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Estimation of runoff and sediment yield under different land uses in Bundelkhand region

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Abstract
Information on runoff and sediment yield is pre-requisite, in design criteria for most of the structures on streams, reservoirs and in soil and water conservation . An attempt was made to estimate the runoff and sediment yield in catchments under different land use in Bundelkhand region. Process involved the actual measurement in controlled experimental catchment by gauging them under different land use systems and applying a process based model to asses the impact of different land uses. The analysis revealed that the agricultural watershed on the normal cultivation slope range of 1-2% yielded 19% runoff, forest watershed area, which exists mostly on hills with undulating terrain was found to yield about 12% of runoff. However, a fully protected forest on the hilly terrain at an average slope of 10% could hardly produce 2% runoff. The watershed under grasses and mixed land use produced the runoff between these two limits. The results very clearly proved the dominance of land use over other characteristics of the watersheds. Similar trend was observed in case of sediment yield which directly adhered to runoff behaviour. The process-based model applied on this data could also respond well to the effects of land use on runoff and sediment yield.

INTRODUCTION

Estimation of runoff and sediment yield are required for assessing the sustainable use of basic resources i.e. soil, water and vegetation in a catchment. Information on runoff and sediment yield is pre-requisite in design criteria for most of structures on streams, reservoirs and in soil and water conservation works. For prediction of runoff volume and peak from a given watershed, it is necessary to obtain reliable rainfall,- runoff relationships derided from historic data. In India due to lack of such information, empirical equation such as rational formula are made use of even now with the value of coefficients of runoff C, assumed on the basis of inadequate data. Thus it was felt important to collect the data for the region in the watershed, under different land use.

The Bundelkhand region is represented by transitional zone of tropical sub- humid in the east and north east to tropical semi-arid in the west. About 70% of the land is subjected to varying degree of erosion and more than 1.02 m ha area in the region is under the category of wasteland. These areas contribute considerable runoff and soil loss due to undulating terrain combined with inadequate vegetative cover. Similarly agricultural land too contribute sizeable runoff and sediment to the ephemeral stream in rainy season. To assess the interaction between natural resources viz., soil, water and vegetation various hydrological units under different land use were identified and gauged by installing weirs and water stage level recorders. The data of rainfall, runoff and sediment yield were recorded during the monsoon. The data was analyzed and the value of runoff and soil loss was assessed. Further, the process based model was applied to assess the impact of land use on runoff and soil loss.

EXPERIMENTAL AREA

The watersheds under study are in the control of Central Soil & Water Conservation Research &Training Institute, Research Centre, Datia. The centre is located at a longitude of 78o 28' East and on latitude of 25o 40' North at an altitude of 342.42 m above MSL in Bundelkhand region of India. All the micro-watersheds, under different land use lies in the research farm except one forest watershed, whose catchment lies out side the research farm and thus it was exposed to biotic interference. The climate of the place is semi-arid with an average rainfall of 861 mm spread over 375 rainy days (Tiwari, et. al., 1992). The erosion index of the place has been worked out as 555units and its daily values were found to be highly correlated with the daily rainfall values. The details of the watersheds selected under the study are given in Table 1.

$$Y = 1.1644\,x - 12.0375 \qquad (r2 = 0.80) \qquad (1)$$

Where Y is the erosion index (EI 30) and x is the daily rainfall in mm.

Table 1. Characteristics of Watersheds under study.

Watershed Characteristics	W1A	W3F	W4F	W8G	W9M
Area (ha)	5.8	1.8	4.0	1.2	7.1
Parameter (m)	976.8	794.8	845.0	426.2	1094.5
Max. length of Watershed (m)	295.3	199.8	275.0	166.5	333.0
Max. width of Watershed (m)	197.6	117.7	186.0	111.0	248.6
Length width Ratio	1:5:1	1:7:1	1:5:1	1:5:1	1:3:1
Total fall (m)	4.0	21.2	8.0	3.1	17.3
Slope (%)	1.4	10.6	6.5	1.9	5.2
Compactness Coefficient	1.13	1.65	1.18	1.10	1.15
Time of Concentration (Min.)	10.1	2.6	4.30	6.0	5.9
Aspect	North South	North South	North South	East West	North South
Land use	Agriculture	Reserve Forest	Forest Open to biotic Interference	Grasses	Forest+ Grasses

MONITORING OF RUNOFF AND SOIL LOSS

All the above catchments have been provided with sharp crested / broad crested triangular weir with automatic water stage recorders for getting the hydrograph i.e. time versus stage curve. With the help of rating table the discharge for the catchment was worked out. Soil loss data was collected by bottle samplers and analyzed in soil lob for sediment yield.

IMPACT OF LAND USE ON RUNOFF & SOIL LOSS

The analysis of the data indicated that agriculture watershed with the normal tillage operation amounted for more runoff and soil loss to the tune of 19% of rainfall and 1.31 t/ha respectively. Grasses with grass cover yielded about 11% runoff with a low sediment yield of 0.5 t/ha. Mixed landuse watershed like forest watershed amounted for 3.5% of runoff and soil loss of 0.12 t/ha.Forest watershed open to biotic interference accounted for 12% runoff with about 1 t/ha sediment yield, however, reserve forest watershed on even 10% slope amounted hardly 2% runoff with almost negligible sediment yield (Table - 2)

Table 2. Runoff and Soil loss under different land uses (1993-1999).

Watershed	Land use	Runoff (%of rainfall)	Soil loss (t/ha)
WIA	Agriculture	19.03	1.31
W3F	Forest	2.11	0.07
W8G	Grasses	11.34	0.58
W9M	Mixed land use	3.41	0.12
W4F	Forest open to biotic interference	11.97	1.07

The result showed clear effect of land use on runoff and soil loss from the catchments. This agricultural watershed refers to the normal slope of cultivation in this region, which is usually 1-3%. Normal tillage operations were taken up in the watershed, which induced silt detachment and hence resulted in sediment yield at the outlet.The forest watershed on a hill slope representing the normal hilly watershed in the area was fully managed under protection to avoid any kind of biotic interference. This natural forest mainly of Kardhai (Anogeissus Pendula) attained every year a full canopy with the onset of rains. The resulting canopy reduced runoff and soil loss to a great extent in the monsoon season.

Mixed land use watershed has a good combination of natural Kardhai forest and this grassland. In due course of time it got converted to 100% forest and the combination could in good retention of soil and water. Tree canopy, bearing the impact of the rain and the trees further offering the resistance to the flowing water has checked the silt flow from catchments. In case of grass watershed however silt is checked by the ground cover but the runoff values remains to be an affected. Tillage and other agriculture operation disturb the system and yields more runoff and soil loss. The study further included a watershed under wasteland and the runoff was found to be 25-30% of rainfall, with soil loss of 5 t/ha. In all these watersheds, the soil depth is very shallow thus loss to the extent of even 1.5 t/ha in case of agriculture is a high value and for wastelands with a low soil depth, 5 t/ha loss is a disaster

APPLICATION OF PROCESS-BASED MODEL

Few storms from the above experimental watersheds, were used in the application of process based model (Tiwari, 1995). The catchment was divided into time–area segments and their numerical solution of the governing equations for flow of water and sediment were obtained along such a grid. The rainfall-runoff-sediment model applied here is described below.

Continuity equation for one dimensional flow assuming uniform condition over width of catchments is given as (Field, 1982)

$$\partial Q/\partial x + B\,(\partial h/\partial t) = B.\, i_e \qquad (2)$$

Where Q is the discharge, h is the depth, B is the catchment width at distance from the beginning of channel, t the time and ie is the total inflow (i.e. rainfall excess), If A is the area of cross – section of flow thus as per Chow et. al., (1982).

$$A = \alpha * Q^{\beta} \qquad (3)$$

Here α and β are coefficients, value of which is determined by roughness, hydraulic radius and bed slope. Here it is assumed that all changes in momentum flux and pressure are negligible so that Sf = So, where, Sf is the friction slope and So is the bed slope.

Assuming A = Bh, Eq (2) can be written as,

$$\frac{\partial Q}{\partial x} + \alpha * \beta * Q^{\beta - 1}\left[\frac{\partial Q}{\partial t}\right] = B * i_e \qquad (4)$$

Eq (4) was solved along a non-uniform spatial grid formed by time-area segments. Newton's iterative procedure is used for solution of the above nonlinear equation. Values of the flow velocity and the discharge are obtained at each grid point through such a solution.

The continuity equation for soil erosion in a plane is expressed as (Foster, 1982).

$$\frac{\partial q_s}{\partial x} + \frac{\partial\left(q_s/U\right)}{\partial t} = D_F + D_I \qquad (5)$$

Here Q is the mass of eroded soil per unit width, U the flow velocity, DI is the detachment due to raindrop impact and DF is the detachment due to flow. DI is the function of rainfall intensity, soil and vegetation characteristics, while DF is a function of unit discharge, segment slope and the soil type (Beasley et al. 1980, Foster, 1982).

The value of qs determined through Eq. (4) is limited by transport capacity of the flow. The flow transport capacity is a function of unit discharge slope and soil characteristics (Beasley et al., 1980). Equation (4) is solved using a four point implicit scheme (Li, 1977). Simultaneous solution of Eqs. (3) and (4) produces temporal variation of sediment yield for a catchment.

RESULTS & DISCUSSIONS

Equations (3) and (4) were solved using time-area segments as the spatial grid points. Data selected for calibration were used to ascertain values of various coefficients appearing in the formulation.

In application of above formulation, parameter α was computed using value of roughness coefficient n varying between 0.01 to 0.5 (Woolhiser, 1977) for various time area segments in a catchment. Phi-index was determined and effective rainfall was worked out. Using non-dimensiondized effective rainfall, roughness coefficient and the kinematic wave parameters as computed above, the value of Q I+1 was obtained at each grid point. The output obtained included the discharge and velocity at each computational grid point.

Table 3. Comparision of observed and computed runoff.

Catchment	Date of storm	Peak Discharge m^3/sec		Time for peak (Hrs.)		Volume of run-off		r^2	Nash Sutcliffe efficienccy
		Obs.	Comp.	Obs.	Comp.	Obs.	Comp.		
W1A (Agriculture)	17.9.93 (c)	.0043	.0042	1.66	2.66	2.51	2.52	0.82	75
	10.9.93 (v)	.0066	.0647	2.33	2.66	2.20	2.32	0.55	55
W4F (Forest without protection)	17.9.93 (c)	.01175	.0120	1.16	1.33	0.94	0.99	0.79	78
	10.9.93 (v)	.0201	.0283	1.33	1.16	1.80	1.82	0.87	77
W8G (Grasses)	17.9.93 (c)	.0075	.0057	1.16	1.16	1.41	1.29	0.95	93
	10.9.93 (v)	.0092	.0129	1.16	1.00	2.95	2.71	0.74	56

Simultaneous computations were made for sediment yield by using the values for flow velocity and discharge at the computational grid points and USLE parameter K & C. The coefficients of the equation were optimized to compute sediment yield and its variation by comparing computed sediment graph with the real time data.

Table 4. Comparision of observed and computed sediment graph.

Catchment	Date of storm	Peak Discharge N/sec		Time to peak (Hrs.)		Total sediment yield		r^2	Nash Sutcliffe efficienccy
		Obs.	Comp.	Obs.	Comp.	Obs.	Comp.		
W1A (Agriculture)	17.9.93 (c)	.0107	.0057	1.65	1.33	.0025	.0026	0.44	42
	10.9.93 (v)	.0167	.0085	2.33	2.33	.0047	.0032	0.82	40
W4F (Forest without protection)	17.9.93 (c)	.0550	.0750	1.16	1.16	.0058	.0153	0.22	57
	10.9.93 (v)	.0608	.0932	1.16	1.16	.2070	.0203	0.76	55
W8G (Grasses)	17.9.93 (c)	.0390	.0390	1.15	1.15	.0080	.0070	0.65	54
	10.9.93 (v)	.0330	.0400	1.00	1.00	.0080	.0090	0.93	95

Data for the three land use i.e. watersheds under forest, grasses and agriculture were selected for two storms dates. One storm was used to fix up the coefficients of watersheds and other was used to validate the model and applicability of these coefficients. Comparison was made between the observed sediment yield and the corresponding computed sediment yield. Nash Sutcliffe (1970) efficiency was used for comparison. The results provided were satisfactory showing the possibility of using this process-based model (Tables 3&4). Model efficiencies were higher in case of runoff as compare to that of sediment however total sediment yield predictions were very close. Validation of the model shows its applicability as well as sensitivity of the model towards the land use.

CONCLUSIONS

The foremost conclusions drawn from the above study is that the land use of the watershed has a direct impact on the hydrology of the catchment. Runoff assessment in the region show that, wastelands contributes runoff about 25 to 30 percent of rainfall, agricultural fields contribute 19 percent runoff, grasslands contribute 11 percent runoff, and forest watershed open to biotic interference contribute 12 percent runoff, whereas, the well protected forest watershed contributes runoff about 2 percent of the rainfall. Results indicate that hilly terrain of Bundelkhand region needs only protection to have a better canopy cover and save sediment loss from the degraded lands. Lastly, it is seen that process based models can contribute to a better understanding of the natural process and can incorporate the effect of land use.

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