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Quantitative precipitation forecasting over Narmada Catchment

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Abstract. Quantitative precipitation forecasting (QPF) has been attempted over the Narmada Catchment following a statistical approach. The catchment has been divided into five sub-regions for the development of QPF models with a maximum lead-time of 24 hours. For this purpose the data of daily rainfall from 56 raingauge stations, twice daily observations on different surface meteorological parameters from 28 meteorological observatories and upper air data from 11 aerological stations for the nine monsoon seasons of 1972–1980 have been utilized. The horizontal divergence, relative vorticity, vertical velocity and moisture divergence are computed using the kinematic method at different pressure levels and used as independent variables along with the rainfall and surface meteorological parameters. Multiple linear regression equations have been developed using the stepwise procedure separately with actual and square root and log-transformed rainfall using 8-year data (1972–1979). When these equations were verified with an independent data for the monsoon season of 1980, it was found that the transformed rainfall equations fared much better compared to the actual rainfall equations. The performance of the forecasts of QPF model compared to the climatological and persistence forecasts has been assessed by computing the verification scores using the forecasts for the monsoon season of 1980.

Keywords. Quantitative precipitation forecasting (QPF); statistical forecasting; dynamical parameters; skill scores; Narmada Catchment

1. Introduction

Precipitation is the most dominant parameter among the various hydrometeorological variables that provide important inputs to hydrological techniques for flood forecasting. Yet, accurate precipitation estimates are often the most elusive, because of the great variability of precipitation in space and time. This is mostly because of the problems associated with achieving accurate mean areal estimates of precipitation that has already occurred; and the accurate quantitative prediction of future precipitation. This represents one of the most challenging hydrometeorological problems. Improvement in hydrologic forecast lead time and accuracy could be achieved if reliable quantitative precipitation forecasts (QPF's) were available for specific river basins as input to the hydrologic forecast models (Georgakakos and Hudlow 1983). Although the daily operational rainfall forecasts issued by the India Meteorological Department for different regions of the country provide some useful guidance in indicating qualitatively the rainfall amounts and location of rainfall areas, they do not provide the required QPF values for assigning them to individual river basins.

The rainfall prediction methods can be broadly grouped into three categories. One general category of methods is the numerical weather prediction (NWP) models which are physically and dynamically based. Another category of rainfall prediction methods constitutes those that use statistical regression techniques to compute rainfall on a station or areal basis with other hydrometeorological and possibly climatological and orographic variables and/or outputs from the large scale NWP models. An example of this approach is represented by the model output statistics (MOS) method (Glahn and Lowry 1972). The third category includes those methods which employ nowcasting procedures which essentially try to extrapolate the recent past and present weather to immediate future, say 1 hour or so.

The current generation of NWP models are essentially large-scale models. The convective process, which is the primary mechanism for producing heavy precipitation is parameterized in NWP models rather than being calculated explicitly. Hence, these rainfall forecasts generally are the large scale precipitation rates. These differ substantially from the observed rainfall using dense network of raingauge stations, particularly when convection is involved. Therefore, the localization of the large-scale numerical model results is currently attempted by the use of regression models (Glahn and Lowry 1972; Lowry and Glahn 1976; Mills *et al* 1986 and Tapp and McNamara 1989). However, in the Indian context, in the absence of any operational NWP model, it is felt useful to develop a QPF model following a statistical approach using the meteorological data from the existing surface and upper air observatory network for a river catchment, as the QPFs when used in conjunction with hydrologic forecasting procedures, the spatial and temporal domains of interest usually are those associated with a drainage basin. For this purpose, the Narmada Catchment is chosen in the present study particularly because, a large number of multipurpose large and small hydrologic projects have been proposed in this basin for the optimum utilization of its water resources. Also from the meteorological point of view, the location of the catchment, which is parallel and close to the mean depression path and the presence of monsoon trough at 700 hPa level over this region, makes it all the more important.

Narmada river is the longest and the largest among the major westward flowing rivers in India. It rises from the Amarkantak Plateau (22°40'N; 81°45'E) of the Satpura in Shahdol district in Madhya Pradesh. It drains an area of 98,800 sq.km. of which 89·8% is in Madhya Pradesh, 8·5% in Gujarat and 1·7% in Maharashtra. After traversing nearly 1310 km from east to west it joins Cambey near Broach in Gujarat. The average annual rainfall of the Narmada basin is about 1250 mm of which 90% is received during the four monsoon months of June to September. More details on the physiography and climatology of this basin can be had from Doria (1990); IMD (1970) and Singh *et al* (1988).

Many attempts have been made in several countries to develop suitable QPF models for hydrological purposes, but with limited success. A detailed account on the status of all these models and their intercomparison is made by Bellocq (1980). In India, the studies on QPF are very few and far between. However, some attempts have been made in the recent past to develop QPF models following different approaches (Gupta *et al* 1979; Upadhyay *et al* 1986 and Sen 1991). In the present study an attempt has been made to develop a set of prediction equations with a maximum lead time of 24 hours, separately for the areal rainfall of five sub-regions in the Narmada Catchment by making use of rainfall, surface meteorological observations and some dynamical parameters computed utilizing aerological data. Here, the areally averaged precipitation rates are preferred to the highly variable point precipitation rates, as the hydrological forecasting techniques require the areal precipitation values as an input.

2. Data and methodology

2·1 *Data*

The daily rainfall data of 56 well-distributed raingauge stations within the catchment and the surface meteorological data from 29 meteorological observatories located in and around the catchment for the nine monsoon seasons of 1972–1980 form the basic surface meteorological data for the study. The monsoon rainfall distribution and the location of raingauge stations in the Narmada Catchment are given in figure 1. The location of surface observatory stations are shown in figure 2. The rainfall is the 24-hr accumulated rainfall measured at 0830 IST and the surface data pertain to twice daily observations of 0830 and 1730 IST. The basic aerological data used are twice daily (0530 and 1730 IST) observations on wind and dew point temperature at every 50 hPa interval from surface to 100 hPa level in respect of 11 radiosonde/radiowind (RS/RW) stations. The location of RS/RW stations are also shown in figure 2.

2·2 *Preparation of surface data sets.*

In view of the large areal extent of the catchment and the high spatial variability in the rainfall, the Narmada Catchment has been divided into 5 sub-regions for the development of suitable QPF models using the multiple linear regression technique. The five sub-regions starting from west are shown in figure 1 with vertical lines. As the catchment is more or less east-west oriented and situated parallel to the normal track of the monsoon depressions, it is felt necessary to use the information on different meteorological parameters of the regions located to the east of the catchment also. For this purpose two more regions east of 82°E with a width of 2° longitudes each are considered.

Representative daily areal values of rainfall and other surface parameters are worked out for each of these seven regions. The daily areal rainfall from 1st June to 30th September during the period 1972–80 for each of the five sub regions are worked out by arithmetically averaging the rainfall of 11, 8, 13, 12, 12 stations respectively. These five rainfall series form the set of dependent variables for the development of multiple regression equations. However, the daily areal average rainfall of regions "six" and "seven" are worked out using a smaller number of surface observatory stations (4 in the 6th region and 5 in the 7th region), and are used with certain lead time as independent variables in the regression analysis. The areal representativeness of these surface observatory stations compared to the dense network of state raingauge stations is assessed by finding out the year wise correlation coefficients between the daily areal rainfall values estimated by using the dense network and the surface observatory network separately for the five sub regions and are presented in table 1. The correlation coefficients which are very highly significant, indicate the possibility of utilizing the surface observatory station network in estimating the areal rainfall values in the event of non availability of state raingauge data on a real time basis, for all practical purposes.

Similarly, the arithmetic averages of surface wind, sea level pressure, cloud amount, relative humidity, and dry bulb temperature with both morning and evening observations are worked out for each of the seven regions using four stations each in the first six regions and five stations in the seventh region for the period mentioned above.

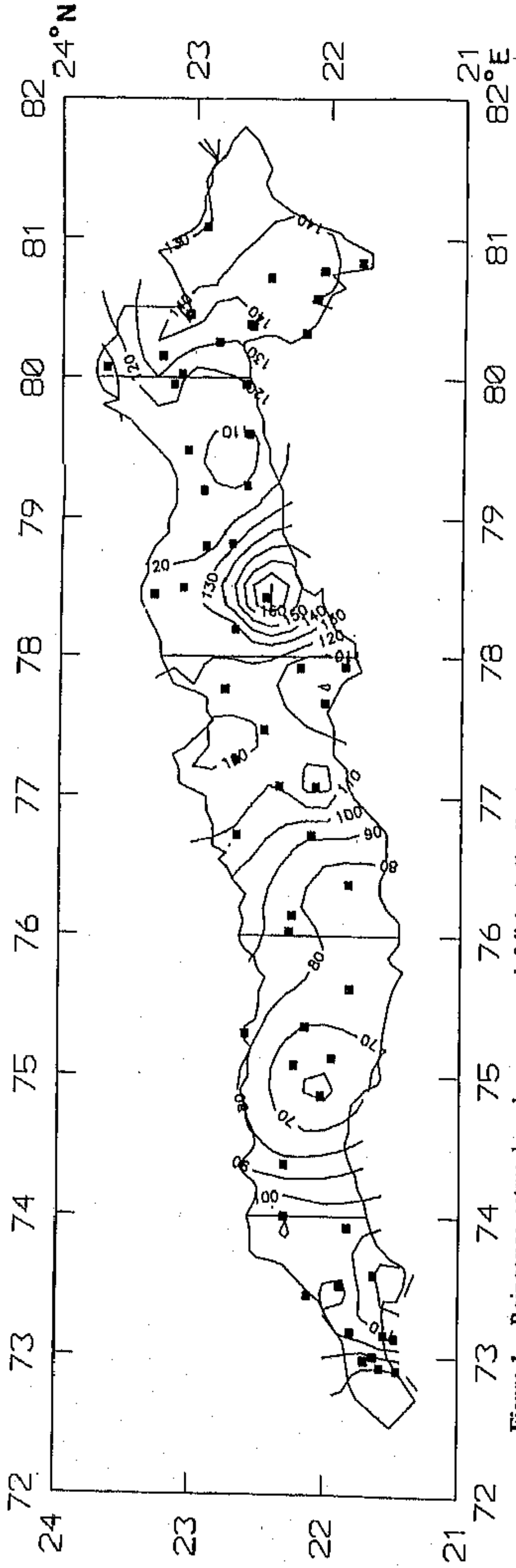

Figure 1. Raingauge network and monsoon rainfall (cm) distribution over Narmada Catchment. The five sub-regions are demarcated by verical lines.

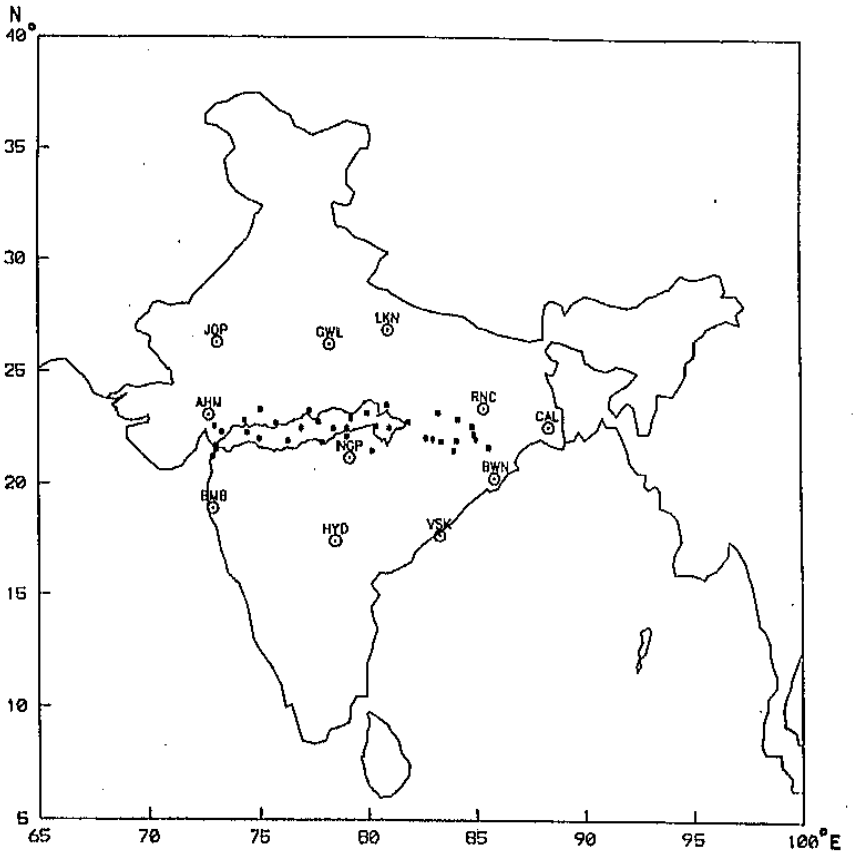

Figure 2. Location of the Narmada Catchment along with the surface (■) and aerological (⊙) station networks. The locations at which the dynamical parameters are computed are indicated by*.

Table 1. Correlation between the areal mean rainfall estimates of five regions using dense raingauge network and those based on only the surface observatory stations, over Narmada Catchment.

Year	Reg. – 1	Reg. – 2	Reg. – 3	Reg. – 4	Reg. – 5
71	0·804	0·842	0·925	0·910	0·803
72	0·683	0·796	0·964	0·966	0·828
73	0·869	0·773	0·884	0·947	0·789
74	0·599	0·622	0·893	0·944	0·798
75	0·779	0·524	0·878	0·877	0·703
76	0·840	0·832	0·796	0·792	0·631
77	0·731	0·893	0·915	0·936	0·886
78	0·732	0·847	0·906	0·877	0·342
79	0·857	0·764	0·984	0·899	0·869
80	0·577	0·691	0·882	0·952	0·862

2·3 *Computation of dynamical parameters*

Besides rainfall and surface meteorological parameters, the dynamical parameters such as relative vorticity, horizontal divergence, vertical velocity and moisture divergence are also computed using the daily RS/RW data from 1st June to 30 Sept, during the period 1972–80 of eleven stations. The seven grids at which the dynamical parameters are computed are shown in figure 2. The grids are located nearly at the centre of each of the seven regions. The relative vorticity, horizontal divergence and vertical velocity are computed using the kinematic method. In the kinematic method the vertical velocity is obtained from a vertical integration of the mass continuity equation. The vorticity and divergence and subsequently the vertical velocity are calculated, by the method of least squares using quadratic representation of the wind observations given by Krishnamurti (1986). These values are estimated at each of the seven grid locations by assuming each time the location of the grid point at the centre of gravity. This is done because the analysis carried out following the above mentioned method will be most accurate at the centre of gravity (Krishnamurti 1986). Due to the uncertainties in the estimation of wind and the sparsity of observations, the errors in the calculation of horizontal divergence are usually large. Because of these inherent errors, the calculated divergence does not satisfy the Dines Compensation, that is, the vertical integration of the divergence will not be identically zero. This in turn produces errors in the estimation of vertical velocity. This has been corrected using the O'Brien correction (O'Brien 1970 and Chien and Smith 1973). Following the procedure described for divergence above, the moisture divergence $\nabla \cdot qV$ is also calculated. The specific humidity 'q' is estimated using the saturation vapor pressure (e) at dew point temperature (T_d), which is estimated by the Goff-Gratch formula (Smithsonian Meteorological Tables 1949).

Following the above procedure, the relative vorticity and horizontal divergence are computed for every 100 hPa layer. This is done by averaging the wind data of three levels, each separated by 50 hPa, right from the surface and the computed layer divergence and vorticity for that layer are taken as representative to the middle level of that layer. The divergence and vorticity are computed up to 150 hPa level. Using these divergence values the vertical velocity is computed for each 100 hPa layer and is taken as representative to the top level of the layer. The vertical velocity is computed up to 100 hPa level, which is considered here as the top of the atmosphere. The vertical velocities at the surface and at the top are taken to be zero. However, in the regression analysis for the development of QPF models, the divergence and vorticity are considered at four selected levels (850, 750, 550 and 250 hPa). Similarly, the vertical velocity is considered at 800, 700, 500 and 300 hPa levels only. The moisture divergence is computed at every 100 hPa interval up to 300 hPa level. However, for the regression analysis the cumulative values of moisture divergence from the surface to 300 hPa level is only considered. All these parameters are computed with both morning and evening observations separately at each of the seven grids mentioned earlier. These dynamical parameters together with the rainfall and surface meteorological parameters form a set of 413 independent variables that are used in developing the QPF model in the present study.

2·4 *Regression technique used*

Multiple linear regression equations for each of the five regions are developed using a stepwise procedure based on the algorithm developed by Jennrich (1977). In this procedure, for a given dependent variable, starting from an equation with one independent variable showing the highest correlation coefficient (CC), further independent variables are added in a stepwise manner based on the F-value criterion.

And also, the addition of the independent variables is terminated when the increase in the explained variance R^2, dropped below one percent.

In this analysis the rainfall of day + 1 (0830 IST) is predicted using the information on different independent predictors described earlier, at 0530 IST and 0830 IST of day-0 and 0530 IST and 1730 IST of Day-1. This gives a maximum lead time of 24 hours.

The procedure adopted in selecting the number of predictors in the final regression equation at each of the five sub regions is somewhat similar to the one described by Tapp and McNamara (1989). The stepwise regression procedure was performed twice for each predictand, with a different year of data excluded arbitrarily from the dependent sample of eight years (1972–79) on each occasion. The data for the year 1980 is kept aside for the independent verification of the regression schemes. Generally, it is observed that the predictors that enter are of similar type up to a certain number of steps after which they begin to differ. For each execution of the regression procedure, the number of predictors was identified at the step beyond which they began to differ. Then the final prediction equations are developed using all the eight years (1972–79) data. At this stage the stepwise procedure was terminated both by following the F-ratio criterion as well as when the additional variance explained by the inclusion of a further predictor first fell below one percent (Mills *et al* 1986). It is observed that at each of the five sub-regions the predictors that are entered in the final regression equation with the above condition are mostly the same as those predictors which have entered in both the regression equations developed earlier using truncated (7 years) data.

In view of the highly skewed nature of the daily rainfall, separate prediction equations are also developed using the logarithmic and square root transformed rainfall series again following the above procedure.

Comparison of multiple correlation coefficient, F-ratio and standard error of estimate in respect of actual, square root and log-transformed rainfall regression equations for the five regions presented in table 2, shows that the regression equations developed using the transformed rainfall series have performed much better compared to those developed using the actual rainfall.

Table 2. Statistical parameters of regression equations developed using actual, square root and log transformed rainfall over five regions in Narmada Catchment.

	Actual			Square root			Log		
Region	MCC	F-Ratio	Error	MCC	F-Ratio	Error	MCC	F-Ratio	Error
1	0·681	164·8	12·3	0·765	450·2	1·35	0·789	527·0	0·77
2	0·669	76·8	9·0	0·745	169·3	1·21	0·747	200·4	0·77
3	0·724	175·2	11·5	0·801	285·4	1·27	0·810	364·4	0·75
4	0·715	200·2	11·9	0·788	223·1	1·33	0·794	232·7	0·78
5	0·635	107·6	11·3	0·696	223·8	1·50	0·712	245·9	0·90

MCC = Multiple Correlation Coefficient

3. Verification of prediction equations

The prediction equations developed using actual, square root and log-transformed rainfall values for all the five regions are verified by forecasting the rainfall values with an independent data set for the monsoon season of 1980. The relative merits of the forecasts obtained using the three sets of prediction equations are evaluated by comparing the correlation coefficients between the observed and estimated rainfall values, the standard errors of the estimated values and the computed biases, percent correct and Heidke skill score values. The standard errors of square root and log transformed rainfall equations are worked out after converting the transformed rainfall estimates back to the actual values to facilitate their inter comparison.

3·1 *Estimation of verification scores*

The biases (BIAS), percent correct (PC) and Heidke skill score (SS) are computed following the methodology given by Perrone and Miller (1985). The scores are worked out by categorizing the rainfall values into four groups ($\leqslant 5$ mm; > 5 mm to $\leqslant 15$ mm; > 15 mm to $\leqslant 30$ mm and > 30 mm). In order to facilitate inter comparisons and to have uniform rainfall categories for the preparation of contingency table, which is a prerequisite in estimating the above scores, the forecasted square root and log-transformed rainfall values are converted back to the actual rainfall values. The following is the procedure for the computation of the above scores.

a) *Contingency table*: It contains all verification information for the discrete variables (table 3). The element X_{ij} in the table is the number of times the forecast was in the j^{th} category and the observation was in the i^{th} category. The actual contingency tables for rainfall forecasts for the year 1980 using the equations developed with square root transformed daily rainfall for all the five regions are given in table 4.
(b) *Percent correct* (*PC*): This gives the percentage of correct forecasts out of the total forecasts, regardless of the category,

$$\mathrm{PC} = \frac{\Sigma X_{ii}}{X_{pp}} \times 100$$

In the present case with four categories of rainfall, the expected percent correct with random forecast is 25.

Table 3. Format of contingency table for the estimation of verification scores.

Observed	Forecast category					
category	1	2	3	...	M	Total
1	X_{11}	X_{12}	X_{13}	...	X_{1M}	X_{1P}
2	X_{21}	X_{22}	X_{23}	...	X_{2M}	X_{2P}
⋮	⋮					
M	X_{M1}	X_{M2}	X_{M3}	...	X_{MM}	X_{MP}
Total	X_{P1}	X_{P2}	X_{P3}	...	X_{PM}	X_{PP}

Table 4. Contingency tables for the computation of verification scores for the forecasts using the equations developed with square root transformed rainfall for all the sub-regions of Narmada Catchment.

Observed category	Forecast category				Total
	1	2	3	4	
Region-1					
1	67	7	3	0	77
2	7	14	3	0	24
3	3	11	3	0	17
4	0	1	1	0	2
Total	77	33	10	0	120
Region-2					
1	63	12	12	0	77
2	14	15	1	0	30
3	1	9	1	0	11
4	1	1	0	0	2
Total	79	37	14	0	120
Region-3					
1	55	14	2	0	71
2	12	11	6	0	29
3	4	3	5	1	13
4	0	3	3	1	7
Total	71	31	16	2	120
Region-4					
1	39	18	8	0	65
2	11	16	8	1	36
3	0	9	2	1	12
4	0	2	2	3	7
Total	50	45	20	5	120
Region-5					
1	37	18	6	2	63
2	7	11	5	0	23
3	1	15	6	0	22
4	0	8	3	1	12
Total	45	52	20	3	120

Category: 1) $\leqslant$ 5 mm
2) $>$ 5 mm and $\leqslant$ 15 mm
3) $>$ 15 mm and $\leqslant$ 30 mm 4) $>$ 30 mm

(c) *Bias* (*BIAS*): This gives the tendency to overforecast (BIAS > 1) or underforecast (BIAS < 1) a particular category. The bias for the i^{th} category is

$$\mathrm{BIAS}_i = X_{pi}/X_{ip}$$

Table 5. Verification statistics of the three sets of regression equations with the independent data set of 1980 monsoon season.

Region	Rainfall transformation	Correlation coefficient: actual vs estimated	Standard error mm	Percent correct	Heidke skill score
Region-1	Actual	0·50	8·0	55·0	0·24
	Square root	0·56	7·5	70·7	0·42
	Log	0·56	7·5	70·8	0·43
Region-2	Actual	0·50	7·6	46·7	0·17
	Square root	0·52	6·9	65·8	0·31
	Log	0·47	7·5	63·3	0·20
Region-3	Actual	0·60	9·2	50·0	0·20
	Square root	0·61	8·7	60·0	0·30
	Log	0·57	9·2	60·0	0·28
Region-4	Actual	0·56	15·2	47·5	0·23
	Square root	0·60	14·5	50·0	0·22
	Log	0·61	14·8	52·5	0·20
Region-5	Actual	0·38	14·7	39·2	0·17
	Square root	0·41	14·5	45·8	0·21
	Log	0·39	15·1	48·3	0·21

(d) *Heidke skill score* (*SS*): This skill score measures the fraction of possible improvement afforded by the forecasts over the forecasts expected by chance or random.

$$\mathrm{SS} = \frac{\mathrm{NC} - E}{T - E}$$

where the number correct $(\mathrm{NC}) = \Sigma X_{ll}$; $T = X_{pp}$; $E = \Sigma(X_{lp} \cdot X_{pl})/T$. This skill score can vary from $-0{\cdot}33$ (for all incorrect forecasts) to 1·0 (for all correct forecasts). The skill score is expected to be zero when the forecasts are random.

In table 5 are given the correlations between observed and estimated rainfalls, standard errors, percent correct and Heidke skill scores for actual, square root and log-transformed equations for the five regions estimated using the daily forecasts of the monsoon 1980. Examination of these parameters along with the estimated biases, which are not presented in the table, suggests that the prediction equations developed using square root and log-transformed rainfall have definitely performed much better than the equations developed using actual rainfall data. Based on this analysis, though both the transformed rainfall equations are found to be equally good, the square root equations are preferred and used in the further analysis, basically due to their relative simplicity. The prediction equations of square root transformed rainfall in respect of the five regions are given in table 6. For convenience the parameters entered in the regression are represented in the form RPT where R is the region number (1 to 7), P is the parameter name and T is the time of observation with respect to the time of forecast issue. The parameters RAIN, QDIV, V500, PRES, UCOM, VCOM, HUMD, TEMP and CLAM are 24 hour rainfall (mm), moisture divergence (mm/12 hrs/sq.cm.col), vorticity at 500 hPa level (sec^{-1}), sea level pressure (hPa) zonal and

Table 6. Regression equations for the square root transformed rainfall for the five regions in the Narmada Catchment.

	1RAIN + 1	2RAIN + 1	3RAIN + 1	4RAIN + 1	5RAIN + 1
E	0·2339	43·7613	54·4363	66·7239	− 0·2148
Q	+ 0·6180 (1RAIN − 0)	+ 0·1975 (1RAIN-0)	+ 0·4308 (3RAIN-0)	+ 0·3941 (4RAIN-0)	+ 0·3808 (5RAIN-0)
U	+ 0·1940 (3RAIN-0)	+ 0·3152 (2RAIN-0)	+ 0·2578 (4RAIN-0)	+ 0·1981 (5RAIN-0)	+ 0·2003 (7V500-0M)
A	− 0·0147 (6QDIV-1E)	+ 0·2025 (4RAIN-0)	+ 0·1689 (7V500-0M)	+ 0·1768 (7V500-0M)	− 0·3703 (5VCOM-0M)
T		− 0·2000 (4PRES-0M)	− 0·2271 (5PRES-0M)	+ 0·0501 (5HUMD-0M)	+ 0·2794 (5CLAM-0M)
I		− 0·2367 (4UCOM-0M)	− 0·3442 (7UCOM-0M)	− 0·0739 (7PRES-0M)	
O		− 0·1793 (7UCOM-0M)	+ 0·1734 (5PRES-1M)	− 0·2789 (7UCOM-0M)	
N		+ 0·1570 (4PRES-1M)		+ 0·1497 (5TEMP-1E)	

meridional components of wind (ms^{-1}), relative humidity (%), dry bulb temperature (°C) and cloud amount (octas) respectively. For RAIN square root transformed values should be used in these equations. 0M indicates the morning observation of the day the forecast is issued and − 1 E means the evening observation of one day before the day forecast is issued.

The observed and estimated values of rainfall using the above equations are presented as scatter diagrams in figure 3 and also as time-series plots from 3rd June to 30 September 1980 in figure 4 for all the five regions. It is seen from the figures that the forecasted rainfall values are generally in good agreement with those observed, excepting for region 5. However, the estimated values on some individual days when the rainfall was very heavy are somewhat underestimated. Examination of monsoon summaries of India Meteorological Department (IMD) for the year 1980 showed that the heavy rainspells are generally associated with the passage of lows and depressions formed either over Bay of Bengal or over Arabian sea. The lull in the rainfall activity is coinciding with the break monsoon situation declared by the IMD.

The performance of the forecasts of QPF model developed compared to the climatological and persistence forecasts is assessed by computing the percent correct and Heidke skill scores using the daily rainfall forecasts for the monsoon season of 1980. The verification scores in respect of QPF model, climatology and persistence are given in table 7. It is seen from the table that percent correct and skill scores achieved by the QPF model are much higher compared to the climatological forecasts. However, the QPF model performed only slightly better than the persistence forecasts. This is particularly true with the region-1 where the prediction equation contains only one parameter other than rainfall. In the other regions though the major contribution is coming from the rainfall parameters, the other parameters are also contributing to a considerable extent.

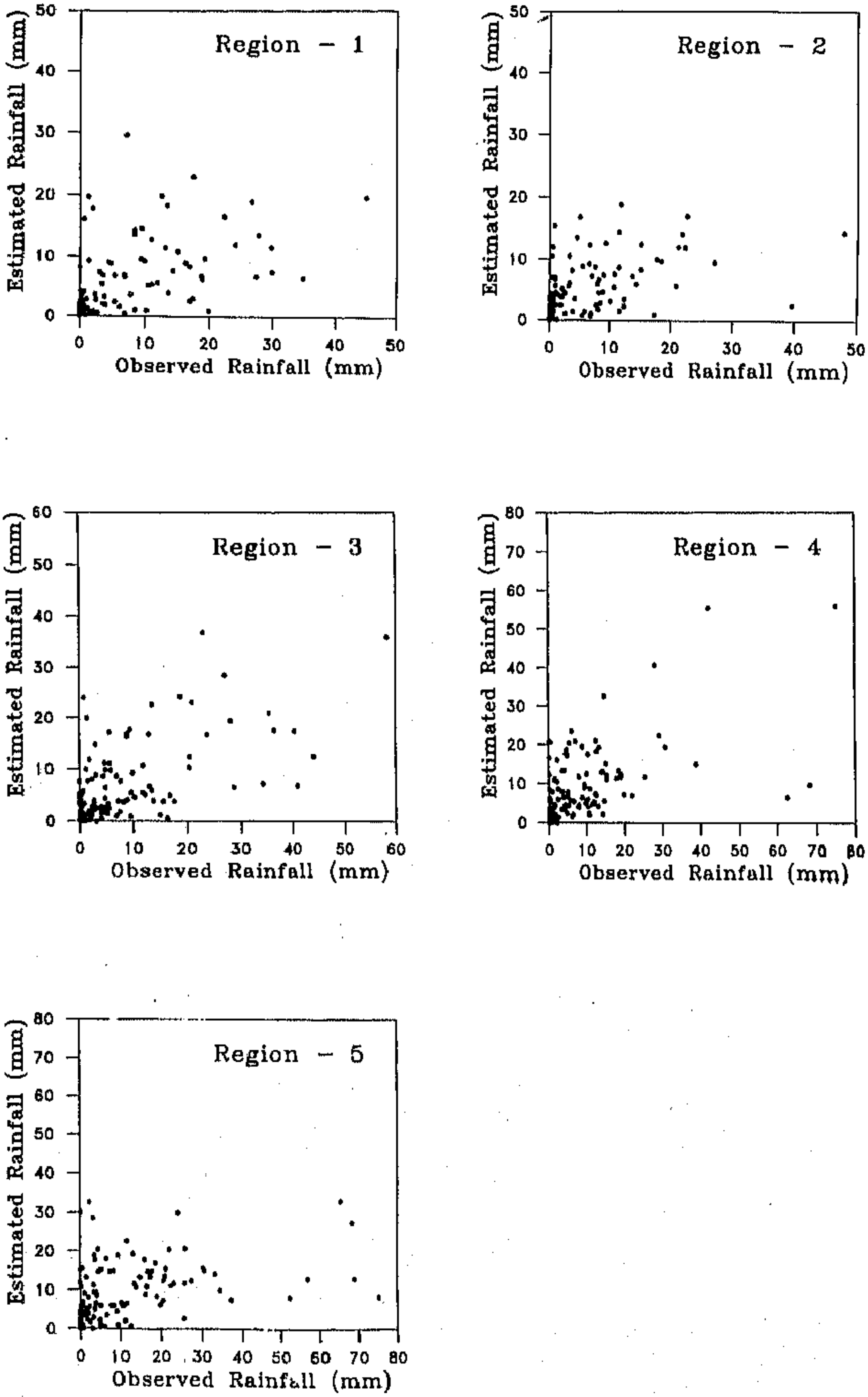

Figure 3. Scatter diagrams of observed versus estimated daily areal rainfall (mm) using the QPF model for the monsoon season of 1980 over the five sub-regions of Narmada Catchment.

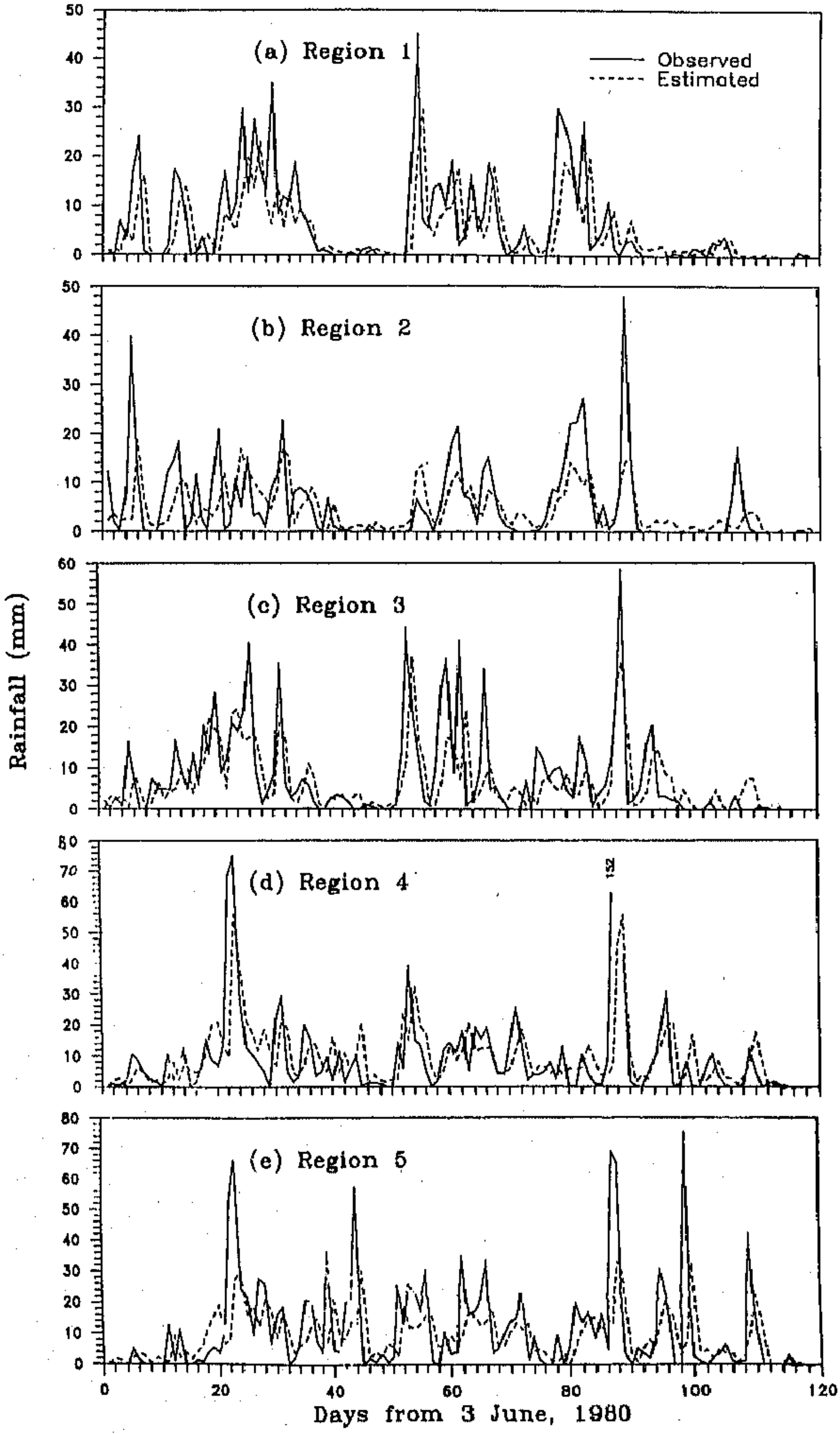

Figure 4. Time-series plots of observed and estimated daily areal rainfall (mm) using the QPF model for the monsoon season of 1980 over the five sub-regions of Narmada Catchment.

Table 7. Comparison of verification scores of climatology, persistence and QPF model computed using the forecasts of 1980 monsoon season (PC = Percent correct; SS = Heidke skill score).

	Region-1		Region-2		Region-3		Region-4		Region-5	
	PC	SS	PC	SS	PC	SS	PC	SS	PC	SS
Climatology	36·7	0·07	29·2		39·2	0·08	45·8	0·10	37·5	0·11
Persistence	66·7	0·40	55·8	0·17	51·7	0·24	46·7	0·19	35·8	0·14
QPF Model	70·0	0·42	65·8	0·31	60·0	0·30	50·0	0·22	45·8	0·21

4. Discussion

In the present study, an attempt has been made to develop suitable QPF models following a statistical approach for forecasting the daily areal rainfall over five sub regions in the Narmada Catchment with a maximum lead time of 24 hours by making use of surface as well as some dynamical parameters. Earlier studies (Pant *et al* 1969; Raghavan 1973 and Bedekar and Banerjee 1969) have shown that the rainfall activity over this region is primarily controlled by the passage of low pressure systems, depressions, orography and also by the occasional intensification of monsoon trough, which is normally present over this region at about 700 hPa level during the monsoon season, in association with the formation of monsoon depressions in the head Bay. In view of this, the dynamical parameters viz., vorticity, divergence, vertical velocity and moisture divergence are computed not only at five grid points in the catchment, but also at two grids outside the catchment to its east and more closer to the head Bay, so that the influence of the approaching disturbances is taken into account by the QPF model with a lead time.

Verification of the prediction equations developed using the actual, square root and log-transformed rainfall values has shown that the transformed rainfall equations fared much better compared to the actual rainfall equations. Examination of the predictors entered in the regression equations at all the five regions shows the importance of persistence in the rainfall of the respective regions. However, it is interesting to note that the rainfall parameters of the other regions, which are located generally to the east of the region concerned, are also entering the regression equations with some lead time. This indicates the predictive potential of the east-west traversing rainstorms in foreshadowing the rainfall over the western sub-regions. Surprisingly, the vertical velocity, which is believed to be generally associated with most of the rain producing systems, is conspicuously missing from the list of predictors that are entered in the regression equations. However, the vorticity parameter has entered the regression at many places. The possible reason for the absence of vertical velocity in the final regression equations could be attributed primarily to the known errors in the estimation of vertical velocity (Chien and Smith 1973) using the kinematic method, rather than to its insensitivity to the rainfall over this region. Such problems could be solved in the future by incorporating the objectively analyzed wind fields and the model derived vertical velocity values in the statistical QPF models.

The examination of skill scores for an independent set of forecasts attempted using the QPF model, climatology and persistence suggests that the QPF model developed in this study performed very well compared to the climatological forecasts but only marginally better than the persistence forecasts. However, there is a good agreement between the wet/dry epochs in the forecasted and the observed rainfall over all the regions (figure 4). This illustrates that there is good scope for developing such QPF models for different river basins in India, which in turn would provide some useful guidance and quantitative rainfall inputs to the hydrological models which are operationally run for the flood forecasting. The QPF model developed in the present study could be improved further in forecasting the isolated heavy rainspells by the possible inclusion of various forecasted meteorological parameters from a large scale numerical weather prediction model into the QPF model. This may be possible in India in the near future when medium range forecasting is made operational.

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