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Geomorphic response runoff model for prediction of June monthly runoff from small watersheds

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■ **ABSTRACT :** Quantitative assessment of runoff is needed for proper management of land and water resources especially for optimum agriculture production. This requires comprehensive knowledge of the various hydrological phenomena occurring in the catchment. All the watersheds cannot be gauged, as it would be costly and time consuming. Therefore, the indirect method of runoff quantification has to be resorted. The geomorphic parameters are quite useful as they reflect all the causative factors of the runoff. In the present study ten watersheds from Tapi catchment, Maharashtra, India were selected for development of geomorphic response models for prediction of June monthly runoff. Twelve geomorphic parameters were selected for development of model out of which two parameters, Sa and Rb are screened out in the principal component analysis. Remaining ten parameters are grouped into three physically significant components. The data sets were used to regress the runoff factor, $R/\sqrt{A}$, on three independent parameters (one each from already established components and rainfall factor, $P/\sqrt{A}$. It is observed that percentage deviation ranged from 0.3 to 7.0 using monthly runoff model for June. Therefore, developed runoff can be conveniently used for prediction of June month runoff from unguaged watersheds of the basin having similar physiographic conditions.

■ **KEY WORDS :** Geomorphic response model, Geomorphological parameters, Runoff, Sediment production rate, PCA

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In recent years, application of models in hydrological studies has become an indispensible tool for understanding of natural processes occurring at the watershed scale. These models are varied from simple empirical relationship for evaluation of flood events to simple ones containing certain physicality, to stochastic models of various kinds and finally more recently numerically more complex physically based distributed models (Borah and Bere, 2003 and Gosain *et al.*, 2009). Soil and water are the most important natural resources within the ecosystem. They form the basis of sustenance of all forms of life. The prosperity and history of nation depends to a great extent on these resources and their management. Yet, the exploitation of these precious resources without check and balance and much thought for future has led to their rapid degradation. Quantitative assessment of runoff, soil erosion and sediment yield are needed for proper management of land and water resources especially for optimum agriculture production. For predicting runoff from the known causative factors, it is important to include topographic or geomorphic characteristics which reflect directly or indirectly on climate, geology and transportation processes from the watershed. The rainfall and watershed characteristics in the form of geomorphic parameters can be utilized in the development of reliable response model for predicting runoff from watersheds which are not gauged (Kumar, 1991 and Singh *et al*., 2009). Leopold and Miller (1956) obtained a geometric progression between discharge and Horton order, by combining the Horton's law of basin area with an empirical relationship between mean annual stream discharge and basin area. The geomorphologic parameters directly or indirectly reflect almost the entire watershed based causative factors affecting runoff. In this study geomorphic response models were developed for prediction of annual runoff and sediment production rate (SRR) from selected watersheds of Tapi basin of Maharashtra state, India.

The use of GIS is increasing in various hydrological applications (Olivera and Maidment, 1999; Jain and Kothyari, 2000 and Pandey *et al.*, 2004). Kumar *et al.* (2001), Binjolkar and Keshari (2007) and Sharma *et al.* (2010) have used the GIS software for quantification of various geomorphological parameters of the watersheds. In this study, selected geomorphological parameters were computed using ArcGIS 9.3 software following the formula suggested by Horton (1945) and Strahler (1957) and well known relationships.

METHODOLOGY

Study area :

The study area is situated between 68°30' to 70 °45' E longitudes and 22°18' to 23°25' N latitude. The Tapi estuary is a tidal estuary originating in the Multai Ghats in Betoul district of Madhya Pradesh (India) at an elevation of 750 m. The Tapi river basin covers an area of 65,145 km² that makes up almost two per cent of the total area of India. The study was confined to ten watersheds (W_1 toW_{10}) of Tapi catchment for which annual time series data on rainfall, runoff and mean monthly sediment yield were used for development of models.

Digitization and georeferencing of toposheets in GIS :

Toposheets of the study area are obtained from the Survey of India (SOI), Dehradoon and Geological Survey of India, Pune regional office in the 1: 250000 and 1: 50000 scale. These toposheets were then used for digitization and georeferencing with the help of ArcGIS 9.3 software. After rectification a new dataset will form in GRID, TIFF or ERDAS IMAGINE format. These rectified maps are then further used for creating new digitized layers of watershed boundary, drainage lines and contour lines of selected watersheds.

Evaluation of geomorphic parameters :

In the present study following 12 dimensionless parameters known as geomorphic parameters for the 10 watersheds of the Tapi catchment of Maharashtra, India were used. The selected geomorphological parameters were average slope of the watershed (Sa), elongation ratio (R_e), circulatory ratio (R_c), basin shape factor (S_b), relief ratio (R_f), relative relief (R_r), ruggedness number (R_N), main stream channel slope (S_c), drainage factor (D_f), stream length ratio (R_l), bifurcation ratio (R_b), and length width ratio (L_{bw}). These twelve parameters were already dimensionless. Other three terms $R/\sqrt{A}$, $P/\sqrt{A}$ and $SPR/\sqrt{A}$ termed as runoff factor, rainfall factor and SPR factor, respectively. Twelve salient parameters were selected in this study which was based on the work conducted at Damodar Valley catchment (Kumar, 1991) and Chambal catchment (Singh *et al.*, 2009), India. The geomorphic parameters used in the present study to predict geomorphic responses were evaluated from the quantified watershed characteristics and ArcGIS 9.3 software interface.

Correlation matrix and PCA :

The intercorrelation matrix was developed to study the intercorrelation among the selected geomorphic parameters. This matrix then subjected to principle component analysis (PCA) to screen out non-significant parameters and to find out the physically significant groups of remaining geomorphic parameters. The selected factor loading matrix is then used as input to obtain the rotated factor loadings using the various methods *viz.*, varimax, quartimax and equamax. The procedure is repeated till the interpretation of 'physical significance' is simplified. These parameters from each physically significant group are being used for development of geomorphic response annual runoff and sediment production rate models.

Development of deterministic prediction models :

After regrouping the geomorphic parameters into physically significant components, SPSS 16.0 software is used to develop dimensionally homogeneous and statistically optimal models of the following linear and log linear form:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 \quad \text{... (1)}$$

$$Y = a_0(X_1)^{a_1}(X_2)^{a_2}(X_3)^{a_3}(X_4)^{a_4}(X_5)^{a_5} \quad \text{... (2)}$$

Where, Y is the dependent variable and X_1, X_2, X_3, X_4, X_5 are the independent variables $a_0, a_1, a_2, a_3, a_4, a_5$ are the regression co-efficients.

The subroutine applies multiple regression techniques and calculates regression co-efficients, multiple correlation co-efficients, F-test value, standard error and the percentage variation explained by the model. In order to obtain the best fit monthly runoff model the data sets were used to regress the runoff factor, $R/\sqrt{A}$, on three independent parameters (one each from already established components) and rainfall factor, $P/\sqrt{A}$. In all eighteen combinations were tried. The same procedure with same combinations is used using logarithmically transformed data. In order to select out the best fit model out of eighteen combinations, the criteria adopted here is the lowest standard error of estimate, highest correlation co-efficient and F-test value.

The best fit models thus identified are used to compute the predicted values of annual runoff and SPR and compared with the observed values to find the percentage deviations. The validation of models is also done. The data set of first eight watersheds was used for development of models and data set of remaining two watersheds was used for validation of the deterministic models.

RESULTS AND DISCUSSION

Geomorphic characteristics of the selected watersheds were evaluated (Table 1) using ArcGIS 9.3

Table 1 : Selected dimensionless geomorphic parameters

	S_a	R_e	R_c	S_b	R_F	Rr	R_N	S_c	D_f	R_l	R_b	L_{bw}
W_1	3.652	0.785	0.806	2.064	0.020	0.0065	0.305	1.223	0.433	0.811	3.303	1.685
W_2	1.180	0.853	0.922	1.751	0.012	0.0040	0.167	0.217	0.397	0.849	2.280	1.791
W_3	2.332	0.697	0.828	2.624	0.009	0.0035	0.332	0.499	0.487	1.127	3.863	2.082
W_4	3.472	0.622	0.763	3.286	0.021	0.0082	0.637	0.476	0.442	0.879	4.570	2.826
W_5	2.875	0.685	0.846	2.712	0.010	0.0041	0.232	0.518	0.527	1.117	2.890	2.613
W_6	4.566	0.738	0.816	2.335	0.016	0.0055	0.368	0.374	0.291	0.800	2.917	1.975
W_7	0.909	0.482	0.639	5.475	0.007	0.0028	0.145	0.464	0.536	1.042	3.319	4.101
W_8	2.297	0.502	0.613	5.053	0.008	0.0031	0.477	0.448	0.387	1.148	3.707	4.399
W_9	1.269	0.798	0.760	2.001	0.021	0.0063	0.531	0.527	0.476	0.968	3.213	2.084
W_{10}	2.317	0.782	0.769	2.080	0.022	0.0069	0.415	0.103	0.595	0.955	4.467	1.788

Table 2 : Principal component loading matrix of final geomorphic parameters

Parameters	Principal components									
	1	2	3	4	5	6	7	8	9	10
Re	0.974	-0.106	-0.165	0.103	0.003	-0.040	0.007	-0.001	0.000	0.000
Rc	0.906	-0.314	-0.241	0.137	0.039	0.057	0.003	0.000	0.000	0.000
Sb	-0.975	0.049	0.162	-0.140	-0.013	0.015	0.000	-0.001	0.000	0.000
Rf	0.881	0.463	0.071	-0.013	-0.06	-0.018	0.002	0.001	0.000	0.000
Rr	0.840	0.527	0.103	-0.046	-0.051	0.035	0.000	0.001	0.000	0.000
R_N	0.155	0.978	0.103	0.007	0.095	-0.004	0.000	0.000	0.000	0.000
Sc	0.286	-0.250	0.907	0.184	0.005	0.002	0.000	0.000	0.000	0.000
Df	0.818	-0.48	0.146	-0.276	0.051	-0.014	0.000	0.002	0.000	0.000
Rl	-0.955	0.024	-0.126	0.268	0.009	-0.012	0.000	0.002	0.000	0.000
Lbw	-0.981	0.081	0.128	-0.119	0.005	0.011	0.012	0.001	0.000	0.000
Eigen value	6.852	1.86	1.013	0.247	0.02	0.007	0.000	0.000	0.000	0.000

software interface. Using these parameters a correlation matrix was obtained to find out the correlation among the parameters. It was observed that out of twelve parameters, two parameters such as S_a and R_b were not correlated significantly to other parameters. After subjecting correlation matrix of twelve parameters to PCA, it was observed that all the parameters were grouped into three physically significant groups having Eigen value greater than one. The parameters S_a and R_b were screened out in the PCA because they were poorly correlated with all the three components and having less significance in explaining the component variance.

Geomorphic response model for prediction of June monthly runoff was developed separately. The model was developed using the data set of first 8 watersheds (W_1 to W_8). The last two watersheds (W_9 to W_{10}) were kept out of analysis for later validation of model. On comparing the linear and the log linear models, on the basis of higher correlation co-efficients and greater F-test values, the following models were chosen as statistically optimal June monthly runoff prediction model for small watersheds of Tapi catchment. Corresponding standard error (S), multiple correlation co-efficient (r) and F-test value (F) for the best fit linear and log linear June monthly runoff are presented in Table 3. Equation 3 represent the best fit model selected between linear and log-linear model on the basis of highest multiple correlation co-efficient.

June monthly runoff model :

$$\mathbf{R_f = \frac{R}{\sqrt{A}} = 0.052 + 0.194P_f + 0.516D_f + 0.194R_n - 2.096S_c} \quad \ldots (3)$$

The value of multiple correlation co-efficient (r = 0.998) and F-test value (F = 189.571) was higher in case of linear model than the log linear model. The mean annual runoff was obtained by multiplying the right hand side of the equation 3 by the square root of the drainage area of the watershed.

The validation of developed model was also carried out on two watersheds data set. It was seen from the

Table 3 : Best fit models (Linear and log-linear) for runoff and SPR - June month

Independent variable	June runoff	
	Linear	Log - linear
Shape component		
R_c		
R_e		-0.311
L_{bw}		
S_b		
R_l		
D_f	0.516	
Drainage component		
R_n	2.397	0.392
R_r		
R_F		
Steepness component		
S_c	-2.096	-0.961
Rainfall factor		
P_f	0.194	1.219
Runoff factor		
R_f		
Intercept	0.052	0.071
Standard error (S)	0.128	0.088
Mul. correlation co-eff. (r)	0.998	0.995
F - test value (F)	189.571	74.145

Fig. 1 that using monthly runoff model for July, the percentage deviations varies from 4.3 to 8.3. It was observed that percentage deviation is within 10 per cent for June monthly runoff model. Therefore, developed June monthly runoff can be conveniently used for prediction of June month runoff from unguaged watersheds of the basin having similar physiographic conditions.

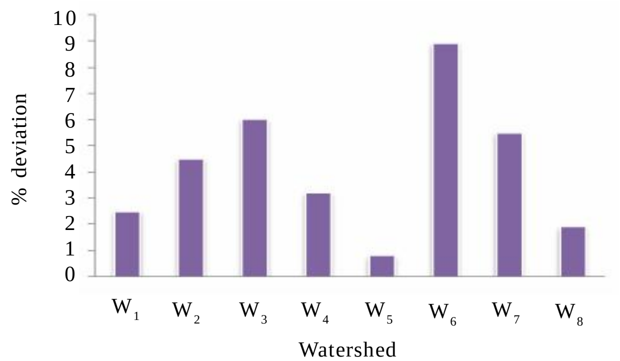

Fig. 1 : Percentage deviatin in June monthly runoff

Conclusion :

In this study, twelve geomorphic parameters were used for the development of geomorphic response June monthly runoff model for Tapi basin, India. Principal component analysis was carried out to find out physically significant groups. For the selected watersheds it is found that parameters S_a and R_b are screened out in the PCA. After orthogonal transformations, remaining ten parameters are grouped into three physically significant groups. To develop runoff model one parameter from each physically significant group and rainfall factor are regressed. The per cent deviation between observed values and predicted values were found below 10 per cent for the runoff model. Therefore, this model can be conveniently used for the prediction of June monthly runoff.

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