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GEOSTATISTICAL APPROACH IN SPATIAL ESTIMATES OF RAINFALL: BETWA RIVER CATCHMENT

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ABSTRACT: As the point-based rainfall observation design has implications in correctly representing spatially continuous rainfall values, therefore methods ranging from simple arithmetic mean to isopleths and Thiessen's polygon-based weighted means have been generally employed by hydrologists in order to obtain mean basin rainfall. The utility of these methods is important especially for analysing the spatial distribution of network and thereafter to suggest locations. Hence, advanced mathematical versions using network theory, geostatistical approach and optimum path analysis have been used to select the optimum design even in the preliminary stage of investigation. At a catchment level, an application of various interpolation methods using geostatistics is demonstrated here in case of Betwa river, one of the important southern tributary of Yamuna river after Chambal. The script for these methods was written in Geographical Information System (GIS) Software – ILWIS (Integrated Land and Water Information System) and it was run for normal rainfall parameters using data from Indian Meteorological Department. In the geostatistical analysis, it was found that trend surface, moving average and kriging based interpolated map provided good estimates of spatial accuracy of mean basin rainfall within 10-12 % of coefficient of variation when compared with normal rainfall at control stations. Among kriging methods, ordinary kriging was found to be best in terms of least root mean square deviation from validation results. Error map based on anisotropic kriging resulted into least amount of absolute error within 10% of estimation in rainfall from the measured normal values. The error can be further reduced if more rain-gauges are located in spatial dispersion zones by taking into account the effect of direction and elevation on rainfall.

KEYWORDS: Spatial interpolation, reflexive nearest neighbour, semi-variogram, anisotropic trend, error rainfall maps

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1. INTRODUCTION: Scale is a key issue in hydrology and the catchment is considered to be the basic unit of measurement. Large-scale design of any monitoring network or planning for water resource project has to overcome some of the point-based sampling difficulties. The decision on operational number of sites of observation is based on the level of accuracy required and the spatial variability of the area or variable under investigation. Till the mid 60's and 70's, the design of hydrological data collection network has been mostly based on minimising cost, which translates into problem of accessibility and maintenance of observation status. But, the present day hydrological capabilities demand high level of accuracy in the statistics obtained from collected data. Not only long-term record, but also spatial representatives of the data is essential to provide reliable inputs for various purposes like-agricultural planning, crop sequence and the acreage, irrigation schedule and canal network, capacity of reservoirs, sustainability of demand for groundwater resources, means for short-term water supply, quality of water used for various purposes, *etc.* Microclimate, local relief, changing land use pattern may result in significant spatial variations of a point-based estimate of the hydrological phenomena (1).

The issue of spatial variation in estimates of mean basin rainfall has been well recognized now and is being addressed scientifically. Besides, simple arithmetic mean to isopleths and Thiessen's polygon-based weighted means, the more mathematical ones using determinants and matrices have been used to determine area of small triangles around a rain gauge. However, due to subjectivity involved in selection of nearest station to create Theissen polygon or triangular mesh, the trial and error method does not differ significantly from the simple arithmetic method so far as mean estimates are concerned. The need to recognise accuracy in the spatial representation of hydrological data has given rise to more sophisticated statistical analysis. Configurations of spatial network based on an estimation of time-averaged areal mean of precipitation have been analysed particularly with respect to their location, duration of observation and measurement of error (2).Use of geostatistics, initially in mining field, started in hydrological investigations too. These spatial data based computations based on kriging methods have been employed to reduce the error of representativeness in estimation of mean basin parameters.

Kriging, named after Krig (3), can be seen as a method of point interpolation. The weight factors in kriging are determined by using a user-specified semi-variogram model (based on the output of the spatial correlation operation), the distribution of input points, that are calculated in such a way that they minimize the estimation error in each output pixel. Semi-variogram is a basic geostatistical measure to determine the rate of change of a regionalized variable along a specific orientation (usually distances). First, the distances between all points pairs which fall within the same user-specified lag, *i.e.* the same distance (and direction) class are calculated, *i.e.* omni-directional and then bi-directional spatial correlation is calculated to ascertain the directional trend (anisotropy) of rainfall by performing a variogram surface operation. The computation of variograms of positional uncertainty is possible when measured by geometrical discrepancy. These variograms prove to be efficient tool to represent spatial autocorrelation (4). In an another study incorporatting the effect of elevation into spatial interpolation of rainfall in a watershed of Portgual showed that larger prediction errors were obtained based on both Thiessen polygon and inverse square distance method. Ordinary kriging yields more accurate predictions than linear regression when the correlation between rainfall and elevation is moderate (5).

In India, however, the use of geostatistical approach to arrive at mean estimates of basin rainfall is limited. Here, mean basin rainfall estimates based on Thiessen polygon and isohyetal method are quite common using the existing network of rain-gauging stations. A locational analysis of the network based on annual data in the case of Dhansiri basin of north-east India stressed upon the need of accuracy level in regional pattern of rainfall. Based on coefficient of variation of rainfall, an optimum network was determined for the basin at 5% error in estimation. But, exact location of the new rain gauge was not proposed (6). Location of proposed rain-gauging network, considering the orientation of sub-catchments, distances among existing rain-gauge sites, accessibility and proximity to nearby river-gauge and discharge sites, has been attempted in another river basin in the east, the Mahanadi (7). However, the method involving the correlation coefficients to compute optimum distances was not illustrated in detail.

Thus, several approaches have been used for estimating regional values from point measurements ranging from simple arithmetic average method to kriging based surface fitting methods. In the light of paucity of works related to correct estimation of mean basin rainfall, spatial interpolation methods need to be intensively explored for better results. The present study seeks to analyse variability in spatial pattern of rainfall at catchment level by interpolation of rainfall data using various geostatistical methods. A comparison of these methods can help decision makers of water resources to choose suitable method of interpolation and in understanding spatial implications of variability in mean basin rainfall.

2. RESEARCH AREA: Betwa catchment, lying between the 77°10′ East to 80°20′ East Longitudes and 22°50′ North to 26°00′ North latitudes, is selected for the present study. It is of rhomboidal shape and covers an area of about 43 thousands km^2, bounded by Vidhyanchal Scraplands on the south, Malwa plateau on the southwest, Chambal-Sindh ravines on the west and the catchment area of Ken river basin marks its eastern boundary (Fig. I a). The Betwa river rises in the Raisen district of Madhya Pradesh near village Barkhari, southwest of Bhopal at an elevation of about 576m above mean sea level and joins Yamuna river at Hamirpur in southern Uttar Pradesh at an elevation of about 101 m above mean sea level. While flowing in a generally northeastern direction, it cuts through lava traps and exposes upper Vindhyan rocks. In Budelkhand region near Jhansi it cuts across granite and gniesses giving way to large reservoirs like Matatila and thereafter it flows through alluvium tract as seventh order river (Fig. I b). Betwa being an inter-state river follows border of Uttar Pradesh and Madhya Pradesh to some extent and, in all, it covers (including parts) four districts of southern Uttar Pradesh (Jalaun, Hamirpur, Jhansi and Lalitpur) and ten districts of Madhya Pradesh (Datia, Shivpuri, Guna, Tikamgarh, Chhatarpur, Sagar, Vidisha,. Bhopal, Sehore and Raisen). The important sub tributaries are: *Bina, Narain, Jamni, Dhasan* and *Birma* on right bank; *Kalisote, Halali, Bah, Sagar, Naren* and *Kethan* on left bank. The catchment area experiences overall higher mean annual temperature ranging from 24 °C to 26.5 °C. Extremes of temperatures show that temperatures can go as high as up to 48°C and as low as up to 2°C. The Banda district often registers the largest number of sunstroke every year, probably, owing to tense terrestrial radiation and lack of haziness in the sky being away from the source regions of dust storms in the west (8). The plateau region experiences a slightly lower range of maximum temperature than that of plains but minimum temperature follows the reverse pattern. Climographs for the region move towards scorching and muggy conditions in the pre-monsoon and monsoon season, respectively (9). Normal annual rainfall varies from 788 to 1358 mm in the catchment area having a network of 58 rain-gauge stations located inside the catchment area and 12 nearby gauges according to state climatological records of Uttar Pradesh and Madhya Pradesh. Mean rainfall is 981 mm with annual variability of 16.8%. About 75 cm (or 75%) of precipitation is concentrated in three months only but the water budget is highly variable with deficit (800 to 1200 mm) surpassing the surplus depth of water (0 to 325 mm) (10). Medium black soil in upper Vindhyan reaches, mixed red and black soil in middle reaches, alluvial soil in lower plains characterize the region with dry deciduous type of vegetation. *'Tendu'* trees are found in abundance in the Panna and Chhatarpur districts. Only Panna and Raisen districts have more than 1/3rd of their total reported area under forest cover. There is very little forest cover (<10%) in the northern plains where the original cover has almost been removed to make room for cultivation.

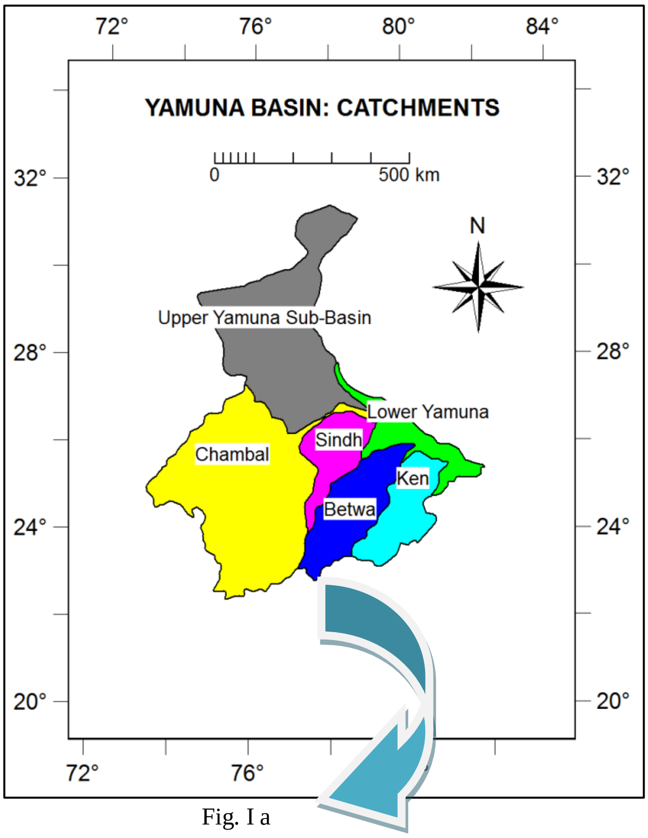


Fig. I a

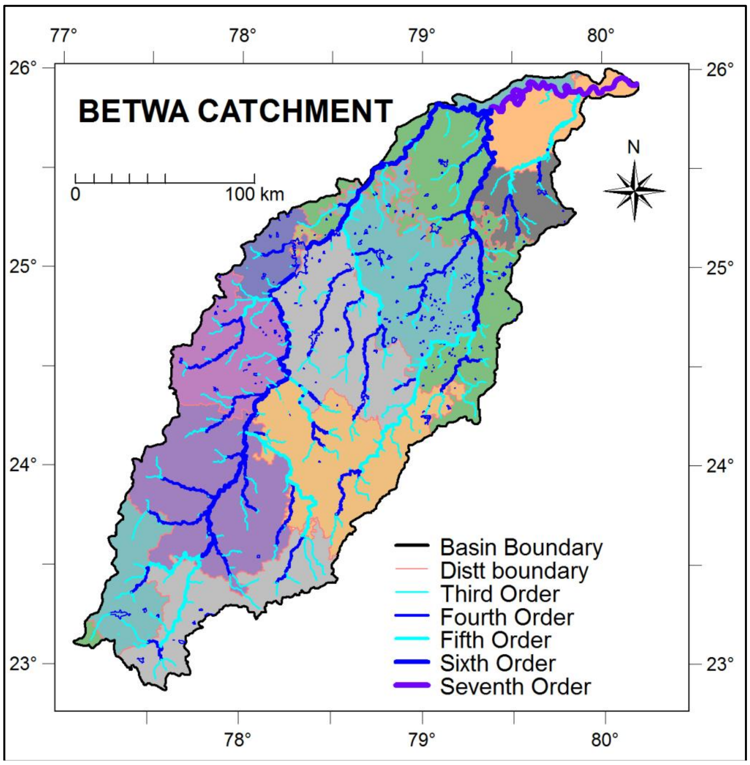


Fig. I b

Fig. 1 (a & b): Location of Research Area (Betwa Catchment)
(Source: Author using ILWIS based on SOI Toposheets and NATMO Atlas)

3. METHODOLOGY: Long-term annual data for meteorological observatories and rain gauges stations was obtained from Indian Meteorological Department (IMD). Besides annual data, monthly and weekly data was also obtained from state-level climatological reports. Further, primary data regarding the nature and functioning of data stations, maintenance, communication and publication of data, and the economic or other managerial problems, was also gathered at some of the selected sites.

The boundaries of the Betwa catchment were drawn according to relief and drainage characteristics as depicted on Survey of India toposheets and Watershed Atlas. Then, location data of rain-gauges was placed on base map. According to latest published records of meteorological observatories in Indian Meteorological Department Report (1999) on Weekly Probabilities of Rainfall, stations having more than 30 years of record (1951-80) were included to get estimates of mean values at 45 rain gauges out of total 58 located inside Betwa river catchment. From these 13 stations, mostly having short-term record, 11 were used for validation of results. First, computations of their areal means based on simple arithmetic average and Theissen polygons were done. Thereafter, spatial distribution of rain-gage stations was analysed based on point-pattern statistics which was compared to the situation of complete spatial randomness (CSR).Various isohyetal maps were drawn in a GIS system by writing a script in ILWIS (Integrated Land and Water Information System) for annual values. Both deterministic and stochastic interpolations methods were used (Fig. II) to get pixel-wise values by fitting different surfaces. Coefficient of variability (Cv) of rainfall and standard error was calculated to compare best estimates of mean rainfall data. Further, a detailed analysis of kriging based operation was performed based on spatial auto-correlation and semi-variogram operations. γ - Geostatistics software was also used to get parameter values for semi-variograms.

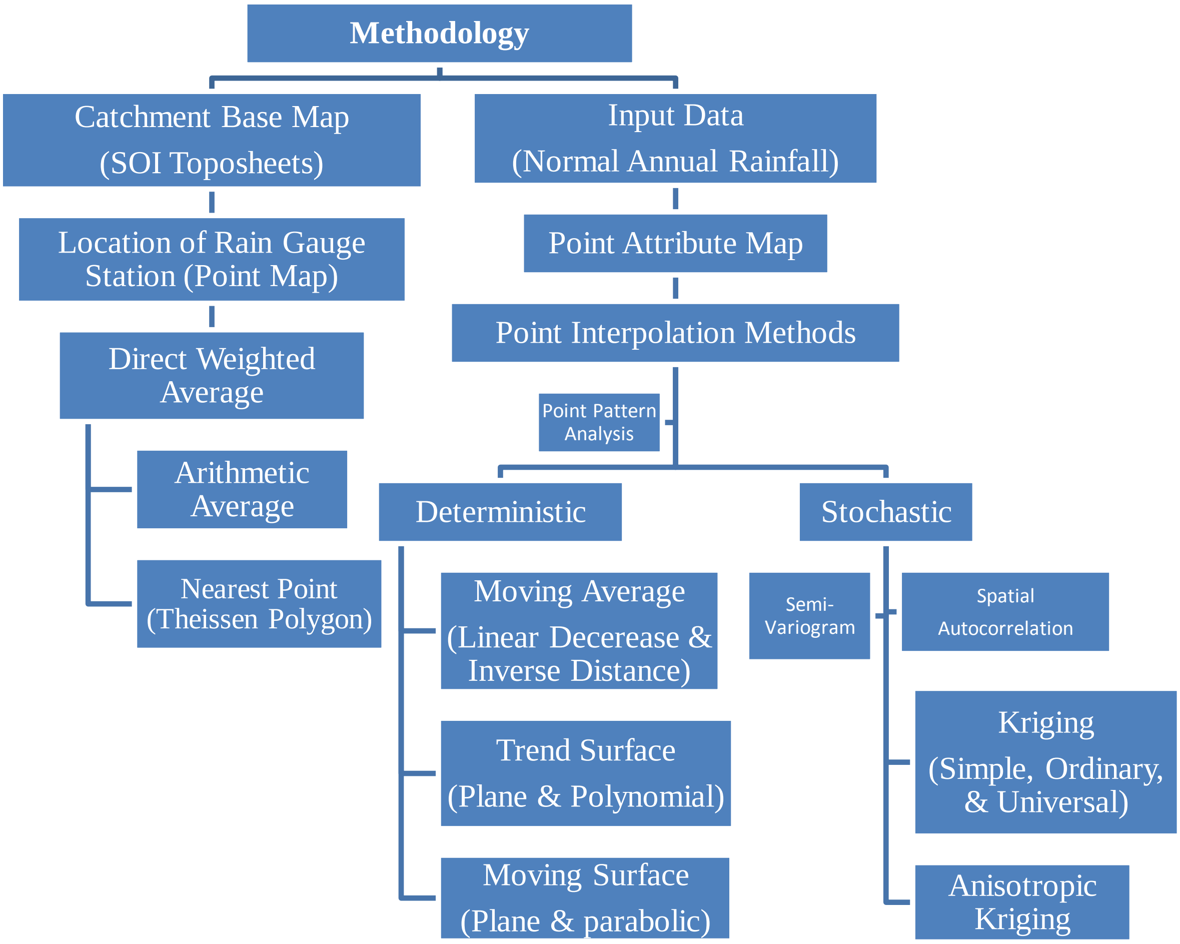
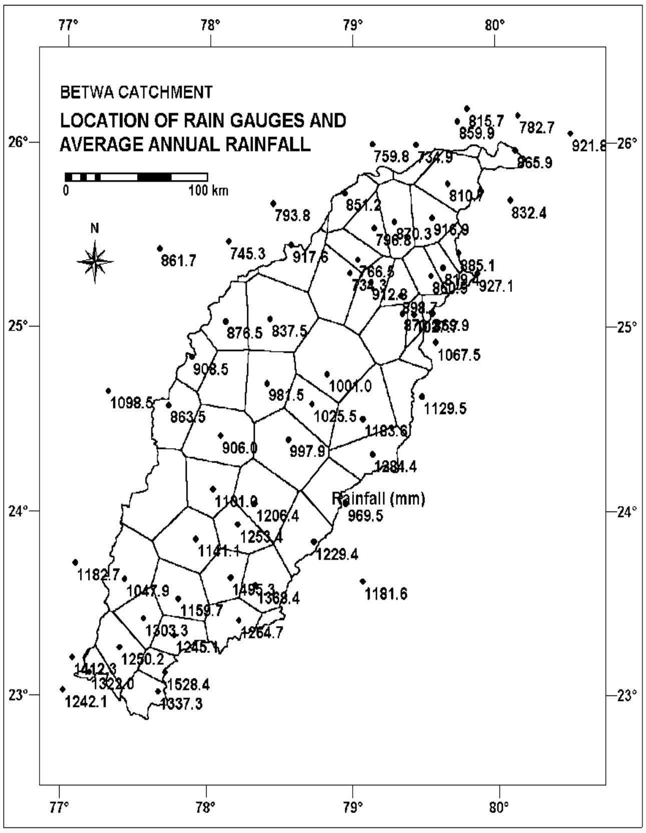


Fig. II: Flow Chart of Methodology

By plotting the answers on autocorrelation against the distance classes, *limiting distance* was calculated to see until which distance spatial autocorrelation exists between point pairs. This value was used for point interpolations such as moving average, moving surface and kriging. Then, for all pairs of points that have a certain distance to each other, the Moran's I (the product of difference of point pair values to the overall difference) and Geary's C (the squared differences of point pair values to the mean of all values for these point pairs) values were calculated within each distance class. Thereafter, for the point pairs in a certain distance class and in the correct direction, experimental semi-variogram values were calculated. By finding a model (Spherical, exponential, Gaussian and wavy semi-variogram models) which fits these experimental semi-variogram values, necessary input information such as model type, sill, range, and nugget) was obtained for kriging operations. For Anisotropic kriging, semi-variogram values for two perpendicular directions were calculated, then zonal anisotropy angle and ratio of the two bands was used to get anisotropic kriging map. Finally, for all kriging methods error maps were obtained in order to choose best interpolation method.

4. RESULTS AND DISCUSSIONS: As estimation of basin rainfall depends on network of rain gauges, therefore status of existing ones was assessed first. Although at every tehsil headquarter has rain-gauge located within its premises but during field survey it was observed that it remains operational during monsoon season only due to official state policy of maintaining rainfall records. Agricultural centres also have their own network of agri-met observatories. Most of the rain gauges, manned by part-time staff are maintained by Meteorological office from where a regional advisory is given. Automatic rain - gauges are located at meteorological stations only and even they are sometimes not fully functions. The overall network of 58 rain gauges is way behind minimum density of 575 Km^2 per gauge as per recommendations of World Meteorological organization (WMO) required in the interior plains and undulating or hilly regions like Betwa Catchment (Fig. III). Here, too, the spatial distribution of existing network of rain gauges is to be analysed first in order to have justification for locations of proposed gauges.



Source: Based on data in Appendix and SOI toposheets (1:250,000)

Fig. III: Rain-Gauge Stations in Study Area and their Influence Area Theissen Polygons

4.1. SPATIAL DISTRIBUTION OF RAIN GAUGE NETWORK: Spatial distribution of rain gauges with respect to their first nearest neighbour in the Betwa river catchment exhibits regular pattern than that of present in a situation of complete spatial randomness pattern - both in terms of number and distance. At some of the higher orders, however, the neighbourhood statistics shows a little clustered pattern at 2nd and 5th order, and a regular pattern regarding number of gauges but a clustered pattern is observed with respect to their distance at all levels (Table I). Thus, meteorological-cum-rain gauge stations at higher hierarchical levels can be located randomly in space. It is only at lower levels, the spatial correlation effects need to be examined in detail.

Order	Number of Nearest Neighbours		Distance to Nearest Neighbours	
	Observed Values	Assumed with CSR	Observed Values	Assumed with CSR
1	28	29.21	22757.85	22703.46
2	18	15.47	30303.24	34055.19
3	8	11.43	36908.84	42568.99
4	6	9.47	42239.14	49661.55
5	10	8.27	47478.47	55873.22
6	6	7.44	52704.97	61458.27

Table I: Reflexive Nearest Neighbour Statistics of Rain Gauge Distribution in Betwa River Catchment
(Source: Computed in ILWIS from location data of rain-gauges)

4.2. BEST ESTIMATES OF MEAN BASIN RAINFALL: Beginning from simplest measure of mean basin rainfall, a detailed geostatistical analysis using GIS software revealed pixel-wise information of rainfall that can be used for any study like digital terrain model correlation with rainfall estimates, water balance etc. based on interpolated values. An overview of different methods along with their results is presented in the following sections.

4.2.1. DIRECT WEIGHTED AVERAGES: The arithmetic average puts the mean annual rainfall in the Betwa catchment as 969.53 mm. But, this approach provides reasonable estimates if, the gauges are distributed uniformly and the topography is flat which, except for the northern region, are not found in abundance in the Betwa catchment. Hence, mean precipitation as 1033.22 mm computed by Thiessen polygon method (Fig. III and Table II) works out to be higher than that of by arithmetic average as it takes into account local variations.

Out of 58 polygons drawn in Figure III, leaving aside influence area of 12 rain gauges located outside Betwa catchment, only 9 have area comparable with the optimally sized hexagons having a uniform influence area of 575 km^2. Generally, rain gauging stations have smaller influence area towards the Bundelkhand plains, whereas, moderate to large-size polygons are found in the central Bundelkhand upland and plateau region. Few polygons with a comparable optimum size occur in the hilly region especially towards the headwater regions of the Betwa river. This distorted distribution of rain gauges can be explained by the overall development in the region. Agricultural intensity in the plains may be attributed to the establishment of more rain gauges there, reflecting the demand for accurate measurement of rainfall in their vicinity. The rugged and inaccessible terrain in the middle course of the river, besides the low level of development, has resulted in relatively large-size polygons. However, with the development of irrigation in the region, new stations have been installed in Madhya Pradesh.

S. No.	Rain-gauge	Influence area (km^2)	Rainfall (mm)	S. No.	Rain-gauge	Influence area (km^2)	Rainfall (mm)
1	Talbahat	1806.86	837.5	30.	Banda	787.86	969.5
2.	Tikamgarh	1791.63	1001	31.	Pathari	783.29	1253.4
3.	Narhat	1648.50	997.9	32.	Bijawar	772.32	1129.5
4.	Sironj	1535.21	1011.2	33.	Devanganj	691.01	1303.3
5.	Mungaoli	1450.24	906.0	34	Raisen	658.12	1245.1
6.	Ghoora Malehra	1359.18	1183.6	35.	Barwasagar	616.40	796.8
7.	Khurai	1292.49	1206.4	36.	Moth	599.65	851.2
8.	Berasia	1271.78	1047.9	37.	Goharganj	585.64	1337.3
9.	Basoda	1219.70	1141.1	38.	Isagarh	558.84	908.5
10.	Lalitpur	1202.65	981.5	39.	Pachwara	526.25	766.5
11.	Magarwara	1113.72	734.3	40.	Belathal	517.73	860.9
12.	Sarila	1103.06	810.7	41.	Alipura	467.78	898.7
13.	Sagar	1063.77	1229.4	42.	Kulpahar	359.06	819.4
14.	Bhilsa	1057.38	1159.7	43.	Bilkisganj	347.49	1322
15.	Begumganj	1017.18	1368.4	44.	Hamirpur	336.52	865.9
16.	Kurwai	1013.83	1101.0	45.	Chiklod Kalan	319.16	1528.4
17.	Chanderi	999.21	920.8	46.	Nowgong	269.22	1027.7
18.	Ashoknagar	983.07	863.5	47.	Orai	265.26	734.9
19.	Chandia Nallah	976.37	1284.4	48.	Chatarpur	243.33	1067.5
20.	Pichhore	958.10	876.5	49.	Charkhari	226.28	885.1
21.	Garaotha	920.33	870.3	50.	Lugasi	172.37	869.9
22.	Bhopal	910.28	1250.2	51.	Silwani	135.52	1150.0
23.	Mahroni	893.84	1025.5	52.	Konch	112.07	759.8
24.	Garrauli	891.40	873.3	53.	Mahoba	88.32	927.1
25.	Jhansi	821.97	917.6	54.	Kalpi	87.40	859.9
26.	Mau Ranipur	806.43	912.8	55.	Karera	54.82	745.3
27.	Mohammadgarh	800.34	1495.3	56.	Bhander	27.41	767.1
28.	Ghairatganj	798.82	1264.7	57.	Maudaha	10.05	832.4
29.	Rath	788.77	916.9	58.	Sehore	5.79	1412.3

Table II: Mean Annual Rainfall and Influence Area of Rain Gauge by Theissen Polygon Method
(Source: Area Computed in ILWIS)

4.3. RAINFALL INTERPOLATION BY SURFACE FITTING: As the best areal estimates can be determined by isohyetal method, therefore, a decision about search radius for points to be included within an isohyetal zone becomes crucial parameter even for GIS software. Point-probability values provided significant clues in this direction (Table III).

Lag class	Distance (meters)	Probability of Finding Point Pairs (Rain-Gauging Stations)						
		All Points	1Point	2 points	3 Points	4 Points	5 Points	6 Points
1	8200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	9100	0.0004	0.0286	0.0000	0.0000	0.0000	0.0000	0.0000
3	10000	0.0012	0.0857	0.0000	0.0000	0.0000	0.0000	0.0000
4	11000	0.0021	0.1286	0.0143	0.0000	0.0000	0.0000	0.0000
5	12000	0.0021	0.1286	0.0143	0.0000	0.0000	0.0000	0.0000
6	13000	0.0029	0.1714	0.0286	0.0000	0.0000	0.0000	0.0000
7	15000	0.0041	0.2143	0.0571	0.0143	0.0000	0.0000	0.0000
8	16000	0.0050	0.2571	0.0714	0.0143	0.0000	0.0000	0.0000
9	18000	0.0062	0.3000	0.1143	0.0143	0.0000	0.0000	0.0000
10	20000	0.0070	0.3429	0.1286	0.0143	0.0000	0.0000	0.0000
11	22000	0.0099	0.4714	0.1714	0.0429	0.0000	0.0000	0.0000
12	24000	0.0145	0.5857	0.2571	0.1286	0.0286	0.0000	0.0000
13	27000	0.0186	0.6286	0.3714	0.1714	0.0571	0.0571	0.0000
14	30000	0.0236	0.7286	0.4571	0.2286	0.1286	0.0714	0.0143
15	33000	0.0306	0.8571	0.5857	0.3143	0.1857	0.1143	0.0429
16	36000	0.0385	0.9143	0.7286	0.4714	0.2714	0.1429	0.0857
17	39000	0.0464	0.9429	0.8143	0.6000	0.3714	0.2571	0.1143
18	43000	0.0555	0.9857	0.8571	0.7000	0.5143	0.3286	0.2000
19	47000	0.0654	0.9857	0.9143	0.7429	0.6143	0.4571	0.3143
20	51000	0.0841	0.9857	0.9571	0.8714	0.8143	0.6429	0.4571
21	56000	0.0994	1.0000	0.9714	0.9143	0.8714	0.8000	0.6429
22	62000	0.1226	1.0000	1.0000	0.9571	0.9143	0.8714	0.7857
23	68000	0.1416	1.0000	1.0000	0.9714	0.9286	0.9000	0.8857
24	75000	0.1681	1.0000	1.0000	1.0000	0.9857	0.9429	0.9286
25	82000	0.1909	1.0000	1.0000	1.0000	1.0000	0.9714	0.9286
26	91000	0.2327	1.0000	1.0000	1.0000	1.0000	1.0000	0.9714
27	100000	0.2687	1.0000	1.0000	1.0000	1.0000	1.0000	0.9857
28	110000	0.3114	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
29	120000	0.3565	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
30	130000	0.3975	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
31	150000	0.4791	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
32	160000	0.5122	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
33	180000	0.5847	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
34	200000	0.6476	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
35	220000	0.7101	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
36	240000	0.7615	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
37	270000	0.8306	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
38	300000	0.8841	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
39	330000	0.9317	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
40	360000	0.9598	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
41	390000	0.9793	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
42	430000	0.9934	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
43	470000	0.9996	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
44	510000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table III: Probabilities of Location of Rain-Gauging Stations in Betwa Catchment
(Source: Computed in ILWIS)

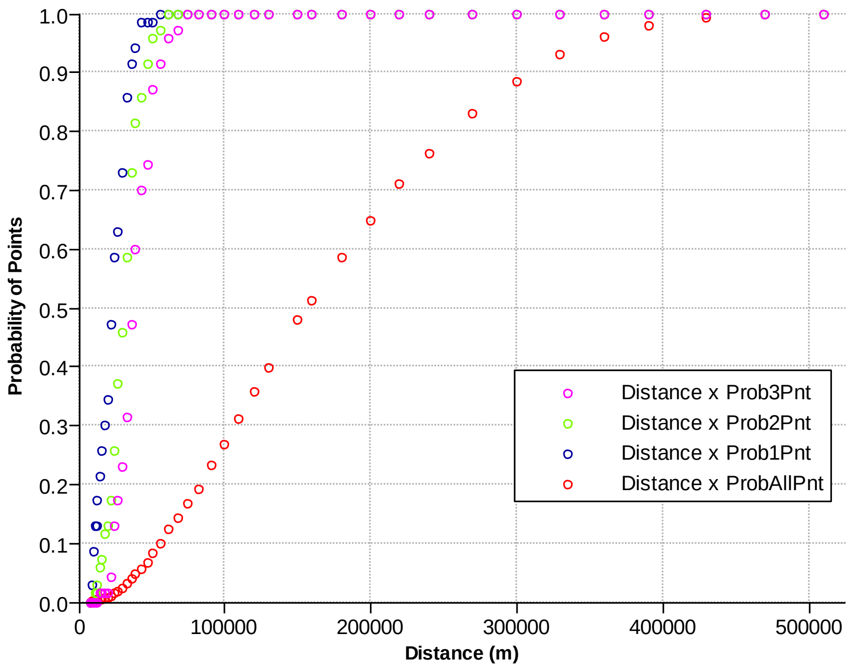


Fig. IV: Probability of Finding a Location of Rain Gauge *vs.* Distance
(Source: Plotted in ILWIS based on Location Data)

A careful investigation of point-pattern graph based on all 70 points including nearby catchment area reveals that the 100% probability to find at least one point lies at a distance of 56 km, 62 km for 2 points and 110 km for 6 points (Fig. IV). Therefore, search radius for any interpolation was used according to these limits. One point probability based radius 56 km results into lesser correlation between modelled and experimental values than with 2 point probability radius. Hence, 62km was used for interpolation of rainfall data having a standard period of 30 year with a network of 45 rain gauges.In order to obtain more comprehensive picture for normal annual rainfall data, the data set having long-term record (>50 year) of rainfall with a network of only 25 rain gauge stations from the total was used for comparison of methods (Table IVa). Isohyetal average obtained by contouring these precipitation values revealed variation in estimates ranging from 962.11mm to 1033.95 mm (Fig. V a to g) A histogram-based analysis for simplest measures like coefficient of variation (C_v) reveals that although moving average linear decrease method minimizes the overall variation but root mean square (RMS) error in rainfall estimates in this case is higher. Thus, local variations remain hidden. Moving average inverse distance method minimizes the error near the station due to close correspondence between the observed and expected values of rainfall in their vicinity. Trend surface (2 degree polynomial method) and kriging provide good results of interpolation but large number of points are required for computations and validations. Validation results for rest of the 11 stations having short-term record, however, show somewhat different picture (Table IV b). Hence, error in both spatial and temporal variation are essential for optimum results. However, utility of kriging method is proved in all three attempts in terms of reduction of overall variation in areal means. Therefore, interpolation by different kriging methods was done to anlayse spatial variation in detail.

S.No.	Method	Results using stations with 30 yr record		Results using stations with long term record (>50 yr)	
		Mean rainfall (mm)	(C_v) (%)	Mean rainfall (mm)	(C_v) (%)
1	Arithmetic average	969.53	16.75	981.00	16.84
2	Theissen polygon	953.72	15.02	962.11	13.90
3	Moving average (inverse distance)	1018.54	12.77	1033.17	10.76
4	Moving average (linear decrease)	1015.80	12.05	1032.96	9.59
5	Moving surface (2degree parabolic)	1019.96	14.28	1028.59	13.92
6	Moving surface (plane)	1023.73	13.12	1029.49	13.37
7	Trend surface (2^{nd} degree polynomial)	1013.99	11.42	1030.21	12.66
8	Kriging (ordinary)	1021.30	12.08	1033.95	11.65
9	Kriging (simple)	1021.30	12.55	1032.91	11.72

Table IVa: Mean Rainfall and Variability

S.No.	Method	(C_v)(%)	RMS	R2
1	Moving average (inverse distance)	12.32	33.44	0.7425
2	Moving average (linear decrease)	12.15	37.24	0.6807
3	Moving surface (2degree parabolic)	12.63	32.28	0.7600
4	Moving surface (plane)	11.94	33.91	0.7353
5	Trend surface (linear)	10.73	36.96	0.6855
6	Trend surface (2nd degree polynomial)	11.04	37.43	0.6744
7	Kriging (ordinary)	11.62	35.34	0.7123
8	Kriging (simple)	11.77	35.43	0.7110

Table IV b: A Comparison of Validation Results

Table IV (a & b): Mean Rainfall of Betwa Catchment estimated using different Interpolation Methods

(Source: Computed in ILWIS based on rainfall data from i) Government of India, Indian Meteorological Department ,1999 *Weekly Rainfall Probabilities. Vol. I and II;* .ii) *Climate of Madhya Pradesh*, 1983; iii) *Climate of Uttar Pradesh*, 1989)

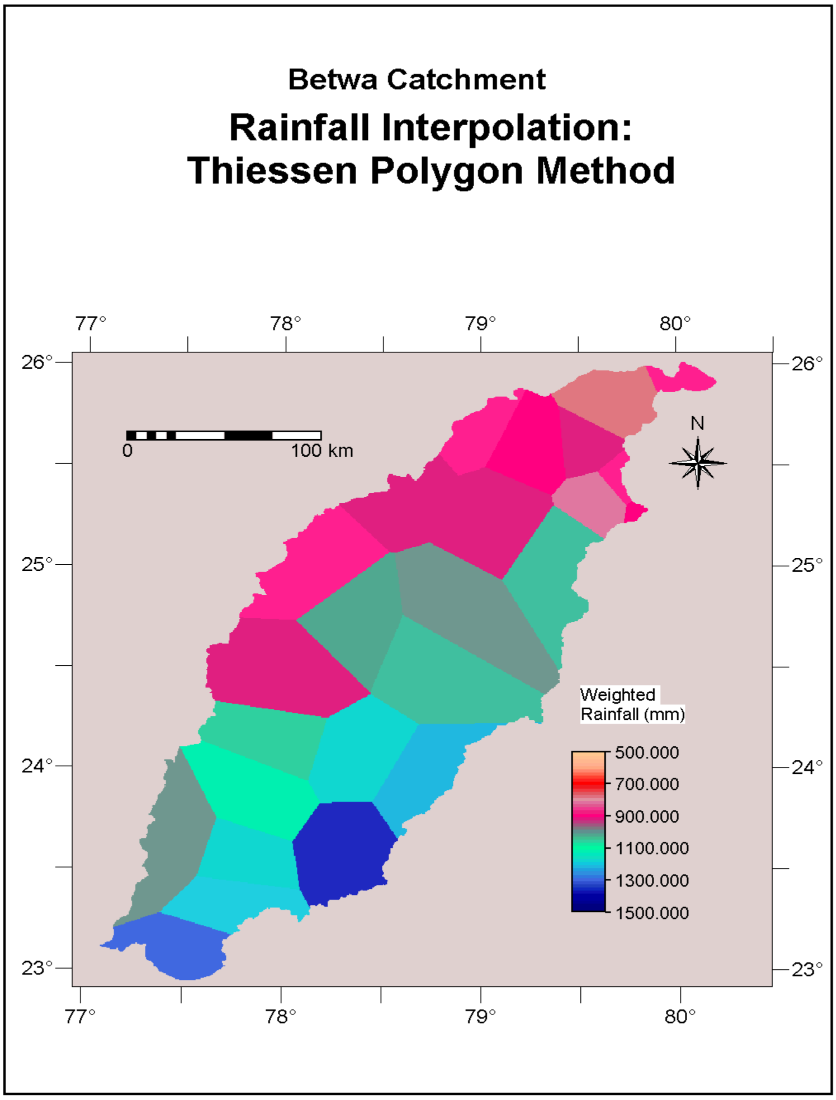


Fig. V a

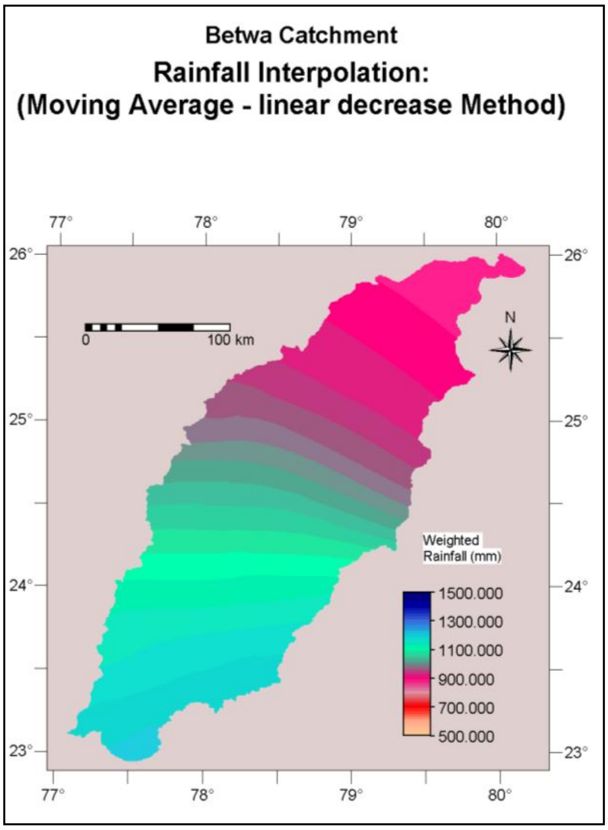


Fig. V b

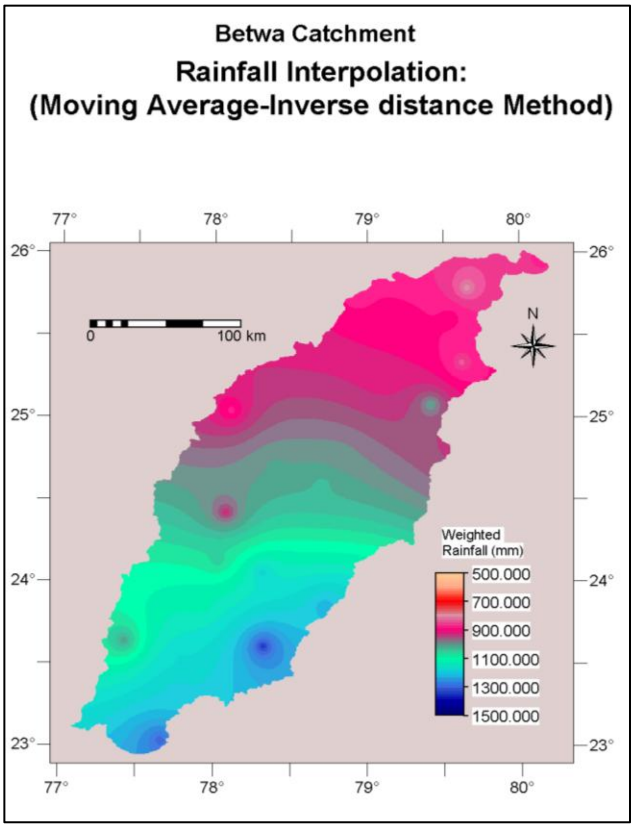


Fig. V c

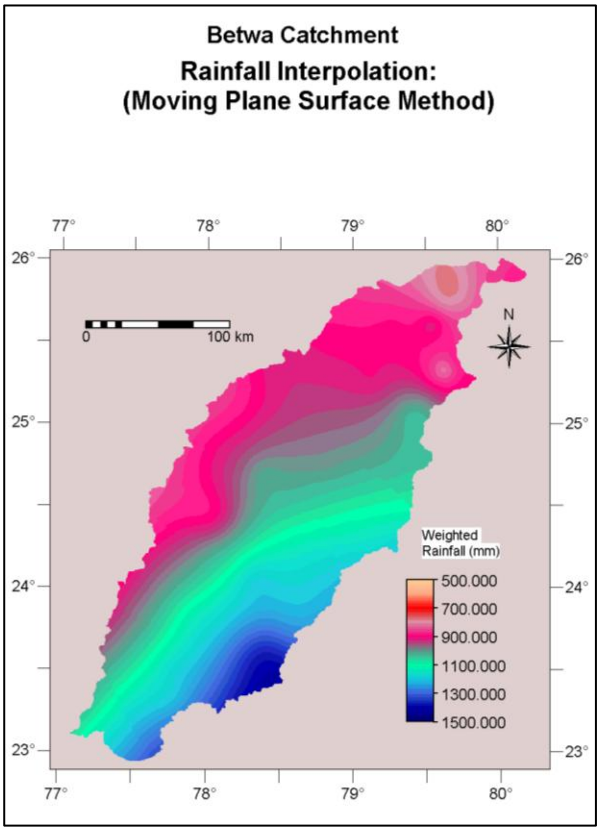


Fig. V d

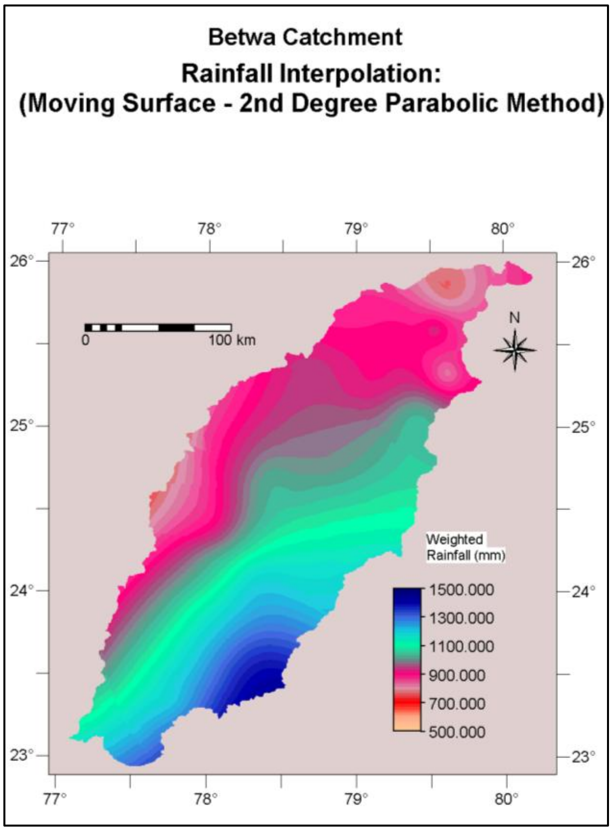


Fig. V e

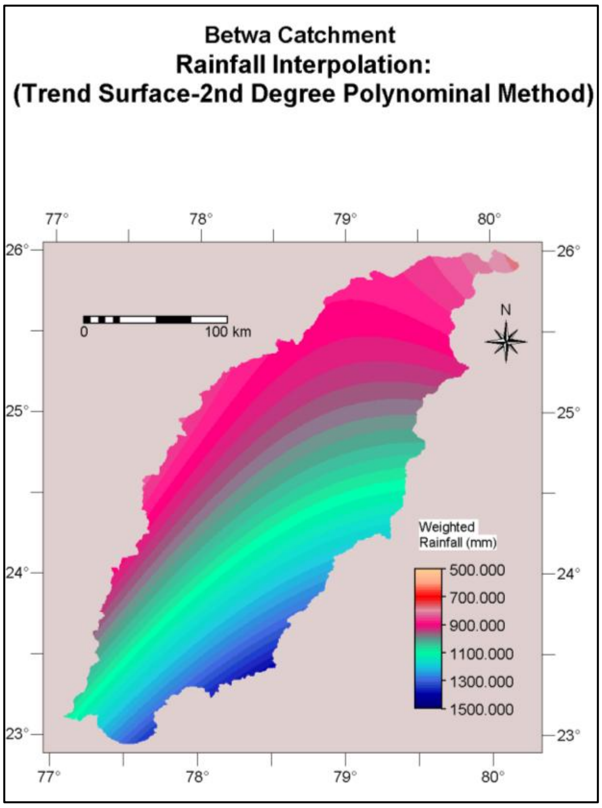


Fig. V f

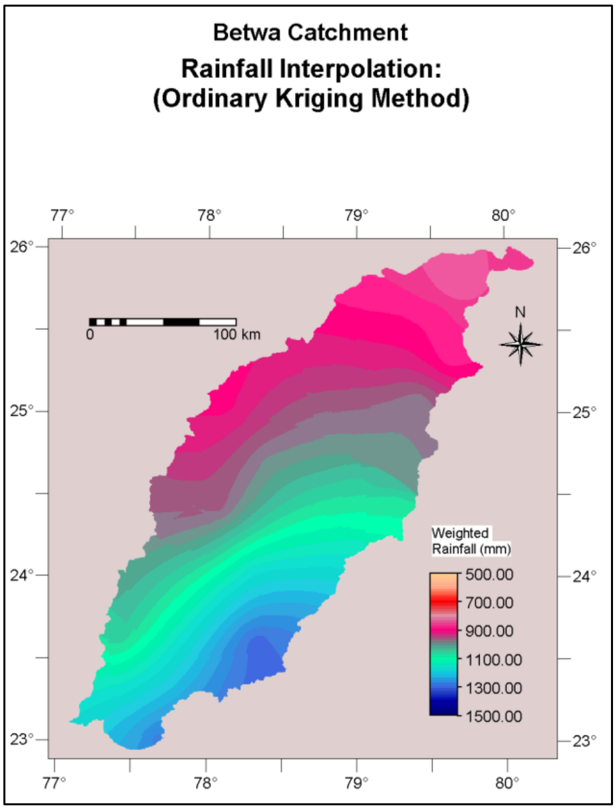


Fig. V g

Fig.V (a to g): A Comparative View of Spatial Interpolation Methods for Rainfall
(Source: Author using ILWIS map computations based on Data cited in Table IV)

Further, the search radius was used to find spatial correlation among the pair of points in each distance class for interpolation by Kriging method. It can be seen from Table V (a) that positive correlation (Moran's I value) exists till the 3rd distance class at 124 km. As the observed semi-variogram resembles the shape of Gaussian curve adaped from the data (Fig. VI), therefore, modelled values of semi-variogram were obtained for different parameters that resulted into good fit (r = 0.9895). Respective values of parameters to be used for kriging interpolation were as follows:

Nugget = 3959.90; Sill = 104095.72; Range = 287761.50 m

S. No.	Distance (m)	Number of Pairs	Moran's I	Geary's C	Average Lag (m)	Semi-Variogram Values	Semi-Variogram Modelled Values	R^2
1	0	25.	0.834	0.11	22238.5	3959.90	0	0.9895
2	62000	290	0.632	0.28	65161.6	10091.81	8503.487	0.9895
3	124000	312	0.313	0.54	123970.4	19160.76	20934.272	0.9895
4	186000	284	-0.099	1.02	185002.5	36625.71	38165.007	0.9895
5	248000	198	-0.476	1.51	245916.8	53999.40	56461.419	0.9895
6	310000	130	-0.827	2.04	307409.9	72819.80	72732.683	0.9895
7	372000	60	-1.091	2.42	368291.5	86733.05	85277.319	0.9895
8	434000	24	-1.238	2.8	424144	100135.82	93805.762	0.9895
9	496000	3	-0.961	2.58	475720.6	92371.78	98968.159	0.9895

Table V (a): Omni directional Spatial Correlation Results
(Source: Author using ILWIS based on rainfall data cited in Table IV)

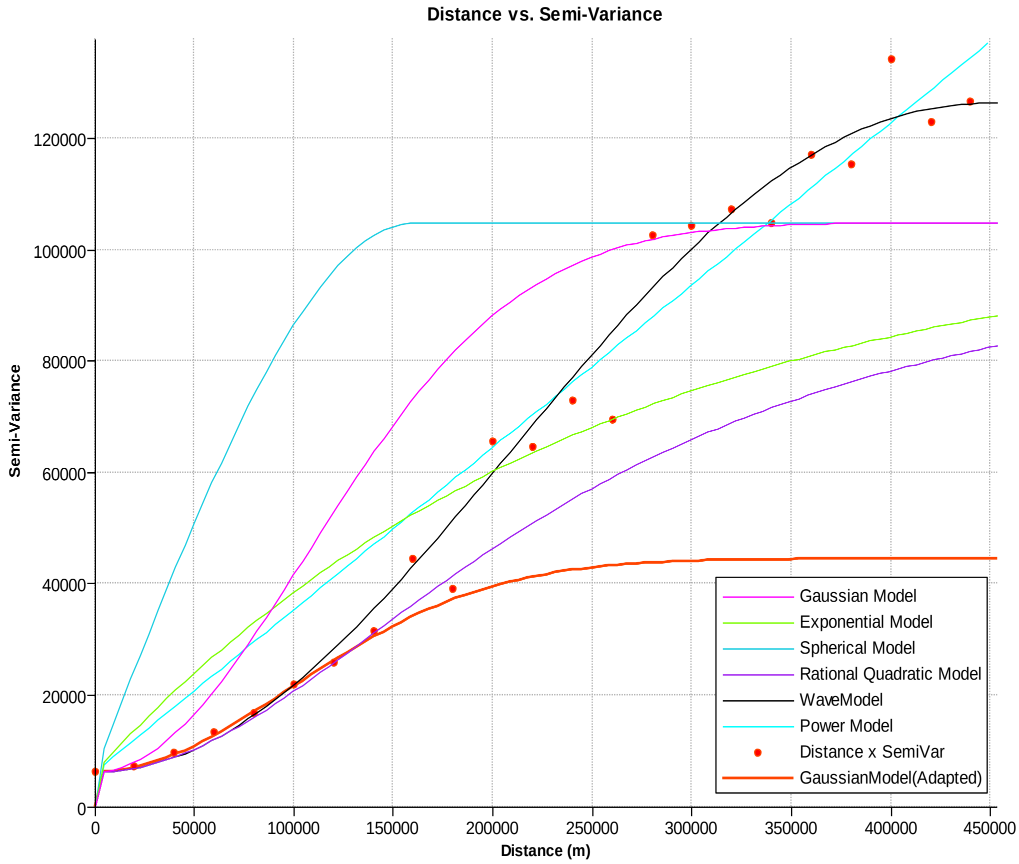


Fig. VI: Semi-Variogram of Omni directional Spatial Correlation
(Source: Author using ILWIS Semi-variogram Plot based on data from Table Va)

Both simple and ordinary kriging methods using variogram operation results provide better estimates (Fig. VII a & b). A localised trend in rainfall pattern can be observed from universal kriging with linear and quadratic surface within a search radius of upto 16 points (Fig. VII c & d).

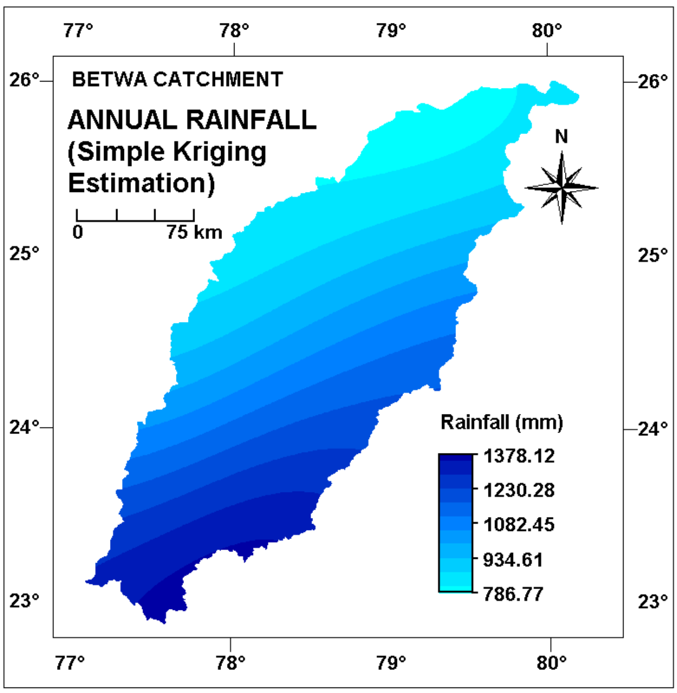


Fig. VII (a)

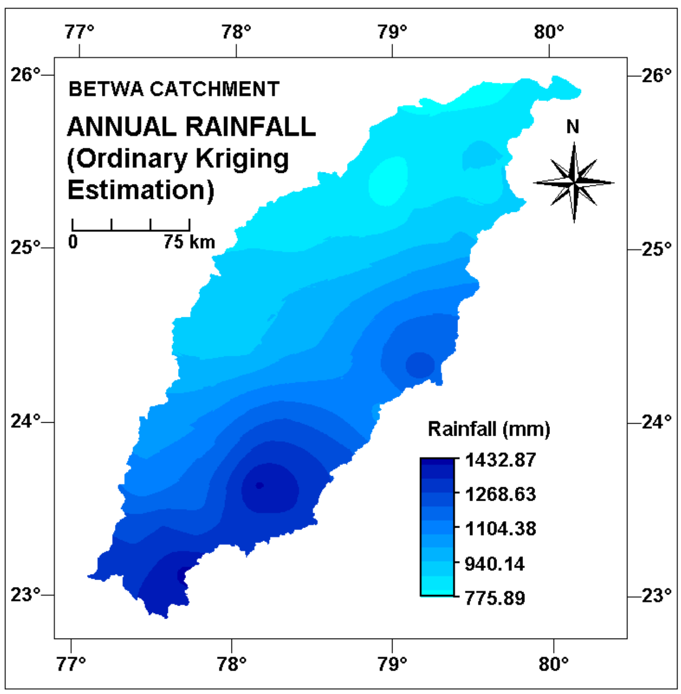


Fig. VII (b)

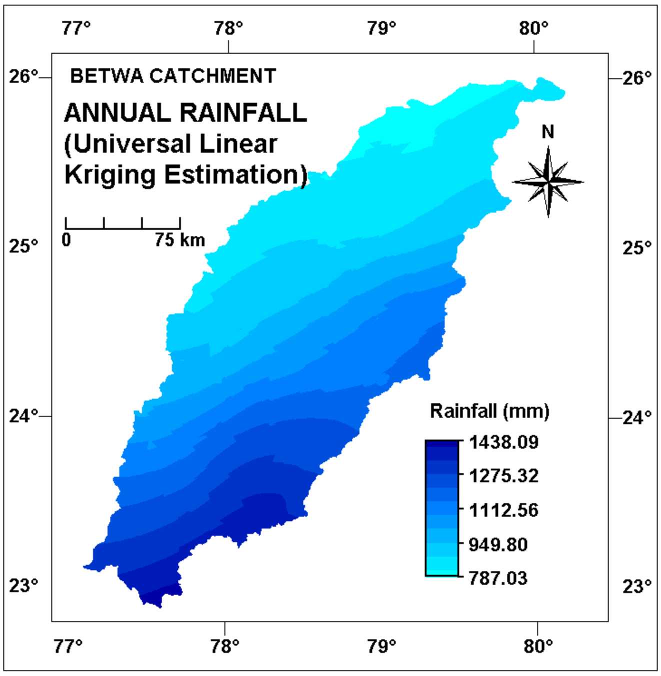


Fig. VII (c)

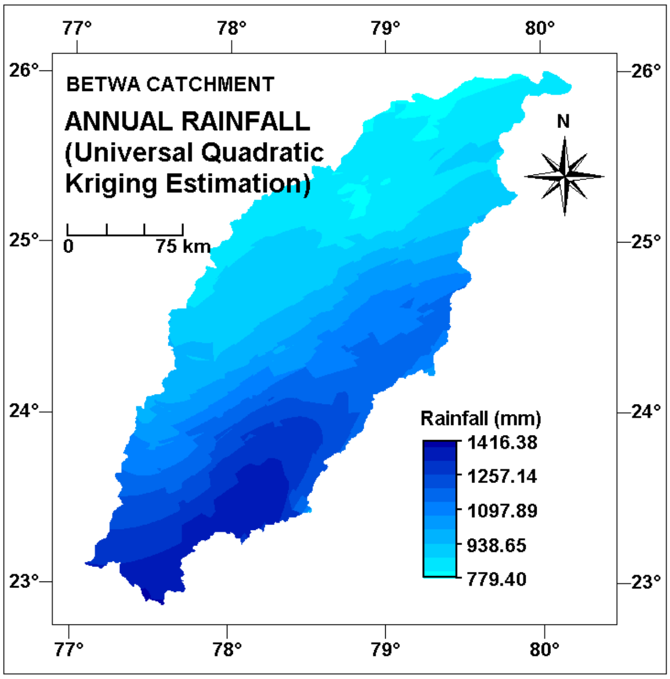


Fig.VII (d)

Fig. VII (a to d): A Comparative View of Kriging-based (Omni Directional) Spatial Interpolation of Rainfall (Source: Author using ILWIS map computations)

As variogram surface reflects anisotropy (Fig. VIII), therefore bidirectional spatial correlation results are examined in Figure IX. Semi-variogram values in both the directions are given in Table V (b).

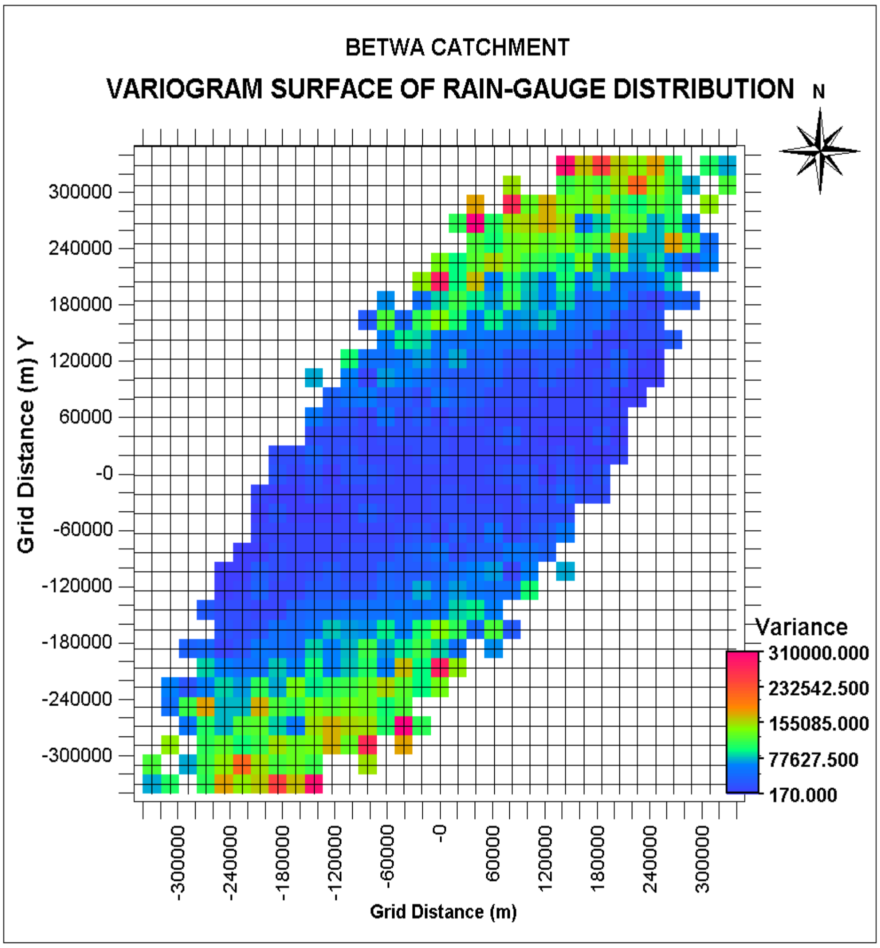


Fig. VIII: Anisotropic Variogram Model for Bidirectional Spatial Correlation (Source: Author using ILWIS)

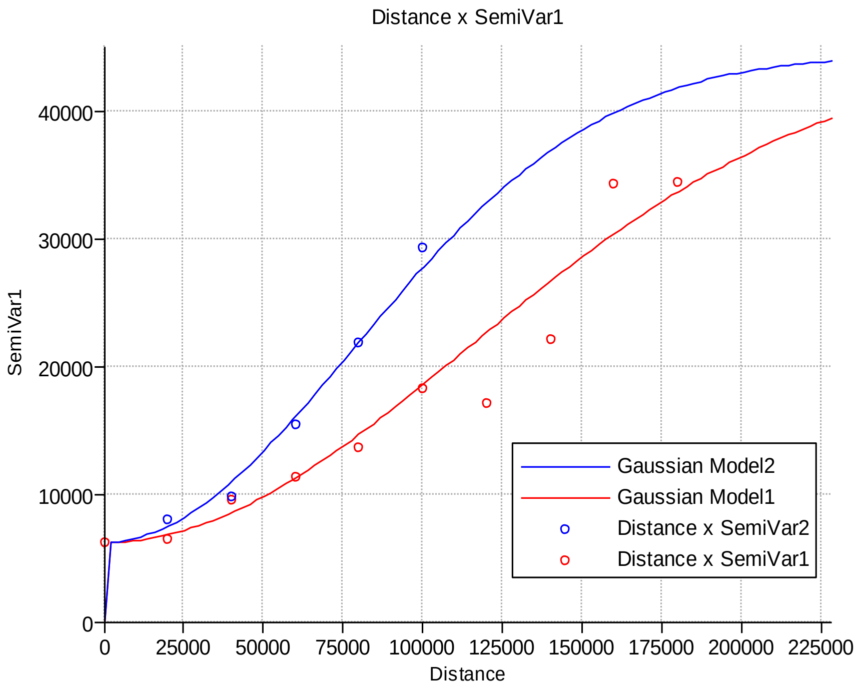


Fig.IX: Semi-Variogram Model Adopted for Bidirectional Spatial Correlation
(Source: Author using ILWIS Semi-variogram Plot)

Lag class	Distance (m)	Moran's I	Geary's C	Horizontal Direction (53.5°)			Mirror Rotate (133.5°)		
				Average Lag (m)	No. of Pairs	Semi-Variogram Values	Average Lag (m)	No. of Pairs	Semi-Variogram Values
1	0	0.894	0.14	8931.1	2	6219.05	?	0	?
2	20000	0.904	0.16	21395.7	19	6489.48	22295.5	23	8062.49
3	40000	0.714	0.21	40632.4	51	9547.63	41466.5	51	9806.59
4	60000	0.665	0.29	59769.9	62	11391.22	58725.8	56	15472.75
5	80000	0.508	0.37	80237.5	94	13689.64	80939.0	56	21839.18
6	100000	0.312	0.48	100436.7	82	18249.61	101137.5	40	29359.03
7	120000	0.315	0.57	120270.3	92	17198.58	119326.5	36	47778.77
8	140000	0.158	0.70	140435.5	79	22143.77	140247.9	34	53428.59
9	160000	-0.166	0.98	160692.5	86	34323.36	160545.0	19	90475.45
10	180000	-0.086	0.86	179124.1	81	34472.81	180217.9	11	73195.59
11	200000	-0.342	1.45	200649.2	83	57813.22	199869.4	8	147340.80
12	220000	-0.387	1.43	219860.1	61	59381.07	222399.0	5	127905.30
13	240000	-0.509	1.61	240380.1	65	73000.65	?	0	?
14	260000	-0.581	1.54	259558.1	57	68955.37	251635.1	1	?
15	280000	-0.922	2.27	279955.5	57	102599.10	?	0	?
16	300000	-1.042	2.31	299066.5	47	104392.90	?	0	?
17	320000	-0.999	2.38	319177.2	45	107419.50	?	0	?
18	340000	-1.045	2.32	338502.9	31	104810.60	?	0	?
19	360000	-1.194	2.59	360309.3	21	117078.10	?	0	?
20	380000	-1.224	2.55	379602.7	15	115511.10	?	0	?
21	400000	-1.420	2.97	398748.9	8	134308.70	?	0	?
22	420000	-1.300	2.72	415395.9	4	1229510.00	?	0	?
23	440000	-1.252	2.80	433633.3	2	1266450.00	?	0	?

? undefined pixels with no value calculated in that direction class

Table V (b): Bidirectional Spatial Correlation Results
(Source: Author using ILWIS based on rainfall data cited in Table IV)

The results of this bidirectional spatial correlation, when used in anisotropic kriging method, provide better estimates (Fig. X a & b).

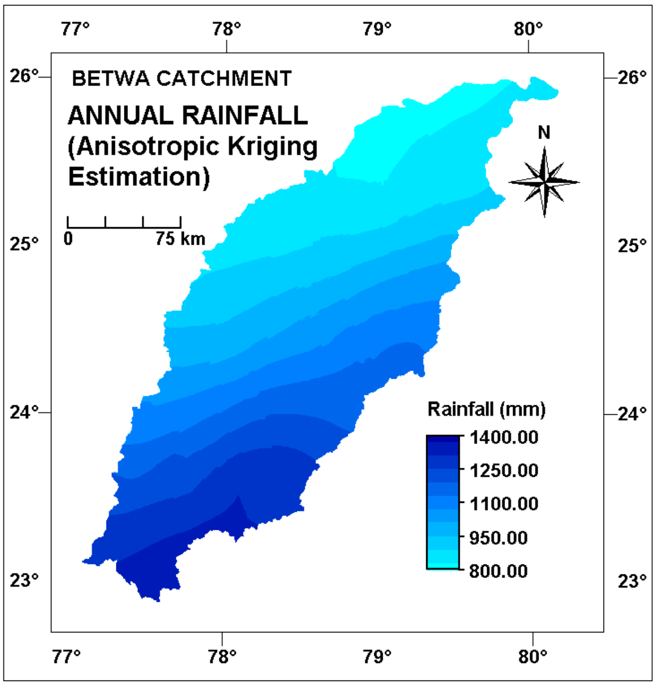


Fig. X (a)

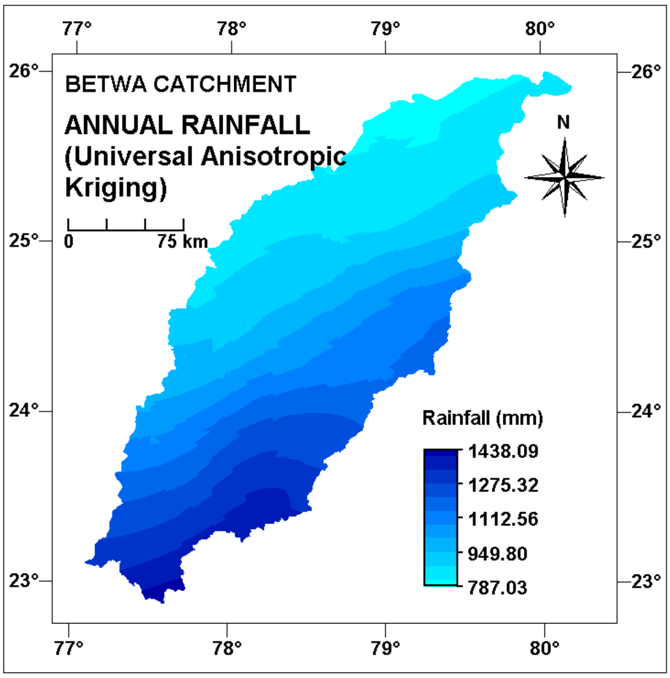


Fig.X (b)

Fig.X (a & b): Bi-Directional Effect in Spatial Interpolation of Rainfall
(Source: Author using ILWIS map computations based on Fig. VIII and IX)

Finally, error maps have been drawn for each type of kriging method that provide scientific guide for planning (Fig. XI a to d).

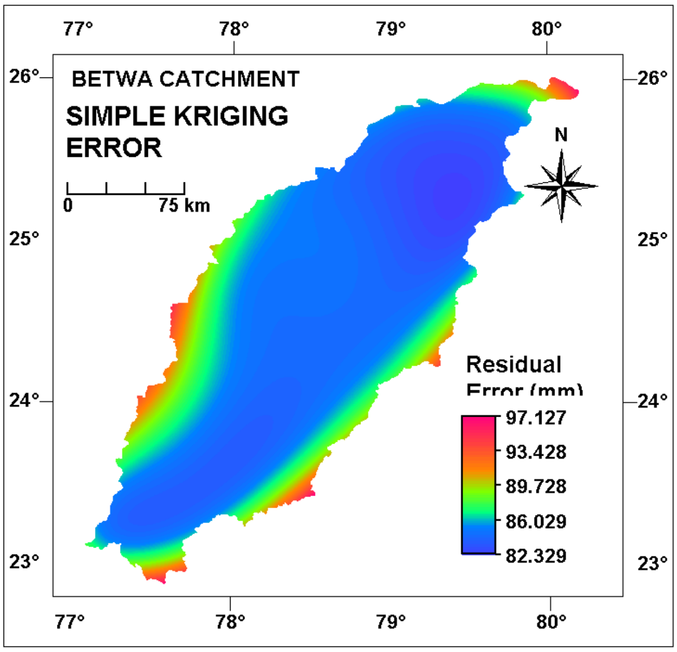


Fig. XI (a)

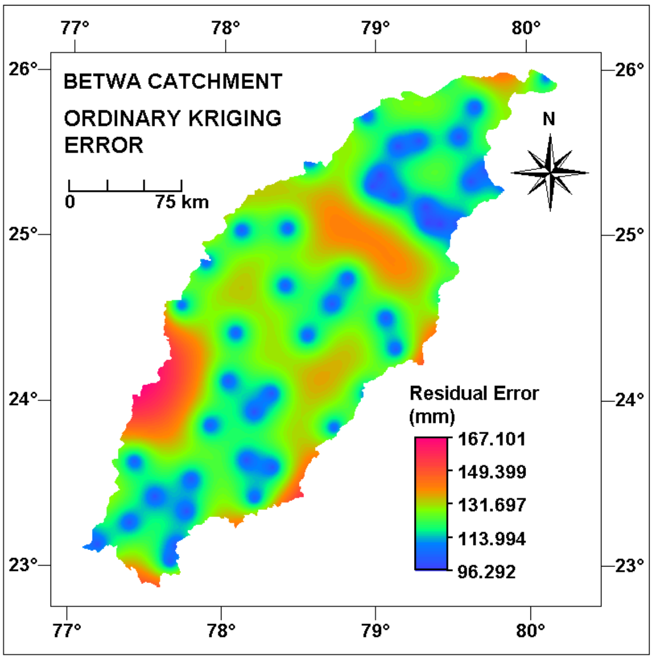


Fig. XI (b)

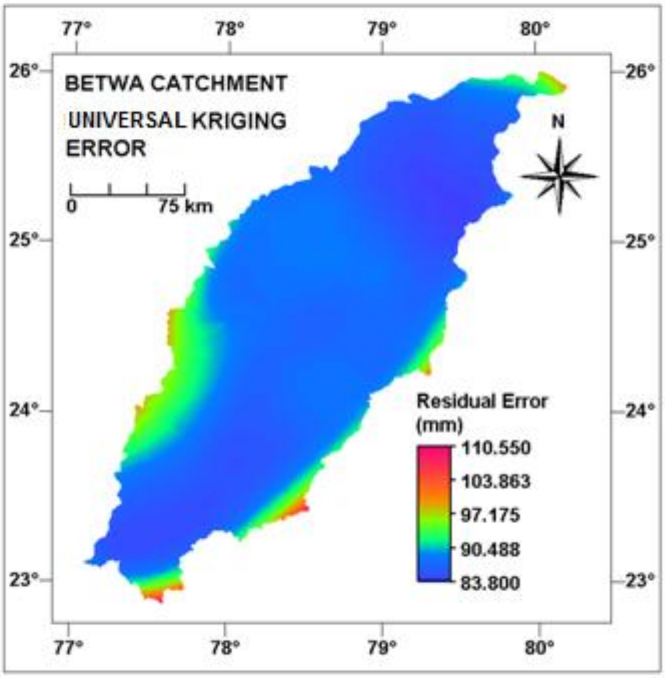


Fig. XI (c)

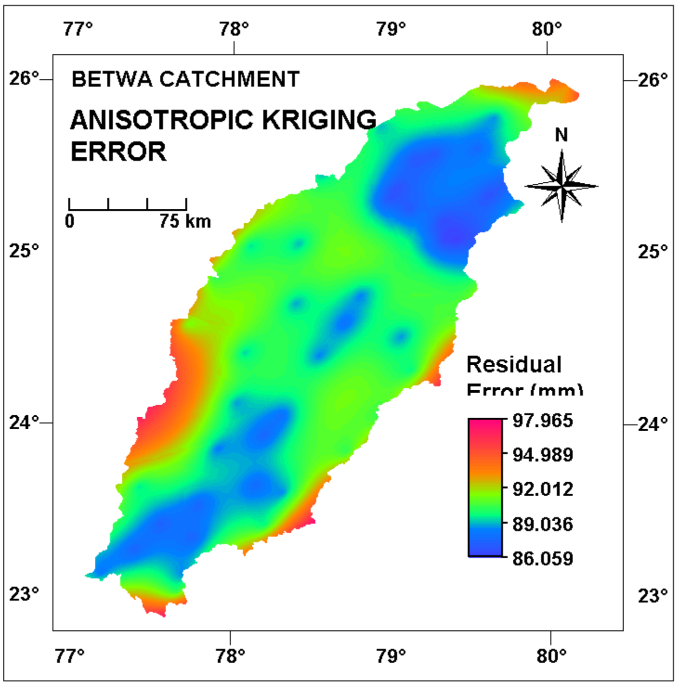


Fig. XI (d)

Fig.XI (a to d): A Comparative View of Kriging Residual Error
(Source: Author using ILWIS map computations based on Fig. X and Fig, VII)

Among error map of all types of kriging methods anisotropic method can be used for knowing the number of stations as per optimum spatial variability. The error map obtained from simple kriging operation results into lowest C_v. Based on error map, 95% confidence level map was drawn. It demarcates the region of 1000 mm rainfall till the southern limit of Bundelkhand plain and a broad zone of transition lies between lower and higher limits, the latter limit found towards the plateau region. However, the utility of kriging method remains limited because of different search radii and several parameters used in semi-variogram model.

5. CONCLUSION: The method used for spatial estimates also affects the results as can be seen from differing results of mean basin rainfall. Corresponding zone of influence of each station would also vary if area based computations are used. Three interpolation methods - ordinary kriging, trend surface (2^{nd} degree polynomial) and moving average method with inverse distance weight function provided better spatial estimates (within 10-12% of coefficient of variation) of mean catchment rainfall figures. Although, there exists no major difference in the results obtained from these various interpolation methods but ordinary kriging method was found to be best. Kriging methods not only considered spatial correlation of rainfall but also provided error map estimates with a maximum range of 15% deviation from their mean. Hence, mean catchment rainfall derived from arithmetic average value of rainfall recorded at stations and even linear interpolation methods like Theissen polygons can no longer be considered as easiest substitute for spatially variable phenomenon. Among deterministic spatial interpolation methods - moving average using inverse distance weight function can provide satisfactory result for less spatially correlated rainfall values in the region. However, Kriging methods need large number of data stations in network for selection of parameters and their calibration.

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