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Annual geomorphic response model for prediction of runoff from ungauged watersheds

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ABSTRACT : 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. 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. In the present study ten watersheds from Tapi catchment of Maharashtra state, India were selected for development of geomorphic response models for prediction of annual runoff. Twelve geomorphic parameters were selected for development of model out of which two parameters, Sa and Rb were screened out in the PCA and remaining ten parameters were grouped into three physically significant components. Developed annual model when validated, it was observed that percentage deviation was within 10 per cent. Therefore developed annual runoff can be conveniently used for prediction of annual runoff from unguaged watersheds of the basin having similar physiographic conditions for design of different water harvesting structures.

KEY WORDS : Unguaged watersheds, Geomorphological parameters, Geomorphic response Runoff model, PCA

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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. Quantitative assessment of runoff is 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. Most of the agricultural watersheds in India are ungauged, having no past records of the rainfall–runoff processes (Sarangi *et al*., 2004). This has led to the development of techniques for estimating surface runoff from ungauged basins (Chattopadhyay and Choudhury, 2006). 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. In this study geomorphic response model was developed for prediction of annual runoff 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 (W1 toW10) of Tapi catchment for which annual time series data on rainfall was used for development of models.

Digitization and georeferencing of toposheets in GIS:

Toposheets of the study area were obtained from the survey of India (SOI), Deharadun 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 was formed in GRID, TIFF or ERDAS IMAGINE format. These rectified maps were further used for creating new digitized layers of watershed boundary, drainage lines and contour lines of selected watersheds.

Evaluation of geomorphic parameters:

Twelve dimensionless parameters known as geomorphic parameters for the ten 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}). Other two dimensionless terms R/√A and P/√A were termed as runoff factor and rainfall factor, respectively. 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 was then used as input to obtain the rotated factor loadings using the various methods *viz*., varimax, quartimax and equamax. The procedure was repeated till the interpretation of 'physical significance' is simplified. These parameters from each physically significant group were being used for development of geomorphic response annual runoff model.

Development of deterministic prediction models :

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

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

$$\mathbf{Y = a_0\ (X_1)^{a1}\ (X_2)^{a2}\ (X_3)^{a3}\ (X_4)^{a4} (X_5)^{a5}} \quad (2)$$

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

The sub-routine 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 annual runoff model, the data sets were used to regress the runoff factor R/√A, on three independent parameters (one each from already established components) and rainfall factor P/√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 was the lowest standard error of estimate, highest correlation co-efficient and F-test value.

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

■ RESULTS AND DISCUSSION

Geomorphic characteristics of the selected watersheds were evaluated using ArcGIS 9.3 software interface and are presented in Table 1. Using these parameters a correlation matrix was obtained to find out the correlation among the 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. It was observed that out of twelve parameters, two parameters such as S_a and R_b were not correlated significantly to other parameters, hence, screened out as shown in Table 2. These two parameters were not used for the development of model.

Geomorphic response models for prediction of annual runoff and SPR for small watershed are developed separately. Four different models *viz.*, annual runoff, annual SPR with runoff, annual SPR with rainfall and annual SPR without rainfall and runoff as dependant parameters are developed. The model was developed using the data set of first 8 watersheds (W1 to W8). The last two watersheds (W9 to W10) 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, below model was chosen as statistically optimal runoff prediction model for small watersheds of Tapi catchment.

Table 1: 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}
W1	3.652	0.785	0.806	2.064	0.020	0.0065	0.305	1.223	0.433	0.811	3.303	1.685
W2	1.180	0.853	0.922	1.751	0.012	0.0040	0.167	0.217	0.397	0.849	2.280	1.791
W3	2.332	0.697	0.828	2.624	0.009	0.0035	0.332	0.499	0.487	1.127	3.863	2.082
W4	3.472	0.622	0.763	3.286	0.021	0.0082	0.637	0.476	0.442	0.879	4.570	2.826
W5	2.875	0.685	0.846	2.712	0.010	0.0041	0.232	0.518	0.527	1.117	2.890	2.613
W6	4.566	0.738	0.816	2.335	0.016	0.0055	0.368	0.374	0.291	0.800	2.917	1.975
W7	0.909	0.482	0.639	5.475	0.007	0.0028	0.145	0.464	0.536	1.042	3.319	4.101
W8	2.297	0.502	0.613	5.053	0.008	0.0031	0.477	0.448	0.387	1.148	3.707	4.399
W9	1.269	0.798	0.760	2.001	0.021	0.0063	0.531	0.527	0.476	0.968	3.213	2.084
W10	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

Corresponding standard error (S), multiple correlation co-efficient (r) and F-test value (F) for the best fit linear and log linear annual runoff models for Tapi catchment are presented in Table 3.

Table 3 : Best fit models (Linear and log-linear) for annual runoff

Independent variable	Annual runoff	
	Linear	Log - linear
Shape component		
R_c		
R_e		
L_{bw}		
S_b		
R_l		
D_f	-29.681	-0.310
Drainage component		
R_n		0.145
R_r	1188.993	
R_F		
Steepness component		
S_c	-2.859	-0.088
Rainfall factor		
P_f	0.139	0.551
Runoff factor		
R_f		
Intercept	20.008	1.779
Standard error (S)	1.811	0.117
Mul. correlation coeff. (r)	0.991	0.982
F - test value (F)	39.235	20.342

Annual runoff model:

$$\mathbf{R_f = \frac{R}{\sqrt{A}} = 20.008 + 0.139P_f - 29.681D_f + 1188.993R_r - 2.859S_c} \quad (3)$$

The value of multiple correlation co-efficient (r = 0.991) and F-test value (F = 39.235) are 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 that percentage deviations for W9 and W10 watersheds were 5.3 and 2.7. It was observed that percentage deviation is within 10 per cent for annual runoff model. Therefore, developed annual runoff can be conveniently used for prediction of runoff from unguaged watersheds of the basin having similar physiographic conditions. The estimated values of runoff can be used for different water harvesting structures and soil and water conservation structures.

Conclusion:

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

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