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Estimation of Spatial Erosion using ANSWERS Model

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Abstract : Four major basic factors that influence runoff and soil erosion in a watershed are climate, soil properties, topography and land cover characteristics. These factors show large spatial variability across the watershed. The distributed parameter models can be best utilized to take spatial heterogeneity of a watershed into consideration. In the present study, ANSWERS, a deterministic and spatially distributed parameter model was applied for computing runoff and soil erosion from a small, hilly forested watershed in Nainital district of Uttarakhand state. Geographic Information System (GIS) techniques were used in the study to generate spatial information on slope, aspect, and land use properties. The results of the study indicated a satisfactory performance of the model in computing the surface runoff, peak runoff and sediment yield from the forested watershed. The model also computed the spatial distribution of soil erosion and deposition in the watershed. A comparative analysis of soil erosion under different canopy classes revealed that the erosion in C3 canopy < C1 canopy < C2 canopy in all the events. The average rate of soil loss from the watershed was found to vary between 17.52 to 151.77 kg/ha for the four events.

INTRODUCTION

Assessment of runoff and soil erosion in watersheds and their sediment yield are required for assessing the sustainable use of soil and water resources and for design and adoption of erosion control measures. The generation of runoff and soil erosion in a watershed is largely governed by climatic, soil, topographic and land cover characteristics which vary spatially across the watershed. The distributed rainfall-runoff-sediment yield models have the capability to account for the spatial variability of watershed characteristics and predict the spatial distribution of runoff and sediment over the land surface in addition to total runoff and soil loss. But, the major constraint in applying these models is their large and space-time variable input data requirement, which are scanty in the country. The Remote Sensing (RS) and Geographic Information System (GIS) techniques these days, however, can provide information in spatial domain used by the distributed models. In the past, GIS techniques have been widely used by researchers in watershed modelling to capture the spatial variation in computed quantities. Needham and Vieux (1989) examined the application of ARC/INFO GIS to generate spatial input data for the AGNPS model. Using a GIS, Van Blargan et al. (1990) generated data for a hydrologic model. Moore et al. (1988) utilized ARC/INFO to provide topographic attributes for modeling hydrology and water quality in a watershed. Olivieri et al. (1991) developed a method for automated generation of input data for the AGNPS model by using the ERDAS GIS software. GIS techniques have now been interfaced with some standard watershed simulation models also (Srinivasan and Engel, 1994; Rewarts and Engel, 1991; Mashriqui and Cruise, 1997; Arnold et al., 1998).

ANSWERS, a distributed parameters model having grid based representation is very well adapted for taking GIS inputs for topography, land cover, soil and other spatially distributed input descriptors. The model was originally developed for simulating runoff and sediment yield from gently-sloping, agricultural watersheds. Subsequently, it has been successfully applied to a much broader range of conditions. The present study aims at application of ANSWERS model to a small, hilly forested watershed in Nainital District of Uttarakhand state and assess its performance in estimating spatial erosion and sediment yield from the hilly watershed that reflect the effects of extreme spatio-temporal variability in topographic, surficial and hydrological conditions.

OVERVIEW OF ANSWERS MODEL

ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation), developed by Beasley et al. (1980) is a distributed parameter, event based model used to simulate surface runoff and erosion response of agricultural watersheds. The model divides the entire watershed into uniform grid of square cells within which all input variables (surface and subsurface soil properties, vegetation, surface condition, crop management and weather) are assumed homogeneous. Connectivity of cells and continuity equations are used to route sediment transport and flow. The model can be divided into two parts, (1) hydrologic sub-model and (2) sediment sub-model. The hydrologic sub-model simulates interception, surface retention/detention, infiltration and overland flow. The sediment sub-model considers three erosion processes: detachment of soil particles by impact of raindrops, detachment of soil particles by overland flow and transport of soil particles by overland flow. The quantity of erosion or deposition occurring within each cell is estimated based on the erodibility of the soil and land cover type of the cell, the rate of flow passing through the cell, and the quantity of sediment in the flow passing through the cell. Every element or cell acts as an overland flow plane with a user-specified slope and slope direction. Channel elements collect flow from overland flow elements and route runoff to the watershed outlet. Soil detached from rainfall or runoff is also available for transport by overland flow.

The input data required for each element include (i) topographic data (elevation, slope, aspect), (ii) soil data (porosity, antecedent moisture content, field capacity, infiltration capacity, USLE 'K' factor), (iii) land cover data (percent cover, interception, USLE 'C' & 'P' factors, surface roughness, surface retention), (iv) channel data (width, and roughness), and (v) rainfall data. ANSWERS outputs an event hydrograph, an event sediment graph, and the erosion and deposition rates for individual grid cell (Beasley and Huggins, 1992).

STUDY AREA

A *sal* forested watershed of about 16.40 ha, located between latitudes 29° 202 29" to 29° 202 57" N and longitudes 79° 182 26" to 79° 182 37" E, was selected in Musabangar village of Kaladhungi Tehsil in Nainital district, Uttarakhand, India. The normal annual rainfall of Nainital district is about 1528 mm, of which about 80% occurs in monsoon months of July to September. The entire watershed is covered under *sal* forest of varying canopy density. The elevation in the watershed varies from 562 m at the upstream to 526 m at the outlet. The slope of the watershed though varies from flat to about 72%, the major area (approx. 80%) falls under slope range of 5 to 25%. Soil samples were collected from 27 locations and analyzed for grain size distribution in the laboratory using mechanical sieve shakers and laser based particle size analyzer. The analysis revealed that the watershed chiefly consists of silt loam with medium to coarse gravel. The canopy density survey of the forest in the watershed was conducted by the Department of Forests, Govt. of Uttarakhand under three canopy density classes of C1, C2 and C3, representing respectively the areas where canopy density has reduced to (0-0.30), (0.30-0.50), and (0.50-0.70).

The watershed was instrumented for measuring rainfall and watershed runoff. The rainfall was recorded using a tipping bucket rain gauge. A stream gauging site consisting of a 90° V notch and a stage level recorder (with data logger) was established at the outlet of the watershed and the discharge was computed from the stage data using the appropriate weir formula. The runoff samples for the storm events were also collected and analyzed for sediment yield from the watershed. The study area, being a very small watershed, produced the discharge during a storm event only.

METHODOLOGY

The methodology used in the study included preparation of thematic maps using GIS techniques, spatial analysis for preparation of space variant input data to ANSWERS model, estimation of model parameters and application of the ANSWERS model.

Preparation of Thematic Maps

A set of thematic maps was prepared for the study watershed using the information derived from various field surveys and investigations. The ILWIS (ITC, 1998) software was used in preparing the GIS layers. A topographic survey of the study watershed was conducted as it was not possible to derive the topography of the watershed from Survey of India toposheets in view of small extent of the study area. The grid point elevations were interpolated at 10 m grid cells to generate Digital Elevation Model (DEM) of the watershed. This DEM was further analyzed to remove pits and flat areas in it to maintain continuity of flow to the watershed outlet. The corrected DEM was used to delineate the watershed boundary using eight direction pour point algorithms (ESRI, 1994). The slope map (Fig. 1) and aspect map (Fig. 2) were then derived from DEM by applying appropriate map calculation formulae. The drainage network of the watershed was generated from DEM using the concept of channel initiation threshold. The grid cells having flow accumulation of 0.5 ha have been treated as cells having channel network passing through them. The generated drainage network (Fig. 3) matches well with that obtained through plain table survey of the watershed. The analysis of soil samples collected from 27 locations in the watershed revealed that the watershed chiefly consists of silt loam with medium to coarse gravel. The canopy density distribution of *sal* forest in the watershed is shown in Fig. 4.

GIS Analysis

ANSWERS model requires slope, aspect, type of soil, type of land use and type of channel if present, for individual grid cells. The cell size for simulation was taken as 10C10 m. The canopy density map, slope map, aspect map, and drainage map were integrated in GIS environment to describe the cell row and column numbers along with their associated attributes. The soil texture in the watershed is chiefly silt loam but its hydrological properties may have some spatial variation depending on the canopy density and organic matter content. The soil type for individual cells was, therefore, assigned in accordance with canopy density.

MODEL APPLICATION

ANSWERS model uses two types of input data files. The first file contains information on rainfall input and the parameter values associated with each type of soil, land use and channels. The second data file providing the information of individual grid cells contains the cell row and column number, slope steepness, direction of slope (aspect), soil type number, land use type number, channel cell indicator with channel type number, rain gauge designator etc. The second data file was derived from various thematic layers as described in previous section.

The model parameters for soil type, land use and surface characteristics, and channels in the watershed were estimated based on the available data and through literature survey. Parameters related with land use for various canopy categories viz., potential interception volume (PIT), and surface storage coefficients (RC and HU) were estimated from ANSWERS Users' Manual (Beasley and Huggins, 1992). The relative

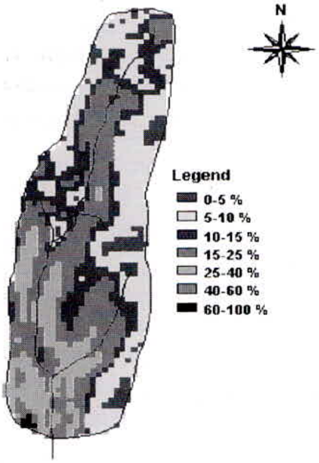

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Fig. 1. Slope map

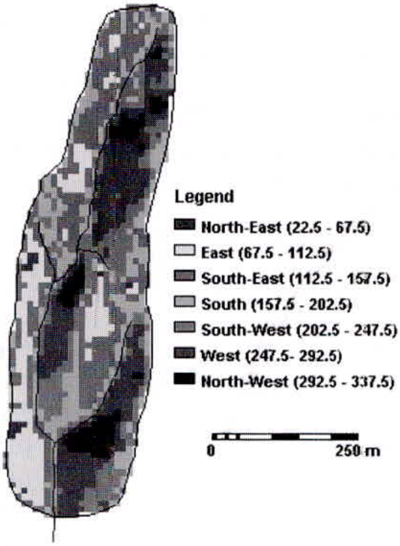


Fig. 2. Aspect map

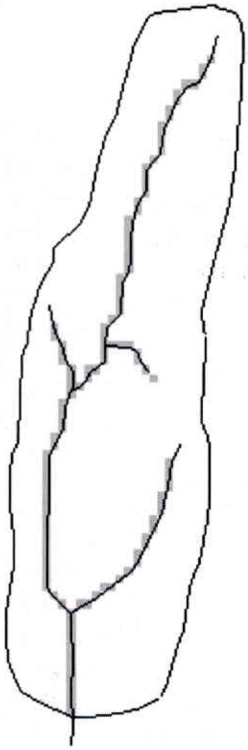


Fig. 3. Drainage network

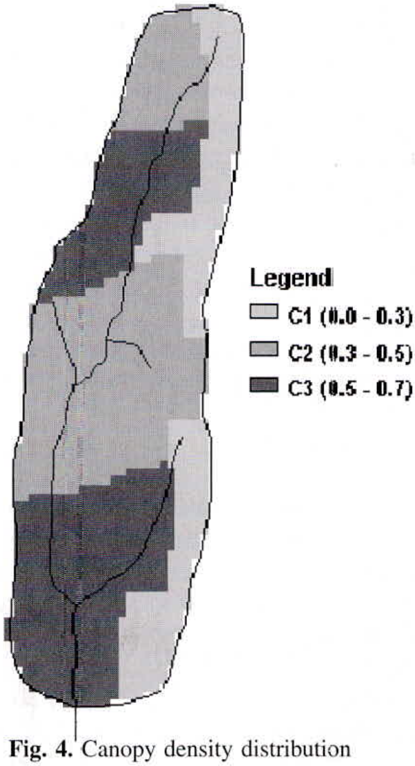


Fig. 4. Canopy density distribution

erosiveness parameter (CDR) is a direct combination of USLE 'C' and 'P' factors and was taken from the tabulated values of Wischmeier and Smith (1978). The value of Manning's 'n' for overland flow were assigned from tabulated values of Hann et al. (1994). The soil parameters such as total porosity (TP), field capacity (FP), and exponent in infiltration equation (p) were also obtained from ANSWERS Users' Manual (Beasley & Huggins, 1992). The steady state infiltration rates (FC) were taken from the tests conducted in the field. The soil erodibility parameter (K) was taken from Morgan (1995). Infiltration control zone depth (DF), which describes the depth of soil that influences the infiltration rate at the surface of the soil, was taken as approximately half of the depth of the 'A' horizon (Beasley & Huggins, 1992). The antecedent soil moisture content (ASM) for each storm event was determined from the observed data. Based on the measurements during field visit, the drainage channels in the watershed were divided into 3 types and average width of each type was computed. Strictly speaking, the parameters of distributed models do not require any calibration since they are supposed to be measured for individual grid cell in the field. But in practice, the land use and soil characteristics are found to vary even within the same cell from one point to another. Therefore, parameters need to be fine tuned through calibration to obtain the representative set of model parameters.

The model was calibrated on individual storm events of July 17, 2006 and September 19, 2007 respectively with respect to their observed values of surface runoff, peak runoff and sediment yield at the watershed outlet. The storm event of July 17, 2006 was first simulated with estimated parameter values. It was seen that the computed values were not far away from the observed values. The parameters which mainly included FC, maximum infiltration capacity in excess of FC (A), DF, K, RC, HU, Manning's 'n' and CDR were then fine tuned by varying one parameter at a time in each successive runs by trial and error till a best possible match between computed and observed values was achieved. These calibrated values were then used to simulate the event of September 19, 2007 and the calibration process repeated for the event. The calibration process was repeated alternatively on each of the two events to narrow down the difference in calibrated parameter values of the two events. Finally, an average set of parameter values was obtained to simulate both the events with a reasonable accuracy.

The model was validated on two events of August 3, 2006 and July 12, 2007 respectively. In simulating these events, the calibrated values of all other parameters except DF and ASM were kept unchanged. The parameters DF and ASM vary with individual storm event (Beasley & Huggins, 1992). The ASM values as determined earlier for individual events were used while DF was calibrated for individual events by trial and error method.

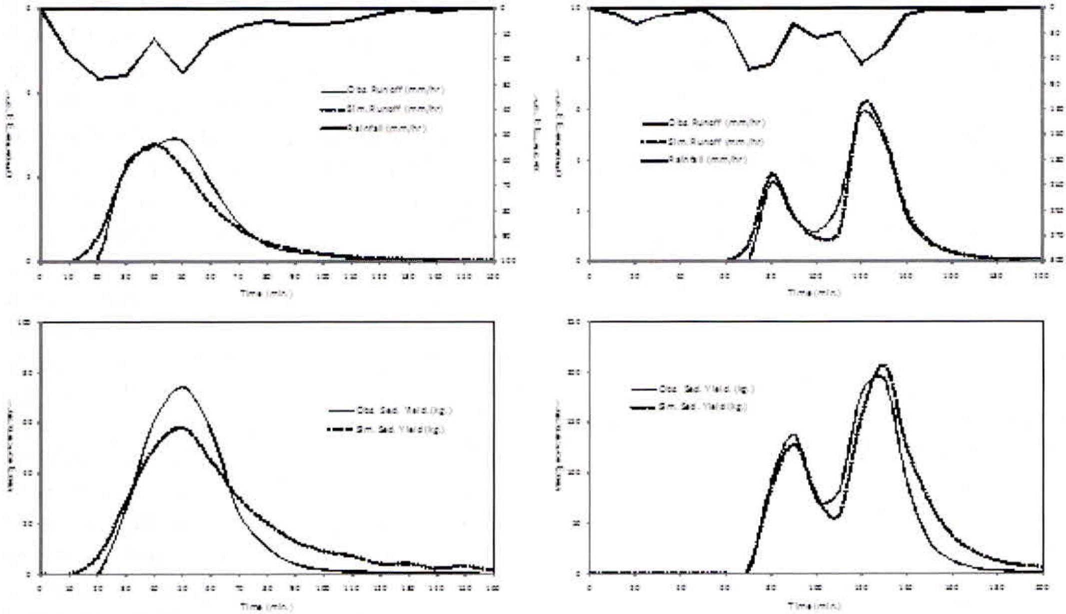
RESULTS

Analysis of Simulated Runoff and Sediment Yield

The simulated and observed hydrographs and sediment yield graphs for two calibration events are presented in Fig. 5. It is observed that the simulated runoff hydrographs and the sediment yield graphs for both the events match reasonably well with the observed ones. In order to assess the model performance quantitatively, Nash and Sutcliffe efficiency and the volumetric error were computed. The summary of simulation performance for calibration events (Table 1) shows that for the event of July 17 of 25.60 mm rainfall, the runoff is under estimated by 4.45% and sediment yield is over estimated by 10.30%, while for the event of September 19 of 68.20 mm rainfall, the runoff and sediment yield are over estimated by 2.41% and 12.50% respectively. The peak rate of runoff is simulated lower by 3.15% on July 17 and higher by 5.55% on September 19. The model efficiencies for simulating the runoff and sediment yield were obtained as 95.88% and 91.70%

respectively for 17th July event and 96.95% and 94.22% respectively for 19th September event. The model performance with these high efficiencies is considered quite well for erosion models.

The runoff hydrographs and sediment yield graphs for the validation events (Fig. 6) also show that the shape and peaks of the simulated



Fg. 5. Simulated and observed runoff and sediment yield graphs for two calibration events

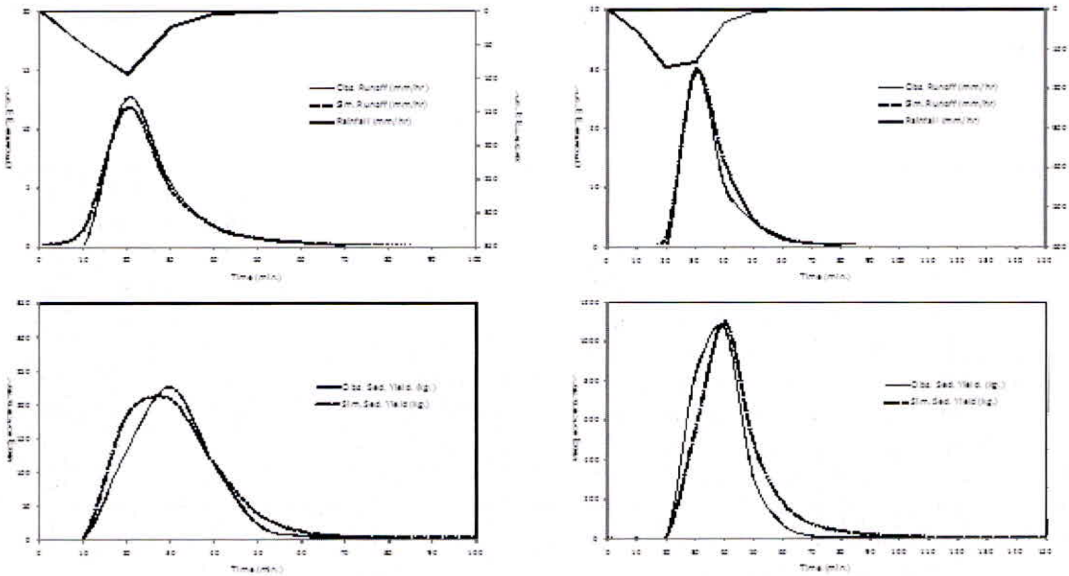


Fig. 6. Simulated and observed runoff and sediment yield graphs for two validation events

hydrographs and sediment yield graphs are in close agreement with those of observed ones. The model performance indices for validation events (Table 1) indicate that the runoff volume is over estimated by 1.39% and 12.17% for the events of August 3 and July 12 respectively. The sediment yield predictions are also found higher by 15.92% and 7.94% for the respective events. The peak rate of runoff is estimated lower by 6.54% and 2.36 % in the respective cases. The model simulated the runoff and sediment yield with an efficiency of 98.14% and 94.92% respectively on August 3, and with 98.00% and 92.14% respectively on July 12.

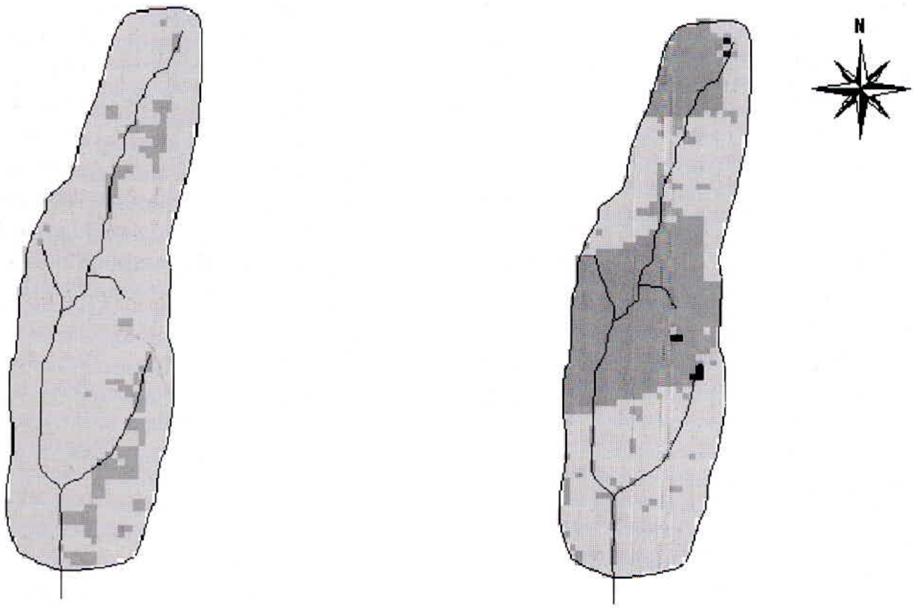
The results of model calibration and validation presented above show a high degree of accuracy in simulating the runoff and sediment yield response at the outlet of the watershed. The model efficiencies achieved in calibration process are maintained in validation also and the two are quite comparable.

Analysis of Spatial erosion

Apart from estimating the temporal runoff and sediment yield at the watershed outlet, the model also estimated the spatial distribution of soil erosion and deposition rates in the watershed. These spatial rates were converted to maps (Fig.7) using GIS techniques. The computation of watershed area under different erosion classes revealed that the soil erosion varied in the range of (0-50 kg/ha) in the entire watershed for the 17th July event of 25.60 mm rainfall that produced 1.88 mm runoff; (0-50 kg/ha) in 62% and (51 to 100 kg/ha) in 38% of the watershed area for the 3rd August event of 29 mm that produced 3.60 mm runoff; (0-50 kg/ha) in 59%, (51-100 kg/ha) in 4%, and (101-200 kg/ha) in 37% of the area for the 19th Sept. event of 68.20 mm rainfall that produced 3.80 mm runoff, and; (0-50 kg/ha) in 7%, (51-100 kg/ha) in 9%, and (101-300 kg/ha) in 84% of the area for the 12th July event of 61.40 mm rainfall that produced 8.82 mm runoff. These figures imply that the rate of soil erosion increased with the increase either in the rainfall intensity or runoff quantity which is obvious. As such, the variation of rainfall intensities and runoff production from event to event results a shift in erosion zones from one erosion category to another category. The average rate of soil loss from the watershed was computed as 17.52, 35.53, 61.72 and 151.77 kg/ha due to the event of 17th July, 3rd August, 19th Sept. and 12th July respectively.

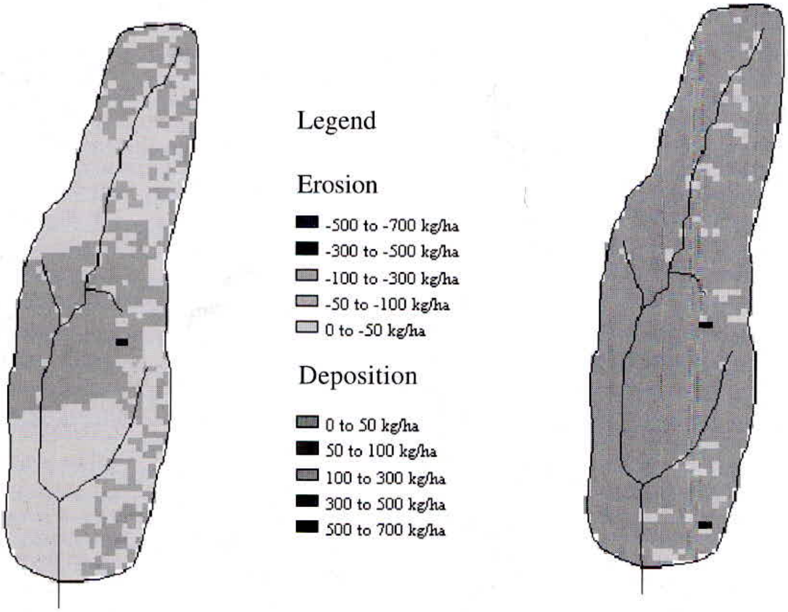
Table 1. Model performance indices for calibration events

S. No.	Performance indices	July 17, 2006	Sept. 19, 2007	Aug. 3, 2006	July 12, 2007
1	Rainfall (mm)	25.60	68.20	29.00	61.40
2	Observed runoff (mm)	1.97	3.71	3.55	7.86
3	Simulated runoff (mm)	1.88	3.80	3.60	8.82
4	Observed sediment yield (kg.)	260.00	898.00	502.00	2303.00
5	Simulated sediment yield (kg.)	287.00	1011.00	582.00	2486.00
6	Vol. error in runoff (%)	4.45	-2.41	-1.39	-12.17
7	Vol. error in sed. yield (%)	10.30	-12.50	-15.92	-7.94
8	Error in peak runoff rate (%)	3.15	-5.55	6.54	2.36
9	Efficiency for runoff (%)	95.88	96.95	98.14	98.00
10	Efficiency for sed. yield (%)	91.70	94.22	94.92	92.14



(a) July 17, 2006 event

(b) Sept 19, 2007 event



(c) August 3, 2006 event

(d) July 12, 2007 event

Fig. 7. Erosion and deposition maps

For assessing erosion under different canopy density, the canopy density map was superimposed with erosion map of each rainfall event and the erosion categories obtained for each canopy class are presented in Table 2. A comparative study of erosion under different canopy classes shows that the erosion in C3 canopy is less than that under C1 and C2 canopies during all the events. Except for 19th Sept. event which shows higher erosion in C2 than C1 canopy, the erosion categories in C1 and C2 canopies are same for the other three events. The lowest erosion in C3 canopy may be attributed to the dense overhead canopy and a good layer of leaf litter which dissipate the erosive energy of the rainfall. Though the overhead canopy of C1 class provides lesser protection than C2 canopy, yet the good regeneration under C1 canopy provides some cushion against rainfall erosion.

CONCLUSIONS

In application of ANSWERS model to the study watershed, the Nash-Sutcliffe efficiencies in estimating the runoff and sediment yield for 4 rainfall events were obtained in the range of (95.88 - 98.14%) and (91.70 - 94.92%) respectively. These efficiencies indicate a more than satisfactory performance of the model for application in forested watersheds. Apart from computing the temporal runoff and sediment yield at the watershed outlet, the model also estimated the spatial distribution of soil erosion and deposition rates in the watershed. Based on spatial computation, the zones of soil erosion have been identified in the watershed. A comparative analysis of soil erosion under different canopy classes revealed that the erosion in C3 canopy < C1 canopy < C2 canopy in all the events. The average rate of soil loss from the watershed was found to vary between 17.52 to 151.77 kg/ha for the four events. A shift in erosion zones from one erosion category to another category was observed from event to event depending on the variation in rainfall intensities and runoff production.

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Table 2. Canopy wise erosion categories for different rainfall events

Canopy classes	Erosion categories (kg/ha)			
	July 17, 2006 event	August 3, 2006 event	Sept. 19, 2007 event	July 12, 2007 event
C1 (up to-0.30)	-(0-50)	-(0-50) -(51-100)	-(0-50)	-(101-300)
C2 (0.30-0.50)	-(0-50)	-(0-50) -(51-100)	-(101-300)	-(101-300)
C3 (0.50-0.70)	-(0-50) +(0-50)	-(0-50) +(0-50)	-(0-50)	-(0-50) -(51-100) -(101-300)

Note: The -ve and +ve signs indicate erosion and deposition respectively.

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