(s_i)$ is the measured value at the i^{th} location,

λ_i is an unknown weight for the measured value at the i^{th} location

S_0 is the prediction location.

In ordinary kriging, the weight λi depends on the semivariogram, the distance to the prediction location and the spatial relationships among the measured values around the prediction location.

B. Spatial dependency

The goal of geostatistical analysis is to predict values where no data have been collected. The analysis will work on spatially dependent data. If the data are spatially independent, there is no possibility to predict values between them. Semi-variogram/covariance cloud is used to examine spatial correlation. Semi-variogram and covariance functions change not only with distance but also with direction. Anisotropy will help in studying the directional effects and identifying the optimal direction. Spatial dependency is given by,

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n} [Z(x_i+h) - Z(x_i)]^2 \quad (3)$$

where x, and x+h are sampling locations separated by a distance h, Z(x) and Z(x+h) are measured values of the variable Z at the corresponding locations.

Data stationarity has been tested, data variance is constant in the area under investigation; and the correlation (covariance or semi-variogram) between any two locations depends only on the vector that separates them, not their exact locations.

Data has been tested for the presence of trend and directional effects. Global trend is represented by a mathematical polynomial which has been removed from the analysis of the measurements and added back before the predictions are made.

The shape of the semivariogram/covariance curve may also vary with direction (anisotropy) after the global trend is removed or if no trend exists. Anisotropy differs from the global trend because the global trend can be described by a physical process and modeled by a mathematical formula. The cause of anisotropy (directional influence) in the semivariogram is not usually known, so it is modeled as random error. Anisotropy is characteristic of a random process that shows higher autocorrelation in one direction than in another. For anisotropy, the shape of the semivariogram may vary with direction. Isotropy exists when the semivariogram does not vary according to direction.

C. Transformations

Certain geostatistical interpolation assumes that the underlying data is normally distributed. Kriging relies on the assumption of stationarity. This assumption requires in part that all data values come from distributions that have the same variability. Transformations can be used to make the data normally distributed and satisfy the assumption of equal variability of data. Data brought to normal with help of suitable transformations. Some of the transformations adopted are Box-Cox, logarithmic, square-root transformation.

Box-Cox transformation

$$Y(s) = (Z(s)^{\lambda} - 1)/\lambda \quad (4)$$

$$\text{for } \lambda \neq 0$$

Square root transformation occurs when $\lambda = ½$.

The log transformation is usually considered as a part of Box-Cox transformation when $\lambda = 0$,

$$Y(s) = \ln(Z(s)) \quad (5)$$

for $Z(s) > 0$ and ln is the natural logarithm. The log transformation is often used where the data has a positively skewed distribution and presence of very large values.

D. Cross validations

It gives an idea of how well the model predicts the unknown values. The objective of cross-validation is to help make an informed decision about which model provides the most accurate predictions.

Statistics of cross validation used to select the variogram model, are the mean error between measured and kriging estimated values, the correlation coefficient between measured and estimated values and the reduced kriging variance and are given in Zhang et. al, 1992.

IV. STUDY AREA

Andhra Pradesh the "Rice Bowl of India", is a state in southern India. It lies between 12°41' and 22°N latitude and 77° and 84°40'E longitude, and is bordered with Maharashtra, Chhattisgarh and Orissa in the north, the Bay of Bengal in the East, Tamil Nadu in the south and Karnataka in the west. Andhra Pradesh is the fifth largest state in India by area and population. It is the largest and most populous state in South India. The state is crossed by two major rivers, the Godavari and the Krishna.

Andhra Pradesh can be broadly divided into three unofficial geographic regions, namely Kosta (Coastal Andhra/Andhra), Telangana and Rayalaseema. Telangana lies west of the Ghats on the Deccan plateau. The Godavari River and Krishna River rise in the Western Ghats of Karnataka and Maharashtra and flow east across Telangana to empty into the Bay of Bengal in a combined river delta. Kosta occupies the coastal plain between Eastern Ghats ranges, which run through the length of the state, and the Bay of Bengal. Rayalaseema lies in the southeast of the state on the Deccan plateau, in the basin of the Penner River. It is separated from Telangana by the low Erramala hills, and from Kosta by the Eastern Ghats. The Location map of study area is shown in Figure 1.

The rainfall of Andhra Pradesh is influenced by the South-West and North-West and North-East monsoons. The normal annual rainfall of the state is 925 mm. Major portion of the rainfall (68.5%) is contributed by South-West monsoon (June-Sept) followed by 22.3% byNorth-East monsoon (Oct.-Dec.). The rest of the rainfall (9.2%) is received during the winter and summer months. The rainfall distribution in the three regions of the state differs with the season and monsoon. The influence of south west monsoon is predominant in Telangana region (764.5 mm) followed by Coastal Andhra (602.26 mm) and Rayalaseema (378.5 mm). The North-East monsoon provides a high amount of rainfall (316.8 mm) in Coastal Andhra area followed by Rayalaseema (224.3) and Telangana (97.1 mm). There are no significant differences in the distribution of rainfall during the winter and hot weather periods among the three regions.

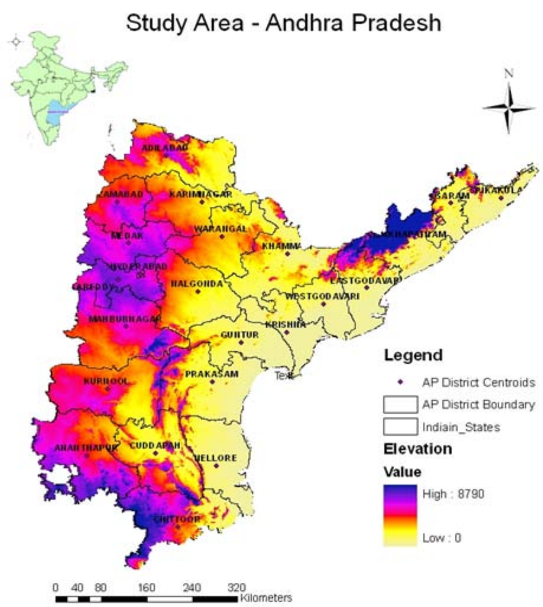

Fig. 1. Location map of study area

V.RESULTS AND DISCUSSIONS

The study used monthly rainfall data from 23 meteorological stations for the period 1970- 2003. The first step in statistical analysis is to investigate descriptive characteristics of the data. Descriptive analysis can help the investigators to have a preliminary judgment of the data and to decide suitable approaches for further analysis. The most important descriptive statistics are mean, standard deviation and coefficient of variation (Cv), calculated as standard deviation divided by mean. In hydrology, however, there are two other important moments namely coefficient of skewness (Cs) as the measure of symmetry and coefficient of kurtosis (Ck) as the measure of shape of frequency function. The monthly, seasonal, and annual rainfalls of selected stations are given in Table 1 and descriptive statistics of annual rainfall are shown in Table 2. One can see that the average annual rainfall is minimum for Anantapur and maximum for Visakhapatnam. In terms of absolute rainfall Nizamabad received highest rainfall and Anantapur received minimum rainfall. It is observed that the rainfall is positively skewed for most of the stations except for Anantapur. In general Cv is high (> 20%) for all districts except for Prakasam and Srikakulam, indicating the high rainfall variability. The highest Cv is for Nizamabad (32%). Lag 1 correlation is negative for Rayalaseema indicating that the high rainfall years are followed by low rainfall and positive for Teleangana indicating that the high years are followed by high rainfall and low rainfall years by low rainfall.

Average rainfall characteristics of mean, standard deviation, skew coefficeint are given in Table 3. It is observed that August, Sept and October receive highest rainfall during monsoon, followed by July, June, Nov and December. Skew coefficient is positive for monsoon months except for June. South-West and North-East monsoon months are also positively skewed with highest coefficient for North-East Monsoon. (Check the next sentence)Annual rainfall is negatively skewed for annual rainfall. Box-Cox transformation has been used for converting the skewed distributed rainfall to normal and their coefficients are shown in Table 3. The transformation greatly reduced the skew and the transformed series can be treated as nearly normal for further analysis.

The trend analysis enables to identify the presence/ absence of trends in the input dataset. If a trend exists in the data, it is the nonrandom (deterministic) component of a surface that can be represented by a mathematical formula and removed from the data. Once the trend is removed, the statistical analysis have been performed on the residuals The trend will be added back before the final surface is created so that the predictions will produce meaningful results. By removing the trend, the analysis that is to follow will not be influenced by the trend, and once it is added back a more accurate surface will be produced. 3D perspective trend plots for June-November are shown in Figure 2 and for South-West, North-East and Annual rainfalls in Figure 3. It is observed that the trend is present in all the cases, and is constant for November and Northe-East monsoon. The first order polynomial fits well for June, August, Sept, October, December, Annual and South-West monsoon. The second order polynomial fits best for July and all fits are tabulated in Table 4. It is further observed that for June - September, and Annual rainfall, trend varies from South-South-West to North-North-East direction; for October, November, December, trend direction is from North-West to South- East.

The Semi-variogram has been used to examine the spatial autocorrelation among the measured sample points. In spatial autocorrelation, it is assumed that (Can we change the word things) things that are close to one another are more alike. The Directional influences are also examined. They are statistically quantified and accounted for when making a map. The parameters of the semi-variogaram viz., major range, minor range, direction, partial sill and nugget are shown in Table 5. It has been observed that the directional effects are predominant in October, November, South-West monsoon and annual rainfall. The Spherical model fits well for June, July, November, South-West and North-East monsoons, where as the Gaussian model fits well for August, September, October, December and annual rainfall. Nugget effect is zero for June, November and North-East rainfalls. The best fit equations are tabulated in Table 6.

After identifying the best fit variogram model, taking into account de-trending and directional influences in the data, prediction surfaces are generated for June - November, South-West, North-East and annual rainfalls. The qualities of prediction map have been examined by creating the prediction standard error surface. The Prediction standard errors quantify the uncertainty for each location in the surface. A simple thumb rule is that 95% of the time, the true value of the surface will be within the interval formed by the predicted value +/- 2 times the predicted standard error if the data are normally distributed. It has been observed that the locations near the sample points have low error. For these analyses, ESRI's Geo-statistical analyst extension has been used.

The cross-validation gives an idea of how well the model predicts the unknown values. For all points, cross-validation sequentially omits a point, predicts its value using the rest of the data, and then compares the measured and predicted values. The calculated statistics serve as diagnostics that indicate whether the model is reasonable for map production. The criteria used for accurate prediction in the cross-validation are : the mean error should be close to zero, the root mean square error and average standard error should be as small as possible and the root mean square standardized error should be close to 1. The cross-validation results are shown in Table 7. The Cross-validation statistics showed that the predicted values are reasonable for map production. The cross-validation plot for South-West monsoon is shown in Figure 8. It shows the error, the standardized error and QQ plot for each data point.

It has also been tested that the inclusion of the elevation as a co-variate would improve the accuracy of prediction. (Check the next line) However it has not improved the accuracy of prediction in the present study. The companion of cross-validation plots of annual, South-West, North-East monsoon seasons are shown in Figure 9.

VI. SUMMARY

Geostatistical analysis was applied to study spatial and temporal distributions of the monthly, seasonal and annual rainfalls in Andhra Pradesh, India. ESRI's Geo-statistical analyst extension has been used for these analyses. The rainfall surfaces were predicted using ordinary kriging method. The co-kriging analysis has been done to improve the accuracy of prediction, by including the elevation as a co-variate. It has not resulted in significant improvement in the prediction. It was observed that the rainfall data is skewed and Box-cox transformation has been used for converting the skewed data to normal. It is observed that the trend is present in all the cases, and is constant for November, and North-East monsoon. The first order polynomial fits well for June, August, September, October, December, annual and South-West monsoon; The second order polynomial fits best for July. It has been observed that the directional effects are predominant in October, November, South-West monsoon and annual rainfalls. The Spherical model fits well for June, July, November, South-West and North-East monsoons, where as the Gaussian model fits well for August, September, October, December and annual rainfalls. The cross-validation statistics showed that the predicted values are reasonable for map production. Finally, the realistic prediction surfaces and prediction error maps are generated.

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Table 1 Mean Monthly, Seasonal and Annual Rainfalls of select stations of Andhra Pradesh

ID	DISTRICT	LONGITUDE	LATITUDE	JAN	FEB	MAR	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	ANNUAL	SW	NE
1	ADILABAD	78.873	19.2862	9.9	7.1	6.6	10.2	22.4	186.6	302.1	306.6	139.8	89.7	13.9	5.4	1100	935.1	109
2	ANANTHAPUR	77.6285	14.4592	1.6	2.5	4.6	15.6	49.3	52.7	62.2	78.8	135.2	115.4	37.4	7.6	563	328.9	160.4
3	CHITTOOR	79.0699	13.3071	8.3	8.7	8	19.3	59.1	67.9	100.7	106.7	144.8	172.3	153.7	61.1	911	420.1	387.1
4	CUDDAPAH	78.7114	14.4955	3.1	3.1	4.4	12.8	42.9	65	94.3	109.4	124.3	146.5	86.2	22.5	715	393	255.2
5	EASTGODAVARI	82.0483	17.1575	7.8	11	7.6	23.8	69.3	134.2	190.6	205.5	181.1	210.3	98.6	9.7	1149	711.4	318.6
6	GUNTUR	80.0607	16.2785	7.4	9.2	7.3	13.7	47.3	90	146.2	163.1	151.1	146.8	84.7	11	878	550.4	242.5
7	HYDERABAD	78.4695	17.3736	9.3	6.9	12.7	17.2	29.3	120.8	160.6	197.9	129.4	117.8	25.9	4.4	832	608.7	148.1
8	KARIMNAGAR	79.4411	18.5386	11.6	6.3	8.3	13.2	21.9	150	253.9	245	133	87.1	17.4	4.3	952	781.9	108.8
9	KHAMMAM	80.7948	17.7091	6.7	7.8	7.7	17.8	46	147.4	281.7	267.6	159.1	117.3	27.7	2.7	1090	855.8	147.7
10	KRISHNA	80.7803	16.4419	5.9	7.6	7	13.5	38.4	108.8	183.1	193.3	153.1	156.9	66.1	9.8	943	638.3	232.8
11	KURNOOL	77.9566	15.531	2.2	2.2	5.4	16.7	44.7	79.5	107	135.4	136.5	120.4	27.6	5.6	683	458.4	153.6
12	MAHBUBNAGAR	78.2426	16.5389	2.4	3.1	5.2	14	35.9	84	129.9	150	134.4	101.9	21.4	2.7	685	498.3	126
13	MEDAK	78.2806	17.8757	7.1	4.4	7.6	17.3	29.1	130.3	206.8	228.7	139.5	97	19	3.8	891	705.3	119.8
14	NALGONDA	79.3783	17.0996	5	4.6	5.6	12	28.5	97.6	139.9	146.7	132.9	112	34.4	3.5	723	517.1	149.9
15	NELLORE	79.6752	14.2946	22.8	16.2	3.5	12.4	43.8	47.6	86.5	89.9	110.5	269.1	302.4	96.5	1101	334.5	668
16	NIZAMABAD	78.0989	18.5354	10	4	7.2	9.3	22.2	166.9	275.1	304.3	150.2	104.5	17.1	4.3	1075	896.5	125.9
17	PRAKASAM	79.612	15.644	10.8	10.6	8.6	12.7	43.8	58.5	92.5	103.1	126.1	197.4	128.6	27.4	820	380.2	353.4
18	RANGAREDDY	78.1147	17.2838	6.1	4	8.1	17.8	31.7	123.4	178.2	188.2	155.5	106.2	21.1	5.7	846	645.3	133
19	SRIKAKULAM	84.1637	18.6038	5.1	16.4	14.6	28	72	141.5	175.2	192.2	195.3	182.9	79.2	3.6	1106	704.2	265.7
20	VISAKHAPATNAM	82.6726	17.8963	7.8	15.3	15	40.4	95.9	132.6	163.3	179.7	181.9	202.7	79.1	3.6	1117	657.5	285.4
21	VIZIANAGARAM	83.377	18.5216	10.7	16.2	21.6	35.4	98.3	132.3	174.3	194.4	189.6	169.2	55.1	4.7	1102	690.6	229
22	WARANGAL	79.7578	17.9798	10.4	9.2	9.6	13.8	30.1	144.7	263.9	244.1	139.1	98.4	23	5.3	992	791.8	126.7
23	WESTGODAVARI	81.3684	16.8965	7.6	9.4	9.5	19.2	57.8	128.4	211.2	234.9	172.6	176.7	71.6	7.8	1107	747.1	256.1

Table 2. Descriptive statistics of select stations

ID	DISTRICT	Mean	SD	CV	Skew	Max	Min	Original Series		Log transformed series		
								Lag 1	Lag2	ln skew	Lag 1	Lag2
1	ADILABAD	1097	295	0.2687	0.9134	2005.0	579.0	0.0763	0.1295	0.0121	0.0875	0.0783
2	ANANTHAPUR	558	122	0.2192	-0.0718	757.0	288.6	-0.1567	0.0750	-0.5273	-0.1541	0.0395
3	CHITTOOR	906	190	0.2100	0.8500	1468.0	620.0	-0.2125	0.2945	0.2069	-0.2203	0.2897
4	CUDDAPAH	711	155	0.2181	0.5197	1153.0	417.1	-0.0713	-0.0115	-0.0754	-0.0697	0.0043
5	EASTGODAVARI	1149	278	0.2415	0.9811	1988.0	706.6	-0.1322	0.2415	0.3352	-0.1187	0.2521
6	GUNTUR	873	204	0.2331	0.7724	1507.0	520.4	0.0877	0.2316	0.0513	0.0878	0.2175
7	HYDERABAD	836	228	0.2725	0.4879	1477.0	437.0	-0.0701	-0.1051	-0.2175	-0.0452	-0.1374
8	KARIMNAGAR	952	229	0.2411	0.8000	1521.0	616.6	-0.0079	0.0307	0.3853	-0.0336	0.0158
9	KHAMMAM	1092	244	0.2236	0.6984	1831.0	647.0	-0.0465	0.0227	0.0009	-0.0739	0.0314
10	KRISHNA	969	220	0.2274	0.6989	1580.0	572.1	-0.0898	0.1391	0.1148	-0.1107	0.1348
11	KURNOOL	684	157	0.2303	0.5251	1027.0	455.0	-0.1978	0.1400	0.1860	-0.1879	-0.0319
12	MAHBUBNAGAR	684	163	0.2387	0.4808	1122.0	392.0	0.0364	0.0639	-0.1352	0.0574	0.0568
13	MEDAK	897	240	0.2680	0.6898	1446.0	470.0	0.1059	-0.1097	0.0804	0.0768	-0.1055
14	NALGONDA	721	172	0.2381	0.5738	1126.0	447.3	0.0031	0.0711	0.0587	0.0123	0.0638
15	NELLORE	1090	263	0.2409	0.6722	1712.0	767.0	-0.2071	-0.8840	0.3802	-0.2205	-0.1303
16	NIZAMABAD	1079	348	0.3221	1.2309	2044.0	521.0	0.2604	-0.0102	0.3487	0.2318	-0.0686
17	PRAKASAM	813	153	0.1883	0.3779	1193.0	539.2	-0.1500	0.0937	-0.0062	-0.1612	0.0966
18	SRIKAKULAM	1098	202	0.1841	1.1928	1680.0	804.0	0.0044	-0.2203	0.7932	0.0103	-0.2123
19	VISAKHAPATNAM	1112	231	0.2076	1.0224	1857.0	703.2	-0.1310	0.1356	0.3528	-0.1068	0.1065
20	WARANGAL	988	223	0.2260	0.6449	1504.0	600.0	0.0673	0.0507	0.1125	0.0497	0.0603
21	WESTGODAVARI	1105	308	0.2784	1.2172	2185.0	589.7	-0.0954	0.2501	0.2704	-0.0946	0.2361

Table 3. Average rainfall characteristics of Andhra Pradesh

Item	JAN	FEB	MAR	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	ANNUAL	SW	NE
Mean	7.8	8.1	8.5	17.7	46.1	112.6	173.0	185.5	148.5	143.4	64.8	13.6	930	619	221
SD	4.4	4.5	4.1	7.7	21.3	38.5	68.3	64.9	22.4	47.5	64.6	22.1	174	170	111
Skew org	1.66	0.64	1.78	1.84	1.21	-0.15	0.32	0.15	0.70	0.92	2.50	3.08	-0.47	0.12	1.20
Kurtosis	5.53	-0.55	3.82	3.24	1.12	-0.86	-0.77	-0.64	-0.24	0.45	7.91	9.71	-0.90	-0.76	1.64
BC Parameter	0.37	0.23	-0.37	-1.02	-0.34	1.00	0.46	0.66	0.79	-0.72	0.37	-0.75	2.15	0.67	-1.20
Skew Trans	0.03	-0.05	0.00	0.05	0.04	-0.15	-0.06	-0.08	0.64	0.09	0.10	0.28	-0.20	-0.089	0.162

Table 4 Trend Estimation by Global Polynomial Interpolation (order of polynomial)

Month	**Trend Estimation by Global Polynomial Interpolation**
June	First
July	Second
Aug	First
Sep	First
Oct	First
Nov	Const
Dec	First
Annual	First
SW Monsoon	First
NE Monsoon	Const

Table 5. Kriging model - Anisotropy parameters

Item	June	July	Aug	Sep	Oct	Nov	Dec	Annual	SW Monsoon	NE Monsoon
Major Range	264480	204360	211470	242620	506470	659770	139100	659760	659760	688910
Minor Range					148400	426540		251630	309930	
Direction					336.5	52.5		54.8	323.3	
Partial sill	242.68	2.5317	27.63	6.7686	7.2E-06	18.106	0.014669	7.04E+10	118.01	9.71E-08
Nugget	0	0.48232	4.8183	13.579	8.6E-06	0	0.000734	3.24E+10	20.454	0

Table 6 Kriging - Model Equations

Month/Season	Model equation
June	242.68*Spherical(264480)+0*Nugget
July	2.5317*Spherical(204360)+0.48232*Nugget
Aug	27.63*Gaussian(211470)+4.8183*Nugget
Sep	6.7686*Gaussian(242620)+13.579*Nugget
Oct	0.0000071924*Gaussian(506470,148400,336.5)+0.0000085911*Nugget
Nov	18.106*Spherical(659770,426540,52.5)+0*Nugget
Dec	0.014669*Gaussian(139100)+0.00073401*Nugget
Annual	7.04e10*Gaussian(659760,251630,54.8)+3.2353e10*Nugget
SW Monsoon	118.01*Spherical(659760,309930,323.3)+20.454*Nugget
NE Monsoon	9.7094e-8*Spherical(688910)+0*Nugget

Table 7 Kriging Model Cross-Validation results

Item	June	July	Aug	Sep	Oct	Nov	Dec	Annual	SW Monsoon	NE Monsoon
Mean	-0.7894	-0.2105	1.185	-1.185	-0.8847	-0.8251	8.281	-2.2	0.3096	-2.185
Root-Mean-Square	13.05	28.93	24.97	12.71	22.89	38.95	46.84	87.22	57.61	54.07
Average Standard Error	11.95	25.43	25.22	12.3	22.74	27.8	37.44	87.14	62.65	62.56
Mean Standardized	-0.0406	-0.06572	0.01705	-0.09328	-0.04675	0.01604	-0.08149	-0.0143	-0.02957	-0.04886
Root-Mean-Square-Standardized	0.998	1.065	0.9995	1.033	1.036	1.093	1.341	0.9837	1.0000	0.9721

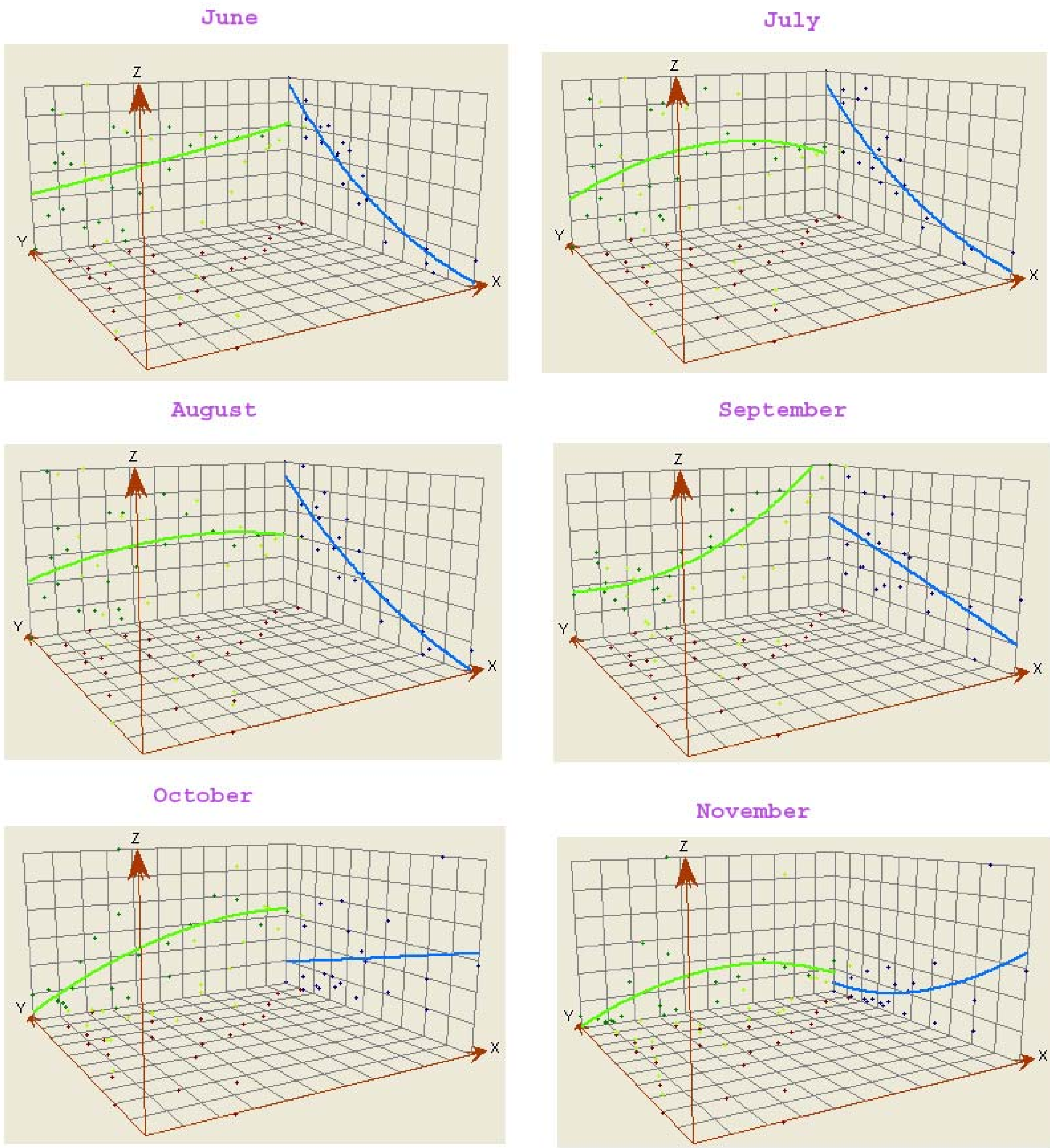


Fig. 2. Three dimensional trend analysis of mean monthly rainfalls

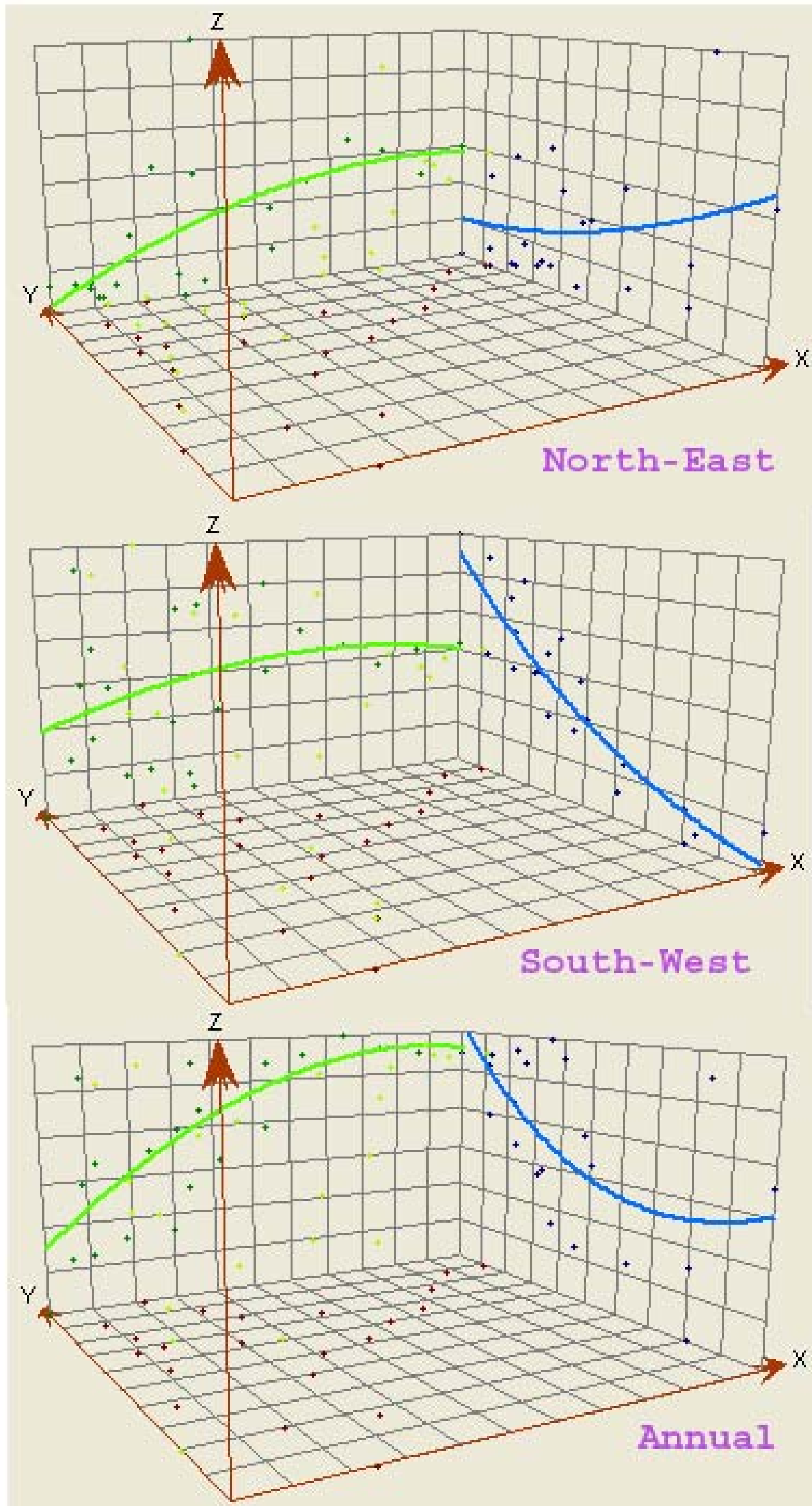


Fig. 3. Three dimensional trend analysis of North-East, South-West and annual rainfalls

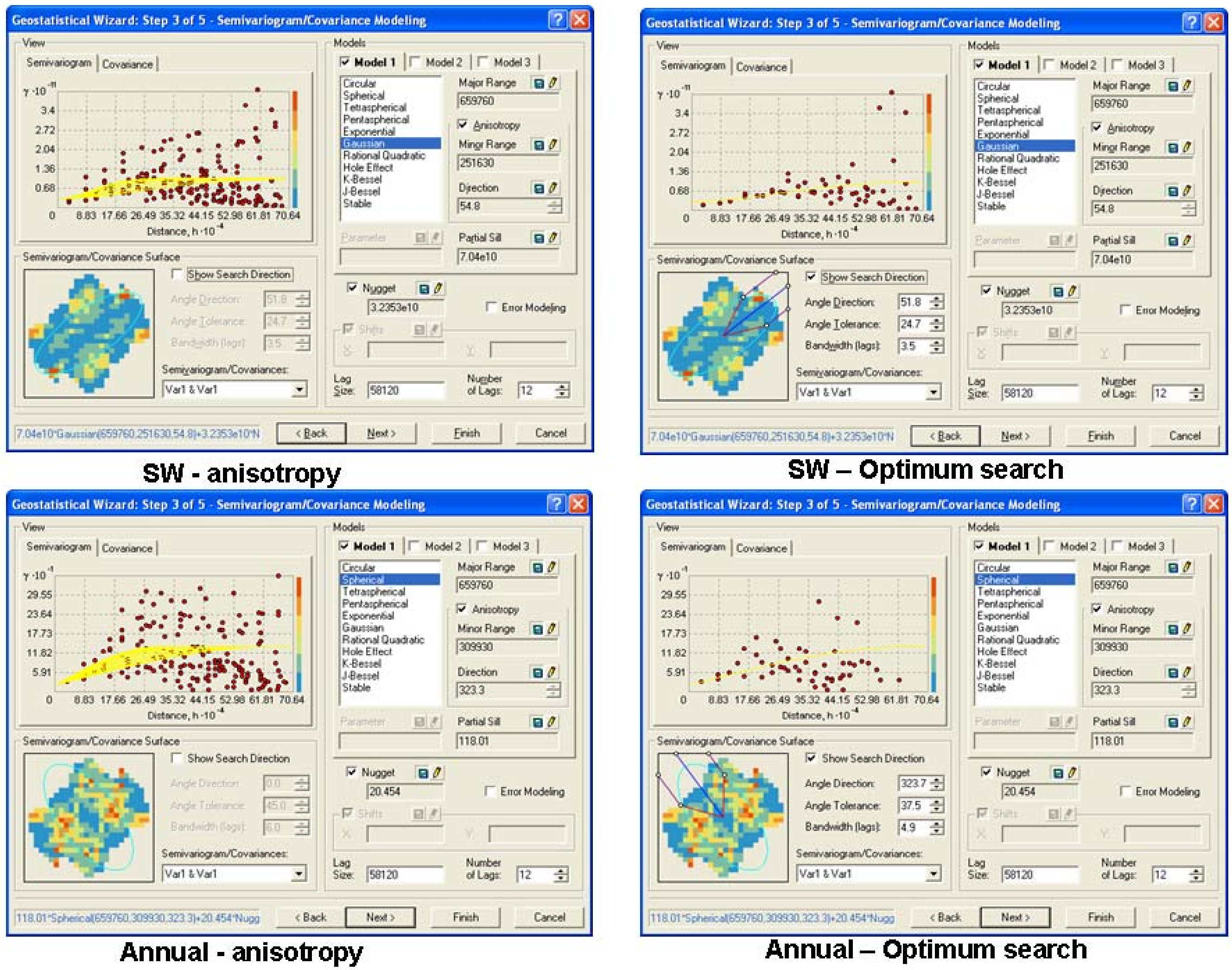
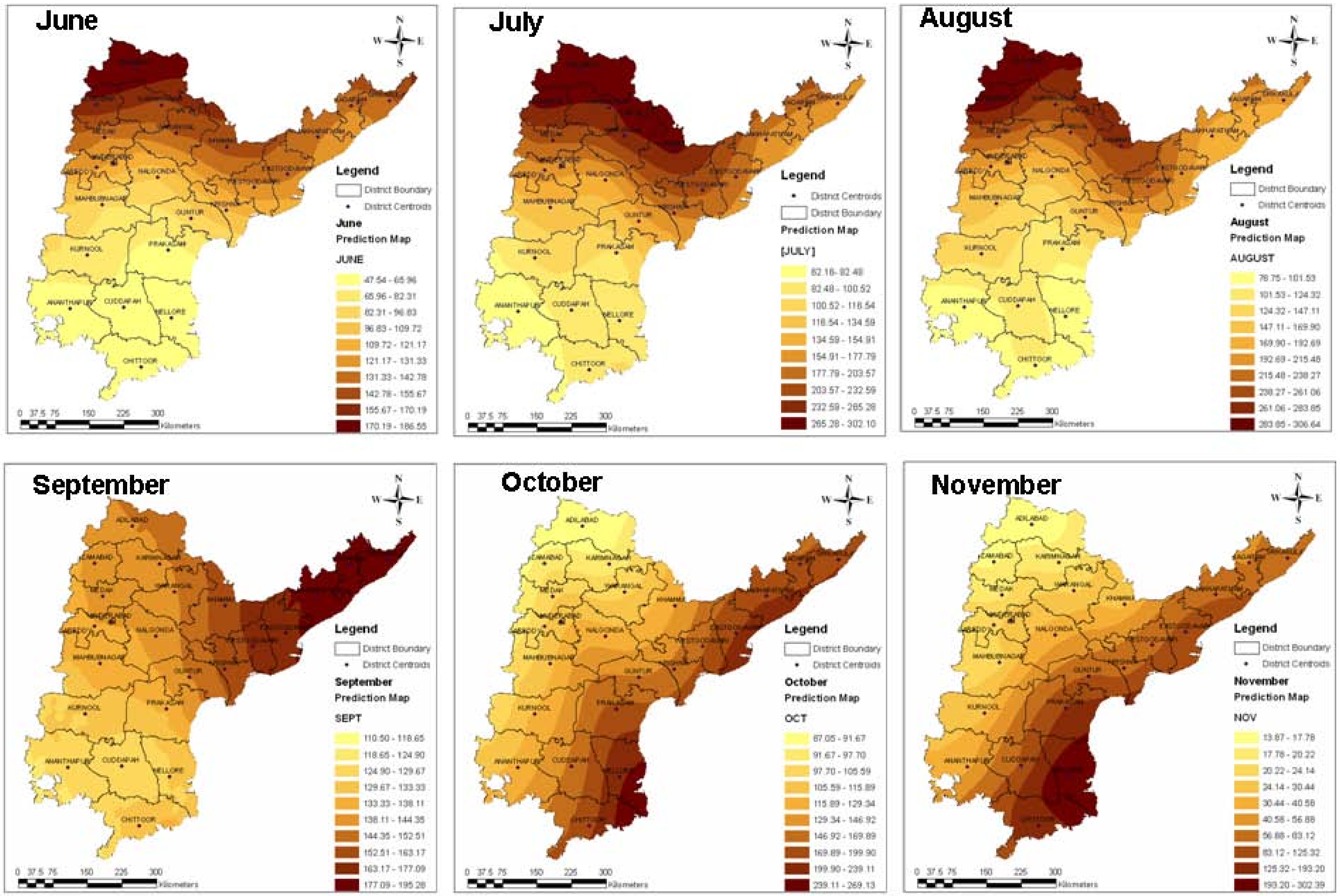
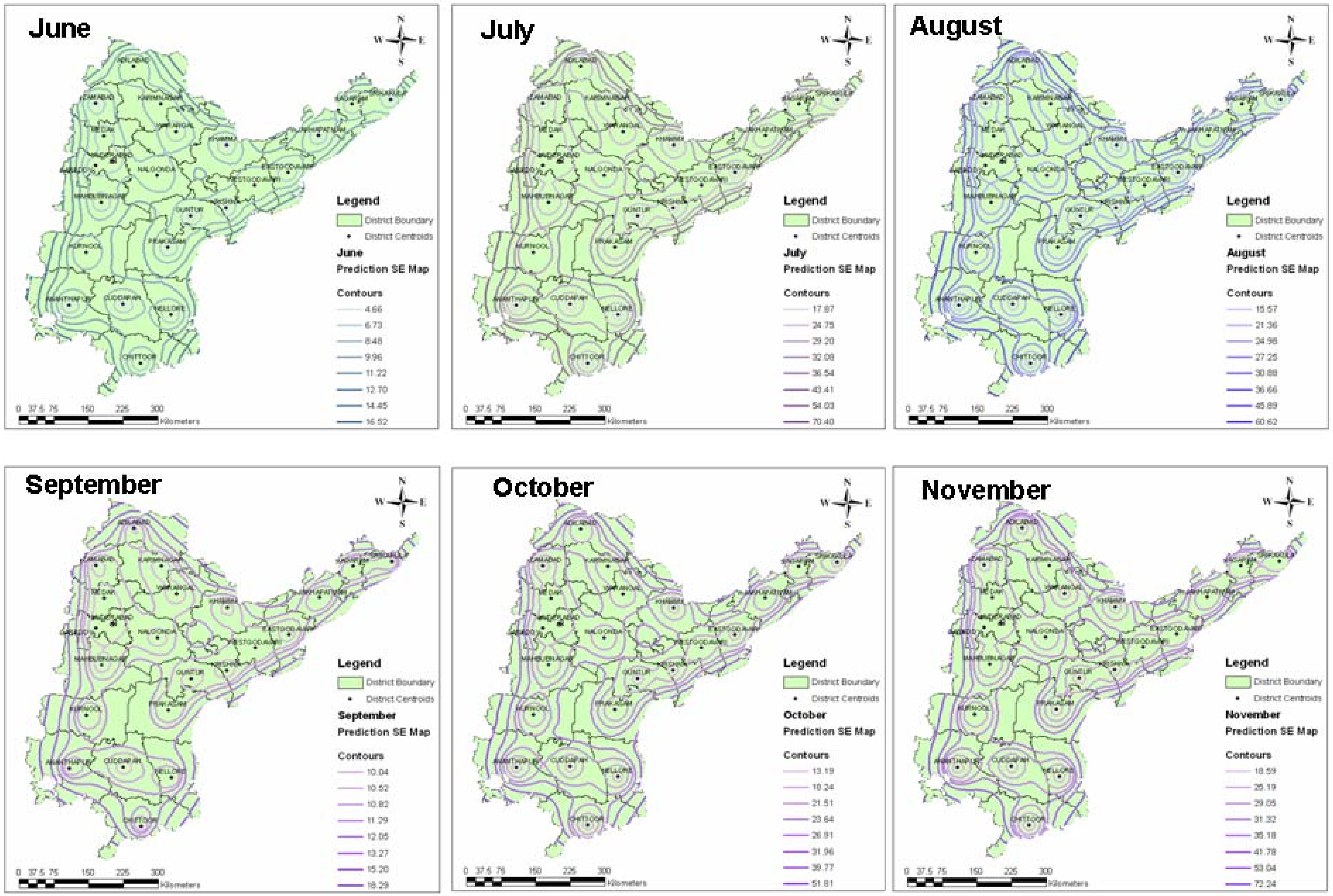


Fig. 4. Semi-variogram plots of South-West monsoon and annual rainfall showing the directional affects



Interpolated Surfaces

Fig. 5. Predicted rainfall surfaces for June – November rainfalls



Prediction Error Maps

Fig. 6. Prediction Error maps for June – November rainfalls

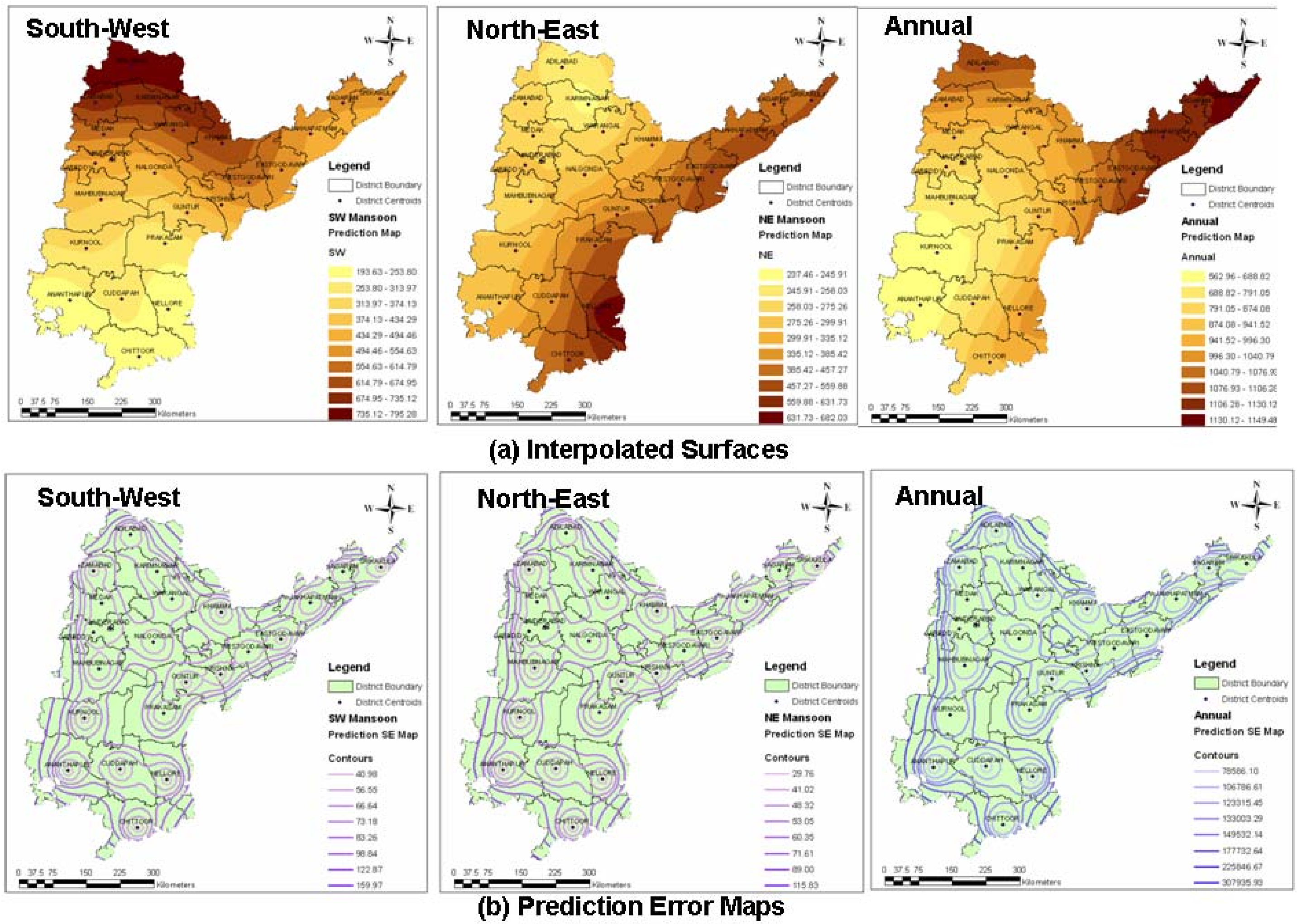


Fig. 7. Prediction surface and Error maps for South-West, North-East Monsoon and annual rainfalls

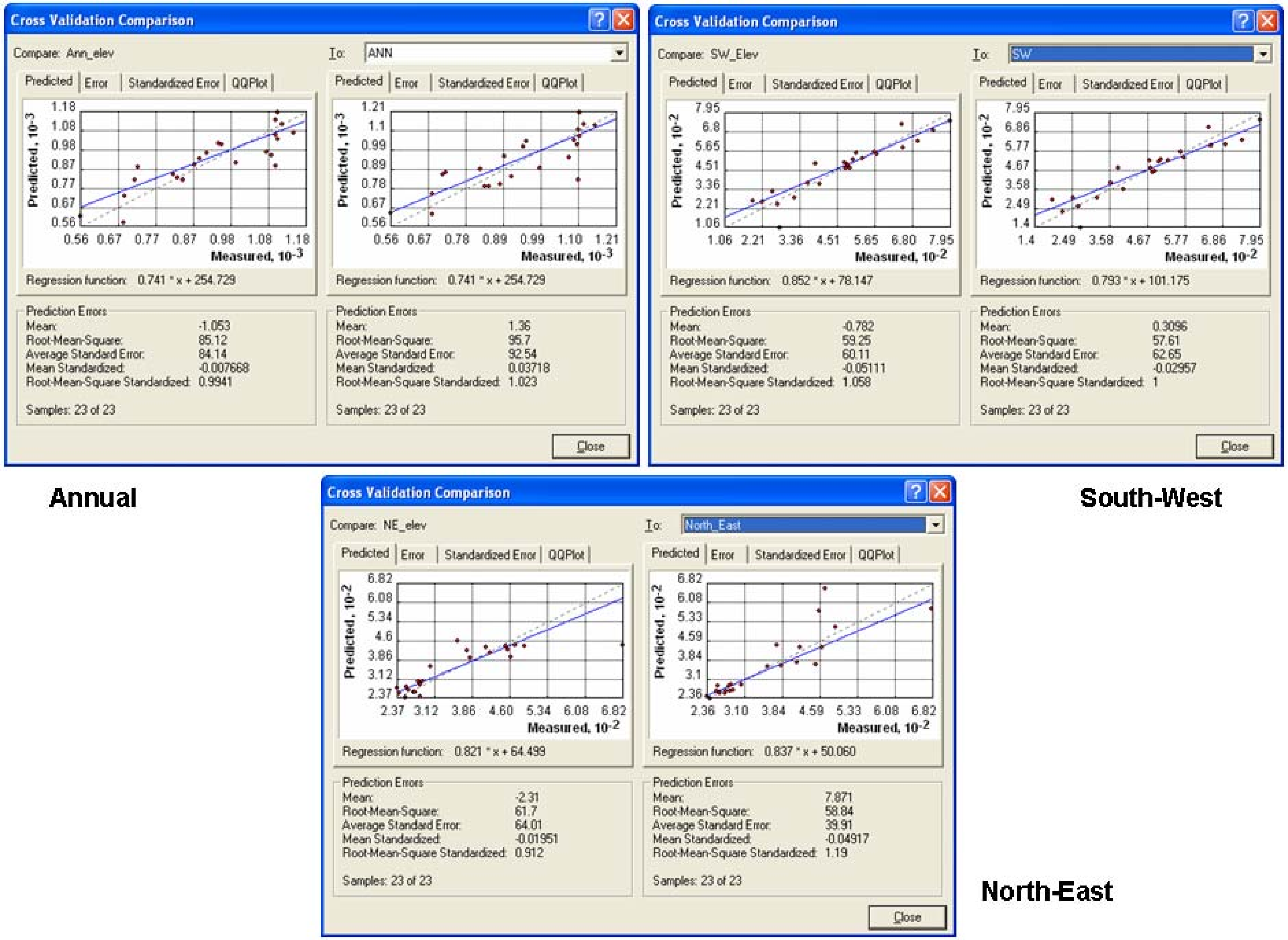


Fig. 8. The Comparison of cross-validation plots for annual, South-West and North-East monsoon seasons with elevation as a co-variate.