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Space-Time Variation in Rainfall and Runoff: Upper Betwa Catchment

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***Abstract*—**Among all geo-hydrological relationships, rainfall-runoff relationship is of utmost importance in any hydrological investigation and water resource planning. Spatial variation, lag time involved in obtaining areal estimates for the basin as a whole can affect the parameterization in design stage as well as in planning stage. In conventional hydrological processing of data, spatial aspect is either ignored or interpolated at sub-basin level. Temporal variation when analysed for different stages can provide clues for its spatial effectiveness. The interplay of space-time variation at pixel level can provide better understanding of basin parameters. Sustenance of design structures for different return periods and their spatial auto-correlations should be studied at different geographical scales for better management and planning of water resources.

In order to understand the relative effect of spatio-temporal variation in hydrological data network, a detailed geo-hydrological analysis of Betwa river catchment falling in Lower Yamuna Basin is presented in this paper. Moreover, the exact estimates about the availability of water in the Betwa river catchment, especially in the wake of recent Betwa-Ken linkage project, need thorough scientific investigation for better planning. Therefore, an attempt in this direction is made here to analyse the existing hydrological and meteorological data with the help of SPSS, GIS and MS-EXCEL software. A comparison of spatial and temporal correlations at sub-catchment level in case of upper Betwa reaches has been made to demonstrate the representativeness of rain gauges. First, flows at different locations are used to derive correlation and regression coefficients. Then, long-term normal water yield estimates based on pixel-wise regression coefficients of rainfall-runoff relationship have been mapped. The areal values obtained from these maps can definitely improve upon estimates based on point-based extrapolations or areal interpolations.

***Keywords*—**Catchment's runoff estimates, influence area regional regression coefficients, runoff yield series,

I. INTRODUCTION

HYDROLOGICAL models have become sophisticated enough to include remote sensing inputs and data assimilation algorithms. The recent initiative of International Association of Hydrological Sciences (IAHS) in setting up a working group in 2003 for prediction in ungauged basins (PUB) is a step to engage scientific community in a coordinative and effective way [1]. Most of the basins with little or no hydrometric data lie in developing countries. The goal of PUB initiative is the prediction of flow, sediment and water quality variables at multiple scales in these basins. Hence, PUB requires the development of new predictive approaches based on a deep understanding of hydrological functioning.

The purpose has been seriously taken up by World Meteorological Organisation and accordingly, average minimum density standards have been recommended for various kinds of network in different physiographic regions. There have been attempts particularly in Western Europe and North America to correlate density of rain gauge with domestic, agricultural and industrial demands, besides the theoretical requirements. An examination of space variations over the Sleepers watersheds in Northern Vermont has revealed the importance of optimum rain-gauge network design. The correlation field about a control gauge was found to be dependent on inter-station distance, azimuth, daily rainfall amount and the season of year [2].

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. A simple regression analysis (used in earlier days to estimate the mean basin stream flow at ungauged stations or even at same stations for the previous time), now, has been investigated by simulating logarithmic regression of the stream flow parameters. Their mean and standard deviation are derived from synthetic stream flow sequences. Accuracy of the analysis of optimum network design as determined by equivalent-year record requires the use of joint prior and posterior probability in the simulation studies. Thus, from the pure deterministic nature of location the stance of analysis has been taken over by advanced methods suggesting a set of feasible network design. From this, optimum solution can be obtained developing upon economic, social and political factors in addition to hydrologic state [3]. Another study, in the case of lower Colorado river stream flow data network, has been made to illustrate the multiple uses of data. Various mathematical methods like linear programming have been suggested to minimise the total uncertainty in the network, subjected to constraints like travel cost and annual frequency of visits to stations [4].

As the accuracy level of regional pattern of rainfall depends upon network of rain-gauge, therefore a locational analysis of the network based on annual data in the case of Dhansiri basin of north-east India stressed the need to extend the work to other river basins of the region. Here, mean basin rainfall was estimated through isohyetal method using the existing network of rain-gauging stations. Then, 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 [5]. Location of

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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 [6]. However, the method involving the correlation coefficients to compute optimum distances was not illustrated in detail.

II. Study Area

The catchment area of Betwa river, a geologically and historically strategic region in central India, is marked by diverse hydrological and physiographic characteristics, is selected for the case study. The catchment area is bounded by northern alluvial plains and southern Vindhyan plateau. It extends from 22°20' North to 26°0' North latitudes and 77°10' East to 80°20' East longitudes and 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) (Fig.1).

The catchment area, under the jurisdiction of Uttar Pradesh and Madhya Pradesh, suffers from uneven agricultural and irrigational developments. Presumably, it has been affected by the spatial network of hydrological data also. Fertile alluvial plains in the north coupled with irregular famines have resulted in great demand for more accurate measurements of rainfall and runoff [7]. Problems like soil erosion in the ravenous belt and large-scale silting of its largest reservoir, i.e. Matalila, can be better monitored if a scientific assessment of data record is made. Most of the studies in the region like that of Indo-British project on surface hydrology of the upper Betwa basin, groundwater target identification by Central Ground Water Board [8] and landuse suitability map preparation by Regional Remote Sensing Application Centre, Lucknow for the lower Betwa plain will become meaningful if their spatial representation reaches optimum standards. The potentiality of water resources in the basin exists in seasonal streams and small water bodies because the water of the perennial river Yamuna cannot be diverted to south due to general relief of the region [9]. Therefore, the study of hydrological data network becomes important in this region dominated by seasonal tributaries.

III. Objectives of Study

In order to analyse space-time variation in rainfall runoff relationship, following objectives have been put forward:

i) Validity of data record and number of stations in different time-periods;
ii) Estimation of rainfall-runoff rainfall relationship for the entire catchment; and
iii) Watershed-wise average estimates of rainfall-runoff coefficients.

Further, it was hypothesized that *optimum network of hydrological data stations depends more upon spatial variation than time-averaged point estimates for the catchment.*

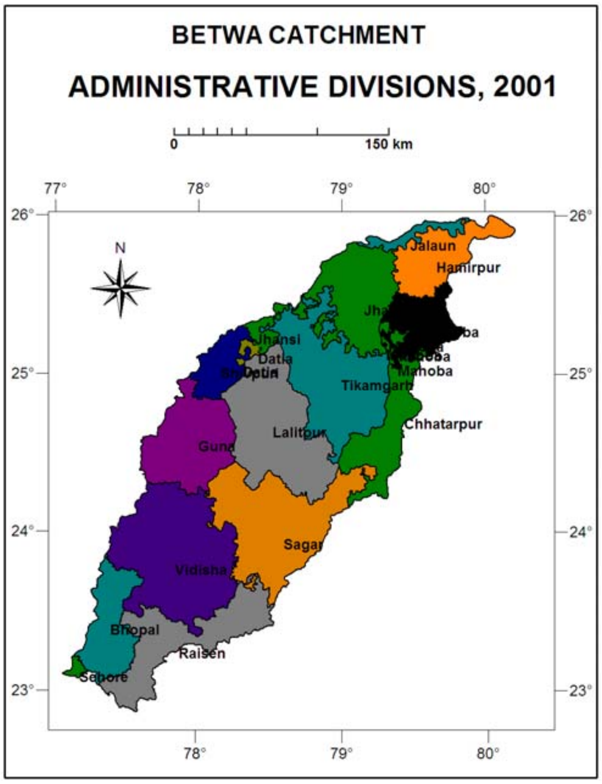

Fig. 1 Study Area

IV. Methodology

The analysis is based on data collected from secondary sources. Long- term annual data for hydrological stations is obtained mainly from Indian Meteorological Department (IMD), Central Water Commission (CWC). Besides annual data, monthly data from these and other state-level organisations is also collected for a period of, at least, 30 years. Base maps are drawn using 11 toposheets of Survey of India at 1:250,000 scale and 4 plates of drainage and water resources series of National Atlas Thematic Mapping Organisation (NATMO) at 1:1,000,000 scale. Further, primary data regarding the nature and functioning of data stations, maintenance, communication and publication of data, and the economic or other managerial problems, is also gathered at some of the selected sites.

The yearly fluctuations in the average monthly discharge are analysed here for monsoon season only because the data was restricted for non-monsoon season. For the monsoon season, which contributes significantly towards annual runoff, the consistency in streamflow record maintained by CWC has been checked by drawing double mass curve.

The relationship of runoff with rainfall has been estimated spatially, although indirectly while taking adequacy of stations into account. To generate long-term series of rainfall-runoff based on rainfall record, which generally covers 50-year period, a relationship was established using the curve estimation procedure in SPSS. A separate model was produced for each dependent variable to save predicted values, residuals, and prediction intervals as new variables. Statistics for each model (linear, logarithmic, inverse, quadratic, cubic, power, compound, S-curve, logistic, growth, and exponential): regression coefficients, standard error of the estimate, analysis-of-variance table, predicted values, residuals, prediction intervals are given. Then, checks the validity of assumptions and the goodness of fit of the model were also performed. In order to get average rainfall-runoff coefficient, depth of virgin runoff is compared with the average weighted monsoon rainfall calculated by employing moving average weighted method for data in each year during the corresponding period. In order to account for spatial variations, pixel-wise rainfall-runoff relationship is estimated using same equation in GIS-based map calculations. The reduction in error vs. number of stations and year of record was analysed here in detail for one of the sub-catchments of Betwa river.

V. Results and Discussions

According to limited data availability for the selected catchment, results are presented in the following sections:

A. Observed Discharge Characteristics

A plot of cumulative monsoon discharge at downstream site against upstream sites - Rajghat vs. Basoda in upper Betwa and Sahijina vs. Mohana in lower Betwa sub-catchment results in a straight line (Fig. 2 a and b).

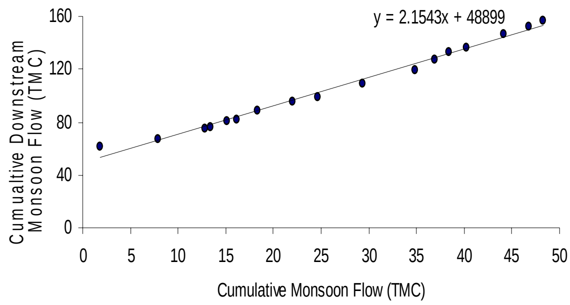

Fig. 2 (a) Double mass curve of flow (1977-93) at Basoda (upstream) *vs.* Rajghat (downstream) sites in upper Betwa

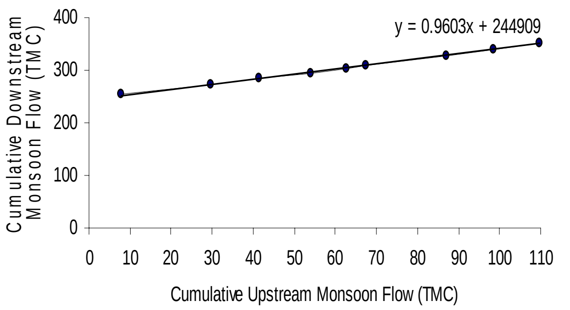

Fig. 2 (b) Double mass curve of flow (1985-93) at Mohana (upstream) vs. Sahijina (downstream) sites in lower Betwa

Another plot of the same, however, gets slightly curved in the middle portion when intermediate sites (Rajghat and Sahijina) are used (Fig. 2 c).

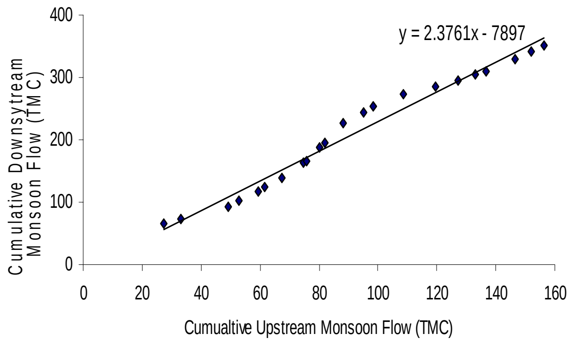

Fig. 2 (c) Double mass curve of flow (1972-93) at Rajghat (upstream) vs. Sahijina (downstream) sites in lower Betwa

Thus, it can be inferred from these plots that greater accuracy in the yield can be achieved, if individual estimates are made for the sub-catchments falling under the catchment area of site. Moreover, the response of a catchment to the increasing or decreasing runoff is different along the course of a river. This behaviour becomes clear from the two plots drawn for upper and lower Betwa sub-catchments where double mass curve is steeper in the former case. Spatial variations in runoff are thus important. Nevertheless, the general straight-line character of double mass curve reflects the reliability of record. The relationship obtained here through Equations in graph can be used to extend the data at site having less number of records.

To determine the reliability of dependable monsoon flow, their yearly frequencies are analysed through flow duration curves. At Rajghat and Sahijina site, the slope of flow duration curve shows a steep decline towards higher values followed by a gradual decline in steps (Fig. 3), whereas at Mohana and Basoda the curve is marked by step-like appearances that may account for a controlled reservoir effect. It means that for smaller differences in runoff, the probability difference does not represent true character of monsoon flows from which dependable flows might have been obtained directly. The observed runoff, thus, has to be adjusted to the level of utilization through irrigation projects, before drawing any inference about the response of a catchment to rainfall.

B. Estimation of Average Catchment Runoff

In the regression analysis, runoff obtained naturally as a response of catchment to rainfall, land, and climatic condition

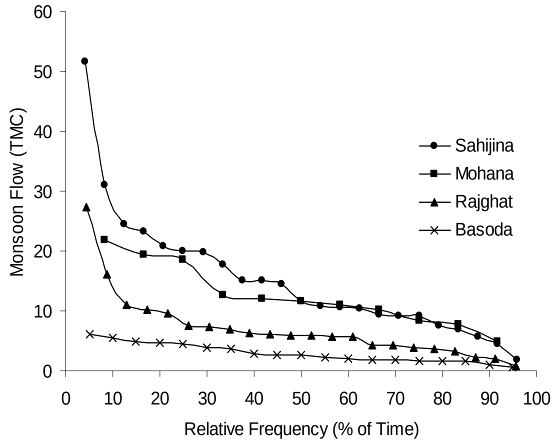

Fig. 3: Flow duration curve (1971-95)

is taken without any human interference. But, as evident from flow duration curves drawn in the preceding section, the observed runoff has been disturbed by utilization from reservoirs. Virgin monsoon runoff, therefore, is calculated here first for upper Betwa sub-catchment for which annual upstream utilization till Rajghat dam was considered. From annual upstream utilization, share of monsoon flow comes out to be 96.5%, calculated by adding share of average monsoon rainfall in the catchment (i.e. 93.01%) to 50% of non-monsoon rainfall (3.09%) as the contribution from base flow. From this, 10% of return flows from major (Mj) and medium (Me) irrigation projects are subtracted (i.e. only 87.2 % of total annual upstream utilization during monsoon season) to get virgin runoff volumes (Mm^3). The average depth is computed by dividing the total volume of runoff to the catchment area of upper Betwa till Rajghat site (16876.53 km^2) (Table 1).

TABLE 1

VIRGIN MONSOON RUNOFF, WEIGHTED MONSOON RAINFALL AND ESTIMATED ANNUAL YIELD AT RAJGHAT SITE (1972-93)

Year	Monsoon Runoff (Mm^3)	Net Upstream Use (Mm^3)	Virgin Monsoon Runoff (Mm^3)	Depth of Virgin Runoff (mm)	Weighted Monsoon Rainfall (mm)	Linear Runoff Y^ (mm)	Log Y^ (mm)	Annual Yield (Mm^3)
1972	27387.47	93.63	27481.10	1629.86	1537.83	919.89	889.36	15299.27
1973	5725.81	89.58	5815.39	344.90	864.03	253.82	242.69	4174.87
1974	16189.80	95.78	16285.58	965.87	1481.05	863.76	817.09	14056.10
1975	3686.80	98.99	3785.79	224.53	1034.38	422.22	364.00	6261.72
1976	6304.09	108.43	6412.52	380.32	1341.18	725.50	653.46	11241.20
1977	2237.74	111.84	2349.58	139.35	840.68	230.74	228.16	3925.00
1978	5956.54	112.99	6069.53	359.97	1111.75	498.70	428.22	7366.54
1979	7345.65	113.38	7459.03	442.38	1050.21	437.87	376.67	6479.66
1980	850.45	143.51	993.96	58.95	450.18	0.00	55.87	961.19
1981	4374.52	171.23	4545.75	269.60	1001.24	389.46	338.25	5818.84
1982	2058.60	175.24	2233.84	132.49	693.62	85.37	147.95	2545.19
1983	6069.64	210.44	6280.08	372.46	1157.62	544.04	469.05	8068.98
1984	6967.09	251.4	7218.49	428.12	1321.28	705.83	631.82	10868.96
1985	3310.26	286.15	3596.41	213.30	781.66	172.40	193.66	3331.39
1986	10123.29	327.3	10450.59	619.81	1343.08	727.38	655.55	11277.11
1987	11077.96	350.62	11428.58	677.81	1089.85	477.05	409.45	7043.68
1988	7600.34	295.29	7895.63	468.28	1149.38	535.90	461.57	7940.17
1989	5618.03	388.09	6006.12	356.21	999.41	387.65	336.86	5794.91
1990	3800.95	368.64	4169.59	247.29	856.89	246.76	238.19	4097.55
1991	9648.47	407.96	10056.43	596.43	1167.34	553.65	477.97	8222.40
1992	5819.57	375.86	6195.43	367.44	862.67	252.48	241.83	4160.08
1993	4306.15	311.15	4617.30	273.85	904.72	294.05	269.20	4630.88

Source: Computed from CWC Data

The relationship between rainfall-runoff works out to be statistically significant. Although linear correlation coefficient of + 0.77 shows a strong positive relationship, but it takes the shape of a curve on scatter diagram. Therefore, a logarithmic correlation coefficient of + 0.89 provides estimates that are more reliable. It becomes clear from graphs as well that logarithmic standard error of estimate is lower than that of obtained from linear estimate (Fig.4 a and b). With the help of logarithmic regression equation, long-term series of monsoon runoff was generated by substituting previous record of weighted rainfall values adjusted for differing number of rain-gauges in earlier years (only 2 in 1901 to 11 in 1995).

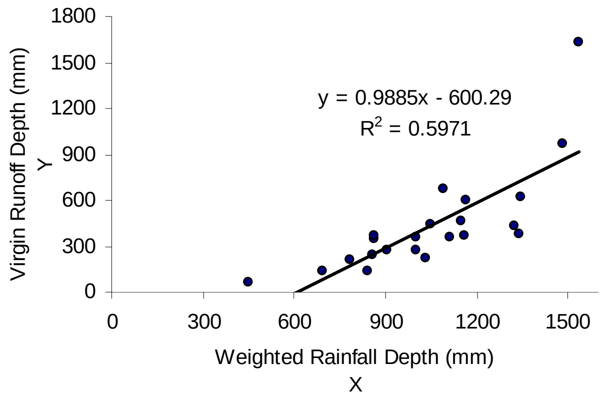

Fig. 4 (a) Monsoon rainfall-runoff linear relationship (1972-93) in upper Betwa catchment

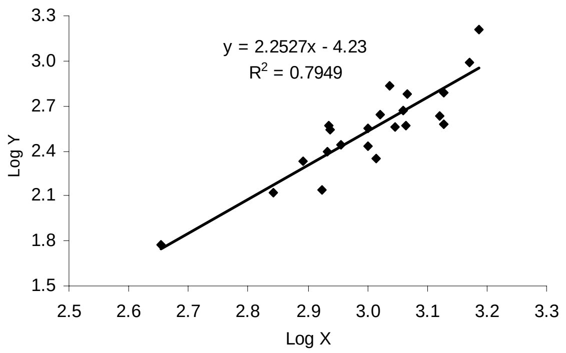

Fig. 4 (b) Monsoon rainfall-runoff logarithmic relationship (1972-93) in upper Betwa catchment

From the depth of virgin monsoon runoff, after its multiplication with the area of the sub-catchment and addition for non-monsoon contribution on pro-rata basis (3.09%, i.e. 203.35 Mm3), average annual surface water yield in the upper Betwa sub-catchment was determined for each year.

It is quite important to note here that if monsoon rainfall in the sub-catchment is determined just by taking arithmetic average of rainfall or even Theissen polygon-based weights for the rainfall recorded at 13 rain gauges are considered in the analysis, then nature of relationship remains same but magnitude of runoff varies. The average monsoon yield based on mean weighted rainfall in the catchment (6,616.45 Mm^3) is higher than that of based on simple point-based estimate from same equation (6,581.10 Mm^3). Thus, it can be stated that location of gauges and the method used for interpolation can alter the yield estimates.

C. Watershed-Wise Yield Estimates

As the yearly data on upstream utilisation could not be obtained for all gauge and discharge sites, therefore, only current utilisation status is considered for determining average depth of virgin monsoon runoff for other sub-catchments. Yield estimates obtained in the preceding section do not reflect spatial variation in rainfall-runoff coefficient because point-based estimates of an areal phenomenon are considered assuming uniform depth of rainfall in the entire sub-catchment. GIS-based map calculations reveal that in the aggregate yield of different watersheds of upper Betwa sub-catchment maximum contribution comes from Halali followed by Baen nadi watershed. The average yield estimates for lower Betwa sub-catchment, derived from logarithmic equation adjusted for its correlation with upper Betwa, also reflect that maximum contribution comes from Dhasan river in its upper reaches. The average monsoon rainfall-runoff coefficient in the region, thus, varies from 0.2 to 0.6 (Fig. 5).

These GIS-based yield estimates are further compared with average annual yield estimates given by National Water Development Agency (NWDA) in their feasibility reports [10]. However, this comparison is only a rough guide as long-term rainfall data at each of the rain-gauge station and annual upstream utilisation statistics along with real restricted data on non-monsoon flows are used by NWDA. The difference lies only in the method used for determining weighted rainfall based on influence factor of Theissen polygons and in determination of aggregate yield. Still, any difference is important especially in the wake of recently implemented Ken-Betwa link, which is primarily based on NWDA's reports [11].

D. Comparison of Runoff Estimates by Climatological and Hydrological Approach

The 50% dependable flows in Betwa river catchment as determined in the preceding section work out to be 14,327 Mm^3 (using same pixel-wise logarithmic equation for the catchment), whereas runoff estimates derived by climatological approach for the Betwa catchment provide yield estimates of about 11,189 Mm^3 based on pixel-wise runoff calculations using Penman method. It works out to be only 4,937 Mm^3 based on Thornthwaite method. It does not mean that Penman-based estimates of runoff are overestimated but rather, due to the decision that observed runoff estimates are considered at 50% dependability [12]. Thus, in the absence of extensive long-term observed runoff record, estimates based on theoretical approaches using Penman method can be taken as good surrogate measure.

E. Optimum Network vs. Spatio-Temporal Variability

Spatio-temporal variations in hydrological phenomena play a significant role in determining the number of stations required. Here, a difference between minimum and optimum network is also needs to be understood. The reduction in error vs. number of stations and year of record becomes pertinent question in deciding about that critical minimum number. Hence, if all 10 rain-gauges located inside the upper Betwa sub-catchment with sufficient long-term data and are included in determining average runoff estimates, then overall coefficient of variation (C_v) comes out to be 31 %, well above desirable error limit (Table 2), even after including nearby stations in analysis.

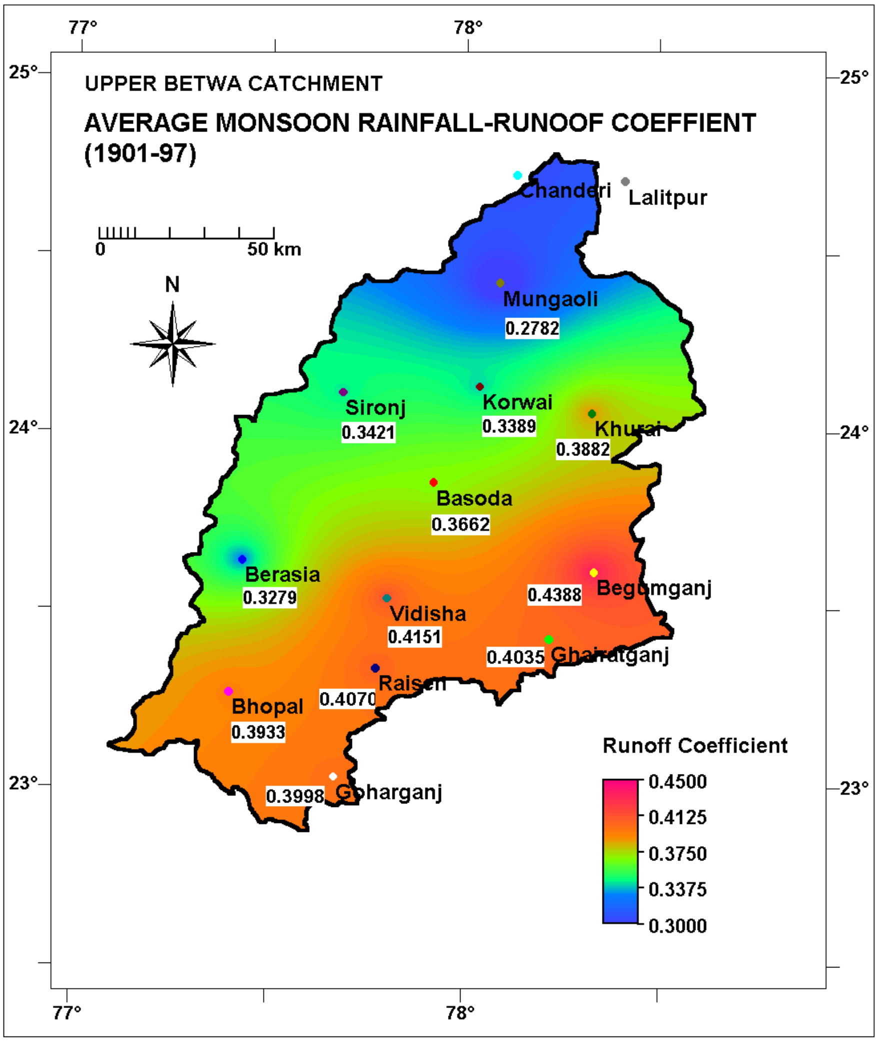

Fig. 5 Spatial variation in rainfall-runoff coefficient

F. Optimum Network vs. Spatio-Temporal Variability

Spatio-temporal variations in hydrological phenomena play a significant role in determining the number of stations required. Here, a difference between minimum and optimum network is also needs to be understood. The reduction in error vs. number of stations and year of record becomes pertinent question in deciding about that critical minimum number. Hence, if all 10 rain-gauges located inside the upper Betwa sub-catchment with sufficient long-term data and are included in determining average runoff estimates, then overall coefficient of variation (C_v) comes out to be 31 %, well above desirable error limit (Table 2), even after including nearby stations in analysis.

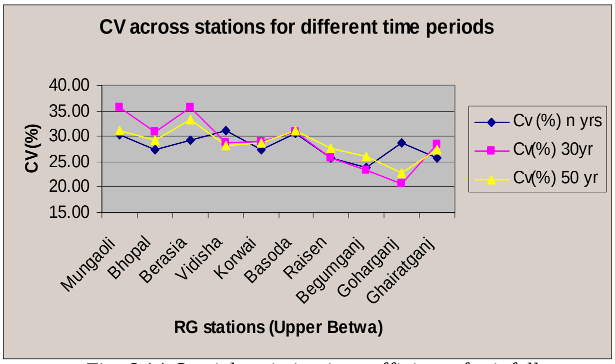

Fig. 6 (a) Spatial variation in coefficient of rainfall

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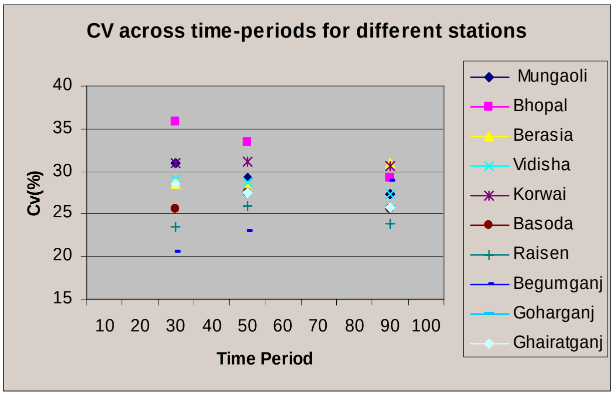

Fig. 6 (b) Temporal variation in coefficient of rainfall

TABLE II
OPTIMALITY OF SPATIAL VS. TEMPORAL VARIABILITY OF RAINFALL IN THE UPPER MIDDLE BETWA SUB-CATCHMENT (BASODA TO RAJGHAT SITE)

Monsoon rainfall	6 rain gauges (long-term record)	8 rain gauges (existing)	10 rain gauges (existing + nearby)
Temporal C_v			
30 yr	29.81	31.74	31.83
50 yr	29.20	31.27	31.17
n yr	27.86	30.26	30.23
Spatial C_v			
30 yr	40.98	37.32	26.05
50 yr	39.01	37.20	26.32
n yr	39.10	38.63	31.58

Source: Computed from IMD data

Thus, spatio-temporal variation analysis of hydrological reveals that there exists a relationship in both so far as error reduction is considered (Fig. 6 a and b). Although the coefficient of correlation between the two is weak (+0.25 only) but convergence of spatial variation becomes quite with more number of station as compared to more number of data record at a particular station. Hence, the hypothesis that optimum network of hydrological data stations depends upon spatial variation that is affected by temporal variation has been proved here.

VI. CONCLUSION

In case of discharge measurements, it was observed that runoff data pose significant constraints for generation of long-term series. After adjusting for data on upstream utilisation and regeneration in each watershed, a map-based logarithmic relationship between weighted rainfall and runoff can be used to obtain yield estimates. These estimates of potential water amount and their spatial variations can be utilized to provide average regional figure for planning and management of water resources in Betwa river catchment. Space-time variation hypothesis in rainfall-runoff coefficient needs to be tested in other basins with more data record.

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