CS/AR-22/1999-2000

ESTIMATION OF SOIL EROSION AND SEDIMENT YIELD IN KARSO CATCHMENT USING ANSWERS MODEL

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE - 247 667 (UTTARANCHAL)

1999-2000

PREFACE

Soil erosion is among the most critical environmental hazards of modern times. Vast areas of land now being cultivated, may be rendered unproductive or atleast economically unproductive if erosion continues unabated. Information on the sediment yield at the outlet of a river basin can provide a useful perspective on the rate of soil erosion and soil loss in the watershed upstream. Information on sediment yield from a catchment can be modelled using lumped and distributed models. With the availability of fast computers and Geographic Information Systems, distributed models are gaining popularity.

Geographic Information Systems 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. For distributed models, spatial distribution of the information such as land cover, soil, rainfall and other related parameters are needed. Satellite remote sensing can provide such inputs for hydrological simulation studies.

In the present study a spatially distributed model ANSWERS have been used to simulate runoff and soil erosion in Karso catchment in Bihar, India. The present study has been carried out by Shri M.K. Jain, Scientist C in the Watershed Development Division.

K.S. Ramasastri
Director

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

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).

In this study, a spatially distributed model, the Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) has been used to simulate surface runoff and erosion in Karso watershed 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. 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. 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.

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. 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.

1 INTRODUCTION

Soil erosion is a process of land denudation involving both detachment and transportation of the surface soil materials. It is a complex dynamic process by which productive surface soils are detached, transported and accumulated in a distant place, resulting in exposure of subsurface soil and siltation of reservoirs and natural streams elsewhere. Information on the sediment yield at the outlet of a river basin can provide a useful perspective on the rate of soil erosion and soil loss in the watershed upstream.

The main factors influencing soil erosion are climate, soil, vegetation and topography and man. Climate factors affecting erosion are precipitation, temperature, wind, humidity and solar radiation. Temperature and wind are the most evident through their effects on evaporation and transpiration. Wind also changes raindrop velocities and angle of impact while low temperatures, frost and snow accumulation can favour subsequent erosion during the soil thawing and snow melting. Humidity and solar radiation are involved less directly involved.

Physical properties of the soil affect its infiltration capacity and the extent to which the soil can be detached, dispersed and transported. The properties which most influence erosion include soil structure, texture, organic matter content, moisture content, density (compactness), shear strength as well as chemical and biological characteristics.

The vegetation effects are usually favourable in reducing erosion by interception of rainfall and absorbing energy of the raindrops and thus reducing the runoff. The vegetation reduces erosion by decreasing surface water velocity and physical restraint of soil movement. The vegetation increase porosity of the soil by action of roots and due to increased biological activity nourished by plant residues and through transpiration, which decreases soil moisture, resulting in increased storage capacity of the soil. Topographic features that influence erosion are degree of slope, length of slope and size and shape of the watershed. High water velocities occurring on steep slopes cause serious erosion by scour and sediment transportation.

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 SHETRANS (Abott et al. 1986, 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 input files for topographic variables and spatially distributed land cover and soil information for making input file for the model have been generated using ILWIS and ERDAS Imagine software. 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.

2 ANSWERS MODEL

The Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS) model was developed by Beasley and Huggins (1982) 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).

2.1 Model structure

ANSWERS is a deterministic model based upon the fundamental hypothesis that "At every point within a watershed, functional relation exists between water flow rates and those hydrological parameters which govern them, e.g., rainfall intensity, infiltration, topography, soil type etc. Furthermore, these flow rates can be utilised in conjunction with appropriate component relationships as the basis for modelling other transport related phenomenon such as soil erosion and chemical movement within that watershed".

In order to apply this approach on a practical scale, the point concept is relaxed to refer instead to watershed element. An element is defined to be an area within which all hydrologically significant parameters are uniform. A watershed to be modelled is assumed to be composed of elements as shown in Figure 1.

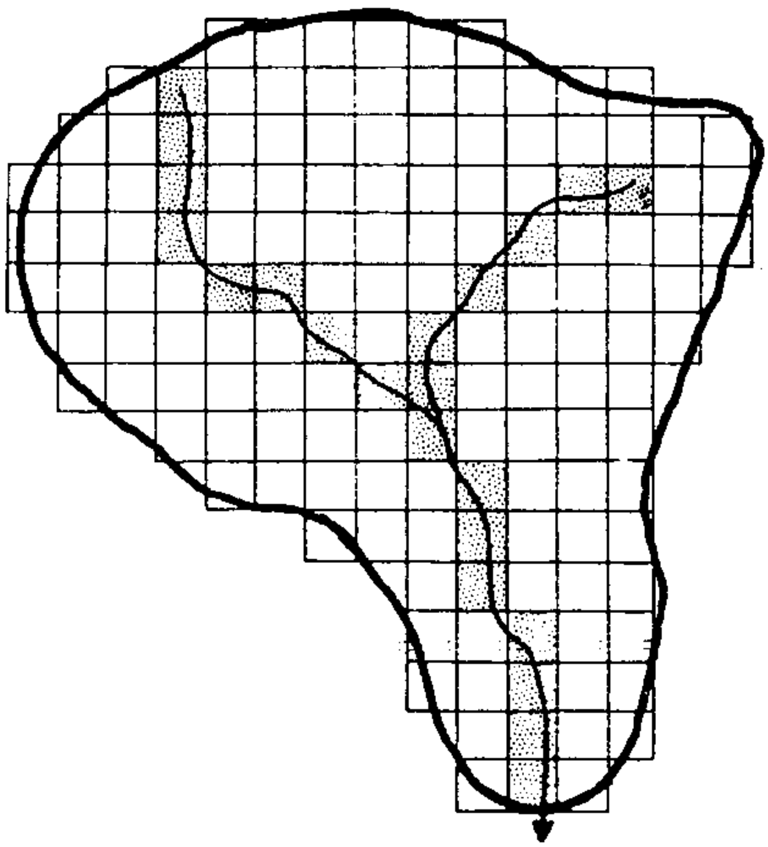

Fig. 1 Watershed divided into elements with channel elements shaded

Component relationships characterising water and pollutants need only simulate the behaviour of a small, uniform elemental area. Parameter values are allowed to vary in an unrestricted manner between elements; thus any degree of spatial variability within a watershed is easily represented. Individual elements collectively act as a composite system because a supplied physiographic data for each element delineates flow directions in a manner consistent with the topography of the watershed being modelled. Element interaction occurs because surface flow (overland and channel), flow in tile lines and ground water flow from each element becomes inflow to its adjacent elements. Pollutants are generated and transported by these flows and by raindrop impact.

2.2 Hydrologic considerations

Hydrological processes, for which component relationships have been incorporated within ANSWERS, are shown qualitatively in Figure 2. After rainfall begins, some is intercepted by the vegetal canopy until such time as the interception storage potential is met. When the rainfall rate exceeds the interception rate, infiltration into the soil begins. Since the infiltration rate decreases in an exponential manner as the soil water storage increases, a point may be reached when the rainfall rate exceeds the combined infiltration and interception rates. When this occurs, water begins to accumulate on the surface in micro-depressions.

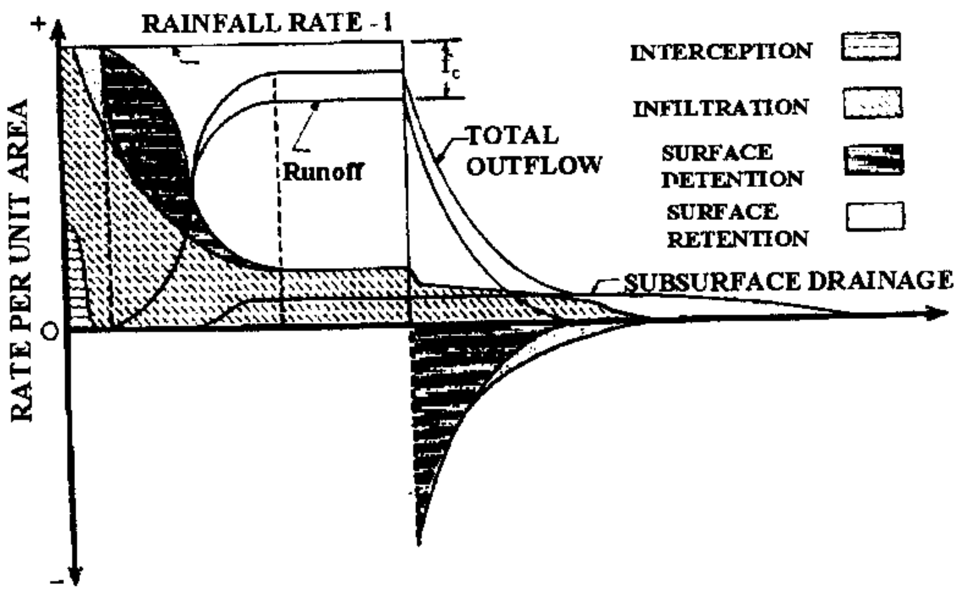

Fig. 2 Water movement relationship for small watershed element.

Once surface retention exceeds the capacity of the micro-depressions, runoff begins. The accumulated water, when in excess of the surface retention capacity, produces surface runoff and is termed as surface detention. Subsurface drainage begins when the pressure potential of the ground water surrounding a tile drain exceeds the atmospheric potential. A steady state infiltration rate may be reached if the duration and the intensity of rainfall event are sufficiently large.

When rainfall ceases, the surface detention storage begins to dissipate until surface runoff ceases altogether. However, infiltration continues until depressional water is no longer available. Subsurface drainage continues as long as there is excess soil water surrounding the drains. The long recession shape on the outflow hydrograph, typical of tile drained areas, is then produced. Slowly falling recession limbs are also produced by interflow, the emergence of the ground water into surface drainage network.

Soil detachment, transport, and deposition are very closely related to concurrent hydrological processes in a watershed. Either raindrop impact or overland flow can accomplishes both detachment and transport. Detachment by rainfall occurs throughout a storm even though overland flow may not occur. Thus, most of the soil particles detached prior to flow initiation are deposited and to some extent, reattached. Detachment of soil particles by overland flow occurs when the shear stress at the surface is sufficient to overcome the gravitational and cohesive forces of the particles. Whether or not a detached soil particle moves, however, depends upon the sediment load in the flow and its capacity for sediment transport.

All materials leaving an element are assumed to be transported with one of the various flow components. Overland flow either moves into an element's shadow channel element, if a channel is specified for that element, or into its adjacent element. Tile and ground water flows are assumed to outlet directly into the specific channel network. It is this network of interacting flows, which causes the independent watershed elements to act together as composite system. Beasley and Huggins (1991) have described the details about specific mathematical relationships used in ANSWERS model.

2.3 Component Relationships

This section outlines the specific mathematical relationships currently used to qualify the various model component processes. It is intended primarily for the person who is doing research in model development or who is interested in modifying some features of the current release of the model.

The specific component relationships selected for the current version of ANSWERS are separately discussed below. All except the time integration of the continuity equation are incorporated on a modular basis. Modification or replacement of component relations such as infiltration or sediment production does not affect the algorithms for other components. In other words, the component relationships are sufficiently independent from each other that user-supplied subroutines may be substituted for those supplied with the "official" release of the model. This framework also permits users to append additional component relationships to simulate other processes important to specific applications.

2.3.1 Flow Characterization

Mathematically, each element's hydraulic response is computed, as a function of time, by an explicit, backward difference solution of the continuity equation:

$$I - Q = \frac{dS}{dt} \quad (1)$$

where, I = inflow rate to an element from rainfall and adjacent element; Q = outflow rate; S = volume of water stored in an element and t = time.

This equation may be solved when it is combined with a stage-discharge relationship. Manning,s equation, with appropriately different coefficients, is used as the stage-discharge equation for both overland and channel flow routing.

Within its topographic boundary, a catchment is divided into an irregular matrix of square elements, as shown in Figure 1. Every element acts as an overland flow plane having a user specified slope and direction of steepest descent. Channel flow is analysed by a separate pattern of channel elements (referred to hereafter as channel segments) which underlie i.e., are in the shadow of the grid of overland flow elements.

Elements designated to have channel flow may be viewed as dual elements. These elements act as ordinary overland flow elements, with the exception that all overland flow out of that element goes into its "shadow" channel segment. Flow from a channel segment goes into the next downstream channel segment. This downstream channel segment will also receive flow from any other channel segments which are directed toward it and from its own overland flow element.

Overland and tile outflow from an element flows into neighbouring elements according to the direction of the element's slope. The slope direction is designated on input as the angle, in degrees, counter-clockwise from the positive horizontal (row) axis. For the example shown in Figure 3 below, slope direction is in the fourth quadrant. The slope direction angle equals 270 degrees plus angle ANG.

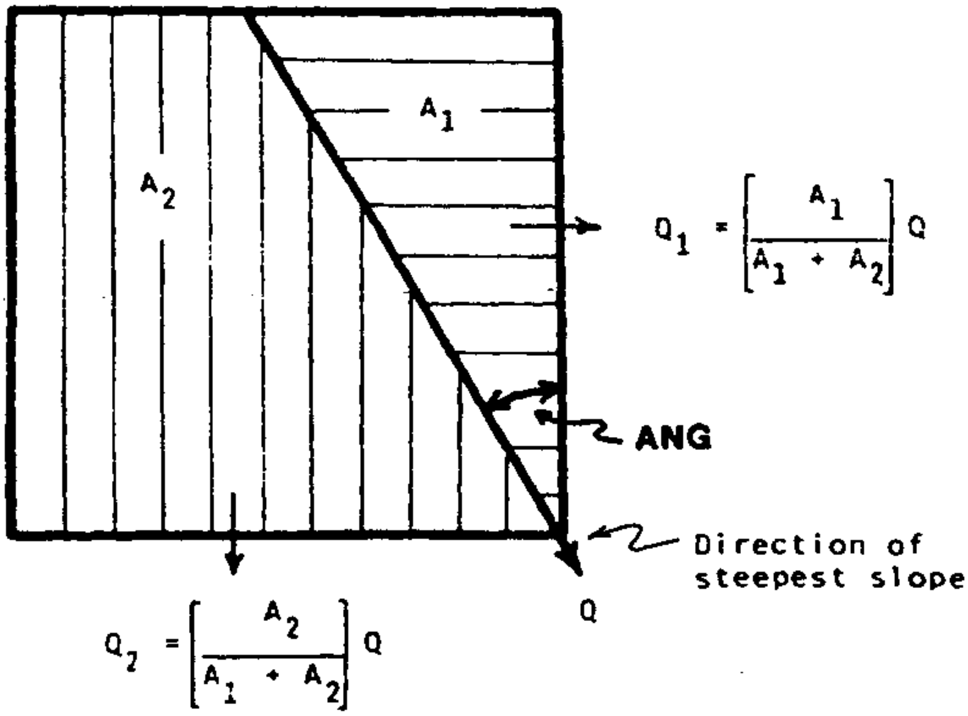

Fig. 3 Partitioning of overland flow.

The fraction of outflow going into the adjacent row element, RFL is:

$$RFL = \frac{\tan(ANG)}{2} \qquad \text{if } ANG \leq 45^\circ \tag{2a}$$

$$RFL = 1 - \frac{\tan(90 - ANG)}{2} \qquad \text{if } 45^\circ < ANG < 90^\circ \tag{2b}$$

With the remaining outflow going into the adjacent column element. Since everything, including surface slope, within an element is assumed to be constant, this method of partitioning overland flow seems intuitively obvious.

The most appropriate manner to partition tile flow is not as obvious as is overland flow. In general, records are seldom available which delineate the layout of tile systems. However, limitations on feasible installation depths mean that tile slopes must, with only temporary deviations, follow the general topography. Therefore, the use of an element's slope properties was chosen as a close approximation which has the secondary benefit of eliminating the need for additional input information.

Baseflow, the emergence of groundwater into the channel system, is simulated only crudely in the current release of ANSWERS. All infiltrated water which moves past the zone on tile drainage is assumed to enter a single groundwater storage reservoir. Water is then released evenly into all channel segments at a rate proportional to the volume of accumulated storage.

The flow relationship utilised in conjunction with the continuity equation to perform the overland flow routing is Manning's equation. The hydraulic radius is assumed equal to the average detention depth in an element. The flow width is assumed to be the maximum width for that element, i.e., the length measured in a direction perpendicular to the overland flow direction.

Surface detention is the water volume which must build up to sustain overland flow. Detention depth is calculated as the total volume of surface water in an element, minus the retention volume (which can only infiltrate), divided by the area of the element. This implies that the entire specified retention volume of an element be filled before any water becomes available for surface detention and runoff.

Surface detention is a component that can have a pronounced effect on surface runoff and drainage characteristics of a watershed. Rough ground can store large amounts of water. Huggins and Monke (1966), using several field surfaces, developed a relationship describing the surface storage potential of a surface as a function of the water depth in the zone of micro-relief. The form of that equation used by ANSWERS is:

$$DEP = HU * ROUGH * \left(\frac{H}{HU}\right)^{1/ROUGH} \quad (3)$$

Where, DEP = volume of stored water, in depth units; H = height above datum; HU = height of maximum micro-relief; and ROUGH = a surface characteristics parameter.

The specified surface roughness determines the volume of surface storage and also influences infiltration rates during the recession limb of a hydrograph, as explained later.

Although the channel flow system is unrestricted in direction and branching, it is necessary that it be continuous and that each element contain only one channel segment. To achieve greater definition it is necessary to assume a smaller element size for all elements, with a consequent increase in core storage and computer execution time.

As all overland flow from a dual element is constrained to enter its shadow channel segment, the surface slope direction of a dual element is irrelevant for partitioning overland flow to adjacent elements. Therefore, instead of specifying the direction of surface slope for a dual element, this parameter position in the data file is used to specify the flow direction for the shadow channel segment. This slope direction is of vital importance in establishing channel continuity. All outflow from a channel segment must enter a single adjacent channel segment located in one of the eight directions of the cardinal axes or the diagonals. Thus, only 45-degree increments in slope direction should be specified for dual elements.

It is permissible to specify the slope, width and Manning's roughness coefficient for each channel segment independent of the corresponding values for its overland flow element. Typically, rather than having a unique set of values for each channel segment, they are grouped into reaches with similar coefficients. Manning's equation is again used as the flow relationship necessary, in conjunction with the continuity equation, to perform the routing calculations.

Much programming effort has been expended to develop computational algorithms which solve the flow routing equations very efficiently. For example, a piece-wise linear segmented curve is used to approximate Manning's equation and thereby eliminate the iteration process that would otherwise be necessary when solving the continuity equation.

2.3.2 Rainfall Rate

The net rainfall rate, that which reaches the ground surface, is dependent on the user specified pluviographs(s) and on the rate of interception by vegetation. The net rainfall rate for each rain gauge and crop is calculated by FUNCTION RAIN. Since a rain gauge identifier is specified for each watershed element, it is theoretically possible to have each element subjected to a different storm pattern. As a practical matter, the standard release of the model is dimensioned to permit only 4 gauges.

Interception is that water extracted from the incoming rainfall upon contact with and retention by the vegetal canopy. Water retained by the vegetation, i.e., interception storage, is held primarily by surface tension forces. This initial interception volume is quickly satisfied. Particularly in more intense storms. Since a dense vegetal cover can expose an immense 3surface area to rainfall, the amount of moisture evaporating during a long duration storm can be appreciable. Intercepted water which evaporates will be replenished during the storm. This creates low level of interception demand throughout a storm. However, for the high intensities of primary interest from the stand-point of nonpoint source pollution from cropland, interception is a relatively minor hydrologic component. In order to reduce simulation costs, interception was assumed to be uniform in rate and total volume over each type of vegetation. Evaporation losses during a storm were assumed to be negligible.

Horton (1919) did a great of work in the area of estimating the amount and mechanisms controlling interception. He studied the water intercepted by several species of trees as well as some economically important crops. Values from 0.5 millimetre to 1.8 millimetres of interception storage volume were found to exist for trees and nearly as much for well developed crops. Values for potential interception storage, PIT, are based primarily equal on his recommended relationship.

The maximum potential interception (PIT), supplied as an input value, represents the available leaf moisture storage in depth units (volume per unit land area). In each time increment in which interception storage remains unsatisfied, rainfall supplied to interception storage is calculated as incremental interception (RIT), i.e., the product of the rainfall amount (RATE) and the portion of the element covered by foliage (PER). The value of potential interception (PIT) and the net rainfall (RAIN) are correspondingly decreased until all interception storage is satisfied. At this stage, PIT is set equal to zero and the net rainfall rate is subsequently equal to the gauge rainfall rate for the remainder of the simulation.

2.3.3 Infiltration

Infiltration is one of the components to which ANSWERS is most sensitive, especially during low to medium runoff storms. Although many years of research have been conducted on infiltration phenomena, there is still no universally accepted method for describing infiltration on a watershed scale. The widely used, time-dependent equations of Horton (1939) and Philip (1957) presume a continuous water supply rate adequate to meet all infiltration demands. This approach does not readily allow for the observed recovery in soil infiltration capacity during periods of light or zero rainfall. To avoid this difficulty, the infiltration relation chosen for ANSWERS was the one developed by Holtan (1961) and Overton (1965). In a dimensionally homogeneous form it can be expressed as:

$$FMAX = FC + A*\left(\frac{PIV}{TP}\right)^{P} \qquad (4)$$

Where, FMAX = infiltration capacity with surface inundation; FC = final or steady state infiltration capacity; A = maximum infiltration capacity in excess of FC; TP = total volume of pore space within the control depth; PIV = volume of water that can be stored within the control volume prior to its becoming saturated and P = dimensionless coefficient relating the rate of decrease in infiltration rate with increasing soil moisture content.

This form uses the soil water content, rather than time, as the independent variable.

During periods of zero rainfall rate, any infiltration which occurs must be supplied by water stored as either retention or detention. Since the surface of an element is seldom entirely inundated, the computed infiltration capacity is reduced in direct proportion to the percent of the soil surface not submerged. Thus, the specified surface micro-relief parameter also can reduce the infiltration capacity during these recession periods.

According to Holtan's conceptualisation of the infiltration process, a "control zone" depth of soil determines the infiltration rate at the surface. He defined the depth of this control zone as the shallower of the depth to an impeding soil layer or that required for the hydraulic gradient to reach unity. Extending this same concept somewhat, the ANSWERS model maintains an accounting of water that leaves this control zone.

Holtan's equation requires six infiltration parameters to be specified for a given soil type: total porosity, field capacity, depth of the control zone, steady-state infiltration rate (FC), and the two unsteady-state coefficients (A and P).

The rate of water movement from the control zone is a function of the moisture content of that zone. The two conditions which can exist are handled according the following rules:

1. when the moisture content of the control zone is less than field capacity, no water moves from this zone.

2. When the control zone moisture exceeds field capacity, the water moves from this zone according to the equation:

$$DR = FC * \left(1 - \frac{PIV}{GWC}\right)^3 \qquad (5)$$

Where; DR = drainage rate of water from control zone; GWC = gravitational water capacity of the control zone (total porosity minus field capacity).

This relationship satisfies the continuity requirement that at saturation, when PIV=0, the drainage rate from the control zone equals the steady state infiltration rate, FC. In addition, it exhibits intuitively desirable properties of rapidly decreasing moisture movement as the soil dries from saturation and of asymptotically approaching a zero drainage rate.

Water leaving the control zone contributes to tile drainage, if the element is tiled, or to baseflow. In both cases the water is assumed to re-emerge into the channel segments. Water movers from the infiltration control zone into the "pools" available for tile and/or base flow at a rate equal to DRA.

Individual elements may selectively be designated as being tile drained. In addition to water coming from the control zone, tile inflow may be occurring from adjacent tiled elements. The sum of these two rates constitutes the rate of subsurface inflow into an element. Subsurface water moves out the element's tile at this inflow rate up to a maximum outflow rate equal to the tile drainage coefficient. Whenever the rate of subsurface inflow to an element exceeds its drainage coefficient, that excess water is diverted to baseflow storage. Elements which are not tiled have a drainage coefficient of zero.

Subsurface water entering an element at rates in excess of its drainage coefficient is stored in a single "pool." To simulate baseflow it is released directly into channel segments at a rate proportional to the volume of water in storage. Water is released at an equal rate to each channel segment. For small catchments having no defined channels, only overland flow will appear at the outlet.

2.3.4 Sediment Detachment and Movement

Soil erosion, as it relates to nonpoint source pollution, can be viewed as two separate processes, detachment of particles from the soil mass and transport of these particles into the streams and lakes. Detachment of either primary soil particles or aggregates can result from either rainfall or flowing water. These same factors can cause detached particles to be transported to the water supply network. Thus, there are four processes for which quantifying relationships must be developed, as shown in Figure 4. Two different transport models are available for use in ANSWERS. The simpler, less descriptive transport relationship is presented in this chapter.

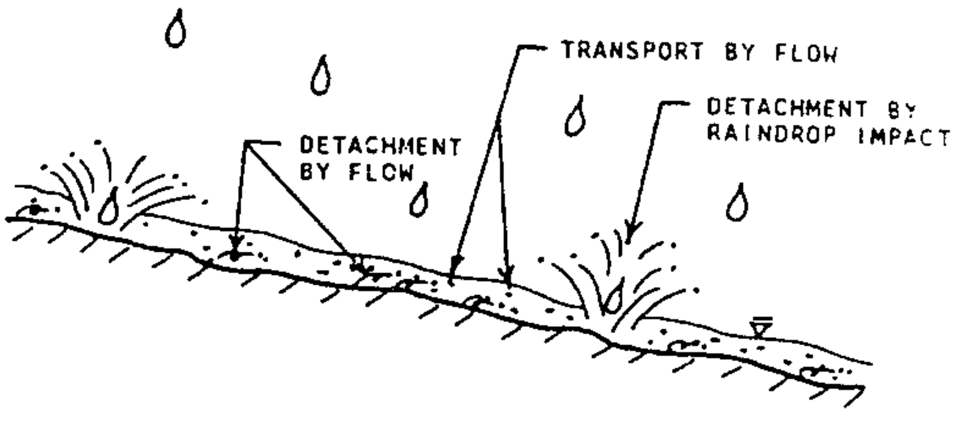

Fig. 4 Sediment detachment and transport

The detachment of soil particles by water is accomplished by two processes. The first involves dislodging soil as a result of the kinetic energy of rainfall. Rainfall is the major detachment process on relatively flat watersheds. The second process involves the separation of particles from the soil mass by shear and lift forces generated by overland flow.

Detachment of soil particles by raindrop impact is calculated using the relationship described by Meyer and Wischmeier (1969):

$$DETR = 0.108 * CDR * SKDR * A_i * R^2 \qquad (6)$$

Where; DETR = rainfall detachment rate, kg/min; CDR = cropping and management factor, C from USLE; SKDR = soil erosivity factor, K from USLE; A_i = area increment, m^2; and R = rainfall intensity during a time interval, mm/min.

The detachment of soil particles by overland flow was described by Meyer and Wischmeier (1969) and modified by Foster (1976) as follows:

$$DETF = 0.90 * CDR * SKDR * A_i * SL * Q \qquad (7)$$

Where; DETF = overland flow detachment rate, kg/min; SL = slope steepness; and Q = flow rate per unit width, m^2/min.

Once a soil particle has been detached, sufficient energy must be available to transport it or the particle will be deposited. The transport of sediment by overland flow is self-regulating, i.e., soil particle detachment by overland flow does not occur unless there is excess energy available in addition to the amount required to transport suspended sediments. However, detachment by rainfall impact often occurs when there is little or no flow available for transport.

After a literature study which included Yalin (1963). Mayer and Wischmeier (1969), Foster and Meyer (1972), and Curtis (1976), as well as an inspection of soils data, a relationship for particle transport in overland flow was chosen as shown in Figure 5. The two portions of the curve generally represent the laminar and turbulent flow regions. Obviously, the transport capacity does not continue to increase as the square of flow forever. However, within the range of flows generally encountered in ANSWERS simulations, this generalized relationship (based in part on Yalin's work and in part on observed data) has produced results. Equations and their region of application are:

$$TF = 161 * SL * Q^{0.5} \qquad \text{if } Q \le 0.046\ m^2/\text{min}$$

$$TF = 16{,}320 * SL * Q^{2} \qquad \text{if } Q > 0.046\ m^2/\text{min}$$

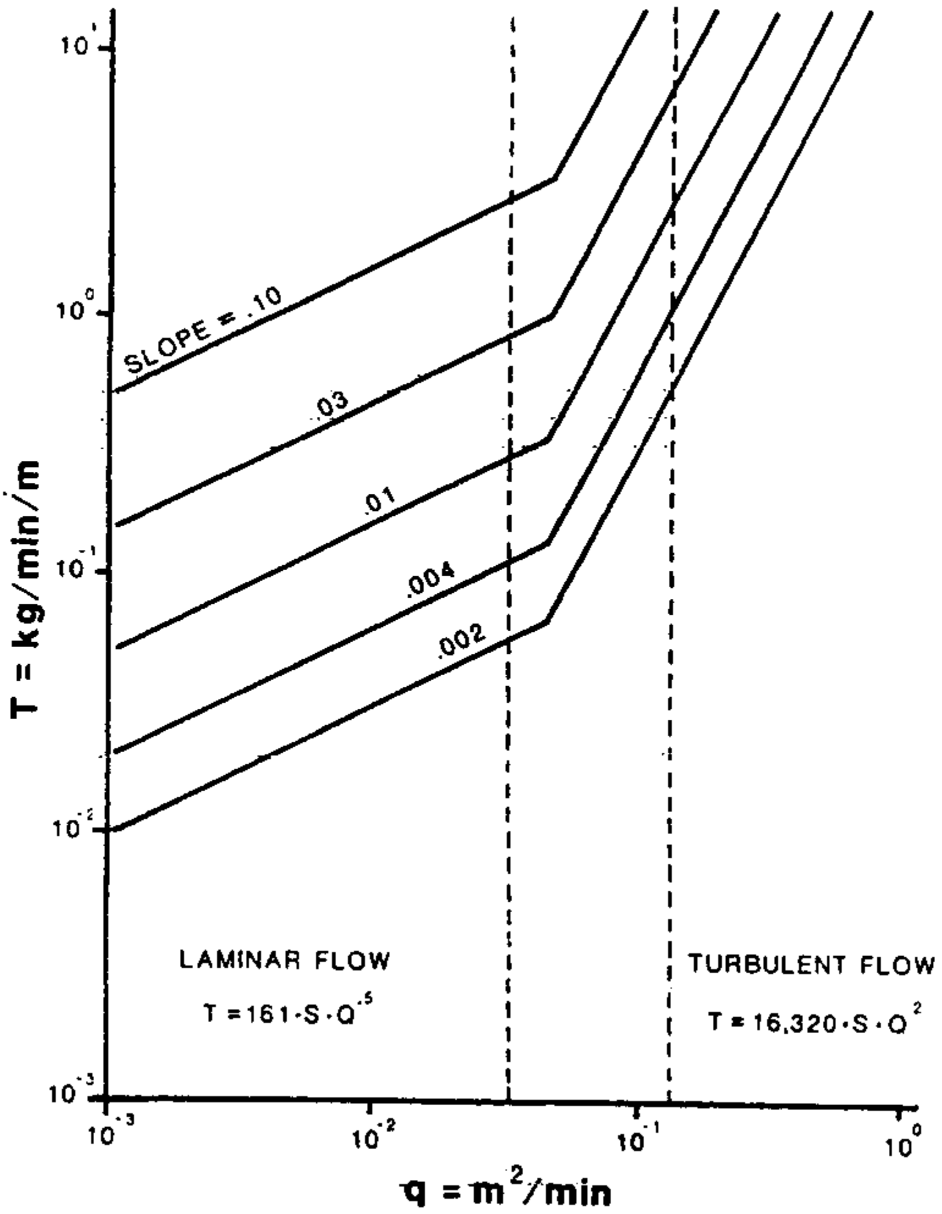

Fig. 5 Transport relation used in ANSWERS model.

The erosion portion of the ANSWERA model was simplified further by the following assumptions:

1. Subsurface or tile drainage produces no sediment. (Data indicate around two percent of the average annual loading originated from subsurface systems on the Black Creek Watershed).

2. Sediment detached at one point and deposited at another is reattached to the soil surface.

3. Re-detachment of sediment requires the same amount of energy as required for the original detachment.

Although these assumptions were made primarily to reduce the computational cost of model were also required because little or no data were available in the literature to quantify the particular process. Also, after consideration of the relative magnitude of the four detachment/transport processes, the transport of soil particles by rainfall was assumed negligible.

Combining the above equations and assumptions gives a composite soil movement model wherein soil particles are dislodged from the soil mass by both rainfall and flowing water. Detached solids then become available for transport by overland flow. Within an element the material available for transport is the combination of that detached within the element and that which enters with inflow from adjacent elements, Once the available detached sediment within an element is known, the transport capacity is computed. If it is insufficient to carry the available material, the excess is deposited in the element. The overall accounting relationship for this process is the differential form of the continuity equation a applied above to water flow. Sediment carried out of an element is apportioned between adjacent elements in direct relation to overland flow.

3 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.

3.1 Location

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 Jharkhand state. The catchment is located near the Tilaiya reservoir, which is built on the river Barakar.

3.2 Climate

The catchment lies in sub-humid tropical climatic zone. The mean annual temperature of the catchment is about 29°C. The maximum temperature of the region varies from 38.9°C to 44.4°C and the minimum temperature varies from 10.6°C to 20.6°C. Evaporation is ranging from 13.9 mm to 23.6 mm with the average of 20.9 mm/day during May-June (SCD, 1983). 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.

3.3 Topography

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%. Topographical information of the watershed has been derived form Survey of India Toposheets at 1:25,000 scale. Figure 6 shows the Digital Elevation Model (DEM) of the watershed. A 3-dimensional plot of the generated DEM is shown in Figure 7. As can be seen from Figures 6 and 7, the area comprises moderate sloping lands in Northern part of the watershed and very steep slopes in southern part of the watershed.

3.4 Soil Characteristics

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 collected from soils Division of DVC Hazaribagh (Table 1) illustrates the characteristics of the soils of the catchments.

Table 1 Soil characteristics at Different Locations in the Karso Catchment

Location	Coarse Sand (%)	Fine Sand (%)	Silt (%)	Clay (%)	App. Density	% water Holding Capacity	Pore Space	Specific Gravity
Higher Elevation	55.30	29.20	7.03	7.73	1.37	27.00	36.57	2.08
Middle Elevation	35.40	26.68	14.75	21.83	1.38	29.67	40.22	2.06
Lower Elevation	14.55	33.28	21.20	29.65	1.40	33.52	43.96	2.09

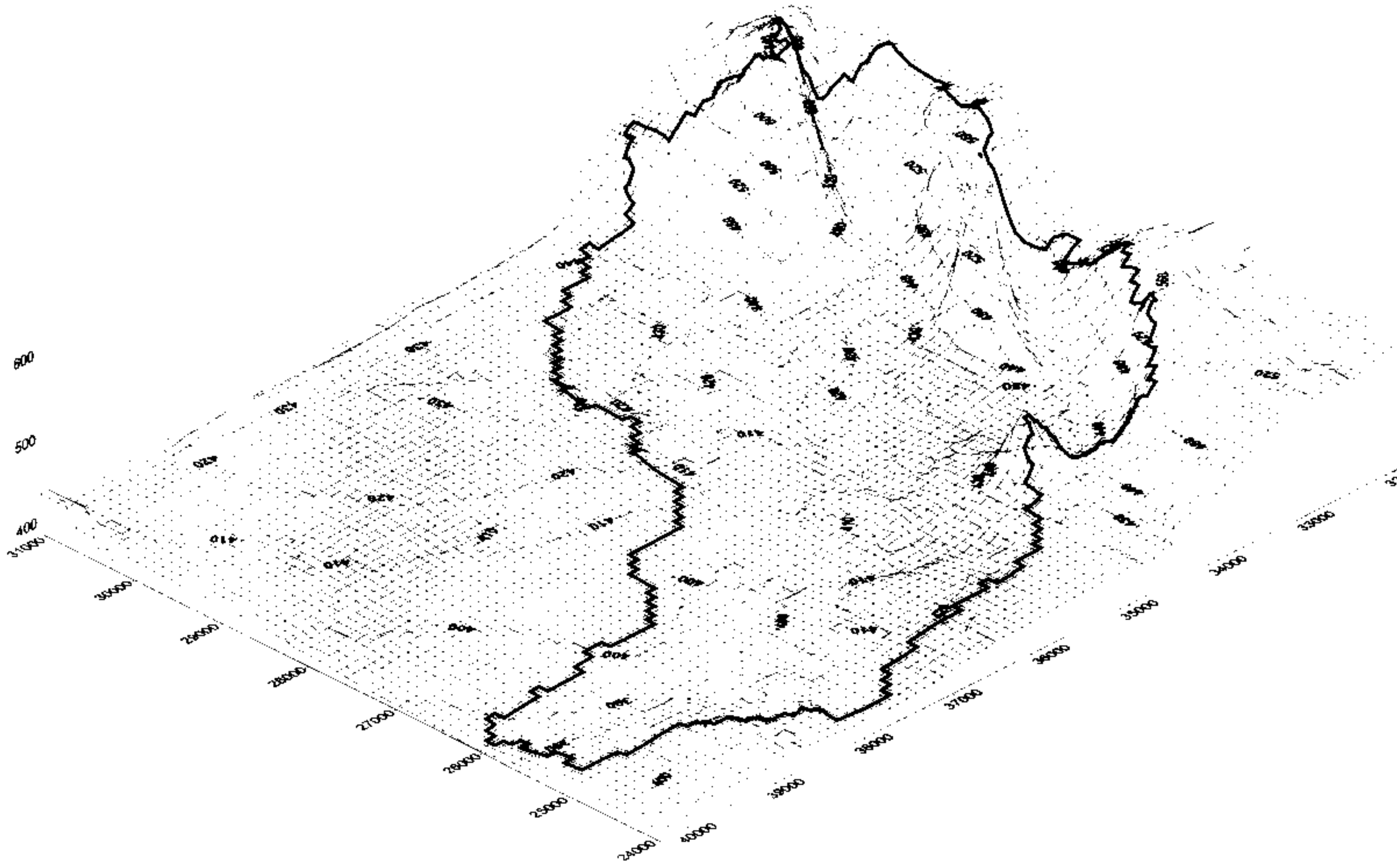

Fig. 7 3-D plot of DEM of Karso watershed

3.5 Land Use Pattern

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.

3.6 Instrumentation, Measurement and Collection of Data.

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) and are summarised in Table 2.

Table 2. Hydro-Climatic Data for Karso Catchment.

Catchment Location	Area (km^2)	Av. Land slope (percent)	Av. Annual precipitation (mm)	Land cover (percent)	Dates for the selected storm events
Karso Barakar catchment, Bihar (India)	27.93	7.3	1243	AG = 60 FO = 35 OS = 5	August 3, 1991 July 28, 1991 July 27, 1991 August 4, 1991 August 17, 1991

Note: AG = Agriculture; FO = Forest; OS = Open scrub

4 ANALYSIS AND DISCUSSION OF RESULTS

4.1 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 2710 grids (area 27.10 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). Figure 8 shows the 100-m grid overlay for the watershed used for simulation. 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.

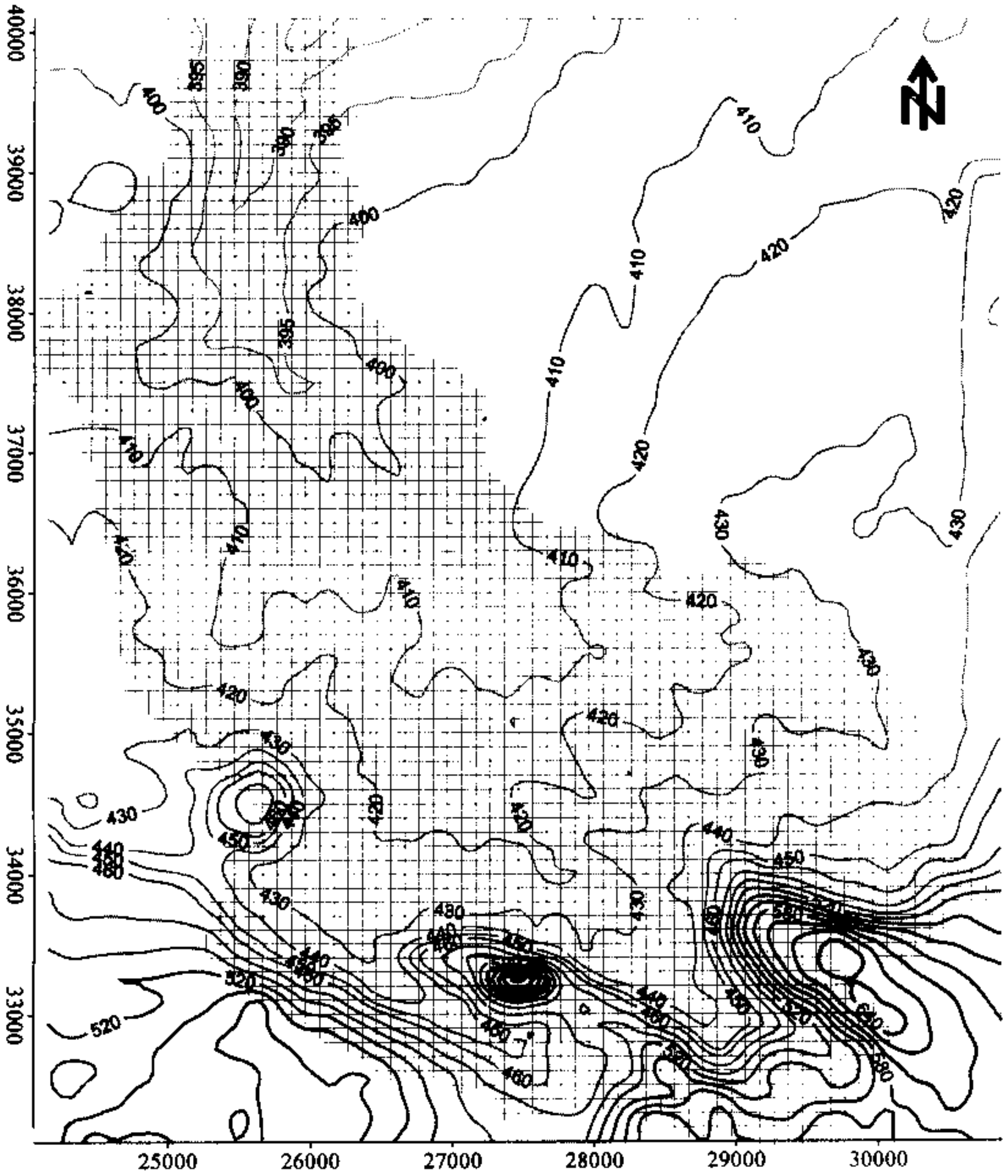

Fig. 8 Grid overlay at 100-m interval over contour map for Karso watershed

The generated channel network is depicted in Figure 9 for illustration. The generated channel network matches well with satellite observable drainage network in this watershed. As can be seen from Figure 9, only prominent drainage channels present in the watershed were considered. Channel properties were taken from SWC&D (1991).

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).

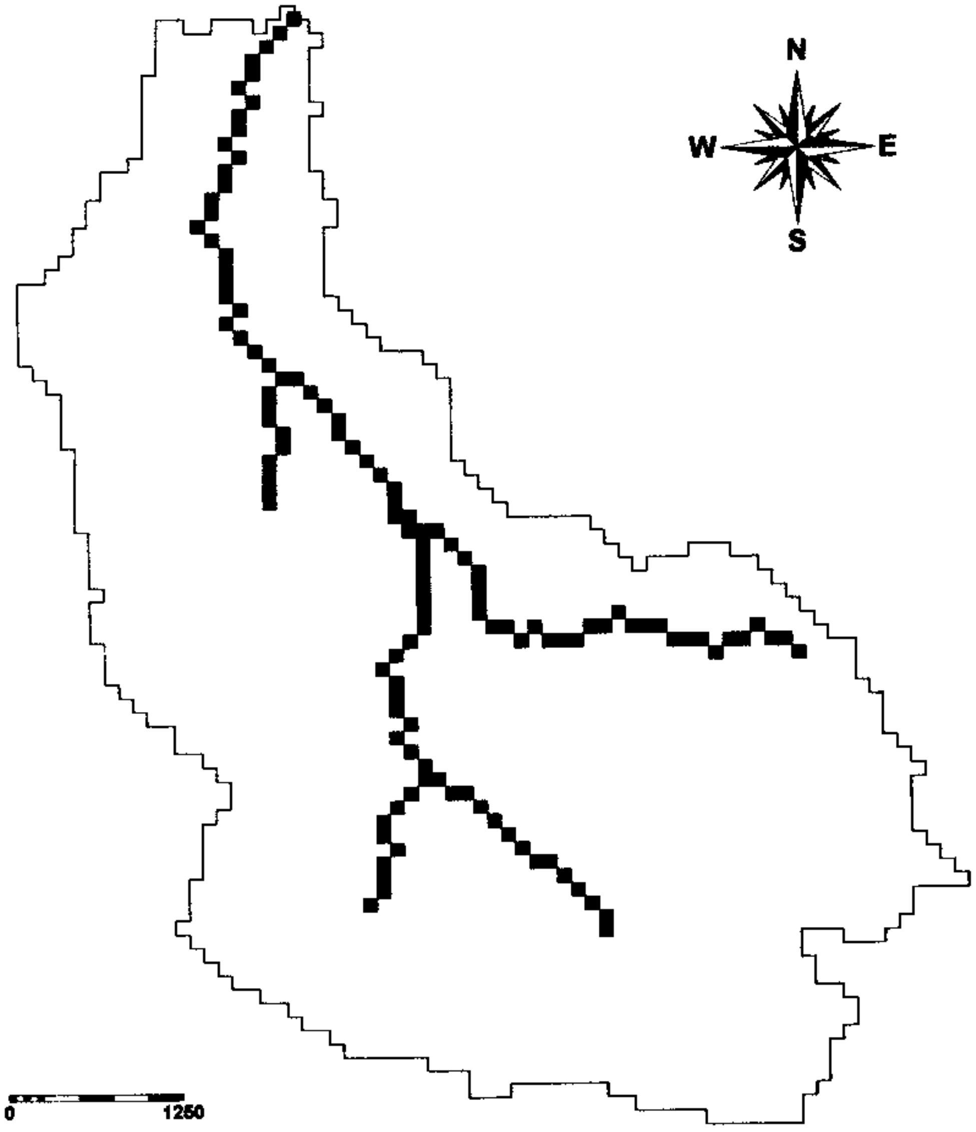

Fig. 9 Channel network used for ANSWERS model simulation

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).

4.2 Model application and discussion of results

The data files for running the ANSEWERS model is then assembled from information derived so far. 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.

The ANSWERS simulated event-1 is depicted in Figure 10 for runoff and sediment part. As can be seen from Figure 10, 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.

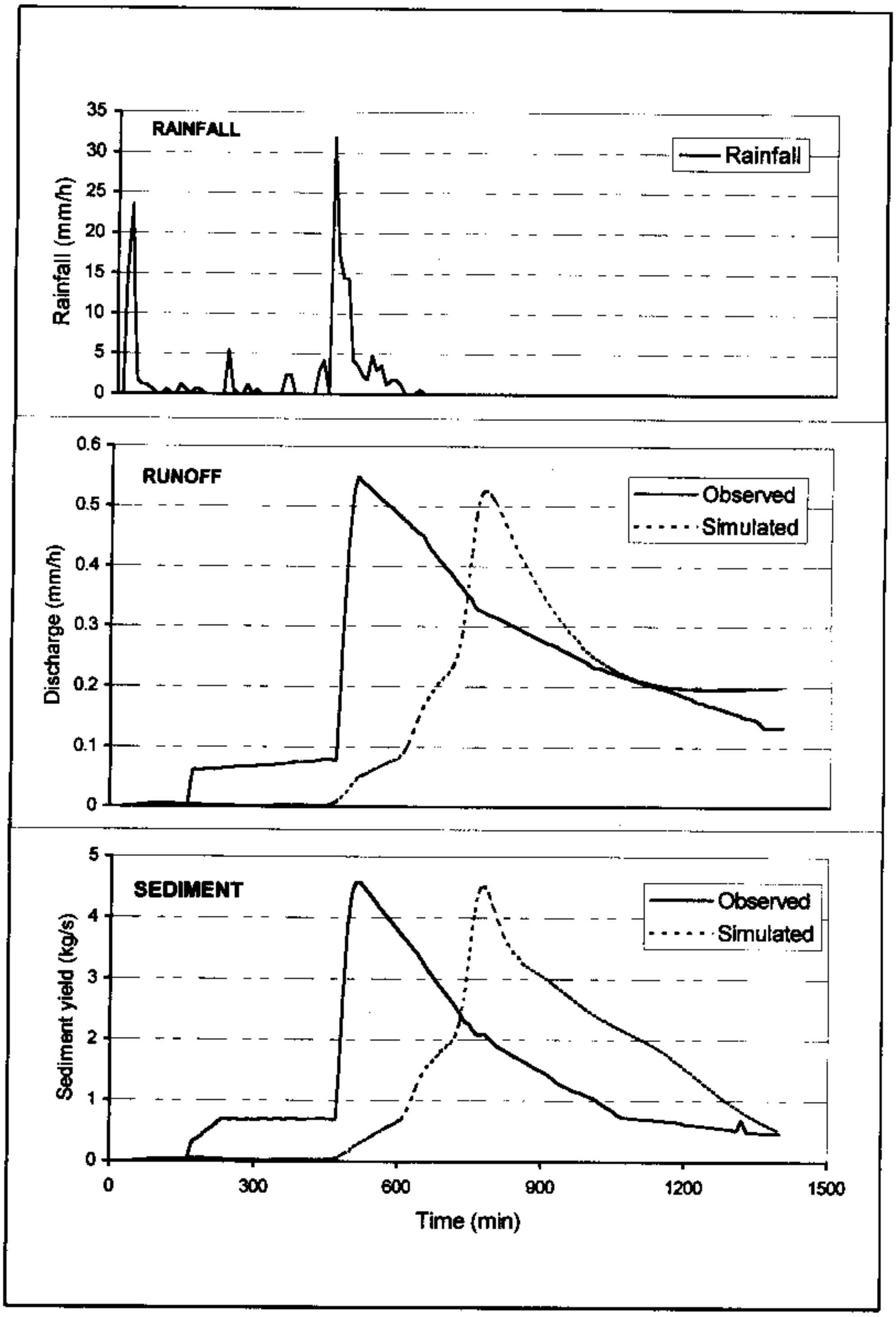

Fig. 10 Plots of observed and simulated runoff and sediment graphs (event dated 3.8.91)

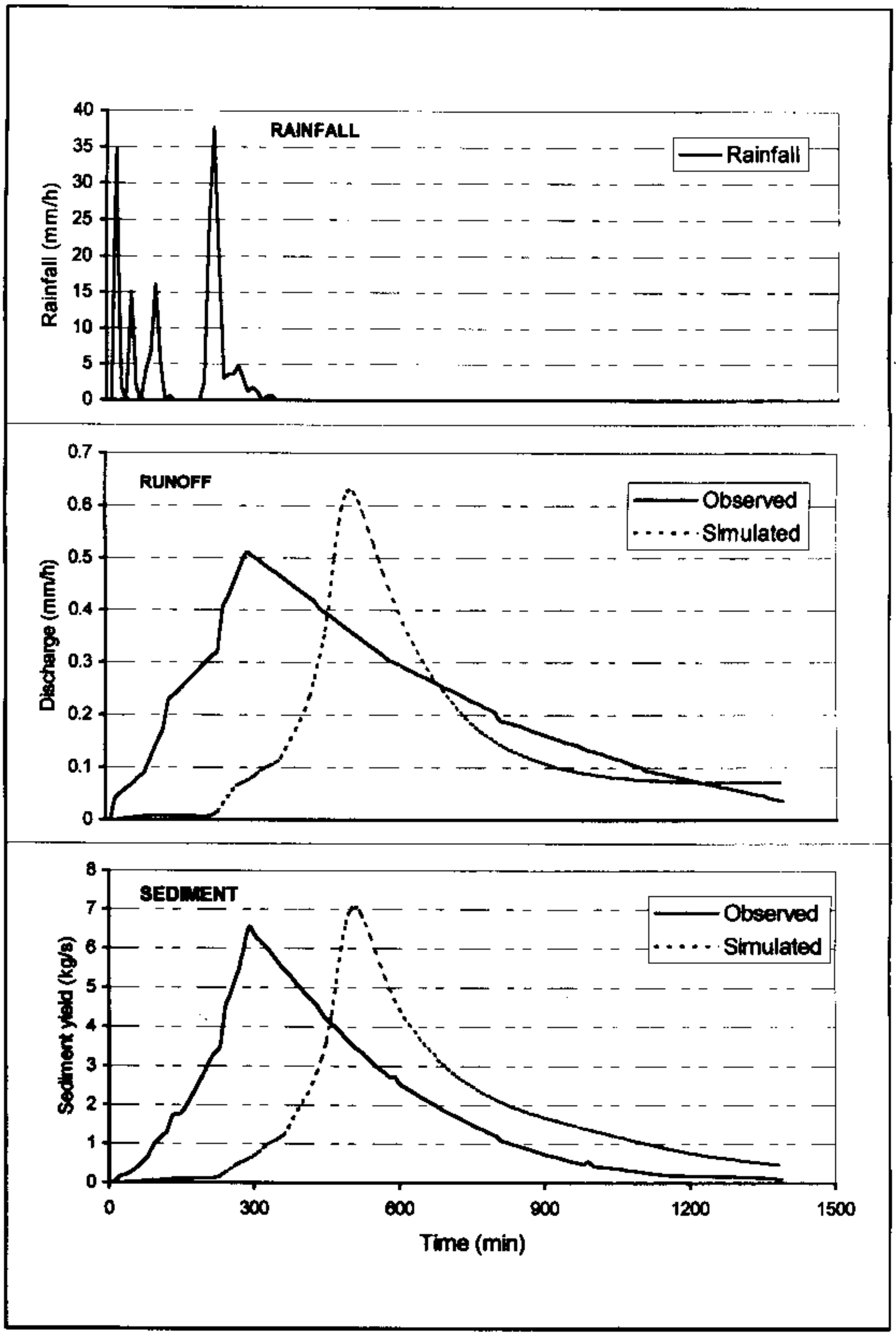

Fig. 12 Plots of observed and simulated runoff and sediment graphs (event dated 5.8.91)

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 Figure 11. As can be seen from Figure 11, 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.

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. Figure 12 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 Figure 13.

A comparison of Figures 11 and 13 reveals that most of the high sediment producing zones (depicted in red tones) 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.

Information about simulation results for other events is summarised in Table-3. As can be seen from Table-3, 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-3 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, baring shift in time to peak discharge, overall simulation results of the model are within acceptable limits.

Table 3. 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

5 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

Beasley, D.B. and Huggins, L.F. (1991) *ANSWERS users manual*. US Environmental Protection Agency, Region V, Chicago, IL, USA.

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

Bathurst, J.C. (1991) Framework for erosion and sediment yield modelling, In D.S.Bowles and P.E. O'Connell (eds.), *Recent advances in the modelling of hydrologic systems*, 269-288, Kluwer Academic Publishers.

Lorup, J.K. and M. Styezen, M. (1996). Soil erosion modelling. In M.B.Abott and J.C. Refsgaard (editors) *Distributed Hydrological Modelling*, Kuwer Academic Publishers, Netherlands.

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.

Singh, V.P. and M. Fiorentino, (1996).*Geographic Information Systems in Hydrology*, Kluwer Academic Publishers, Netherlands

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

Hadley, R.F., Lal, R., Onstad, C.A., Walling, D.E and Yair, A. (1985) *Recent Developments in Erosion and Sediment Yield Studies*. UNESCO (IHP) Publication, Paris: 127 pp.

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.

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.

Jain, M.K. and Kothyari, U.C. (2000) Estimation of soil erosion and sediment yield using GIS. *Hydrol. Sci. J.*, 45(5): 771-786.

Beasley, D.B., Huggins, L.F., and Monke, E.J. (1982) Modeling sediment yields for agricultural watersheds. *Journal of Soil and Water Conservation* 37(2): 113-117.

Bliss, N.B., and Reybold, W.U. (1989) Small-scale digital soil maps for interpreting natural resources. *Journal of Soil Water Conservation* 44(1): 30-34.

Brown, D.G., Bian, L., and Walsh, S.J. (1993) Response of a distributed watershed model to variations in input data aggregation levels. *Computers and Geosciences* 19(4): 499-509.

De Roo, A.P.J., Hazelhoff, L., and Burrough, P.A. (1989) Soil erosion modelling using ANSWERS and geographical information systems. *Earth Surface Processes and Landforms* 14: 517-532.

Griffin, M.L., Beasley, D.B., Fletcher, J.J., and Foster, G.R. (1988) Estimating soil loss on topographically nonuniform field and farm units. *Journal of Soil and Water Conservation* 43, 326-331.

Sharma, K.D. and Singh, S. (1995) Satellite remote sensing for soil erosion modelling using the ANSWERS model. *Hydrological Sciences Journal*, 40(2), 259-272.

Hairsine, P.B., and Rose, C.W. (1991) Rainfall detachment and deposition: Sediment transport in the absence of flow-driven processes. *Soil Science Society of America Journal* 55(2): 320-324.

Hession, W.C., and Shanholtz, V.O. (1988) A geographic information system for targeting nonpoint- source agricultural pollution. *Journal of Soil and Water Conservation* 43(3): 264-266.

Laflen, J.M., Lane, L.J., and Foster, G.R. (1991) WEPP: A new generation of erosion prediction technology. *Journal of Soil and Water Conservation* 46(1): 34-38.

Moore, I.D., Turner, A.K., Wilson, J.P., Jenson, S.K., and Band, L.E. (1993b) GIS and land surface-subsurface modeling. pp. 196-230 in Goodchild, M.F., Parks, B.O. and Steyaert, L.T., eds, *Environmental Modeling with GIS*. New York: Oxford University Press.

Morris, D.M., and Heerdegen, R.G. (1988) Automatically derived catchment boundaries and channel networks and their hydrological applications. *Geomorphology* 1(2): 131-141.

DIRECTOR: *K. S. Ramasastri*

DIVISIONAL HEAD: *B. Soni*

STUDY GROUP: *M.K. Jain*
Scientist C