HYDROLOGICAL STUDIES OF A SMALL WATERSHED IN INDIA USING ANSWERS MODEL

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled **"HYDROLOGICAL STUDIES OF A SMALL WATERSHED IN INDIA USING ANSWERS MODEL"** in partial fulfillment of the requirement of the award of the Degree of Master of Technology, Department of Hydrology, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried out during a period from July 2007 to June 2008 under the supervision of Dr. M. K. JAIN, Assistant Professor, Department of Hydrology .

The matter presented in this dissertation has not been submitted by me for the award of any other degree.

Joshi

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Soil erosion is a serious problem which if left unchecked can have disastrous consequences on our environment. Every year millions of tonnes of top soil is are washed away into the rivers and sea by erosion. Proper and effective management of land and water resources demands a quantitative assessment of runoff and soil erosion. Soil is naturally removed by the action of water or wind. Soil erosion by water is the result of rain detaching and transporting vulnerable soil, either directly by means of rain splash or indirectly by rill and gully erosion. Four basic factors influence runoff and soil erosion by water: climate, soil properties, topography and land use practices. Spatial variability of these parameter must be taken into account during runoff and sediment outflow simulation. Distributed parameter models are applicable for these kinds of simulations. The mapping and management of such spatial information require the use of new technologies such as satellite remote sensing and geographical information system (GIS).

In the present study, a spatially distributed model, the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) has been used to simulate runoff and erosion in Karso watershed in the Hazaribagh district of Jharkhand state. The watershed is discretized into square elements assumed to have all hydrologically significant parameters uniform. The GIS techniques have been utilized to spatial discretization of the Karso catchment in to grids. The integration of GIS with distributed parameter reduces the time needed for generating large number of input data associated with these models as compared to conventional methods. Slope and aspect information were generated in GIS from Survey of India Toposheets. Information of input parameters such as land forms, drainage, soil, land use/land cover was derived from digital analysis of Landsat Thematic Mapper data with limited ground truth. Values of variables such as slope; aspect, soil variables (porosity, moisture content, field capacity, infiltration capacity and erodibility factor), surface variables (roughness and surface retention) and channel variables (Width and roughness) are defined for each element. The continuity equation is used 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.

Available storm events were divided into two groups for calibration and validation of the model. An optimization algorithm is linked with the model to arrive at value of model parameters which produce minimum value of objective function. Results obtained for calibration and validation period is analysed according to size and maximum 6o minimum rainfall intensity of a event. Statistical and visual analysis of results obtained indicates that the model is capable of producing runoff and sediment outflow within acceptable level of deviation. This indicates suitability of the model to simulate storm events in Karso catchment.

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CHAPTER I
INTRODUCTION

1.1 Introduction

Degradation of water and land resources is an issue of societal and environmental concern. Accelerated erosion due to human induced environmental alterations at global scale is causing extravagant increase in sediment fluxes in many parts of the world (Turner et. al., 1990). In India, an estimated 175 Mha of land constituting about 53% of the total geographical area suffers from deleterious effect of soil erosion and other forms of land degradation (Reddy, 1999). Active erosion caused by water and wind alone accounts for 150 Mha of land, whereas 25 Mha has been degraded due to ravine/gullies, shifting cultivation, salinity/alkalinity, and water logging (Reddy, 1999).

Soil erosion is a process of land denudation involving both detachment and transportation of 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. Sedimentation studies of major reservoirs in India revealed that the annual rate of siltation from unit catchments has been 2-3 times more than the designed values (Misra 1999). The dynamics of the processes of soil erosion and sediment yield are influenced by spatial and temporal characteristics of input climatic variables affecting them and by controls exerted by the land surface. The climatic factors affecting erosion are precipitation particularly the amount and intensity of rainfall which determine the degree of erosivity, temperature, wind, humidity and solar radiation. Wind also changes raindrop velocities and the angle of impact. The controls related to the land surface include elevation, soil, vegetation cover and underlying geology.

Physical properties of the soil have a greater hand in affecting soil erosion. The properties which influence the most are soil structure ,texture ,organic matter content

,moisture content ,density (compactness) ,shear strength as well as chemical biological characteristics. Coarse texture soils e.g. Sandy loam, loamy sands and sand are most susceptible to erosion. Erodibility is specifically influenced by the proportion, size and bulk density of the erodible soil particles. The single condition that leads to maximum soil erosion is exposed bare soil. It can also occur when vegetation is removed for construction purposes, clear cutting of forests or forest fires. Living or dead vegetative matter greatly protects the soil surface from wind action. It not only reduces wind velocity of the surface but also absorbs much of the force exerted by the wind. In addition to reducing wind velocity vegetative 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 the surface water velocity and traps the drifting soil particles. It also aides in increasing the soil porosity by the action of the 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 soil erosion are degree of slope, length of slope and the size and shape of the watershed. Steeper slopes favour greater erosion when water flows over it with greater velocity, by scour and sediment transportation. The length of the slope also plays an important role. A longer slope favours high water velocity and thus increases soil erosion. Information on runoff and sediment outflow from a watershed in spatial and temporal domain is required for planning and management of water and land resources. Mathematically models capable of handling spatial variability of topography, soil, land cover etc can aid in understanding hydrological behaviour of a catchment in present scenario and possibly future behaviour. Models can also be used to simulate the experiments instead of conducting the experiments on the watershed itself. Thus, research in hydrological modeling and related watershed planning issues form a strong component of the environmental activities. Models available in the literature for runoff and sediment yield estimation can be grouped into broad categories (1) lumped models and (2) distributed models.

Lumped models are often associated with averaging spatial variation of rainfall, topography, management practices, soil types etc. These models invariably employ some weighting function to account for spatial variability of watershed parameters such as soil type, cover and slope steepness. Lumped models are easy to use but lack detailed output required for planning and management. Examples of lumped models are CREAMS (Kinsel et al., 1980; Kinsel and Williams, 1995); GLEAMS (Leonard et al., 1987); SWRRB (Arnold et al., 1990; Arnold and Williams, 1995). Distributed models, on the other hand, take into account the spatial variability of watershed characteristics. The watershed is discritized into units which are assumed homogeneous. All the hydrologic, climatic and management parameters are assumed homogeneous within each discretized units but may vary among different units. These models are expected to provide reliable estimates for runoff and sediment yield from a catchment in spatial and temporal domain.

Hydrological models like SWAT (soil and water assessment tool) (Arnold et al., 1993), AGNPS (agricultural non-point source pollution) (Young et al., 1989), ANSWERS (areal non-point source watershed environment response simulation) (Beasley et al., 1980) and WEPP (Water Erosion Prediction Project) (Laflen et al., 1991); MIKE SHE (Refsgaard and storm, 1995) etc. are well known distributed models being used extensively for modeling runoff and sediment outflow in spatial and temporal domain from watersheds. These hydrological models provide the basis for improved understanding of hydrological processes and also for assessing the impact of human activities on environment and agricultural production. However; these models require the coordinated 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 applications of these models is still limited because of availability of information in the spatial domain .Recent advances in remote sensing (RS) and use of geographic information system(GIS) can provide information in spatial domain required by some of these distributed models.

Numerous studies are available in literature wherein use of RS and GIS in hydrologic modeling has been used (Hession and Shanholtz, 1988; Tim et al., 1992; Maidment, 1993a; Srinivasan and Engel, 1994; Bhaskar et al., 1992; Sekhar and Rao, 2002; Chowdary et al., 2004; Jain et al. 2004, 2005; Pandey et al., 2005, 2007). In all these studies, the potential benefits of RS and GIS in hydrologic and water quality modeling have been clearly demonstrated.

The upper Damodar Valley (17,513 km2) comprising 39 sub catchments is infested with serious problems of land degradation by soil erosion affecting the agricultural forests and waste lands of the region. About 66% of the total land of the upper Damodar valley (UDV) is affected by different types of erosion and 35% of the agricultural land is moderately to severely eroded under sheet erosion (Misra 1999) . The sedimentation survey of Panchet and Maithon reservoirs of Damodar valley revealed that the siltation rate was a s high as seven times of the designed rate (Misra and Satyanarayana, 1991; Misra 1999). Hence, in order to preserve natural resources and the useful life of the reservoirs, there is a need to identify the critical areas in this region that contribute higher runoff and sediment.

The present study is undertaken to model runoff and soil erosion in Karso catchment in UDV, India using ANSWERS model. The ANSWERS model is chosen due to its distributed model structure, which inherently provides the ability to simulate the fate of any type of pollutant and to integrate the response of individual elements to yield a composite watershed simulation. It can simulate the response of each cell to different cover conditions and management practices. Furthermore the structured approach used in the development of the model facilitates the incorporation of new components. In addition ANSWERS has been subjected to extensive validation and has been found to work for different management practices and climatic conditions in different parts of world. However very few studies have been reported in literature using ANSWERS model on Indian catchment.

1.2 Objectives

The main aim of this study is to use ANSWERS model to simulate rainfall –runoff – sediment response from a watershed in UDV, India.

The specific objectives are:

- To construct a database for the model.
- To link suffled complex optimization algorithm (SCE-UA) with ANSWERS model for optimizing model parameters.

- To calibrate the model parameters based on observed data on runoff and sediment outflow.
- To perform sensitivity analysis of model parameters to determine how the change in parameter values can bring about changes in model output.
- To validate the model using data which is not used in calibration.

CHAPTER II

LITERATURE REVIEW

2.1 General overview

The Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) was developed as a hydrologic model in 1966 by L.F. Huggins (Huggins and Monke, 1966) as a dissertation project. The 1966 version was written in FORTRAN IV and named “Mathematical Model of a Small Watershed.” The original model was a distributed parameter, single event model developed for simulating the hydrologic response of small agricultural watersheds. Erosion and water quality were not simulated. In the late seventies, Beasley et al. (1980) added components to the model to simulate sediment loss, tile drainage, and the effects of selected agricultural BMPs on runoff and sediment loss. The ANSWERS model was modified almost continuously during the next two decades. Additions included improved sediment (Dillaha and Beasley, 1983), phosphorus (Storm et al., 1988), and nitrogen (Bouraoui and Dillaha, 2000) transport submodels. A major advancement for the model occurred in 1994 when the model was modified for continuous simulation, and components were added for crop growth, improved simulation of the infiltration process, and simulation of nitrogen and phosphorus losses (Bouraoui, 1994; Bouraoui and Dillaha, 1996, 2000). At this time the model was renamed ANSWERS-2000. Byne (2000) replaced the sediment detachment submodel with critical shear stress components from the WEPP model and added a channel erosion component. Shortly thereafter, QUESTIONS, an Arc Info-based user interface written in Visual Basic, was developed for ANSWERS to simplify data file creation (Veith et al., 2002).

2.2 Studies conducted outside India

De Roo et al., (1992) studied the effects of spatial variations in the values of the infiltration parameter on the results of ANSWERS distributed runoff and erosion model using Monte Carlo simulation. The Etzenrader Grub catchment was chosen for the study. Values of variables related to topography, soil, land use and management practices, e.g. slope, aspect, infiltration capacity and soil erodibility, were determined for each element using (geostatistical) interpolation techniques. Single median infiltration values, based on the field experiments, were used for the two populations: arable land and grassland. Three rainfall events were simulated using these conditions. This study revealed that how spatial variation in a single soil parameter namely infiltration capacity, affects the ability to model surface runoff under rainfall events of different intensity, using ANSWERS model. The results indicated that rainstorms with low rainfall intensities were more difficult to simulate accurately than extreme events with high rainfall intensities. This was explained by the greater influence of the infiltration uncertainties at low rainfall intensities.

The ANSWERS model was modified by Bouraoui et al., (1997) to include Green and Ampt infiltration. The model tested using measured runoff from several tilled, black earth catchments on the eastern Darling Downs, Queensland. Rainfall and runoff data from rainfall simulator plots (1 m^2 and 88 m^2), and three small catchments (0.07 ha, 0.2 ha and 3.2 ha) were used to test predictions of runoff. Important infiltration parameter values were determined from a separate set of 1 m^2 rainfall simulator plots. Other parameter values were measured directly or estimated from ANSWERS user manual and other published sources. Measured runoff from the simulator plots and catchments was accurately predicted by the modified ANSWERS; a linear regression explained 93% and 81% of the variation between predicted and measured peak runoff rate and runoff volume, respectively. Runoff was accurately predicted with the modified ANSWERS, as processes controlling runoff from the catchments, including infiltration and routing of runoff, were realistically characterized. This allowed parameter values to be derived independently of runoff, and transported to different size catchments without distortion or optimization.

Wu et al., (1993) used three runoff and erosion models -agricultural non–point-source pollution model (AGNPS), areal non–point-source watershed environmental response simulation (ANSWERS), and chemicals runoff and erosion from agricultural management systems (CREAMS) to evaluate runoff and erosion in three experimental watersheds. The results are compared with measured runoff and sediment yield. The computed and measured runoffs show reasonable to poor agreement. The average ratios of computed to measured sediment yields for the various storms and watersheds show a large scatter. ANSWERS provide the most consistent results for estimates of runoff and sediment yield. All three models tend to underestimate sediment yield for large storms. For high intensity and low intensity storms on two small watersheds, the detachment models in ANSWERS and CREAMS have biases (ratio of calculated to measured sediment yields) that range between 0.9–1.0 and 0.4–1.6, respectively.

An investigation was made by Wu et al., (1996) to determine whether available erosion models can work for mine soils and can account for gully erosion. The investigation at an abandoned surface mine consisted of measurement of soil and sediment properties, measurement of runoff and erosion, observation of armour by rock fragments on gully floor and calculations with available theories of sediment transport and slope stability .For calibration the soil properties (total porosity, field capacity, steady state infiltration rate ,infiltration exponent, control zone depth and USLE soil erodibility factor K) and the land use properties are obtained using the equations and values given in the ANSWERS user's manual(Beasley et. al. 1980). The results indicated that prediction with the ANSWERS model have about the same accuracy as those made for agricultural lands; detachment by rainfall impact is the primary cause of erosion on steep slopes; armour provided by rock fragments are temporary as they are periodically removed by debris flows and finally a simplified method can be used for estimating erosion on such slopes.

Bouraoui et. al., (1996) developed a non point source pollution management model, ANSWERS 2000 to simulate long term average annual runoff and sediment yield from agricultural watersheds. The model was based on event based ANSWERS model and is intended to use without calibration .The physically based Green Ampt infiltration equation was incorporated into ANSWERS -2000 to improve estimates of infiltration. An evapotranspiration submodel was added to permit long-term continous simulation. The model is validated without calibration using data from the field-sized P2 and P4 watersheds in Watkinsville, Ga. Additional validation with limited calibration was done on Owl Run Watershed in Virginia. Model .Model predictions of cumulative sediment yield were within 12% and 68% of observed values. Predicted cumulative runoff values ranged from 3% to 35% of observed values. Predictions of sediment yield and runoff volume for individual storms were less accurate but generally within 200% of observed values.

Bouraoui et al., (1997), modified the ANSWERS model to include the simulation of water transport in the vadose and saturated zones. The site selected for the calibration and validation is 'La C&e St Andre', 60 km northeast of Grenoble (southeast of France). They validated the modified model at multiple scales: local scale, field scale and watershed scale. At the local and field scale, it predicts accurately drainage below the root zone and evapotranspiration on different type of soil cover. At the watershed scale, it reproduces well the piezometric levels and trends of variation.

Zagolski et al., (1999) introduced some major improvements to a physically based hydrological and soil erosion model, namely ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation). Simulations conducted on an experimental agricultural watershed in Springvale (USA) for different patterns of agricultural planning stressed the importance of human influences on dynamic hydrological processes. Modifications were implemented in ANSWERS to take into account two aspects of human interventions, i.e., the spatial structures which define the agricultural landscapes and the oriented feature of tillages. This improved model provides a powerful tool for decision-making processes, especially in the context of soil conservation. In fact, different patterns of agricultural planning with control techniques against erosion or water pollution can be easily simulated. In particular, the effects of commonly used cultural practices such as boundary implementations or ploughing in perpendicular direction to the terrain slope can be predicted. Moreover, such a model would be also useful for studies relying on the changes of the landscapes resulting from a complex interaction between natural and human disturbance regimes.

Another study was conducted by. Braud, et al., (1999) to study the rainfall–runoff process in the Andes region using continuous distributed model-ANSWERS. The year 1985 was chosen for the first sensitivity test and calibration of the model. The climate and rainfall data were used as input variables. The time step used in simulations was 10s. Bouraoui (1995) has provided tables for the main parameters of the model in case of agricultural watersheds .But the unmeasured parameters such as soil field capacity, saturated hydraulic conductivity of the quasi-impervious soil type and roughness coefficients for the channel flow were adjusted. The saturated hydraulic conductivity of the quasi-impervious soil type was set to a value of 0.05mm/h. The model was able to produce runoff volume with an efficiency of 0.6 and peak discharge with an efficiency of 0.46. The largest events were however underestimated, although the model was able to reproduce sharp increases in stream flow. The combination of rainfall and soil variability, mainly associated with a quasi –impervious area in the middle of the catchment was found to explain the rapid increases in stream flow. Vegetation, surface storage capacity and initial soil moisture were also influential but with much smaller magnitude than the combination of rainfall and soil variability.

Veith et al., (1999) used ANSWERS model to examine the hydrologic response of an agricultural watershed FD-36, in the hydrologic response of an agricultural watershed, FD-36, in the Appalachian Valley and Ridge physiographic region. Three computer simulation models – Areal Nonpoint Source Watershed Environmental Response Simulation (ANSWERS-2000), Soil and Water Assessment Tool (AVSWAT2000), and Soil Moisture Distribution and Routing (SMDR) – were used to simulate the surface hydrologic processes in FD-36. This study assessed the ability of three models to depict spatial and temporal processes of a small, agricultural watershed with fragipan soils. All three models captured most major temporal variations seen in total surface runoff from the watershed. AVSWAT2000 achieved the strongest temporal statistical correlation. In contrast, spatial identification of runoff generation areas varied distinctly among the three models. Unlike SMDR, AVSWAT2000 and ANSWERS-2000 recognized differences in land use and soil characteristics within the watershed. ANSWERS-2000 and, to a lesser extent, AVSWAT2000 depicted higher runoff depths from the near-stream, fragipan soils than from other areas. Differences were also seen in the ranges of simulated runoff depths. AVSWAT2000 was chosen out of the three models as most accurately depicting the hydrological processes of the FD-36 watershed.

Bouraoui et al., (2000) modified ANSWERS 2000 to simulate long-term nitrogen (N) and phosphorus (P) transport from rural watersheds. The model simulated infiltration, evapotranspiration, percolation, and runoff and losses of nitrate, adsorbed and dissolved ammonium, adsorbed total Kjeldahl N, and adsorbed and dissolved P losses. Eight soil nutrient pools were modeled: stable organic N, active organic N, nitrate, ammonium, and stable mineral P, active mineral P, organic P, and exchangeable P. The model was validated on two small watersheds without calibration and on a large watershed with calibration of only the sediment detachment parameters. Predicted cumulative runoff, sediment, nitrate, dissolved ammonium, adsorbed total Kjeldahl N, and orthophosphorus P losses were within a factor of 2 of observed values (240 to 144% of observed values). Predictions of individual runoff event losses were not as accurate (298 to 1250%). The model seriously underpredicted adsorbed ammonium losses by up to 97%.

Bhuyan et al., (2001) used three soil erosion prediction models — the Water Erosion Prediction Project (WEPP), the Erosion Productivity Impact Calculator (EPIC), and the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) for simulating soil loss and testing the capability of the models in predicting soil losses for three different tillage systems (ridge-till, chisel-plow, and no-till). The measured soil erosion data were collected from an erosion experiment field of Kansas State University at Ottawa (Kansas), USA. For each model, the most sensitive model parameters were calibrated using measured soil erosion data. In order to calibrate the models, sensitivity analyses were performed for the first seven rainfall events by changing the value of a parameter within a certain acceptable range and observing the soil loss output. For calibration of model parameters, the smallest and the largest storm events during each year were considered. The values of different soil parameters were adjusted to bring the model predicted soil loss values within the range of the observed soil loss values as well as closer to the mean of the observed soil loss values. The parameter that produced the maximum sensitivity was adjusted first, followed by the other parameters .Results showed that all the three models performed reasonably well and the predicted soil looses were within the range of measured values. For ridge-till and chisel-plow systems, WEPP and ANSWERS gave better predictions than those by EPIC model. For no-till system, WEPP and EPIC predictions were better than those by ANSWERS. The overall results indicate that WEPP predictions were better than those by the other two models in most of the cases, and it can be used with reasonable degree of confidence for soil loss quantification for all the three tillage systems.

Braud et al., (2001) used ANSWERS model to study the vegetative influence on runoff and sediment yield in the Andes region. Two catchments namely Divisadero Largo (DL) and Cuenca Alluvional Piloto (CAP) were instrumented in order to study rainfall-runoff process and soil management impact on and/or sediment yield. In this study, the ANSWERS model was applied in the Andes region of Mendoza at three scales: the local scale (30-50 m^2), the slope scale (0.2-0.5 ha) and the small catchment scale (5.47 km^2). For the CAP catchment, out of 16 storm events, 5 events were selected for model validation. For the DL catchment, year 1995 was used for model calibration and the 33 events available on the 1983-1994 period used for model validation (Braud et al., 1999). The derivation of input data maps, as needed by the ANSWERS model was described in Braud et al., (1999). All the soil and land use parameters are obtained using ANSWERS user manual. The derivation of input data maps, as needed by the ANSWERS model was described in Braud et al., All the results showed contrasting performance of the ANSWERS model. It proved to be very well adapted to the simulation of the DL catchment whereas it failed to properly reproduce measured runoff within the sub-catchments of the CAP catchment. Model results are sensitive to vegetation cover within the CAP catchment whereas it has little influence within the DL catchment. Within the DL catchment, soil characteristics and rainfall variability appear as the most influential processes on runoff generation; whereas vegetation cover (spatial and temporal variability) is of second order.

Walling et al., (2003) used ^{137}Cs measurements to validate the application of the AGNPS and ANSWERS erosion and sediment yield models on two neighboring small catchments, the Moorlake catchment (4.65 km2) and the Keymelford catchment (0.52 km2), located near Crediton, in Devon, UK. The study compares two approaches to test these models in these catchments. The first approach involves the traditional use of runoff and sediment yield data recorded at the basin outlets to compare measured and simulated catchment outputs, whereas the second uses the spatial pattern of soil redistribution derived from ^{137}Cs measurements within two cultivated fields where detailed investigations of soil erosion and sediment delivery processes have been undertaken, and the basin sediment delivery ratios derived from the sediment budgets for the catchments established using ^{137}Cs measurements. They used the AGNPS (version 5.00) and ANSWERS (version 4.880215) models to simulate runoff and sediment outputs from the two catchments using seven representative events with similar antecedent conditions. Since the emphasis was on testing the consistency between the model-simulated and observed data, detailed model calibration was not undertaken and values for some of the parameters, including the SCS curve number, Manning's n, K, C, and P from the USLE, the surface condition constant, total porosity, field capacity and antecedent soil moisture, were estimated using the guidelines provided in the model manuals and the procedures recommended by Wischmeier and Smith (1978). The results obtained indicate that catchment outputs simulated by both models are reasonably consistent with the recorded values, although the AGNPS model appears to provide closer agreement between observed and predicted values. However, the spatial patterns of soil redistribution and the sediment delivery ratios predicted for the two catchments by the AGNPS and ANSWERS models differ significantly. Comparison of the catchment sediment delivery ratios and the pattern of soil redistribution in individual fields predicted by the models with equivalent information derived from 137Cs measurements indicates that the AGNPS model provides more meaningful predictions of erosion and sediment yield under UK conditions than the ANSWERS model and emphasizes the importance of using information on both catchment output and sediment redistribution within the catchment for model validation.

Moehansyah et al., (2004) used three models, viz., areal non-point source watershed environment response simulation (ANSWERS), universal soil loss equation (USLE) and adapted universal soil loss equation (AUSLE) to evaluate their performance under the field conditions of the Riam Kanan catchment in South Kalimantan province of Indonesia. While ANSWERS is evaluated for its accuracy to predict both runoff and soil loss, USLE and AUSLE are evaluated for soil loss only. The study was carried out in the context of sedimentation concerns for the Muhammad Nur Reservoir --- an important source of drinking and irrigation water supply for the catchment. The models are evaluated using field data collected under four different land uses and during 2 years of field experiments. The input data obtained form the field measurements included rainfall information for up to four rain gauges, soil information for up to 20 soil types, land use information (crop type), channel descriptions and individual element information. The ANSWERS model was used to predict runoff and soil erosion for four events during the first year and five events during the second year of field experiments. The other rainfall events, not included for analysis here, had either insufficient rainfall to generate runoff or the data logger failed to record all the required data for the event. It was found that the ANSWERS model over predicted the runoff and soil loss. In general, the overall prediction error of the models to predict soil loss is in the order of ANSWERS< AUSLE<USLE, indicating the ANSWERS model is the most accurate and the USLE model is the least accurate among the three models considered for this study.

Ahmad et al., (2006) used ANSWERS model to simulate sediment concentration at watershed outlet by applying two sediment transport capacity equations. The study was conducted in a 3·63 ha watershed located in the college of Agriculture, Shiraz University, south of Iran. ANSWERS model code was changed and the original equation for sediment transport capacity was replaced by Yalin's equation. Although the new equation underestimates sediment concentration, the original model resulted in closer agreement between observed and simulated sediment concentration in different rainfall events. Results of this study suggested that adding some components considering fine particles of soil such as silt and clay to the new and original equations, may improve the accuracy of prediction of sediment concentration by the ANSWERS model. Although, both equations revealed that tend to underestimate sediment concentration; however, the original equation overestimated sediment concentration whenever the runoff coefficient exceeded 0·3 under relatively moderate rainfall intensity. Furthermore, the results showed that soil moisture conditions, rainfall depth and rainfall intensity affect underestimation or overestimation of the model; and initial soil moisture is a key factor in simulation of sediment concentration. Wet and dry soil conditions caused overestimation and underestimation of sediment concentration for the original model, respectively.

2.3 Studies conducted in India

Sharma et al., (1993) used the ANSWERS model to predict runoff and soil loss from three small agricultural watersheds Auwa, Somesar and Soneimaji within Bandi river basin. Model input parameters such as landform, drainage, soil and land use /land cover were derived from Landsat Thematic Mapper false colour composite and limited ground truth. Soil erodibility factor was estimated using the equation presented by Wischmeier and Smith (1978). Other soil characteristics such as total porosity, field capacity and infiltration characteristics were obtained from Shankarnarayan and Kar (1983). The infiltration exponent and the daily antecedent moisture condition were obtained from ANSWERS user manual (Beasley and Huggins, 1990). The values of parameters such as maximum roughness height, roughness coefficient and potential interception were obtained from Beasley and Huggins (1990).Manning's roughness coefficient and relative erosiveness of surface (C) were estimated using Wischmeier and Smith (1978) .The slope of the main channel was obtained from the survey of India Topographical maps .Width was measured using aerial photographs. The channels are classified into five categories according to the width and their roughness coefficients were obtained from Vangani and

Kalla (1985). Results of the study indicated that there was variation in the occurrence of peak sediment concentration in different watersheds after the onset of rainfall. This may be attributed to the location of sediment prone areas with respect to the outlet. The difference in the time of concentration is another reason for it. The total soil loss was under predicted for all three watersheds .The under prediction factors in this study were 2.6 to 3.6 .The inability of ANSWERS model to model the resuspension of deposited particles served as an explanation for this under prediction

Singh et al., (2006) used ANSWERS model to study runoff and sediment yield behaviour of Banha catchment of the Upper Damodar Valley of Hazaribagh district in Jharkhand state of India. The model was calibrated by using 16 storms of 1993 and 1994 and validated for fifteen storms of 1995 and 1996. The model was calibrated using trial and error procedure of parameter adjustment and optimization. The LULC based parameters were varied according to vegetative growth stages. For calibration storms the model simulates surface runoff, peak flow and sediment yield with average percent deviation equal to -9.32, 1.24 and -3.04 and coefficient of efficiency equal to (E) equal to 0.964, 0.881 and 0.884 respectively. During calibration and validation the peaks of the simulated hydrograph for majority of the storms were found to occur after the peaks of the observed hydrograph. The statistical comparisons indicate that the model simulated runoff, peak flow and sediment yield well for most of the storms with Dv less than 15% from the observed values and average value of E greater than .80. The model calibration and validation results indicate that the ANSWERS can be successfully used for simulating the watershed response under varying soil moisture and watershed conditions. The study reveals the suitability used for the ANSWERS model application for the other Indian watersheds of similar hydro-geological characteristics.

CHAPTER III

MODEL DESCRIPTION

3.1 General Overview

The distributed parameter model ANSWERS is the acronym for Areal Non-Point Source Watershed Environment Response Simulation (Beasley et. al., 1980 a; Beasley & Huggins 1990). The model is intended to simulate the behaviour of watersheds having agriculture as their primary land use, during and immediately following a rainfall event. Its primary application was envisioned to be planning and evaluating various strategies for controlling non point source pollution from intensively cropped areas. A detailed description is available in Beasley et al., (1980 a). However a brief description drawn heavily from Beasley et al. (1980) is presented below for completeness of the thesis.

3.2 Model structure

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

A watershed to be modeled is assumed to be composed of "elements" as shown in Fig 3.1. An element is defined to be an area within which all hydrologically significant parameters are uniform. To ease data file preparation and facilitate computational convenience a square shaped elemental shape was considered.

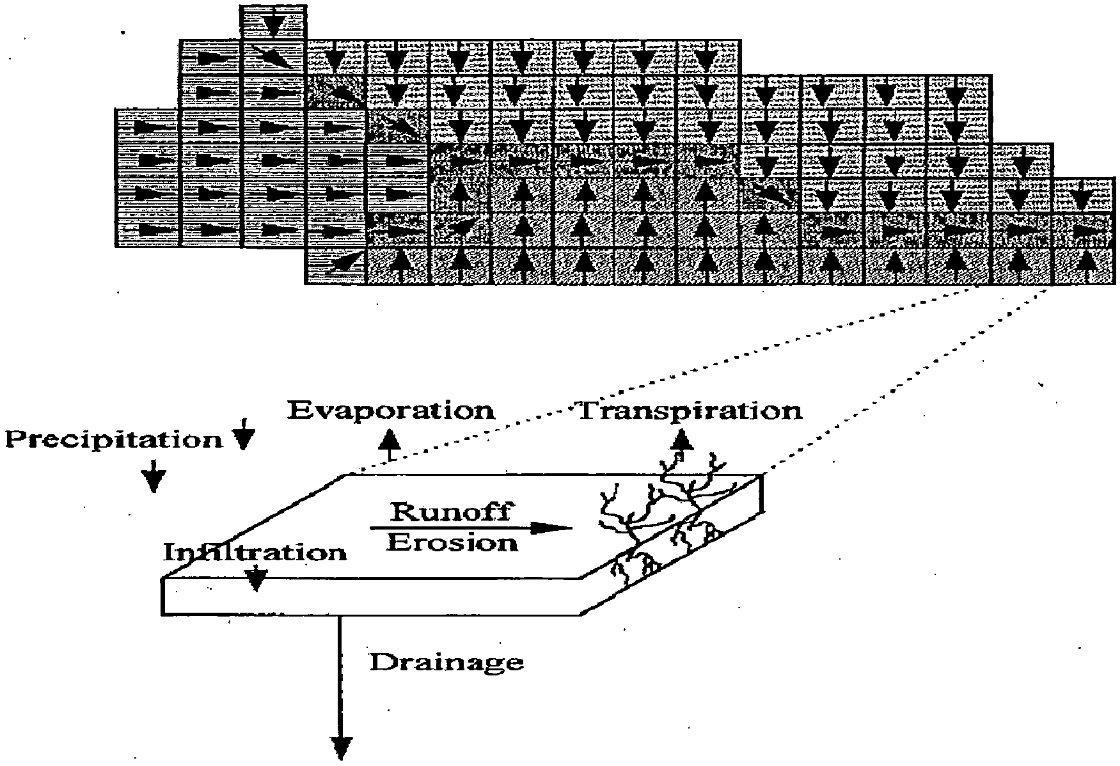


Fig 3.1 Schematic representation of a watershed in ANSWERS model

The 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 of supplied topographic data for each element delineating flow directions in a manner consistent with the topography of the watershed being modeled. Elemental interaction occurs because surface flow (overland and channel), flow in tiles and groundwater flow from each element becomes inflow to its adjacent elements. Pollutants are generated and transported by these flows and by raindrop impact.

3.3 Hydrologic considerations

Hydrologic processes are the driving force within the model. Fig 3.2 shows the hydrologic processes for which component relationships have been incorporated within ANSWERS. The hydrological processes represented in the ANSWERS model can be summarized as follows .After rainfall begins ,precipitation is intercepted by the vegetation canopy until the interception storage potential is satisfied .Then ,through fall can be infiltrated into the soil (Green and Ampt ,1911 model) .When rainfall intensity exceeds the infiltration capacity (Horton ,1940) or the soil reservoir is saturated (saturation excess) ,water accumulates in the micro-depressions. Once the storage capacity of micro-depressions exceeds, surface runoff overland flow begins .Excess water is transferred to the channel and routed to the outlet (Bras, 1990). Water in excess of the field capacity can drain to the groundwater, if it exists. In the interstorm period, water is allowed to evaporate from the soil surface or to be transpired by the vegetation (Richie, 1972).

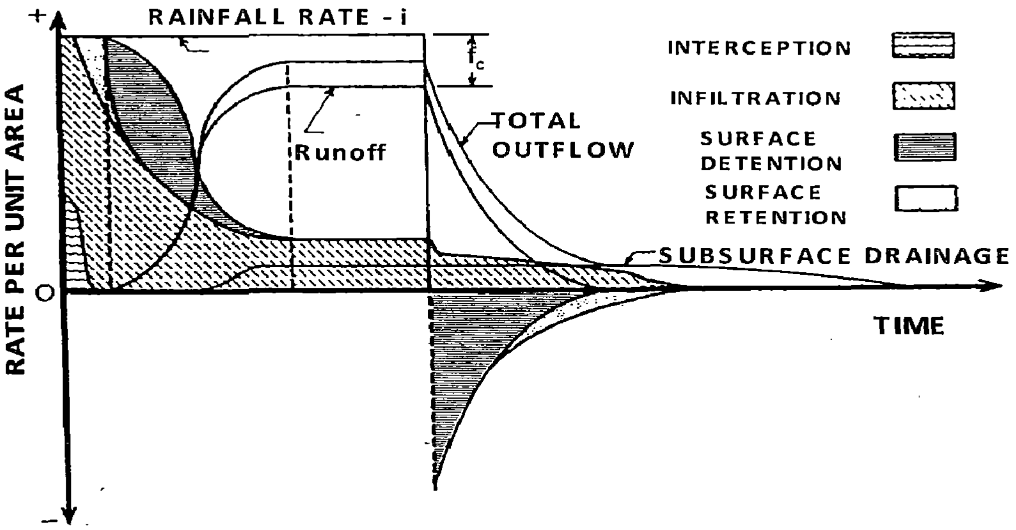


Fig 3.2 Water Movement Relationships for Small Watershed Elements

3.4 Mathematical formulations in ANSWERS model

The various mathematical relationships used to quantify the various model component processes are given below. The 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.

3.4.1 Flow characterization

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

$$I-Q=d(s)/d\ (t)$$

Where I=inflow rate to an element from rainfall and adjacent elements, Q =outflow rate, s=volume of water stored in an element, 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 a stage discharge equation for overland and channel routing. The hydraulic radius in Manning's equation is assumed equal to the average detention depth in the element. Within its topographic boundary, a catchment is divided into an irregular matrix of square elements as shown in fig (1). Every element acts as an overland flow plane having a user specified slope and direction of steepest descent. Channel flow is analyzed by a separate pattern of channel elements which underlie i.e. are in the shadow of, the grid of overland flow elements. Overland and tile flow from an element flows into neighboring elements according to the direction of the element's slope. The slope direction is designated on input as the angle, in degrees, counterclockwise from the positive horizontal (row) axis. The fraction of outflow going into the adjacent row element, RFL, is:

$$RFL = \tan(ANG)/2 \qquad \text{if } ANG <= 45\ DEG$$

$$RFL = 1 - \tan(90 - ANG)/2 \qquad \text{if } 45\ DEG < ANG < 90\ DEG$$

3.4.2 Surface detention

It is that volume of water which must be building 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. A surface detention model developed by Huggins and Monke (1966) is used to describe the surface storage potential of a soil surface as a function of roughness of a soil surface. The form of that equation used by ANSWERS is:

$$DEP = HU * ROUGH * (H/HU)^{1/ROUGH}$$

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

3.4.3 Rainfall rate

The net rainfall rate, which reaches the ground surface, is dependent on the user specified pluviographs 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 identified for each watershed element, it is theoretically possible to have each element for each element subjected to a different storm pattern.

3.4.4 Interception

It is that water extracted from incoming rainfall upon contact with and retention by vegetal canopy. Water retained by vegetation i.e. interception storage is held primarily by surface tension forces .Horton (1919) did a great deal of work in the area of estimating the amount and mechanisms controlling interception. He found the water intercepted by various species of trees and some economically important crops .The values from 0.5 mm to 1.8 mm of interception storage volume were found to exist for trees and nearly as much for well developed crops.

The maximum potential interception (PIT) represents the available leaf moisture storage in depth units (volume per unit land area). In each time increment in which the interception storage remains unsatisfied, rainfall supplied to interception storage is calculated as Incremental interception (RIT) = (the rainfall amount)*(the portion of the element covered by foliage).

The value of potential interception storage (PIT) and the net rainfall are correspondingly decreased until all the interception storage is satisfied. At this stage PIT is set equal to 0 and the net rainfall rate is subsequently equal to the gauge rainfall rate for the remainder of the simulation.

3.4.5 Infiltration

It is one of the components to which ANSWERS is most sensitive, especially during low to medium runoff storms. The infiltration equation chosen for ANSWERS was the one developed by Holton (1961) and Overton (1965). Soil moisture in excess of field capacity is allowed to drain from the soil profile using a percolation equation developed by Huggins and Monke (1966). The infiltration equation used in ANSWERS is expressed as

$$\mathbf{FMAX=FC+A*(PIV/TP)^{P}}$$

Where FMAX=infiltration capacity with surface inundated, 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 control volume prior to its becoming saturated, P=dimensionless coefficient relating the rate of decrease in infiltration rate with increasing soil moisture content. This form uses the soil water rather than time as the independent variable. According to Horton's conceptualization of the infiltration process, a "control zone" depth of soil determines the infiltration rate at the surface. 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. 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 to the following rules:

1 -when the moisture content of that 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:

$$\mathbf{DR=FC*(1-PIV/GWC)^3}$$

Where DR=drainage rate of water from control zone, GWC=gravitational water capacity of the control zone (total porosity- field capacity)

3.4.6 Sediment detachment and movement

Soil erosion, as it relates to non-point source pollution, can be viewed as two separate processes, detachment of particles from the soil mass and transport of these particles into streams and lakes. Sediment detachment from the soil mass is assumed to be a function of soil properties, soil cover conditions and raindrop impact and overland flow. Detachment of either primary soil particles or aggregates can result from either rainfall or flowing water. The detachment of soil particles by water is accomplished by two processes. The first involves dislodging as a result of the kinetic energy of rainfall. The second involves the separation of particles from the soil mass by shear and lift forces generated by overland forces.

Detachment of soil particles by raindrop impact occurs throughout the storm. Meyer and Wischmeier (1969) described a relationship to evaluate the detachment of soil particles by raindrop impact .It is given by

$$\mathbf{DETR=0.108*CDR*SKDR*A_i*R^2}$$

Where DETR=rainfall detachment rate, kg/min, CDR=cropping and management factor from universal soil loss equation, SKDR=soil erodibility factor, K (from USLE), A_i=area increment, m^2 , R=rainfall intensity during a time interval, mm/min. The detachment of soil particles by overland flow occurs when shear stress due to overland flow exceeds the gravitational and cohesive of the soil mass and when there is a sediment transport capacity excess. The detachment of soil particles by overland flow, developed by Meyer and Weischmeier (1969) is given as:

$$\mathbf{DETF=0.90*CDR*SKDR*A_i*SL*Q}$$

Where: DETF=overland flow detachment rate, kg/min, SL= slope steepness, Q=flow rate per unit width, m^2 /min .The sediment load in the flow and the flow's sediment transport capacity decides whether the detached soil particle moves or not. Particles smaller than 10μm (colloidal particles) are assumed to remain in suspension once detached as long as there is runoff. Sediment transport from an element is apportioned to adjacent elements in direct proportion to the flow to downslope cells .Yalin's equation (Yalin 1963), as modified by Foster and Meyer (1972) is used to predict the transport capacity of each particle size class .The potential transport rate of sediment is given by:

$$\mathbf{TF=161*SL*Q^{0.5}} \quad \textbf{if } \mathbf{Q<=0.046m2/min}$$

$$\mathbf{TF=16,320*SL*Q^2} \quad \textbf{if } \mathbf{Q>0.046m2/min}$$

Where: TF=potential transport rate of sediments.

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

1 Subsurface or tile drainage produces no sediment.

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

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

4 For channel segments rainfall detachment is assumed to be zero and only deposited sediment is made available for flow detachment i.e. original channel linings are not erodible.

The transport relationship used in the ANSWERS model is shown in Fig 3.3.

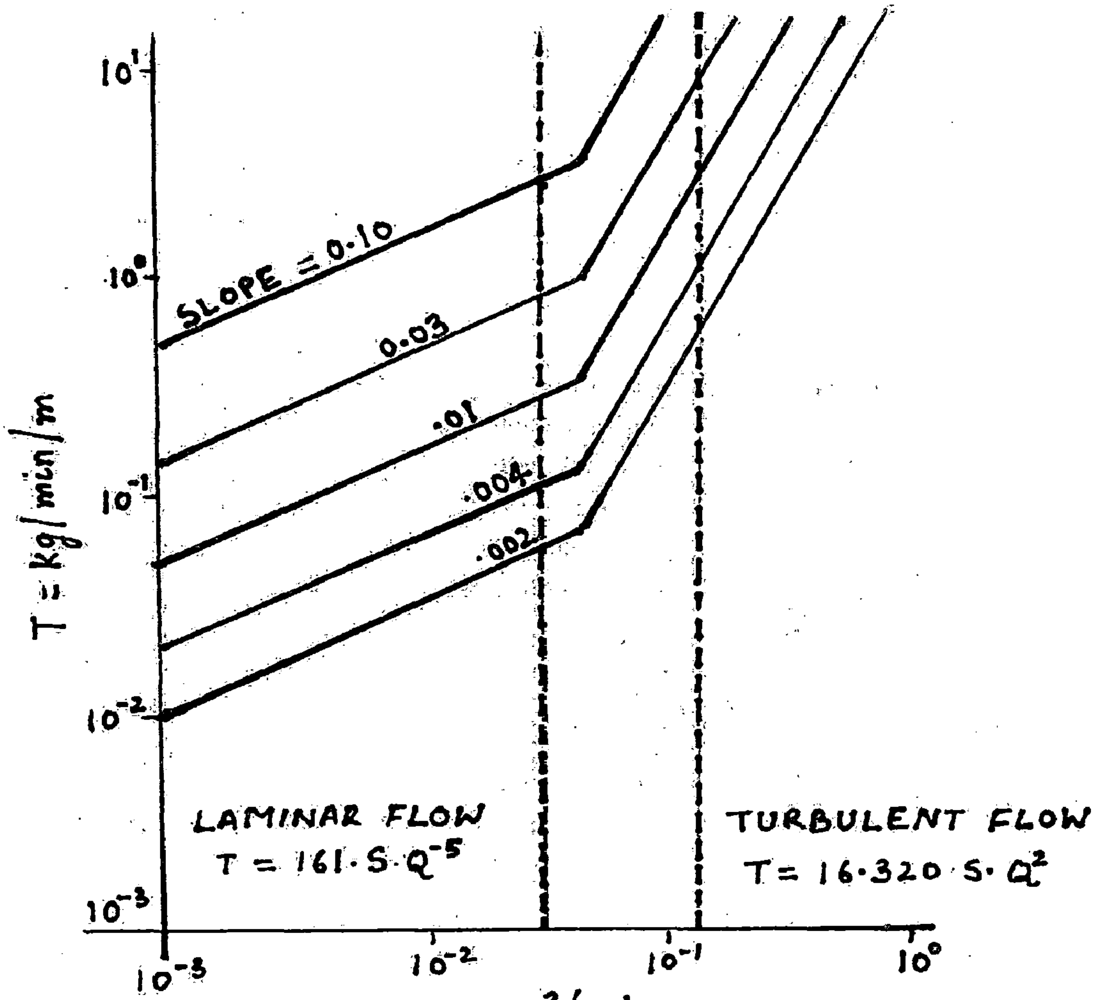


Fig 3.3 Transport Relationship Used in the ANSWERS model

CHAPTER IV

THE STUDY AREA AND GENERATION OF INPUT DATABASE

4.1 Location

The Karso watershed covering 27.93 sq. km. area of the Damodar Barakar catchment has been selected as the study area. The catchment is traversed by the stream named Kolhuwatari, which finally joins the Barhi nadi, a tributary of Barkar River. The catchment is situated between 85^0 23′ and 85^0 28′ E longitude and 24^0 12′ and 24^0 18′ N latitude in the Hazaribagh district of Jharkhand state. The catchment is located near the Tilaiya reservoir, which is built on the river Barkar. Fig 4.1 depicts location of Karso watershed in India.

4.2 Climate

The catchment lies in sub-humid tropical climatic zone .The mean annual temperature of the catchment is about 29^0 C. The maximum temperature of the region varies from 38.9^0 c to 44.4^0 c and the minimum temperature varies from 10.6^0 c to 20.6^0 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 average annual precipitation of the area is 1243 mm.

4.3 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 from survey of India Toposheets at 1:25,000 scales. The area comprises of moderately sloping lands in the Northern part of the watershed and very steep slope in the southern part of the watershed.

4.4 Soil characteristics

The soil within the area is primarily coarse granular .The texture of the soil is 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. Soil characteristics at different location of watershed are given in table 4.1.

Table 4.1 Soil characteristics at different location of the Karso catchments

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

4.5 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 form digital analysis of satellite data. Most of the cultivated areas have been treated by soil conservation measures like terracing, bunding etc.

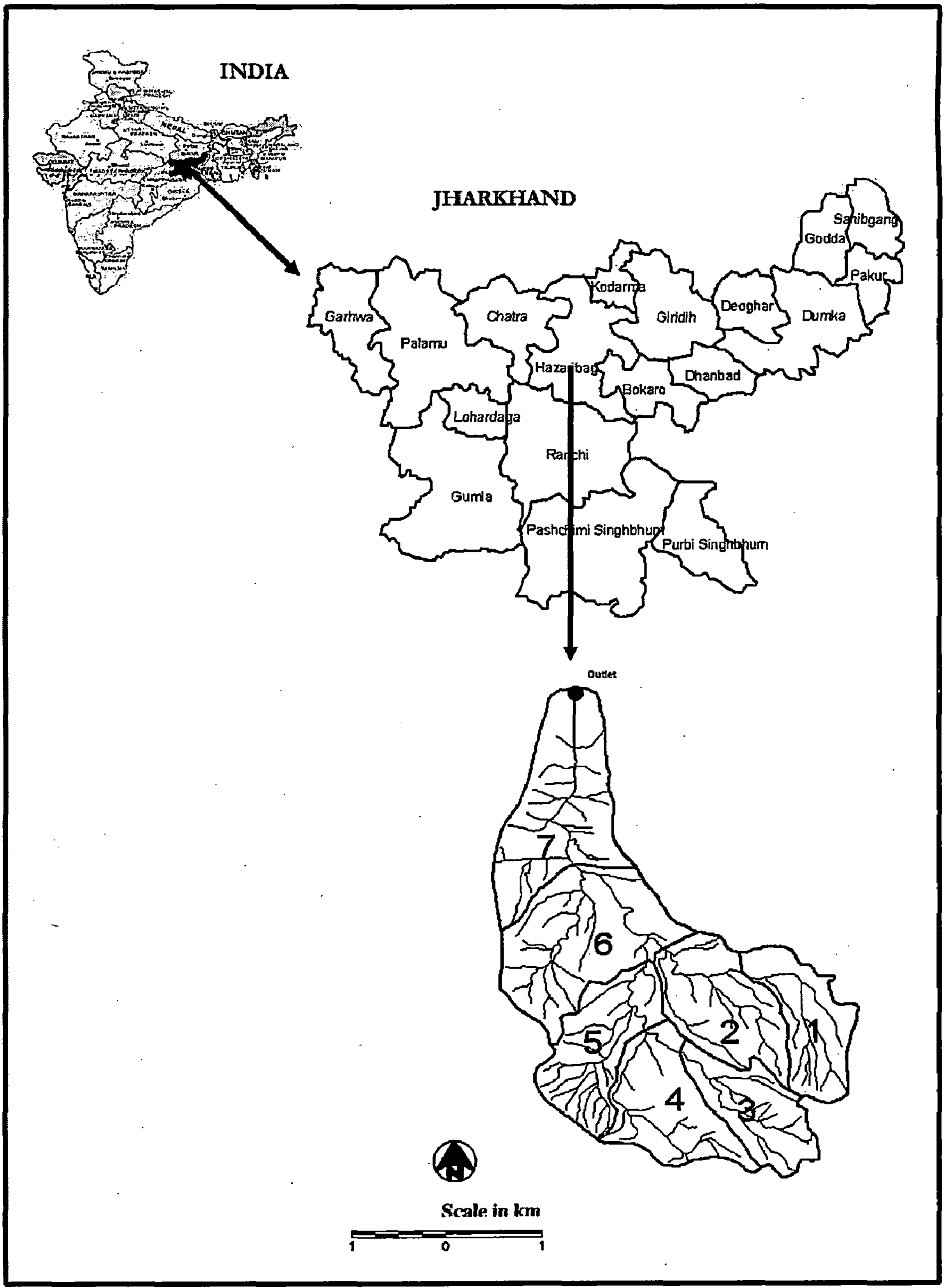


Fig 4.1 Location of Karso watershed

4.6 Generation of Geo-database for watershed and preparation of input files

The gauging network of Kohuwatari river flow and collection of sediment load data were initiated in the year for hydrological studies to assess the effects of soil conservation measures on surface runoff and erosion under the Indo-German Bilateral project report on watershed management. Under this scheme, existing and newly constructed sediment monitoring stations were equipped with tipping bucket type automatic rainfall recorder and water level recorder devices, linked to an electronic data logger system. Samples for sediment load were collected using USDA bottle sampler. 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 is available in the literature(S&WCD, 1991).

The river network and contour map of the study areas were digitized using the Integrated Land and Water Information system, ILWIS (ITC, 1998) from the survey of India toposheets at a scale 1:25,000.Thus digitized 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.

Further analysis of DEM is done to remove pits and flat areas in it in order to maintain the 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 algorithms (ESRI, 1994). Delineated DEM of the Karso watershed is shown in fig. 4.2. 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.

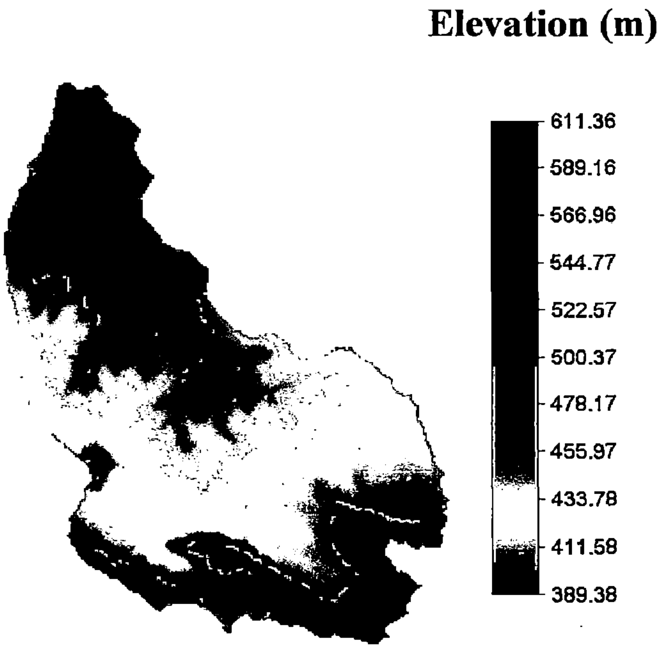


Fig 4.2 DEM of the Karso watershed

The generated channel network is depicted in fig (4.3) for illustration. As can be seen from fig (4.3), only prominent drainage channels present in the watershed were considered. Channel properties were taken from SWC&D (1991).

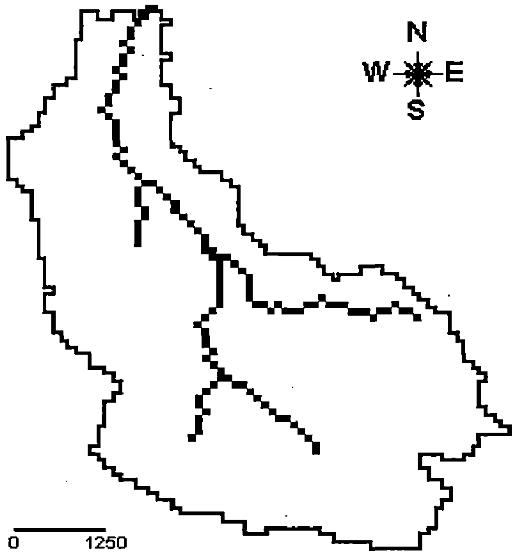


Fig 4.3 Channel network used in ANSWERS model

The land use 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 geocoded 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 ANSWER 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 (2000) 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 the categories viz. clay loam, silty loam and silty loam in Karso catchment. The soil characteristics such as fraction of sand, silt, clay and organic natter, 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 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).

For creating the input file for ANSWERS, individual element description is used. The measured slope steepness and aspect, soil type, land use type, sub-surface drainage and channel features of each element is required in the model. Different soil parameter values including total porosity, field capacity, steady state inflation rate, soil erodibility factor (USLE-K factor) were taken from the Soil Survey Report as well as from the user manual of ANSWERS. Measured rainfall intensity at 60-min and 30 min (as per the data availability) time interval were used. The antecedent soil moisture content in terms of percent saturation before the start of each rainfall event was determined with a moisture balance equation as described in the ANSWERS user manual (Beasley and Huggins, 1991).The parameters for land use and surface condition information also were obtained from the model user manual.

CHAPTER V

MODEL PERFORMANCE EVALUATION

The qualitative judgment of the model performance is not as precise as the quantitative one. The results obtained from model calibration need to be analysed through visual comparison and statistical tests. Visual comparison provides an idea about the general match of the hydrograph characteristics for example peaks, recession limbs. Whereas statistical based criteria provide a more objective method for evaluation of the performance of the models (El Sadek et. al., 2001). Most of the statistical techniques for performance evaluation of hydrologic models suggest the suitability of the model whereas most commonly used student's t-test does not support the statement. Therefore, it emphasizes the need of using more than one statistical test for performance evaluation of hydrologic and NPS pollution models before drawing any conclusion about their actual suitability in actual applications (Ahmed et al., 2006). Statistical parameters such as per cent deviation Dv., Nash and Sutcliffe's coefficient of efficiency, NSE (Nash and Sutcliffe, 1970), coefficient of determination (C_D) , root mean square error (RMSE) , index of agreement of difference, goodness of fit (R^2) IOD-d (Willmott. 1981) and student's t test for significant difference at 95% confidence level are some of commonly used error statistics and used to test the performance of the model. The above mentioned statistical parameters used to evaluate model simulation have been defined below:

5.1 Root mean square error

The root mean square error (RMSE) is given by

$$E_{RMS} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}}{\overline{O}}$$

Where: O_i is observation at time step i; P_i is prediction at time step i; n is the number of data points; E_{RMS} is the root mean square error; and $\bar{O}$ is the mean of the observed values. The E_{RMS} has a minimum value of 0, with a better agreement close to 0 and quantifies how much the simulations overestimate or underestimate the measurements.

5.2 Nash–Sutcliff Coefficient of efficiency (NSE)

The coefficient of Nash–Sutcliff (NSE) is given by

$$C_{NS} = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}$$

Where: C_{NS} denotes the Nash–Sutcliff coefficient and ranges from minus infinity to 1, with higher values indicating better agreement. As per C_{NS} criteria simulation results are considered to be very good for values of $C_{NS} > 0.75$, whereas for values of C_{NS} between 0.75 and 0.36, simulation results considered as satisfactory (Motovilov et al., 1999). If the value of C_{NS} is negative, the model prediction is worse than the mean observation. In other words, a negative value for C_{NS} indicates that the averaged measured values give a better estimate than the simulated values.

5.3 Coefficient of determination

The coefficient of determination (C_D) is given by

$$C_D = \frac{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2}{\sum_{i=1}^{n} \left(P_i - \overline{O}\right)^2}$$

Where: C_D is the coefficiency of determination. The C_D describes the ratio of the scatter of the simulated values and the observed values around the average of the observations. A value for the C_D of 1 indicates the simulated and observed values match perfectly. It is positive defined without upper limit and with zero as a minimum. This criterion has been applied by El-Sadek *et al.* (2001) and is completely different from the definition of R^2 which is commonly known as coefficient of determination.

5.4 Goodness of fit

The goodness of fit R^2 is denoted by

$$R^2 = \frac{\left[\sum_{i=1}^{n} \left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)\right]^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n} \left(P_i - \overline{P}\right)^2}$$

Where: R^2 is the measure of relationship between two data sets and describes the proportion of the total variance in the observed data that can be explained by the model (Legates & McCabe, 1999). The value of R^2 ranges from 0 to 1, with higher values indicating better agreement.

5.5 Index of agreement of difference

$$IA = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left(|P_i - O_i| + |P_i + O_i|\right)^2}, \quad 0 \leq IA \leq 1$$

The index of agreement IOA-d (Willmott 1981) is a statistical measure of the correlation of the predicted and measured concentrations.

5.6 Student's t-test

Suppose we want to test if two independent samples x_i (i=1, 2... n_1) and y_j, (j=1, 2... n_2) of sizes n_1 and n_2 have been drawn from two normal populations with means μ_x and μ_y respectively.

$$t = \frac{x' - y'}{s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

Where: $x' = \frac{1}{n_1}\sum_{i=1}^{n} x_i$, $y' = \frac{1}{n_2}\sum_{j=1}^{n} y_j$

And $S^2 = \frac{1}{n_1 + n_2 - 2}\left[\sum (x_i - x')^2 + \sum (y_j - y')^2\right]$

If

$$|t| \prec t_{0.05, n_1 + n_2 - 1}$$

Then the means do not differ significantly

The student's t-test is performed at 95% significance level. The value of $t_{0.05,\, n1+n2-1}$ is evaluated from the t-distribution tables and then compared with the t value obtained from the formula given above. If $|t| < t_{0.05,\, n1+n2-1}$, then it is concluded that the two means i.e. the sample mean and the population mean do not differ significantly at 95% significance level.

5.7 Percent deviation (Dv)

The percent deviation (Dv) is a measure of the average tendency of the model to overestimate or underestimate the measurements. The optimal deviation value is 0; a positive value indicates underestimation, whereas a negative value indicates overestimation (Gupta *et al.* 1999). Dv may be expressed as

$$D_v = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \times 100$$

Where: Dv denotes the percent deviation, O_i denotes the observed values and P_i denotes the predicted values and n denotes the number of observations..

The under prediction / overprediction by the model within or equal to 20% of observed values as the criteria of success suggested by Bingner et al., (1989) is considered acceptable level of accuracy for the simulations. The under predictions /overprediction with per cent deviation less than 10% are considered as low (slight), 10-20% as moderate, 20-30% as severe and greater than 30% as very severe.

CHAPTER VI

MODEL CALIBRATION

6.1 Model calibration

Calibration of a distributed model is necessary because it is difficult to choose values of parameters which are representative of the entire catchment and the hydrologic conditions. Also in case of distributed hydrological models, such as ANSWERS, several interdependent parameters do exist in the model. It is generally difficult to arrive at appropriate value of parameters using manual trial and error. In such situations, automated optimization algorithms are very helpful (Duan et al., 1993). In present study, the suffled complex optimization algorithm (SCE-UA) (Duan et al., 1993) is linked to ANSWERS model to optimize model parameters. Nine storms (5 storms of 1993 and 4 storms of 1995) were used for model calibration. Fifteen parameters viz. total porosity, field capacity, Fc, steady state infiltration rate, infiltration exponent, K (erosion constant), Potential interception, roughness coefficient, rough height, Manning's constant for overland flow, erosion constant (C) and Manning's N for channel flow were considered for optimization. A range is defined for each parameter along with the initial value in the input file (SCEUA.IN). The range and the initial values of these parameters can be adjusted. The model runs many times using different values of the parameters to arrive at minimum value of objective function defined as sum of the squared difference between observed and model computed output. The output of the optimization subroutine is writing in the SCEUA. OUT file. The optimum multipliers for each parameter are listed in this file .This string of optimum multipliers is then located in the OUT file (the model output file). After each parameter adjustment the simulated and observed runoff, peak flow and sediment yield values were compared to judge the improvement in simulations. The watershed soil properties used in ANSWERS model simulation are given in table (6.1). Evaluation of model performance is done by dividing rainfall pattern of the study area into four classes, as given below, in order to assess the model simulation results under varying conditions.

Rainfall <=25mm	very small storm
25mm< rainfall<=50mm	Small storm
50mm< rainfall<=75mm	Medium storm
Rainfall>75mm	Large storm

The intensity of the storms is also divided into different groups as given below.
The maximum 60 day storm is considered for simulation analysis as most of the rainfall data is available at 60 minutes interval.

I60 <=15mm/hr	Very Low intensity storm
15mm/hr< I60<=30mm/hr	Low intensity storm
30mm/hr< I60<=45mm/hr	Medium intensity storm
45mm/hr<I60<=60mm/hr	High intensity storm
I60>60mm/hr	Very high intensity storm

Table 6.1 Watershed soil properties used in ANSWERS model simulation

Soil texture class/Soil parameter(s)	Silty loam	Clay loam	Silty clay loam
"A" horizon depth (mm)	(190-22	(225-252)	(210-240)
Wilting point WP (% sat)	(25-32)	(34-41)	(27-37)
Total Porosity TP (%)	(38-45)	(42-52)	(40-51)
Field capacity (% sat.)	(73-77)	(80-87)	(75-85)
Final infiltration Capacity,Fc(mm/hr)	(5-8.5)	(1.6-3)	(4.5-7)
Maximum infiltration Capacity, A (mm/hr)	(41-63)	(10-25)	(15-37)
Parameter for Infiltration, P	(0.49-0.	(0.52-0.58)	(0.50-0.58)
Control Zone depth DF (mm)	100.4	113.7	104.2
USLE K factor	(0.40-0.	(0.42-0.64)	(0.45-0.6)

During model calibration process the sensitive parameters such as ASM and field slope were not adjusted as these were known and measured parameters. Soil moisture values were calculated using the moisture condition during the five days prior to the occurrence of storm. The antecedent moisture condition (AMC) values were obtained using the formula stated in the ANSWERS user manual. Some of the LULC based parameters were varied according to vegetative growth stages and some were considered fixed. The calibrated values of land use and land cover based input parameters of the ANSWERS such as potential interception volume (PIT), Percent cover (PER), roughness coefficient (RC), maximum roughness height (HU), Overland Manning's (n) and relative erosiveness parameter(C`) are given in table 6.2 and table 6.3.

Table 6.2 Values of land use and land cover based input parameters used in model calibration whose values were fixed

Land use/land cover	PIT	PER	RC	HU
Dense jungle	0	40	55	110
Scrub	0	30	40	10
Paddy	0	10	38	30
Waste	0	15	35	40
Water	0	0	0.09	0.1

Table 6.3 Values of land use and land cover based input parameters used in model calibration were varied according to vegetative growth stages

Land use/land cover	Overland Manning's (n)		relative erosiveness parameter(C`)	
Dense jungle	VGS-I	0.180	VGS-I	0.040
	VGS-II	0.200	VGS-II	0.030
	VGS-III	0.280	VGS-III	0.020
	VGS-IV	0.320	VGS-IV	0.020
Scrub	VGS-I	0.020	VGS-I	0.280
	VGS-II	0.040	VGS-II	0.350

	VGS-III	0.060	VGS-III	0.400
	VGS-IV	0.090	VGS-IV	0.420
Paddy	VGS-I	0.024	VGS-I	0.300
	VGS-II	0.080	VGS-II	0.350
	VGS-III	0.160	VGS-III	0.400
	VGS-IV	0.230	VGS-IV	0.500
Waste	VGS-I	0.026	VGS-I	0.801
	VGS-II	0.030	VGS-II	0.701
	VGS-III	0.040	VGS-III	0.601
	VGS-IV	0.065	VGS-IV	0.601
Water	0.001		1.000	

The vegetative growth stages used in the above table have been defined in the following manner. VGS-I: rough fallow and crop pre sowing stage, VGS-II: crop seeding /sowing and branching stage, VGS-III: Crop establishment stage, VGS-IV: crop growth and maturity stage.

The following sections discuss about the total runoff volume, peak flow and total sediment yield simulation for all the calibration events and their statistical computations.

6.2 Runoff simulation

The storms occurred on 10/14/1995 and 08/04/1995 show over prediction in the total runoff values with deviations 10.06% and 10% respectively. Thus the model over predicts total storm runoff with an average deviation of 10.03% for very small storms of low intensity occurring under AMC-III (antecedent soil moisture condition-III). For the storms occurring on 06/14/1993 and 09/02/1993 the total storm runoff is under predicted with deviations, -7.48% and -0.76% respectively. Thus for very small storms of very low intensity occurring under AMC-III, the model under predicts the total storm runoff with an average deviation of -4.12%. In the case of very small storms of low intensity occurring under AMC-II (07/29/1995) total runoff value is moderately under predicted with deviation equal to -17.73%.

For medium storms of high intensity occurring under AMC-I (10/12/1993) the model severely under predicts total storm runoff with deviation -27.38%. The large storms of medium intensity, occurring under AMC-III (09/14/1993) the model severely under predicts total storm runoff with deviation -23.26% .Finally for small storms of medium intensity occurring on 08/30/1993 and 08/07/1995, under AMC-II, the total storm runoff is predicted with deviations -25.30% and -25.90% respectively .The average deviation in this case is found to be -25.6% indicating severe under prediction. Thus the model predicts total runoff well within the acceptable range (Dv<=20%) for very small storms of low and very low intensity occurring under AMC-III and for very small storms of low intensity occurring under AMC-II .The average deviation is -11.88% which indicates a trend of under prediction .

The simulated total storm runoff values are found to be distributed on the lower side of 45^0 line (1:1 line) for all the storms, indicating a trend of under prediction(fig 6.1(A)). The high value of R^2=0.96 and CNS=0.93 and IOA-d=0.97 indicates a good correlation between the measured and simulated total runoff values. The high value of C_D=1.66, indicates a poor agreement between observed and predicted values and the value of root mean square error (=0.42) shows a fair simulation. Finally the student's t-test for difference (t-diff) indicates that the difference between the mean of observed and simulated runoff is not significant at 95% level of confidence. The model simulated total runoff values with average deviation Dv= -11.88%. Hence, statistical tests indicate that the model has simulated total storm runoff well within the acceptable level of accuracy (average Dv<=20%).

6.3 Peak runoff rate simulations

For the storms on 10/14/1993 and 08/04/1995 the model simulates peak runoff rate with deviations 7.23% and -0.50% respectively. Thus the model over predicts peak runoff rate with an average deviation, 3.365% for very small storms of low intensity occurring under AMC-III. In the case of very low intensity storms occurring on 09/02/1993 and 07/14/1995 the peak runoff rate is simulated with deviations 3.23% and -1.30% respectively. Thus the model over predicts peak runoff rate with an average deviation 0.965% for very small storms of very low intensity occurring under AMC-III. For very small storms of low intensity occurring under AMC-II storm (07/29/1995) the model predicts peak runoff rate with deviation, 0.93% indicating a good agreement between the observed and simulated values.

The storms occurring on 08/30/1993 and 08/07/1995 show over prediction in peak runoff rate with deviations 4.82% and 5.48% respectively. Thus for small storms of medium intensity occurring under AMC-II, the model over predicts peak runoff rate with an average deviation of 5.15%. For medium storms of high intensity occurring under AMC-I (10/12/1993) the peak runoff rate is over predicted with deviation 5.75% and for large storms of medium intensity occurring under AMC-I (09/14/1993) the peak runoff rate is over predicted with a deviation of 4.065%.Hence in all the cases the deviations are less than 10% indicating a close match between the observed and predicted values. The average deviation is found to be 3.30% which indicates a trend of slight over prediction. Thus the model simulates peak runoff rate well within the acceptable range (Dv<=20%). From fig 6.1(B) one can see that some of the simulated peak runoff rate values are lying above the 1:1 line showing slight overprediction.. The high value of R^2 (=0.99), C_D (=0.917), CNS (=0.97) and IOA-d=0.98 indicates a close agreement between observed and simulated peak runoff rate. The low value of RMSE (= 0.07) indicates a good match. Finally the student's t-test for difference (t-diff) indicates that the difference between the mean values of observed and simulated peak runoff rate is not significant at 95% level of confidence. The model predicted peak runoff rate values with average deviation, 3.30%. Thus statistical tests indicate that the model has simulated peak runoff rate well within the acceptable level of accuracy (average Dv<=20%).

6.4 Sediment yield simulations

For the storms occurring on 10/14/1993 and 08/04/1995 the model simulates total sediment yield with deviations -2.55% and 2.62 % respectively. Thus the model over predicts total sediment yield with an average deviation 0.035% for very small storms of low intensity occurring under AMC-III. The storms occurring on 09/02/1993 and 07/14/1995 shows under prediction with deviations -11.22% and -3.12% respectively. Thus for very small storms of very low intensity occurring under AMC-III. the model under predicts sediment yield with average deviation -7.17% .In the case of very small storms of low intensity occurring under AMC-II (07/29/1995) there is a slight under prediction with deviation, -2.09 % .For the storms occurring on 08/30/1993 and 08/07/1995 the model predicts total sediment yield with deviations 0.94% and -12.21% respectively. Thus the model under predicts total sediment yield with average deviation -5.635% for small storms of medium intensity occurring under AMC-II. Finally for high intensity storm occurring under AMC-I, (10/12/1993) the total sediment yield is predicted with deviation -3.77% and for large storms of medium intensity occurring under AMC-I (09/14/1993) the total sediment yield is predicted with deviation 1.65% indicating a close match between the observed and simulated values. The average deviation is found to be -3.31% indicating a trend of under prediction. Hence in case of all the events the model predicts total sediment yield reasonably well within acceptable range (Dv<=20%). From figure 6.1(C) one can see that most of the simulated sediment yield values are lying on the 1:1 line and few values are lying below the 1:1 line. The high value of R^2 (=0.998), C_D (=0.98), CNS (=0.94), IOA-d (=0.80) indicates a good agreement between observed and simulated total sediment yield values .The RMSE=0.30, showing an average agreement between observed and predicted values. The student's t-test indicates that the difference between mean values of observed and simulated sediment yield is not significant at 95% level of confidence. The model predicted sediment yield with average deviation -3.31%, .Thus the statistical tests indicates that the model simulates total sediment yield values well within acceptable (Dv<20%). Table 6.4 is a tabular representation of all the above described statistical test results.

Table 6.4 Performance evaluation statistical parameters

Mean mm,m3/sec, * 10-3 t/ha	9.56	9.26	1138.57
Average Dv (%)	-11.88	3.3	-3.31
Coefficient of Nash Sutcliffe Efficiency (NSE)	0.93	0.97	0.94
Coefficient of determination (C_D)	1.66	0.91	0.98
Root mean square error (RMSE) mm,m3/sec,*10-3t/ha	0.42	0.07	0.3
Index of agreement for difference (IOA-d)	0.97	0.98	0.80
Student's t-test for difference (t-diff)	0.025	-0.006	0.00017
t-table value for two tailed distribution	2.131	2.131	2.131
Goodness of fit (R^2)	0.96	0.99	0.9986

The Nash Sutcliffe efficiency (E) values evaluated by the model (table 6.5) for the calibration events range from 0.72 to 0.95 with an average value of 0.80 indicating a good model fit. For one event viz. 10/02/1993 the value of E is above 90%. For three events (10/12/1993, 10/14/1993 and 08/07/1995) the values of the E are ranging from 0.80 to 0.90. For two events (06/14/1995 and 07/29/1995) the values are within 0.75-0.80 indicating a good match. For three events (09/4/993, 08/30/993 and 08/07/1995) the values are within 0.70-0.75 indicating a satisfactory match. A tabular representation of runoff, peak flow and sediment yield simulation for storms used in calibration of the ANSWERS model is shown in table 6.5.

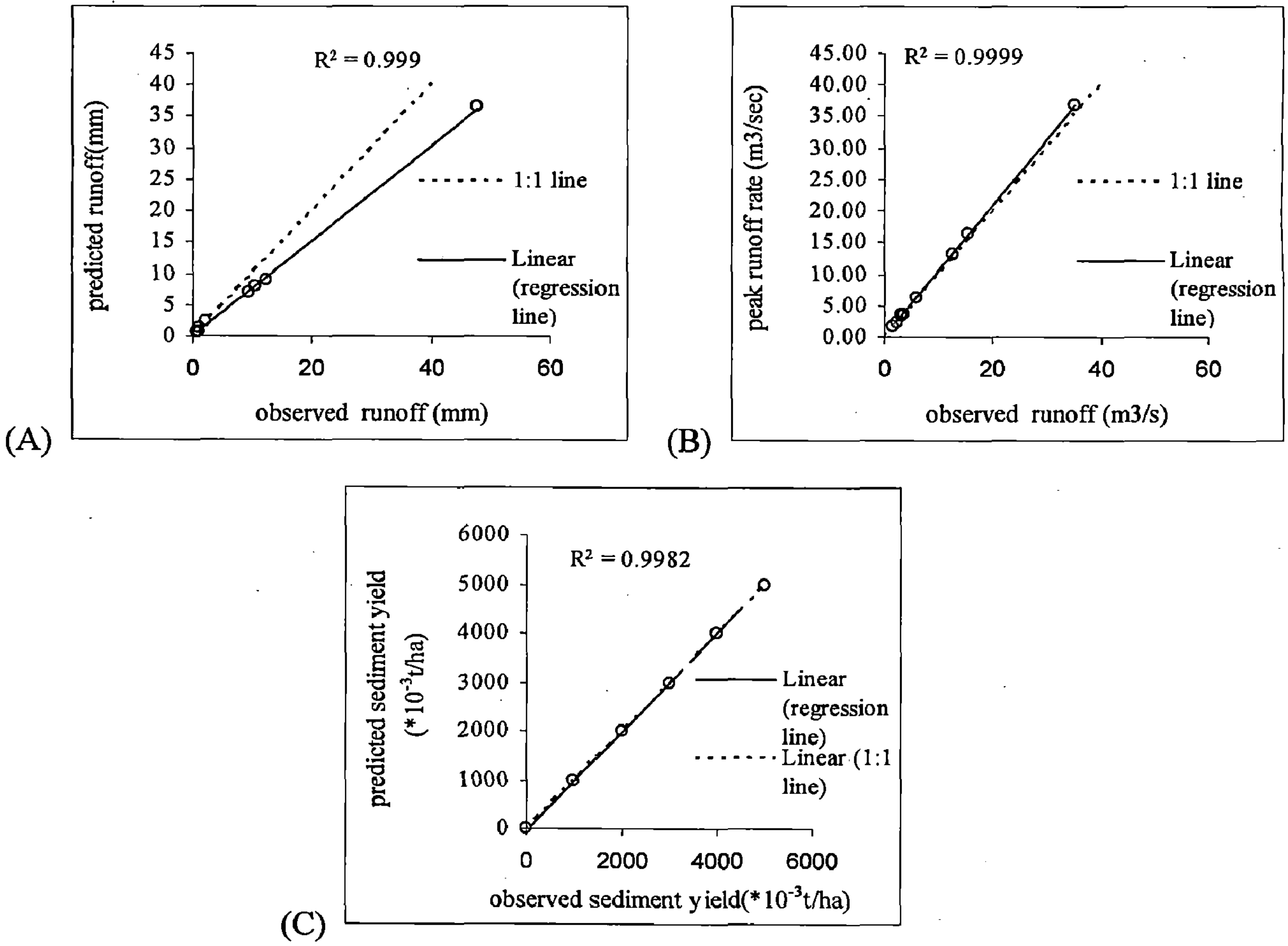
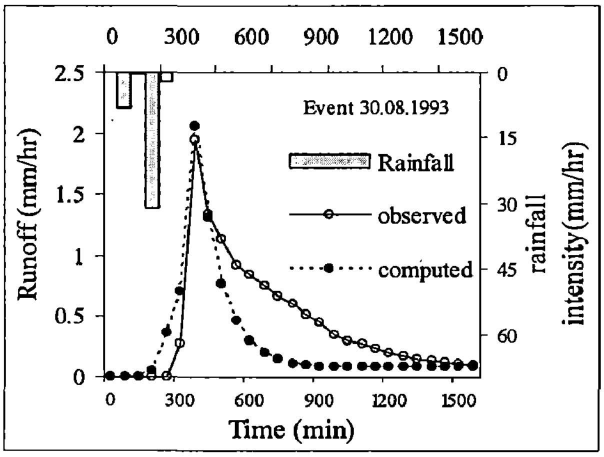
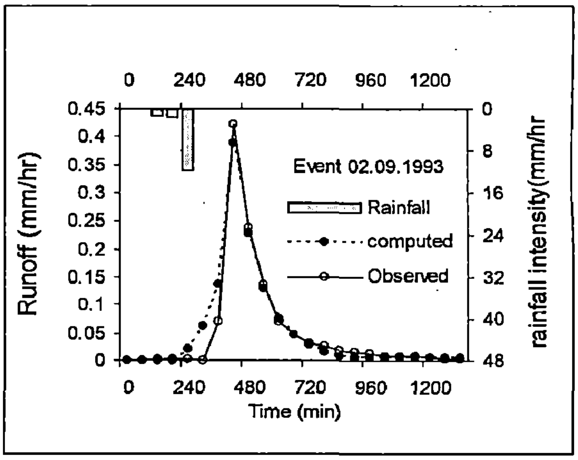


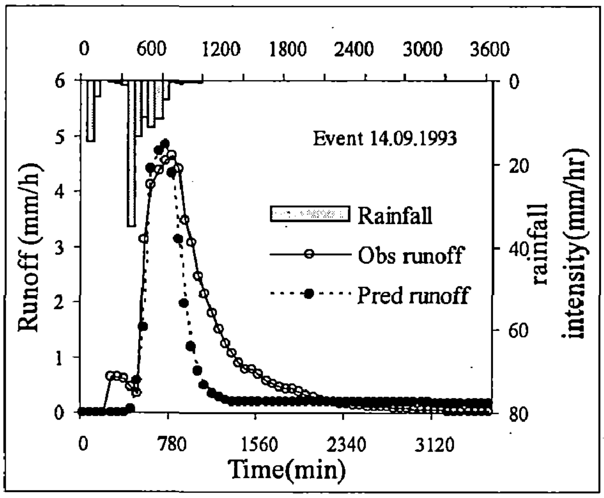
Fig 6.1 (A) Runoff, (B) Peak flow and (C) Sediment yield simulated values for calibration storms.

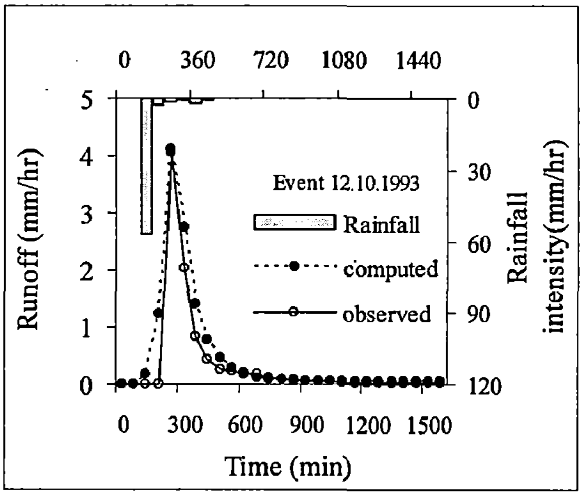
Table 6.5 Runoff, peak flow and sediment yield simulation for storms used in calibration of the ANSWERS model

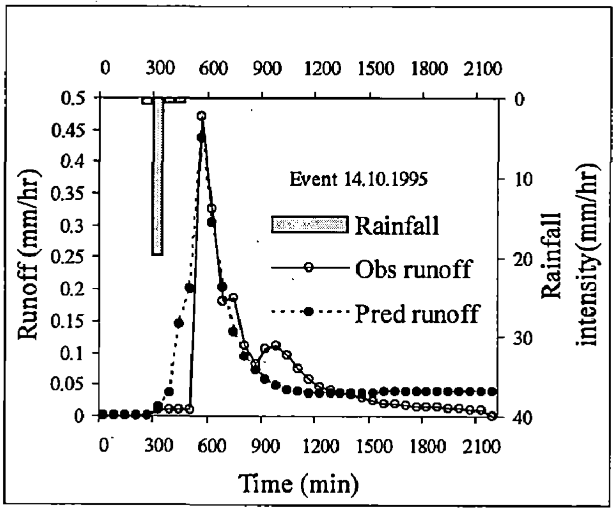
				observed			simulated	deviation (%)		Model computed efficiency
AMC	storm date	storm size	I60(mm/hr)	RO(mm)	Q_P(m3/sec)	SY* 10^{-3}(t/ha)	RO	Q_P	SY	E
3	2-Sep-93	0-25	11.9	1.19	3.1	198.127	-0.76	3.23	-11.22	0.95
3	14-Oct-93	0-25	19.8	2.187	3.32	266.123	10.56	7.23	-2.55	0.84
3	14-Jun-95	0-25	6.7	0.829	1.772	98.658	-7.48	-1.30	-3.12	0.76
2	29-Jul-95	0-25	21.8	0.976	2.26	131.835	-17.73	0.93	-2.09	0.77
3	4-Aug-95	0-25	15.7	1.26	3.621	147.958	10.34	-0.50	2.62	0.72
2	7-Aug-95	>25-50	37.3	9.31	12.59	1119.550	-25.90	5.48	-12.21	0.82
2	30-Aug-93	>25-50	31.1	10.392	15.55	1107.682	-25.30	4.82	0.94	0.73
1	12-Oct-93	>50-75	56.9	12.311	5.91	2731.126	-27.38	5.75	-3.77	0.87
1	14-Sep-93	>75	35.3	47.54	35.25	4446.058	-23.26	4.06	1.65	0.73

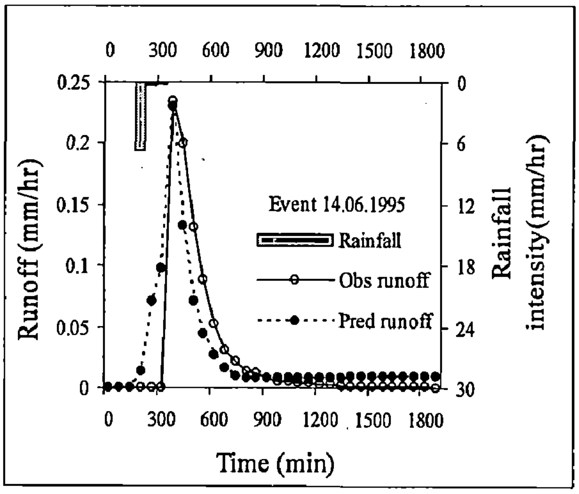

Event 30.08.1993
Rainfall
observed
computed
Runoff (mm/hr)
rainfall intensity(mm/hr)
Time (min)
0
300
600
900
1200
1500
0
0.5
1
1.5
2
2.5
0
15
30
45
60


Event 02.09.1993
Rainfall
computed
Observed
Runoff (mm/hr)
rainfall intensity(mm/hr
Time (min)
0
240
480
720
960
1200
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
8
16
24
32
40
48


Event 14.09.1993
Rainfall
Obs runoff
Pred runoff
Runoff (mm/h)
rainfall intensity(mm/hr)
Time(min)
0
600
1200
1800
2400
3000
3600
0
780
1560
2340
3120
0
1
2
3
4
5
6
0
20
40
60
80


Event 12.10.1993
Rainfall
computed
observed
Runoff (mm/hr)
Rainfall intensity(mm/hr)
Time (min)
0
360
720
1080
1440
0
300
600
900
1200
1500
0
1
2
3
4
5
0
30
60
90
120


Event 14.10.1995
Rainfall
Obs runoff
Pred runoff
Runoff (mm/hr)
Rainfall intensity(mm/hr)
Time (min)
0
300
600
900
1200
1500
1800
2100
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
10
20
30
40


Event 14.06.1995
Rainfall
Obs runoff
Pred runoff
Runoff (mm/hr)
Rainfall intensity(mm/hr)
Time (min)
0
300
600
900
1200
1500
1800
0
0.05
0.1
0.15
0.2
0.25
0
6
12
18
24
30

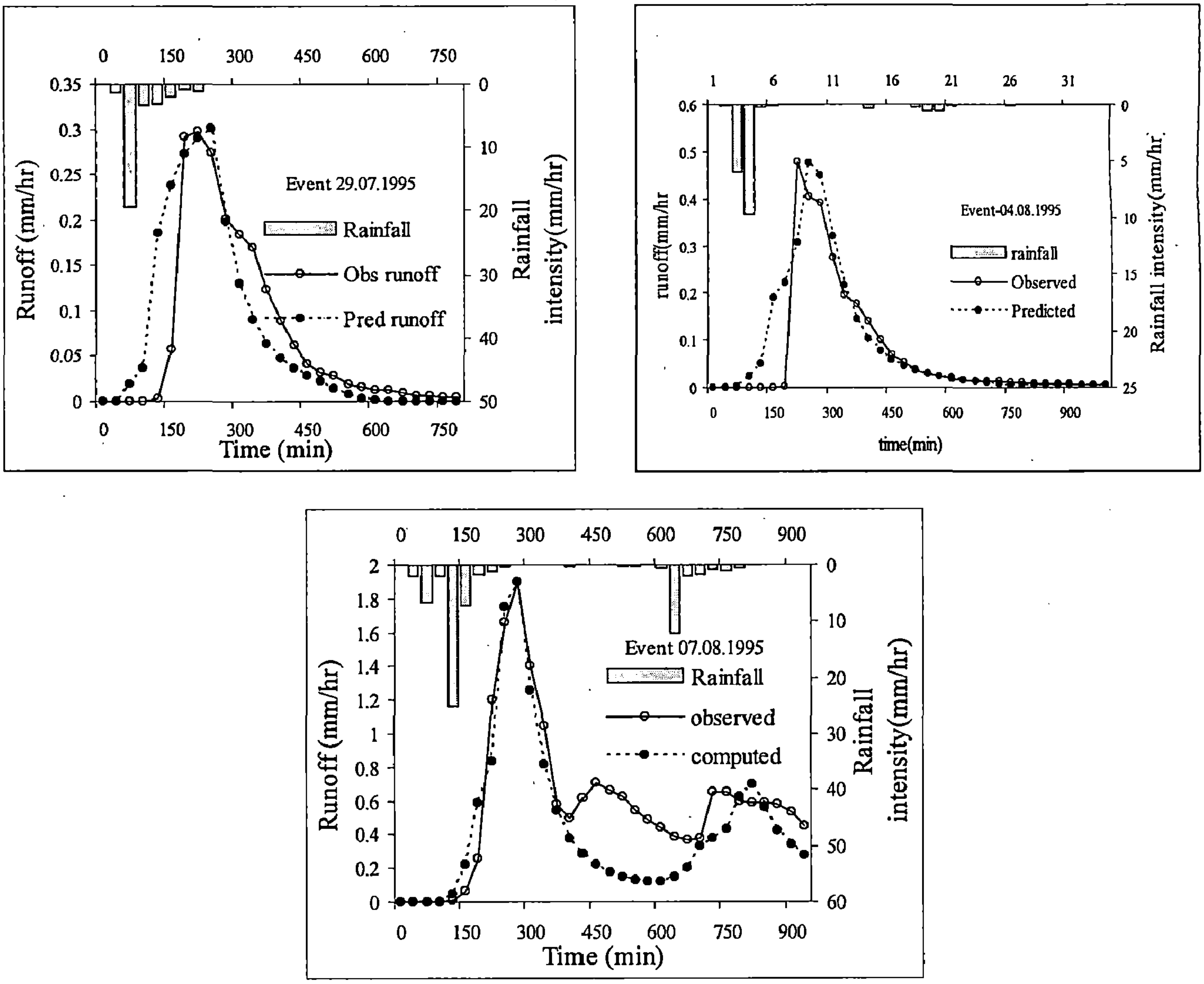


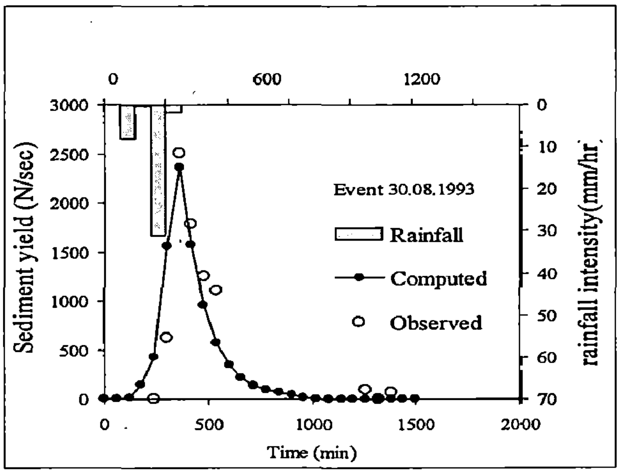
Fig 6.2 Runoff hydrographs of calibration storms

On the basis of statistical tests performed for each event separately the following conclusions have been drawn about the runoff hydrographs (table 6.6). The values of C_D are close to 1 for most of the events except for two events on 09/4/993 and 06/4/995 showing a fair agreement between the simulated and observed values. The values of NSE range from 0.61 to 0.95 with an average value of 0.76 indicating a good match. The values of R^2 range from 0.72 to 0.95 with an average value of 0.81 which indicates a good correlation between the observed and simulated values. The values of RMSE are generally high for most of the events except for two events viz. 09/02/1993 and 08/07/1995 where it indicates a fair agreement. Finally the index of agreement of difference (IOA-d) values range from 0.63 to 0.84, giving an average of 0.71 which shows a satisfactory match.

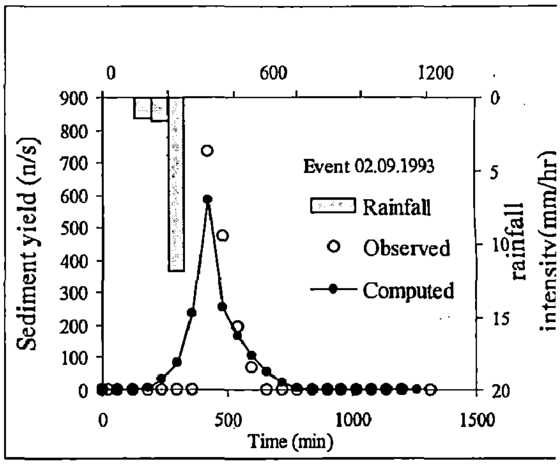
For the purpose of visual comparison, plots were made between observed and simulated runoff values shown in fig 6.2. The hydrographs show that the simulated hydrographs recede rapidly as compared to observed hydrographs. The mismatch is prominently seen in the recession limb of the hydrographs of the events 08/30/1993, 09/14/1993, 07/29/1995 which has resulted in low value of efficiency. The peaks of most of the hydrographs are quite close. This result is supported by the statistical comparisons done for peak flows for all the events (section 6.3). As stated in this section there is trend of slight over prediction with average deviation<5%. The hydrograph of the event 09/02/1993 shows a very good match except for a slight mismatch in the rising limb. This is also evident from good values of Nash Sutcliffe efficiency and other statistical parameters.

Table 6.6 Statistical comparison of runoff hydrographs for each event of calibration storm

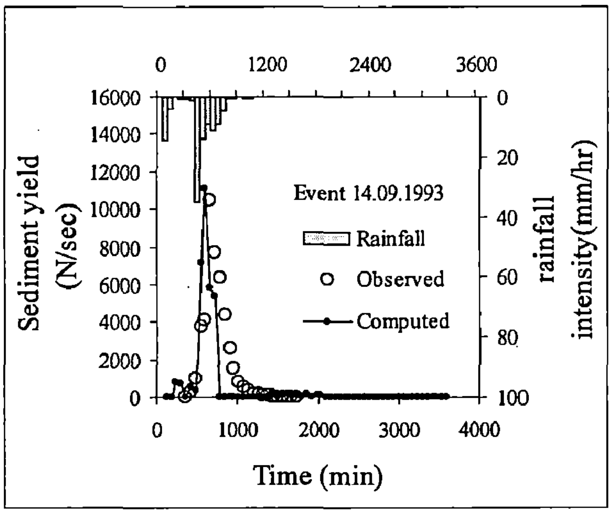
date of the event	storm size	C_D	NSE	R^2	RMSE	IOA-d
Aug-93	>25-50	0.97	0.61	0.72	0.68	0.63
2-Sep-93	0-25	1.11	0.95	0.95	0.40	0.84
14-Sep-93	>75	1.22	0.77	0.81	0.72	0.71
12-Oct-93	>50-75	0.80	0.87	0.91	0.92	0.77
14-Oct-93	0-25	1.17	0.76	0.77	0.78	0.69
14-Jun-95	0-25	1.45	0.74	0.74	1.11	0.69
29-Jul-95	0-25	0.92	0.66	0.75	0.78	0.71
4-Aug-95	0-25	0.96	0.76	0.78	0.84	0.76
7-Aug-95	>25-50	0.89	0.71	0.80	0.42	0.62
average		1.05	0.76	0.81	0.74	0.71


Event 30.08.1993
Rainfall
Computed
Observed
Sediment yield (N/sec)
rainfall intensity(mm/hr)
Time (min)
0
600
1200
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
0
500
1000
1500
2000

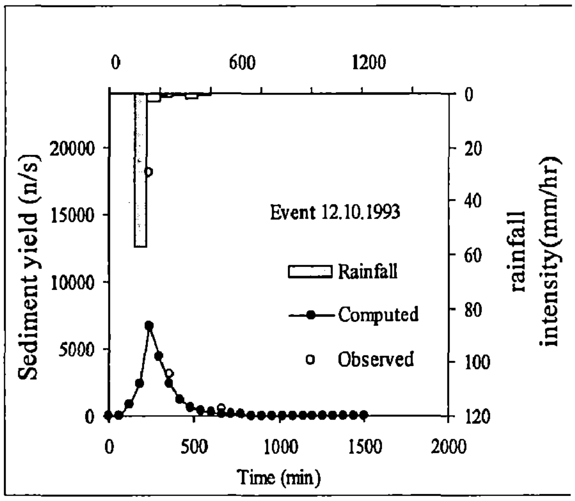
(A)


Event 02.09.1993
Rainfall
Observed
Computed
Sediment yield (n/s)
rainfall intensity(mm/hr)
Time (min)
0
600
1200
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
0
500
1000
1500

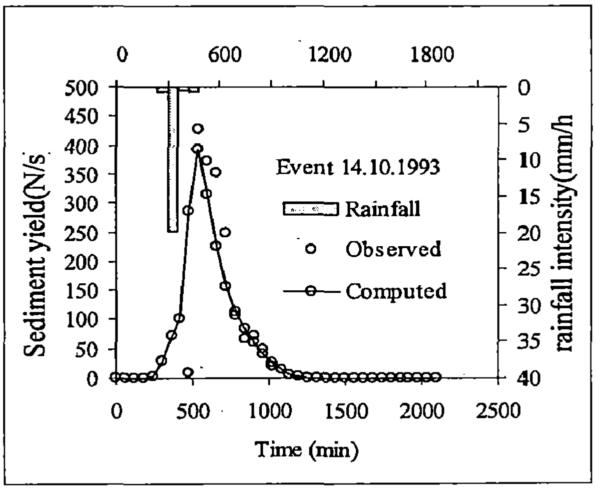
(B)


Event 14.09.1993
Rainfall
Observed
Computed
Sediment yield (N/sec)
rainfall intensity(mm/hr)
Time (min)
0
1200
2400
3600
16000
14000
12000
10000
8000
6000
4000
2000
0
0
20
40
60
80
100
0
1000
2000
3000
4000

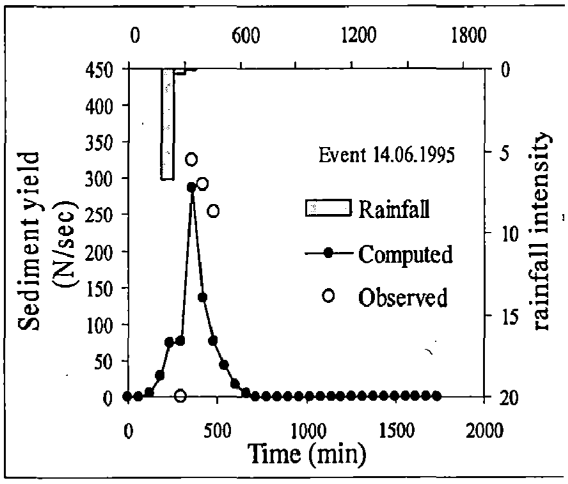
(C)


Event 12.10.1993
Rainfall
Computed
Observed
Sediment yield (n/s)
rainfall intensity(mm/hr)
Time (min)
0
600
1200
20000
15000
10000
5000
0
0
20
40
60
80
100
120
0
500
1000
1500
2000

(D)


Event 14.10.1993
Rainfall
Observed
Computed
Sediment yield(N/s
rainfall intensity(mm/h
Time (min)
0
600
1200
1800
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
0
500
1000
1500
2000
2500

(E)


Event 14.06.1995
Rainfall
Computed
Observed
Sediment yield (N/sec)
rainfall intensity
Time (min)
0
600
1200
1800
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
0
500
1000
1500
2000

(F)

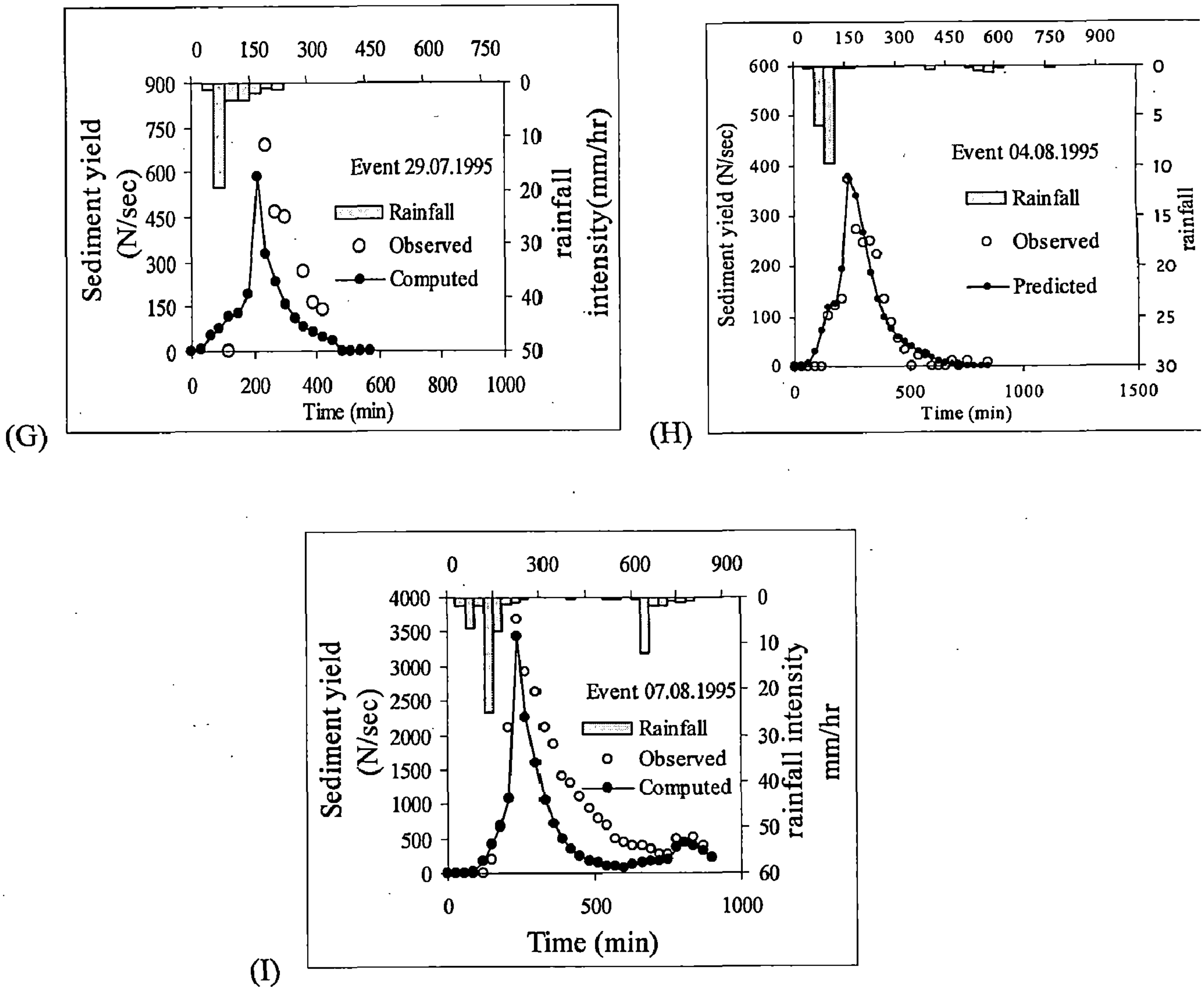


Fig 6.3 Sediment hydrographs for calibration storms

Visual comparison and statistical tests were performed for sediment hydrographs of each calibration event and the following conclusion have been drawn table 6.7. The valued of C_D ranges from 1.01 to 5.06 resulting in an average of 1.89 .This indicates a poor match between the simulated and observed sediment yield values. The value of C_D is quite high the events occurring on 10/12/1993, 06/14/1995 and 07/29/1995 whereas for the events on 09/14/1993 and 08/04/1995 the values are close to 1 indicating a good match. The value of NSE ranges from 0.02 to 0.90 giving an average of 0.61 which indicates a satisfactory match. The values of R^2 range from 0.90 to0.13 giving an average of 0.65, indicating a satisfactory match. The RMSE values range from 0.44 to 2.8 with an average of 1.40 which is satisfactory. Finally the index of agreement values range from 0.19 to 0.45 giving an average of 0.31 which indicates a poor simulation.

From the visual comparisons of the sediment hydrographs one can say that the peaks of observed hydrographs are generally higher than the peaks of the simulated hydrographs. The peak of the hydrograph of the event on 10/2/993 is quite high and very less data is available for simulation which has lead to poor statistical results.. The simulated values are widely scattered particularly on the recession limb of the hydrographs of the events occurring on 07/29/995 and 0/07/995.

Table 6.7 statistical comparison of sediment hydrographs for calibration storms

storm event	storm size	C_D	NSE	R^2	RMSE	IOA-d
Aug-93	>25-50	1.14	0.83	0.84	0.86	0.25
2-Sep-93	0-25	1.75	0.80	0.69	1.16	0.26
14-Sep-93	>75	1.07	0.33	0.43	2.22	0.35
12-Oct-93	>50-75	5.07	0.50	0.62	2.84	0.37
14-Oct-93	0-25	1.34	0.71	0.71	1.01	0.27
14-Jun-95	0-25	2.25	0.69	0.73	1.68	0.28
29-Jul-95	0-25	2.01	0.03	0.14	1.78	0.46
4-Aug-95	0-25	1.01	0.90	0.91	0.45	0.20
7-Aug-95	>25-50	1.32	0.65	0.82	0.64	0.35
average		1.89	0.61	0.65	1.40	0.31

CHAPTER VII

MODEL VALIDATION

7.1 VALIDATION RESULTS

Four storms viz. 08/02/1996, 08/06/1996, 08/09/1996 and 08/17/1996 are used for validation. The values of various parameters that were set for calibration have been used for validation events. Table 7.2 gives a description of runoff, peak flow and sediment yield simulations for validation events.

7.2 Runoff simulation

For very small sized storm of very low intensity occurring under AMC-III (08/09/1996), the model under predicts total storm runoff with deviation -5.49%. Thus the model has under predicted total storm runoff for very small storm of very low intensity storms occurring under AMC-III, with deviation, Dv<10%. The model is found to behave in similar ways as in the case of calibration storms occurring under same conditions.. For medium sized storm of low intensity occurring under AMC-II (08/17/1996), the model highly under predicts total storm runoff with a deviation of -24.93%. For large storm of low intensity occurring under AMC-I (08/02/1996) the total storm runoff is highly under predicted with a deviation -22.11%. For the event 08/06/1996 the total storm runoff is under predicted severely with deviation -27.41 %. Thus, similar to calibration, the total storm runoff for a large event of medium intensity, occurring under AMC-I, is severely under predicted. From fig 7.1(A) one can see that the simulated total storm runoff values are found to be distributed on the lower side of the 45^0 line (1:1 line) for all the storms which indicate the trend of under prediction. The average deviation is found to be -19.98% which shows a trend of under prediction.

Similar to calibration the model simulates total storm runoff within an acceptable level of deviation (Dv<=20%).

As in the case of calibration events, a high value of R^2 (=0.98) and IOA-d (=0.91) indicates a close agreement between observed and simulated values. The value of coefficient of determination, C_D (=1.26), RMSE (=0.29) and NSE (=0.70) shows an average agreement between observed and simulated values. Finally the student's t-test for the difference of means shows that the difference between the mean values of observed and simulated runoff is significant at 95% level of confidence. Thus statistical tests indicate that the model has simulated total storm runoff well within the acceptable level of accuracy

7.3 Peak runoff rate simulation

For the storm on 08/09/1996, under AMC-III, the model under predicts peak runoff rate with a deviation of -5.08%. Thus the model under predicts peak runoff rate for very small storms of very low intensity, occurring under AMC-III with deviation, Dv<5%.This result is similar to calibration results for the same condition. For medium storms for low intensity, occurring under AMC-II (08/17/19996) the model slightly over predicts peak runoff rate with a deviation of 0.54% which is within the acceptable level of accuracy. For large storms of low intensity occurring under AMC-I (08/02/1996) the model slightly over predicts peak runoff rate with a deviation of 0.40% which indicates a good match. Finally for the storm on 08/06/1996 the model over predicts the peak runoff rate with deviation 4.57%. Similar to calibration storms result, the model over predicts peak runoff rate with Dv<5% for large storms of medium intensity occurring under AMC-I. The average deviation for peak runoff rate is 0.081% .Thus similar to calibration storms there is a trend of slight over prediction.

Figure 7.1(B) indicates a trend of slight over prediction as the peak runoff values are above the 1:1 line. The statistical values are similar to that of calibrated values. A values of R^2 (=0.96), C_D (= 0.94), NSE (=0.99), RMSE (=0.04) and IOA-d (=0.97) indicates a close agreement between observed and simulated values. Finally the student's t-test for the difference of means shows that the difference between the mean values of observed and simulated runoff is significant at 95% level of confidence. Thus similar to calibration storms the statistical tests indicate that the model has simulated peak runoff rate well within the acceptable level of accuracy.

7.4 Sediment yield simulation

For very small storms of very low intensity occurring under AMC-III (08/09/1996), the model over predicts sediment yield with a deviation of 2.42%. For the storm on 08/17/19996, occurring under AMC-II, the sediment yield data is not available. For the storm occuring on 08/02/1996 the model slightly under predicts total sediment yield with a deviation of -3.17%. Thus for large storms of low intensity, occurring under AMC-I, the model under predicts sediment yield with deviation Dv<5%. For the storm on 08/06/1996 the model under predicts sediment yield with deviation -16.78%. Thus for large storms of medium intensity the model under predicts sediment yield well within acceptable level of deviation (Dv<20%). The average deviation for total sediment yield is found to be -4.43%, which indicates a trend of under prediction as in the case of calibration storms.

Figure 7.1(C) indicates a trend of under prediction as the sediment yield values are below the 1:1 line. The model predicted sediment yield with a deviation Dv = -4.43%, Similar to calibration storms the values of R^2 (=0.96), NSE (=0.95) indicate a good correlation between observed and simulated values. The values of C_D = 1.20, IOA-d (=0.6) and RMSE (=0.15) indicate an average agreement between observed and simulated values. Finally the student's t-test for the difference of means shows that the difference between the mean values of observed and simulated runoff is significant at 95% level of confidence. Thus statistical tests indicate that the model has simulated peak runoff rate well within the acceptable level of accuracy (average = -4.43%).

Table 7.1: Performance evaluation statistical parameters

Mean mm,m3/sec, * 10-3 t/ha	14.499	16.72	1853.309
Average Dv (%)	-19.98	0.081	-4.43
Coefficient of efficiency (E)	0.70	0.99	0.95
Coefficient of determination (R^2)	0.98	0.96	0.96
Root mean square error (RMSE) mm,m3/sec,*10-3t/ha	0.29	0.04	0.15
Index of agreement for difference (IOA-d)	0.91	0.97	0.60
Student's t-test for difference (t-diff)	0.079	-0.00437	0.00016
t-table value for two tailed distribution	2.131	2.131	2.131
Coefficient of Nash Sutcliffe (N)	0.70	0.99	0.95

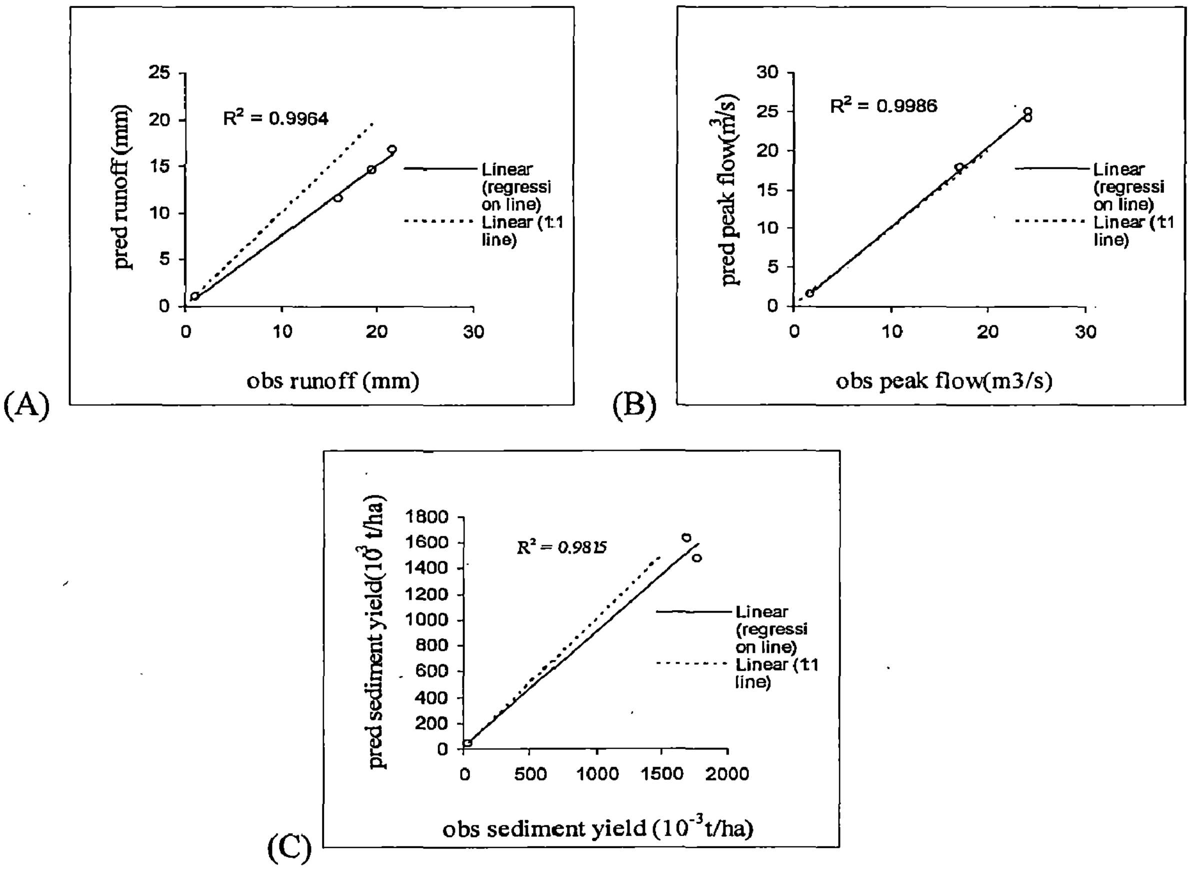


Fig7.1 (A) Runoff, (B) peak flow and (C) sediment yield simulated values for validation storms

Table 7.2 Runoff, peak flow and sediment yield simulation for storms used in validation of the ANSWERS model

					observed		simulated	Deviation (%)		Model evaluated efficiency
AMC	storm date	storm size	I60(mm/hr)	RO(mm)	Q_P(m3/sec)	SY* 10^{-3}(t/ha)	RO	Q_P	SY	E
3	9-Aug-96	0-25	9.8	1.056	1.718	-3.325	-5.492	0.396	2.420	0.81
2	17-Aug-96	>50-75	23.4	19.42	24.06	na	-24.928	4.569	na	0.87
1	2-Aug-96	>75	26.4	21.55	24.03	-6.265	-22.107	-5.080	-3.173	0.78
1	6-Aug-96	>75	30.8	15.97	17.07	-20.926	-27.414	0.540	-16.985	0.74
	average						-19.98	0.081	-4.43	0.80

na =not available

The Nash Sutcliffe efficiency evaluated by the model is found to range from 0.74-0.87 giving an average value of 0.805 .This value indicates a good match between the observed and simulated hydrographs. For two storms viz. 08/09/1996 and 08/17/1996 the values are above 0.80 and for the remaining two events namely 08/02/1996 and 08/07/1996 the values are within 0.70-0.80.

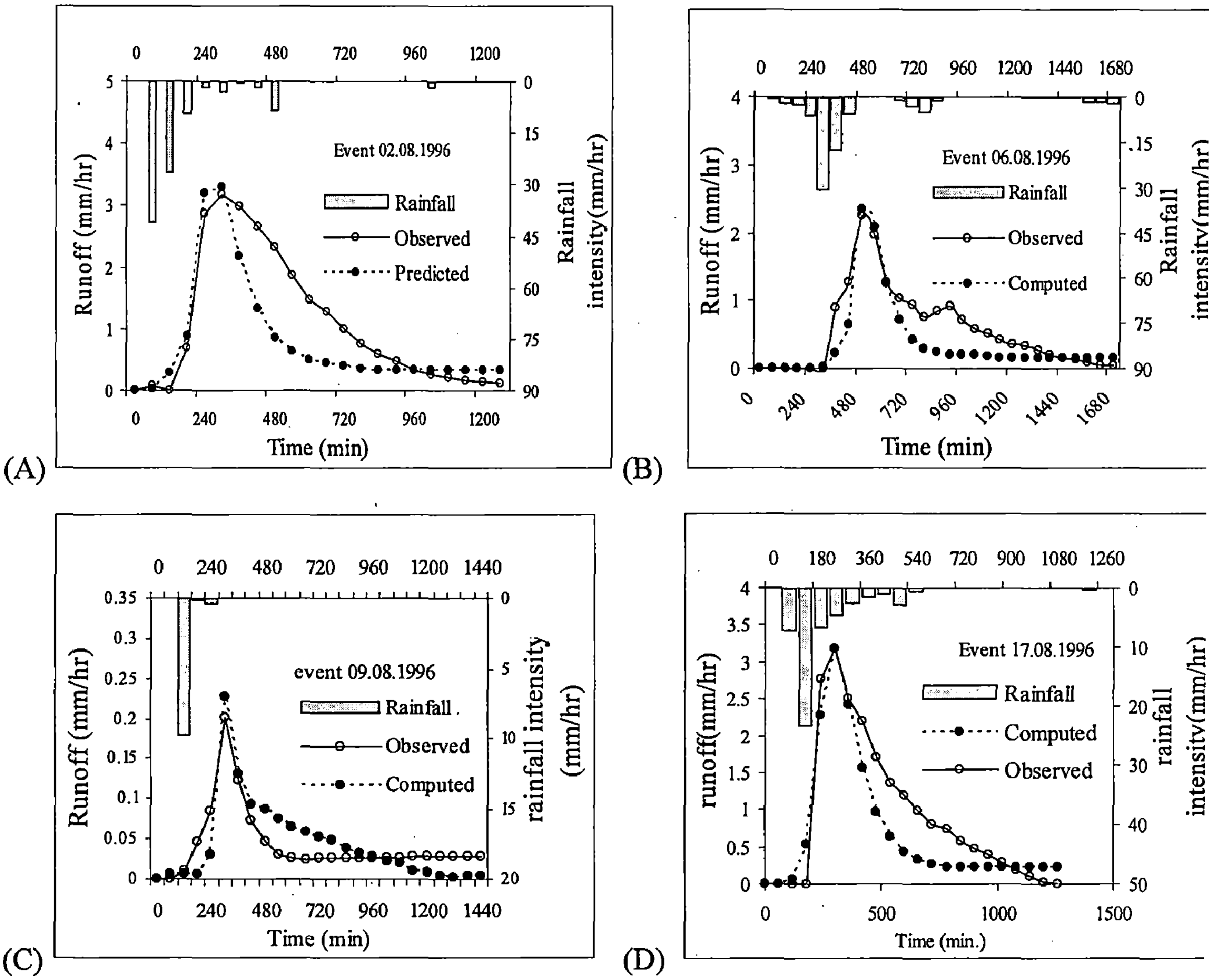


Fig 7.2 Runoff hydrographs of Validation storms

As done for calibration storms visual and statistical comparisons are done for each event of validation storm. Table 7.3 gives the values of various statistical parameters for each validation event. The value of C_D ranges from 0.34 to 1.49 with an average of 1.06

indicating a good match between the simulated and observed values. The values of NSE range from 0.49-0.68 giving an average of 0.47 which indicates a fair agreement. The values of R^2 range from 0.0149 to 0.91 with an average value of 0.62 indicating a fair agreement. The RMSE values range from 0.10 to 1.81 resulting in an average of 0.78 which indicates a fair agreement. Finally the IOA-d values range from 0.27-0.59 with an average of 0.40 indicating an unsatisfactory agreement.

By comparing the hydrographs, one can see that the simulated hydrographs recede rapidly as compared to observed hydrographs. The mismatch is more prominent in the recession limb of the hydrographs and is quite good in the rising limb. The result is similar to that of calibration storms. The peaks runoff values are quite close to each other and the time of occurrence of peaks is same in all the cases.

Table 7.3 Statistical comparison of runoff hydrograph for each event of validation storm

storm event	date of the event	C_D	NSE	R^2	RMSE	IOA-d
2-Aug-96	>75	0.34	0.65	0.01	1.82	0.60
6-Aug-96	>75	0.94	0.70	0.82	0.58	0.36
9-Aug-96	0-25	1.49	0.02	0.75	0.61	0.37
17-Aug-96	>50-75	1.46	0.50	0.91	0.10	0.27
average		1.06	0.47	0.62	0.78	0.40

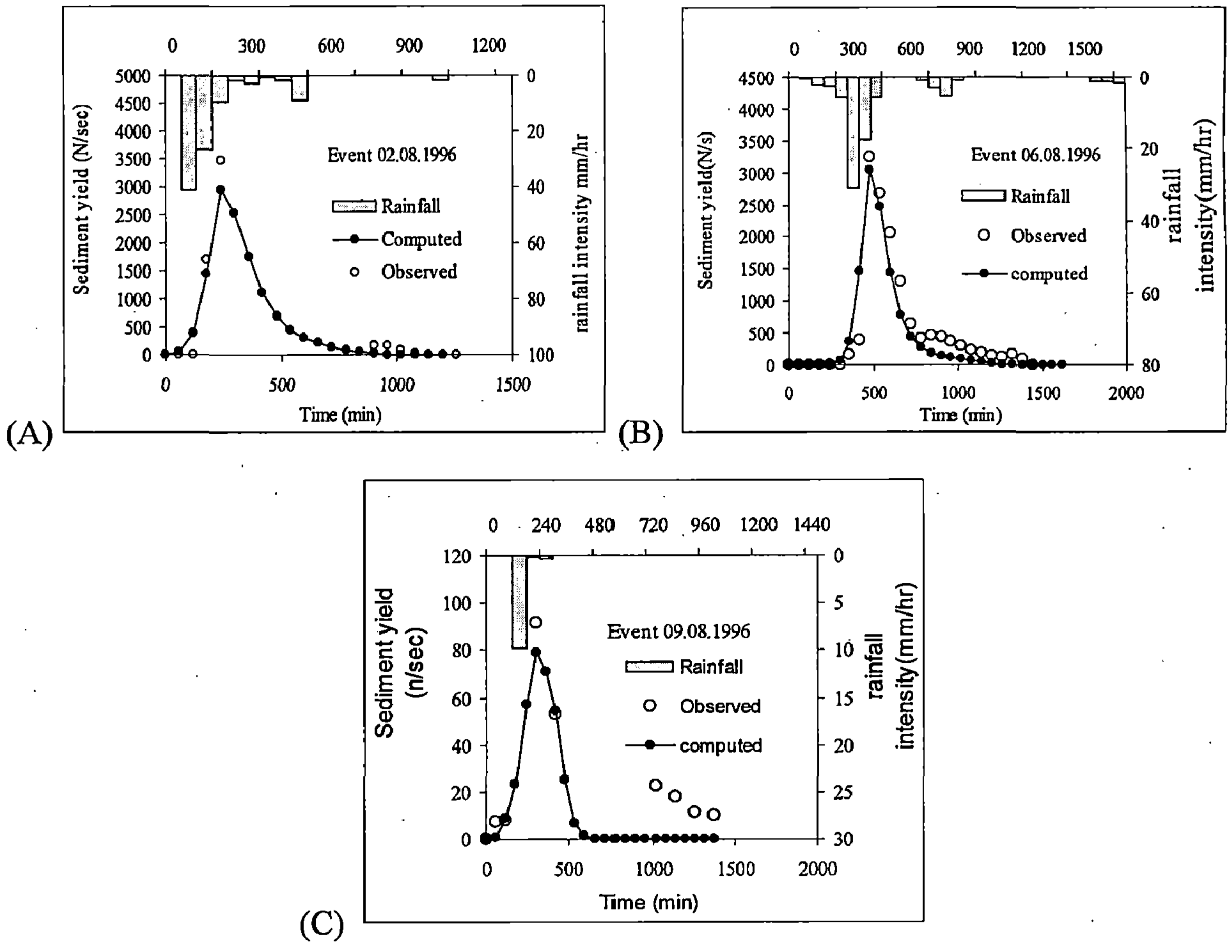


Fig 7.3 Sediment hydrograph for the event 08/09/1996

Statistical (table 7.4) and visual comparison is done for sediment hydrographs of validation storms. Due to the non-availability of data no conclusion could be drawn for the event occurring on 08/17/1995. The values of C_D range from 0.70 to 1.13 giving an average of 0.86 indicating a good match. The values of NSE range from 0.12 to 0.87 with average 0.58 indicating a fair agreement. The value of R^2 ranges from 0.43 to 0.75 with average 0.69 indicating a fair agreement. The values of RMSE lie in the range (0.66-3.02) giving an average of 1.99 leading to a conclusion that the simulation is poor. Finally the IOA-d is giving negative values for two storms viz 08/02/1996 and 08/09/1996 indicating a poor simulation. The reasons for poor simulation can be given to availability of scarce sediment yield data for simulation. Visual representation of the storms on 08/02/1996 and 08/09/1996 clearly support this reason. Most of the data is available for the end part of the hydrograph after the occurrence of peak. The peak values for the simulated hydrographs are lower than that of observed hydrographs but are occurring at the same time, as seen in the case of calibration events.

Table 7.4 Statistical comparison of sediment hydrograph for each event of validation storm

storm event	date of the event	C_D	NSE	R^2	RMSE	IOA-d
2-Aug-96	>75	0.76	0.12	0.43	3.02	-56.13
6-Aug-96	>75	1.13	0.87	0.88	0.66	0.58
9-Aug-96	0-25	0.70	0.74	0.75	2.29	-17.63
average		0.86	0.58	0.69	1.99	-24.40

7.5 Sensitivity analysis

The main purpose of sensitivity analysis is to observe the change in model output with the change in model input parameter. The relative sensitivity of a parameter is defined as:

$$\mathbf{Sr = ((\partial O/O) / (\partial P/P))}$$

Where

Sr = relative sensitivity

O = output

P = input.

Three calibration events viz. 08/12/1993, 09/02/1993, 08/07/1995 and one validation event 08/09/1996 are considered for sensitivity analysis. The parameters considered for sensitivity analysis are porosity, field capacity, infiltration parameters (steady state infiltration, infiltration exponent, maximum infiltration capacity), ASM (antecedent soil moisture condition), K (USLE K factor), Roughness coefficient, roughness height, Manning's N for overland flow, C parameter and manning N (channel property). The optimum values of the coefficients determined through the calibration of the model are altered by +-10%. Since sensitivity analysis is event dependent, each event is sensitive to different parameters. Figures 7.4(A-D) illustrates the results of sensitivity analysis for the various events.

For the event 10/12/1993 the total storm runoff is most sensitive to total porosity followed by A (steady state infiltration) and control zone depth. The peak runoff rate is most sensitive to A followed by Manning's N for overland flow and Porosity. The total sediment yield is most sensitive to porosity, A, Manning's N for overland flow and control zone depth. The total sediment yield is most sensitive to porosity followed by A, control zone and Manning's N for overland flow and C. Thus the most sensitive parameters for the entire event are total porosity, control zone depth and Manning's N for overland flow. For the remaining parameters the percent change in the model determined values is within +-10%.

For the event 09/02/1993 the total storm runoff and peak runoff rate are most sensitive to field capacity followed by ASM (Antecedent moisture condition) and Fc. The total sediment outflow and peak sediment rate are most sensitive to Field capacity, Fc and ASM. Thus the sensitive parameters for this event are field capacity, Fc and ASM. The remaining parameters alter the model result by+-10%.

For the event 08/07/1995 the total storm runoff and peak runoff rate are most sensitive to ASM, porosity, control zone and field capacity. The total sediment and peak sediment rate is most sensitive to ASM succeeded by porosity, control zone, P and A. Thus the event is most sensitive to ASM followed by porosity and control zone. The remaining parameters vary the calibrated values within +-15%.

Finally for the validation event of 08/09/1996 the total storm runoff is most sensitive to ASM and for the rest of the parameters the calibrated values are within +-10%. The peak runoff rate is most sensitive to ASM followed by field capacity and Fc. The total sediment outflow and peak sediment rate are most sensitive to ASM, Field capacity, Fc, K and C. The other values are within +-15% of the calibrated values.

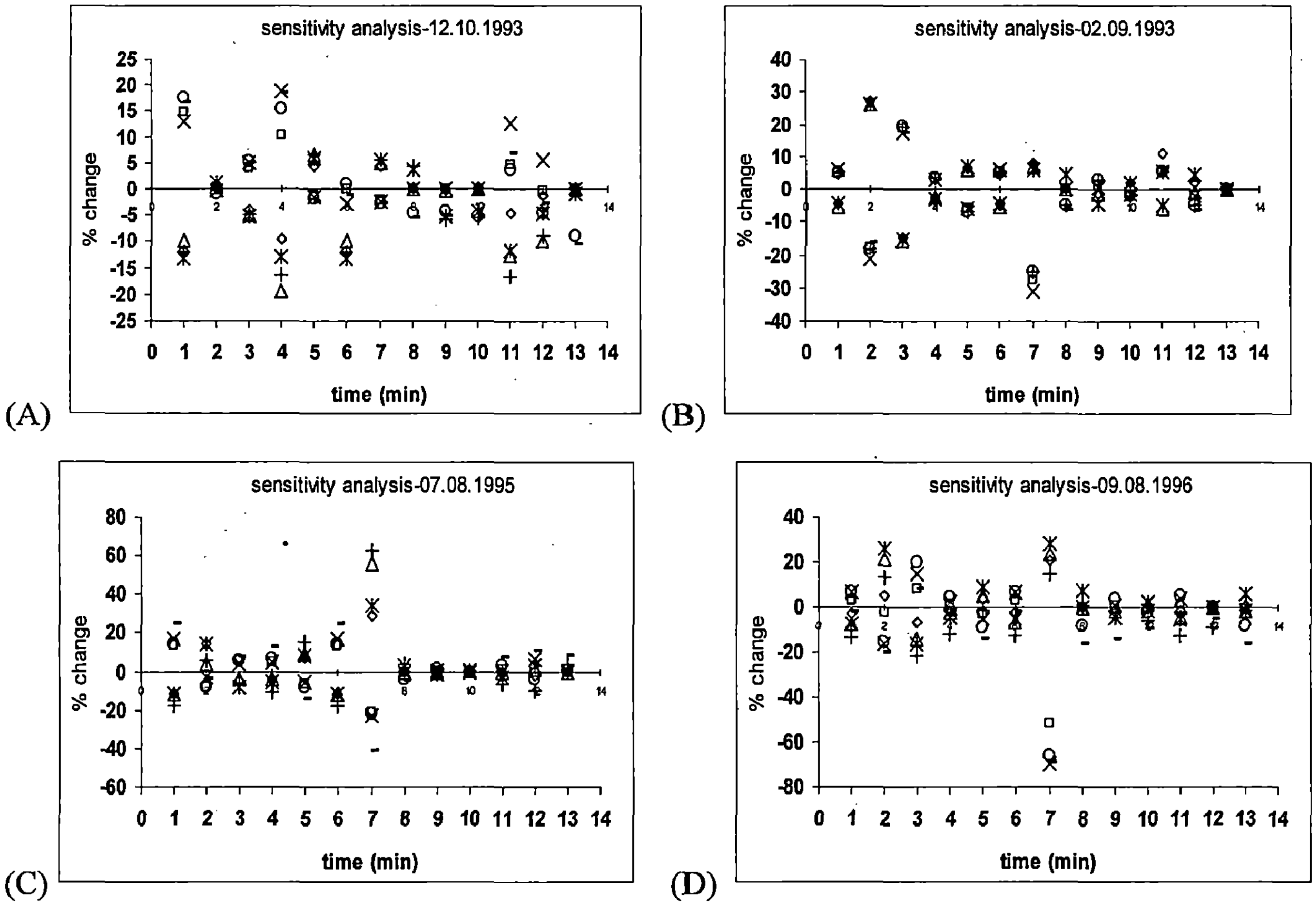


Fig 7.4 Sensitivity analysis

◇ Total storm runoff with 10% increase	□ total storm runoff with 10% decrease
Δ Peak runoff rate with 10% increase	× Peak runoff rate with 10% decrease
⋇ Total sediment yield with 10% increase	° Total sediment yield with 10% decrease
+ Peak sediment flow with 10% increase	– Peak sediment flow with 10% decrease

1- Porosity 2- field capacity 3- steady state infiltration rate (Fc) 4- Difference between maximum and steady state infiltration rates (A) 5- Infiltration exponent 6- control depth 7- Antecedent soil moisture 8- USLE soil erodibility factor 9- roughness coefficient 10- Maximum roughness height 11- Manning's N for overland flow 12 - Manning's N for channel flow 13- relative erosiveness

CHAPTER VIII

CONCLUSION

Based on the present study the following conclusions have been drawn.

- The model simulates surface runoff, peak flow and sediment yield with the average per cent deviation Dv equal to -11.88, 3.30 and -3.31 and the coefficient of efficiency (E) equal to 0.93, 0.97, 0.94 respectively for the storms used in model calibration. For the ANSWERS model validation, average per cent Dv equal to -19.985, 0.08, -4.43 and the coefficient of efficiency (E) equal to 0.70, 0.99, 0.95 respectively for surface runoff, peak flow and sediment yield simulations respectively. Thus the model showed consistency in simulating peak flow and sediment yield during calibration and validation process.

- The peaks of simulated and observed hydrographs are found to lie at the same time for majority of storms considered for model calibration and validation. The model under predicts runoff and sediment yield and over predicts peak runoff rate for majority of storms within acceptable level of deviation.

- The ANSWERS model is capable of simulating runoff, peak flow and sediment yield from a watershed with the acceptable level of deviation (avg Dv<20%) under varied soil moisture and rainfall conditions. This indicates the suitability of the model for ungauged watersheds of similar hydro-goelogical characteristics.

CHAPTER XI
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