ICIWRM – 2000, Proceedings of International Conference on Integrated Water Resources Management for Sustainable Development, 19 – 21 December, 2000, New Delhi, India

Soil erosion modelling using satellite remote sensing and GIS

MANOJ K. JAIN
Scientist C, National Institute of Hydrology, Roorkee – 247 667, India

Abstract
In this study, a spatially distributed parameter model the Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model has been used to simulate surface runoff and soil erosion in Karso catchment in Bihar, India. The model divides catchment into square elements (grid cells) and uses the connectivity of the cells (derived from slope aspect values) and the continuity equation to route flow to the catchment outlet. The quantity of erosion or deposition occurring within each cell is estimated based on the erodibility of the soil, 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.

The GIS techniques have been utilised for spatial discretization of the Karso catchment in to grids. Model input parameters such as land forms, drainage, soil, landuse/land cover were derived from digital analysis of Landsat Thematic Mapper data with limited ground truth. Information about slope and aspect were generated in a GIS from Survey of India Toposheets. The model predicted hydrographs and sediment graphs within acceptable limits. Besides temporal variation of soil erosion, the model also predicted spatial distribution of soil erosion in the watershed. Based on spatial predictions of the model, the sources of soil erosion have been identified in the watershed. Changes in spatial distribution in sediment production zones with varying rainfall intensities and duration have also been studied and discussed.

INTRODUCTION

Quantitative assessments of runoff and soil erosion are needed for proper management of land and water resources. Four basic factors influence runoff and soil erosion by water: climate, soil properties, topography and landuse practices. It a common knowledge that these factors show large spatial variability and any effort to simulate runoff and soil erosion must take this fact into consideration. The distributed parameter models could be used to take spatial heterogeneity of a watershed into consideration. The mapping and management of such spatial information require use of new technologies such as satellite remote sensing and Geographical Information System (GIS).

Models available in the literature for sediment yield estimation can be grouped in to two categories (a) physically based models (b) lumped models. Generally in physically based models the ground surface is separated into inter-rill and rill erosion areas. Detachment over inter-rill areas is considered to be by the impact of rain drop because flow depth are shallow, while runoff is considered to be the dominant factor in rill detachment and sediment transport over both rill and inter-rill areas. The physically based models include AGNPS (Young et al., 1987), ANSWERS (Beasley et al., 1980), WEPP (Nearing et al., 1989) and SHESHED (Wicks and Bathrust, 1996). The physically based models are expected to provide reliable estimates for the sediment yield. However, these models require the co-ordinated use of various sub-models related to meteorology, hydrology, hydraulics and soil. As a result, the number of input parameters for some of these models is high. Therefore, practical application of these models is still limited because of availability of information in spatial domain. Recent advances in remote sensing and use of GIS can provide information in spatial domain used by some of these process-based models.

Geographic Information Systems (GIS) link land cover data to topographic data and to other information concerning processes and properties related to geographic location. When applied to hydrologic systems, nontopographic information can include description of soils, land use, ground cover, ground water conditions, as well as man-made systems and their characteristics on or below the land surface. ANSWERS model due to its distributed nature and grid based representation is very well adapted for taking GIS inputs for topography, land cover, soil and other spatially distributed input descriptors.

The present study is undertaken to study rainfall-runoff soil erosion behaviour of Karso catchment in Bihar using Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model. The land cover and soil map of the study area were derived using ERDAS Imagine image processing software using supervised classification of Landsat TM and IRS 1C LISS-III satellite data with limited ground truth data. Other thematic layers such as DEM, slope, flow direction etc were generated using ILWIS software. Bases on generated thematic layers input data files for ANSWERS model application were generated and used for rainfall-runoff soil erosion simulation of Karso catchment. Model parameters were then derived based on soil and landuse information. Some of the storm dependent parameters were fine-tuned for individual storm events to simulate the behaviour of the watershed. Results of the study are then discussed.

ANSWERS MODEL

The Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model was developed by Beasley and Huggins (1992) to simulate surface runoff and erosion in predominantly agricultural catchments. The model divides catchments into square elements (grid cells) and uses the connectivity of the cells (derived from slope aspect values) and the continuity equation to route flow to the catchment outlet (Beasley et al. 1982). Three erosion processes are considered: detachment of soil particles by raindrop impact, 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 (Brown et al. 1993). A series of topographic (elevation, slope, aspect), soil (porosity, moisture content, field capacity, infiltration capacity, USLE K factor), land cover (percent cover, interception, USLE CP factor, surface roughness, retention), channel (width, roughness), and rainfall inputs are required for each element (De Roo *et al*. 1989). For complete details about equations used and other modeling details, the reader may refer to Beasley *et al*. (1980); Beasley and Huggins (1992).

THE STUDY AREA

For the present study, the Karso catchment in the Barakar basin has been selected due to availability of data. The stream named Kolhuwatari traverses through this catchment and finally joins the Barhi nadi, a tributary of Barakar River. The total area of the catchment is 27.93 sq. km. Geographically this catchment lies between longitudes 85°24′20″ East and 85°28′6″ East and latitudes 24°16′47″ North and 24°12′18″ North in Hazaribagh district of Bihar. The catchment lies in sub-humid tropical climatic zone. Precipitation occurs in the form of rainfall during July to September. July and August are the wettest months. The annual precipitation of the area is 1243 mm.

The catchment has extremely undulating and irregular slopes ranging from moderate 1.8% to steep 31.94%. The average slope of the catchment is 7.3%. The soil within the area is primarily coarse granular. The texture of soil is light sandy loam with the average percentage of coarse sand, fine sand, silt and clay as 30%, 28%, 17% and 25% respectively (Singhal, 1982). The soils are low in organic matter content. The data related to soil characteristics have been taken from soils Division of DVC Hazaribagh. The land use in this area can be grouped under three categories viz. agricultural land, forest and open scrub. Agricultural land has paddy cultivation and mixed cultivation areas. Land use pattern of the area was derived from digital analysis of satellite data. Most of the cultivated area has been treated by soil conservation measures like terracing, bunding etc.

The gauging work of Kohuwatari river flow and collection of sediment load data were initiated in the year 1991 for hydrological studies to assess the effects of soil conservation measures on surface runoff and erosion under the Indo-German Bilateral Project on Watershed Management (S&WCD, 1991). Under this scheme, existing and newly constructed sediment monitoring stations were equipped with tipping bucket type automatic rainfall recorder and water level recording devices, linked to an electronic data logger system. Samples for sediment load were collected using the Punjab or USDA bottles. Sediment samples were taken for every 15-cm of rise and fall of water level with a maximum time interval of one hour during a flood event. The data on rainfall, runoff and sediment yield for the catchment is available in the literature (S&WCD, 1991).

ANALYSIS AND DISCUSSION OF RESULTS

Generation of Digital Input Maps

The river network and contour map of the study areas were digitised using the Integrated Land and Water Information System, ILWIS (ITC, 1998) from the Survey of India Toposheets at a scale of 1:25 000. Thus digitised segment contour maps were then interpolated at 10 m-grid cells by using ILWIS to generate the Digital Elevation Models (DEM) of the Karso catchment. The interpolated DEM is then aggregated at 100-m pixel resolution to reduce number of pixels used for calculation. The original DEM at 10-m pixel resolution has 2,79,300 cells and after aggregation at 100-m pixel resolution the DEM has only 2790 grids (area 27.90 sq. km.) which are easier to handle for present application.

This DEM was further analysed to remove pits and flat areas in it to maintain continuity of flow to the catchment outlet. The corrected DEM was next used to delineate the catchment boundaries of Karso catchment using eight direction pour point algorithm (ESRI, 1994). The channel network used in simulation was generated using the concept of channel initiation threshold. According to this concept the grid cells having flow accumulation of 200 ha have been treated as cells having channel network passing through them. The generated channel network matches well with satellite observable drainage network in this watershed.

The landuse and soil map of the study catchment was derived from the classification of satellite data. The study catchment was covered by the satellites namely Landsat TM path 140 and row 43 on 7 May 1991 and IRS 1C LISS-III path 105 and row 55 on 28 November 1996. The area of interest were first cut from the entire path/row of LANDSAT TM and IRS 1C LISS-III scenes and further they were geo-coded as per method suggested by Sabins (1997) at 30 and 24 meter pixel resolutions respectively by using Earth Resources Data Analysis System (ERDAS) Imagine image processing software (ERDAS, 1998). The geo-coded scenes were then masked by the boundaries of the catchments derived earlier for delineating the areas lying within the catchment. Land cover and soil maps were then generated using the supervised classification scheme (Sabins, 1997) using TM data. The IRS 1C LISS-III data was used only to classify confusing pixels to the class they belong. In Karso catchment three-land cover categories viz. Agriculture (mainly paddy), fairly dense forest and open scrub were identified and mapped. Parameters related with various land use categories were then obtained from ANSWERS Users' Manual (Beasley & Huggins, 1991). Based on land cover categories, the relative erosiveness parameter C were assigned to individual grids from the tabulated values of Wischmier and Smith (1978) and values reported by Jain and Kothyari (in press) for this watershed. The value of Manning's n was assigned from tabulated values of Haan et al. (1994).

Soil types could not be evaluated directly from Landsat TM images. However, based on morphological features, Landsat tonal variations and associated soil texture, and limited ground truth data, different soil types were distinguished, classified and mapped in the study catchment. The soils were classified in three categories viz. clay loam, silty loam and silty clay loam in Karso catchment. The soil characteristics such as fraction of sand, silt, clay and organic matter, total porosity, field capacity, infiltration characteristics and other related parameters for mapped soil categories were taken from SWCD (1991). Exponent in infiltration equation was obtained from Users' Manual of the ANSWERS model (Beasley & Huggins, 1991) for each soil category present in the watershed. Thus the information on soil type in individual grids of the catchment was known. Based on the soil type The parameter K for mapped soil categories were then calculated for each of the grids using the procedure stated in the nomograph of Wischmier and Smith (1978).

Model Application and Discussion of Results

Input data file for ANSWERS model comprises of two sections. The first section deals with storm input and soil and landuse physical properties or model parameters based on soil and landuse type. The second section of the data file contains information of individual pixel elements. This include soil type number, landuse type number, slope steepness of the element, direction of the steepest slope, row and column number of the pixel, channel cell indicator, raingauge designator etc. Information about second part of the data file have been derived from various thematic layers generated so far using MAP CALCULATION, CROSS and some TABLE CALCULATION operators available in ILWIS GIS package.

After assembling the data file to run the model, preliminary runs were initiated with a storm event. There were 5 storm events available for simulation. A runoff event that occurred on 03 August 1991 (referred here after as event-1) was first simulated to assess the performance of the model. As reported earlier all parameters were assigned for various landuse and soil categories of the catchment except infiltration control zone depth (DF) and antecedent soil moisture content (ASM). The parameter DF and ASM were found to vary with individual storm event (Beasley & Huggins, 1991) and calibrated for individual storm events by trial and error.

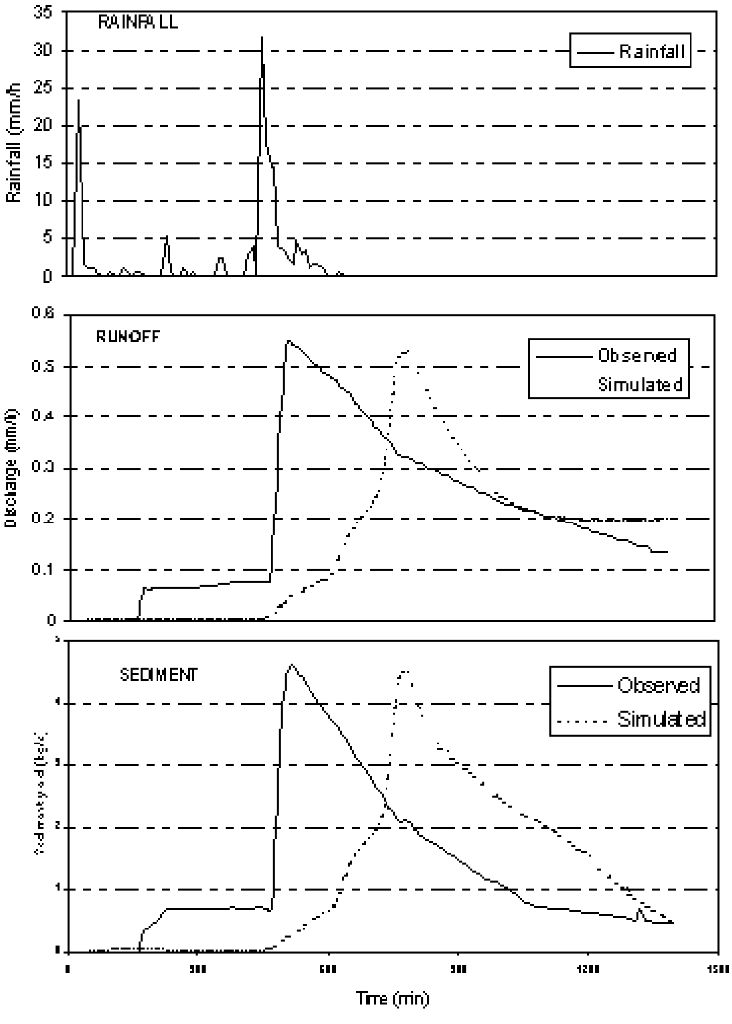

Figure 1. Plots of observed and simulated runoff and sediment graphs (event 03.08.1991).

The ANSWERS simulated event-1 is depicted in Fig. 1 for runoff and sediment part. As can be seen from Fig. 1, the model simulated runoff and sediment graphs shows lag of about 270 minutes. The model-simulated volume of runoff was 3.66 mm against observed volume of 4.81 mm. The model simulated a peak discharge of 0.5264 mm/hr against observed peak discharge of 0.5482 mm/hr. The total observed sediment yield resulted from this event is 112 MT and the model predicted total sediment yield at 105 MT. The spatial distribution of sediment production zones is shown in Fig. 2. As can be seen from Fig. 2, the areas of high sediment yield coincide with the places having high slope in the watershed. However, high slope areas covered with dense forest shows low to moderate soil erosion.

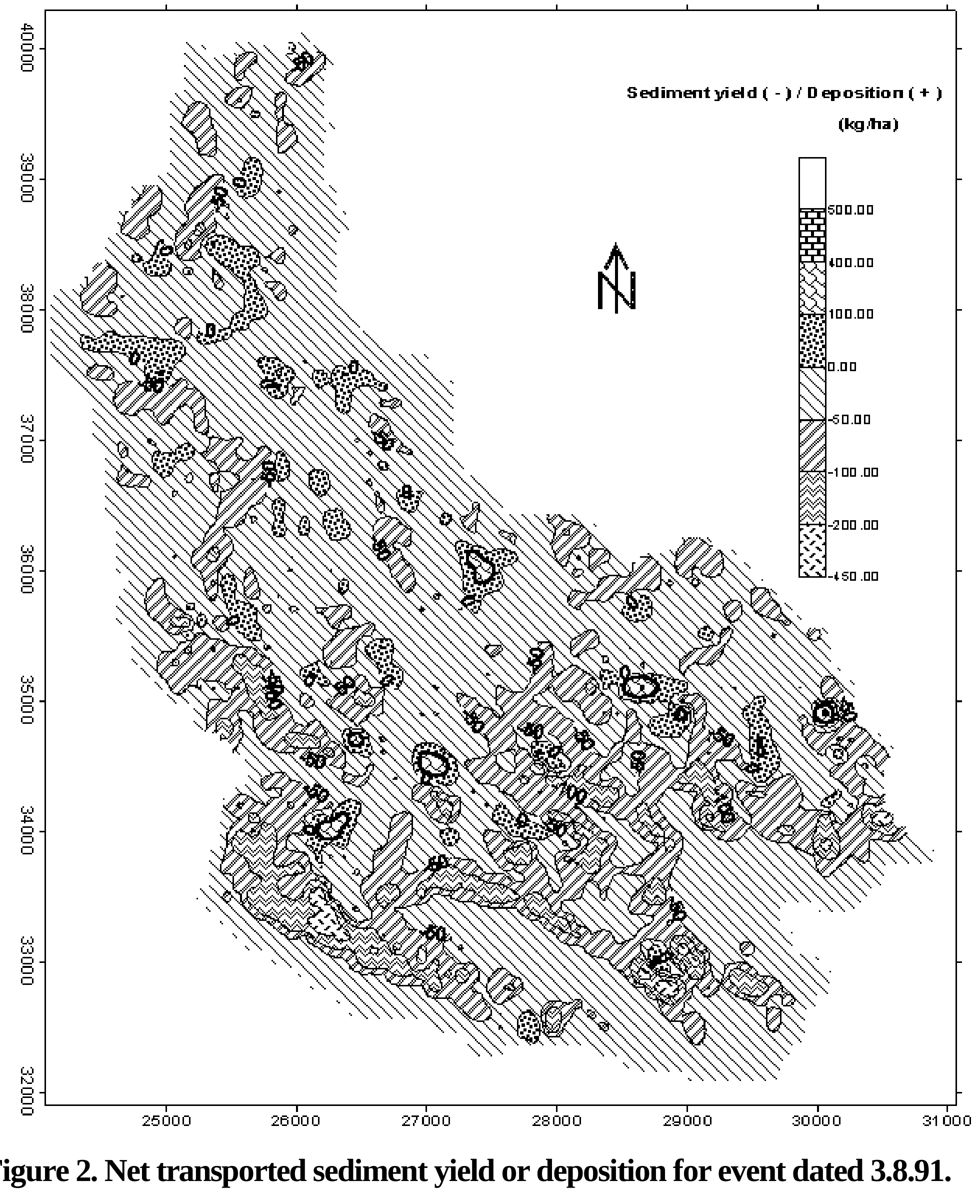

Figure 2. Net transported sediment yield or deposition for event dated 3.8.91.

The second event used for simulation was occurred on 5.08.1991. In this event, 32.4 mm of rainfall produced 5.06 mm of runoff. The model simulated runoff volume for this event is 3.50 mm. The observed peak discharge was 0.5117 mm against simulated peak of 0.6296 mm. The observed time to peak of 290 minutes was simulates as 510 minutes again a lag of 220 minutes. Fig. 3 shows the overall shape of observed and simulates runoff and sediment graphs. This event produced a sediment yield of 156 MT and the model simulated sediment yield is 147 MT. The spatial distribution of sediment production zones resulting from this event is shown in Fig. 4.

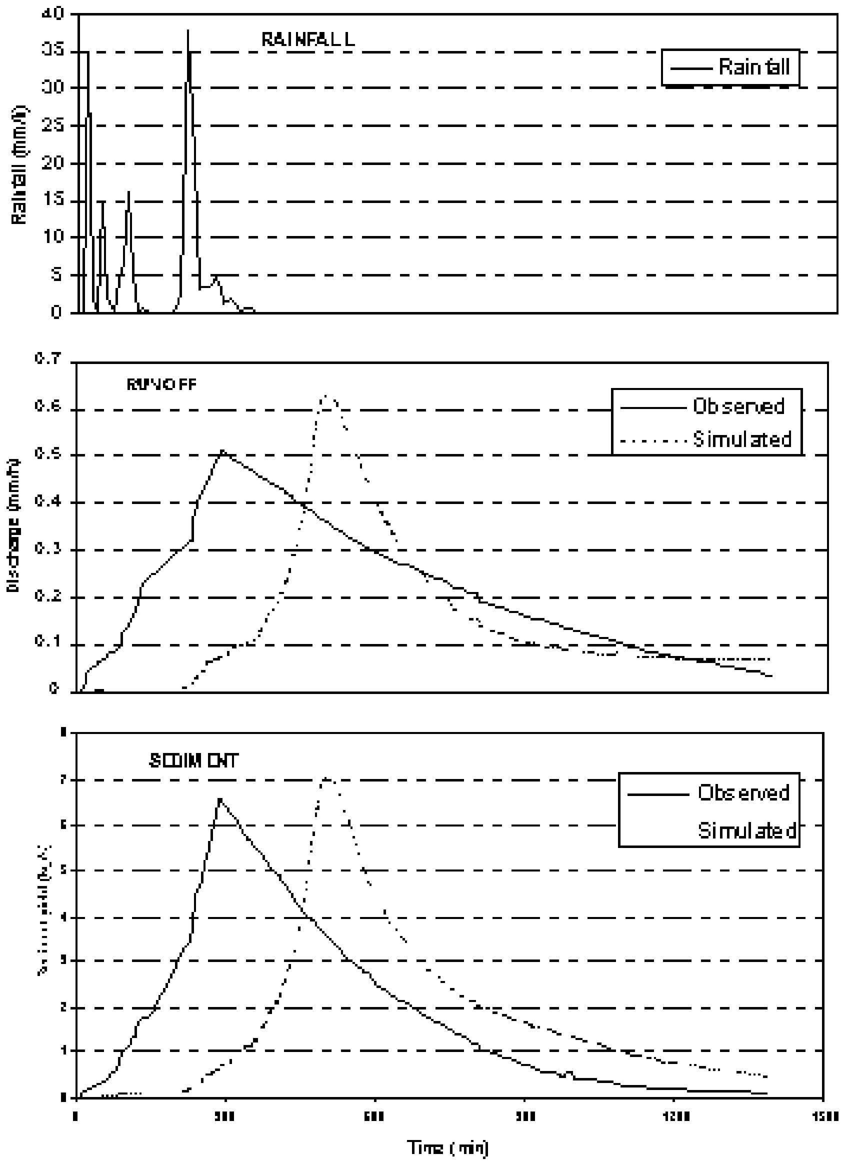

Figure 3. Plots of Observed and Simulated runoff and sediment graphs (event 05.08.1991).

A comparison of Fig. 2 and 4 reveals that most of the high sediment producing zones in both the events remains almost same in areal extent. However, the erosion zone of 0-50 kg/ha shows a high rate of variability. As can be seen from rainfall hyetographs of both the events, the event-2 has two intense rainfall peaks and several moderate rainfall pulses as compared to only one intense rainfall peak and less rainfall duration in event-1, a lot of area belonging to 0-50 kg/ha has shifted into 50-100 kg/ha category in event-2 due to this reason.

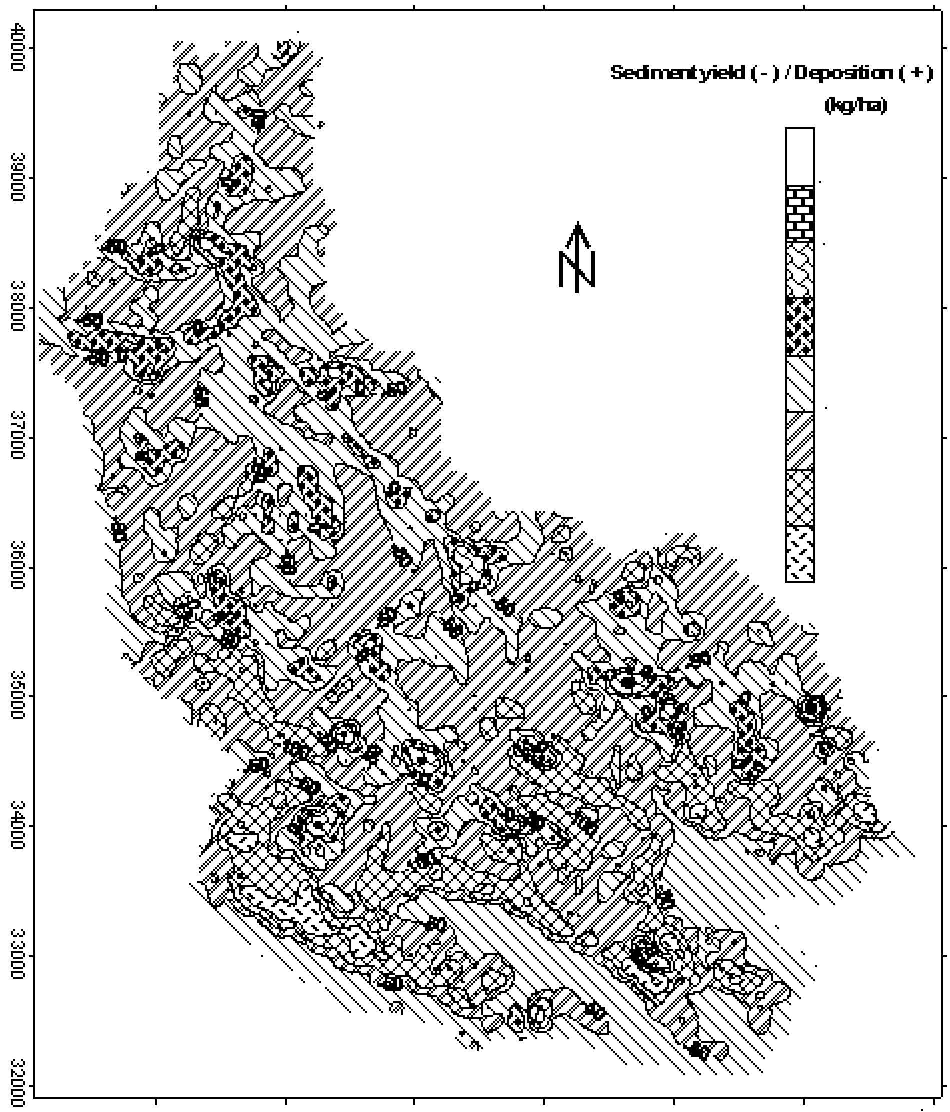

Figure 4. Net transported sediment yield or deposition for event dated 5.8.91.

Information about simulation results for other events is summarised in Table-1. As can be seen from Table-1, there is very poor simulation both for runoff and sediment yield for event-3. This could be attributed to uncertainties in observations (Kothyari and Jain, 1997). Table-1 also gave simulation statistics for event-4 and event-5. In these events also there was lag in observed and simulated time to peak as well as under prediction of the volume of runoff by the model. One of the reasons for such behaviour of the model could be the use of data of only one raingauge for entire watershed. The other reason could be the infiltration model used in the model. The infiltration model requires so many parameters and information for all these parameters is difficult to generate. Further investigations are needed to ascertain this by replacing existing infiltration model with simpler, less parameter intensive infiltration model. Also there was consistent lag in predicted time to peak in runoff and sediment graphs. The reasons for such behaviour need further investigations. Although there was under prediction in total sediment yield for almost all events, this yield prediction can be rated as satisfactory. One of the reasons for under prediction of sediment yield could be the under prediction of runoff by flow component of the model. However, overall simulation results of the model are within acceptable limits.

Table 1. Comparison of observed and simulated runoff and sediment yield.

Event no.	Date of event	Total rainfall (mm)	Vol. Of runoff (mm)		Peak discharge (mm/hr)		Time to peak (min)		Sediment yield (MT)	
			Obs.	Sim.	Obs.	Sim.	Obs.	Sim.	Obs.	Sim.
1	3.8.91	29.12	4.81	3.66	0.5482	0.5264	510	780	112	105
2	5.8.91	32.40	5.06	3.50	0.5117	0.6295	290	510	156	147
3	17.8.91	18.7	11.52	8.64	0.9743	0.2511	540	920	187	95
4	27.8.91	27.00	9.49	5.75	0.9066	0.9751	170	370	117	185
5	28.8.91	14.30	4.84	3.15	0.6262	0.4755	70	330	283	125

CONCLUSIONS

Modern techniques such as Remote Sensing and Geographical Information System (GIS) are very useful tools for generation of information for distributed hydrological models. The ANSWERS model due to its distributed nature and use of regular square grids for catchment discretization make it very convenient for GIS integration and display of simulation results in a GIS. The Landsat TM and IRS-1C LISS III digital data are very useful to evaluate landform features such as soils, drainage, landuse/land cover etc. The use of GIS is found to be very helpful for generation input information for distributed parameter model ANSWERS.

In this study, the GIS techniques have been utilised to spatial discretization of the Karso catchment in to grids. Model input parameters such as land forms, drainage, soil, landuse/land cover were derived from digital analysis of Landsat Thematic Mapper data with limited ground truth. Information about slope and aspect were generated in a GIS from Survey of India Toposheets.

Simulation results indicate that the model under predicts simulated volume of runoff and there is a lag in predicted time to peak as well for all events. One of the reasons for such behaviour could be use of single raingauge station for entire watershed. The other reason could be the parameter intensive infiltration model used in the model. However, further studies are needed to ascertain this fact by replacing existing infiltration model with simpler infiltration model. The model also under predicted sediment yield for all the events. Besides temporal variation of soil erosion, the model also predicted spatial distribution of soil erosion in the watershed. Based on spatial predictions of the model, the sources of soil erosion have been identified in the watershed.

Bibliography

Wicks, J.M. Bathurst, J.C. (1996) "SHESED: A physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system". Jr. of Hydrol., 175, 213-238.

Beasley, D.B., Huggins, L.F and Monk, E.J. (1980) ANSWERS: a model for watershed planning. *Trans. ASAE*, 23(4): 938-944.

Beasley, D.B. and Huggins, L.F. (1992) *ANSWERS users manual*. US Environmental Protection Agency, Region V, Chicago, IL, USA.

Earth Resources Data Analysis System ERDAS (1998) *ERDAS Imagine 8.3.1*. ERDAS, Inc., Atlanta, GA.

Environmental Systems Research Institute ESRI (1994) *Cell based modelling with GRID*. Environmental Systems Research Institute Inc., Redlands, CA.

Haan, C.T., Barfield, B.J. and Hayes, J.C. (1994) *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, New York.

International Institute for Aerospace Survey and Earth Sciences, ITC. (1998) *The Integrated Land and Water Information System (ILWIS)*. Int. Inst. For Aerospace Survey and Earth Sciences, Enschede, The Netherlands.

Jain, M.K. and Kothyari, U.C. (in press) Estimation of soil erosion and sediment yield using GIS. *Hydrological Sciences Journal*.

Kothyari, U.C., Jain, S.K. (1997) Sediment yield estimation using GIS. *Hydrol. Sci, J.*, 42(6), 833-843.

Nearing, M.A., Foster, G.R., Lane, L.J. and Finkner, S.C. (1989) "A process based soil erosion model for USDA water erosion prediction project technology". Trans. ASAE, 32 (5), 1587-1593.

Sabins, F.S. (1997) *Remote Sensing: principles and interpretations*. 3rd ed. W.H. Freeman and Company, New York.

SWCD (Soil and Water Conservation Division) (1991) *Evaluation of hydrological data* (Vol. I and II), 269. Ministry of Agriculture, Govt. of India, New Delhi, India.

Young, R.A., Onstad, C.A., Bosch, D.D. and Anderson, W.P. 1987. AGNPS: An agricultural non point source pollution model. Conservation Research Report 35, U.S. Deptt. of Agric. Res. Services, Washington, D.C.