Modeling of Rainstorm-Generated Sediment Yield from Small Watersheds

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by

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This thesis is dedicated to

My Grandfather

Late Shri. Lal Chand Gupta

&

My Beloved Parents

Smt. Madhuri Devi & Shri Raj Bahadur Gupta

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DECLARATION

I **Sushindra Kumar Gupta**, declare that this thesis titled, "**Modeling of Rainstorm-Generated Sediment Yield from Small Watersheds.**" and the work presented in it, are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this university.
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- I have acknowledged all main source of help.
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CERTIFICATE

This is to certify that the thesis entitled **"Modeling of Rainstorm-Generated Sediment Yield from Small Watersheds"** being submitted by **Sushindra Kumar Gupta**, **ID: 2013RCE9564**, is a bonafide research work carried out under my supervision and guidance in fulfillment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Civil Engineering, Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

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ABSTRACT

Sediment yield models find application in numerous diverse fields of hydrology. That include soil-water conservation, watershed planning and management, water quality assessment etc. The overarching goal of this thesis is to develop simple sediment yield and sediment graph models that will be beneficial to the soil conservation planners, field engineers, water resources engineers. The Soil Conservation Service Curve Number (SCS-CN) method is frequently used for the estimation of sediment yield and direct surface runoff depth from the small watershed. Various researchers have given different techniques (both physical and empirical) for estimation of sediment yield. It was observed that robust and straightforward models may be developed for quick evaluation of sediment yield from small Indian and USDA-ARS watersheds.

In this thesis, coupling the SCS-CN method with the Soil Moisture Accounting (SMA) procedure has been used to derive new simple sediment yield and runoff models. Potential maximum erosion, potential maximum retention and static infiltration (3-parameter model) and potential maximum retention and static infiltration (2-parameter model) have been developed for the determination of sediment yield and runoff respectively. The proposed sediment yield (S2) and runoff (R2) models have been tested for a large set of rainfall-runoff-sediment yield data (98 storm events) obtained from twelve watersheds from different landuse/ landcover and climatic conditions. Nash Sutcliffe Efficiency (NSE) of the proposed sediment yield and runoff models ranges from 74.55 % to 91.13 % and from 55.23 % to 92.48 % respectively for various watersheds of the study area. The proposed sediment yield (S2) and runoff (R2) models show superior results as compared to the existing Mishra et al (S1) and original SCS-CN (R1) models as revealed by statistical analysis and indices.

Soil moisture proxies (SMP) play a central role in hydrologic modeling for computation of runoff and sediment yield. In the thesis, an analytical development of sediment yield model is proposed based on SMP for computation of the rainstorm-generated sediment yield from all applications of the watersheds. The

potential maximum retention, potential maximum erosion, alpha and beta (4-parameter model) have been proposed in which input variables before and after rainfall occurrence have been utilized for deriving sediment yield model analytically. The NSE of the proposed sediment yield model ranges from 74.01 % to 96.84 % respectively for various watersheds. The proposed sediment yield model it exhibited more accurate and compatible results than the existing Mishra et al. (2006) model and evaluating the proposed model using the large set of rainfall and sediment yield data (98 storm events) from small watersheds. Various statistical indices show that the newly derived sediment yield model compute more consistent results than the Mishra et al. (2006) model.

The sediment graph model (SGM) is useful for computation of sediment yield as well as total sediment outflow rate from the watershed. The analytical development of proposed sediment graph models are based on SMA, SCS-CN, Nash’s, Instantaneous Unit Sediment Graph (IUSG) and Power law to estimate the time distributed sediment graphs. The proposed SMA-sediment graph models (SMA-SGMs) has been applied on nineteen storm events and different landuse/ landcover and climatic condition (arid, semi-arid, humid and sub-tropical) of six small watersheds. The proposed SMA-SGMs of the optimized parameters are close to Mishra et al. (2006), Bhunya et al. (2010) and Singh et al. (2008) models. The NSE of the proposed SMA-SGMs ranges from 57.73 % and 99.86 % for calibration events and 66.81 % to 99.56 % for validation events respectively for various watersheds of the study area. The proposed SMA-SGMs are compared with existing Bhunya et al. (2010) model and found to be more superior to existing Bhunya et al. (2010) model.

The present study highlights the use of SMA procedure of sediment yield models for proper calibration of the conceptual-based watershed model that are used for sediment yield prediction and watershed management. The newly derived models have been proposed for estimating of sediment yield from upland phase at various landuse/ landcover, climatic conditions and hydrologic condition of the watersheds. The various models proposed in the thesis are considered to be more valuable for sediment yield modeling as SMA/SMP approach is used for sediment yield and sediment graphs of the watersheds. Hence the proposed models are useful for an ungauged watershed of similar hydro-meteorological and geological conditions. The optimized parameters of sediment yield (potential maximum retention and static infiltration) are used in proposed runoff model for computation of runoff. The analysis show higher NSE and lowers PBIAS, RMSE, nRMSE values of proposed models as compared to the existing Mishra et al. (2006) and Bhunya et al. (2010) models.

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A	Actual potential maximum erosion
AMC	Antecedent moisture condition (AMC I for dry, AMC II for normal, and AMC III for wet soil)
A_w	Watershed area
ARS	Agriculture Research Service
BJSM	Bhunya, Jain, Singh, and Mishra
C	Runoff coefficient; a hydrologic soil group; cover management factor
CN	Curve number (CN_{II} = curve number for AMC II)
D	Hydrologic soil group
DR	Sediment delivery ratio
f_c	Final or minimum infiltration rate
f_d	Dynamic rate of infiltration rate
f_o	Initial infiltration rate
F	Cumulative infiltration
F_c	Cumulative static (steady) portion of total infiltration
F_d	Cumulative dynamic portion of total infiltration
h	Hour
ha	Hectare
I_a	Initial abstraction
i_0	Uniform rainfall intensity
$I_{s1}(t)$	Sediment input to the first reservoir
IUSG	Instantaneous unit sediment graph
j	Integer
k	Horton parameter
kN	Kilo newton
K_s	Sediment storage coefficient
LPF	Line of perfect fit
M	Antecedent moisture amount
M_c	Soil moisture content before the rainfall occurrence
mm	Millimeter

MUSLE	Modified universal soil loss equation
NEH	National Engineering Handbook
NSE	Nash Sutcliffe efficiency
N	Numbers of observations
nRMSE	Normalized root mean square error
n_s	Shape parameter
P	Cumulative rainfall depth; supporting practice factor
PE	Daily potential evapotranspiration
PBIAS	Percent bias
P_5	Five day rainfall
Q	Cumulative direct surface runoff
q_{ps}	Peak sediment flow rate
$Q_{s1}(t)$	Sediment discharge
Q_S	Observed total sediment outflow
$Q_{S(C)}$	Computed total sediment outflow
Q_{obs}	Observed sediment yield
$\overline{Q_{obs}}$	Mean of the observed sediment yield
$Q_{S(mean)}$	Mean of observed sediment outflow rate
Q_{comp}	Computed sediment yield
RMSE	Root mean square error
R1	Existing SCS-CN model
R2	Proposed rainfall-runoff model
$RE(t_{ps})$	Relative error in time to peak sediment flow rate
$RE_{(QS)}$	Relative error in peak sediment flow rates
$RE_{(QPS)}$	Relative error in total sediment outflow rate
S	Potential maximum retention
SCS	Soil Conservation Service
S_a	Intrinsic parameter
$S_{s1}(t)$	Sediment storage within the reservoir
SMA	Soil moisture accounting
SMA-SGM	Soil moisture accounting-sediment graph model

SMP	Soil moisture proxies
S1	Existing Mishra et al. (2006) model
S2	Proposed rainfall-sediment yield model
t	Time
t_{ps}	Time to peak sediment flow rate
USDA	United State Department of Agriculture
V	Soil moisture at time t
V_0	Initial soil moisture
Y	Mobilized sediment per storm
Y_T	Total amount of mobilized sediment
α	Coefficient
β	Exponent
θ	Soil moisture
β_s	Non-dimensional parameter
Γ()	Gamma function
λ	Initial abstraction coefficient

CHAPTER-1
INTRODUCTION

1.1 BACKGROUND

Rainfall-runoff and sediment yield modeling is one of the significant and live area of research in hydrology. The origin of rainfall-runoff modeling, the comprehensive grasp, originated in the second half of the 19th century when the engineers were confronted with the problems related to urban areas, drainage of basins and river training works. Most of the engineers used empirical formulae or rational methods the end of 19th century and before 20th century (Dooge, 1957, 1973). These approaches were mainly confined to small and mountainous watersheds and during 1920s, these were attempted on larger catchments. As a modification to it, the idea of isochrones (i.e. lines of equal travel time) was developed, which be seen as the first rainfall-runoff model based on transfer function.

Rainfall-runoff and sediment yield modeling may have a broad meaning depending on its objectives. Briefly, the objective of any rainfall-runoff and sediment yield model (RRSYM) is to assess the quantum of runoff and sediment yield generated from a given rainfall, using simple to complex (analytical) techniques applying a number of assumptions and simplification in representing the actual processes. The term modeling represents the mathematical representation used at different stages of the hydrologic system components to relate the rainfall and other hydrological parameters of the watershed with the parameters of the runoff characteristics. Erosion and sediment yield from rain water include the process of detachment, transportation and deposition of soil particles (sediment) by the erosive and transport agents of raindrop impacts and runoff over the soil surface. Although, the impact of accelerated erosion is readily evident in terms of degradation of soil resource. The eroded sediment may generate other adverse effects when it is transported downstream (Tyagi et al., 2008; Pandey et al., 2016).

The land degradation from water-induced soil erosion is a serious problem around the globe, which is not only eroding the top fertile soil but is also responsible for swelling of river beds and reservoirs, thereby, causing floods and reducing the life span of cost intensive dams. Though, it is difficult to assess reliably and accurately the rate and magnitude of runoff and associated soil loss, the information available in literature is often based on reconnaissance surveys and extrapolations that provide an idea of the severity of the problem. Judson (1981) estimated that river-born sediments carried into the oceans increased from 10 billion tonnes per year before the introduction of intensive agriculture, grazing, and other activities to 25-50 billion tonnes per year thereafter. Dudal (1981) reported that the current rate of agricultural land degradation worldwide by soil erosion along with other factors led to an irreversible loss in annual productivity of about six Mha of fertile land. Narayana and Babu (1983) estimated that in India about 5334 million tonnes of soil is being eroded annually, due to which 8.4 million tonnes of nutrients are also lost. Another estimate reveals that the average soil loss in India is about 16.3 tonnes/ha/ year against the permissible range of 5-12.5 tonnes/ha/year for various regions (Narayana, 1993).

Reliable estimates of soil erosion and sediment yield are required for the design of efficient erosion control measures, assessment of reservoir sedimentation, determination of reservoir life, water quality management and evaluation of watershed management strategies. The detachment and displacement of soil particles over short distances, referred to as erosion, do not wholly represent the sediment delivered at the watershed outlet known as sediment yield. Much deposition and reduction in sediment load occurs between the sediment sources and the outlet (Narayana and Babu, 1983). Sediment yield is limited by the transport capacity of runoff (Beasley and Huggins, 1981; Morgan, 1995). Measurement of sediment yield on a number of watersheds is operationally difficult, expensive, time consuming, and tedious, and therefore modeling is carried out for simulating, generating or augmenting the sediment yield data base.

The rain falling on a watershed undergoes a number of transformations and abstractions through various component processes of hydrologic cycle, viz., interception, detention, evaporation and evapotranspiration, overland flow, infiltration, interflow, percolation, base flow etc., and finally emerges as runoff at the watershed outlet. These component processes are functions of various climatic and watershed characteristics, such as rainfall intensity and duration, topography, land use and vegetation cover, drainage pattern, drainage density, geology etc., which are not uniform in time and space. Soil erosion by water that refers to the removal of soil particles from the land surface due to erosive action of water depends on both rainfall intensity and consequent runoff. When raindrops fall on the surface, soil particles are detached due to the kinetic energy of drops. The higher the rainfall intensity, the greater will be the amount of the soil detached. When the rainfall-excess (or direct runoff) flows downhill, it gets concentrated. During the process of overland flow, soil particles are detached when shear stress of the flow exceeds the gravitational and cohesive forces of the soil mass. The movement of detached soil particles depends on the sediment load in the flow and the flow’s sediment transport capacity. Once a soil particle has been detached, sufficient energy must be available to transport it or the particle will be deposited. Thus, the soil loss is greatly influenced by the intensity of rainfall, rate of overland flow, vegetation cover, and soil texture.

The sediment flow rate plotted as a function of time during a storm at a given location is known as sediment graph. Without a sediment graph, only the average sediment rate for the storm can be computed. The average sediment yield is not adequate for computing dynamic suspended sediment load and pollutants load during the storm (Raghuwanshi et al., 1994). Rendon-Herrero (1974) developed a sediment graph model; based on unit sediment graphs approach defined as the unit sediment graph generated from one unit of sediment for a given duration distributed uniformly over a watershed. The ordinates of these unit sediment graphs, called series graphs, were related to source runoff volume to calculate storm sediment graphs. This technique is completely dependent upon measured data and could not be used to show differences in land management.

Several models, varying in complexity from lumped empirical models to physically based models have been developed by various researchers to model the soil erosion and consequent sediment yield (Wischmeier and Smith, 1965, 1978; Foster and Meyer, 1972a; Nearing et al., 1989; Woolhiser et al., 1990; Govindaraju and Kavvas, 1991; Kothyari et al., 1997; Tayfur, 2001; Su et al., 2003; Kalin et al., 2004; Jain et al., 2005; Mishra et al., 2006; Pandey et al., 2016). A common approach to the assessment of soil erosion and sediment yield is the use of empirical equations, such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965; 1978) or its extensions viz., Modified Universal Soil Equation (MUSLE) (Williams, 1975) and Revised Universal Soil Equation (RUSLE) (Renard et al., 1991). The USLE predicts sheet and rill erosion and does not take into account the deposition of sediment enroute. Therefore, a concept of sediment delivery ratio has been used with USLE for estimation of sediment discharge from large watersheds (Hadley et al, 1985). The sediment delivery ratio, DR, represents the ratio of the sediment yield to the gross upland erosion in the watershed and depends on many factors, including watershed physiography, sediment source, transport system, texture of eroded material and depositional areas (Dendy, 1982).

Because of the close dependence of sediment yield process on the surface runoff, the erosion models, or the component processes of detachment, transport and deposition thereof, are coupled with models capable of simulating the rainfall-runoff response of a watershed (Knisel, 1980; Leonard et al., 1987; Rode and Frede, 1997). Examples of such a coupling include a number of models, such as empirical Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and the model of Williams and Berndt (1977); physically based Water Erosion Prediction Project (WEPP) (Nearing et al., 1989), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley and Huggins, 1980), Agricultural Nonpoint Source Pollution Model (AGNPS) (Young et al., 1987), and SWAT (Arnold et al., 1993) models, among others.

1.2 NEED OF THE PRESENT STUDY

The world is facing continuous increase in erosion and sediment yield, which is mainly due to overland slopes, landuse/landcover, top soil cover conation, rainfall intensity, drainage patterns and channel flow conditions. Thus, quite a good deal of literature is available on rainfall-runoff-erosion modeling to simulate the complex processes of soil erosion and sediment yield under different field conditions. These models have also proved very useful as a research tool but are of limited use in field, especially in developing countries, because they require sufficient skill and large amount of data. Nevertheless, search is still continuing for developing new and simpler models which, at the same time, should retain their prediction ability as close to the reality as possible. In the present study, an attempt has therefore been made to develop simple rainfall-runoff, sediment yield and sediment graph models using the well-accepted hydrologic concept of proportional equality of the Soil Conservation Service Curve Number (SCN-CN) method (SCS, 1956). The SCS-CN method is a popular method for computing the volume of direct surface runoff for a given rainfall event from small agricultural watersheds. The method is simple, easy to understand and apply, and useful for ungauged watersheds. The method utilizes proportional equality hypothesis in combination with water balance equation for computing the direct surface runoff.

The soil texture determines both permeability and erodibility of soils. Permeability describes infiltration, which, in turn, determines hydrologic activeness of the soil surface in terms of both runoff generation and soil erosion. The method accounts for most of the runoff producing watershed characteristics, viz., soil type, land use/treatment, surface condition, and antecedent moisture condition through curve number (Mishra et al., 1999; 2005; 2006; Singh et al., 2002; Singh et al., 2008; Tyagi et al., 2008; Singh et al., 2015; Ajmal et al., 2015; 2016; Verma et al., 2017). The Soil Moisture Accounting (SMA) or Soil Moisture Proxies (SMP), used to compute the sediment yield from small watersheds, also accounts for these watershed characteristics, albeit differently. Thus, the processes of runoff generation and soil erosion are closely interrelated. However, the SCS-CN method, SMA, Instantaneous Unit Sediment Graph (IUSG), Nash's and Power law model have not yet been investigated for their interrelationship. The SCS-CN proportionality concept can be extended to the sediment delivery ratio to allow a coupling of the SCS-CN method with the SMA and to compute the sediment yield from the knowledge of rainfall, soil type, land use and antecedent soil moisture condition, since the sediment yield greatly depends on runoff.

1.3 OBJECTIVES OF THE PRESENT STUDY

Based on the above discussion, the specific objectives set out for the present research work are summarized as follows.

1. A critical review of rainfall-runoff and sediment yield models;
2. To develop SCS-CN based event rainfall-runoff and sediment yield model for estimating the runoff and sediment yield from a rainfall event;
3. To develop SMP based rainstorm-generated sediment yield model for estimating the sediment yield from a rainstorm event;
4. To develop SMA, SCS-CN, Nash's, IUSG and Power law model based sediment graph models for computing event sediment graph from rainstorm event at watershed scale;
5. To calibrate and validate the models developed herein and assess their general applicability using the available hydrological and sediment yield data of a number of watersheds.

The proposed simple models may be useful for field engineers and conservation workers in estimation of the sediment yield required for water resources planning and management, water quality modeling, conservation planning, reservoir planning, project planning and soil erosion inventories.

1.4 ORGANIZATION OF THESIS

For the convenience in the presentation, the thesis has been divided into seven chapters. Chapter 2 describes the review of literature, whereas the present work is reported in chapter 3 to 6. Chapter 7 describes the conclusions and recommendation. A brief account of the chapter-wise contents of the thesis is given as follows:

- **Chapter 2-Literature Review:** It brings out literature survey relevant to the study. Besides presenting a brief review of the SCS-CN method, rainfall-runoff and sediment yield modeling, the chapter also discusses the pertinent aspects of soil erosion by water and the erosion and sediment yield modeling reported by various researchers.
- **Chapter 3-Study Area:** The details of the watersheds and availability of their hydrologic and sediment yield data that have been used for application of the proposed sediment yield models are discussed.
- **Chapter 4-An Event-Based Sediment Yield and Runoff Modeling Using Soil Moisture Accounting (SMA) Method:** It deals with the analytical

development and application of the event-based lumped rainfall-runoff and sediment yield model. The pertinent aspects of SCS-CN method and SMA procedure, and their coupling, crucial to the model development, are presented in this chapter.

- **Chapter 5-Rainstorm-Generated Sediment Yield Based on Soil Moisture Proxies (SMP):** It deals with the analytical development of sediment yield model based on soil moisture proxies (SMP). The results of the model verifications and comparative analysis are also discussed in this chapter.
- **Chapter 6-Sediment Graph Models Based on Soil Moisture Accounting from Small Watersheds:** It presents a detailed description of the SCS-CN based soil moisture accounting (SMA) procedure and its coupling with the Nash's, IUSG model and Power law leading to the development of the sediment graph models. The results of model calibration, validation and comparative analysis are also discussed in this chapter.
- **Chapter 7-Conclusions**: Finally, in this chapter, the summary and conclusions drawn from the present study, major contributions of the study, recommendations and future scope of the research work is also given in this chapter.

CHAPTER-2
REVIEW OF LITERATURE

The process of sediment yield closely depends on the direct surface runoff. Therefore, a sediment yield model utilizes either a lumped estimate of direct surface runoff for computing total sediment yield from a storm event or, as in most cases, a suitable rainfall-runoff model to generate the sediment yield rate that is primarily responsible for delivering the temporally varying sediment rate at the watershed outlet. The present research work is carried out with an objective to develop event-based lumped and sediment graph models for natural watersheds by coupling the upland potential erosion with the SCS-CN and SMA (SCS, 1956) method through its proportional equality hypothesis. Accordingly, in the present work the review of literature has been carried out with a focus on SCS-CN methodology and its applications in watershed hydrology for computation of surface runoff, pertinent aspects of soil erosion by water, and; the erosion and sediment yield modeling as reported by various researchers.

2.1 SCS-CN METHOD

The Soil Conservation Service (now called the Natural Resources Conservation Service) Curve Number (SCS-CN) method was developed in 1954 and is documented in Section 4 of the National Engineering Handbook (NEH-4) published by the Soil Conservation Service, U.S. Department of Agriculture in 1956. The document has since been revised in 1964, 1971, 1972, 1985 and 1993. The SCS-CN method is the result of exhaustive field investigations carried out during late 1930s and early 1940s and the works of several early investigators, including Mockus (1949), Sherman (1949), Andrews (1954) and Ogrosky (1956). The method is well established in hydrologic engineering and environmental impact analysis (Ponce and Hawkins, 1996) and is one of the most popular methods for computing the volume of direct surface runoff for a given rainfall event from small agricultural, forest and urban watersheds (Mishra and Singh, 2003).

The SCS-CN method is based on the water balance equation and two fundamental hypotheses. The first hypothesis equates the ratio of the actual amount of direct surface runoff (Q) to total rainfall (P) (or potential maximum surface runoff) to the ratio of the amount of actual infiltration (F) (or actual retention) to amount of potential maximum retention (S). The infiltration (F) (or actual retention) to amount of potential maximum retention (S). The second hypothesis relates the initial abstraction (I_a) to the potential retention. Expressed mathematically, the water balance equation and the two hypotheses, respectively, are:

$$P = I_a + F + Q \tag{2.1}$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \tag{2.2}$$

$$I_a = \lambda S \tag{2.3}$$

The initial abstraction accounts for the short-term losses, such as interception, surface storage and initial infiltration. Parameter λ is frequently viewed as a regional parameter dependent on geologic and climatic factors (Bosznay, 1989). The existing SCS-CN method assumes λ to be equal to 0.2 for practical applications. Many other studies carried out in the United States and other countries (SCD, 1972; Springer et al., 1980; Cazier and Hawkins, 1984; Bosznay, 1989) report λ to vary in the range of (0-0.3). Combining Eq. 2.1 and Eq. 2.2, the popular form of SCS-CN method is obtained:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{2.4}$$

Eq. 2.4 is valid for $P > I_a$, Q = 0, otherwise. For λ = 0.2, Eq. 2.4 can be re-written as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2.5}$$

Thus, the existing SCS-CN method (Eq. 2.5) has only one parameter, S, for computing surface runoff from storm event. Since S can vary in the range of $0 \le S \le \infty$, it is mapped into a dimensionless curve number (CN), varying in a more appealing range $0 \le CN \le 100$, as follows:

$$S = \frac{25400}{CN} - 254 \text{ (for S expressed in mm)} \tag{2.6}$$

Although CN theoretical varies from 0 to 100, the practical design values validated by experience lie in the range (40-98) (Van Mullem, 1989; Mishra and Singh, 2003).

2.2 FACTORS AFFECTING CURVE NUMBERS

The curve number (CN) indicates the runoff response characteristics of a drainage basin and is affected by soil type, landuse/ treatment, hydrologic condition, antecedent moisture condition, and climate of the watershed (SCS, 1956; Mishra and Singh, 2003). The combination of soil type, hydrologic condition, and landuse/ treatment is referred to as Hydrological Soil-Cover Complex (Miller and Cronshey, 1989). These characteristics primarily affect the infiltration potential of a watershed. NEH-4 (SCS, 1956) presents CN values for several typical Hydrological Soil-Cover Complexes.

2.2.1 Soil Type

Soil properties such as texture, organic matter, aggregation, soil structure and tilth greatly influence the amount of runoff. In the SCS-CN method, these properties are represented by a hydrological parameter: the minimum rate of infiltration obtained for a bare soil after prolonged wetting. The influence of both the soil's surface condition (infiltration rate) and its horizon (transmission rate) are thereby included. The Soil Conservation Service identified four hydrologic groups of soils based on their infiltration and transmission rates as given below.

- **Group A*:*** The soils falling in this group exhibit high infiltration rates even when they are thoroughly wetted, high rate of water transmission, and low runoff potential. Such soils include primarily deep, well to excessively drained sands or gravels.
- **Group B*:*** These soils have moderate infiltration rates when thoroughly wetted and a moderate rate of water transmission. They include moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures, for example, shallow loess and sandy loam.

- **Group C*:*** Soils in this group have low infiltration rates when thoroughly wetted and a low rate of water transmission. These soils primarily contain a layer that impedes downward movement of water. Such soils are of moderately fine to fine texture as, for example, clay loams, shallow sandy loam, and soils in low organic content.
- **Group D*:*** These soils have very low infiltration rates when thoroughly wetted and a very low rate of water transmission. Such soils are primarily clay soils with a high swelling potential, soils with a permanently high water table, soils with a clay pan or clay layer at or near the surface, or shallow soils over nearly impervious material.

2.2.2 Landuse/ Treatment

The landuse characterizes the uppermost surface of the soil system and has a definite bearing on infiltration. It describes watershed cover and includes every kind of vegetation, litter and mulch, and fallow as well as nonagricultural uses, such as water surfaces, roads, roofs, etc. A forest soil, rich in organic matter, allows greater infiltration than a paved one in urban areas. On an agricultural land or a land surface with loose soil whose particles are easily detached by the impact of rainfall, infiltration is affected by the process of rearrangement of these particles in the upper layers such that the pores are clogged and lead to reduction in infiltration rate. A grassy or vegetated land will help reduce such a clogging and allow more infiltration. Land treatment applies mainly to agricultural land uses and includes mechanical practices such as contouring or terracing, and management practices such as rotation of crops, grazing control, or burning. In the SCS-CN method, the following categories of land use are distinguished:

I. Fallow is the agricultural land use with the highest potential for runoff because the land is kept bare;

II. Row crops are field crops planted in rows far enough apart that most of the soil surface is directly exposed to rainfall;

III. Small grain is planted in rows close enough that the soil surface is not directly exposed to rainfall;

IV. Close-seeded legumes or rotational meadow are either planted in close rows or broadcasted. This kind of cover usually protects the soil throughout the year;

V. Pasture range is native grassland used for grazing, whereas meadow is grassland protected from grazing and generally mown for hay;

VI. Woodlands are usually small isolated groves of trees being raised for farm use.

2.2.3 Hydrologic Condition

The hydrologic condition of an agricultural watershed is defined in terms of the percent area of grass-cover. The larger the area of grass cover in a watershed, the lesser will be the runoff potential of the watershed and more will be infiltration. Such a situation describes the watershed to be in a good hydrologic condition. It is good because it favours the protection of watershed from erosion for soil conservation purposes. Similarly, a watershed having lesser acreage of grass cover can be defined to be in a poor hydrologic condition. Alternatively, a good hydrologic condition allows more infiltration than does a poor hydrologic condition. Thus, the hydrologic condition of a forest area also represents its runoff-producing potential. The curve number will be the highest for poor, average for fair, and the lowest for good condition, leading to categorizing the hydrologic condition into three groups: good, fair, and poor, depending on the areal extent of grasslands or native pasture or range. These conditions are based on cover effectiveness. Grazing on dry soils generally results in lowering of infiltration rates due to the compaction of the soil by hooves. Determination of CN for forest areas for various hydrologic conditions is primarily guided by the U.S. Forest Service (USFS) (1959). SCS (1985) has also briefly described it.

2.2.4 Agricultural Management Practices

Agricultural management systems involve different types of tillage, vegetation and surface cover. Freebairn et al. (1989) illustrated the effects of tillage practices (mouldboard plough, chisel plough, and no till) on infiltration. Such practices primarily alter the porosity of the soils. Brakensiek and Rawls (1988) reported that mouldboard increases soil porosity from 10-20%, depending on the soil texture and, in turn, increases infiltration rates over non-tilled soils. It is shown (Rawls, 1983) that an increase in organic matter in the soil lowers bulk density or increases porosity, and hence increases infiltration and, in turn, decreases the runoff potential.

2.2.6 Antecedent Moisture Condition

The antecedent moisture condition (AMC) refers to the wetness of the soil surface or the amount of moisture available in the soil profile, or alternatively the degree of saturation before the start of the storm. In the event that the soil is fully saturated, the whole amount of rainfall will directly convert to runoff without infiltration losses and if the soil is fully dry, it is possible that the whole rainfall amount is absorbed by the soil, leading to no surface runoff. Thus, the AMC affects the process of rainfall-runoff significantly. In the SCS-CN method, the soil moisture condition is classified in three AMC classes: AMC I. AMC II, and AMC III. AMC I refers to practically dry condition of a soil (i.e. the soil moisture content is at wilting point), AMC II to normal or average, and AMC III to the wet situation (i.e. the soil moisture content is at field capacity). Thus, the CN corresponding to AMC I refer to the dry CN or the lowest runoff potential while the CN corresponding to AMC III refers to the wet CN or the highest runoff potential. AMC classes are based on the 5-day antecedent rainfall (i.e. the accumulated total rainfall preceding the runoff under consideration). In the original SCS method, a distinction was made between the dormant and the growing season to allow for differences in evapotranspiration. Using the NEH-4 tables (SCS, 1956; 1985), the CN is first computed for AMC II which is later converted to AMC I or III depending on the AMC of the watershed. By Rao et al. (2003) using the NEH-4 procedure, the AMC for an individual event was determined by taking a 5-day antecedent rainfall as less than 12.7 mm for AMC-I; above 12.7 but less than 38 mm for AMC-II; and above 38 mm for AMC III.

In an attempt to justify the rationale for developing individual curve numbers, Mockus (1964) explained: “The CN associated with the soil-cover complexes are median values, roughly representing average conditions of a watershed. We took the average condition to mean average soil moisture condition because we had to ignore rainfall intensity”. Since the sample variability in CN can be due to infiltration, evapotranspiration, soil moisture, lag time, rainfall intensity, etc., the AMC was supposedly used to represent this variability (Mishra and Singh, 2003).

Even though the CN is treated as an exact value for a watershed, experience (SCS, 1985; Hjelmfelt, 1991) indicates that a set of curve numbers can exist for a given watershed. Ponce and Hawkins (1996) summarized the likely sources to lie in the spatial and temporal variability of rainfall, quality of measured rainfall-runoff data, and the variability of antecedent rainfall and the associated soil moisture amount. Until individual effects of each cause are investigated, the variation of CN can be attributed to random variation, which implies that confidence intervals are appropriate for characterizing the variation (Hjelmfelt, 1982; Hawkins et al., 1985). McCuen (2002) in his approach to estimate confidence interval for CN used the method of moments for parameter estimation and pooled data for assigning confidence intervals. Bhunya et al. (2003) described the random variation of CN as Gamma distributed for estimation of confidence intervals for CN-values ranging from 65 to 95.

2.3 APPLICATION OF SCS-CN METHOD IN WATERSHED HYDROLOGY

Since its development, the SCS-CN method has witnessed myriad applications all over the world (Mishra and Singh, 2003). The method has been used in long-term hydrologic simulation and several models have been developed in the past three decades (Huber et al. 1976; Hawkins, 1978; Williams and LaSeur 1976; Knisel 1980; Soni and Mishra 1985; Mishra and Singh 2004a). A significant literature has also been published on the SCS-CN method in the recent past, and several recent articles have reviewed the method at length. For example, McCuen (1982) provided guidelines for practical application of the method to hydrologic analyses. Ponce and Hawkins (1996) critically examined this method; discussed its empirical basis; delineated its capabilities, limitations, and uses; and identified areas of research in the SCS-CN methodology. Hjelmfelt (1991), Hawkins (1993), Bonta (1997), McCuen (2002), Bhunya et al. (2003), and Schneider and McCuen (2005), suggested procedures for determining curve numbers for a watershed using field data. Steenhuis et al. (1995) used SCS-CN method to predict the contributing area of a watershed and concluded that the SCS-CN equation is directly based on principles used in partial-area hydrology. Yu (1998) derived the SCS-CN method analytically assuming the exponential distribution for the spatial and temporal variation of the infiltration capacity and rainfall rate, respectively. Mishra and Singh (1999, 2002a) derived the method from the Mockus (1949) method and from linear and non-linear concepts, respectively. Mishra and Singh (2003) presented a state- of-the-art account and a mathematical treatment of the SCS-CN methodology, and its application to several areas, other than the originally intended one.

Mishra and Singh (2002b) developed a modified SCS-CN method to incorporate the antecedent soil moisture in the existing method. Jain et al. (2006a) applied existing SCS-CN method, its variant and the modified Mishra and Singh (2002 b) model to a large set of rainfall- runoff data from small to large watersheds and concluded that the existing SCS-CN method was more suitable for high runoff producing agricultural watersheds than to watersheds showing pasture/range land use and sandy soils. This was in conformity with Ponce and Hawkins (1996) that the SCS-CN method performs best on agricultural watersheds, fairly on range sites and poorly on forest sites (Hawkins, 1984; 1993). Mishra et al. (2006) investigated a number of initial abstraction-potential maximum retention relations incorporating antecedent moisture as a function of antecedent precipitation. Bhunya et al. (2003) evaluated the use of individual-event watershed-scale AMC values to adjust field-scale CN using the stream flow data. For individual runoff events, calibration was achieved with AMCs that averaged 1.5 and ranged from 0.9 to 2.4. It was concluded that an AMC of 2, as used in many hydrologic models, would overestimate the surface runoff amounts in the sub-humid Kansas watershed, U.S.A.

Recently Ajmal et al. (2015) evaluated this method and its inspired versions using the large set of rainfall-runoff data of fifteen watersheds of South Korea (total 658 large storm events). Nevertheless, there are only a few studies providing an insight into the structural soundness of SMA procedure of the existing SCS-CN model (Verma et al., 2017). Michel et al. (2005) is pointed out several inconsistencies in the one parameter of SCS-CN. But they highlighted several structural inconsistencies, arising partly from the misperception between intrinsic parameters and initial conditions, and partly from an incorrect use of the underlying soil moisture accounting (SMA) procedure. They emphasized the incorporation of initial soil moisture rather than an impractical intrinsic parameter in the form of initial abstraction. With the changed parameterization of threshold soil moisture required for runoff generation in place of I_a and underlying SMA procedure, they proposed the an improved SCS-CN inspired model. The SMA procedure is based on the notion that the higher the moisture store level, the higher the fraction of rainfall that is converted into runoff. If the soil is saturated, i.e., if the moisture store is full, all rainfall will become runoff (Michel et al., 2005; Mishra et al., 2006; Jain et al., 2006; Sahu et al., 2007, 2010, 2012, Singh et al., 2015, Rajib et al., 2015; Ajmal et al., 2015, 2016; Verma et al., 2017; Shi et al., 2017). Initially the foundation of sediment yield model based SCS-CN model give the Mishra et al. (2006), the model is coupled with the Universal Soil Loss Equation (USLE) for prediction of lumped sediment yield from natural watershed.

The model is simple, easy to understand, and useful for ungauged watersheds. The primary reason for its wide applicability and acceptability lies in the fact that it accounts for most runoff producing watershed characteristics such as landuse/ landcover, soil type, hydrological soil group and antecedent moisture condition (Mishra and Singh, 1999; Michel at al., 2005; Mishra et al., 2006; Sahu et al., 2007, Singh et al., 2008; Tyagi et al., 2008; Ajmal et al., 2015, 2016).Williams and LaSeur (1976) are the first to incorporate the soil moisture accounting (SMA) procedure and coupling the SCS-CN model. However, only a few attempts have been made to identify the impacts of soil initial water content on the storm runoff characteristics. The surface runoff is only controlled by soil moisture, with some of the threshold depending on the depth over which the soil moisture is averaged (Western et al., 1998). Therefore advocated for incorporation of the SMA procedure in order to better interpret the runoff generation dynamics from a watershed (Brocca et al., 2008; Mishra and Singh (2002) incorporated the effect of antecedent moisture amount and developed and improved version of the SCS-CN inspired model. Different researchers developed different expression of antecedent moisture on the basis of 5-day antecedent rainfall amount (Mishra and Singh. 2002, 2004, 2005; Jain et al., 2006; Babu and Mishra 2012). Singh et al. (2010) critically review of the updated model on the recent development in the SCS-CN methodology and discussed its physical and mathematical significance in hydrology and environmental applications.

Yuan et al. (2001) modified the SCS-CN method to estimate subsurface drainage flow for five drainage monitoring stations. The flows predicted during calibration and validations were not significantly different from the observed subsurface flows. Jain et al. (2006b) incorporated storm duration and a nonlinear relation for initial abstraction (I_a) to present an enhanced version of the SCS-CN-based Mishra–Singh model (2002 b). The proposed version was found to perform better than all other existing versions on watershed of USDA-ARS. Sahu et al. (2006) suggested a soil moisture accounting procedure for SCS curve number method. A summary of some recent rainfall-runoff models proposed by various investigators are presented in Tables 2.1.

Table-2. 1: Summary of rainfall-runoff models based on SCS-CN method

S.No.	Author(s)	Models	Parameters
1	Ajmal et al. (2016)	$Q = P\left(\frac{P_5 + P + 0.174324S}{P_5 + P + 0.85S}\right)^2$ for $P > 0.15S \frac{P}{P + P_5}$	where, Q is the direct surface runoff, P is the precipitation, P_5 is the previous five days rainfall and S is the potential maximum retention
2	Ajmal et al. (2015)	$Q = \frac{(P - 0.02P)^2}{S + 0.98P} = \frac{0.9604P^2}{S + 0.98P}$	where, Q is the direct surface runoff, P is the precipitation and S is the potential maximum retention
3	Ajmal et al. (2015)	$Q = P\left[\frac{P + P_5 + 0.25S}{P + P_5 + 0.8S}\right]^2$	P_5 = previous five day rainfall
4	Ajmal and Kim (2014)	$Q = P\left(\frac{P}{P + S} - \frac{1}{S}\right)$ $Q = \left(\frac{P^2}{P + S} - \frac{P + P_5}{S^2}\right)$ $Q = \left(\frac{P^2}{P + S} - \frac{P_5}{S}\right)$	where, P is the precipitation, S is the potential maximum retention, Q is the direct surface runoff and P_5 is the previous five days rainfall.
5	Ali and Sharda (2008**)**	$Q = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S}$, $Q = \frac{254\left[\frac{P}{254} - \frac{200}{CN} + 2\right]^2}{\left[\frac{P}{254} + \frac{800}{CN} - 8\right]}$	where, P is the precipitation, S is the potential maximum retention, λ is the initial abstraction coefficient and CN is the curve number

S.No.	Author(s)	Models	Parameters
6	Bofu Yu (2012)	$Q = \frac{{P_e}^2}{{P_e}^2 + \lambda T_e}$ $q_p = P_p - \lambda(1 - e^{-} P_e/\lambda)$	where, λ is the average maximum infiltration rate, P_e is the effective rainfall, T_e is the effective storm duration, Q is the storm runoff amount, q_p is the peak runoff rate, p_p is the peak rainfall
7	Choi et al. (2002)	$Q_{dr} = \sum_{j=1}^{M} (Q_{sub_i} \times AF_j)$	where, qdr_i is the direct runoff from a grid, Q_{sub_i} is the sub-watershed direct runoff, Q_{dr} is the total direct runoff of the main watershed, M is number of sub-watersheds and AF_j is the area ratio of the Jth sub-watershed to the main watershed
8	Geetha et al. (2007)	$RO_t = \frac{{P_e}^2}{P_e + S_t}$	where, RO_t is the surface runoff with respect to time, P_{e_t} is the effective rainfall with respect to time, S_t is the potential maximum retention with respect to time
9	Hawkins (1978)	$Q = P - S\left(1.2 - \frac{S}{P + 0.8S}\right)\ P \geq 0.2S$	Evidently $P \to \infty$, the maximum possible water loss is equal to S_t, which equal 1.2S
10	Hawkins et al.(1985)	$Q_I = \frac{(P - 0.456S_{II})^2}{P + 1.824S_{II}}$, $Q_{II} = \frac{(P - 0.2S_{II})^2}{P + 0.8S_{II}}$ $Q_{III} = \frac{(P - 0.085S_{II})^2}{P + 0.342S_{II}}$	where, Q, P and S are respectively, runoff, rainfall depth and potential maximum retention, Q_I = direct surface runoff for AMC-I, Q_{II} = direct surface runoff for AMC-II and Q_{III} = direct surface runoff for AMC-III

S.No.	Author(s)	Models	Parameters
11	Jain et al. (2006)	$I_a = \lambda S(P/P+S)^{\alpha}$ $P_c = P_o(t_p/\bar{t}_p)^{\beta}$ $I_{ad} = \lambda S(P_c/P_c+S)^2$ $Q = \frac{(P_c - I_{ad})(P_c - I_{ad} + M)}{P_c - I_{ad} + M + S}$	wher**e,** P_c is the adjusted rainfall, I_{ad} is the adjusted initial abstraction, M is the antecedent moisture and S is the potential maximum retention, P_o = observed rainfall, t_p = storm duration and $\bar{t}_p$ = mean storm duration
12	Mishra et al. (2005)	$Q = \frac{(P - I_a)^2}{S + 0.5(P - I_a)}$	where, Q is the direct surface runoff, I_a is the initial abstraction and S is the potential maximum retention
13	Mishra et al. (2003)	$Q = \frac{(P - I_a - F_c)(P - I_a - F_c + M)}{P - I_a - F_c + M + S}$ for $P \geq I_a + F_c$ Otherwise, $Q = 0$, for practical purpose M can be computed as $M = (P_5 - I_a)S_l/P_5 - I_a + S_l$	where, P is the precipitation, F is the cumulative infiltration, S is the potential maximum retention, F_d is the dynamic infiltration, F_c is the static infiltration, M is the antecedent moisture and I_a is the initial abstraction.
14	Mishra and Singh (2004)	$q = \left\{1 - \frac{1}{[1 + k(t - t_p)]^2}\right\} i_e A$	where, A is the catchment area, i_e is the effective uniform rainfall intensity, t is the time from the beginning of infiltration and $(t - t_p)$ is the time past ponding.

S.No.	Author(s)	Models	Parameters
15	Mishra and Singh (2006)	$Q = \frac{(P - I_a)(P - I_a + M)}{P - I_a + M + S}$ $F = \frac{(P - I_a)S}{P - I_a + M + S}$ $Q = \frac{(P - I_a - F_c)(P - I_a - F_c + M)}{P - I_a - F_c + M + S}$ $F_d = \frac{(P - I_a - F_c)S}{P - I_a - F_c + M + S}$	where, P is the rainfall, I_a is the initial abstraction, M is the antecedent moisture, S is the potential maximum retention, F_c is the static infiltration and F_d is the dynamic infiltration.
16	Mishra et al. (2006a)	$Q = \frac{(P - \frac{\lambda S^2}{S+M})(P - \frac{\lambda S^2}{S+M} + M)}{P - \frac{\lambda S^2}{S+M} + M + S}$	where, P is the rainfall, I_a is the initial abstraction, M is the antecedent moisture, S is the potential maximum retention and λ is the initial abstraction coefficient.
17	Mishra et al. (2006b)	$Q = \frac{\left(P - \frac{\lambda S^2}{S+M}\right)\left(P - \frac{\lambda S^2}{S+M} + M\right)}{P - \frac{\lambda S^2}{S+M} + M + S}$ Differentiated partially with respect to P to yield $\frac{\delta Q}{\delta P} = \frac{\left(P - \frac{\lambda S^2}{S+M} + S + M\right)^2 - S(S + M)}{\left(P - \frac{\lambda S^2}{S+M} + S + M\right)^2}$	where, Q is the direct surface runoff, P is the precipitation, S is the potential maximum retention, M is the antecedent soil moisture and λ is the initial abstraction coefficient.

S.No.	Author(s)	Models	Parameters
		Form the partial area concept $0 \leq \delta Q/\delta P \leq 1$ $\frac{\delta Q}{\delta P} \geq 0, \frac{P}{S} \geq \sqrt{1} + M^* - \left(1 + M^* - \frac{\lambda}{1+M^*}\right)$ whereM^* =M/S. For $\delta Q/\delta P \leq 1$, $S^2(1 + M^*) \geq 0$	
18	Mishra et al. (2006c)	$Q = (P^2)/(P + S)$ $Q = \left((P - \lambda S)^2\right)/(P + (1 - \lambda)S)$ $Q = \left((P - \lambda S)(P - \lambda S + M)\right) / (P + (1 - \lambda)S + M)$ $Q = \left((P - 0.2S)(P - 0.2S + M)\right)/(P + 0.8S + M)$	where, P is the precipitation, S is the potential maximum retention, λ is the initial abstraction coefficient and M is the antecedent soil moisture
19	Michel et al. (2005)	then $Q = 0$ $Q = \frac{(P + V_0 - S_a)^2}{P + V_0 - S_a + S}$ $Q = P\left[1 - \frac{(S + S_a - V_0)^2}{S^2 + (S + S_a - V_0)P}\right]$	where, P is the rainfall, V_0 is the initial soil moisture, S_a is the threshold soil moisture and S is the potential maximum retention.

S.No.	Author(s)	Models	Parameters
20	Patil et al. (2008)	$Q=\frac{(P-F_s)^2}{P-F_s+S}$	where, P is the rainfall, F_s is the static infiltration, S is the potential maximum retention, F is the cumulative precipitation, Q is the direct surface runoff
21	SCS 1954	$Q=\frac{(P-I_a)^2}{P-I_a+S}$	where, Q is the direct surface runoff, I_a is the initial abstraction and S is the potential maximum retention
22	Sahu et al. (2007)	$V_0=V_{00}+\beta(P_5-Q_5)$ $Q_5=0$ $Q_5=0$ $V_0=V_{00}+\beta P_5$ Then $Q_5=\frac{(P_5+V_{00}-S_a)^2}{P_5+V_{00}-S_a+S}$ $V_0=V_{00}+\beta\left[P_5-\frac{(P_5+V_{00}-S_a)^2}{P_5+V_{00}-S_a+S}\right]$ $Q_5=P_5\left[1-\frac{(S+S_a-V_{00})^2}{S^2+(S+S_a-V_{00})P_5}\right]$ $V_0=V_{00}+P_5\beta\left[1-\frac{(S+S_a-V_{00})^2}{S^2+(S+S_a-V_{00})P_5}\right]$	where, V_0 is initial soil moisture store level, V_{00} is the pre antecedent moisture level, P_5 is the previous five days rainfall, S_a is the threshold soil moisture and S is the potential maximum retention

S.No.	Author(s)	Models	Parameters
23	Sahu et al. (2010)	$Q = \frac{(P - I_q)(P - I_a + M)}{P - I_a + S_0}$ if $P > I_a$	where, S_0 is the absolute potential maximum retention, I_a is the initial soil moisture, P is the precipitation, M is the antecedent soil moisture
24	Sahu et al. (2012)	$Q = \frac{(P - I_a - F_c)(P - I_a - F_c + M)}{P - I_a - F_c + S_0}$	P is the precipitation, I_a is the initial abstraction, F_c is the static infiltration, S_0 is the absolute potential maximum retention and M is the antecedent moisture

25	Singh et al. (2015)	If $V_0 < S_a - P$ then $Q = 0$
		If $S_a - P < V_0 < S_a$, then
		$Q = \frac{(P + V_0)(P + V_0 - S_a)}{P + S + V_0}$
		If $S_a \leq V_0 \leq S_b$, then
		$Q = P\left(1 - \frac{(S_b - V_0)^2}{SS_b + P(S_b - V_0)}\right)$
			where, V_0 is the initial soil moisture storage, S_a is the threshold soil moisture, S_b is the absolute potential maximum retention = $(S + S_a)$.

S.No.	Author(s)	Models	Parameters
26	Shi et al. (2017)	$Q = \frac{(P + V_0 - S_a - F_c)(P + V_0 - F_c)}{(P + S + V_0 - F_c)}$ if $S_a + F_c - P < V_0 < S_a \& P > F_c$ $Q = \frac{(P - F_c)(P - F_c + V_0)}{(P - F_c + S_b)}$ if $S_a \leq V_0 \leq S_b \& P > F_c$	where, Q is the direct surface runoff, P is the precipitation, V_0 is the initial soil moisture, F_c is the static infiltration S_a is the threshold soil moisture
27	Tramblay et al. (2010)	$P_e(t) = Pb(t)\left(\frac{P(t) - 0.2S}{P(t) + 0.8S}\right)\left(2 - \frac{P(t) - 0.2S}{P(t) + 0.8S}\right)$	where, F_a is the initial abstraction, t is the time, $P_e(t)$ is the effective rainfall rate, $Pb(t)$ the precipitation rate and $P(t)$ is the cumulative rainfall since the beginning of the event.
28	Verma et al. (2017)	If $V_o \geq S_a - P$, then $Q = 0$ If $S_a - P < V_o < S_a$, then Q $Q = \frac{(P - S_a + V_o)(P - S_a + 2V_o)}{(P - S_a + 2V_o + S)}$ If$S_a \leq V_o \leq S_a + S$, then Q $= \left[1 - \frac{(S_a + S - V_o)^2}{(P(S_a + S - V_o) + S(S + V_o))}\right]$	V_o= initial soil moisture, S_a= threshold soil moisture

S.No.	Author(s)	Models	Parameters
29	Woodward et al. (2003)	$Q = \dfrac{(P - 0.05S)^2}{P + 0.95S}$ for $P > 0.05S$	where, Q is the direct surface runoff, P is the precipitation and S is the potential maximum retention.
30	Yu (1998)	$Q = \bar{Q}T_s \dfrac{(\bar{\imath}T_s)^2}{\bar{\imath}T_s + f\bar{T_s}} = \dfrac{{P_e}^2}{P_e + S}$	$G_f(f) =$ are the cumulative distribution functions of the infiltration capacity, f, and rainfall rate, i, respectively; $\bar{\imath}$ is the average rainfall rate; $\bar{f}$ is the average infiltration capacity. The total rainfall-excess, Q (=$\bar{Q}T_s$) is the same as storm runoff for individual events; $\bar{\imath}T_s$ = is the same as P_e if $\bar{\imath}$refers to the average rainfall rate after runoff has begun; and $f\bar{T_s}$ can be interpreted as the potential maximum retention, S, or equivalently the CN, because $f\bar{T_s}$ is the maximum amount of infiltration that could have occurred during the runoff event

SCS-CN method is also construed as an infiltration model (Aron et al., 1977; Chen, 1982; Ponce and Hawkins 1996). Hjelmfelt (1980) proposed a SCS-CN based infiltration equation comparable with Holtan and Overton infiltration equations, to compute the infiltration rate from rainfall of uniform intensity. Mishra (1998) and Mishra and Singh (2002b) introduced a term for steady state infiltration rate and proposed an infiltration equation by expressing the SCS-CN method in the form of the Horton method and assuming constant rainfall intensity. It has been employed for determination of infiltration and runoff rates (Mishra 1998; Mishra and Singh 2002b, 2004b). Besides above applications, the SCS-CN method has also been used in association with erosion models for computation of sediment yield. The Modified Universal Soil Loss Equation, MUSLE (Williams, 1975), Agricultural Non-Point Source Model, AGNPS (Young, et al., 1987), Soil and Water Assessment Tool, SWAT (Arnold et al., 1993, 1998), Erosion-Productivity Impact Calculator, EPIC (Williams et al., 1983), are, but a few examples. Sharda et al. (2002) used SCS-CN method in combination with USLE to compare runoff and soil loss from conservation bench terrace system and the conventional farming system.

The sediment yield from a watershed depends on rainfall characteristics (amount, intensity, duration, and spatiotemporal distribution), soil characteristics (structure, texture, porosity, and spatial variability), land use, slope, and anthropogenic factors. Control of sediment yield by detachment or transport can change from storm to storm, from season to season and even within a storm. Sediment yield models can be classified into three groups: (1) lumped, (2) quasi-lumped and (3) distributed (Singh et al., 2015). Probably the most widely used lumped model for estimating sediment yield from small agricultural watersheds (agricultural, forest, and urban) is the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978). Williams (1975) and Williams and Berndt (1977) have modified USLE by explicitly including the effects of runoff and designated it as MUSLE. Later, Renard et al. (1993) further revisited it and called it the revised USLE (RUSLE). To apply USLE to large watersheds, the concept of sediment delivery ratio (ratio of sediment generated to the amount of erosion) has been incorporated. Another lumped sediment yield model was developed by Mishra et al. (2006) by coupling the Soil Conservation Service Curve Number (SCS-CN) method (SCS, 1956) and USLE. Later on, a sediment yield was developed by Tyagi et al. (2008) by utilizing the SCS-CN based infiltration model for computation of rainfall-excess rate, and the SCS-CN-inspired proportionality concept for computation of sediment-excess. Singh et al. (2008) developed conceptual sediment graph models based on SCS-CN method, Nash's IUSG and power law from an agricultural watershed.

However, these models ignore the concept of soil moisture accounting (SMA) in their formulation. Notably, a sound SMA has to incorporate all soil moisture conditions (Mishra and Singh, 2004; Michel et al., 2005; and Kannan et al., 2008). Michel et al. (2005) discussed the SMA procedure is based on the notion that higher the moisture store level, higher the fraction of rainfall that is converted into runoff. Camici et al. (2011) termed it as 'design soil moisture' and argued that it is the most important factor to determine the predictive outcome of an event (De Michele and Salvadori, 2002; Berthet et al., 2009; Brocca et al., 2009a). On the contrary, other investigations have inferred that it might be not so critical, particularly in the case of large events (Bronstert and Bardossy, 1999; Castillo et al., 2003).

In physically based models, fundamental physical equations, concerning stream flow and sediment transport in a basin, are solved (Merritt et al. 2003). They describe the natural process by combining all the individual physical components into a composite model. The physical basis of these models can, in principle, contribute to overcoming many of the short coming of the empirical models (Marino and Simonovic 2001). Some of the most widely used physically-based models are Erosion Kinematic Wave Model (Hjelmfelt et al. 1975), Quasi-Steady State (Foster et al. 1977), Areal Non-Point Source Watershed Environment Response Simulation (ANSWER); (Beasley et al., 1980), Chemical Runoff and Erosion from Agricultural Management System (CREAMS); (Knisel, 1980), Water Erosion Prediction Project (WEPP); (Laflen et al., 1991) and European Soil Erosion Model (EUROSEM); (Morgan et al., 1998). If a model is constructed by using mass conservation equation of sediment yield, it is called a process-based model such as sedimentology simulation (SEDIMOT) model (Wilson et al., 1984), Agricultural Non-Point Source

(AGNPS) model (Young et al., 1987) and Watershed Environment Hydrology (WEHY) model (Kavvas et al., 2004, 2006).

The empirical and lumped sediment yield models have been found to yield satisfactory results for watersheds where needed data are available but have limited capacity for ungauged watersheds. The sediment graph models have been previously developed by Rendon-Herrero (1974) and further investigated by Rendon-Herrero et al. (1980) and Singh and Chen (1982). Rendon-Herrero (1974, 1978) extended the unit hydrograph (UH) concept to directly derive the unit sediment graph for a small agricultural watershed. Williams (1978) and Chen and Kuo (1986) extended the concept of UH or instantaneous unit hydrograph (IUH) to derive the instantaneous unit sediment graph (IUSG) and the determined sediment discharge and yield from agricultural watersheds. Singh et al. (1982), Chen and Kuo (1986), Srivastava et al. (1984), among others, employed USG or IUSG for sediment graph derivation. Sharma and Dickinson (1979) developed a conceptual sediment model for daily and monthly sediment yield modeling. These models have been shown to be satisfactory but have not been applied as extensively as USLE or its variants.

The development of storm-wise sediment graph model is a reasonable solution to understanding the complexities and to reducing the uncertainties. The sediment graph or sedigraph (SG), which is the temporal distribution of sediment load during flood events (Sadeghi and Singh, 2005), has many applications, and its shape and specification is perhaps controlled by many factors. Sediment availability and the dynamics of storage-mobilization-depletion process of available sediment (Walling and Webb, 1982; Lenzi and Marchi 2000) and location (Klein, 1984; Sayer et al., 2006; Lana-Renault et al., 2007), rainfall specification (Wood, 1977; Klein, 1984; Lana-Renault et al., 2007), effective precipitation, and transmission losses, respectively, in the upland and channel phases (Sharma and Murthy, 1996), flow hydrograph components and characteristics (Wood, 1977; Terajima et al., 2007) are the important parameters controlling sediment transport and the consequent shape of SGs.

To conclude, the SCS-CN method and SMA procedure is a well-accepted technique in applied hydrology and has been extensively used for determining direct surface runoff from the given rainfall on a watershed. Since the method relies only on one parameter, it is simple, easy to understand and applicable to those watersheds with a minimum of hydrologic information.

2.4 MECHENICS OF SOIL EROSION BY WATER

Mechanics of water erosion is often a two-fold process. Raindrops falling on soil surface can cause particles to detach and splash upward. Upon returning to the soil, splashed particles disperse and clog soil pores, causing surface crusting and a reduction in the soil’s infiltration rate. The pounding action of rain may also compact the soil, further decreasing infiltration. When water is applied in excess of the soil’s infiltration rate, water will puddle and the runoff leads to additional detachment of soil particles due to shear stress of flow and transport of these particles by the flowing water. Particle transport by water requires a critical speed to effectively carry sediment; when water velocity slows below this speed, deposition occurs. Because coarse particles fall out of suspension sooner than fine particles as runoff velocity slows down, they are more apt to remain on the field while fine particles are moved farther downstream. Thus, for a given physiography, the energy required for the detachment and the transportation of soil particles is supplied by raindrops and the overland flow. Besides acting as energy source, raindrops also act as wetting source. Mode of detachment of soil particles by impact of raindrops varies with the degree of wetness of land surface (Garde and Kothyari, 1987). The shear strength of soil decreases with increasing wetness. The overland flow exerts shear stress on the surface thereby inducing both the detachment and transportation of soil particles. Maximum soil splash takes place when the land surface is covered by overland flow of small depth (Mutchler and Young, 1975). Deposition of detached material takes place when the transport capacity of flow is less than the sediment load being transported. Three main forms of water erosion are sheet, rill and gully erosion. Sheet erosion is the removal of a thin layer of soil from the surface and is caused by overland flow moving uniformly across the surface. As the sheet erosion continues, water begins to concentrate in small channels or rills, and rill erosion occurs. Rills tend to be uniformly distributed over the field and are defined as being small enough to be smoothed over by cultivation practices. The concentration of running water causes rill erosion to be more erosive than sheet erosion. Gully erosion occurs when large quantities of runoff concentrate and create large channels in the landscape. Gullies are relatively permanent features that cannot be removed by tillage.

2.5 FACTORS AFFECTING EROSION AND SEDIMENT YIELD

The four principal factors that affect soil erosion and quantity of sediment that may reach the outlet of a watershed are climate, soil properties, watershed characteristics and land use/ land cover characteristics. The effects of these factors on erosion and sediment yield are reviewed below.

2.5.1 Climate

Climate has always been observed to have a strong influence on erosion and sediment yield. Intensity, duration and frequency of rain events all appear to play a role in the amount of soil that erodes. In general, the most severe erosion occurs when rains are of relatively short duration, but high intensity. Heavy raindrop action coupled with higher rain intensity than the soil infiltration capacity can lead to high surface runoff and large soil loss. Long, low intensity storms can also be highly erosive due to saturated soil conditions causing increased runoff (Morgan, 1995). Soil detachment by wind driven rain is different from that by rain falling under calm air (Lal, 1976). The wind action on rain drops may add to their erosive energy and also may increase the velocity of flow and thereby its transport capacity. The temperature plays an important role in the process of weathering which leads to disintegration of rocks. For the same rainfall, temperature also affects runoff and hence the sediment yield.

2.5.2 Soil Properties

Soil properties affecting water erosion and sediment yield include those that influence infiltration and soil stability, such as texture, organic matter, aggregation, soil structure and tilth. The effect of these properties in terms of infiltration/ runoff were presented in Section 2.2.1. Soil erodibility or the vulnerability of soil to erosion refers to the resistance of soil to both detachment and transportation (Wischmeier and Smith, 1978). Key factors that affect erodibility are soil texture, soil permeability, soil structure, and amount of organic matter. Because water readily infiltrates into sandy soils, the runoff, and consequently the erosion potential, is relatively low. Clay, because of its stickiness, binds soil particles together and makes it resistant to erosion. However, once heavy rain or fast flowing water erodes the fine particles, they will travel great distances before settling. The soils with 40 to 60 percent silt content are more erodible in spite of large particles being resistant to transport and the fine particles offer resistance to detachment due to their cohesiveness. Soil with clay fraction between 9 to 30 percent is more susceptible to erosion (Evans, 1980). Organic matter consists of plant and animal litter in various stages of decomposition. Organic matter improves soil structure and increases permeability, water holding capacity, and soil fertility. Moldenhauer and Long (1964) studied the effect of different textures of soil on erosion under simulated rainfall. The relative soil loss at high intensity rainfall varied as follows: soil loss from silty clay > silty clay loam > silt > loam > fine sand. However, at low intensity rainfall the order of soil loss was as follows: soil loss from silty clay loam > silty clay > loam > silt > fine sand. With equal water loss, the order of erodibility was as follows. Soil loss from fine sand > silty clay > silty clay loam > silt > loam. The works of Wischmeier and Mannering (1969), Wischmeier et al. (1971), and Alberts et al. (1980) on soil erodibility factor and its relationship with soil texture and available organic contents are worth mentioning. Flaxman (1972) included percent of soil particles greater than 1.0 mm in his annual sediment yield equation.

2.5.3 Catchment Characteristics

Catchment area, slope, and drainage density are some of the catchment characteristics that influence the runoff production and thus the sediment yield (Jansen and Painter, 1974; Garde and Kothyari, 1987). Because fast moving water can carry more sediment than slow moving water, there is a greater potential to lose a larger amount of material on steep slopes than gradual slopes (Morgan, 1979). In an analysis of data from 27 catchments in India, Garde et al. (1983) concluded that the catchment slope was an important variable and established a relationship between the soil erosion per unit area (A) and the topographic factor, given by: ($A = \mathrm{f}(S^m L^n)$), where S is the slope and L is slope length, m and n are the exponents ranging respectively, between 1.3 to 2.0 and 0.3 to 0.7. Many researchers have investigated the effect of slope steepness on the erosion and found a power relationship of the form of ($y = ax^b$); where y is the erosion, x is the slope steepness, a and b are, respectively, the constant and exponent of the power relationship (Zingg, 1940). Schumm (1954) demonstrated the variation of sediment delivery ratio with catchment area and derived an inverse correlation between sediment yield per unit area and the area. A similar effect was observed by several other investigators (Roehl, 1962; Wilson, 1973; Taylor, 1983).

2.5.4 Landuse/ Landcover

Vegetative cover reduces detachment of soil particles by intercepting raindrops and dissipating their energy. Type of land use and vegetative cover also influence the overland flow in terms of the roughness (Chow, 1959). Surface vegetation and residue act as dams that slow down flow velocity and promote deposition. Roots of vegetation play significant role in reducing the soil erosion by binding the soil mass to increase its resistance to flow (Wischmeier, 1975). This factor was included in the Universal Soil Loss Equation as Cover Management Practice Factor, ‘C’. A wider range of the literature is available on the studies of the effects of residue on soil erosion rates (Meyer et al., 1975a; Laflen and Colvin, 1981; Foster, 1982; Hussein and Laflen, 1982; Cogo et al., 1984; Dickey et al., 1985; Norton et al., 1985; Gilley et al., 1986; Franti et al., 1996).

2.6 MODELING SOIL EROSION AND SEDIMENT YIELD

The processes controlling sediment detachment, transport, and deposition on the hill slope scale, lumped under the term erosion processes, are complex and interactive (Lane et al., 1988). This complexity leads to the need for upland erosion models as tools in resource management. Since runoff is the main carrier of sediment, the erosion models are used in combination with a hydrologic model to estimate the sediment yield at the outlet of the watershed. The models are simplified representations of the actual physical processes of the rainfall-runoff-soil erosion mechanism. Several models have been developed over the last three to four decades that vary greatly in complexity and range from simple regression models to physically based models. More precisely, these models may be categorized into: (i) empirical soil erosion models, for example, the equation of Musgrave (1947), USLE -Wischmeier and Smith (1965, 1978), MUSLE - Williams (1975), Brown and Foster (1987), RUSLE - Renard et al., 1991; (ii) conceptual soil erosion models, for example, the models of Johnson (1943), Rendon-Herrero (1978), Williams (1978), Kalin et al. (2004); and (iii) physically based erosion models, for example the models of Meyer and Wischmeier (1969), Foster and Meyer (1972a, b), Bennett (1974), Hjelmfelt et al. (1975), Meyer et al. (1975a), Foster et al. (1977a), Shirley and Lane (1978), Foster (1982), Singh and Regi (1983), CREAMS (Knisel, 1980), WEPP (Nearing et al., 1989), ANSWERS (Beasley et al., 1980), KINEROS (Woolhiser, et al., 1990), and SHESED (Wicks and Bathurst, 1996). Empirical models are developed using long records of observed data and are spatially lumped. In reality, the physically based models still rely on empirical equations to describe erosion process and, therefore, they are termed as physically process based models.

2.6.1 Empirical Erosion Models

The development of erosion prediction technology perhaps began with analysis such as the one by Cook (1936) who identified three major variables that affect soil erosion as (i) susceptibility of soil to erosion, (ii) potential erosivity of rainfall and runoff, and (iii) soil protection afforded by plant cover. Later, Zingg (1940) published the first equation for soil erosion that described the effects of slope steepness and slope length on erosion. Smith (1941) added factors for cropping systems and supporting practices to this equation. Browning et al. (1947) added soil erodibility and management factors to Smith equation and prepared extensive tables for relative factor values for different soils, rotations, and slope lengths. Smith and Whitt (1947) presented a method for estimating soil losses from fields of clay pan soils. The following year, Smith and Whitt (1948) presented a rational erosion-estimating equation, A=CSLKP. The C factor was the average annual soil loss for a specific rotation, slope length, slope steepness, and row direction. The other factors for slope (S), slope length (L), soil group (K), and supporting practice (P) were dimensionless multipliers to adjust value of C to other conditions.

Erosion experiment stations were established in the 1930’s by the U.S Soil Conservation Services (USSCS), which were concerned about the conservation of agricultural lands. These stations were responsible for measuring rainfall, runoff, and soil erosion from small plots. As a result of the plot erosion research, the first erosion models (equations) were developed. Ellison (1944) showed the effect of rainfall energy on sheet erosion by the equation $E = KV^{4.33} d^{1.07} I^{0.65}$, where E is the grams of soil intercepted in splash sampler during a 30 minute period, V is the velocity of drops in ft/sec, d is the diameter of the drops in mm, I is the intensity of rainfall in in/hr, and K is a constant. Musgrave (1947) analyzed 40000 plot-years of data to develop his relationship to incorporate the land characteristics, and expressed the relationship as:

$$A_L = C_s R_s S^{1.35} L^{0.35} {P_{30}}^{1.75} \quad (2.7)$$

where, A_L = long term average soil loss from sheet and rill erosion (acre-inch per year), C_s = soil erodibility factor (inch per year), R_g = crop management factor, S = slope (percent), L = length of slope (feet), and P_{30} = two year, 30 minutes rainfall amount (inches).

Graphs to solve the Musgrave equation were prepared by Lloyd and Eley (1952). Van Doren and Bartelli (1956) proposed an erosion equation for different soils and cropping conditions that estimated annual soil loss as a function of nine factors. Einstein (1950) developed methodology for bed load functions and bed load transport for rivers and streams.

Wischmeier and Smith (1958) re-examined the erosion plot data used by Musgrave and the US Weather Bureau rainfall data and published their first results which ultimately led to the development of the Universal Soil Loss Equation (USLE). USLE was published by Wischmeier and Smith (1965) based on over 10,000 plot years of natural and simulated runoff data, expressed as:

$$A = RKLSCP \quad (2.8)$$

where A is the annual potential soil erosion (t ha^{-1} year^{-1}); R is the rainfall erosivity factor (MJ mm ha^{-1} hr^{-1} year^{-1}) taken as the long term average of the summation of the product of total rainfall energy (E) and maximum 30 minute rainfall intensity (I_{30}), i.e. EI_{30}; K is the soil erodibility factor (t ha hr ha^{-1} MJ^{-1} mm^{-1}); LS is the slope length and steepness factor (dimensionless); C is the cover management factor (dimensionless); and P is the supporting practice factor (dimensionless). The dimensions used here are consistent with the work of Renard et al. (1991). The R factor of USLE can be computed from:

$$R = \frac{\sum_{i=1}^{j}(EI_{30})}{N} \tag{2.9}$$

where, $(EI_{30})_i = EI_{30}$ for storm i, j = number of storms in an N year period and I_{30} is maximum 30 minute rainfall intensity. The kinetic energy, E can be computed using Laws and Parsons (1943) equations. The soil erodibility factor (K), a function of soil texture, is a measure of the potential erodibility of soil. The slope length and steepness factor (LS) accounts for the overland runoff length and slope. For slopes > 4%, it can be determined as:

$$LS = L^{1/2}(0.0138 + 0.00974Y + 0.001138Y^{2}) \tag{2.10}$$

where Y is the gradient (%) over the runoff length and L is the length (m) of slope from the point of origin of the overland flow to the point where the slope decreases to the extent that sedimentation begins. The cover management factor (C)estimates the effect of ground cover conditions, soil conditions, and general management practices on erosion rates. The supporting conservation practice factor (P) accounts for the effectiveness of erosion control practices, such as land treatment by contouring, compacting, establishing sedimentation basins, and other control structures. Generally, C reflects the protection of the soil surface against the impact of rain drops and subsequent loss of soil particles, whereas P includes treatments that retain eroded particles and prevent them from further transport. The experimentally derived values of the above factors for various soil-vegetation-land use complexes are available elsewhere (Ponce, 1989; Singh, 1992; Novotny and Olem, 1994; Singh and Singh, 2001).

Three major limitations of the USLE restricted its application in many modeling analysis. First, it was not intended for estimating soil loss from single storm events (Haan et al., 1994); second, it was an erosion equation, and consequently did not estimate the deposition (Wischmeier, 1976); and third, it did not estimate gully or channel erosion.

Since 1965, efforts have been to improve the USLE and it has been expanded for additional types of land use, climatic conditions and management practices. Renard et al. (1974) modified the USLE to approximate soil loss from rangeland watersheds by including an additional term in the USLE to accommodate channel erosion. Williams (1975) presented a Modified Universal Soil Loss Equation (MUSLE) for predicting sediment yield from individual storm events. The rainfall energy term of the USLE was replaced by the runoff energy factor because the runoff is more closely related to the sediment yield than the rainfall energy, as the former is responsible for transporting detached sediment to the catchment outlet. The MUSLE is expressed as,

$$Y = 11.8(V \cdot Q_p)^{0.56} KLSCP \qquad (2.11)$$

where, Y is the sediment yield (t), V is the storm runoff volume (m^3), Q_p is the peak runoff rate ($m^3\ s^{-1}$), and other factors are same as that of USLE.

Since the procedure suggested by Wischmeier and Smith (1965) for determining R-values of USLE is applicable for computation of annual erosion, its use in estimation of soil loss from a single storm would yield errors (Haan et al., 1994). Foster et al. (1977b) suggested a modification of R-values applicable to individual storm events as:

$$R = 0.5R_r + 0.35Qq^{1/3} \qquad (2.12)$$

where R_r is the rainfall energy factor for the storm (= EI_{30} for the storm) (N hr^{-1}), Q is the runoff volume (mm), and q is the peak runoff rate (mm/hr). Since q is related to the detachment of soil particles more than is Q, a reduction in peak discharge by the vegetative cover will also reduce sediment transport (Williams and Berndt, 1977).

The USDA Forest service, under an interagency agreement with USEPA compiled a set of watershed analyses and prediction procedures (Snyder, 1980). These state-of-the-art techniques are collectively referred to as WRENSS (Water Resources Evaluation of Nonpoint Sources-Silvicultural). The objective of the soil erosion component in WRENSS was to estimate the quantity of accelerated soil loss under given silvicultural activity condition. An empirical procedure was chosen for estimating soil loss using the USLE, modified for use in forest environments. The cropping management factor and the erosion control practice factor have been replaced by a vegetation management factor to form the Modified Soil Loss Equation (MSLE).

Renard et al. (1991) proposed revised USLE (RUSLE) incorporating a method for computing kinetic energy of rainfall for individual storm events using the equation proposed by Brown and Foster (1987):

$$e = 1099[1 - 0.72\exp(-1.27\,i)] \quad (2.13)$$

The total energy in the storm is computed by multiplying the above computed e-value with the depth of rainfall (i.e. $E = e.P$).

USLE so far remains the well accepted and most widely used empirical approach for estimation of upland erosion despite the development of a number of conceptual and physically process based models (Lane et al., 1988; Narula et al., 2002). Researches and investigators have applied USLE with suitable modifications for estimation of annual soil loss and sediment yield as well as its temporal variation on single storm event basis, and to study the effect of various parameters that affect the soil loss. The works of Foster and Wischmeier (1974), Onstad and Foster (1975), Onstad and Bowie (1977), Cooley (1980), Hadley et al. (1985), McCool et al. (1987), Liu et al. (1994), Jain and Kothyari (2000), Kothyari et al. (1996) are worth mentioning.

2.6.2 Conceptual Erosion Models

The conceptual models lie somewhere between empirical and physically based models and are based on spatially lumped forms of continuity equations for water and sediment and some other empirical relationships. Although highly simplified, they do attempt to model the sediment yield, or the components thereof, in a logical manner. To summarize, conceptual models of sediment are analogous in approach to those of surface runoff, and hence, embody the concepts of the unit hydrograph theory.

Johnson (1943) was perhaps the first to derive a distribution graph for suspended sediment concentration employing the hypothesis analogous to that embodied in the unit hydrograph. Rendon-Herrero (1978) extended the unit hydrograph method to directly derive a unit sediment graph (USG) for a small watershed. The sediment load considered in the USG is the wash load only.

Williams (1978) extended the concept of an instantaneous unit hydrograph (IUH) to instantaneous unit sediment graph (IUSG) to determine the sediment discharge from an agricultural catchment. The concept of USG has been also employed by Singh et al. (1982), Chen and Kuo (1986), Kumar and Rastogi (1987), Raghuwanshi et al. (1994), Banasik and Walling (1996), among others, for the purpose of estimating the temporal variation of sediment yield.

Kalin et al. (2004) developed a modified unit sedimentograph approach for identification of sediment source areas within a watershed. The watershed was partitioned into a number of elements. The sediment flux response of the elements at the basin outlet was computed by characterizing the rainfall event by the pulses of excess rainfall depths. The application of these methods requires considerable input data for their calibration and they inherit the limitations of unit hydrograph theory.

2.6.3 Physically Based Erosion Models

Significant research and understanding of basic processes of erosion and sediment yield led to the development of more complicated, physically based sediment yield models. These models have been developed in a coupled structure such that the algorithms for computing runoff are combined with the algorithms for computing sediment detachment, deposition and their transport. In physically based sediment yield models, the simulation of hydrological and erosion processes involves solutions to the simultaneous partial differential equations of mass, momentum and energy conservation, which being non-linear in nature are difficult to solve. However, the kinematic wave simplification of the Saint Venant equations of flow is adequate to describe the process of surface runoff in upland areas of a watershed (Bennett, 1974; Woolhiser, 1977; Laguna and Giraldez, 1993). Physically based models are expected to provide reliable estimates of sediment yield. However, these models require a large number of input parameters and, therefore, the practical application of these models is still limited because of uncertainty in specifying model parameter values and also due to the difference between the scales of application i.e. a catchment versus a field (Hadley, et al., 1985; Wu, et al., 1993).

The physically based models generally separate the ground surface into inter-rill and rill erosion areas (Wu et al., 1993; Meyer et al., 1975b; Kothyari and Jain, 1997). Detachment over inter-rill areas is considered to be by the impact of rain drops because flow depths are shallow, while runoff is considered to be the dominant factor in rill detachment and sediment transport over both rill and inter-rill areas. During the last four decades, the development of mathematical theory to describe the mechanics of soil erosion, sedimentation, and their interrelationship, provide the needed foundation for the development of physically based models (Bennett, 1974; Foster et al., 1977a; Foster, 1982; Hirschi and Barfield, 1988; Nearing et al., 1989; Elliot and Laflen, 1993). Ellison (1947) presented a comprehensive analysis of various soil erosion sub-processes, an essential requirement for more recent soil erosion modelling. Meyer and Wischmeier (1969) formulated the latest concept using mathematical descriptions of rainfall and runoff detachment and transport processes. Foster and Meyer (1972a) described the relationship for runoff detachment where its rate is a function of the ratio of sediment flux to the sediment transport capacity of the flow. Pandey et al. (2016) critically reviews of 50 physically based erosion and sediment yield models with respect to these factors including short-coming and strengths. The study generally suggests the use of models like SWAT, WEPP, AGNPS, ANSWERS and SHETRAN for soil erosion and sediment yield studies. The study proposes future research suggested to improve the simulation and prediction capability of physically based soil erosion and sediment yield models, and should focus on incorporation of improved global web based weather database, inclusion of sediment associated water quality and gully erosion simulation module, and improvement in reservoir siltation and channel erosion simulation processes. Many more relationships developed by various researchers and subsequently used by many other investigators are available for estimation of the inter-rill detachment, rill detachment, and transport of the detached sediment. The works of David and Beer (1975a, b), Foster and Meyer (1975), Mutchler and Young (1975), Foster et al. (1977 a, b), Meyer (1981), Foster and Lane (1983), Schultz (1985), Nearing et al. (1989), Watson and Laflen (1986), Woolhiser et al. (1990), Govindaraju and Kavvas (1991), Haan et al. (1994), Sharda and Singh (1994), Tayfur and Kavvas (1994), Foster et al. (1995), Sander et al. (1996), Hjelmfelt and Wang (1999), Tayfur (2001, 2002), Hogarth et al. (2004 a, b), and Jain et al. (2005) are worth mentioning. A summary of some important relationships proposed by various investigators for inter-rill process, rill process and the transport process are presented in Tables 2.2, 2.3 and 2.4 respectively.

Table-2.2: Important relationships available for the inter-rill erosion computation

S.No	Authors with Year	Relationship	Parameters
(i)	**(ii)**	**(iii)**	**(iv)**
1.	Ellison (1947)	$D_R = f[(I^{2.14})]$	D_R = soil splash loss; I = 30 min rainfall intensity
2.	Meyer and Wischmeier (1969)	$D_R = S_{DR} A_I I^2$	D_R = soil detachment due to rainfall; S_{DR} =a constant for the soil effect; A_I = the incremental area; I = 30 min rainfall intensity
3.	David and Beer (1975)	$D_R = SC_F . LS_F . I^a . \exp(-ky)$	SC_F = soil and soil cover factor; LS_F = land slope factor; k = exponent greater than one; y = overland flow depth; I = rainfall intensity; a = exponent (= 1).
4.	Foster et al. (1977a)	$D_i = K_i I(bS + c)$	D_i = soil detachment due the rainfall; I = rainfall intensity; S = slope steepness; and $a$and$b$ are the constant determined from experiments and analysis.
5.	CREAMS (Knisel, 1980)	$D_i = 4.57(EI)(\sin\theta + 0.014)KC_u P[Q_p/Q_w]$	D_i = interrill detachment rate [g s^{-1} m^{-2})]; EI = EI_{30} value of storm [MJ m^{-2}·mm^{-1} h]; θ = slope angle (degree); Q_p = peak runoff rate (m s^{-1}); Q_w = discharge rate per unit area [m^3 s^{-1} m^{-2})]; and K (g EI_{30}^{-1}), C_u and P are the soil erodibility, cover and management, and supporting conservation practice factors, respectively, from the USLE. P factor is used in the presence of contouring.
6.	Meyer (1981)	$D_I = aI^b$	D_I= inter-rill erosion; I = rainfall intensity; a= coefficient; b = exponent (ranges between 1.6 and 2.1 depending upon the clay content of the soil).

S.No	Authors with Year	Relationship	Parameters
7.	Singh and Prasad (1982); Blau et al. (1988); Shirley and Lane (1978)	$E_i = K_i R^m$	E_i = interrill erosion rate (kg m^{-2} s^{-1}); K_i = interrill erodibility factor (kg m^{-3}); R = rainfall excess rate (m s^{-1}); and m is an exponent taken to be unity
8.	Croley (1982); Foster (1982); Croley and Foster (1984)	$E_i = K_i R^m$	E_i = interrill erosion rate (kg m^{-2} s^{-1}); K_i = interrill erodibility factor (kg m^{-3}); R = rainfall excess rate (m s^{-1}); andm = 2
9.	Gilley et al. (1986)	$D_s = 0.2 K_d \rho Cos^2 \theta a_i {V_i}^2 (d_i/Y)^{1.83}$ $Y = \{[(b\ I^c + K_w)(\upsilon\ I\ x)]/8gS\}^{1/3}$	D_S = soil detachment (kg m^{-2} s^{-1}); K_d = soil detachment factor (s m^{-1}); ρ = density of soil (kg m^{-3}); θ = slope angle, a_i = number of drops in the i^{th} class; V_i = velocity of drop (m s^{-1}) with diameter I; d_i = mean drop diameter of class *i* (m); and Y = depth of overland flow (m). I = rainfall intensity (m s^{-1}); b and c are the regression coefficients; K_w = 24 for laminar flow over smooth surface; υ = kinematic viscosity of water (mm^2 s^{-1}); *x* = distance in flow direction (m); and *S* = channel bottom slope (m m^{-1})
10.	Schultz, (1985)	For $t \leq t_p$: $\ln(SR) = 4.27 - 0.339\ \ln(\tau - 3.22)$ $\ln(SR) = 17.2\ \ln(10.3 - D) - 35.0$ $\tau = 3.22 + 15.4\ \exp(-2.68\ t)$	SR = soil splash rate (kg $ha^{-1} min^{-1}$); and D = depth of ponded water (mm); t_p = time of initial ponding (equal to 1.5); τ = shear strength of the soil.

S.No	Authors with Year	Relationship	Parameters
11.	Watson and Laflen (1986)	$D_i = A\,\tau_a{}^B I^c\,S$	D_i = soil detachment; τ_a= soil shear strength after rainfall (Pa); I = rainfall intensity; S = slope; and A, B and C are the constants
12.	Hirschi and Barfield (1988)	$SSR = C\,R^{e_1}E^{e_2}P_{cl}{}^{e_3}S^{e_4}$	SSR = soil splash (g cm^{-2}) during Δt; *C* = empirical constant; $e_1,\ldots e_4$ are the exponents; *R* = rainfall intensity (cm h^{-1}); *E* = applied rainfall energy during Δt (Joules cm^{-2}); P_{cl} = percent clay of the surface layer; and S = soil surface slope.
13.	Nearing et al. (1989)	$D_i = K_i\,I_e{}^2 C_e\,G_e\,(R_s/w)$ $w = cQ_e{}^d$ $C_e = 1 - F_c \exp(-0.34H_c)$ $G_e = \exp(-2.5g_i)$	D_i= interrill erosion rate (kg m^{-2} s^{-1}); K_i = baseline interrill erodibility; I_e = effective rainfall intensity; C_e = effect of canopy on interrill erosion; G_e = effect of ground cover on interrill erosion; R_s = spacing of rills, and *w* is the computed rill width. Q_e = flow discharge at the end of slope; *c* and *d* are the coefficient derived from Laflen et al. (1987). F_c = fraction of the soil protected by canopy cover; H_c effective canopy height (m) (Laflen et al., 1985). g_i = fraction of interrill surface covered by residue
14.	Laguna and Giraldez (1993)	$D_i = 0.0138K_i.Cr^2$	D_i= interrill erosion rate (kg m^{-2} h^{-1}); K_i= soil erodibility factory for raindrop impact (kg h N^{-1} m^{-2}); C = USLE' C parameter; r = rainfall intensity (mm h^{-1}).

S.No	Authors with Year	Relationship	Parameters
15.	Foster et al. (1995)	$D_i = K_{iadj} I_e \sigma_{IR} SD\, R_{RR}(R_s/w)$	K_{iadj} = interrill erodibility adjusted for consolidation effects (kg s m^{-4}); I_e = effective rainfall intensity (m s^{-1}) ($\int Idt/t_e$); I = breakpoint rainfall intensity (m s^{-1}); t_e = duration for which rainfall exceeds the infiltration rate (s); σ_{IR}= interrill runoff rate (m s^{-1}); SDR_{RR} = sediment delivery ratio; R_s = rill spacing (m); and w = rill width (m)
16.	Sander et al. (1996)	$e_1 = \frac{(1 - H)a\,P}{I}$	e_i = rate of rainfall detachment of sediment of settling class i (kg $m^{-2}s^{-1}$); H = fraction of surface shields due to raindrop effect; a = rainfall detachability (kg m^{-1}); P = rainfall rate (m s^{-1}); and I = number of classes.
17.	Wicks and Bathurst (1996)	$D_i = K_r F_w (1 - C_G)[(1 - C_C)M_R + M_D]$ $M_R = \alpha I^{\beta}$ $M_D = \frac{(V\,\rho\,\pi\,D^3)^2 DRIP\,\%.\,DRAIN}{(\pi D^3/6)}$ $F_w = \exp(1 - h/D_m)$ if $h > D_m$ $F_w = 1.0$ if $h \leq D_m$ $D_m = 0.00124 I^{0.182}$	D_i = soil detached by raindrop impact (kg m^{-2} s^{-1}); K_r = raindrop soil erodibility coefficient (J^{-1}); C_G = e proportion of soil covered by ground cover; C_C = proportion of ground covered by canopy cover; F_w = flow depth correction factor; M_R= momentum squared for rain [(kg m $s^{-1})^2 m^{-2}$ s^{-1}]; and M_D = momentum squared for leaf drip [(kg m $s^{-1})^2 m^{-2}$ s^{-1}]. I = rainfall intensity (mm/h); α and β are the empirical coefficient which vary with rainfall intensity. V = leaf drip fall velocity (m s^{-1}); ρ = density of water (kg m^{-3}); D = leaf drip diameter (m) taken between 5-6 mm; DRIP % = proportion of drainage which falls as leaf drip; and DRAIN is the canopy drainage (m s^{-1}). h = water depth (m); and D_m = median raindrop diameter (m) which is computed from Laws and Parsons (1943); I = rainfall intensity (mm h^{-1}).

S.No	Authors with Year	Relationship	Parameters
18.	Li (1979); Tayfur and Kavvas (1994); Tayfur (2001); Tayfur (2002)	$D_{rd} = \alpha r^{b}(1 - Z_w/Z_m)\ if\ Z_w > Z_m$ $D_{rd} = 0$otherwise $Z_m = 3(2.23\ r^{0.182})$	D_{rd} = soil detachment rate (kg m^{-2} h); α = soil detachability coefficient that depends on the soil characteristics (kg m^{-2} mm); r = rainfall intensity (mm h^{-1}); Z_w = flow depth plus loose soil depth (mm); and Z_m = maximum penetration depth of the raindrop splash (mm) which is given by (Li, 1979).
19.	Jain et al. (2005)	$D_i = \omega F_w C_F K_F I^a (2.96\ {S_0}^{0.79} + 0.56)$	ω = coefficient for rainfall detachment; F_w = flow correction factor computed using the relationship proposed by Park et al. (1982); C_F = cover management factor of the USLE; K_F = soil erodibility factor of the USLE (kg h N^{-1} m^{-2}); I = rainfall intensity (mm/h); and a = exponent of rainfall intensity (=2).

Table-2. 3: Important relationships available for the rill erosion process

S.No	Authors with Year	Relationship	Parameters
(i)	**(ii)**	**(iii)**	**(iv)**
1.	Meyer (1964)	$D_r = K_r(\tau - \tau_c)^a$ $\tau = \gamma_w r_h S$	D_r = rill detachment rate (g m^{-2} s^{-1}); K_r= soil erodibility (g m^{-1} s^{-1} Pa^{-1}); τ = average shear stress (Pa); τ_c= critical shear stress (Pa); γ_w = specific weight of water (N m^{-3}); r_h= rill hydraulic radius (m); *S* is the hydraulic gradient (m m^{-1}); and a = is an exponent equal to 1.0 (Foster et al., 1977a), 1.05 (Knisel, 1980), 1.5 (Foster and Meyer, 1972).
2.	Meyerand Wischmeier (1969)	$D_F = S_{DF} A_I \{[S_s{}^{2/3} Q_s{}^{2/3} + S_e{}^{2/3} Q_e{}^{2/3}]/2\}$	D_F = detachment due to runoff; S_{DF} = constant for detachment due to runoff; AI = incremental area; S = slope steepness; Q = flow rate, and subscripts s and e represents for starting and end values.
3.	Meyer et al. (1975a); Piest et al. (1975)	$D_r = a_s(\tau_e - \tau_{cr})^\xi$	a_s = factor related to the soil's susceptibility to rilling; τ_e = effective shear stress; τ_{cr} = critical shear stress; and ξ = exponent.
4.	David and Beer (1975)	$E_r = C' y^{\beta 6}$	E_r = amount of overland flow scour, β6 = an exponent (≥1); C'= constant representing soil characteristics and the overland flow surface slope. If the flow is concentrated along well-defined rills and the actual flow depth is greater than the average overland flow depth, y, the value of β6 will be greater than one.

S.No	Authors with Year	Relationship	Parameters
5.	Foster (1976)	$D_F = 0.90. C_F. K_F. A_I. S. Q$	D_F = detachment due to runoff (kg/min); A_I = incremental area (m^2); S = slope steepness; Q = flow rate (m^2 min^{-1}); C_F = cropping and management factor from USLE; K_F = soil erodibility factor from USLE.
6.	Foster et al. (1977)	$D_r = a_s C_\tau{}^{3/2} \gamma^{3/2} (f_c/2g)^{1/2} S\, \sigma\, x$ $D_r = 2K_r(aS^e)\sigma x$	a_s = factor related to the soil's susceptibility to rilling; $C_\tau{}^{3/2}$ = lumped equal to ($2K_r$);γ = weight density of water; f_c = coefficient of friction; g = acceleration due to gravity; S = slope steepness; σ = excess rainfall rate (rainfall rate – infiltration rate); x = distance along the slope. The portion of $C_\tau{}^{3/2}$ (=aS^e) where a and e are function of tillage pattern, soil roughness, and other factors that interact with slope steepness to influence rill pattern.
7.	Foster et al. (1981)	$D_r = 6.86 \times 10^6 m Q_w Q_p{}^{\frac{1}{3}} (x/22.1)^{m_c - 1}$ $\times \mathrm{Sin}^2\theta K C_u P(Q_p/Q_w)$	D_r = rill detachment rate [g s^{-1} m^{-2})]; m_c = slope length exponent from USLE (0.5 for straight slope); and *x* = slope length (m), θ = slope angle (degree); Q_p = peak runoff rate (m s^{-1}); Q_w = discharge rate per unit area [m^3 s^{-1} m^{-2})]; and *K* (g $EI_{30}{}^{-1}$), C_u and P are the soil erodibility, cover and management, and supporting conservation practice factors, respectively, from the USLE. *P* factor is used in the presence of contouring.
8.	Foster (1982)	$D_{RC} = \xi C_F K_F \tau^{1.5}$	C_F = cover management factor of USLE; K_F = soil erodibility factor of USLE; ξ = coefficient; and $\tau = \gamma h S_f$

S.No	Authors with Year	Relationship	Parameters
9.	Foster (1982); Woolhiser et al., (1990)	$D_{fd} = \beta(T_c - q_s)$ $\beta = 0.5\,V_f/g$ $V_f^2 = [4g(S_s - 1)d]/(3D_c)$ $D_c = 24/R_{Pn} + 3/R_{Pn}^{0.5} + 0.34$ $R_{Pn} = V_f d/\upsilon$	D_r = rill erosion rate [$ML^{-2}T^{-1}$]; β = a first order reaction coefficient for deposition [L^{-1}]; T_c = transport capacity [$ML^{-1}T^{-1}$]; q_s= sediment load [$ML^{-1}T^{-1}$]; V_f= fall velocity [LT^{-1}]; q = discharge per unit width [L^2T^{-1}]; g = gravitational acceleration [LT^{-2}]; S_s= particle specific gravity; d = particle diameter [L]; D_c= drag coefficient; R_{Pn}= particle Reynolds number; and υ = kinematic viscosity of water [L^2T^{-1}].
10.	Hirschi and Barfield (1988)	$D_r = (1 - G_f/T_c)\,\alpha(\tau - \tau_c)^{\beta}$ $D_r = \left(1 - \frac{G_f}{T_c}\right)\alpha(\tau - \tau_c)^{\beta}(1 - f_{cd})$	D_r = actual detachment rate; G_f = flow sediment load; T_c = flow sediment transport capacity; α and $\beta$are empirical constants; τ and τ_c are bed shear stress and critical bed shear stress (N m^{-2}), respectively. f_{cd}= a fraction of the bed
11.	Blau et al. (1988)	$D_f = (B/k)q - cq$	D_f = rill erosion rate (g m^{-2} s^{-1}); B = a sediment transport parameter; k = a slope resistance parameter; q = discharge per unit width (m^3 s^{-1} m^{-1}); and c = sediment concentration (g m^{-1}).
12.	Nearing et al. (1989); Wicks and Bathurst (1996); Laguna and Giraldez (1993)	$D_f = D_c[1 - G/T_c]$ $D_c = K_r(\tau_f - \tau_c)$ $D_F = K_f[(\tau_f/\tau_c) - 1];\ K_f = K_r/\tau_c$ $\tau_f = \gamma\left((P_r/C)\ x\ s\right)^{2/3}$	D_f = rill erosion rate (kg s^{-1} m^{-2}); D_c = detachment at capacity rate (kg s^{-1} m^{-2}); G = sediment load (kg s^{-1} m^{-1}); and T_c = transport capacity in the rill (kg s^{-1} m^{-1}). K_r = rill soil erodibility parameter (s/m), τ_f = flow shear stress (Pa); T_c = critical shear stress (Pa); K_f = overland flow erodibility coefficient; P_r = peak flow rate (m s^{-1}); γ = specific weight of water (kg m^{-2} s^{-2}); x = distance down slope (m), s = slope gradient.

S.No	Authors with Year	Relationship	Parameters
13.	Elliot and Laflen (1993)	$D_c = K_p[(\gamma_w Q_s/W_r) - P_c]$	D_c = detachment capacity ($gm^{-2}s^{-1}$); K_p= soil erodibility coefficient ($g\ j^{-1}$) (= 2.19 to 51.97); W_r =rill width; and P_c = critical stream power ($w\ m^{-2}$) below which no detachment (varies between 0.14 to 1.36).
14.	Govindaraju and Kavvas, (1991); Tayfur (2001, 2002)	$D_{fd} = \beta(T_c - q_s)$ $q_s = \rho_s cq$	D_{fd} = soil detachment/deposition rate by sheet flow [$ML^{-2}T^{-1}$]; ρ_s= sediment article density [ML^{-3}]; q = unit flow discharge [L^2T^{-1}]; c = sediment concentration by volume [L^3L^{-3}]; T_c = transport capacity of sheet flow [$ML^{-1}T^{-1}$]; q_s= unit sediment discharge [$ML^{-1}T^{-1}$]; and β = transfer rate coefficient may vary over a wide range depending on the soil type [L^{-1}].
15.	Zhang et al. (2002)	$D_c = 5.43 \times 10^6 q^{2.04} S^{1.27} R^2 = 0.97$ $D_c = 1.17 \times 10^3 h^{4.62} S^{2.37} R^2 = 0.92$ $D_c = 6.20\ V^{4.12} R^2 = 0.90$ $D_c = 0.0429 \omega^{1.62} R^2 = 0.89$	D_c= detachment rate ($kg\ m^{-2}\ s^{-1}$); q = flow discharge ($m^3\ s^{-1}$); S = slope gradient; h = depth of flow; V = flow velocity ($m\ s^{-1}$); τ = shear stress (Pa); ρ = density of water ($kg\ m^{-3}$); g = acceleration due to gravity ($m\ s^{-2}$); and ω is stream power ($kg\ s^{-3}$).

Table-2.4: Important relationships available for the transport process

S.No	Authors with Year	Relationship	Parameters
(i)	**(ii)**	**(iii)**	**(iv)**
1.	Meyer and Wischmeier (1969)	$T_R = S_{TR}SI$	T_R = transport capacity due to rainfall; S_{TR} = constant that include soil effect; S = slope steepness; and I = rainfall intensity.
2.	Meyer and Wischmeier (1969)	$T_F = S_{TF}S^{5/3}Q^{5/3}$	T_F = transport capacity due to flow; S_{TF} = constant depends on effect of particle size and density of soil to account soil's transportability; S = slope steepness; and Q = flow rate.
3.	David and Beer (1975)	$T = ns^{\delta}y^{K}$	n = Manning's roughness coefficient; s = overland flow surface slope, y = depth of flow, δ = an exponent, and K= a constant.
4.	Foster (1982); Tayfur 2001, 2002)	$T_c = \eta(\tau_f - \tau_\alpha)^{3/2}$; $\tau_{cr} = \delta_s(\gamma_s - \gamma_w)^d \tau_f = \gamma_w hS$	T_c = transport capacity; η = soil erodibility coefficient, τ_f = flow shear stress; τ_{cr} = critical shear stress, δ_s = constant dependent on flow conditions (= 0.047), γ_s = specific weight of sediment, γ_w = specific weight of water, d = particle diameter, h = depth of overland flow, S = slope
5.	Foster (1982); Yalin (1963)	$T_c = 0.635\delta V_t S_u \rho_w d[1 - (1/\sigma)\log(1+\sigma)]$; $\sigma = A_s\delta$; $A_s = 2.45{S_g}^{-0.4}{Y_c}^{0.5}$ $\delta = 0$, if $Y < Y_c$	T_c = transport capacity in mass per unit width per unit time [$ML^{-1}T^{-1}$]; S_g = particle specific gravity; ρ_w = mass density of water; d = diameter of the particle; V_τ = shear velocity; Y_c = critical lift

S.No	Authors with Year	Relationship	Parameters
		$\delta = (Y/Y_c) - 1, \text{if } Y \geq Y_c; V_\tau = (\tau/\rho_w)^{0.5};$ $Y = {V_\tau}^2/(S_g - 1)gd\ ; V_\tau = (\tau/\rho_w)^{0.5};$ $\tau = \gamma h S_f (n_b/n_r)^{0.9}; h = \left(Q_w n_b/{S_f}^{1/2}\right)^{0.6}$	force obtained from Shield's diagram; *g* = acceleration due to gravity; h = flow depth; S_f = energy slope; γ = specific weight of water; n_b = Manning's roughness coefficient for bare soil; n_r = Manning's roughness coefficient for rough or vegetated surface; and Q_w= discharge rate per unit area.
6.	Beasley et al. (1980)	$T_F = 161. S. Q^{0.5}$ for $Q \leq 0.046$ $m^2\ min^{-1}$ $T_F = 16320. S. Q^2$ for $Q > 0.046$ $m^2 min^{-1}$	T_F = transport capacity (kg m^{-1} min^{-1}); S = slope steepness (m m^{-1})
7.	Nearing et al. (1989)	$T_c = k_t. {\tau_f}^{3/2}$	T_c= transport capacity; τ_f= hydraulic shear acting on the slope; and k_t= transport coefficient. Transport capacity at the end of the slope is computed using Yalin equation and the coefficient $k_t$is calibrated from the transport capacity (Finkner et al., 1989)

2.7 CONCEPT OF SEDIMENT DELIVERY RATIO

The concept of sediment delivery ratio, DR, owes its origin to the observation that the erosion predicted by the USLE overestimates the amount of sediment delivered from hill slopes because sediment deposition often occurs on hill slopes whereas the USLE does not account for deposition. The sediment yield of a catchment is only a part of gross erosion that equals the gross erosion minus sediment deposited enroute to the point of reference. Sediment produced by sheet and rill erosion often move only short distances and may get deposited away from the stream system. They may remain in the areas of their origin or be deposited on a milder slope downstream. Therefore, sediment yield is often computed based on the use of a sediment delivery ratio, DR, which is defined as the ratio of the sediment reaching the watershed outlet to the gross surface erosion. The dimensionless ratio, DR, is expressed mathematically as:

$$DR = \frac{Y}{A} \tag{2.14}$$

where, Y is the total sediment yield at watershed outlet, and A is the total material eroded (gross erosion) on the watershed area above the outlet. Many factors including catchment physiography, sediment source, proximity and magnitude of source, transport system, texture of eroded material, depositional areas and land cover etc. affect sediment delivery ratio (Dendy, 1982; Walling, 1983, 1988). However, variables such as catchment area, land slope, and land cover have been mainly used as parameters in empirical equations for DR (Hadley et al., 1985; Roehl, 1962; Williams and Berndt, 1972; Kothyari and Jain, 1997). The U.S. Soil Conservation Service has developed a generalized relationship between delivery ratio and catchment area. The inverse relationship between delivery ratio and catchment area has been explained in terms of decreasing slope and channel gradients and the increasing opportunity for deposition associated with increasing catchment size. Schumm (1954) also demonstrated an inverse correlation between sediment yield per unit area and the catchment area. Walling (1983, 1988) has summarized some of the relationships between sediment delivery ratio and the catchment characteristics.

2.8 SOME USEFUL WATERSHED MODELS FORSEDIMENT YIELD MODELLING

In earlier times, hydrology and erosion/sediment transport models were generally developed independently. It was not until the development of the digital computers that these components were put together to develop comprehensive watershed models for simulation of runoff and sediment yield behaviour of watersheds with varying complexities. Some of the watershed models that are in common use around the world (Wurbs, 1994; Narula et al., 2002) are briefly presented below.

Areal Non-Point Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al., 1980) is an event based, distributed parameter watershed model to simulate the runoff and sediment yield from agricultural watersheds and to evaluate the effect of various management practices on the runoff and sediment response of the watershed. ANSWERS-2000 (Bouraoui and Dillaha, 1996), a recent version of the ANSWERS model is capable of simulating the runoff and sediment yield on continuous basis.

Williams and Hann (1978) developed a basin scale model to consider surface runoff, sedimentation, and plant nutrients. The hydrologic component is a modification of the SCS-CN model. The USLE was modified for the erosion component by replacing rainfall energy term with a product of storm runoff volume and peak rate of discharge raised to a power.

Agricultural Non-point Source Pollution Model (AGNPS) (Young, et al., 1987) is a distributed parameter, single event model that simulates runoff, sediment and nutrient transport from agricultural watersheds. The model uses the SCS-CN method and the revised version of the USLE to estimate runoff and upland erosion respectively. Erosion-Productivity Impact Calculator (EPIC) (Williams et al., 1983) is a continuous model that uses a modified SCS method for computing surface runoff by estimating S as a function of NEH-4 CN value and soil moisture parameters. Subsurface flow is computed separately based on soil moisture parameters.

Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993, 1998) is a distributed parameter, continuous simulation model designed to evaluate the long-term impacts of management of water, chemicals, and sediment in large ungauged watersheds. The model utilizes the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) to compute the sediment yield. Runoff volume and peak rate of runoff, as required in the MUSLE, are calculated using the SCS-CN method and a modified rational formula respectively. Muttiah and Wurbs (2002) used SWAT model on large watersheds to study the change in water balance components due to variability of soils and climate. Gosain and Rao (2004) employed SWAT model to simulate the quantity of water and sediment erosion for local level planning, incorporating the sustainability aspects of watershed development.

Water Erosion Prediction Project (WEPP) (Nearing et al., 1989) is a continuous simulation, field or watershed scale model that incorporates new erosion prediction technology developed by the USDA. The model requires input data of rainfall amount and intensity; soil texture; plant growth; residue decomposition; effects of tillage implements on soil properties, slope shape, steepness, and orientation; and soil erodibility parameters. The watershed version of WEPP routes runoff and sediment from fields and incorporates channel scour based on the work of Foster and Meyer (1972b), and Knisel (1980).

Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), a physically based daily simulation model maintains the elements of USLE, but includes sediment transport capacity of flow. KYERMO (Hirschi and Barfield, 1988), an event based model that isolates important sub-processes within the overall erosion process; STAND model (Zeng, 2000; Zeng and Beek, 2001) for simulation of stream flows, sediment transport and interactions of sediment with other attributes of water quality; EUROSEM (Morgan et al., 1998), a dynamic distributed model capable to simulate sediment transport, erosion and deposition over the land surface by rill and interrill processes in single storm for both individual fields and small watersheds are some of the useful watershed models, among others.

2.9 SUMMARY

In Summary, the review of literature reveals that there exists a considerable interest in estimation of soil erosion throughout the world. As a result, a number of approaches that vary from simple empirical to physically based models involving mathematical treatment of detachment, transport and deposition processes have been used to estimate the sediment yield. The complex physically based models are expected to provide reliable estimates of the sediment yield. However, these models require the coordinated use of various sub-models related to meteorology, hydrology, hydraulics, and soil erosion. As such, the large input parameter requirement and uncertainty in estimation of these parameters limit the practical applications of physically based models to those areas which have little or no data. More often, USLE based approaches have been successfully used to estimate the sediment yield from the watersheds. The SCS-CN method has also been used in many of the sediment yield models to simulate the surface runoff. The main reason the SCS-CN method and SMA/SMP procedure has been well received by most hydrologist's lies in its simplicity and applicability to those watersheds with a minimum of hydrologic information. It relies only on one parameter that relates runoff to the most runoff producing watershed characteristics and the required inputs can easily be estimated. In the present study, an attempt has, therefore, been made to develop SCS-CN and SMA/SMP based simple sediment yield models to suit the data availability of watersheds in developing countries like India.

CHAPTER-3
DESCRIPTION OF STUDY WATERSHEDS

3.1 GENERAL

The present research work aims at developing SCS-CN based lumped and temporal simple rainfall-runoff and sediment yield models for small and medium-sized watersheds for application in field by conservation planners in watershed management. The accuracy of sediment yield models is largely determined by the availability and quality of the hydrologic and sediment yield data used for calibration. Equipment like automated rain gauge and stage level recorder are commonly used in watersheds for recording, respectively, the temporal rainfall and the variation of flow stage. The runoff hydrograph is generally computed by converting the stages into discharge rates using the discharge rating curve of the measuring station. However, in India, sampling for sediment rate is generally carried out manually, leaving a scope for some gaps at time intervals especially at odd hours, because the equipment like automatic pumping samplers are not commonly available. Also many a times, a record of only event's total rainfall from ordinary rain gauge is available due to non-functioning of automated equipment and delay in their repairing because of remote site location. Thus, the continuous record of rainfall, runoff, and sediment data is rare for most of the watersheds in India. Such data are available in plenty in developed countries, for example, USA. To test the general applicability of the proposed models, the watersheds for the present study were, therefore, selected from different river catchments of India and USA based on the availability of the hydrologic and sediment yield data of these watersheds. The watersheds vary in size, physiographic, climatic, soil and land use characteristics.

3.2 STUDY WATERSHEDS

Twelve watersheds were selected from India and USA for application of sediment yield models proposed in the study. These watersheds, depending on their monitoring agencies, are briefly described under three categories as follows. For a quick reference, a summary of these watersheds is presented in Table 3.1 and their drainage maps are shown in Figs. 3.1 to 3.12.

3.2.1 IGBP Watersheds

Nagwa watershed (92.46 km^2), Karso watershed (27.93 km^2) and Banha watershed (17.51 km^2) in Hazaribagh district, Bihar, India, and Mansara watershed (8.70 km^2) in Barabanki district, Uttar Pradesh, India, were monitored for rainfall, runoff and sediment yield under the 'Indo-German Bilateral Project (IGBP) on Watershed Management'. Rainfall was measured using tipping bucket rain gauges linked with a data-logger system, and also with ordinary rain gauges. Automatic stage level recorders were used to measure stream stage, and runoff was computed using relevant rating curves. The USDH-48 sampler and the Punjab bottle sampler were used to collect sediment samples. The hydrological data of these watersheds are available in SWCD (1991; 1993; 1994; 1995; and 1996).

The Nagwa watershed, located between 85° 16' 41" and 85° 23' 50" E longitudes and 23° 59' 33" and 24° 05' 37" N latitudes, lies in the Damodar river basin. It is drained by Upper Siwani stream that joins the river Konar, a tributary of Damodar river. The watershed is undulating in nature and its slope varies from 2.1 to 9.1%., the average slope being 2.3%. It falls in the sub-humid, tropical region of India, receiving an annual rainfall of 1,076 mm. The major soil type is sandy loam but silty clay, clay loam, loam and loamy sand soils are also found. The land use categories of agriculture, forest, open scrub, and waste land account for 64%, 6%, 9%, and 21% of the watershed area, respectively. Major crops grown in the watershed are paddy, maize, minor millets in summer, and mustard in winter season.

The Karso watershed is drained by Kolhuwatari stream that joins the Barhinadi, a tributary of Barakar River. Geographically, the watershed lies between 85° 24' 20" and 85° 28' 06"E longitudes and 24° 16' 47" and 24° 12' 18" N latitudes. It lies in sub-humid, tropical climatic zone having an annual rainfall of about 1243 mm that occurs mostly during July to September. The watershed has extremely undulating and irregular slopes ranging from moderate 1.8% to steep 32%, the average slope being 7.3%. The soils in the watershed are primarily coarse granular. The texture of the soil is light sandy loam with the average percentage of coarse sand, fine sand, silt and clay as 30%, 28%, 17% and 25% respectively. The soils are low in organic matter content. The land use consists of agricultural lands, forests and open scrub which account for 49%, 41% and 10% of the watershed area respectively. Agricultural lands has paddy cultivation and mixed cultivation areas. Most of the cultivated area is treated with soil conservation measures like terracing, bunding etc.

Banha watershed in Upper Damodar Valley spreads between 85° 12' 02" and 85° 16' 05" E longitudes and 24° 13' 50" and 24° 17' 00" N latitudes. The topography of the major part of the watershed is nearly flat, with an average slope of about 3 to 4%. The soils of the watershed are sandy loam, loam, and clay loam covering approximately 47.7%, 28.5%, and 23.8% of the watershed area, respectively. The area has a sub-humid, tropical climate with a mean annual rainfall of 1,277 mm. About 90% of the rainfall occurs during June to October (monsoon months). The elevations of the highest and lowest points are 450 m and 406 m above the mean sea level, respectively. The geology of the watershed falls under the Archaean group, consisting of granite gneiss. The watershed comprises of 32% land under agriculture, 35% under forest, 18% under waste land, and 15% under grasses and others.

The Mansara watershed is a part of Gomti river basin and lies between 81° 23' 42" and 81° 26' 15" E longitudes and 26° 41' 04" and 26° 43' 15" N latitudes. Although the slope of the watershed varies from flat to about 12%, the major area (93%) has a slope up to 1%. The watershed is bounded on top, right, and left by the minors of Sarda Sahayak irrigation project. The watershed has only one stream that receives runoff from overland flow. The watershed has a maximum relief of 7 m. The upper portion of the watershed is subjected to sheet erosion while rills are witnessed in the lower portion. The climate of the watershed is semi-arid subtropical and the temperature varies from 4.7°C in winter to 44°C in summer. The annual average rainfall of the watershed is about 1021 mm. The soils in the watershed are deep alluvial, grouped into three textural classes, viz., loam, sandy loam, and sandy soils. The watershed is predominantly comprised of agriculturally cropped lands. Mango gardens also occupy a sizeable area of the watershed. The major crops grown during Kharif (summer season) are maize, minor millets, paddy, groundnut, and pigeon pea, and during Rabi (winter season) these include wheat, gram, pea, and mustard, etc. (Agriculture Department, 1990). The watershed has been treated with soil and water conservation measures.

3.2.2 USDA-ARS Watersheds

Watershed W2 (0.33 km^2) (ARS code 71002) is located near Treynor in IA, USA. It is one of the four experimental watersheds (W1, W2, W3, and W4) of the Deep Loess Research Station established by the US Department of Agricultural Research Service (USDA-ARS) in 1964 (Bradford, 1988; Vanliew and Saxton, 1984). Mean annual precipitation over the watershed is 814 mm. The topography consists of deeply incised channels, with slopes of 2-4% on the ridges and bottoms, and 12-18% on the sides. The watershed, with an average slope of 8%, is field contoured (Vanliew and Saxton, 1984; Kalin et al., 2003, 2004). The soil series in the watershed as described by the county soil series map are Monona (fine silty, mixed mesic typic Hapludolls), Napier (fine silty, mixed mesic cumulic Hapludolls), and Ida (fine silty, mixed calcareous mesic typic Udorthents) (Vanliew and Saxton, 1984). The surface soils consist of silt loam and silty loam textures that are prone to erosion. 95% of the watershed area is grown in continuous corn and the remaining 5% consists of grassed waterways and active gullies at the watershed outlet. The Treynor experimental watersheds have been the subject of watershed studies for almost 30 years (Kalin et al., 2003, 2004). Simultaneous data of rainfall, runoff and sediment yield for six storms events on W2 watershed were collected for use in the present study. The data of two rain gauges 115 and 116 located around the watershed revealed some differences in measured precipitation and therefore, the average of the two rain gauges was taken as the mean watershed rainfall for use in the present study.

Three sub-watersheds of Goodwin Creek (GC) experimental watershed, namely, W6 (1.25 km^2) (ARS code 62906), W7 (1.66 km^2) (ARS code 62907), and W14 (1.66 km^2) (ARS code 62914), located in the bluff hills of the Yazoo River basin near Batesville, MS, USA, were also utilized in the present study. The Goodwin Creek experimental watershed is operated by the National Sedimentation Laboratory (NSL), and it is organized and instrumented for conducting extensive research on upstream erosion, in stream sediment transport, and watershed hydrology (Blackmarr, 1995). Terrain elevation ranges from 71 to 128 m above mean sea level, with an average channel slope of 0.004 in Goodwin Creek. The climate of the watershed is humid, hot in summer and mild in winter. The average annual rainfall during 1982-1992 was 1440 mm (Blackmarr, 1995). Mainly soybeans and small grains are grown in the cultivated areas. The watershed is divided into fourteen nested sub-watersheds with a flow measuring flume constructed at each of the drainage outlets. Twenty-nine standard recording rain gauges are located within and just outside the watershed. Instrumentation at each gauging site includes an electronic data acquisition and radio telemetry system that collects, stores and transmits the data to a central computer at the NSL for processing and archival. Measurements collected at each site include water stage, accounting of automatically pumped sediment samples, air and water temperature, precipitation, and climatological parameters. The runoff, sediment, and precipitation data of Goodwin Creek sub-watersheds are available on WWW at URL: http://msa.ars.usda.gov/ms/oxford/nsl/cwp_unit/Goodwin.html. The mean rainfall over the study sub-watersheds was computed as the average of rain gauges 6, 34, and 43 for W6 sub-watershed; 7 and 65 for W7 sub-watershed; and 14, 52, and 53 for W14 sub-watershed.

In addition, three North Appalachian Experimental Watersheds (NAEW) of USDA-ARS, namely, 123 ($5.50\text{x}10^{-3}$ km^2) (ARS code 26010), 129 ($1.10\text{x}10^{-2}$ km^2) (ARS code 26003), and 182 (0.28 km^2) (ARS code 26040) watersheds, near Coshocton, OH, USA, were utilized. Watershed 123 is cultivated and planted to a corn and soybean rotation. Watersheds 129 and 182 are predominantly pasture and are subjected to grazing. Watersheds 123 and 129 have relatively uniform slopes with no well-defined channels. Watershed 182 is subjected to two land uses, woods and pasture. There are two well-defined channels on this watershed. The soils of the three watersheds are mostly silt loam, with some sandy loam (Kelly et al., 1975). Most of these soils are in hydrologic group C, exhibiting slow infiltration and moderate runoff rates (Kelly et al.,1975; Wu et al., 1993). Precipitation data were collected at several locations in or adjacent to each watershed. Storm runoff and sediment data were collected at the outlets of the watersheds. Sediment was collected with

Coshocton wheels. On watersheds 123 and 129, the sediment that was deposited in the approach flume was also collected. This was not done on watershed 182 and some small bed load was not included in the measured sediment yield. The rainfall-runoff and sediment yield data of these watersheds are available in Wu et al. (1993).

3.2.3 Cincinnati Watershed

The rainfall-runoff-water quality data of Cincinnati watershed (3.0×10^{-4} km^2) were collected during 1995-97 (Sansalone and Buchberger, 1997) on a 15x20 m asphalt pavement at milestone 2.6 of I-75 that is a major north-south interstate in Cincinnati, OH, USA. The details of the site are available elsewhere (Sansalone and Buchberger, 1997; Soil, 1982). The runoff from the selected stretch was contributed by four southbound lanes, an exit lane, and a paved shoulder, all draining to a grassy v-section median at a transverse pavement cross-slope of 0.020 m m^{-1}. The runoff from the highway site (longitudinal slope = 0.004) finally drains to Mill Creek. The flow of the highway is primarily characterized by sheet flow, and the land use as urban (industrial, commercial, and residential) (Sansalone and Buchberger, 1997). The storm water runoff diverted through the epoxy-coated converging slab, a 2.54 cm diameter Parshall flume, and a 2 m long 25.4 cm diameter PVC pipe to a 2000 l storage tank, was measured at a regular 1-min interval using an automated 24 bottle sampler with polypropylene bottles. Rainfall was recorded in increments of 0.254 mm using a tipping bucket gauge. The water quality data at every 2 min interval were collected during rainfall-runoff events at the experimental site and samples were analyzed for dissolved and particulate bound metals for several rainfall-runoff events. The total solids which are the sum of dissolved and suspended solids represented the sediment yield (Sansalone and Buchberger, 1997; Sansalone et al., 1998; and Li et al., 1999).

3.3 DATA STATUS

The hydrologic and sediment yield data of 98 storm events were compiled for all twelve watersheds from the respective sources mentioned above. The data of all the events on W2 Treynor watershed and Goodwin Creek (W6, W7, and W14) watersheds consisted of the temporal rates of rainfall, runoff and sediment yield. These temporal data were also available for most of the events on Karso, Banha and

Mansara watersheds, except for a few events where the data consisted of a lumped value of event rainfall from the ordinary rain gauge. However, in the case of Nagwa watershed all the events consisted of lumped value of event rainfall. The reason for lumped values of rainfall was reportedly attributed to the malfunctioning or the non-functioning of the automated rain gauge system. The data available for NAEW (123, 129 and 182) watersheds in Wu et al. (1993), and for Cincinnati watershed in Sansalone and Buchberger (1997) consisted of lumped values of the event rainfall, runoff and sediment yield for all the events. Thus, among a total of 98 events, 49 events had temporal data of rainfall, runoff and sediment yield on Karso, Banha, Mansara, W2 Treynor, W6 GC, W7 GC, and W14 GC watersheds, and these were used in the application of time-distributed sediment yield model. Nevertheless, the data of 49 events provided a good data base for application of temporal sediment yield model, while the data of all 98 events on twelve watersheds were used in the lumped model. Table 3.1 (column 9) shows the total number of available events and the events available with temporal rates (in parentheses) for each of the study watersheds.

Table-3.1: Hydro-climatic characteristics of the watersheds selected for the study

S. No.	Watershed/size/location	Climate	Av. annual rainfall (mm)	Soils	Av. slope (percent)	Land use (percent)	Source of watershed details/rainfall-runoff-sediment yield data	No. of available events in the study
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1.	Nagwa (92.46 km^2) Hazaribagh, Bihar, India (85° 16' 41" and 85° 23' 50" E) (23° 59' 33" and 24° 05' 37" N)	Sub-humid, tropical	1076	Sandy loam, silty clay, clay loam, loam	2.3	AG=64 FO=6 OS=9 WL=21	SWCD (1991; 1993; 1994)	7
2.	Karso (27.93 km^2) Hazaribagh, Bihar, India (85° 24' 20" and 85° 28' 06"E) (24° 16' 47" and 24° 12' 18" N)	Sub-humid, tropical	1243	Light sandy loam	7.3	AG=49 FO=41 OS=10	SWCD (1991; 1993; 1994; 1995; 1996)	9
3.	Banha (17.51 km^2) Hazaribagh, Bihar, India (85° 12' 02" and 85° 16' 05" E) (24° 13' 50" and 24° 17' 00" N)	Sub-humid, tropical	1277	Sandy loam, Loam, clay loam	3.5	AG=32 FO=35 WL=18 GR=15	SWCD (1993; 1994; 1995; 1996)	16
4.	Mansara (8.70 km^2) Barabanki, Uttar Pradesh, India (81° 23' 42" and 81° 26' 15" E) (26° 41' 04" and 26° 43' 15" N)	Semi-arid, sub-tropical	1021	Loam, sandy loam, sandy	1	AG=84 OS=16	SWCD (1994; 1996) Agriculture Dept. (1990)	11

S. No.	Watershed/size/location	Climate	Av. annual rainfall (mm)	Soils	Av. slope (percent)	Land use (percent)	Source of watershed details/rainfall-runoff-sediment yield data	No. of available events in the study
5.	W2 Treynor (0.33 km^2) Treynor, IA, USA (95° 39' 00" W) (40° 10' 10" N)	Sub-tropical	814	Silt loam	8	AG=95 GR=5	Bradford (1988); Vanliew and Saxton (1984); Kalin et al., 2003; 2004)	6
6.	W6 Goodwin Creek (1.25 km^2) Batesville, MS, USA (89° 51' 44.665" E) (34° 16' 16.082" N)	Humid	1440	Silty, silt loam	5	AG=35 GR=23 Idle=10 FO=32	Blackmarr (1995); http://msa.ars.usda.go v/ms/oxford/nsl/cwp _unit/Goodwin.html	7
7.	W7 Goodwin Creek (1.66 km^2) Batesville, MS, USA (89° 51' 34.479" E) (34° 15' 10.342" N)	Humid	1440	Silty, silt loam	4	AG=28 GR=49 Idle=3 FO=20	Blackmarr (1995); http://msa.ars.usda.go v/ms/oxford/nsl/cwp _unit/Goodwin.html	7
8.	W14 Goodwin Creek(1.66 km^2) Batesville, MS, USA (89° 52' 53.252" E) (34° 15' 07.040" N)	Humid	1440	Silty, silt loam	5	AG=34 GR=40 Idle=9 FO=17	Blackmarr (1995); http://msa.ars.usda.go v/ms/oxford/nsl/cwp _unit/Goodwin.html	7

S. No.	Watershed/size/location	Climate	Av. annual rainfall (mm)	Soils	Av. slope (percent)	Land use (percent)	Source of watershed details/rainfall-runoff-sediment yield data	No. of available events in the study
9.	Cincinnati ($3.0x10^{-4}$ km^2) Asphalt pavement at milestone 2.6 of I-75, Cincinnati, OH, U.S.A. (Not known)	Not known	1020	Asphalt pavement	0.4	urban=100	Sansalone and Buchberger (1997); Soil (1982); Sansalone et al. (1998); Li et al. (1999)	11
10.	123 NAEW ($5.50x10^{-3}$ km^2) Coshocton, OH, USA (81° 47' 20" E), (40° 22' 23" N)	Not known	Not known	Silt loam	0.1	AG=100	Wu et al. (1993); Kelly et al. (1975)	5
11.	129 NAEW ($1.10x10^{-2}$ km^2) Coshocton, OH, USA (81° 47' 52" E), (40° 22' 19" N)	Not known	Not known	Silt loam	17	GR=100	Wu et al. (1993); Kelly et al. (1975)	5
12.	182 NAEW (0.28 km^2) Coshocton, OH, USA (81° 46' 55" E), (40° 21' 36" N)	Not known	Not known	Silt loam	7	GR=90 FO=10	Wu et al. (1993); Kelly et al. (1975)	7

Note: AG = Agriculture; FO = Forest; OS = Open scrub; GR = Grass/Pasture; WL = Waste land; NAEW = North Appalachian Experimental Watersheds

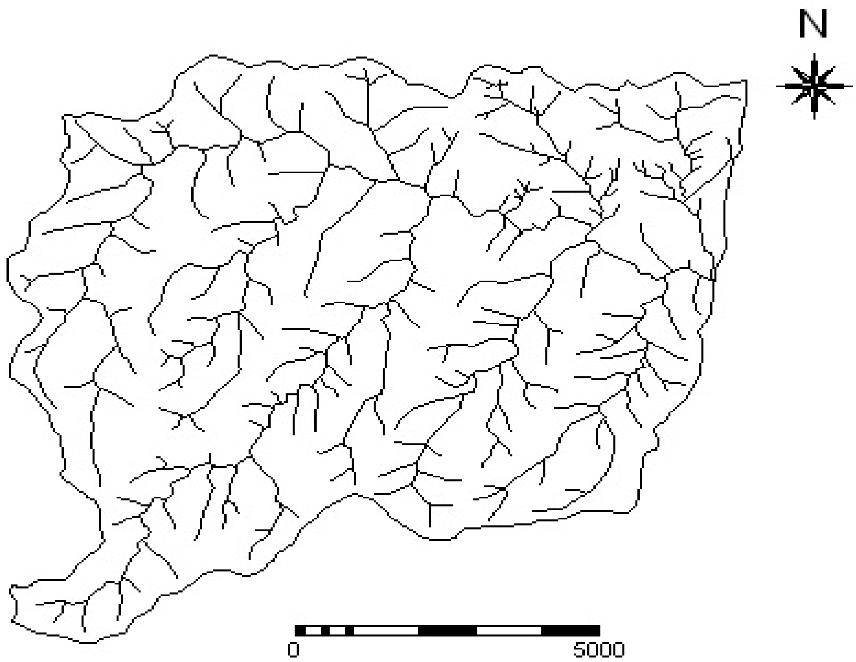


Figure-3.1: Drainage map of Nagwa watershed

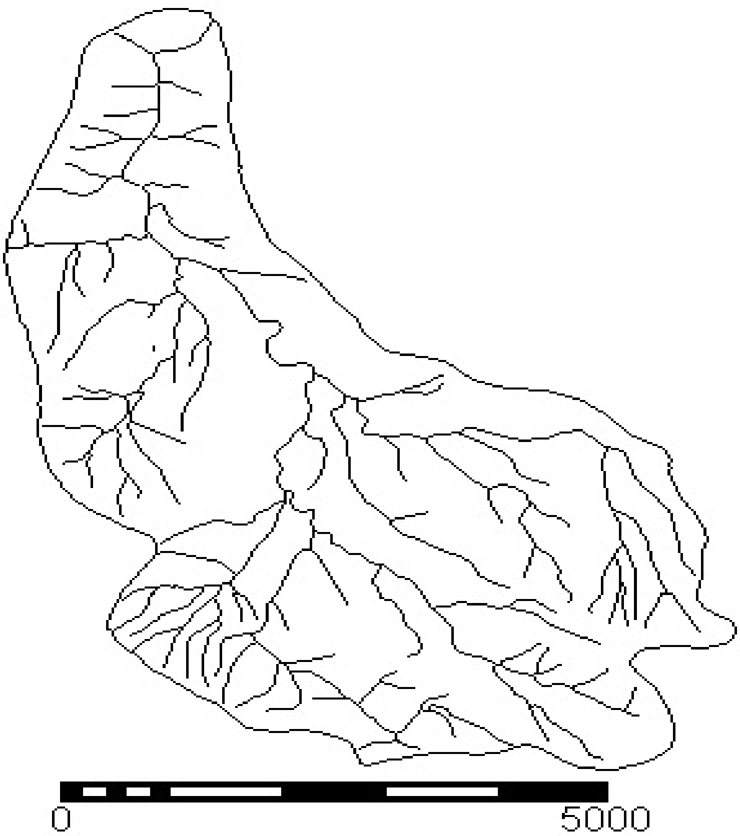


Figure-3.2: Drainage map of Karso watershed

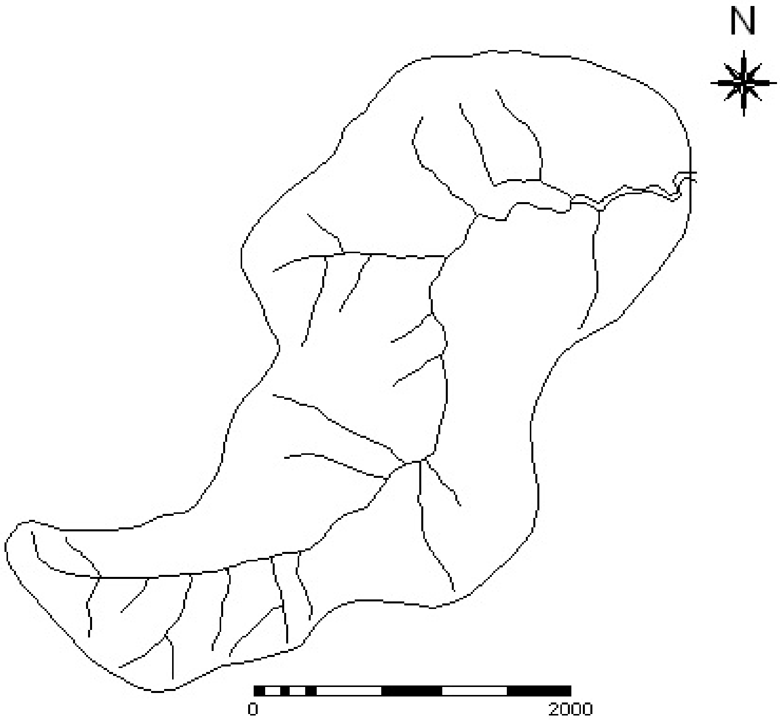


Figure-3.3: Drainage map of Banha watershed

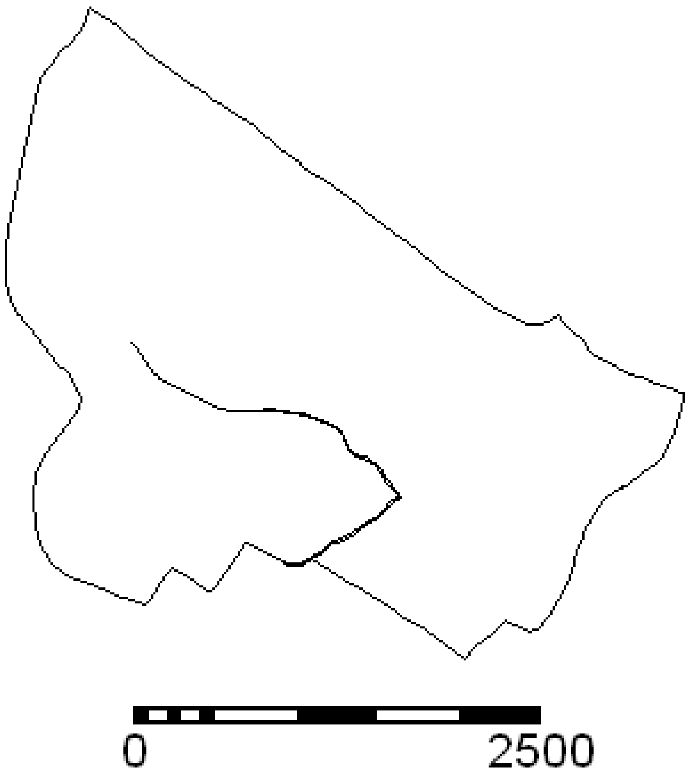


Figure-3.4:Drainage map of Mansara watershed

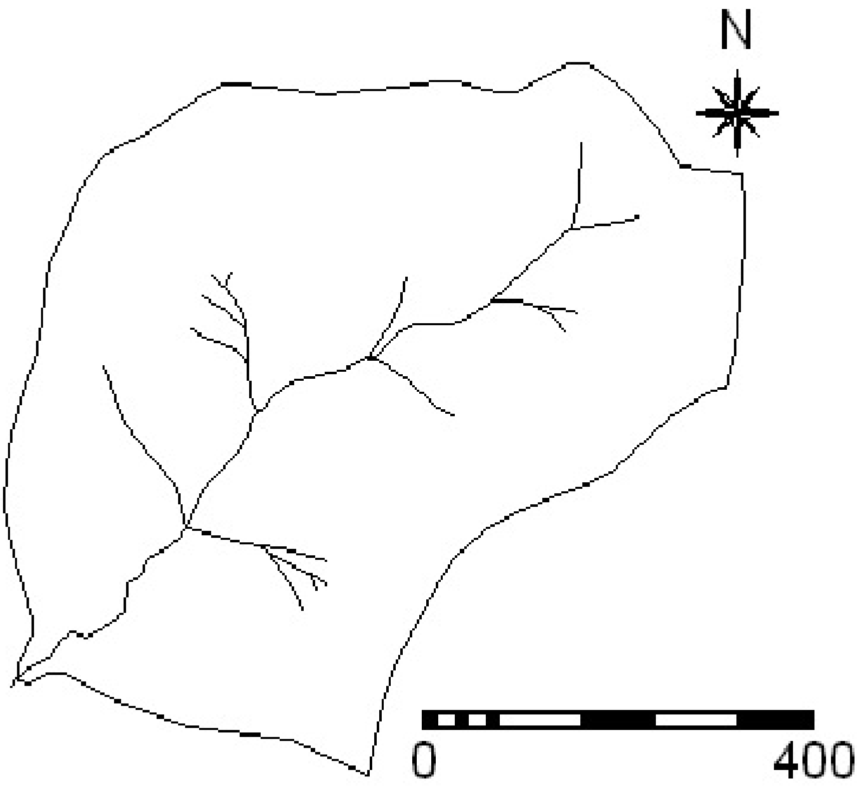


Figure-3.5: Drainage map of W2 Treynor watershed

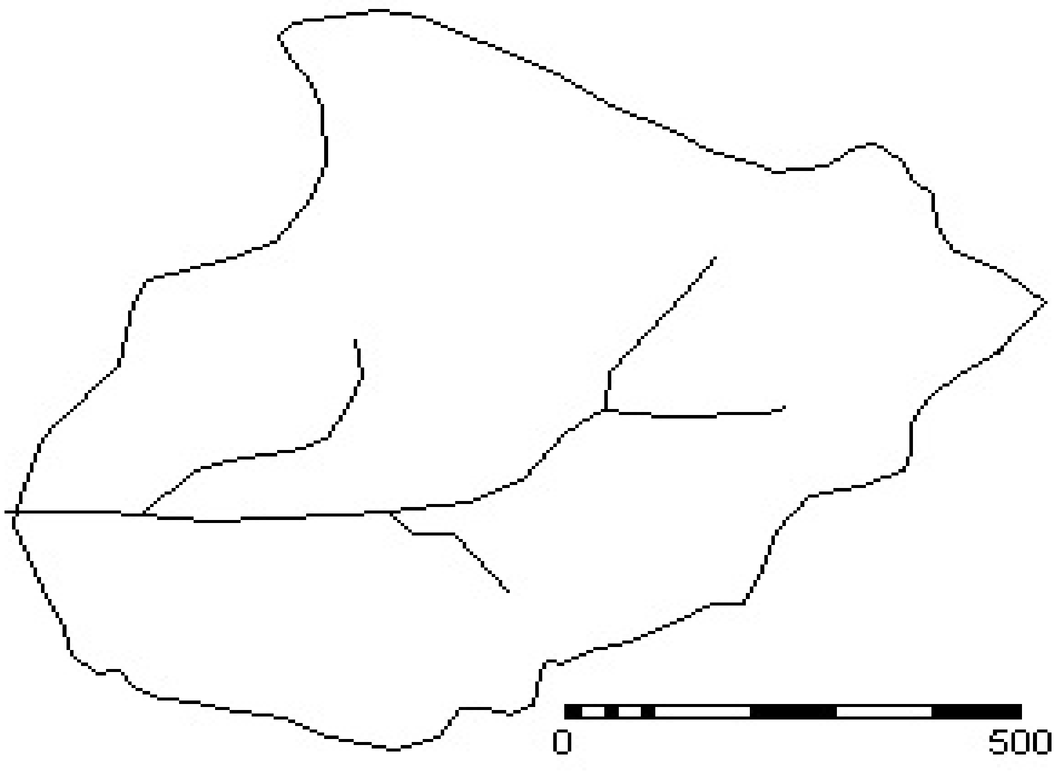


Figure-3.6: Drainage map of W6 Goodwin Creek watershed

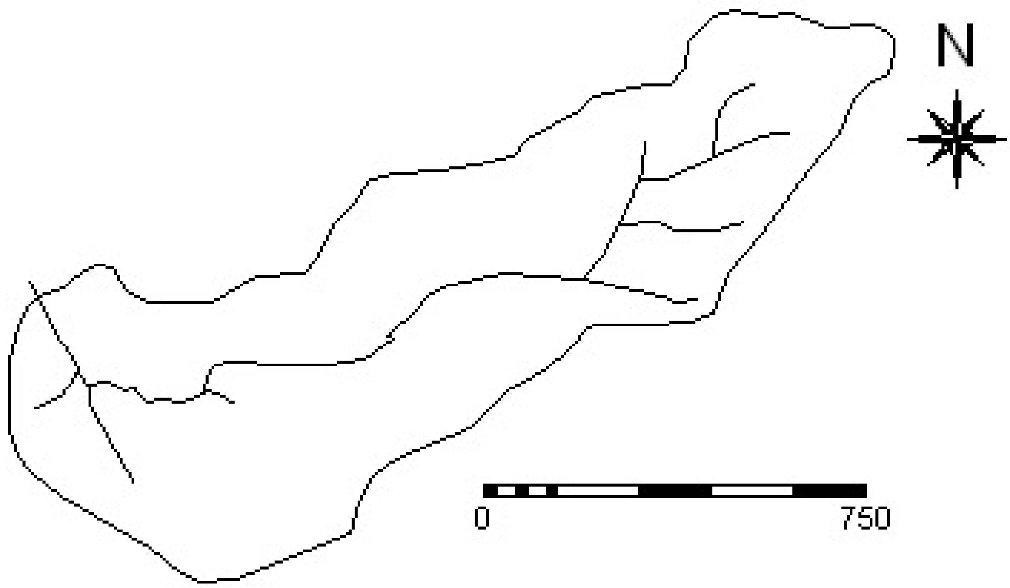


Figure-3.7: Drainage map of W7 Goodwin Creek watershed

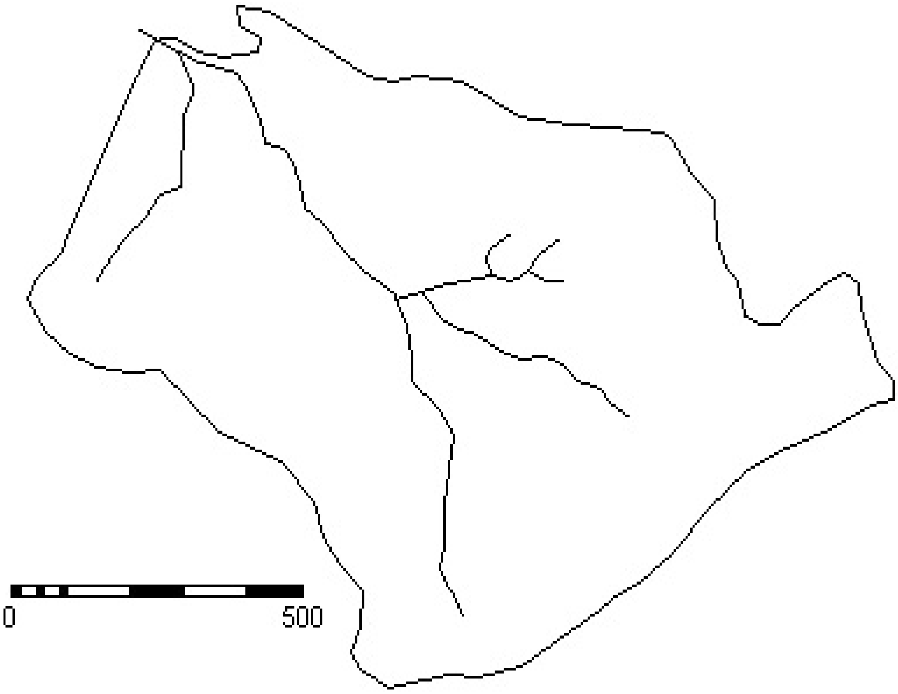


Figure-3.8: Drainage map of W14 Goodwin Creek watershed

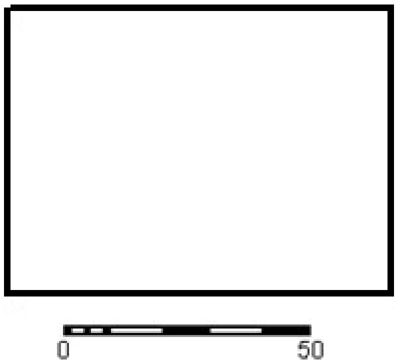


Figure-3.9: Drainage map of Cincinnati watershed

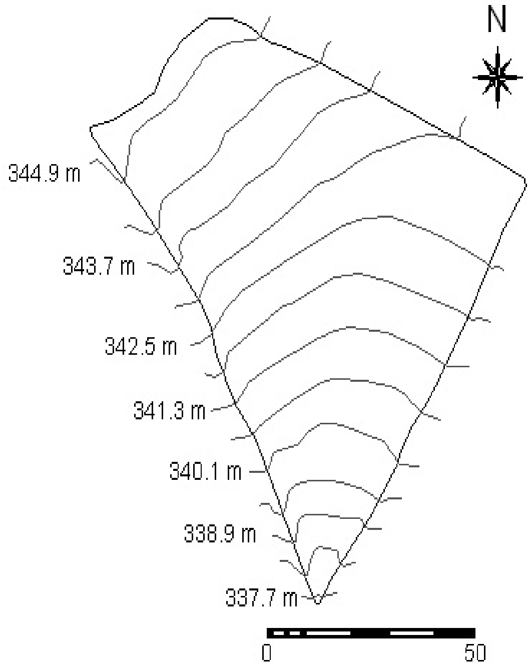


Figure-3.10: Contour map of 123 NAEW

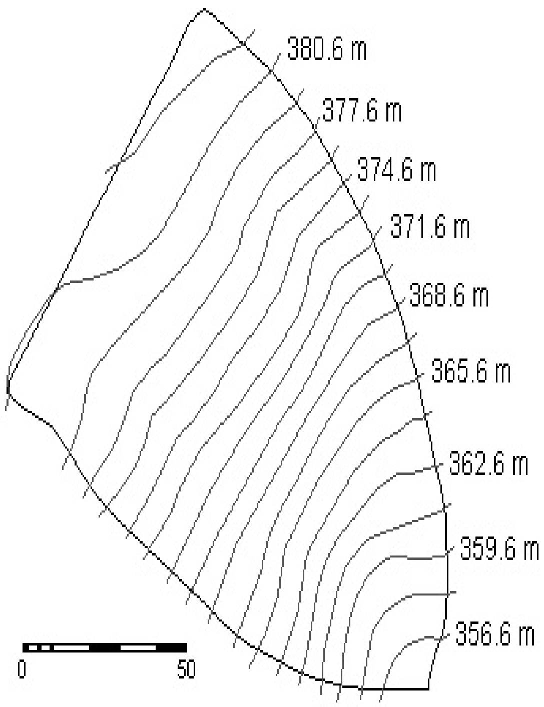


Figure-3.11: Contour map of 129 NAEW

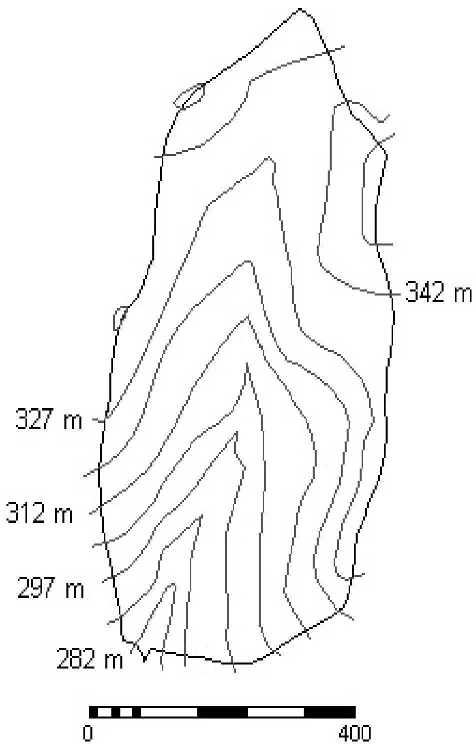


Figure-3.12: Contour map of 182 NAEW

CHAPTER 4

AN EVENT-BASED SEDIMENT YIELD AND RUNOFF MODELING USING SOIL MOISTURE ACCOUNTING (SMA) METHOD

4.1 INTRODUCTION

Sediment yield and runoff modeling are of paramount importance in water resources, environmental engineering and hydrology. These are majorly used in applications such as assessment of watershed yield, watershed behavior, morphometric analysis of the watershed, dam break analysis and impact of climate change on the watershed (Mishra and Singh, 1999). The runoff and sediment yield of a watershed is affected by its four properties, i.e. its soil types, the hydrologic conditions, hydrological soil group and landuse/ landcover. The Soil Conservation Service Curve Number (SCS-CN) model is frequently used for computation of direct surface runoff and sediment yield from the watershed. The 1-parameter model of SCS-CN method, also known as natural resource conservation service curve number (NRCS-CN) method, was developed by USDA-ARS in 1954. This method is simple, give results with reasonable accuracy and hence is one of the most widely used model for runoff computation. (Verma et al., 2017; Sahu et al., 2012; Tyagi et al., 2008; Mishra et al., 2006; Garen and Moore 2005; Chong and Teng., 1986; Wood and Blackburn., 1984; William and LaSeur., 1976; Ragan and Jackson., 1980; Hjelmfelt., 1980; Chiang., 1975; and Hawkins., 1973).This model can be applied to large watersheds with multiple land uses (Singh. 1988).

The processes of sediment yield modeling is a more complex compared to other types of watershed modeling reason being that the major output from a watershed is in the form of erosion. This result in a complex interaction of various hydro-meteorology and hydro-geology process and mainly consist of detachment and transport of soil particles from raindrop and runoff (Bennett, 1974). The sediment yield phenomena are generally categorized into two phases, (i) upland phase and (ii) the lowland stream or the channel phase. The upland phase occurs on an upland area, which is an area within a watershed where runoff is predominately overland flow (Foster and Meyer., 1975). Beside rainfall being the significant factors affecting the sediment yield, soil characteristics, vegetation, topography, and human activities also play a significant role while computing sediment yield under the upland phase (Ekern., 1953; Free., 1960; Barnett and Rogers., 1966; Greer., 1971; and Park et al., 1982).

The channel phase receives sediment yield from the upland phase. These channels are characterized by a rapidly varying cross-sectional shape in the direction of flow and are generally meandering. Here, the rainfall has little influence on the sediment yield; the channel flow can usually transport all of the fine material $(\leq 0.62 \text{ mm})$ supplied by the upland erosion. In spite of extensive studies on the erosion process and sediment transport modeling, there exist a lack of universally accepted sediment yield formulae (Bogardi et al., 1986; Kothyari et al., 1996). A physically-based model is developed in a coupled structure that combines the erosion model, or the component processes of detachment, transport and deposition thereof, with a rainfall-runoff model (Knisel, 1980; Leonard et al., 1987; Rode and Frede, 1997).

The initial soil moisture play a paramount important role in the restructuring of the SCS-CN method as it prevents the unreasonable sudden jump in runoff and sediment yield estimation. The concept of soil moisture accounting (SMA) procedure lead to improvement in SCS-CN based models (Singh et al., 2015). Academician and hydrologists across the globe have been struggling over the past several decades to enhanced rainfall-sediment yield and rainfall-runoff models (Perrin et al., 2003; Ajmal et al., 2015). Accordingly to manage some the fundamental hydrological problems and their applications, such as forecasting, exploitation, and control of river flows and for development and improvement of hydrological processes SCS-CN coupled with SMA proved to be beneficial (Senbeta et al., 1999). The need for accurate information on watershed runoff and sediment yield has grown rapidly during the past decades because of the mathematical rainfall-sediment and rainfall-runoff models has involved a recurring theme in increasing the understanding acceleration of watershed management programs for conservation, development, and beneficial use of all natural resources, including soil and water (Gajbhiye and Mishra 2012; Mishra et al., 2013). Several watershed models are available and ranging from empirical relationships to physically based models have been developed for the computation of runoff and sediment yield. Physically based models are better because they consider the controlling physical processes, but at the same time their data requirements are also high (Hadley et al., 1985; Tien et al., 1993; Kothyari and Jain, 1997; Tyagi et al., 2008).

The present chapter main goals are (i) to develop a simple rainfall-runoff and sediment yield models based on SMA procedure for small watersheds, (ii) to apply large set of rainfall-runoff-sediment yield data from small watersheds, (iii) to apply four statistical indices for assessment of proposed models, and based on calibration and verification, suggesting the suitability of proposed model.

4.1.1 Existing SCS-CN model

The SCS-CN method couples the water balance equation (4.1) with two fundamental hypothesis, which are given by Eqs. (4.2) and (4.3), respectively, mathematically expressed as:

$$P = I_a + F + Q \qquad 4.1$$

$$\frac{Q}{P - I_a} = \frac{F}{S} \qquad 4.2$$

$$I_a = \lambda S \qquad 4.3$$

where, P is the rainfall (mm), Q is the direct surface runoff (mm), F is the cumulative infiltration (mm), Ia is the initial abstraction (mm), S is the potential maximum retention (mm), and λ is the initial abstraction coefficient. Coupling of Eqs. (2.1) and (2.2) leads to the SCS-CN method.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad 4.4$$

Eq. (4.4) is valid for $P \geq I_a$, Q = 0, otherwise. Coupling of Eq. (4.4) with Eq. (4.3) for $\lambda = 0.2$ enables determination of S from the rainfall-runoff data. In practice, S is derived from a mapping equation expressed in terms of curve number (CN).

$$S = \frac{25400}{CN} - 254 \qquad 4.5$$

The non-dimensional CN is derived from the tables given in the National Engineering Handbook, Section-4 (NEH-4) (SCS, 1956) for catchment characteristics, such as land use, types of soil, antecedent moisture condition (AMC). The CN values varies from 0 to 100. The higher the CN value, greater the runoff factor, C, or runoff potential of the watersheds, and vice versa (Daniel., 2011; Sahu et al., 2012; Sahu et al., 2010; Ajmal et al., 2015; Singh et al., 2015; Shi et al., 2009, Verma et al., 2018).

4.1.2 Mishra et al. (2006) Model

Mishra et al. (2006) developed sediment yield model based on SCS-CN method for computation of sediment yield from natural watersheds. This model was the coupling of three hypothesis viz (i) the runoff coefficient is equal to the degree of saturation, (ii) the relationship between potential maximum retention and USLE, (iii) the sediment delivery ratio is equal to the runoff coefficient. Mishra et al. (2006) mathematically expressed as

$$Y = A\frac{(P - 0.2S)}{P + 0.8S} \qquad 4.6$$

where Y, is the sediment yield (kN) A is the potential maximum erosion (kN/ha).

4.2 Mathematical Treatment

4.2.1 Derivation and interpretation of the proposed rainfall-runoff and sediment yield models.

The proposed model coupled with SCS-CN method for computation of sediment yield and runoff from different events. The proposed model is based on the first hypothesis of traditional CN models, it is analytically expressed as

$$\frac{Q}{P - I_a} = \frac{F}{S} \qquad 4.7$$

Eq. (4.7) shows that ratio of actual runoff to potential runoff is equal to the ratio of actual retention to potential retention, in Eq. (4.7) incorporating static infiltration yield (Mishra et al., 1999; Shi et al. 2017)

$$\frac{Q}{P - I_a - F_c} = \frac{F_d}{S} \qquad 4.8$$

where, the sum of the dynamic portion of infiltration (F_d, occurring mainly due to capillary) and static potion of infiltration (F_c ,occurring largely due to gravity) yields F. simplification of Eq. (4.8) yields

$$Q = \frac{(P - I_a - F_c)^2}{P - I_a - F_C + S} \qquad 4.9$$

where Q is the direct surface runoff (mm), I_a is the initial abstraction, it is assumed that initial abstraction (I_a) equal to zero in Eq. (4.9), simplification of Eq. (4.9) yields

$$Q = \frac{(P - F_c)^2}{P - F_c + S} \qquad 4.10$$

Differentiating Eq. (4.10) with respect to time t

$$q = \frac{dP}{dt}\frac{(P - F_c)^2}{P - F_c + S} \qquad 4.11$$

On simplification of Eq. (4.11) give

$$q = p\frac{(P-F_c)(P-F_c+2S)}{(P-F_c+S)^2} \qquad \text{if } P > F_c \text{ q = 0 for } P \leq F_c \qquad 4.12$$

q = 0 for $P \leq F_c$

where $q = dQ/dt$, $p = dp/dt$, Soil moisture accounting (SMA) procedure is based on the notion that higher the moisture store level, higher the fraction of rainfall that is converted into the runoff. If the moisture store level is full, all the rainfall become runoff (Michel et al. 2005). The SMA model can be an analytically expressed as

$$V = V_0 + P - Q \qquad 4.13$$

Differentiating Eq. (4.13) with respect to time t yields, to obtained the continuity equation as

$$\frac{dV}{dt} = p - q \qquad 4.14$$

Substituting Eq. (4.10) into Eq. (4.13) yields

$$V = V_0 + P - \frac{(P - F_c)^2}{P - F_c + S} \qquad 4.15$$

Simplification of Eq. (4.15) we get

$$V = V_0 + \frac{P(S + F_c) - Fc^2}{P - F_c + S} \qquad 4.16$$

Mathematical interpretation from Eq. (4.16) for $(P - F_c), (P - F_c + 2S)$ and $(P - F_c + S)^2$ substituting into Eq. (4.12) yields

$$p\frac{(P - F_c)(P - F_c + 2S)}{(P - F_c + S)^2} = \frac{\{V - (V_0 + F_c)\}}{S}\left[2 - \frac{V - (V_0 + F_c)}{S}\right] \qquad 4.17$$

Coupling of Eq. (4.10), Eq. (4.12) and Eq. (4.13), where $V' = V_0 + F_c$, it is mathematically expressed as

$$q = p\frac{V - V'}{S}\left[2 - \frac{V - V'}{S}\right] \quad \text{if } V > V' \qquad 4.18$$

$q = 0$ otherwise

$$\frac{dV}{dt} = \frac{dp}{dt}\left[1 - \left[\frac{V - V'}{S}\right]\right]^2 \qquad 4.19$$

Simplification of Eq. (4.19) yields

$$\frac{dV}{\left(\frac{V-S-V'}{S}\right)^2} = \frac{dp}{dt}dt \qquad 4.20$$

Mathematical interpretation of Eq. (4.20) yields

$$\frac{dV}{[V-S-V']^2} = \frac{pdt}{S^2} \qquad 4.21$$

Integration of Eq. (4.21) with respect to time t and using upper (V, V_0) and lower limit (t, 0), yields

$$\int_{V_0}^{V} \frac{dV}{[V-S-V']^2} = \int_{0}^{t} \frac{Pdt}{S^2} \qquad 4.22$$

After integration of Eq. (4.22) yields

$$\frac{1}{(S-V-V')} - \frac{1}{S-V-V_0} = \frac{P}{S^2} \qquad 4.23$$

Replacing V by $(V_0 + P - Q)$ from Eq. (4.23) yield

$$\frac{1}{(S-(V_0+P-Q)-V')} - \frac{1}{S-(V_0+P-Q)-V_0} = \frac{P}{S^2} \qquad 4.24$$

Simplification of Eq. (4.24) yield

$$Q = P\left[1 - \frac{(S+V'-V_0)^2}{S^2 + P(S+V'-V_0)}\right] \qquad 4.25$$

The mathematical formulation of model can be summarized by the following set of model and their relevant hypothesis:

(i) if $(V_0 + P) \leq V'$ then Q = 0 (4.26)

(ii) if $(V_0 + P) > V'$ then

$$Q = P\left[1 - \frac{(S+V'-V_0)^2}{S^2 + P(S+V'-V_0)}\right] \qquad 4.27$$

Substituting $V' = V_0 + F_c$ into Eq. (4.27) yields

$$Q = P\left[1 - \frac{(S + V_0 + F_c - V_0)^2}{S^2 + P(S + V_0 + F_c - V_0)}\right] \quad 4.28$$

Simplification of Eq. (4.28) yield

$$Q = P\left[1 - \frac{(S + F_c)^2}{S^2 + P(S + F_c)}\right] \quad 4.29$$

where, F_c is the static infiltration which is directly proportional to minimum infiltration and storm duration. Eq. (4.29) is the proposed rainfall-runoff model. The static infiltration can be calculated using the equation proposed by Tyagi et al., (2008) and Sahu et al., (2012).

$$F_C = f_c T \quad (4.30)$$

where f_c is the minimum infiltration (mm/hr), and T is the storm duration (h) are constant for all the watersheds (Shi et al., 2017). Simplification of Eq. (4.29) we get

$$\frac{Q}{P} = \left[1 - \frac{(S + F_c)^2}{S^2 + P(S + F_c)}\right] \quad 4.31$$

where Q/P is the runoff coefficient, Eq. (4.31) substituting into Eq. (4.32) yields

$$Y = AC_r \quad (4.32)$$

where, Y, A and C_r are respectively, sediment yield, potential maximum erosion andrunoff coefficient,

$$Y = A\left[1 - \frac{(S + F_c)^2}{S^2 + P(S + F_c)}\right] \quad 4.33$$

Eq. (4.33) is the proposed simple 3-parameters of sediment yield model based on soil moisture accounting procedure. Mathematical formulation of sediment yield and runoff models included parameters in proposed (S2 and R2) and existing models (S1 and R1) are summarized in Table.4.1

Table-4.1: Model formulations

Model	Parameters	Model formulation for computing runoff (Q)
R1	S	Equations (4.3), (4.4) and (4.5)
R2	S, Fc	Equations (4.26),(4.29) and (4.30)
		Model formulation for computing sediment yield (Y)
S1	A, S	Equation (4.6)
S2	A, S, Fc	Equations (4.33)

4.3. Model Application

4.3.1 Data Used

The proposed model, being lumped in nature, requires for its calibration and verification of observed data on total rainfall, runoff and sediment yield for the storm events. Therefore, as discussed in Chapter 3, the data of all 98 storms events for twelve watersheds (Table 3.1 and Figs. 3.1 to Figs 3.12) has been used for application of the models.

4.3.2 Performance Evaluation Criteria

From the academic, scientific and practical point of view, the goal of any watershed models is to give results with near to precision with acceptable accuracy (Seibert, 2001). Several statistics tools are utilized to assess these models quantification performance (Moriasi et al., 2007). The performance evaluation of proposed sediment yield and runoff models were evaluated based on Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), root mean square error (RMSE) and normalized root mean square error (nRMSE). The performance evaluation criteria of NSE, it is mathematically expressed as.

$$\mathrm{NSE} = \left[1 - \frac{\sum_{I=1}^{N}\left(\mathrm{Q_{obs}} - \mathrm{Q_{comp}}\right)^2{}_i}{\sum_{i=1}^{N}(\mathrm{Q_{obs}} - \overline{\mathrm{Q_{obs}}})^2{}_i}\right] \times 100 \quad 4.34$$

where $\mathrm{Q_{obs}}$ is the observed sediment yield, $\overline{Q_{obs}}$ is the mean of the observed sediment yield, $\mathrm{Q_{comp}}$ is the computed sediment yield, NSE is the Nash Sutcliffe efficiency and N is the numbers of observations. The Nash Sutcliffe efficiency (NSE) may vary from minus infinity to 100 %.

Higher NSE indicates a good model performance and vice versa (Mishra et al., 2006). NSE is categorized into three groups i.e., very good when NSE is greater than 75 %, satisfactory when NSE is between 36 to 75 % and unsatisfactory when NSE is lower than 36 % (Tyagi et al., 2014). Accordingly, Ritter and Munoz-Carpena (2013) established watershed model performance rating in which an NSE < 65 % (Unsatisfactory) was deemed a lower threshold. Other model performance rating were acceptable$(65\ \% \le \mathrm{NSE} < 80\%)$, good $(80\ \% \le \mathrm{NSE} < 90\ \%)$, and very good$(\mathrm{NSE} \ge 90\ \%)$. Similarly, the PBIAS quantifies a models tendency to underestimate or overestimate values, where a value of zero (optimum) shows perfect fit. PBIAS it is mathematically expressed as

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{N}\left(\mathrm{Q_{obs}} - \mathrm{Q_{comp}}\right)_i}{\sum_{\mathrm{i=1}}^{\mathrm{N}}(\mathrm{Q_{obs}})_{\mathrm{i}}}\right] \times 100 \qquad 4.35$$

PBIAS is the percent bias, it is basic performance evaluation criteria of the model and it is defined as the ratio of the difference between total computed and observed sediment yield to the divided by total observed sediment yield, expressed in percentage. Similarly, RMSE is also the basic criteria for model assessment; the lower value of RMSE indicates better performance and vice versa. It means RMSE = 0 show a good agreement between observed runoff and computed runoff or observed sediment yield and computed sediment yield. Analytically, this can be expressed as

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i=1}}^{\mathrm{N}}\left(\mathrm{Q_{obs}} - \mathrm{Q_{comp}}\right)^2{}_{\mathrm{i}}} \qquad 4.36$$

Normalized root mean square error (nRMSE) is another most extensively used statistical indicator for model performance evaluation (Santhi et al., 2001; Van Liew et al., 2003), it is analytically expressed as

$$nRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Q_{obs} - Q_{comp}\right)^2{}_i}}{\overline{Q_{obs}}} \qquad 4.37$$

4.4 Results and Discussion

4.4.1 Parameter Estimation

In the present research work, analytical models is developed for assessment of rainfall-runoff and sediment yield, the parameter of which were optimized using the non-linear Marquardt (1963) algorithm. This algorithm is an elegant and improved version of the non-linear optimization and provides a smooth variation between the two extremes of the inverse-Hessian method and the steepest descent method. Initially, the parameters of A and S were set as zero and Fc was set as ranges from 1.90 to 14.91, the minimum value of A, S and Fc varied in between 0.0 to 100.10, and, the maximum values were as per the watershed characteristics.

The computed parameters of potential maximum retention (S) for proposed rainfall-runoff (R2) and sediment yield model (S2) was varying from 22.15 to 172.85 mm, and, the static infiltration (Fc) was varying from 0.40 to 24.33 mm/hr. The existing SCS-CN model (R1) of potential maximum retention (S) was varying from 7.87 to 233.68 mm from all the watersheds. The range of variation of potential maximum erosion (A) for proposed sediment yield model (S2) was varied from 0.016 to 170093.23 kN and existing Mishra et al. (2006) model (S1) of parameters of potential maximum retention (S) and potential maximum erosion (A) was varying from 7.87 to 233.68 mm, 0.009 to 197950.01 kN are respectively. The statistical range for models R1, R2, S1, and S2 are summarized in Table 4.2.

The SCS-CN method is widely used for computation of sediment yield and runoff from small watershed using soil moisture accounting procedure (Michel et al., 2005; Sahu et al., 2007). The unavailability of any reliable initial SMA procedure in the model leads to inefficient sediment yield and runoff computation which result in overall underperformance of model (Brocca et al., 2008). From the proposed sediment yield model the computed S and Fc values were utilized in the proposed rainfall-runoff model for computation of runoff from the small watersheds and similarly the computed S value of sediment yield is higher than runoff model (Mishra et al., 2006).

Table-4.2: Statistical range of parameters obtained from model application in twelve watersheds

Model	Parameters	Mean	Median	Minimum	Maximum	90 % confidence level	
						Lower	Upper
R1	S (mm)	114.21	118.04	7.87	233.68	84.53	143.88
R2	S (mm)	68.90	56.13	22.15	172.85	46.43	91.38
	Fc (mm/hr)	12.37	12.10	0.40	24.33	9.05	15.69
S1	A (kN)	23718.01	5714.74	0.009	197950.01	-2703.09	50139.12
	S (mm)	114.21	118.99	7.87	233.68	84.54	143.88
S2	A (kN)	20347.72	5010.07	0.016	170093.23	-2400.18	43095.63
	S (mm)	68.90	56.13	22.15	172.85	46.43	91.38
	Fc (mm/hr)	12.37	12.10	0.40	24.33	9.05	15.69

For the proposed model, existing Mishra et al. (2006), and NRSC-CN models, the performance is analyzed by four statistical indices viz NSE, RMSE, nRMSE and PBIAS. The NSE of proposed sediment yield model (S2) of individual watershed are varied from 84.31 % for Karso, 74.55 % for Banha, 91.13 % for Nagwa, 80.03 % for Mansara, 89.40 % for Cincinnati, 83.46 % for W2 Treynor, 80.54 % for W6, 80.32 % for W7, 87.97 % for W14, 79.05 % for 182, 88.42 % for 129 and 84.73 % for 123 watersheds respectively as shown in Table 4.3 and Fig. 4.1.

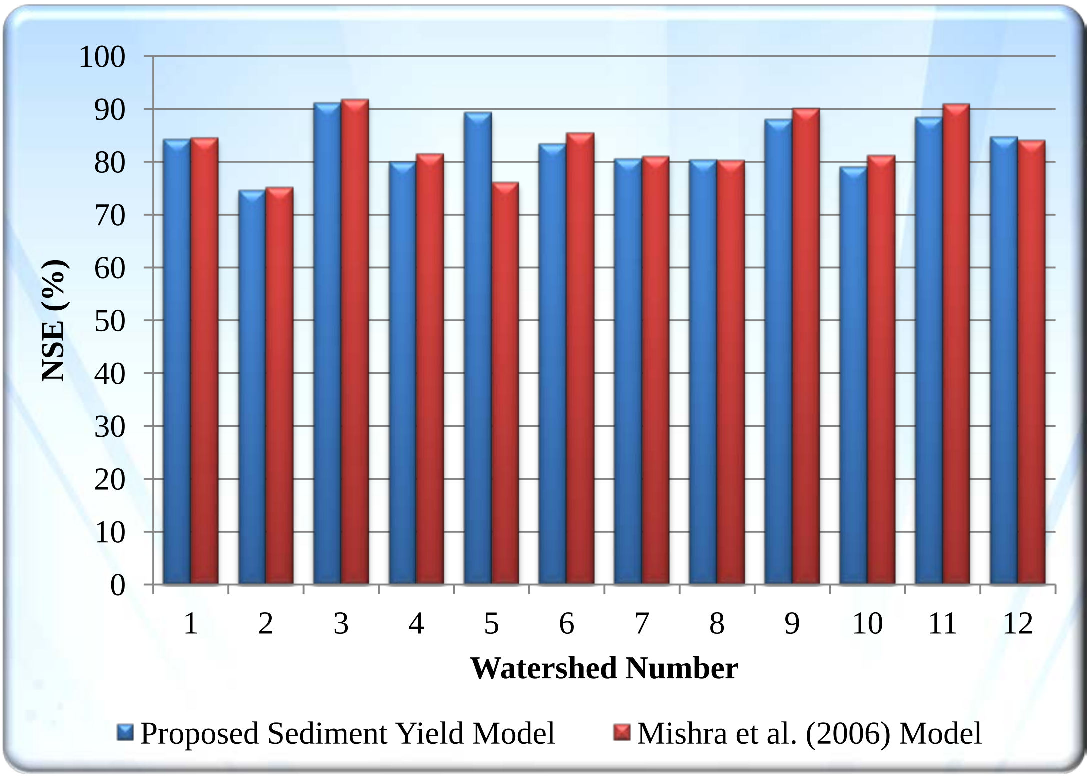


Figure-4.1: Visualization of watershed number versus NSE of the S2 and S1 models from the application of twelve watersheds

Table-4.3: Comparative analysis between proposed rainfall-sediment yield and Existing Mishra et al. (2006) models

S. No	Name of WS	Proposed rainfall-sediment yield model				Existing Mishra et al (2006) sediment yield model			
		PBIAS (%)	RMSE (kN)	nRMSE (kN)	NSE. (%)	PBIAS (%)	RMSE (kN)	nRMSE (kN)	NSE. (%)
1	Karso	0.062	0.71	0.0018	84.31	1.19	13.48	0.03	84.51
2	Banha	0.035	0.56	0.001	74.55	0.208	3.32	0.00	75.21
3	Nagwa	0.013	0.475	0.00	91.13	0.62	22.35	0.016	91.78
4	Mansara	-1.48	2.78	0.049	80.03	1.58	2.97	0.052	81.45
5	Cincinnati	0.50	4.58	0.017	89.40	1.35	113.88	0.42	76.15
6	W2 Treynor	0.062	0.29	0.001	83.46	0.71	3.37	0.017	85.43
7	W6GWC	-0.90	0.57	0.024	80.54	2.68	1.71	0.07	81.03
8	W7GWC	-0.71	1.54	0.019	80.32	2.33	5.04	0.06	80.20
9	W14 GWC	0.32	0.32	0.008	87.97	1.34	1.32	0.03	90.04
10	182	-0.49	0.09	0.013	79.05	0.35	0.07	0.009	81.20
11	129	-11.11	0.011	0.25	88.42	0.0	0.0	0.0	90.95
12	123	-0.66	0.002	0.015	84.73	-0.13	0.0	0.00	84.04

PBIAS of proposed sediment yield model was found to vary from 0.062 % for Karso, 0.035 % for Banha, 0.013 % for Nagwa, -1.48 % for Mansara, 0.50 % for Cincinnati, 0.062 for W2, -0.92 % for W6, -0.71 % for W7, 0.32 % for W14, -0.49 % for 182, -11.11 for 129 and -0.6 % for 123 watershed, respectively. Visualization of watershed number versus NSE of the S2 and S1 models from all the applications of twelve watersheds as shown in Table 4.3 and Fig. 4.2.

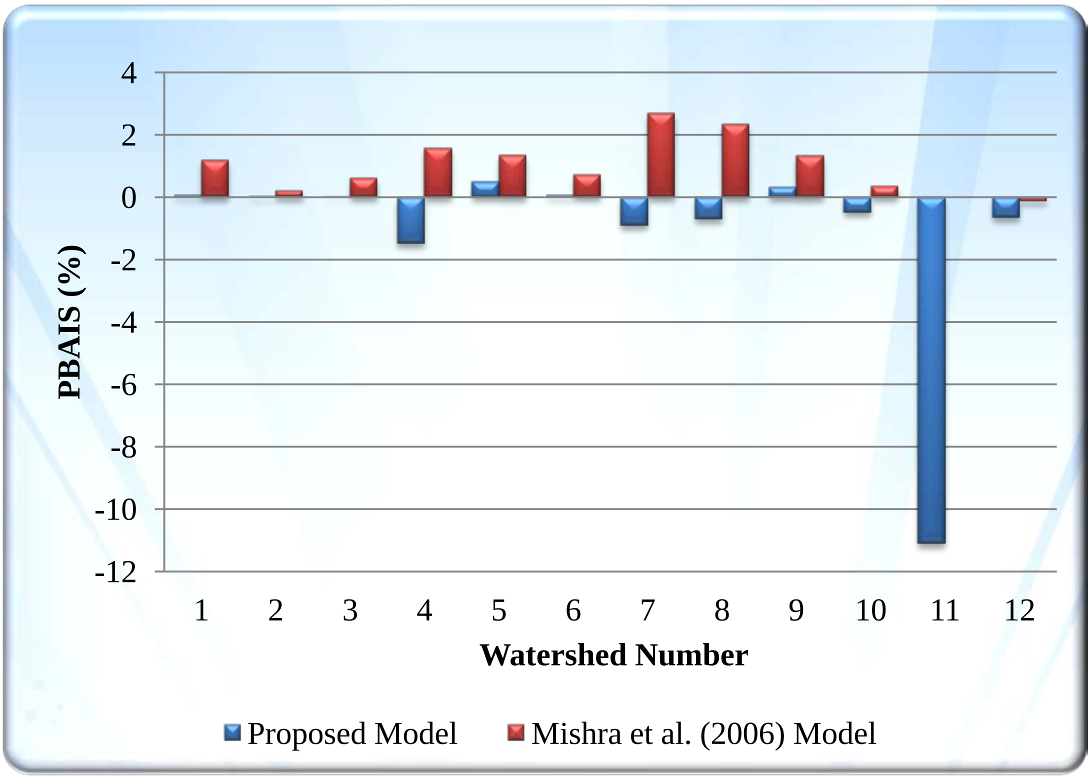


Figure-4.2: Visualization of watershed number versus PBIAS of the S2 and S1 models from the application of twelve watersheds

The RMSE were used for performance evaluation of S2 model. The obtained values of RMSE are 0.71 mm for Karso, 0.56 mm for Banha, 0.47 mm for Nagwa, 2.78 mm for Mansara, 4.58 mm for Cincinnati, 0.29 mm for W2, 0.57 mm for W6, 1.54 mm for W7, 0.32 mm for W14, 0.09 mm for 182, 0.011 mm for 129 and 0.002 mm for 123 watersheds, the proposed sediment yield model (S2) of lowest RMSE as compared to S1 model as shown in Table 4.3 and Fig.4.3.

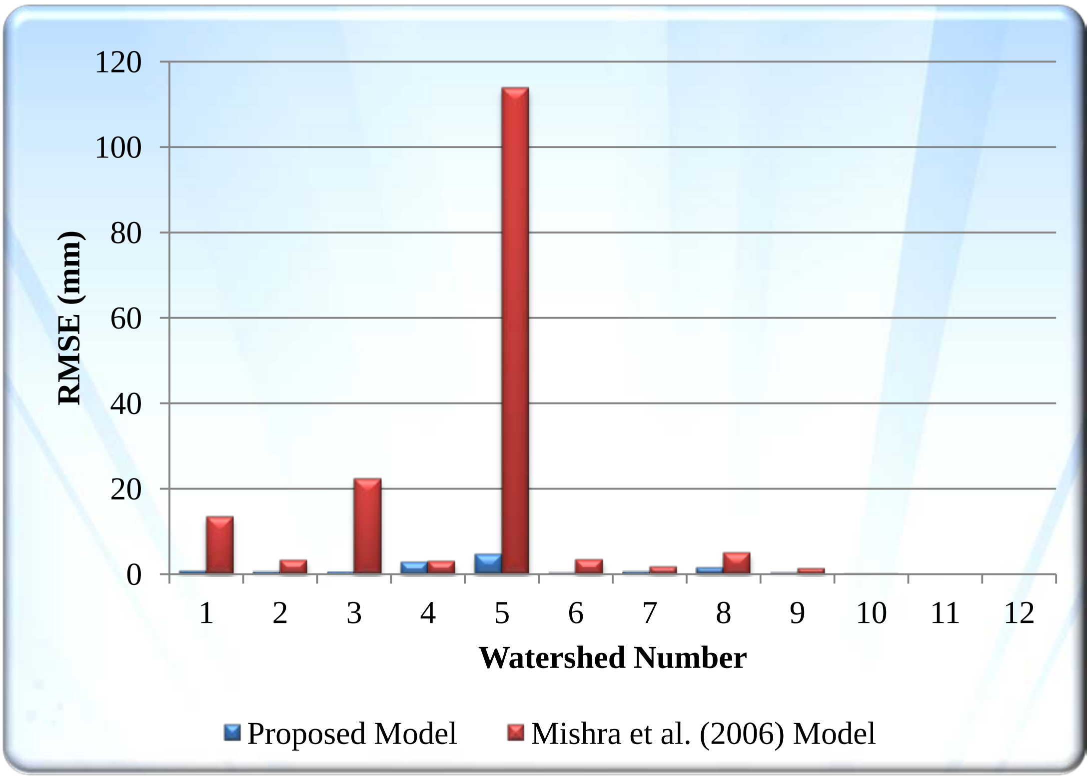


Figure-4.3: Visualization of watershed number versus RMSE of the S2 and S1 models from the application of twelve watersheds

Similarly nRMSE of S2 model are 0.0018 mm for Karso, 0.001 mm for Banha, 0.00 mm for Nagwa, 0.049 mm for Mansara, 0.017 mm for Cincinnati, 0.001 mm for W2 Treynor, 0.024 mm for W6 GWC, 0.019 mm for W7 GWC, 0.008 mm for W14, 0.013 mm for 182, 0.25 mm for 129 and 0.015 mm for 123 watershed respectively as shown in Table 4.3 and Fig. 4.4.

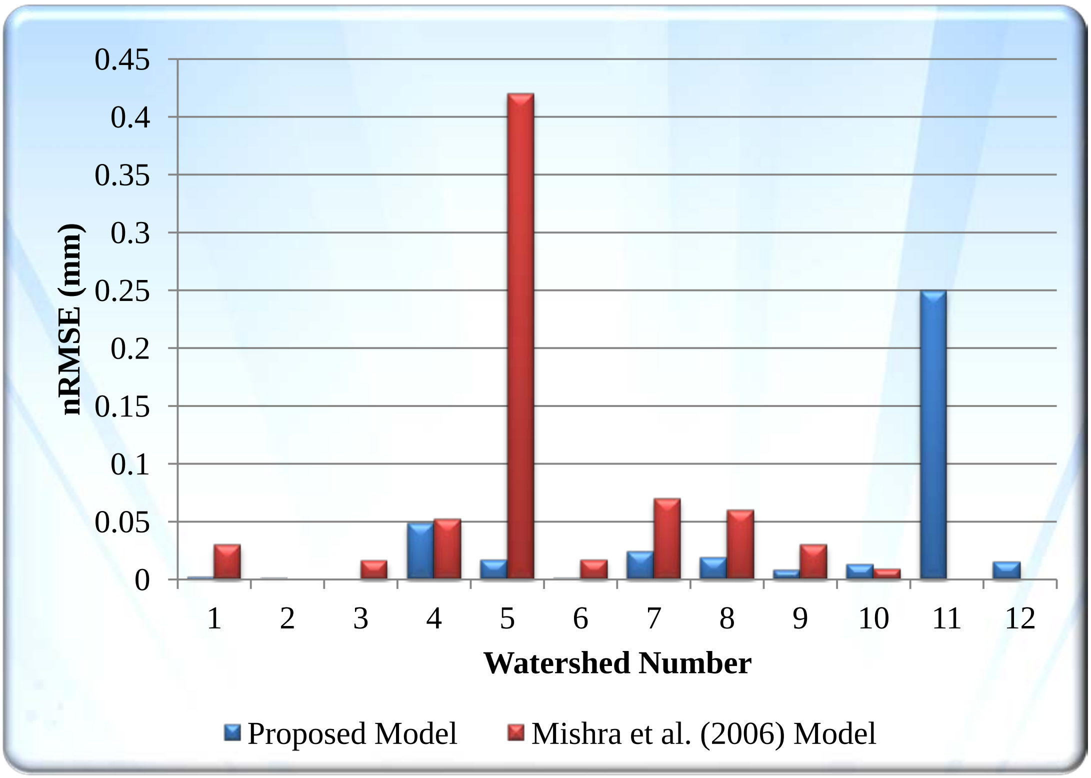


Figure-4.4: Visualization of watershed number versus nRMSE of the S2 and S1 models from the application of twelve watersheds

The computed values of potential maximum retention (S) and static infiltration that were used for the S2 model were also used to compute the runoff of R2 model as shown in Table 4.2. Similarly, the performance of R2 model was evaluated using statistical indicator used for NSE, PBIAS, RMSE, and nRMSE and the same technique used for R1 model. Among all the watersheds, The NSE of R2 model is observed to be superior as compared to R1 model from all the watersheds as shown in Table 4.4 and Fig. 4.5.

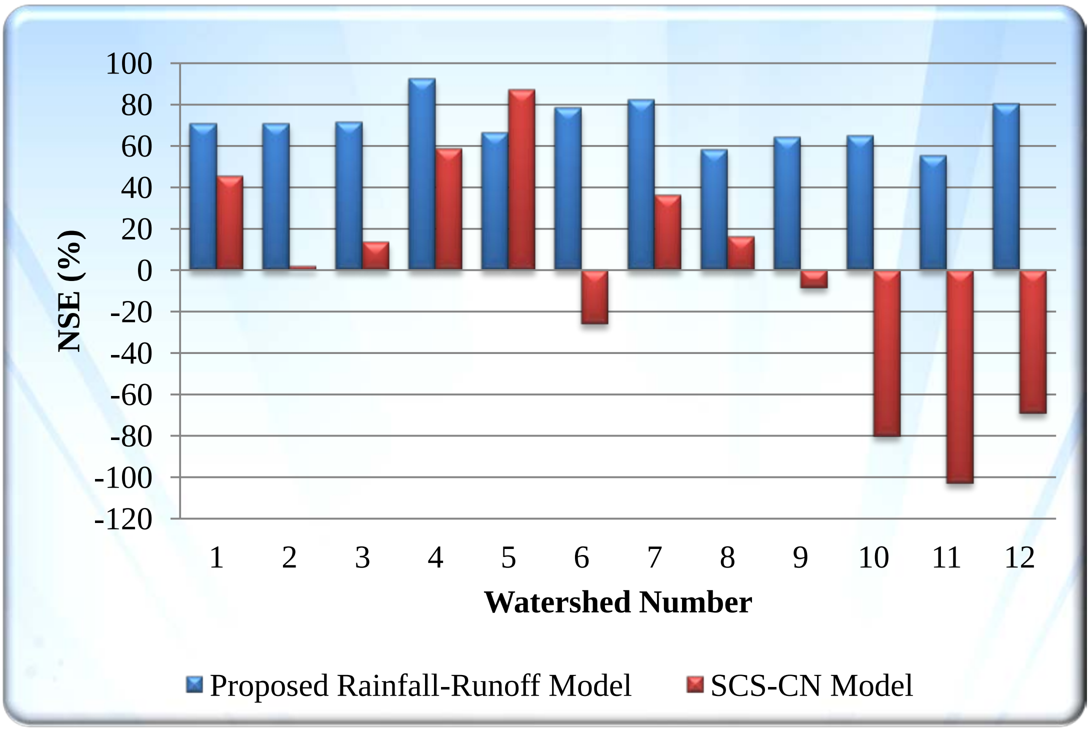


Figure-4.5: Visualization of watershed number versus NSE of the R2 and R1 models from the application of twelve watersheds

Table-4.4: Comparative analysis between proposed rainfall-runoff and Existing SCS-CN models

S. No	Name of WS	Proposed rainfall-runoff model				Existing SCS-CN model			
		PBIAS (%)	RMSE (mm)	nRMSE (mm)	NSE. (%)	PBIAS (%)	RMSE (mm)	nRMSE (mm)	NSE. (%)
1	Karso	32.69	6.98	0.98	70.77	-59.92	12.79	1.8	45.62
2	Banha	26.41	18.89	1.05	70.86	-54.07	38.67	2.16	1.76
3	Nagwa	43.4	10.68	1.15	71.36	-76.25	18.76	2.02	13.55
4	Mansara	7.07	1.37	0.23	92.48	-63.58	15.46	2.64	58.79
5	Cincinnati	49.85	7.54	1.65	66.43	-29.55	4.47	0.98	87.34
6	W2 Treynor	22.21	3.58	0.54	78.44	-68.43	11.05	1.68	-26.1
7	W6GWC	28.98	6.01	0.77	82.22	-59.16	12.27	1.57	36.26
8	W7GWC	46.24	17.76	1.22	58.28	-68.71	26.4	1.82	15.97
9	W14 GWC	33.79	7.5	0.89	64.46	-70.8	15.71	1.87	-8.67
10	182	32.55	10.9	0.86	64.82	-82.92	27.78	2.19	-80.28
11	129	21.82	5.89	0.49	55.23	-82.81	22.39	1.85	-102.94
12	123	34.77	5.84	0.77	80.39	-89.18	14.99	1.99	-69.26

However, in some of the watershed the performance were inferior due to deposition of sediment yield (Mishra et al., 2006). The PBIAS of R2 model was estimated on the basis of observed runoff and computed runoff PBIAS of R2 model are lowest as compared to R1 model form all the watersheds as shown in Table 4.4 and Fig. 4.6.

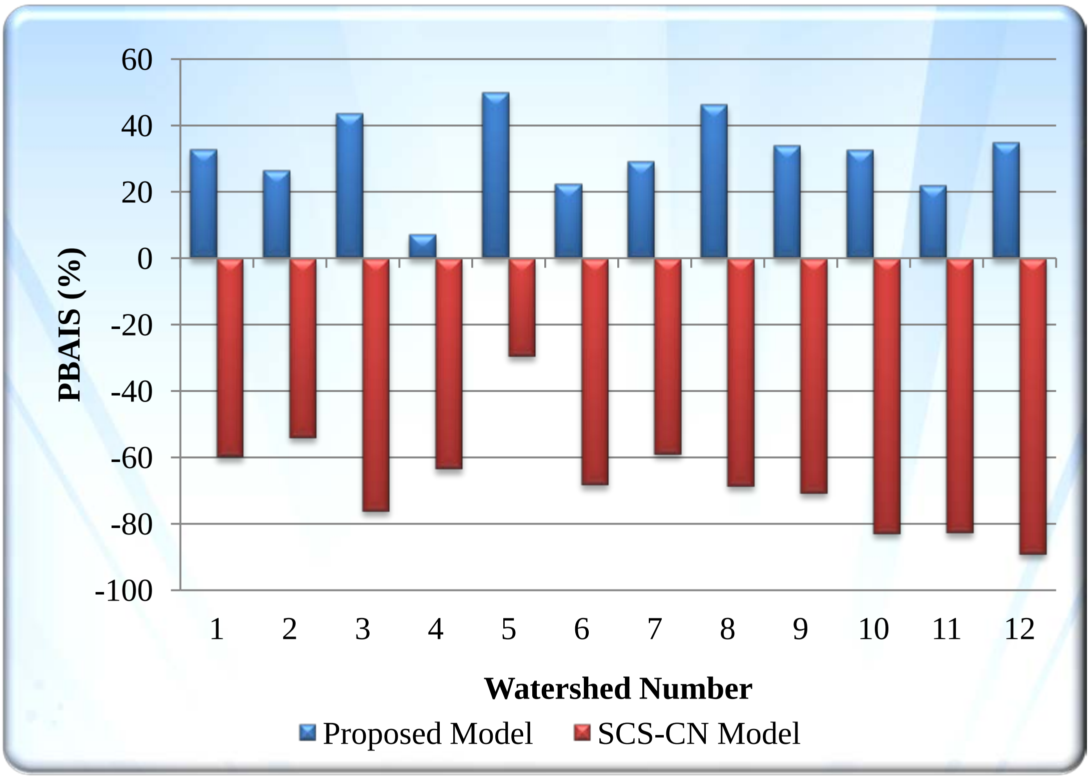


Figure-4.6: Visualization of watershed number versus PBIAS of the R2 and R1 models from the application of twelve watersheds

Accordingly, performance of R2 model is superior as compared to R1 model from the respective watersheds as shown in Table 4.4 and Fig. 4.7.

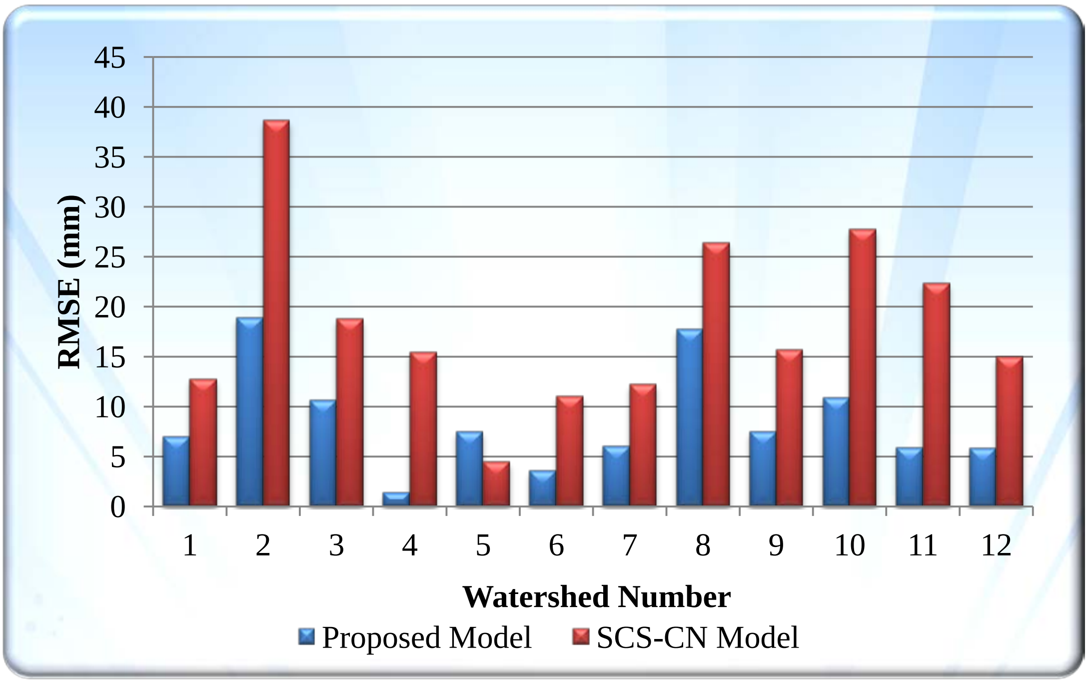


Figure-4.7: Visualization of watershed number versus RMSE of the R2 and R1 models from the application of twelve watersheds

The nRMSE of R2 model varies from 0.23 to 1.15 mm from all the watersheds and for R1 model it varies from 0.98 to 2.64 mm respectively as shown in Table 4.4 and Fig. 4.8.

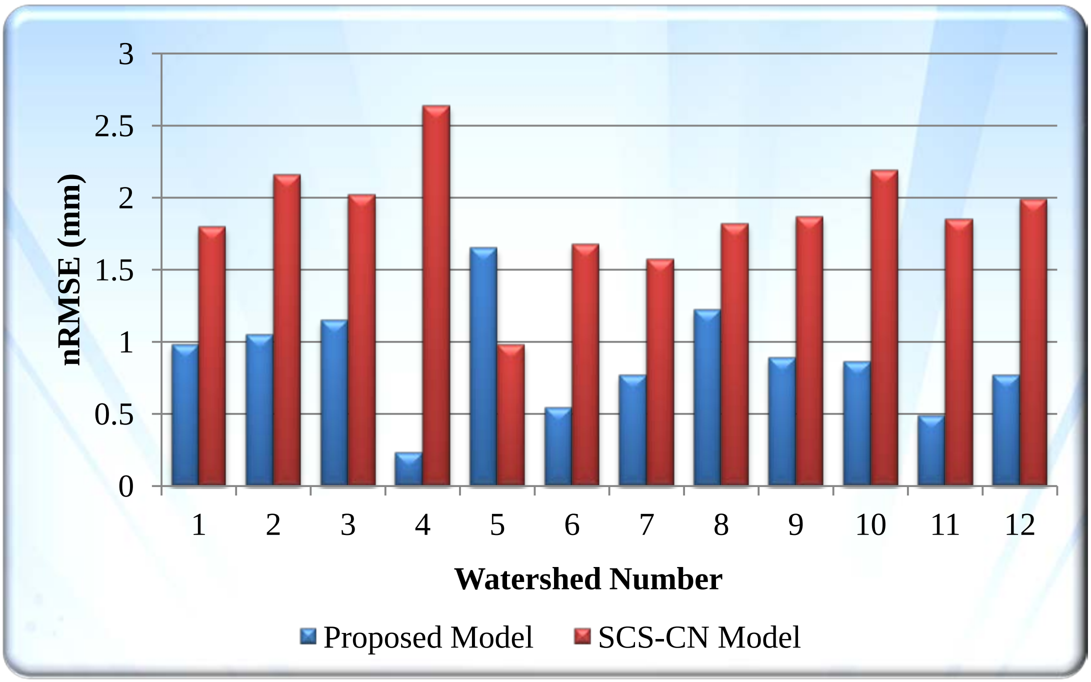


Figure-4.8: Visualization of watershed number versus nRMSE of the R2 and R1 models from the application of twelve watersheds

Finally, sediment yield and runoff models were compared for the twelve watersheds via scatter plots in sequence to visualize the model reliability for application of the present study. For model reliability the observed sediment yield and computed sediment yield are plotted on both sides of the line of perfect fit. Similarly for runoff model, observed runoff and computed runoff are plotted on both sides of the line of perfect fit (Figs.4.9-4.20).

4.5 SUMMARY

In the present study, new sediment yield and rainfall-runoff models with coupling the SCS-CN method and SMA procedure have been developed for estimation of sediment yield and runoff from all the watersheds. From the newly derived sediment yield model, the optimized parameters of static infiltration 'F_c' and potential maximum retention 'S' was used in the rainfall-runoff model for computation of runoff from the small watersheds. The proposed sediment yield model can be applied to different hydro-meteorological data. Results of the proposed models show that it can be used for field application as well as an academic purpose.

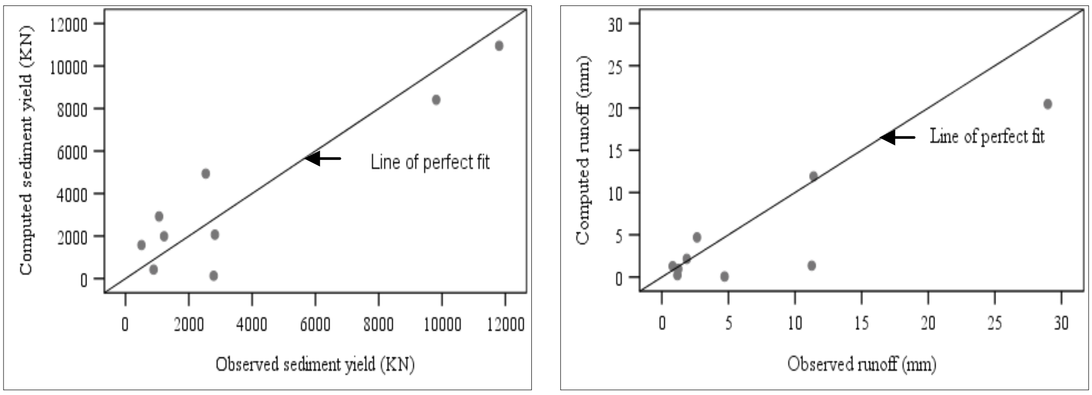


Figure-4.9: Comparison between sediment yield (S2) and runoff (R2) models from Karso watershed

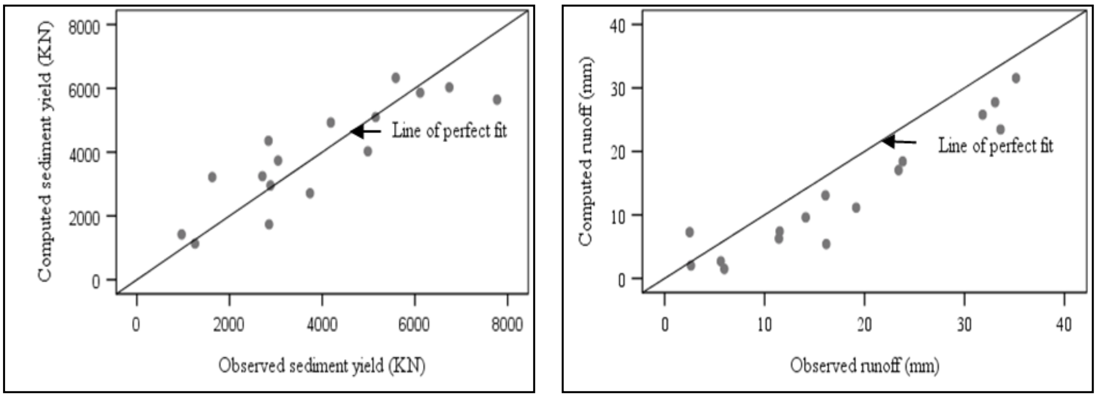


Figure-4.10: Comparison between sediment yield (S2) and runoff (R2) models from Banha watershed

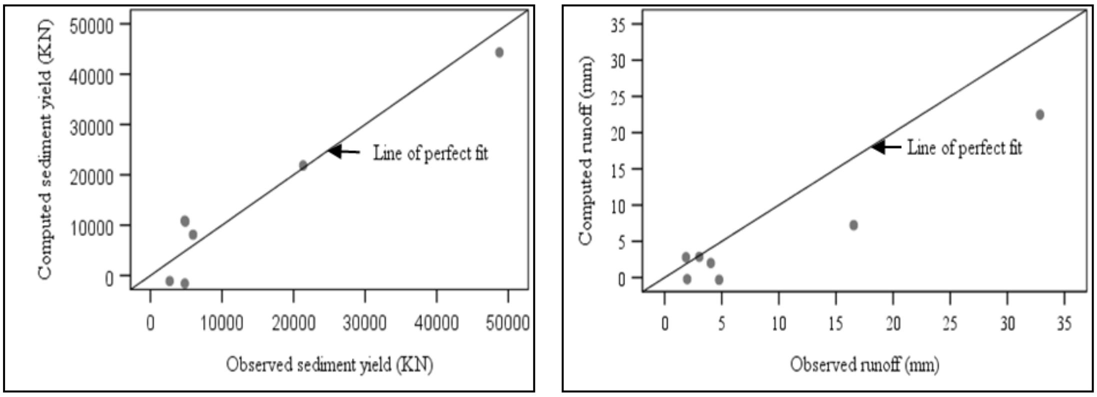


Figure-4.11: Comparison between sediment yield (S2) and runoff (R2) models from Nagwa watershed

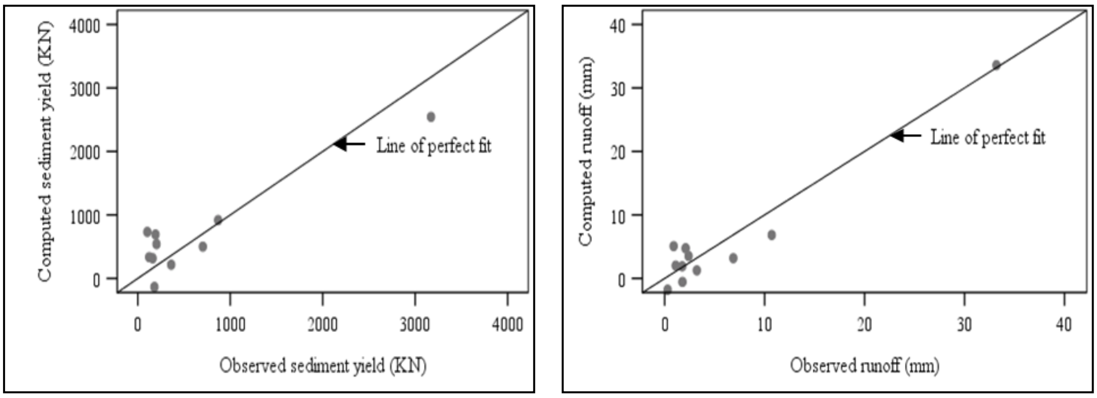


Figure-4.12: Comparison between sediment yield (S2) and runoff (R2) models from Mansara watershed

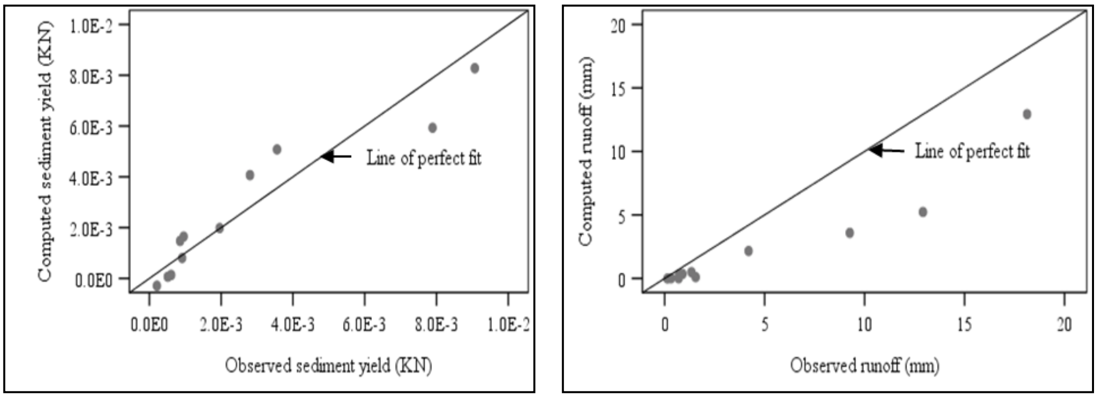


Figure-4.13: Comparison between sediment yield (S2) and runoff (R2) models from Cincinnati watershed

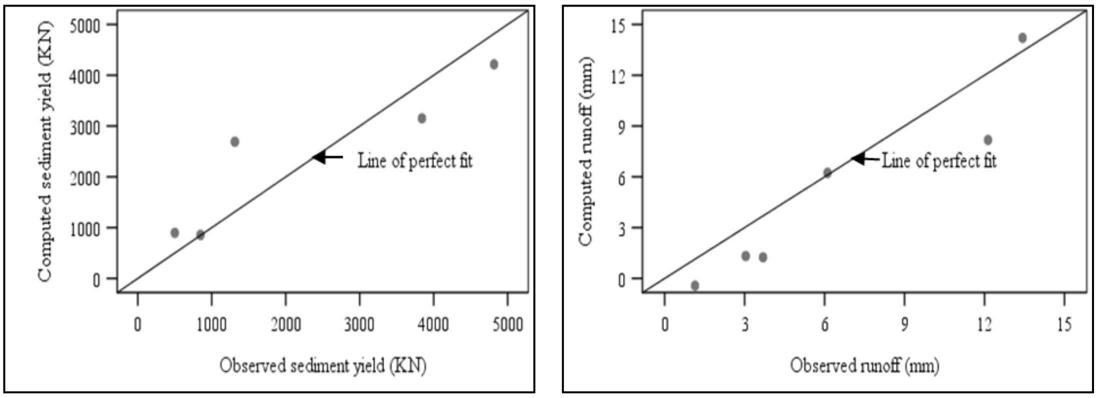


Figure-4.14: Comparison between sediment yield (S2) and runoff (R2) models from W2 watershed

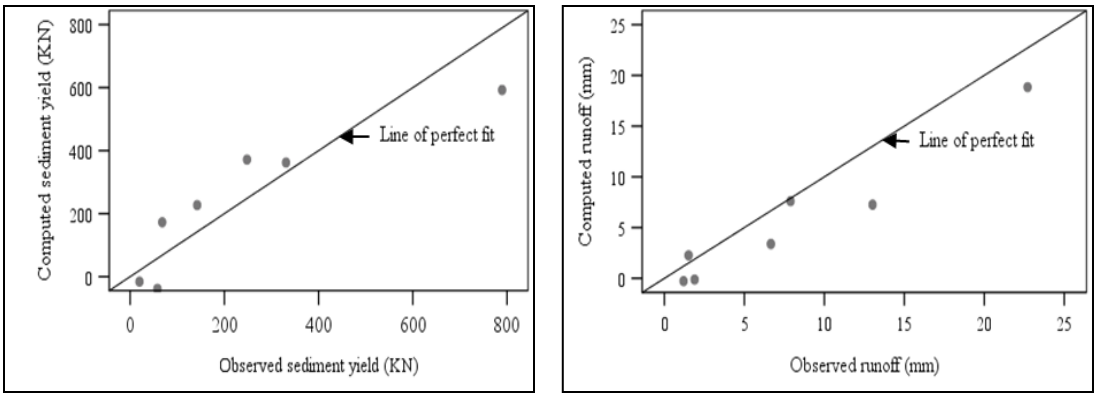


Figure-4.15: Comparison between sediment yield (S2) and runoff (R2) models from W6 watershed

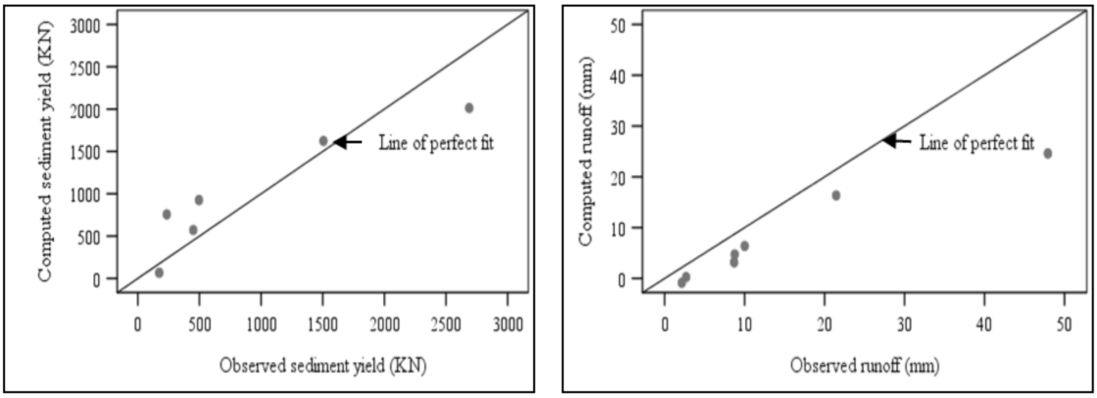


Figure-4.16: Comparison between sediment yield (S2) and runoff (R2) models from W7 watershed

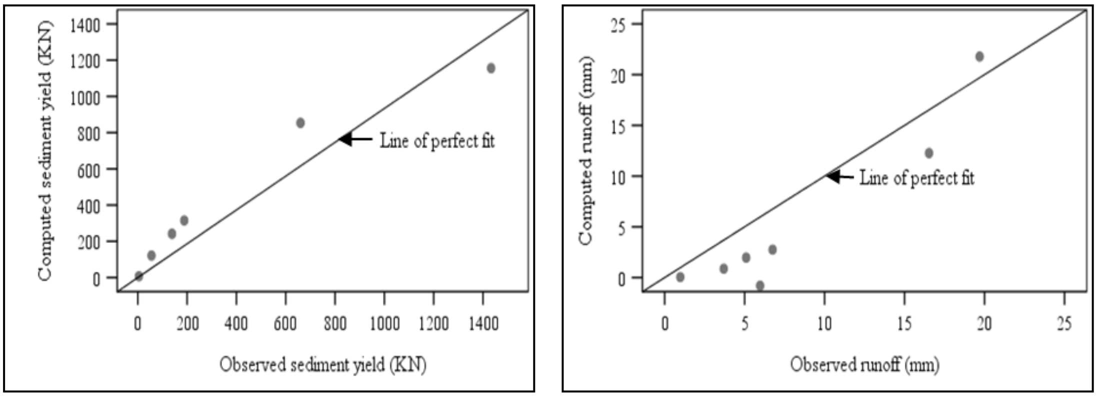


Figure-4.17: Comparison between sediment yield (S2) and runoff (R2) models from W14 watershed

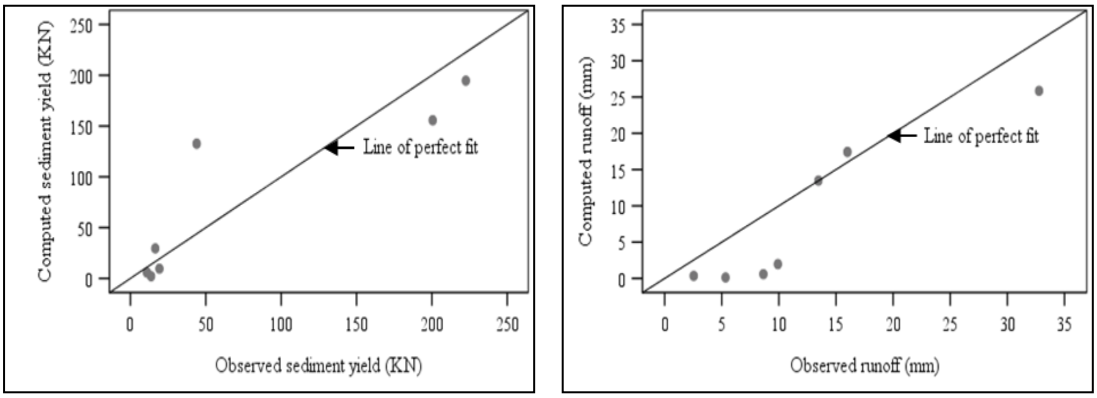


Figure-4.18: Comparison between sediment yield (S2) and runoff (R2) models from W182 watershed

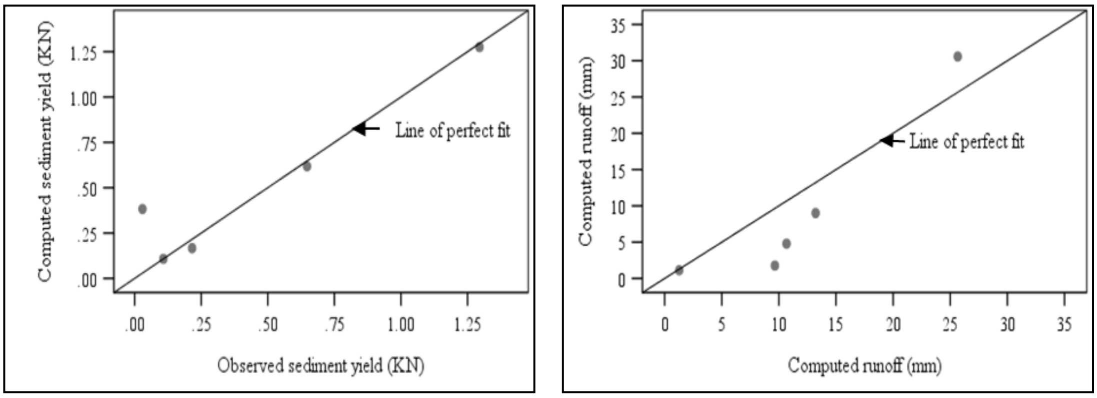


Figure-4.19: Comparison between sediment yield (S2) and runoff (R2) models from W129 watershed

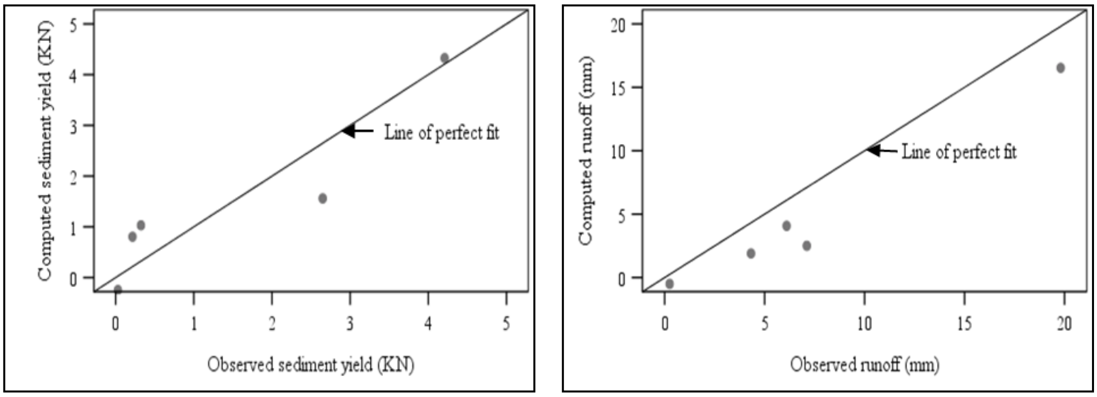


Figure-4.20: Comparison between sediment yield (S2) and runoff (R2) models from W123 watershed

CHAPTER 5

RAINSTORM-GENERATED SEDIMENT YIELD MODEL BASED ON SOIL MOISTURE PROXIES (SMP)

5.1 INTRODUCTION

Sediment yield is defined as the total sediment outflow from a watershed per unit time. It is obtained by multiplying the sediment loss by a sediment delivery ratio (Novotny and Chesters 1989). Its modeling is necessary for computation of watershed yield and watershed health behavior. Sediment yield by rainfall and overland flow is a widespread threat to soil fertility and water quality. Accurate estimation of sediment yield and its spatial distribution is often needed for pollutant risk analyses, reservoir management, agricultural productivity forecasts, and soil and water conservation (Singh et al., 2008; Tyagi et al., 2008; Zi et al., 2016). Soil erosion and soil loss are one of the most environmental problems leads to the loss of land fertility and reduce the agricultural production (Mondal et al., 2016). Erosion and sedimentation phenomena govern the hydrological phenomena of rainfall and runoff. Factors that affect either rainfall or runoff, directly affect erosion and sedimentation. Thus, the analysis of erosion and sediment yield extensively depends upon the hydrology of the catchment under consideration. Estimation of sediment yield associated with individual storm events of varying magnitude is necessary for erosion control planning, whereas estimates of annual or mean annual sediment yield is adequate for water resources planning. Sediment yield models vary mostly in complexity from simple regression relationships, linking spatial variations in annual sediment yield, to climatic and physiographic characteristics, to compelling distributed simulation models (Wischmeier and Smith, 1978; Jial et al., 1987; Richard et al., 1987; Wang, 1987; Haider., 1994; Suyanto et al., 1995; Xie et al., 2002; Tang, 2004; Wei et al., 2006; Wei et al., 2006; Hou et al., 2006; Hou et al., 2007; Yin et al., 2007; Grace., 2008; Tyagi et al 2008; Li and Wei., 2011; ,2014; Abd Elbasit et al., 2013.).

Sediment transport during flood events can sometimes reveal hysteretic patterns because flow discharge can peak before or after the peak of sediment transport (Lenzi, 2001; Lenzi et al., 2006; Comiti et al., 2009; Mao et al., 2014). A number of studies have considered the relationships between soil erosion and storm characteristics using forecast models or measured values of sediment concentration in runoff hydrological stations (Xu, 1998. Hogarth et al., 2004; Zheng et al., 2008; Wei et al., 2010). Increased sediment yield due to accelerated soil loss may cause silting of reservoirs, irrigation canals, harbours and navigation channels accelerated valley and flood plain sedimentation. In the recent year, in rainfall-sediment yield model; more emphasis has been placed on the development of physically based rainfall-sediment yield model; however, empirical and conceptual model have their own advantages (Senbeta et al., 1999). Over parameterization in hydrological modeling increase the complexity of parameter identification and is obviously problematic for computation of hydrological phenomena in ungauged watersheds (Skaugen et al., 2015).

The aim of this chapter is to (1) develop rainstorm-generated sediment yield model based on soil moisture proxies (SMP), (2) to compare the proposed model with Mishra et al. (2006) model (3) to apply statistical indices on proposed and Mishra et al. (2006) models for model performance assessment. Before discussing the proposed rainstorm-generated sediment yield models, therefore, revisit the original SCS-CN model in chapter 2

5.2 MODEL DEVELOPMENT

Development of mathematical sediment yield model is based on SMP for estimation of sediment yield from all application of small watersheds. The newly derived sediment yield model is not presented in any literature, prior and after rainfall occurrence were taken as input parameters.

5.2.1 Mishra et al. (2006) Model

Mishra et al. (2006) developed lumped based sediment yield model using SCS-CN method for computation of sediment yield from the natural watersheds. The concept of this model are discussed in Chapter 4.

5.3 PROPOSED SEDIMENT YIELD MODEL

Mishra et al. (2006b) developed the modified initial abstraction (I_a) model to prevent the sudden jump of CN in SCS-CN method for runoff computation, the relationship for I_a was modified a new parameter of M_c to account for soil moisture content before the rainfall occurrence. The new model for the estimation of I_a, it is expressed as

$$I_a = \frac{\lambda S^2}{S + M_c} \tag{5.1}$$

where M_c, is the antecedent moisture, Ajmal et al. (2016) modified the 'I_a' model developed by Mishra et al. (2006b) model is replaced the 'M_c' in Eq. (5.1) with $'V_0'$. It is an analytically expressed as

$$I_a = \frac{\lambda S^2}{S + V_0} \tag{5.2}$$

Incorporating initial soil moisture'$V_0' = 0.33S$ into Eq. (5.2) yields

$$I_a = \frac{0.2S^2}{S + 0.33S} = I_a = 0.150S \qquad \text{AMC} - \text{I} \tag{5.3}$$

Incorporating the initial soil moisture '$V_0' = 0.61S$ into Eq. (5.2) yields

$$I_a = \frac{0.2S^2}{S + 0.61S} = I_a = 0.124S \qquad \text{AMC} - \text{II} \tag{5.4}$$

Therefore, incorporating the initial soil moisture $'V_0' = 0.87S$ into Eq. (5.2) yields

$$I_a = \frac{0.2S^2}{S + 0.87S} = I_a = 0.107S \tag{5.5}$$

By expanding the numerator and employing the polynomial division from the original SCS-CN method of Eq. (4.4), it is mathematically expressed as:

$$C = \frac{Q}{P} = 1 - \left(\frac{S}{P}\right)\left[(1+\lambda) - \frac{S}{P - I_a + S}\right] \tag{5.6}$$

or

$$\frac{Q}{P} = \frac{P - S}{P}\left[(1+\lambda) - \frac{S}{P - I_a + S}\right] \tag{5.6a}$$

or

$$Q = P - S\left[(1+\lambda) - \frac{S}{P - I_a + S}\right] \qquad 5.6b$$

or

$$P - Q = S\left[(1+\lambda) - \frac{S}{P - I_a + S}\right] \qquad 5.7$$

Substituting Eq. (5.3) and $\lambda = 0.2$into Eq. (5.7) yields

$$P - Q = S\left[(1+0.2) - \frac{S}{P - 0.15S + S}\right] \qquad 5.8$$

On simplification of Eq. (5.8) we get

$$P - Q = \left[\frac{1.2PS + 0.02S^2}{P + 0.85S}\right] \qquad 5.9$$

Therefore the modified form of the GR4J runoff model is presented by Michel et al. (2005), it is analytically expressed as

$$Q = (P - PE)x\left(\frac{V}{S + S_a}\right)^2 \qquad P > PE \qquad 5.10$$

where, PE is the daily potential evapotranspiration, Yuan et al. (2014) considered that daily potential evapotranspiration to be zero because runoff from rainfall usually lasts for an event of sufficiently limited duration. The modified form of GR4J model is expressed as follows

$$Q = P\left(\frac{V}{S + S_a}\right)^2 \qquad 5.11$$

where S_a is the intrinsic parameter expressed mathematically as equal to $S_a = V_0 + I_a$ hence Eq. (5.11) yields $Q = P$ for $V = S + S_a$ as a maximum capacity of 'V'.

Substituting $V = V_0 + P - Q$ and $S_a = V_0 + I_a$into Eq. (5.11) we get

$$Q = P\left(\frac{V_0 + P - Q}{S + V_0 + I_a}\right)^2 \qquad 5.12$$

Substituting Eqs. (5.3), (5.9) and $V_0 = 0.33S$ into Eq. (5.12) yields

$$Q = P\left(\frac{0.33S + \frac{1.2PS+0.02S^2}{P+0.85S}}{S + 0..33S + 0.15S}\right)^2 \qquad 5.13$$

On simplification of Eq. (5.13) yields

$$Q = P\left(\frac{P + 0.1964S}{0.967P + 0.822S}\right)^2 \qquad AMC - I \qquad 5.14$$

Substituting Eq. (5.4) and λ =0.2 into Eq. (5.7) yields

$$P - Q = \left[\frac{1.2PS + 0.051S^2}{P + 0.876S}\right] \qquad 5.15$$

Substituting Eqs. (5.15), (5.4) and $V_0{}' = 0.61S$ into Eq. (5.12) we get

$$Q = P\left(\frac{0.61S\frac{1.2PS+0.0512S^2}{P+0.876S}}{S + 0.61S + 0.124S}\right)^2 \qquad 5.16$$

After simplification of Eq. (5.16) give

$$Q = P\left(\frac{P + 0.323S}{0.958PS + 0.839S}\right)^2 \qquad AMC - II \qquad 5.17$$

Substituting Eq. (5.5) and λ =0.2 into Eq. (5.7) yields

$$P - Q = \left[\frac{1.2PS + 0.0716S^2}{P + 0.893S}\right] \qquad 5.18$$

Substituting Eqs. (5.5), (5.18) and $'V_0{}' = 0.87S$ into Eq. (5.12) give

$$Q = P\left(\frac{0.87S\frac{1.2PS+0.0716S^2}{P+0.893S}}{S + 0.87S + 0.107S}\right)^2 \qquad 5.19$$

On simplification of Eq. (5.19) we get

$$Q = P\left[\frac{P + 04095S}{0.955P + 0.85S}\right]^2 \qquad AMC - III \qquad 5.20$$

Replacing S by $S\left(\frac{P}{P+P_5}\right)$, substituting into Eq. (5.14) yields

$$Q = P\left(\frac{P + \frac{0.1964PS}{P+P_5}}{0.967P + \frac{0.822PS}{P+P_5}}\right)^2 \qquad 5.21$$

After simplification of Eq. (5.21) yield

$$Q = P\left(\frac{P + P_5 + 0.1964S}{0.967(P + P_5) + 0.822S}\right)^2 \qquad \text{AMC} - \text{I} \qquad 5.22$$

where Q/P is the runoff coefficient 'C' it varies from 0 to 1. Interpretation of Eq. (5.22) is presented in the form of runoff coefficient 'C'. Simplification of Eq. (5.22) yields

$$\frac{Q}{P} = \left(\frac{P + P_5 + 0.1964S}{0.967(P + P_5) + 0.822S}\right)^2 \qquad 5.23$$

5.3.1 Power Law

Novotny and Olem (1994) proposed the runoff coefficient 'C' with sediment delivery ratio 'DR' in the power form as

$$DR = \alpha C^{\beta} \qquad (5.24)$$

where $'\alpha'$ and $'\beta'$ is the coefficient and exponent respectively, and 'DR' is the sediment delivery ratio is a dimensionless ratio of the sediment yield 'Y' to the potential maximum erosion 'A':

$$DR = \frac{Y}{A} \qquad (5.25)$$

The runoff coefficient 'C' is defined as actual runoff 'Q' to potential rainfall, 'P' it is expressed as

$$C = \frac{Q}{P} \qquad (5.26)$$

A substitution of the expressions of 'DR' and 'C' into Eq. (5.24) yields

$$Y = \alpha A\left(\frac{Q}{P}\right)^{\beta} \qquad (5.27)$$

Incorporating Eq. (5.23) into Eq. (5.27) yields

$$\mathrm{Y} = \alpha\mathrm{A}\left(\left(\frac{\mathrm{P}+\mathrm{P}_5+0.1964\mathrm{S}}{0.967(\mathrm{P}+\mathrm{P}_5)+0.822\mathrm{S}}\right)^2\right)^{\beta} \mathrm{AMC} - \mathrm{I} \tag{5.28}$$

Eq. (5.28) is the proposed rainfall-sediment yield model is based on soil moisture proxies.

5.4 Model Application

5.4.1 Hydrological Data for Model Application

In this study the Indian watersheds and the USDA-ARS watersheds has been selected for testing the workability of the proposed sediment yield model these included Karso, Banha, Nagwa and Mansara watersheds in India; and Cincinnati, W2 Treynor, W6 GC, W7 GC, W14 GC, W182 GC, W129 GC and W123 GC watersheds in the USDA-ARS (Table 3.1 and Figs. 3.1 through 3.12) are presented in chapter 3.

5.4.2 Model Formulation

This analytical development of sediment yield model based on soil moisture proxies (SMP) can be used for the computation of sediment yield from small watersheds. The proposed sediment yield model is coupling the SMP for newly derived sediment yield model incorporating before and after rainfall occurrence for model formulation. Also, as standard initial abstraction coefficient, $\lambda = 0.2$ was utilized in the analytical derivation of model, where P > 0.2S was the limitation of Mishra et al. (2006) model. Hence, the limitation for the proposed sediment yield model was changed to$\mathrm{P} > 0.2S \times [\mathrm{P}/(\mathrm{P}+\mathrm{P}_5)]$; in the present study the S value was adjusted to $S_1 = 2.281S_2$ and $S_3 = 0.427S_2$ (S_2 is the S value representing the normal watershed conditions) for the wet and dry conditions respectively. The newly derived sediment yield model provided continuous S variation directly based on P and P_5 to avoid sudden jumps in sediment yield computation.

5.4.3 Performance Evaluation Criteria

The performance evaluation of proposed sediment yield model was evaluated based on Nash-Sutcliffe Efficiency (NSE), percentage bias (PBAIS), and normalized root mean square error (nRMSE) are presented in chapter 4.

5.5 RESULTS AND DISCUSSION

5.5.1 Parameter Estimation

The models parameters are computed by Marquardt algorithm of constrained least squares. It has the advantage that the final parameter estimate does not depend on its initial estimate. Initially, parameters are set as zero in all applications and the lower and upper limits are decided by trial and error. If the computed value of a parameter in a run did not fall in the prescribed range, the limit was extended accordingly in the next run. If the subsequent runs produced the estimate was assumed to be optimal globally. Approximately, three-five runs or a few more in some cases are required to obtain the final estimates of model parameters.

The optimized parameter of potential maximum erosion (A) shows the range of 0.00441 to 181711.6 kN for all applications of the watersheds. Accordingly the potential maximum retention (S) varies from 1.27 to 46.97 mm as shown in Table 5.1. The optimized parameters of A and S are close agreement with the results obtained by Mishra et al. (2006); Tyagi et al. (2008); Singh et al. (2008); and Bhunya et al. (2010). The parameters β of proposed model is an exponent it varies from 0.029 to 0.699. Singh et al. (2008) showed that the value of β varies from 0.325 to 1.0. Thus Gajbhiye et al. (2014) reported that the value of β in the range of 0.89 to 1.46. In the present study, the value of β was taken as 0.0 to 1.0. From experiment studies point of view, it is shown that β = 2.0 (Meyer 1971; Foster 1982). Sharma et al. (1993) showed that the value of β is in the range of 1.09 to 1.44. Foster et al. (1977) was used a value of β of 1.0. Tayfur (2001) showed that the change in the value of β in between 1.0 to 1.8 does not affect the sediment discharge appreciably. In the 4-parameter of this proposed sediment yield model variable A is taken as parameters due to the lack of their observations (Mishra et al. 2006; Bhunya et al. 2010).

Table-5.1: Optimized parameters of proposed sediment yield and Mishra et al. (2006) models

S. No	Name of Watershed	Proposed sediment yield model				Existing Mishra et al (2006)	
		Potential maximum erosion A (kN)	Potential maximum retention S (mm)	α	β	Potential maximum erosion A (kN)	Potential maximum retention S (mm)
1	Karso	44763.03	21.287	0.211	0.100	32872.05	79.86
2	Banha	36040.87	9.679	0.146	0.029	16626.55	75.25
3	Nagwa	181711.61	24.146	0.205	0.100	215689.23	195.15
4	Mansara	43214.26	46.97	0.899	0.029	11196.48	239.73
5	Cincinnati	4.41E-03	1.27	0.296	0.100	9.55E-03	7.98
6	W2 Treynor	29058.39	11.15	0.010	0.699	18269.06	78.94
7	W6GWC	18247.58	13.36	0.269	0.400	1903.57	80.67
8	W7GWC	53614.59	35.82	1.00	0.100	7213.32	142.35
9	W14 GWC	73577.94	34.89	0.800	0.200	5410.20	136.95
10	182	19374.89	40.39	0.538	0.400	1078.83	170.32
11	129	57.52	21.68	0.296	0.039	6.20	149.12
12	123	272.86	36.93	1.00	0.070	30.13	148.90

The existing SCS-CN model is mainly used for determination of direct surface runoff depth from watersheds using the dimensionless curve number values for dry, normal and wet conditions distinguished based on previous five days rainfall P_5 (Sahu et al., 2007). The absence of any reliable initial SMA procedure in the model leads to inefficient sediment yield computation and, consequently, inferior performance (Brocca et al., 2008). The input parameters in Mishra et al. (2006) and proposed sediment yield models are A, S, α and β respectively. In order to maintain the simplicity rule and to allow the use of proposed models in ungauged watersheds, the parameters of existing and proposed models are calibrated in the present study. Improved sediment yield model, formulation suggested by Mishra et al. (2006) model was used.

Three statistical indices of NSE, PBAIS and nRMSE were applied on proposed sediment yield and Mishra et al. (2006) models. Large set of 98 events of rainfall, previous five days rainfall, runoff and sediment yield data were analyzed in order to depict and evaluate the Mishra et al. (2006) and proposed sediment yield models performance. Since the proposed sediment yield model was derived based on SMA procedure, the input parameters in the proposed model are previous five days rainfall, rainfall and potential maximum retention respectively. The newly derived sediment yield model performed better than Mishra et al. (2006) model for sediment yield estimation from small watersheds. Based on statistical indices (NSE, PBAIS and nRMSE) the observed sediment yield and computed sediment yield from the newly derived sediment yield model are similar, therefore proposed sediment yield model is hydrological more precise.

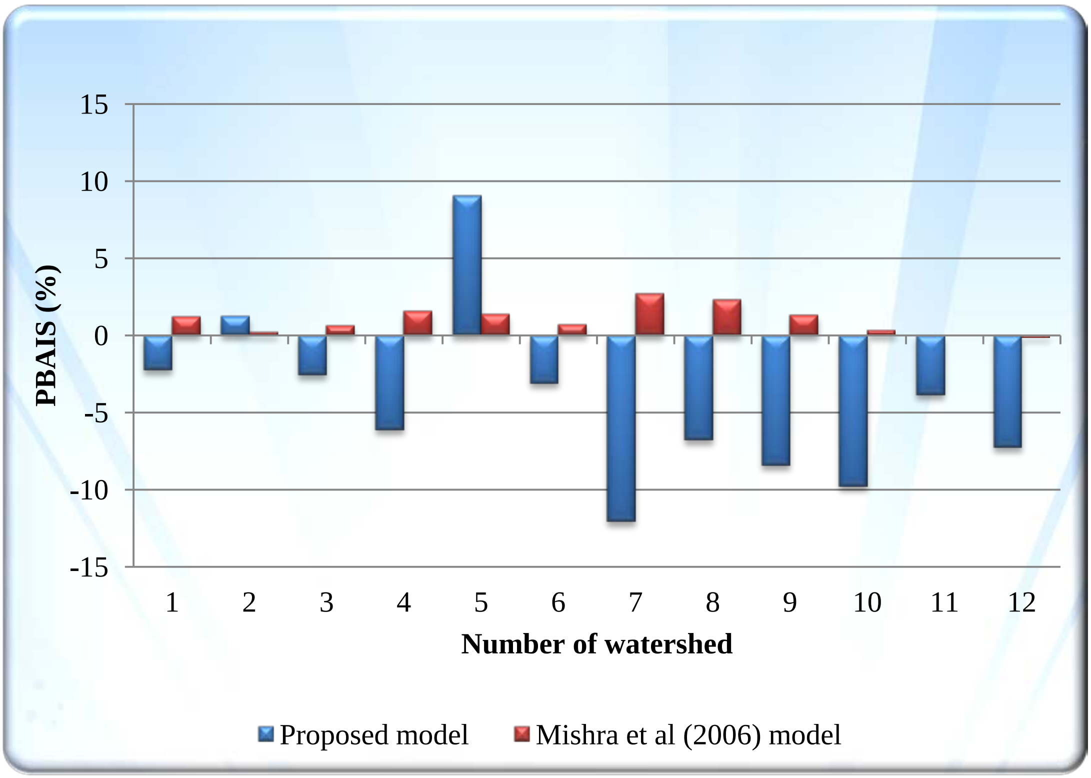


Figure-5.1: Variation of PBIAS (%) using proposed and Mishra et al. (2006) models for watersheds

Ajmal et al. (2016) reported that the RMSE and NSE cannot over estimated or underestimated of a performance the model. From the Fig 5.1 it observed that the performance evaluation from proposed model for determining sediment yield of 98 event data set gave comparatively lower PBAIS. With a mean of PBAIS -4.329 % compared to 1.019 % determined for the Mishra et al. (2006) model. Similarly, nRMSE was assessed for model performance evaluation of proposed sediment yield.

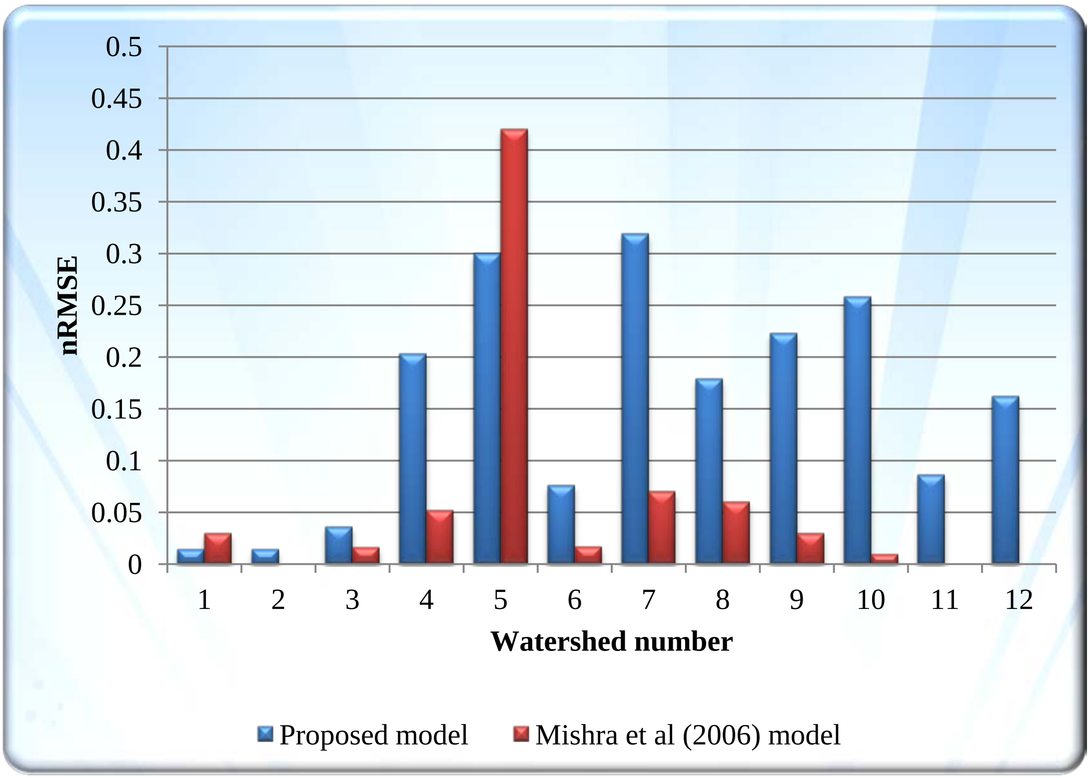


Figure-5.2: Variation of nRMSE (kN) using proposed and Mishra et al. (2006) models for watersheds

The nRMSE derived from the application of a proposed sediment yield model it ranges from 0.014 to 0.319 kN as shown in Table 5.2, comparatively the nRMSE of Mishra et al. (2006) model varies from 0.0 to 0.42 kN respectively as shown in Fig.5.2 and Table 5.2.

Table 5. 2 Comparative analysis between proposed sediment yield and Mishra et al. (2006) models

S. No	Name of Watershed	Proposed sediment yield model			Mishra et al. (2006) model		
		PBIAS (%)	nRMSE (kN)	NSE. (%)	PBIAS (%)	nRMSE (kN)	NSE. (%)
1	Karso	-2.247	0.014	87.24	1.19	0.03	84.51
2	Banha	1.228	0.014	85.28	0.208	0.00	75.21
3	Nagwa	-2.567	0.036	92.63	0.62	0.016	91.78
4	Mansara	-6.130	0.203	89.51	1.58	0.052	81.45
5	Cincinnati	9.055	0.300	91.27	1.35	0.42	76.15
6	W2 Treynor	-3.096	0.076	92.78	0.71	0.017	85.43
7	W6GWC	-12.08	0.319	85.63	2.68	0.07	81.03
8	W7GWC	-6.783	0.179	89.60	2.33	0.06	80.20
9	W14 GWC	-8.435	0.223	96.84	1.34	0.03	90.04
10	182	-9.784	0.258	84.11	0.35	0.009	81.20
11	129	-3.846	0.086	89.11	0.0	0.0	90.95
12	123	-7.265	0.162	74.01	-0.13	0.00	84.04

Analyzing the sediment yield prediction efficiency illustrated by proposed model and Mishra et al. (2006) models using the NSE as the statistical indices demonstrated modest improvement as shown in Fig. 5.3. The proposed sediment yield model had the highest mean NSE (88.167) indicating its reliability for accurate sediment yield prediction from all applications of the watersheds. The mean NSE (83.499) for Mishra et al. (2006) model was lowest as compared to improved sediment yield model. Fig.5.3 shows that the proposed sediment yield model mostly significant from all the applications of the watersheds, followed by Mishra et al. (2006) model. The improved sediment yield model exhibited satisfactory results in Karso, Banha, Nagwa, Mansara, Cincinnati, W2, W7, W14, W182 and W129 watersheds respectively. The W 123 watershed compute the lower sediment yield as compare the Mishra et al. (2006) model. The reason of the poor performance of sediment yield from W123 watershed is the different land slope, landuse/ landcover change, data quality, climatic condition and geomorphology of the watershed in the present study.

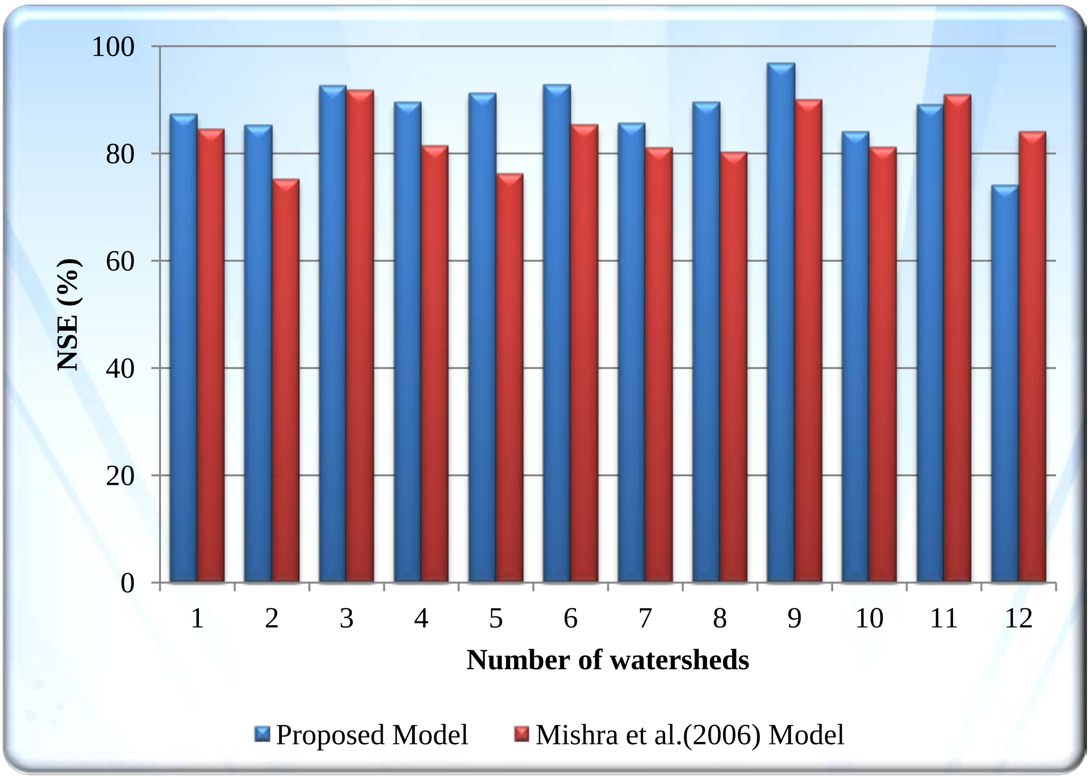


Figure-5.3: Variation of NSE for watersheds using proposed sediment yield model and Mishra et al. (2006) model

For visual performance assessment the observed and computed sediment yield the newly derived sediment yield and Mishra et al. (2006) models are plotted on both sides of line perfect fit as shown in Fig.5.4-5.15.

5.6 SUMMARY

The newly derived sediment yield model is more applicable for estimation of sediment yield from watersheds with the evidence of visual assessment and comparative analysis with Mishra et al. (2006) model. Therefore the advantage of proposed sediment yield model is the reduction of sudden jump of CN for computation of sediment yield. Considering the integral effects of initial soil condition before rainfall and the initial abstraction after the rainfall and employing a new expression for continuous S variation for each of the individual storms improved the newly derived sediment yield model performance based on all statistical indices as well as visual the assessment. In the present chapter, this study identified the potential of soil moisture proxies in an analytically derived newly sediment yield model that demonstrated encouraging results for the computation of sediment yield.

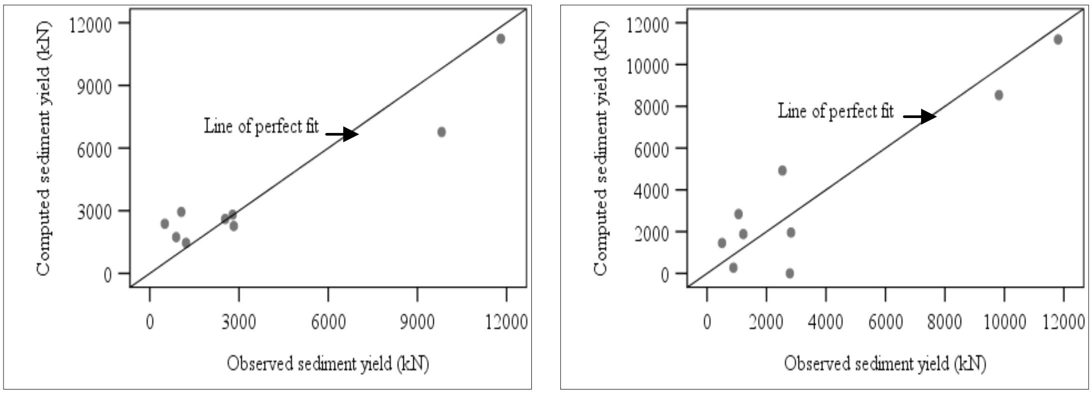


Figure-5.4: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for Karso watershed

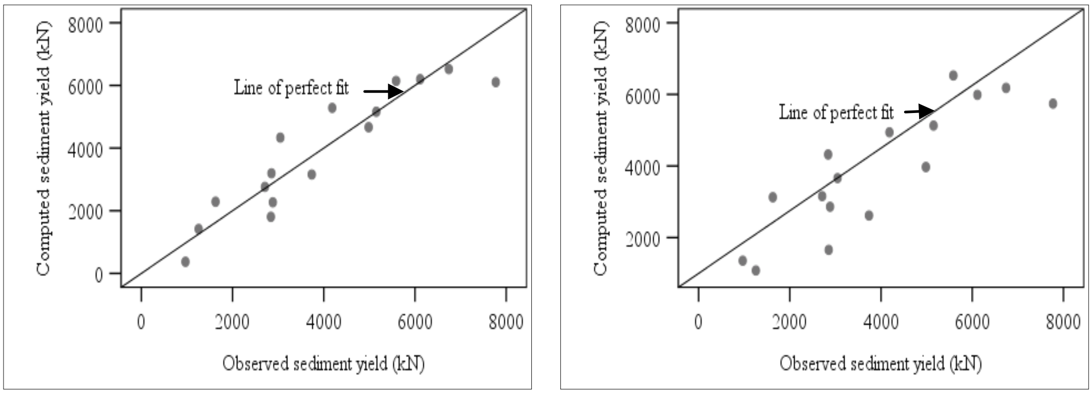


Figure-5.5: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for Banha watershed

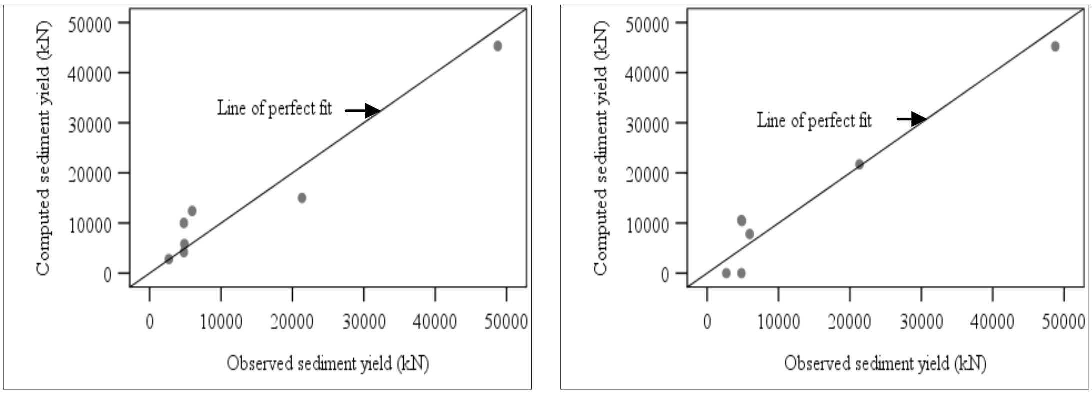


Figure-5.6: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for Nagwa watershed

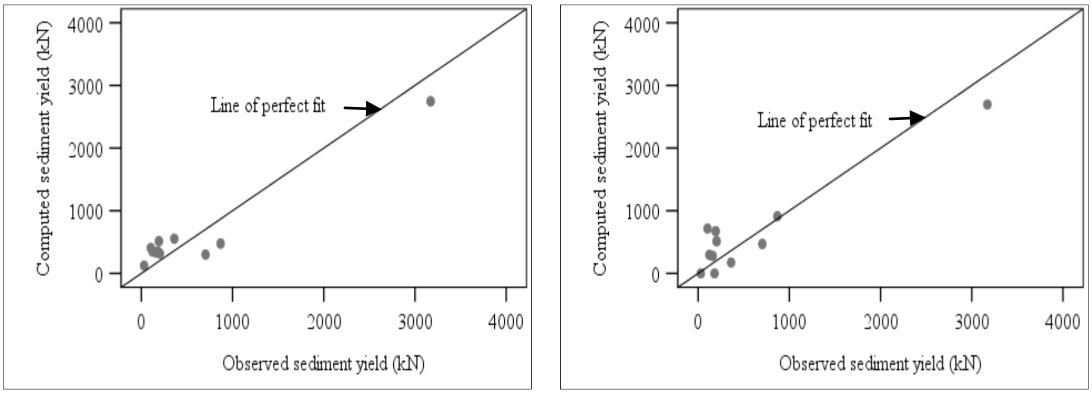


Figure-5.7: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for Mansara watershed

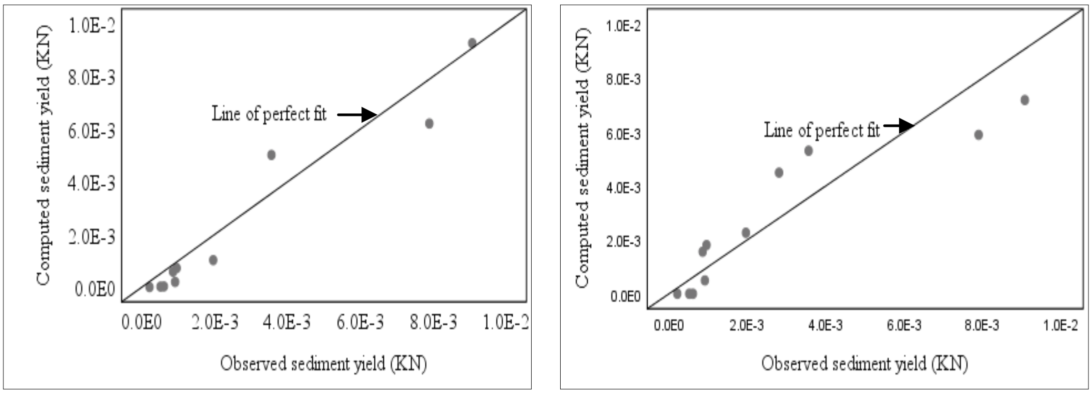


Figure-5.8: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for Cincinnati watershed

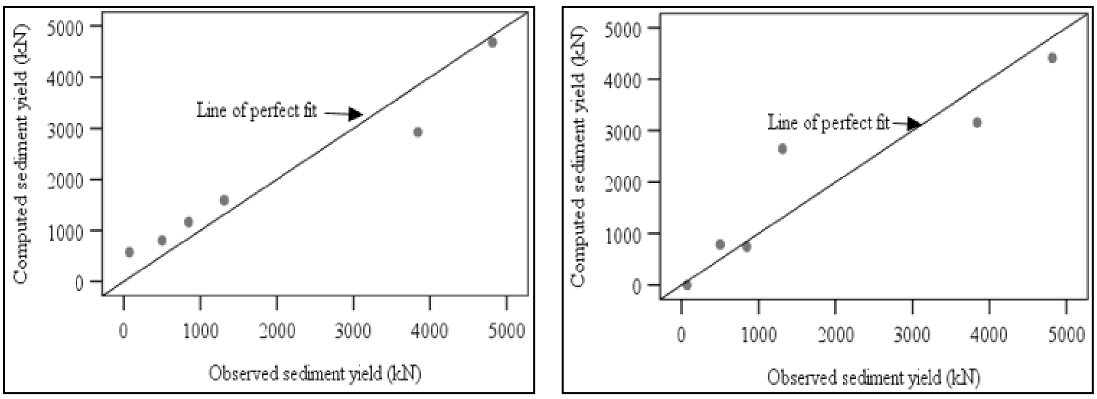


Figure-5.9: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for W 2 watershed

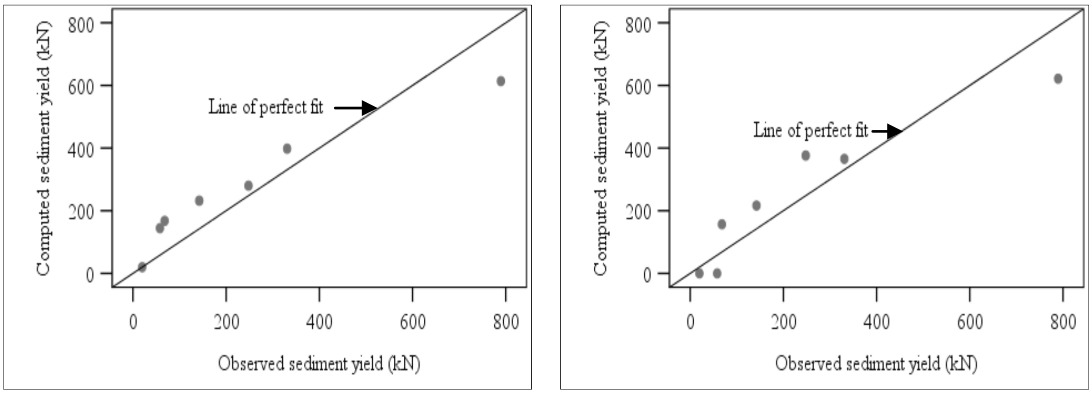


Figure-5.10: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for W 6 watershed

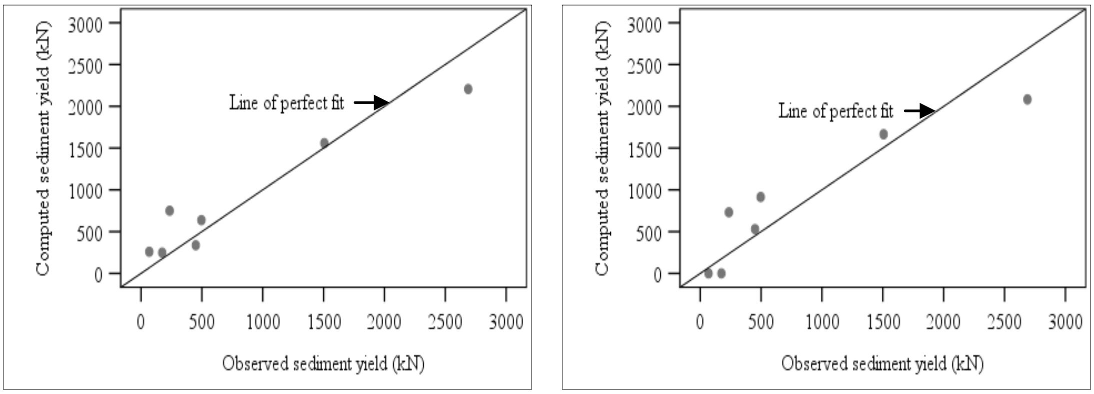


Figure-5.11: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for W 7 watershed

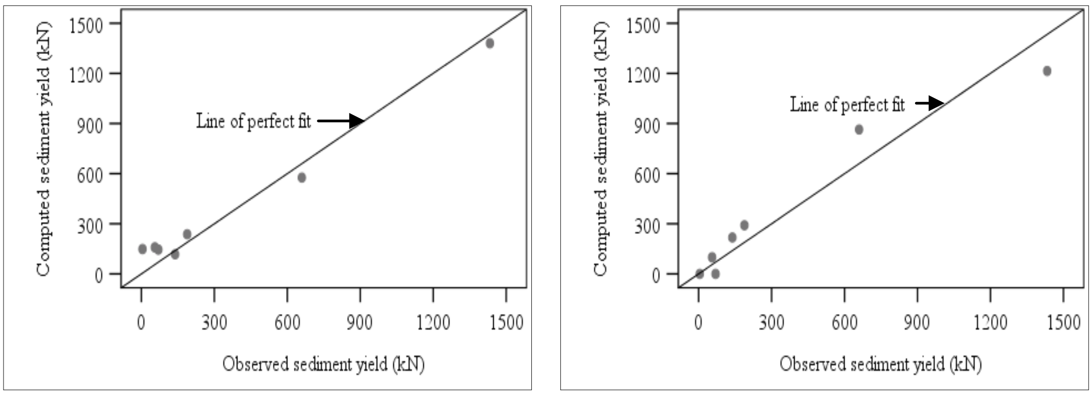


Figure-5.12: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for W 14 watershed

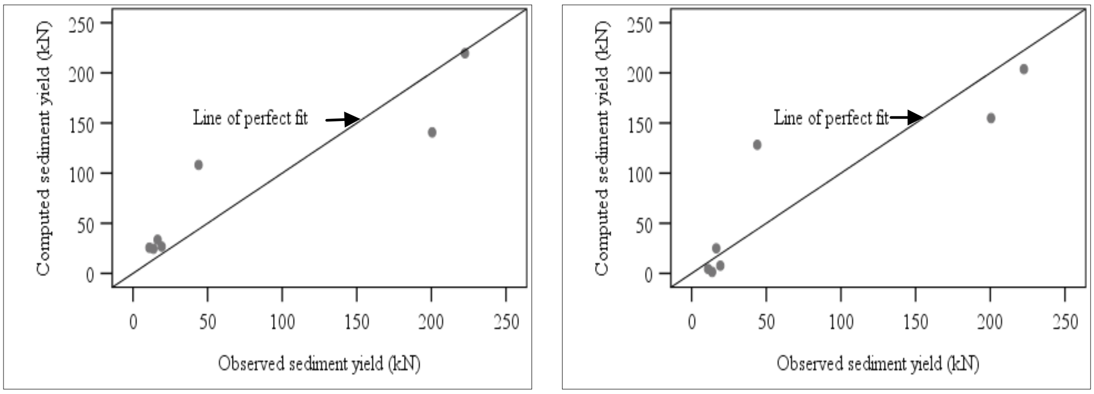


Figure-5. 13: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for W 182 watershed

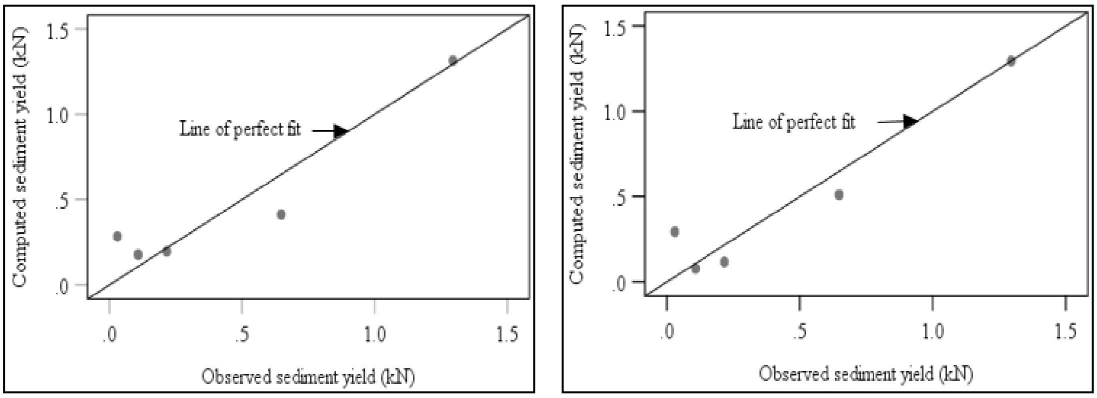


Figure-5.14: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for W 129 watershed

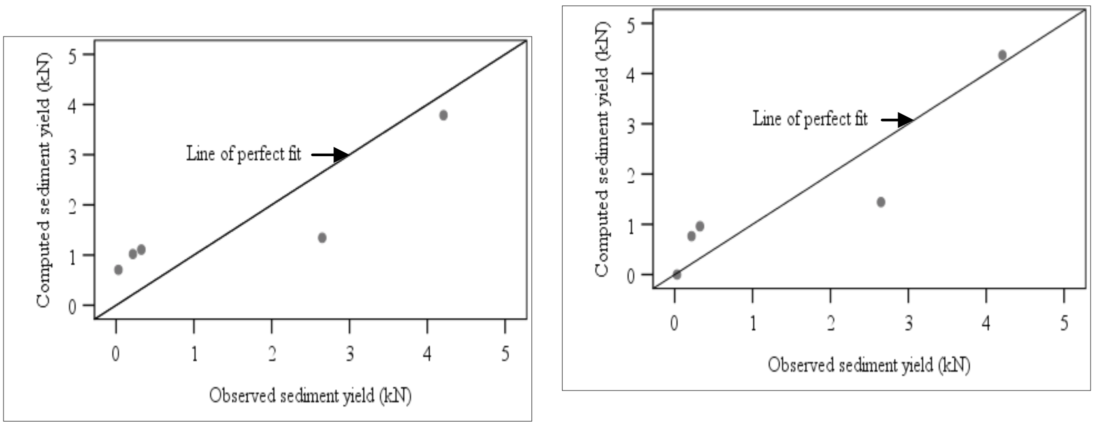


Figure-5.15: Comparison between observed and computed sediment yield using proposed and Mishra et al. (2006) models for W 123 watershed

CHAPTER 6

SEDIMENT GRAPH MODEL BASED ON SOIL MOISTURE ACCOUNTING (SMA) FROM SMALL WATERSHEDS

6.1 INTRODUCTION

The sediment flow rate plotted as a function of time during a storm at a given location is known as sediment graph. Without a sediment graph, only the average sediment rate for the storm can be computed. The average sediment yield is not adequate for computing dynamic suspended sediment load and pollutants load during the storm (Raghuwanshi et al., 1994). Rendon-Herrero (1974) developed a sediment graph model; based on unit sediment graphs approach defined as the unit sediment graph generated from one unit of sediment for a given duration distributed uniformly over a watershed. The ordinates of these unit sediment graphs, called series graphs, were related to source runoff volume to calculate storm sediment graphs. This technique is entirely dependent upon measured data and could not be used to show differences in land management. Sediment rate distribution during a flood event can be of paramount importance if the sediment is transporting pollutants that are toxic at high concentrations. The average sediment rate is unacceptable for use in estimating dynamic pollutants loads during a flood. Knowledge of the sediment rate distribution during large floods event would further aid engineers in designing structures for maximum trap efficiency.

Therefore, looking into the importance of sediment graph based studies and SMA concept in event-based rainfall-runoff-sediment yield modeling, in the present study aimed at (1) to develop an improved sediment graph model based on coupling of soil moisture accounting (SMA) in the SCS-CN methodology, Nash's, IUSG model and Power law, (ii) to test the applicability of the proposed model by using data of six small watersheds, and finally (3) to compare the performance of the proposed model with the existing Bhunya et al. (2010) model.

6.2 Existing Soil Conservation Service Curve Number Method

The Soil Conservation Service Curve Number (SCS-CN) method for computing storm runoff from event rainfall was developed by the Soil Conservation Service of USDA 1972. For the storm as a whole, the depth of excess rainfall realizable as direct runoff Q is always less than, or equal to, the depth of rainfall P; likewise, once runoff begins, the additional depth of water retained in the watershed (F), is less than or equal to, some potential maximum retention (S). There is some amount of rainfall (I_a) (initial abstraction before ponding) for which no runoff will occur; so the potential runoff is ($P-I_a$). The hypothesis underlying this method is that the ratio between the two corresponding actual quantities is the same as between the two corresponding potential quantities. From continuity principle:

$$P = I_a + F + Q \qquad (6.1)$$

$$\frac{Q}{P-I_a} = \frac{F}{S} \qquad (6.2)$$

$$I_a = \lambda S \qquad (6.3)$$

where, P is the rainfall (mm), Q is the direct surface runoff (mm), F is the cumulative infiltration (mm), I_a is the initial abstraction (mm), S is the potential maximum retention (mm), and λ is the initial abstraction coefficient. Coupling Eq. (6.1) and Eq. (6.2) leads to the existing SCS-CN method as:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad 6.4$$

Eqs. (6.4) is valid for $P \geq I_a$, Q = 0, otherwise. Coupling of Eqs. (6.4) with Eq. (6.3) for $\lambda = 0.2$ enables determination of S from the rainfall-runoff data. In practice, S is derived from a mapping equation expressed in terms of curve number (CN).

$$S = \frac{25400}{CN} - 254 \qquad 6.5$$

The non-dimensional CN is derived from the tables given in the National Engineering Handbook, Section-4 (NEH-4) (SCS, 1956) for catchment characteristics, such as land use, types of soil, antecedent moisture condition (AMC).The CN values vary from 0 to 100. The higher the CN value, the higher the runoff factor, C, and vice versa (Mishra et al., 2006; Tyagi et al., 2008; Daniel, 2011; Sahu et al., 2010, 2012; Ajmal et al., 2015; Singh et al., 2015; Verma et al., 2017).

6.3 SMA Coupled SCS-CN Sub-Model

This section deals with the development of SMA coupled SCS-CN model as discussed here

$$\frac{Q}{P} = \frac{F}{S} \tag{6.6}$$

After simplification of Eq. (6.6) yield

$$Q = \frac{P^2}{P + S} \tag{6.7}$$

Assume V_0 represents the soil moisture storage level at the beginning of the storm event and V is the soil moisture storage at any time t. If P and Q are the accumulated rainfall and corresponding runoff, then the following expressions can be easily obtained as (Michel et al., 2005):

$$V = V_0 + P - Q \tag{6.8}$$

Coupling of Eq. (6.7) and Eq. (6.8) yields.

$$V = V_0 + P - \frac{P^2}{P+S} \tag{6.9}$$

A further simplification of Eq. (6.9) yields

$$V = \frac{V_0(P+S)+PS}{P+S} \tag{6.10}$$

Now the simplified form of the GR4J runoff model can be expressed in cumulative form as:

$$Q = (P - PE) \times \left(\frac{V}{S+S_a}\right)^2 \quad P > PE \tag{6.11}$$

where PE is the potential evapotranspiration and is assumed negligible because the runoff from rainfall usually lasts for an event of sufficiently limited duration. Hence simplification of Eq. (6.11) yield

$$Q = P \times \left(\frac{V}{S+S_a}\right)^2 \tag{6.12}$$

Eq. (6.12) yields Q = P for $V = S + S_a$ as a maximum capacity of V, substituting the expression for V from Eq. (6.10) into Eq. (6.12) and simplifying yields

$$Q = P\left[\frac{V_0(P+S)+PS}{(P+S)(S+S_a)}\right]^2 \tag{6.13}$$

Threshold soil moisture (S_a) is defined as growing linearly with initial soil moisture and initial abstraction, it is mathematically expressed as (Michel et al., 2005):

$$S_a = V_0 + I_a \tag{6.14}$$

Now, substituting Eq. (6.14) into Eq. (6.13) and simplifying yields

$$Q = P\left[\frac{V_0(P+S)+PS}{(P+S)(S+V_0+I_a)}\right]^2 \tag{6.15}$$

Simplification of Eq. (6.15) in the form of runoff coefficient it is an analytically can be expressed as

$$\frac{Q}{P} = \left[\frac{V_0(P+S)+PS}{(P+S)(S+V_0+I_a)}\right]^2 \tag{6.16}$$

6.3.1 Nash IUSG Sub-Model

The suspended sediment dynamics for a linear time distributed watershed is reported by a spatially lumped form of the continuity equation and linear-storage discharge relationship. The first linear reservoir model, can analytically be expressed as

$$I_{s1}(t) - Q_{s1}(t) = dS_{s1}(t)/dt \tag{6.17}$$

$$S_{s1}(t) = K_s Q_{s1}(t) \tag{6.18}$$

where, $I_{s1}(t)$is the sediment input to the first reservoir (kN/h), $Q_{s1}(t)$ is the sediment discharge (kN/h), $S_{s1}(t)$ is the sediment storage within the reservoir (kN), and K_s is sediment storage coefficient (h). If A_w is the watershed area (km^2), and Y is the mobilized sediment per storm (kN/km^2), then the total amount of mobilized sediment $(Y_T) = A_w Y$ (kN). If it occurs instantaneously and is one unit (i.e.$I_{s1}(t) = 0$), the coupling of Eq. (6.17) and Eq. (6.18) it is mathematically expressed as

$$Q_{s1}(t) = (1/K_s)\exp(-t/K_s) \tag{6.19}$$

Eq. (6.19) indicates that the rate of sediment output from the first reservoir, and analytically from the $n_s th$ reservoir, the resultant output is given as

$$Q_{sn_s}(t) = \frac{1}{K_s \Gamma(n_s)} (t/K_s)^{n_s - 1} \exp(-t/K_s) \ (6.20) \tag{6.20}$$

where, Γ() is the Gamma function. For the condition, at $t = t_{ps}$, the time to peak sediment flow rate; $dQ_{s_{ns}}(t)/dt = 0$. Therefore,

$$K_s = t_{ps}/(n_s - 1) \tag{6.21}$$

Coupling of Eqs. (6.20) and (6.21) its can be analytically expressed as

$$Q_{sn_s}(t) = (n_s - 1)^{n_s}/t_{ps}\Gamma(n_s) \left[\left(\frac{t}{t_{ps}} \right) \exp\left(-\frac{t}{t_{ps}} \right) \right]^{n_s - 1} \tag{6.22}$$

Eq. (6.22) shows that the IUSG ordinates at time t in units of h^{-1} (Singh et al. 2008)

From experience with infiltration tests (Mein and Larson, 1971), $f_0 = i_0$, where i_0 is the uniform rainfall intensity, at time t = 0, the relationship between initial infiltration rate (LT^{-1}), uniform rainfall intensity (i_0), Horton parameter (k) and potential maximum retention (S) can mathematically be expressed as:

$$f_0 = i_0 = ks \tag{6.23}$$

We know that the rainfall is directly proportional to uniform rainfall intensity and time t, it is mathematically expressed as:

$$P = i_0 t \tag{6.24}$$

Which is a valid and reasonable assumption of usually derived infiltration rates from field/ laboratory tests (Mishra and Singh, 2004). Substituting the value of i_0 into Eq. (6.24) yield

$$P = kst \tag{6.25}$$

6.3.2 Power Law

Novotny and Olem (1994) related the runoff coefficient (C) with sediment delivery ratio DR in the power form as below (Singh et al., 2008):

$$DR = \alpha C^{\beta} \tag{6.26}$$

where, α and β are the coefficient and exponent of the power relationship respectively, and DR, is a dimensionless ratio of the sediment yield (Y) to the potential maximum erosion (A):

$$DR = \frac{Y}{A} \tag{6.27}$$

The runoff coefficient is defined as the ratio of runoff to rainfall, it is mathematically expressed as:

$$C = \frac{Q}{P} \tag{6.28}$$

A substitution of the expression of Eq. (6.27) and Eq. (6.28) into Eq. (6.26) yields

$$Y = \alpha A \left(\frac{Q}{P}\right)^{\beta} \tag{6.29}$$

Now, the three sub-models, i.e., SMA-based SCS-CN model (Eq. 6.16), Nash IUSG model (Eq. 6.22) and Power law (Eq. 6.29) will be used to develop proposed sediment graph models for estimation of time distributed sediment yield during a storm event as follows.

6.3.3 Formulation of SMA Inspired Sediment Graph Models (SMA-SGMs)

Case-I: Substituting initial soil moisture (V_0) = 0 and initial abstraction (I_a) = 0 into Eq. (6.16) yields

$$\frac{Q}{P} = \left(\frac{P}{P + S}\right)^2 \tag{6.30}$$

Coupling Eqs. (6.29) and (6.30) yields, it is mathematically express for Y as

$$Y = \alpha A[(P/P + s)^2]^{\beta} \tag{6.31}$$

Substituting the value of P from Eq. (6.25) into Eq. (6.31) yield

$$Y = \alpha A[(kts/kts + s)^2]^{\beta} \qquad (6.32))$$

On simplification of Eq. (6.32) yields

$$Y = \alpha A[((kt)/(kt + 1))^2]^{\beta} \tag{6.33}$$

Eq. (6.33) compute the amount of mobilized sediment due to an individual storm event occurring equally over the watershed. Multiplication of Eq. (6.33) with the watershed area, Aw gives the expression for total mobilized sediment yield Y_T as:

$$Y_T = \alpha A A_w[((kt)/(kt + 1))^2]^{\beta} \tag{6.34}$$

Coupling Eqs. (6.22) and Eq. (6.34) results the expression for proposed SMA-sediment graph model (SMA-SGM$_1$) $Q_s(t)$ as:

$$Q_s(t) = \left[\alpha A A_w[[(kt)/(kt+1)]^2]^\beta (n_s-1)^{n_s} / t_{ps}\Gamma(n_s)\left[(t/t_{ps})\exp(-t/t_{ps})\right]^{n_{s-1}}\right] \tag{6.35}$$

Case-II Substituting initial soil moisture $(V_0) \neq 0$ and initial abstraction $I_a = 0$ into Eq. (6.16) yields, after simplification of Eq. (6.16) yields

$$Y = \alpha A[[V_0(P+S) + PS/(P+s)(S+V_0)]^2]^\beta \tag{6.36}$$

Substituting the value of P from Eq. (6.25) into Eq. (6.36) it derived sediment yield

$$Y = \alpha A[[V_0(kst+S) + ks^2t/(kst+s)(S+V_0)]^2]^\beta \tag{6.37}$$

On simplification of Eq. (6.37) yield

$$Y = \alpha A\left[\left[\frac{V_o}{S}(kst+S) + ks^2/(kst+S)(1+\frac{V_0}{S})\right]^2\right]^\beta \tag{6.38}$$

For a given watershed and storm event, the ratio (θ) for V_0 and S is constant and it varies from 0 to 1 (Michel et al., 2005). Hence the substitution of θ (V_0/S) into Eq. (6.38) for computation of sediment yield it is expressed as:

$$Y = \alpha A[[\theta(1+kt) + kst/(1+kt)(1+\theta)]^2]^\beta \tag{6.39}$$

Multiplication of watershed area Aw in Eq. (6.39), Y_T can be an analytically expressed as

$$Y_T = \alpha A A_W\,[[\theta(1+kt) + kst/(1+kt)(1+\theta)]^2]^\beta \tag{6.40}$$

Coupling Eqs. (6.22) and (6.40), it time distributed total sediment outflow is expressed as

$$Q_S(t) = \left[\begin{matrix}\alpha A A_W\,[[\theta(1+kt) + kst/(1+Kt)(1+\theta)]^2]^\beta (n_s-1)^{n_s} \\ / t_{ps}\Gamma(n_s)\left[(t/t_{ps})\exp(-t/t_{ps})\right]^{n_s-1}\end{matrix}\right] \tag{6.41}$$

Eq. (6.41) is the proposed SMA-sediment graph model (SMA-SGM$_2$)

Case-III Substituting initial soil moisture $(V_0) = 0$and $(I_a) \neq 0$ into Eq. (16) yields

$$Y = \alpha A[[PS/(P+S)(S+I_a)]^2]^\beta \tag{6.42}$$

Substituting the value of P from Eq. (6.25) and the value of I_a from Eq. (6.3) into Eq. (6.42) yield

$$Y = \alpha A[[ks^2t/(kst + s)(S + \lambda S)]^2]^\beta \tag{6.43}$$

After simplification of Eq. (6.43) yield

$$Y = \alpha A[[kst/(1 + kt)(1 + \lambda)]^2]^\beta \tag{6.44}$$

Eq. (6.44) computes the amount of mobilized sediment. Now multiplication of Eq. (6.44) with watershed area A_W yields, it is an analytically expressed for total mobilized sediment Y_T as:

$$Y_T = \alpha A A_w[[kst/(1 + kt)(1 + \lambda)]^2]^\beta \tag{6.45}$$

Coupling of Eq. (6.22) and Eq. (6.45) yields it derived the proposed sediment graph model (SMA-SGM$_3$) $Q_S(t)$ as:

$$Q_s(t) = \Big[\alpha A A_w[((kst)/(1 + kt)(1 + \lambda))^2]^\beta (n_s - 1)^{n_s} / t_{ps}\Gamma(n_s)\big[(t/t_{ps})\exp(-t/t_{ps})\big]^{n_s-1}\Big] \tag{6.46}$$

Eq. (6.46) is the proposed SMA-sediment graph model (SMA-SGM$_3$)

Case-IV Substituting initial soil moisture $(V_0) \neq 0$ and initial abstration $(I_a) \neq 0$ into Eq. (6.16) yields

$$Y = \alpha A\big[[V_0(P + S) + PS/(P + S)(S + V_0 + I_a)]^2\big]^\beta \tag{6.47}$$

Substituting the value of I_a and P from Eqs. (6.25) and (6.3) respectively into Eq. (6.47) yield

$$Y = \alpha A\Big[[V_0(kst + S) + ks^2t/(kst + S)(S + V_0 + \lambda S)]^2\Big]^\beta \tag{6.48}$$

After simplification of Eq. (48) yields

$$Y = \alpha A\big[[\theta(1 + kt) + kst/(1 + kt)(1 + \theta + \lambda)]^2\big]^\beta \tag{6.49}$$

Hence the total amount of mobilized sediment Y_T can be an analytically expressed as

$$Y_T = \alpha A A_w\big[[\theta(1 + kt) + (kst)/(1 + kt)(1 + \theta + \lambda)]^2\big]^\beta \tag{6.50}$$

Coupling of Eq. (6.22) and Eq. (6.50) yields

$$Q_S(t) = \begin{bmatrix} \alpha A A_W\,[[\theta(1+kt)+(kst)/(1+Kt)(1+\theta+\lambda)]^2]^\beta (n_s-1)^{n_s} \\ /t_{ps}\Gamma(n_s)\left[(t/t_{ps})\exp\,(-t/t_{ps})\right]^{n_s-1} \end{bmatrix} \quad (6.51)$$

Eq. (6.51) is the proposed SMA-sediment graph model (SMA-SGM_4)

6.4 MODEL APPLICATIONS

6.4.1 Study Areas

In this chapter three Indian watersheds were used such as Karso, Banha and Mansara watersheds and three USA watersheds was used such as W 6, W 7 and W 14 watersheds were used for calibration of the model and validation of the models as discussed in Chapter 3.

6.4.2 Model Formulations

The sediment graph models were formulated are based on soil moisture accounting (SMA) procedure. The analytical development of sediment graph model SMA-SGM_1 excludes $'I_a'$ and $'V_0'$, SMA-SGM_2 accounts only for$'$ I_a', SMA-SGM_3 does for $'V_0'$ and excludes $'I_a'$ and SMA-SGM_4 accounts for both $'I_a'$ and $'V_0'$. $PSGM_1$ (four parameters) is the simplest of all, SMA-SGM_2 andSMA-SGM_3, (six parameters), therefore SMA-SGM_4 (Seven parameters) the most complex based on the criterion number of parameters are involved in the model formulation. In this study, the potential maximum erosion A has also been taken as a parameter due to lack of their observation. The characteristics of the storm events of the proposed SMA-SGMs from six watersheds are given as in Table 6.1.

Table-6.1: Characteristics of the storm events from six watersheds

Name of watershed	Events	q_{ps} (kN/h/kN)	t_{ps} (hr)	β_s	Q_s (kN)	Q_{ps}(kN/h)
Karso	August 17, 1991	0.22	6.0	1.36	2868.53	650.81
	July 28, 1991	0.34	2.0	0.67	3180.34	1076.44
	June 14, 1994	0.62	2.0	1.24	1218.74	761.57
	August 30, 1993	0.30	4.0	1.20	9815.50	2970.88
Banha	August 31, 1993	0.62	2.0	1.24	1229.8	759.05
	July 17, 1996	0.72	1.0	0.72	1509.87	1093.42
	June 14, 1994	0.39	2.0	0.78	3053.44	1191.44

	August 20, 1996	0.19	3.0	0.57	1256.03	244.00
	August 30, 1996	0.40	1.0	0.80	2882.62	1159.63
Mansara	August 10, 1994	0.30	3.0	0.90	182.65	54.96
	July 19, 1994	0.40	3.0	1.22	154.78	63.11
	July 25, 1994	0.52	2.0	1.03	183.58	95.46
	August 16, 1994	0.31	2.0	0.63	368.64	117.34
W 6	January 2, 1982	0.84	1.0	0.84	183.82	155.78
	March 15, 1982	0.51	1.0	0.51	20.26	10.45
W 7	May 25, 1982	0.74	1.0	0.74	517.07	383.45
	June 3, 1982	0.76	1.0	0.76	612.86	470.09
W 14	June 16, 1982	0.42	1.0	0.42	4.01	1.72
	Sep 12, 1982	0.58	2.0	1.17	73.4	43.03

6.5 RESULTS AND DISCUSSION

The large set of 19 storm events of sediment yield data are applied over proposed SMA-SGMs, ten events data set were used for model calibration and nine events data set were used for model validation.

6.5.1 Calibration of the Model

6.5.1.1 Parameter Estimation

The shape parameter (n_s) of Nash based IUSG sub-model was estimated by the relationship given by Bhunya et al. (2003) as

$n_s = 5.53\beta_s^{1.75} + 1.04$ for 0.01 <β_s< 0.35

$$n_s = 6.29\beta_s^{1.998} + 1.157 \text{ for } \beta_s \geq 0.35 \quad (6.52)$$

where, $'\beta_s'$ is an non-dimensional parameter defined as the multiplication of peak sediment flow rate (q_{ps}) (kN/h/kN) and time to peak sediment flow rate (t_{ps}) [h]. $'\beta_s'$ is also defined as shape factor (Singh 2000; Singh et al., 2008 and Bhunya et al., 2003). The model parameters, optimized using the non-linear Marquardt algorithm (Marquardat 1963) of the least square procedure, computed parameters of proposed SMA-SGMs are presented in Table 6.2. In the SMA-SGM$_1$ the proposed SMA-sediment graph model (SMA-SGM_1) has 4 parameters, viz., $'\alpha'$, $'\beta,'$ k and $'n_s'$, in model second the proposed SMA-sediment graph model (SMA-SGM_2) has 6 parameters, viz., $'\alpha'$, $'\beta'$, $'k, ''n_s'$, $'\theta'$ and 'S', and therefore in the model third the proposed SMA-sediment graph model (SMA-SGM_3) has 6 parameters, viz., $'\alpha'$, $'\beta'$, $'k', 'n_s'$, $'\lambda'$ and 'S' and similarly in model fourth the proposed SMA-sediment graph model (SMA-SGM_4) has 7 parameters $'\alpha'$, $'\beta'$, $'k', 'n_s'$, $'\lambda', '\theta'$ and 'S' respectively.

Table-6.2: Optimized parameters of calibration of the proposed SMA-SGMs from six watersheds

Event	Model	Optimized parameters of the proposed models						
		α	β	k	θ	λ	S	A (kN/km^2)
Karso								
17.08.1991	SMA-SGM_1	0.400	0.317	0.1E-07	-	-	-	121.337
	SMA-SGM_2	0.009	1.00	0.5E-05	0.039	-	73.628	85.400
	SMA-SGM_3	0.300	0.918	0.079	-	0.23	75.199	10000.0
	SMA-SGM_4	0.003	0.890	0.2E-04	0.070	0.04	60.400	50.299
28.07.1991	SMA-SGM_1	0.684	0.303	0.070	-	-	-	188.124
	SMA-SGM_2	0.301	0.261	0.043	0.039	-	34.117	86.282
	SMA-SGM_3	0.003	0.986	0.079	-	0.03	60.00	1134.679
	SMA-SGM_4	0.815	0.500	0.002	0.070	0.04	34.258	185.662
Banha								
31.08.1993	SMA-SGM_1	0.400	0.300	0.4E-04	-	-	-	110.00
	SMA-SGM_2	0.002	0.016	0.079	0.029	-	65.099	68.400
	SMA-SGM_3	0.001	0.029	0.079	-	0.009	20.310	158.085
	SMA-SGM_4	0.001	0.069	0.079	0.004	0.02	56.778	121.684
17.07.1996	SMA-SGM_1	1.00	0.300	0.070	-	-	-	688.219
	SMA-SGM_2	0.077	0.003	0.033	0.050	-	4.349	2328.235
	SMA-SGM_3	0.171	0.029	0.041	-	0.009	10.614	1086.496
	SMA-SGM_4	0.054	0.004	0.079	0.004	0.02	85.099	3251.242
14.06.1994	SMA-SGM_1	1.00	0.512	0.070	-	-	-	590.273
	SMA-SGM_2	0.020	1.00	0.052	0.039	-	65.099	618.301
	SMA-SGM_3	0.042	0.631	0.079	-	0.009	30.651	265.149
	SMA-SGM_4	0.009	0.533	0.079	0.004	0.03	84.821	554.035
Mansara								

Event	Model	Optimized parameters of the proposed models						
		α	**β**	**k**	**θ**	**λ**	**S**	**A (kN/km²)**
10.08.1994	SMA-SGM$_1$	0.511	0.300	0.7E-03	-	-	-	140.663
	SMA-SGM$_2$	0.279	0.317	0.2E-04	0.041	-	58.633	522.129
	SMA-SGM$_3$	0.342	0.400	0.1E-03	-	0.050	37.832	117.918
	SMA-SGM$_4$	0.332	0.818	0.2E-03	0.050	0.03	2.244	824.331
19.07.1994	SMA-SGM$_1$	0.400	0.302	0.1E-05	-	-	-	110.00
	SMA-SGM$_2$	0.051	0.754	0.00	0.049	-	11.943	50.717
	SMA-SGM$_3$	0.100	0.400	0.5E-05	-	0.050	16.172	184.314
	SMA-SGM$_4$	0.052	0.994	0.000	0.050	0.03	22.699	217.779
W 6								
02.01.1982	SMA-SGM$_1$	1.00	0.009	0.059	-	-	-	90.199
	SMA-SGM$_2$	0.044	0.267	0.079	0.050	-	68.122	155.542
	SMA-SGM$_3$	0.155	0.039	0.004	-	0.020	54.077	3312.374
	SMA-SGM$_4$	0.021	0.050	0.079	0.050	0.03	60.200	7164.00
W 7								
25.05.1982	SMA-SGM$_1$	1.00	0.300	0.070	-	-	-	246.221
	SMA-SGM$_2$	0.399	0.122	0.079	0.050	-	48.299	1068.076
	SMA-SGM$_3$	0.586	0.039	0.009	-	0.050	84.600	1247.307
	SMA-SGM$_4$	0.323	0.500	0.800	0.059	0.30	26.316	151.935
W 14								
16.06.1982	SMA-SGM$_1$	0.645	0.200	0.8E-04	-	-	-	175.321
	SMA-SGM$_2$	0.263	0.145	0.079	0.050	-	13.492	112.159
	SMA-SGM$_3$	0.242	0.200	0.2E-05	-	0.039	28.086	535.146
	SMA-SGM$_4$	0.423	0.969	0.3E-04	0.070	0.03	18.348	1171.517

6.5.2 Performance Evaluation Criteria

The performance of the analytical development of proposed SMA-sediment graph models (SMA-SGMs) and Bhunya et al. (2010) model were evaluated using two statistical indices viz NSE and RE, and it can be analytically derived as one by one.

$$\text{NSE} = \left(1 - \frac{\sum_{j=1}^{N}(Q_S - Q_{S(C)})}{\sum_{j=1}^{N}(Q_S - Q_{S(\text{mean})})}\right) \times 100 \quad (6.53)$$

where, NSE is the Nash Sutcliffe Efficiency, N is the number of an event, j is an integer varying from 1 to ‘N’, $'Q_S'$ and $'Q_{S(C)}'$ are the observed and computed total sediment outflow, respectively, $Q_{S(mean)})$ is the mean of observed sediment outflow rate,

$$RE_{(QS)} = \frac{Q_{S(C)} - Q_S}{Q_{S(C)}} \times 100 \tag{6.54}$$

$$RE_{(QPS)} = \frac{Q_{PS(C)} - Q_{PS}}{Q_{PS(C)}} \times 100 \tag{6.55}$$

$$RE(t_{ps}) = \frac{t_{PS\,(C)} - t_{PS}}{t_{PS(C)}} \times 100 \tag{6.56}$$

where Q_{PS} and $Q_{PS(C)}$ are observed and computed peak sediment flow rate respectively; t_{PS} and $t_{PS\,(C)}$ *a*re observed and computed time to peak sediment flow rate respectively; and $RE(t_{ps})$, $RE_{(QS)}$, and $RE_{(QPS)}$ are relative error in time to peak sediment flow rate, relative error in peak sediment flow rate and relative error in total sediment outflow rate respectively.

The NSE from Eq. (6.53) was used for computation of model accuracy from observed sediment flow rate and computed sediment flow rate. For computation of the RE Eqs. (6.54) to (6.56) were used from observed peak sediment out flow rate and computed peak sediment out flow rate, and time to peak sediment flow rate and computed peak sediment out flow rate respectively. Calibration of the model in SMA-SGM$_1$, the resulting efficiency of NSE it varies from 65.67 to 99.56 % for SMA-SGM$_1$, therefore in SMA-SGM$_2$, the resulting efficiency of NSE it varies from 73.19 to 99.81 % for SMA-SGM$_2$, hence in SMA-SGM$_3$, the NSE it varies from 57.73 % to 99.75 % for SMA-SGM$_3$ and similarly SMA-SGM$_4$ the NSE it varies from 66.39 to 99.86 % for SMA-SGM$_4$ respectively. If NSE is higher it indicates the good performance of the model and vice versa. Therefore RE of total sediment outflow it varies from -6.30 to 52.89 %, for SMA-SGM$_1$, from0.09 to 27.19 % for SMA-SGM$_2$, from -10.97 to 44.37 % for SMA-SGM$_3$ and from -8.81 to 36.61 % for SMA-SGM$_4$ respectively. The RE of peak sediment outflow rate it varies from -0.29 to 55.79 % for SMA-SGM$_1$, from -0.57 to 32.19 % for SMA-SGM$_2$, from 1.72 to 47.35 % for SMA-SGM$_3$ and from -0.35 to 47.90 % for SMA-SGM$_4$. Hence RE of time to peak sediment outflow it perhaps varies from -33.33 to 0.00 % for SMA-SGM_1, from -33.33 to 0.00 % for SMA-GM_2, from -50.00 to 0.00 % for SMA-SGM_3 and from -50.00 to 0.00 % for SMA-SGM_4 respectively as shown in Table 6.3. The relative error of the proposed model is similar to Bhunya et al. (2010), Tyagi et al. (2008) and Singh et al. (2008) models.

Table-6.3: Characteristics of observed and computed sediment graph of proposed SMA-SGMs for calibration events from six watersheds

Name of Watershed	Event	Model	Total sediment out flow (kN)			Peak sediment out flow rate (kN/h)			Time to peak sediment outflow (h)			NSE (%)
			Q_S	Q_S (c)	RE (%)	Q_{ps}	Q_{ps}(c)	RE (%)	t_{ps}	t_{ps} (c)	RE (%)	
Karso	17.8.1991 (C)	SMA-SGM$_1$	2868.53	2174.87	24.18	650.81	472.68	27.37	6.0	6.0	0.00	83.44
		SMA-SGM$_2$	2868.53	2295.09	19.99	650.81	515.51	20.79	6.0	6.0	0.00	80.20
		SMA-SGM$_3$	2868.53	1595.76	44.37	650.81	342.62	47.35	6.0	7.0	-16.67	75.47
		SMA-SGM$_4$	2868.53	2239.72	21.92	650.81	501.15	23.00	6.0	6.0	0.00	80.95
	28.7.1991 (C)	SMA-SGM$_1$	3180.34	2005.77	36.93	1076.44	607.29	43.58	2.0	2.0	0.00	70.37
		SMA-SGM$_2$	3180.34	2384.69	25.02	1076.44	729.91	32.19	2.0	2.0	0.00	73.19
		SMA-SGM$_3$	3180.34	2163.59	31.97	1076.44	618.08	42.58	2.0	3.0	-50.00	57.73
		SMA-SGM$_4$	3180.34	2016.01	36.61	1076.44	560.79	47.90	2.0	3.0	-50.00	68.39
Banha	31.8.1993 (C)	SMA-SGM$_1$	1229.08	1121.25	8.77	759.05	663.10	12.64	2.0	2.0	0.00	85.26
		SMA-SGM$_2$	1229.08	1076.94	12.38	759.05	670.86	11.62	2.0	2.0	0.00	88.01
		SMA-SGM$_3$	1229.08	1182.80	3.77	759.05	735.11	3.15	2.0	2.0	0.00	84.75
		SMA-SGM$_4$	1229.08	1094.80	10.93	759.05	677.69	10.72	2.0	2.0	0.00	88.57
	17.7.1996 (C)	SMA-SGM$_1$	1509.87	1289.07	14.62	1093.42	808.27	26.08	1.0	1.0	0.00	92.42
		SMA-SGM$_2$	1509.87	1508.52	0.09	1093.42	1080.40	1.19	1.0	1.0	0.00	99.81

Name of Watershed	Event	Model	Total sediment out flow (kN)			Peak sediment out flow rate (kN/h)			Time to peak sediment outflow (h)			NSE (%)
			Q_S	Q_S (c)	RE (%)	Q_{ps}	Q_{ps}(c)	RE (%)	t_{ps}	t_{ps} (c)	RE (%)	
		SMA-SGM$_3$	1509.87	1505.03	0.32	1093.42	1065.38	2.56	1.0	1.0	0.00	87.24
		SMA-SGM$_4$	1509.87	1509.03	0.06	1093.42	1079.20	1.30	1.0	1.0	0.00	99.86
	14.6.1994 (C)	SMA-SGM$_1$	1191.44	3245.77	-6.30	1191.44	1038.40	12.84	2.0	2.0	0.00	95.53
		SMA-SGM$_2$	1191.44	2997.61	1.83	1191.44	1015.58	14.76	2.0	2.0	0.00	93.98
		SMA-SGM$_3$	1191.44	3388.45	-10.97	1191.44	1106.78	7.11	2.0	3.0	-50.00	95.79
		SMA-SGM$_4$	1191.44	3322.37	-8.81	1191.44	1082.22	9.17	2.0	2.0	0.00	95.76
Mansara	10.8.1994 (C)	SMA-SGM$_1$	182.65	162.18	11.21	54.96	44.83	18.43	3.0	3.0	0.00	91.15
		SMA-SGM$_2$	182.65	173.39	5.07	54.96	51.65	6.02	3.0	3.0	0.00	96.08
		SMA-SGM$_3$	182.65	149.28	18.27	54.96	39.59	27.97	3.0	3.0	0.00	85.47
		SMA-SGM$_4$	182.65	173.11	5.22	54.96	51.54	6.22	3.0	3.0	0.00	96.08
	19.7.1994 (C)	SMA-SGM$_1$	154.78	150.02	3.08	63.11	58.16	7.84	3.0	3.0	0.00	78.48
		SMA-SGM$_2$	154.78	154.07	0.46	63.11	62.72	0.62	3.0	3.0	0.00	89.77
		SMA-SGM$_3$	154.78	145.09	6.26	63.11	54.96	12.91	3.0	3.0	0.00	74.13
		SMA-SGM$_4$	154.78	155.56	-0.50	63.11	63.33	-0.35	3.0	3.0	0.00	89.74
W 6	2.1.1982 (C)	SMA-SGM$_1$	183.82	86.59	52.89	155.78	68.87	55.79	1.0	1.0	0.00	65.67
		SMA-SGM$_2$	183.82	176.81	3.81	155.78	130.22	16.41	1.0	1.0	0.00	94.57

Name of Watershed	Event	Model	Total sediment out flow (kN)			Peak sediment out flow rate (kN/h)			Time to peak sediment outflow (h)			NSE (%)
			Q_S	Q_S (c)	RE (%)	Q_{ps}	Q_{ps}(c)	RE (%)	t_{ps}	t_{ps} (c)	RE (%)	
		SMA-SGM$_3$	183.82	181.40	1.32	155.78	148.82	4.47	1.0	1.0	0.00	99.27
		SMA-SGM$_4$	183.82	182.98	0.46	155.78	144.00	7.56	1.0	1.0	0.00	98.08
W 7	25.5.1982 (C)	SMA-SGM$_1$	517.07	461.53	10.74	383.45	296.26	22.74	1.0	1.0	0.00	93.76
		SMA-SGM$_2$	517.07	513.27	0.73	383.45	357.16	6.86	1.0	1.0	0.00	99.21
		SMA-SGM$_3$	517.07	513.85	0.62	383.45	368.49	3.90	1.0	1.0	0.00	99.75
		SMA-SGM$_4$	517.07	512.84	0.82	383.45	336.66	12.20	1.0	1.0	0.00	97.39
W 14	16.6.1982 (C)	SMA-SGM$_1$	4.01	3.65	8.98	1.72	1.36	20.93	1.0	1.0	0.00	78.53
		SMA-SGM$_2$	4.01	3.81	4.99	1.72	1.55	9.88	1.0	1.0	0.00	80.29
		SMA-SGM$_3$	4.01	3.83	4.49	1.72	1.43	16.86	1.0	1.0	0.00	78.13
		SMA-SGM$_4$	4.01	3.78	5.74	1.72	1.54	10.47	1.0	1.0	0.00	81.84

Note: C indicate the calibration of the model

If RE is lower, it shows the good agreement between observed sediment flow rate and computed sediment flow rate of the model and vice versa. The computed total sediment outflow (kN) it varying from 3.65 to 3245.77 kN, 3.81 to 2997.61 kN, 3.83 to 3388.45 kN, 3.78 to 3322.37 kN, for SMA-SGM$_1$ to SMA-SGM$_4$, peak sediment outflow rate (kN/h) it varying from 1.36 to 1038.4 kN/h, 1.55 to 1080.4 kN/h, 1.43 to 1106.78 kN/h, 1.54 to 1082.22 kN/h for SMA-SGM$_1$ to SMA-SGM$_4$, time to peak sediment outflow (h) it varying from 1.00 to 6.00 h from, 1.00 to 6.00 h, 1.00 to 7.00 h, 1.00 to 6.00 h for SMA-SGM$_1$ to SMA-SGM$_4$ models respectively, are presented in Table 6.3.

It can be observed that from Table 6.3 and Figs. 6.1 to 6.10 for calibration of the proposed SMA-SGMs the parameter of potential maximum retention (S) is highly impact for computation of sediment graph. The proposed SMA-SGM$_1$ excludes initial abstraction (I_a) and initial soil moisture (V_0) it produced lowest sediment graph as compared to SMA-SGM$_2$ model. The initial soil moisture (V_0) is incorporated in SMA-SGM$_2$, its impact was significant on computation of sediment graph as compared to other parameters. In mathematical formulation of sediment graph models, in SMA-SGM$_3$ incorporation of initial abstraction 'I_a', has the lowest impact for computation of sediment graph as compared to V_0 parameter. These hydrological phenomena of initial soil moisture and initial abstraction are incorporated for mathematical formulation of SMA-SGM$_4$. This model where used for computation of sediment graph, it computes the lower sediment graph as compared to SMA-SGM$_2$ model. It can be observed from the computed results of the calibration of the model (Table 6.3), the model overestimated the total sediment outflow for Banha watershed and underestimated for rest of the watersheds. These graphs were as exhibited that proposed SMA-SGM is in good agreement between observed sediment flow rate and computed sediment flow rate from each watershed as shown in Figs 6.1 to 6.10.

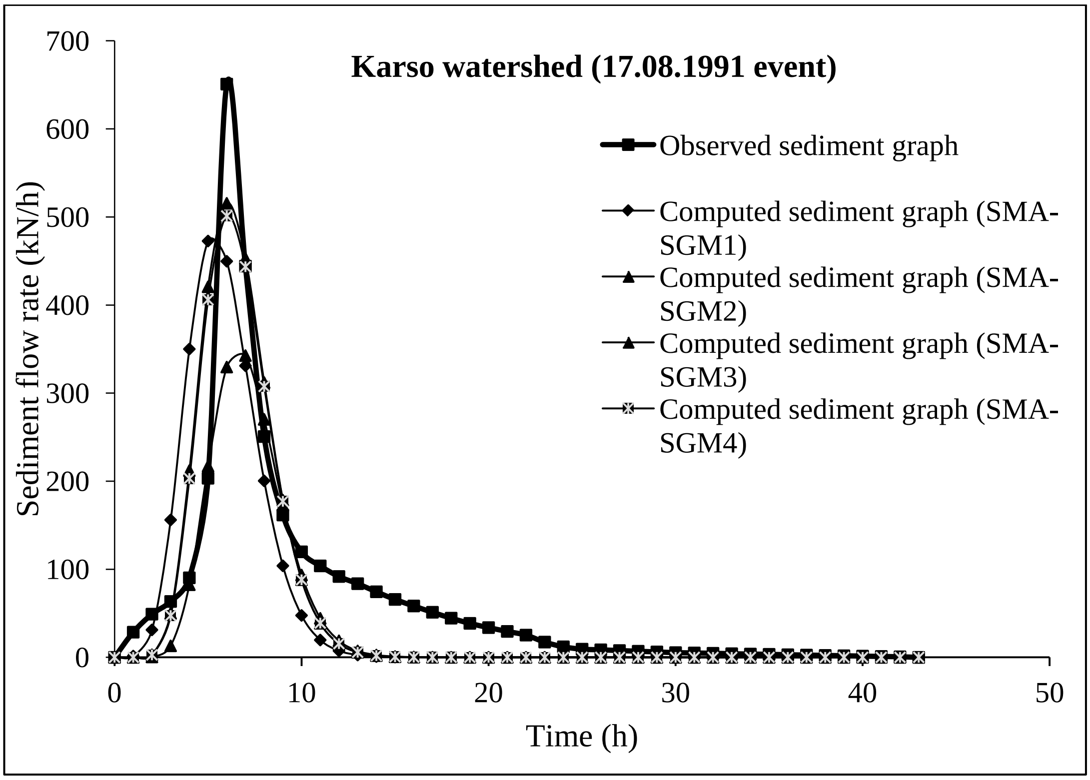


Figure-6.1: Comparison of observed and computed sediment graphs for calibration of the models for Karso watershed (17.08.1991 event)

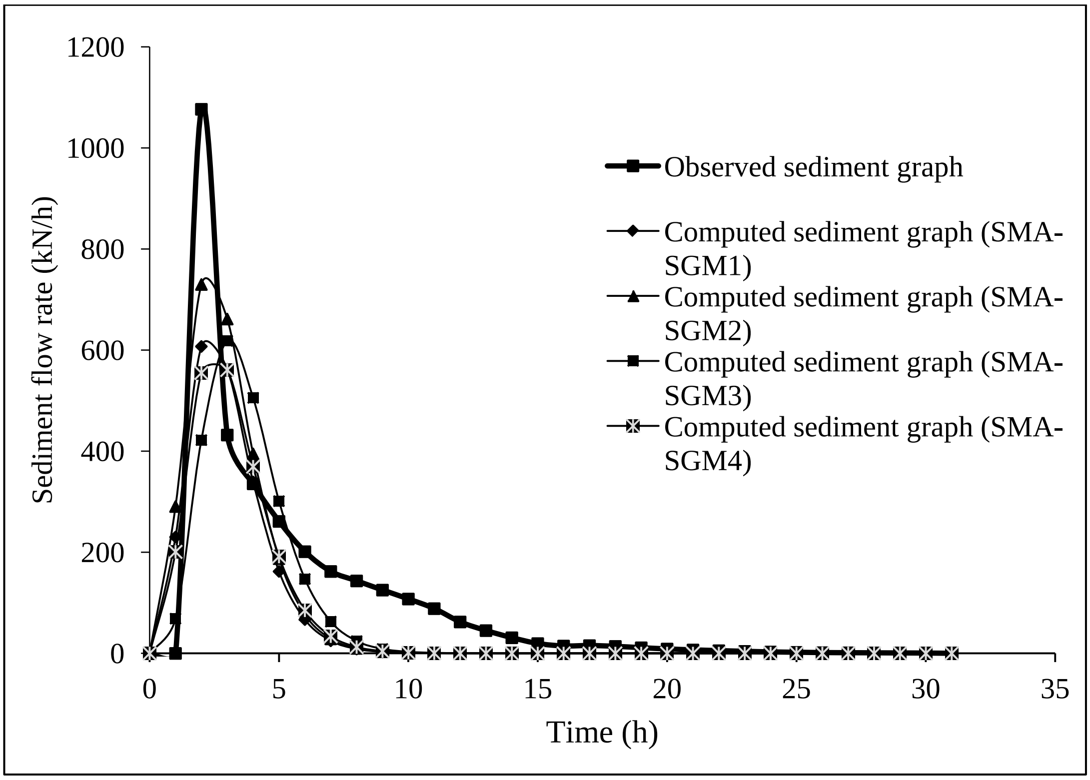


Figure-6.2: Comparison of observed and computed sediment graphs for calibration of the models for Karso watershed (28.07.1991 event)

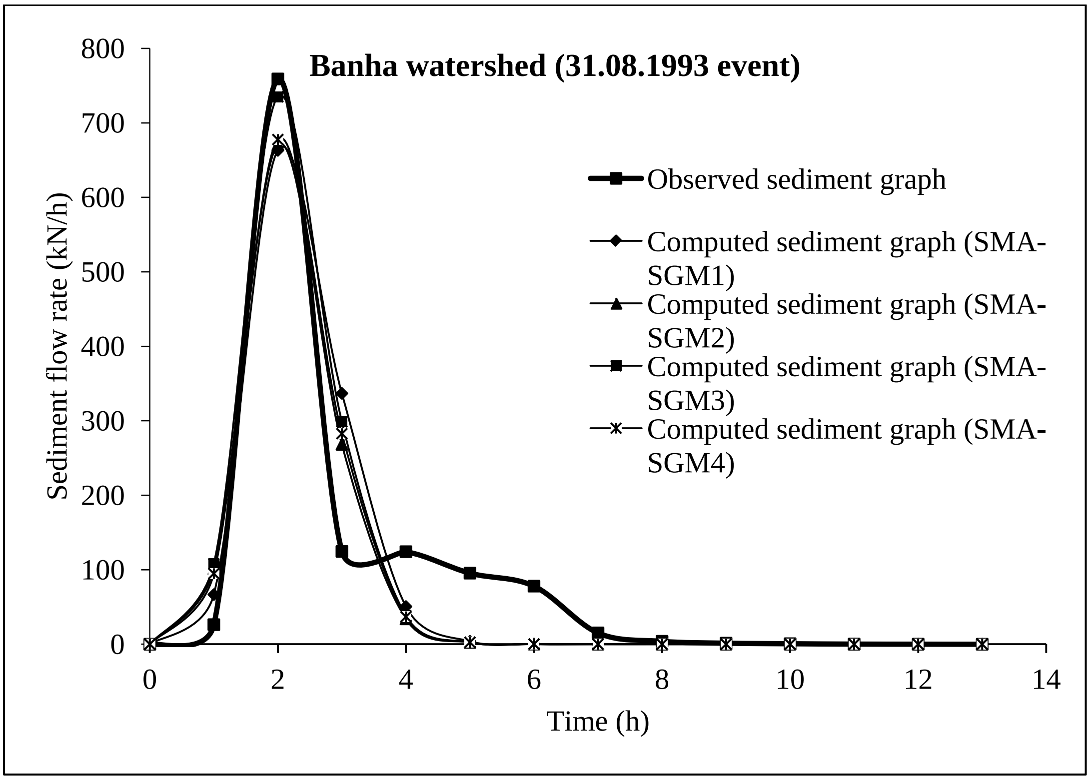


Figure-6.3: Comparison of observed and computed sediment graphs for calibration of the models for Banha watershed (31.08.1993 event)

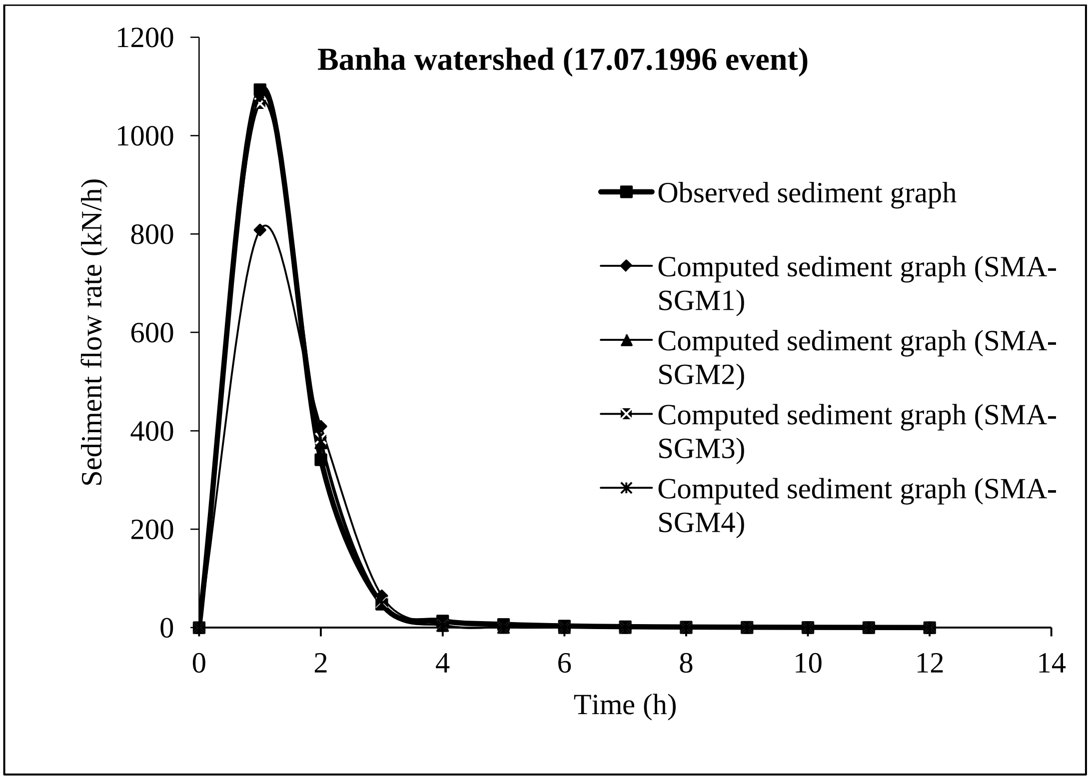


Figure-6.4: Comparison of observed and computed sediment graphs for calibration of the models for Banha watershed (17.07.1996 event)

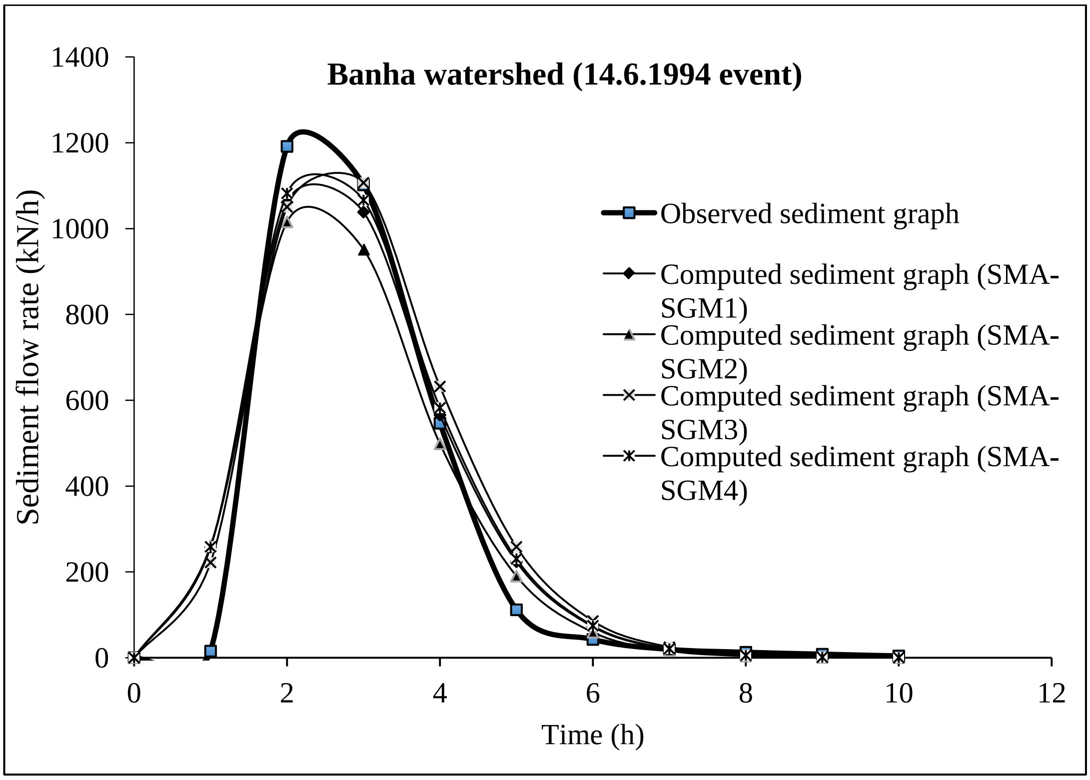


Figure-6.5: Comparison of observed and computed sediment graphs for calibrations of the models for Banha watershed (14.06.1994 event)

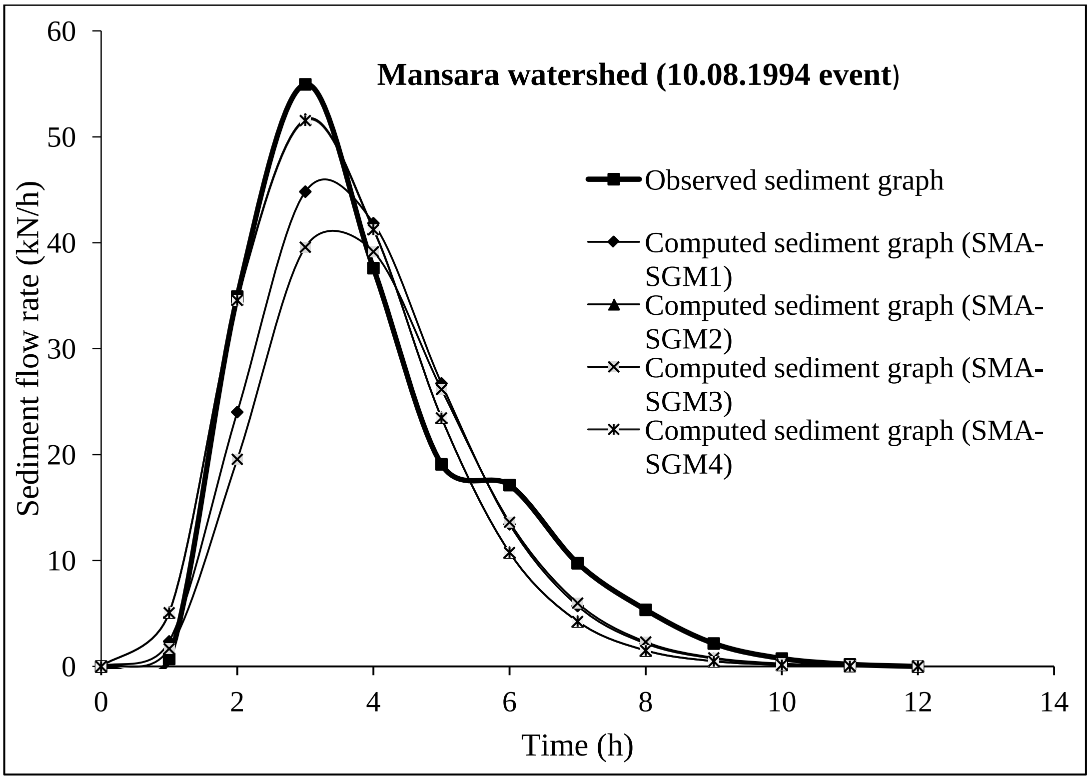


Figure-6.6: Comparison of observed and computed sediment graphs for calibration of the models for Mansara watershed (10.08.1994 event)

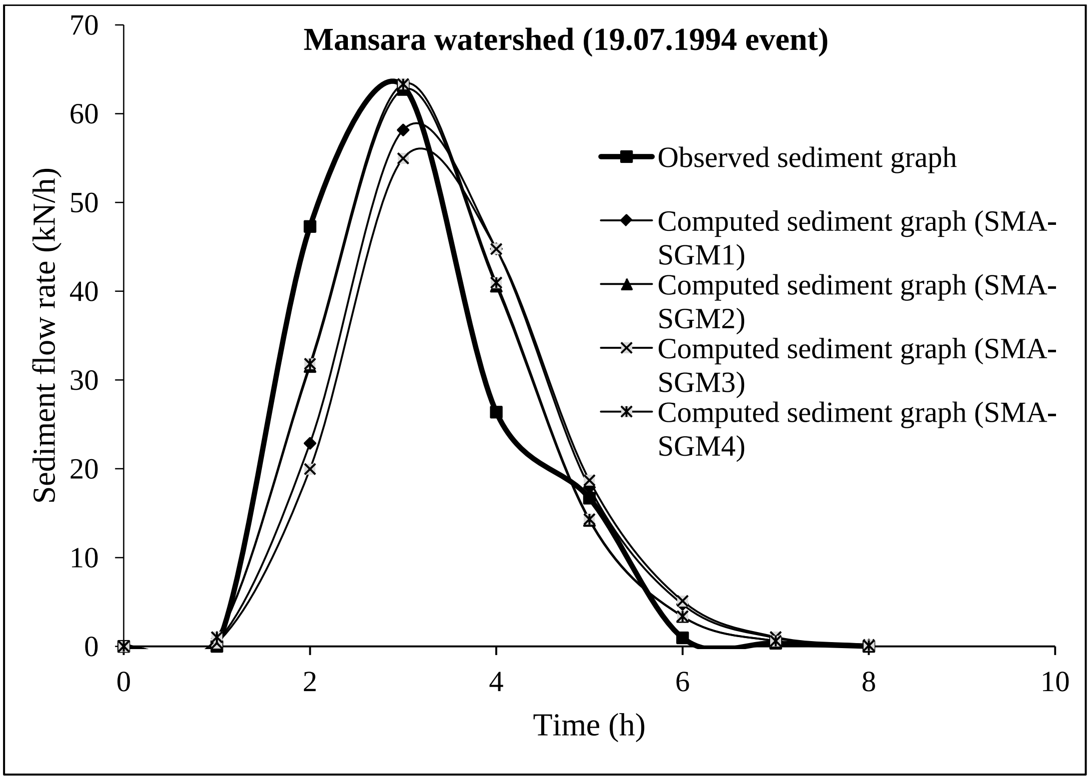


Figure-6.7: Comparison of observed and computed sediment graphs for calibration of the models for Mansara watershed (19.07.1994 event)

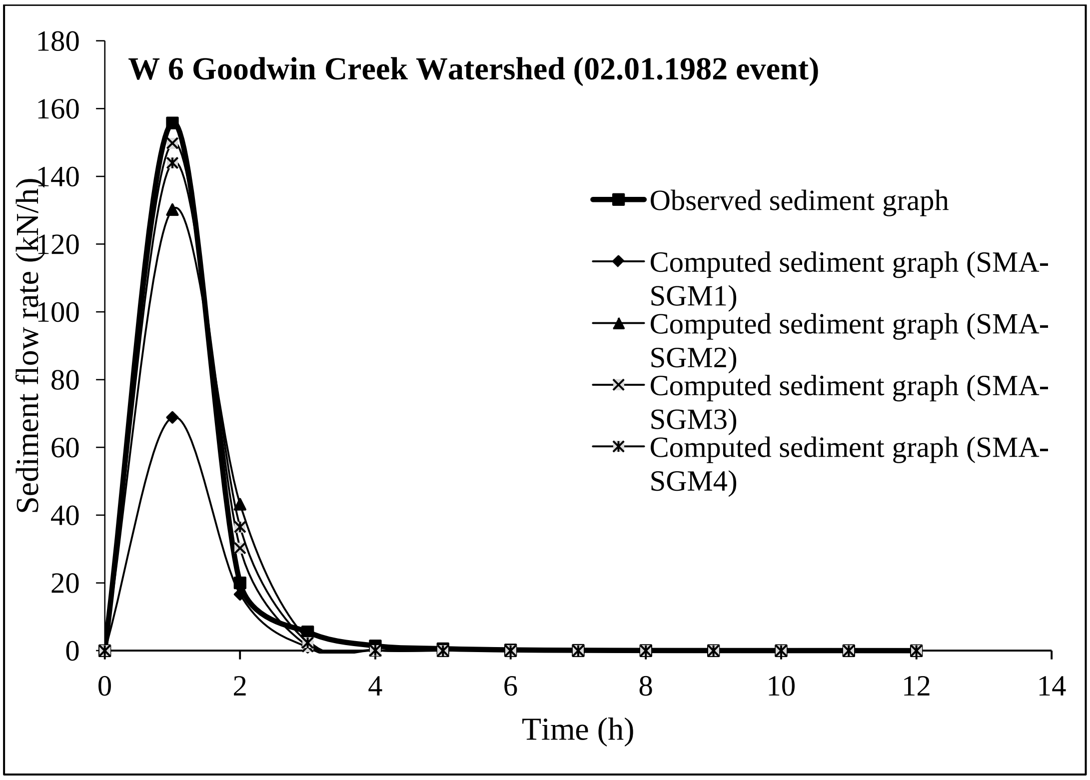


Figure-6.8: Comparison of observed and computed sediment graphs for calibration of the models for W 6 Goodwin Creek watershed (02.01.1982 event)

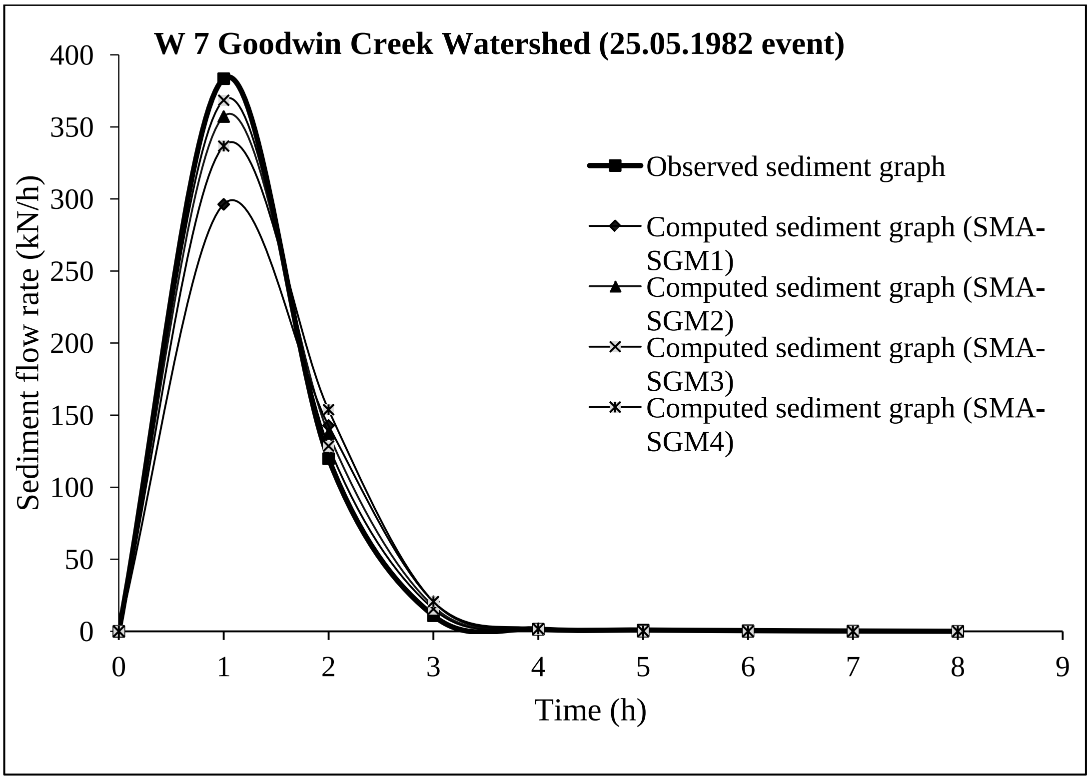


Figure-6.9: Comparison of observed and computed sediment graphs for calibration of the models for W 7 Goodwin Creek watershed (25.05.1982 event)

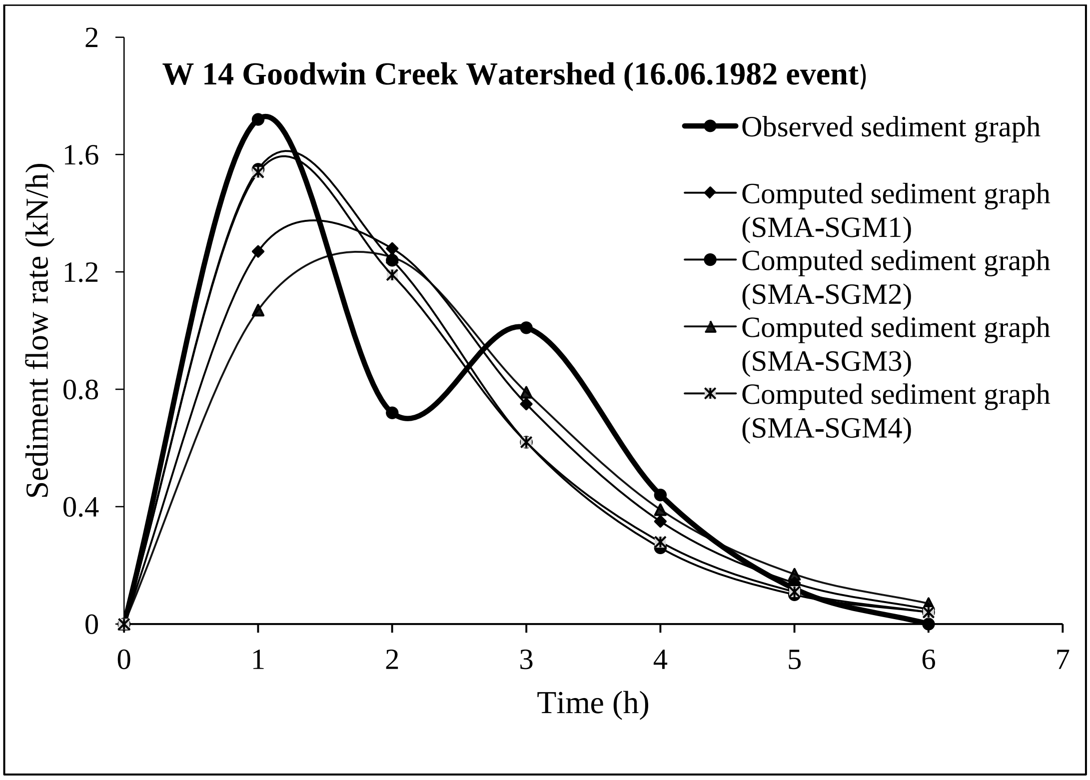


Figure-6.10: Comparison of observed and computed sediment graphs for calibration of the models for W 14 Goodwin Creek watershed (16.06.1982 event)

6.5.3 Validation of the Model

For calibration of the model and validation of the models the parameters α, β k, n_s, θ, λ and S of the proposed SMA-SGMs and Bhunya et al. (2010) model which depends on landuse/ landcover, soil characteristics, individual storm event and climatic condition. The computed parameter α varies from 0.377 to 0.917, from 0.006 to 0.823, from 0.003 to 0.849 and from 0.005 to 0.98 for SMA-SGM_1 to SMA-SGM_4, respectively. Accordingly, β varies from 0.019 to 0.995, from 0.013 to 0.989, from 0.039 to 0.808 and from 0.05 to 0.724 for SMA-SGM_1 to SMA-SGM_4, step by step. Similarly k varies from 0.01E-04 to 0.07, from 0.00 to 0.079, from 4E-07 to 0.079 and from 0.00 to 0.80 for SMA-SGM_1 to SMA-SGM_4 respective models. Hence θ varies from 0.004 to 0.05 and from 0.004 to 0.070 for SMA-SGM_2 to SMA-SGM_4 each of the models. The computed parameters values are in good agreement with Mishra et al. (2006), Singh et al. (2008) and Bhunya et al. (2010) models. Therefore λ varies from 0.009 to 0.133 and from 0.03 to 0.3 for SMA-SGM_3 to SMA-SGM_4, respective models, these values are in close to SCS 1978. The optimized value of S varies from 10.001 to 75.4 mm, from 5.189 to 75.199 mm and from 11.942 to 85.099 mm (Mishra et al., 2006) SMA-SGM2 to SMA-SGM_4, respective models as shown in Table 6.4.

Table 6. 4 Optimized parameters of validation of the proposed SMA-SGMs from six watersheds

Event	Model	Optimized parameters of the proposed models						
		α	β	k	θ	λ	S	A (kN/km^2)
Karso								
14.06.1994	SMA-SGM_1	0.520	0.300	0.1E-05	-	-	-	143.050
	SMA-SGM_2	0.012	0.924	0.9E-05	0.039	-	75.400	2498.782
	SMA-SGM_3	0.849	0.654	0.079	-	0.133	75.199	4616.198
	SMA-SGM_4	0.020	0.500	0.7E-04	0.070	0.04	48.135	54.303
14.10.1993	SMA-SGM_1	0.400	0.995	0.070	-	-	-	110.00
	SMA-SGM_2	0.013	0.243	0.014	0.039	-	21.052	119.571

Event	Model	Optimized parameters of the proposed models						
		α	β	k	θ	λ	S	A (kN/km^2)
	SMA-SGM$_3$	0.003	0.808	0.079	-	0.03	10.955	1181.980
	SMA-SGM$_4$	0.320	0.724	0.8E-03	0.070	0.04	60.400	80.299
Banha								
20.08.1996	SMA-SGM$_1$	0.503	0.553	0.070	-	-	-	137.331
	SMA-SGM$_2$	0.006	0.989	0.067	0.039	-	65.099	198.960
	SMA-SGM$_3$	0.026	0.529	0.053	-	0.009	16.746	162.996
	SMA-SGM$_4$	0.005	0.406	0.045	0.004	0.03	74.362	325.053
30.08.1996	SMA-SGM$_1$	0.837	0.306	0.070	-	-	-	229.673
	SMA-SGM$_2$	0.015	0.954	0.079	0.039	-	65.099	467.828
	SMA-SGM$_3$	0.058	0.313	0.057	-	0.009	40.464	372.886
	SMA-SGM$_4$	0.011	0.384	0.079	0.005	0.03	85.099	667.297
Mansara								
25.07.1994	SMA-SGM$_1$	0.429	0.300	0.4E-03	-	-	-	135.454
	SMA-SGM$_2$	0.823	0.576	0.000	0.049	-	60.00	50.000
	SMA-SGM$_3$	0.241	0.400	0.3E-03	-	0.050	26.785	89.351
	SMA-SGM$_4$	0.109	0.580	0.000	0.050	0.03	27.524	384.055
16.08.1994	SMA-SGM$_1$	0.518	0.300	0.043	-	-	-	142.125
	SMA-SGM$_2$	0.256	0.032	0.079	0.040	-	10.001	90.145
	SMA-SGM$_3$	0.284	0.400	0.007	-	0.050	28.204	99.270
	SMA-SGM$_4$	0.980	0.501	0.000	0.050	0.03	32.585	420.236
W 6								
15.03.1982	SMA-SGM$_1$	0.377	0.019	0.059	-	-	-	90.199
	SMA-SGM$_2$	0.029	0.013	0.069	0.004	-	70.897	1012.855
	SMA-SGM$_3$	0.030	0.039	0.057	-	0.020	9.150	1050.478
	SMA-SGM$_4$	0.008	0.050	0.079	0.050	0.03	59.880	2958.733
W 7								
0.3.06.1982	SMA-SGM$_1$	0.917	0.300	0.069	-	-	-	3263.790

Event	**Model**	**Optimized parameters of the proposed models**						
		α	**β**	**k**	**θ**	**λ**	**S**	**A (kN/km^2)**
	$SMA\text{-}SGM_2$	0.452	0.020	0.079	0.050	-	48.299	1209.369
	$SMA\text{-}SGM_3$	0.595	0.039	0.019	-	0.050	6.522	1263.593
	$SMA\text{-}SGM_4$	0.313	0.500	0.800	0.059	0.30	25.108	157.152
W 14								
12.09.1982	$SMA\text{-}SGM_1$	0.402	0.200	0.4E-05	-	-	-	90.688
	$SMA\text{-}SGM_2$	0.020	0.264	0.000	0.050	-	13.361	86.923
	$SMA\text{-}SGM_3$	0.203	0.230	0.4E-06	-	0.039	5.189	509.544
	$SMA\text{-}SGM_4$	0.135	0.500	0.000	0.070	0.03	11.942	4096.266

From the validation of the models the resulting NSE of the proposed models varies from 67.89 to 99.56 %, 67.11 to 99.56 %, 67.57 to 99.52 % and 66.81 to 99.53 % for $SMA\text{-}SGM_1$ to $SMA\text{-}SGM_4$ respectively as shown in Table 6.5. Therefore from the validation of the model, it's observed that the RE of the proposed SMA-SGMs is less than Bhunya et al. (2010) model from similar to calibration events from all application of the watersheds. It can be observed that a graphical representation of the observed sediment graphs and computed sediment graphs also indicated a good agreement between the proposed model and observed sediment graph for the validation events (Figs 6.11 to 6.19). Form the computed and observed sediment graphs results are discussed above, it is evident that the proposed sediment graph models for all the events the resulting NSE in both calibration and validation of the models were reasonably high which shows the satisfactorily model performance.

Table-6.5: Characteristics of observed and computed sediment graph for validation of the proposed SMA-SGMs from six watersheds

Name of Watershed	Event	Models	Total sediment out flow (kN)			Peak sediment out flow rate (kN/h)			Time to peak sediment outflow (h)			NSE (%)
			Q_S	Q_S (c)	RE (%)	Q_{ps}	$Q_{ps}(c)$	RE (%)	t_{ps}	t_{ps} (c)	RE (%)	
Karso	14.6.1994 (V)	$SMA\text{-}SGM_1$	1218.74	1209.59	0.75	761.57	687.84	9.68	2.0	2.0	0.00	96.52
		$SMA\text{-}SGM_2$	1218.74	1166.85	4.26	761.57	731.03	4.01	2.0	2.0	0.00	97.12
		$SMA\text{-}SGM_3$	1218.74	1125.59	7.64	761.57	633.03	16.88	2.0	2.0	0.00	93.47
		$SMA\text{-}SGM_4$	1218.74	1149.16	5.71	761.57	717.62	5.77	2.0	2.0	0.00	97.08
	14.10.1994 (V)	$SMA\text{-}SGM_1$	1058.56	939.17	11.28	344.57	274.99	20.19	3.0	4.0	-33.3	83.95
		$SMA\text{-}SGM_2$	1058.56	868.23	17.98	344.57	268.86	21.97	3.0	3.0	0.00	79.54
		$SMA\text{-}SGM_3$	1058.56	902.35	14.76	344.57	262.04	23.95	3.0	4.0	-33.3	85.11
		$SMA\text{-}SGM_4$	1058.56	1016.84	3.96	344.57	278.11	19.29	3.0	3.0	0.00	83.29
Banha	20.8.1996 (V)	$SMA\text{-}SGM_1$	1256.03	953.26	24.11	244.00	163.65	32.93	3.0	4.0	-33.3	67.89
		$SMA\text{-}SGM_2$	1256.03	914.54	27.19	244.00	167.00	31.56	3.0	4.0	-33.3	67.11
		$SMA\text{-}SGM_3$	1256.03	970.71	22.72	244.00	165.49	32.18	3.0	4.0	-33.3	67.57
		$SMA\text{-}SGM_4$	1256.03	925.23	26.34	244.00	161.20	33.93	3.0	4.0	-33.3	66.81

Name of Watershed	**Event**	**Models**	**Total sediment out flow (kN)**			**Peak sediment out flow rate (kN/h)**			**Time to peak sediment outflow (h)**			**NSE (%)**
			$\mathbf{Q_S}$	$\mathbf{Q_S}$ **(c)**	**RE (%)**	$\mathbf{Q_{ps}}$	$\mathbf{Q_{ps}(c)}$	**RE (%)**	$\mathbf{t_{ps}}$	$\mathbf{t_{ps}}$ **(c)**	**RE (%)**	
	30.8.1996 (V)	SMA-SGM$_1$	2882.62	2502.36	13.19	1159.63	926.27	20.12	2.0	2.0	0.00	89.75
		SMA-SGM$_2$	2882.62	2272.72	21.16	1159.63	830.63	28.37	2.0	2.0	0.00	88.85
		SMA-SGM$_3$	2882.62	2535.95	12.03	1159.63	932.60	19.58	2.0	2.0	0.00	89.77
		SMA-SGM$_4$	2882.62	2365.99	17.92	1159.63	854.15	26.34	2.0	2.0	0.00	89.08
Mansara	25.7.1994 (V)	SMA-SGM$_1$	183.58	164.32	10.49	95.46	80.29	15.89	2.0	2.0	0.00	90.49
		SMA-SGM$_2$	183.58	181.34	0.89	95.46	94.89	0.60	2.0	2.0	0.00	98.18
		SMA-SGM$_3$	183.58	149.56	18.53	95.46	70.76	25.87	2.0	2.0	0.00	84.24
		SMA-SGM$_4$	183.58	181.88	0.93	95.46	94.86	0.63	2.0	2.0	0.00	98.18
	16.8.1994 (V)	SMA-SGM$_1$	368.64	288.25	21.81	117.34	80.39	31.49	2.0	2.0	0.00	80.10
		SMA-SGM$_2$	368.64	291.25	20.99	117.34	92.52	21.15	2.0	2.0	0.00	87.79
		SMA-SGM$_3$	368.64	280.87	23.81	117.34	71.48	39.08	2.0	2.0	0.00	73.96
		SMA-SGM$_4$	368.64	301.63	18.18	117.34	95.82	18.34	2.0	2.0	0.00	87.80
W 6	15.3.1982 (V)	SMA-SGM$_1$	20.26	19.45	4.00	10.45	10.48	-0.29	1.0	1.0	0.00	99.56
		SMA-SGM$_2$	20.26	19.42	4.15	10.45	10.51	-0.57	1.0	1.0	0.00	99.56

Name of Watershed	Event	Models	Total sediment out flow (kN)			Peak sediment out flow rate (kN/h)			Time to peak sediment outflow (h)			NSE (%)
			Q_S	Q_S (c)	RE (%)	Q_{ps}	$Q_{ps}(c)$	RE (%)	t_{ps}	t_{ps} (c)	RE (%)	
		SMA-SGM$_3$	20.26	19.35	4.49	10.45	10.27	1.72	1.0	1.0	0.00	99.52
		SMA-SGM$_4$	20.26	19.80	2.27	10.45	10.45	0.00	1.0	1.0	0.00	99.53
W 7	3.6.1982 (V)	SMA-SGM$_1$	612.86	604.08	1.43	470.09	400.58	14.79	1.0	1.0	0.00	89.09
		SMA-SGM$_2$	612.86	533.42	12.96	470.09	395.41	15.89	1.0	1.0	0.00	93.92
		SMA-SGM$_3$	612.86	595.56	2.82	470.09	437.89	6.85	1.0	1.0	0.00	94.85
		SMA-SGM$_4$	612.86	530.05	13.51	470.09	358.84	23.67	1.0	1.0	0.00	88.33
W 14	12.9.1982 (V)	SMA-SGM$_1$	73.4	68.40	6.81	43.03	39.13	9.06	2.0	2.0	0.00	82.14
		SMA-SGM$_2$	73.4	69.59	5.19	43.03	41.15	4.37	2.0	2.0	0.00	88.32
		SMA-SGM$_3$	73.4	69.04	5.94	43.03	39.24	8.81	2.0	2.0	0.00	81.23
		SMA-SGM$_4$	73.4	71.31	2.85	43.03	42.16	2.02	2.0	2.0	0.00	88.62

It is seen in Table 6.5, that the results total computed sediment flow rate and observed sediment flow rate, computed peak sediment flow rate and observed sediment flow rate, computed time to peak and observed time to peak obtained from the proposed SMA-SGMs are more accurate. Therefore both calibration and validation events are plotted between line of perfect fit (LPF) of computed sediment yield and observed sediment yield The closeness of data point in calibration and validation of the model indicate the good agreement of all applications of the models performance as shown in Figs 6.39. The sediment producing characteristics of the watersheds have been subjected to change by the landuse treatments and soil conservation measures taken in the watershed in sequence to estimate the effect of soil conservation measures on sediment flow. The calibration and validation of the proposed SMA-SGMs shows definite trend in attenuation of crest segments and peak ordinates during the nineteen storm events for successive years. In the present study, several types of SMA-SGMs were developed for the India watershed and USDA-ARS watershed and their efficacies were evaluated using various and rarely applied statistical indices and the corresponding results were then interpreted.

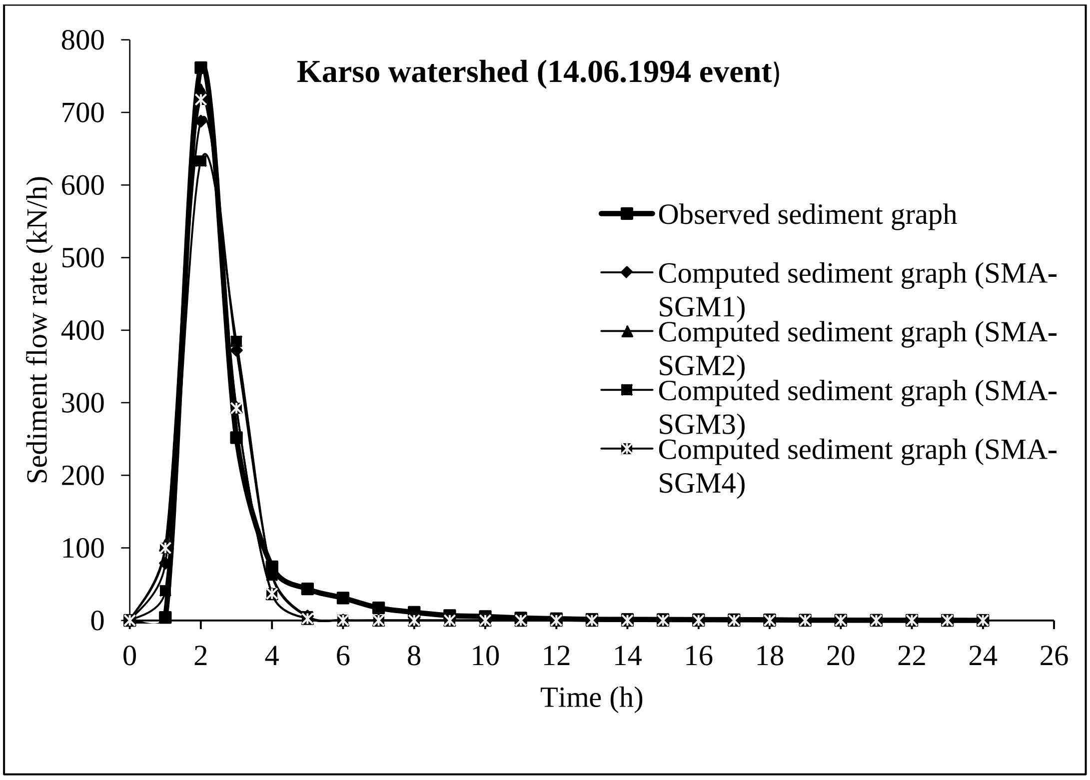


Figure-6.11: Comparison of observed and computed sediment graphs for validation of the models for Karso watershed (14.06.1994 event)

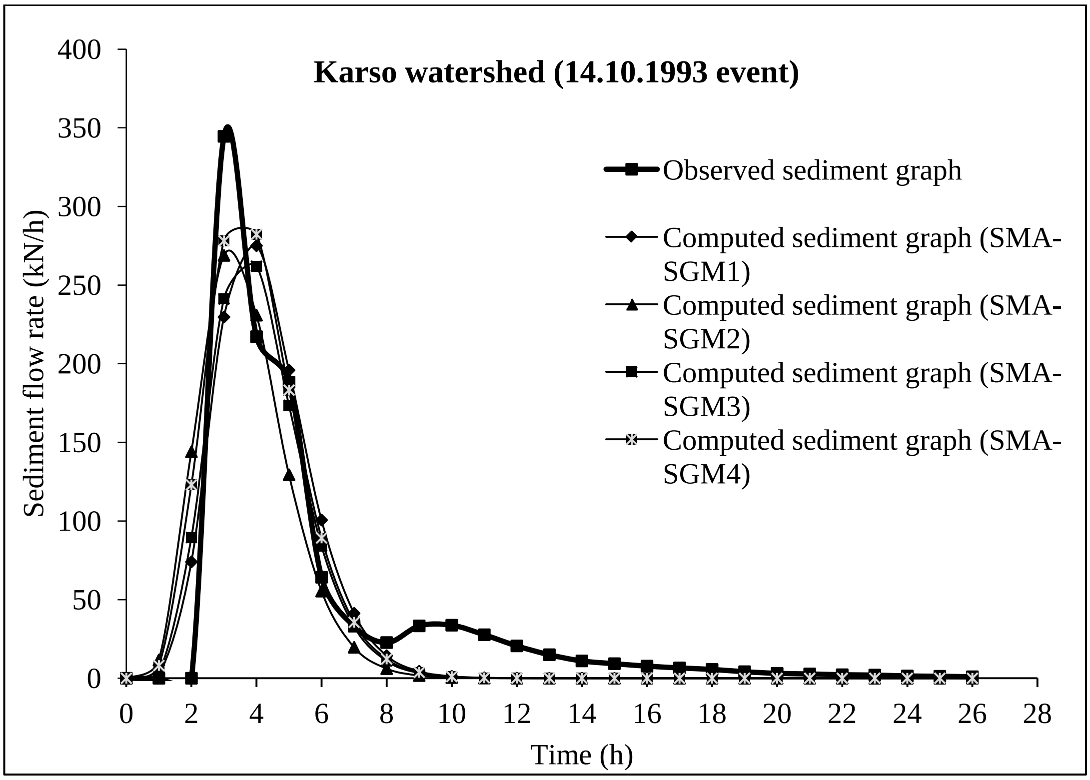


Figure-6.12: Comparison of observed and computed sediment graphs for validation of the models for Karso watershed (14.10.1982 event)

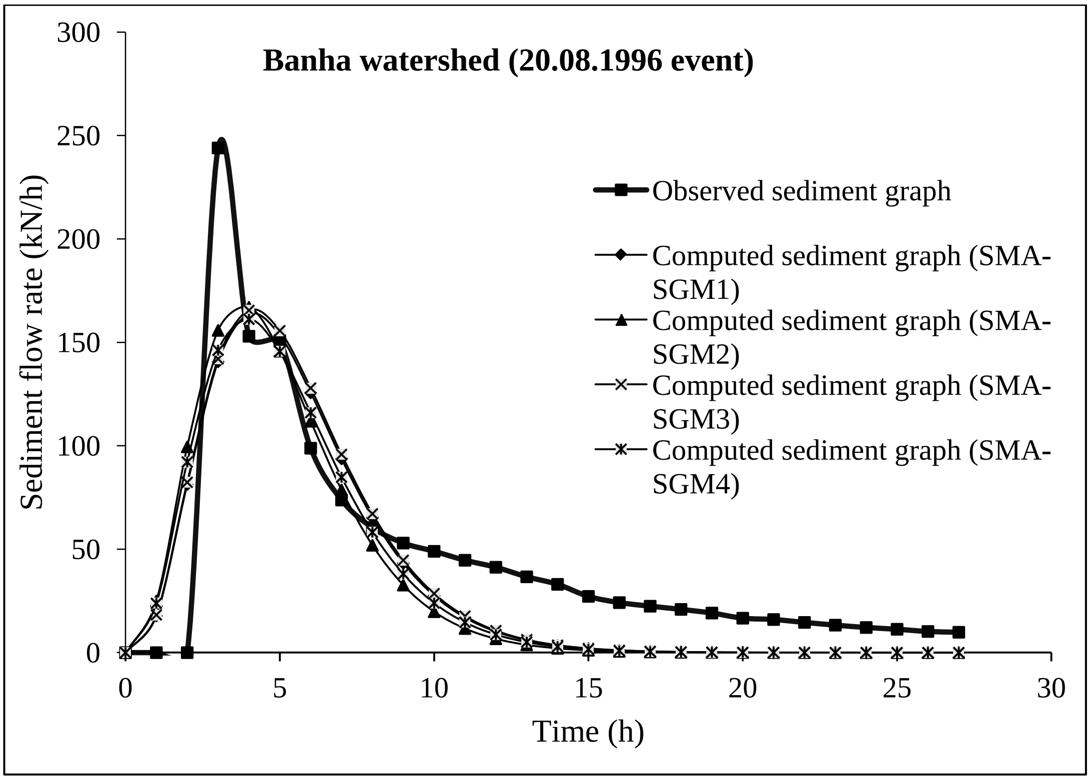


Figure-6.13: Comparison of observed and computed sediment graphs for validation of the models for Banha watershed (20.08.1996 event)

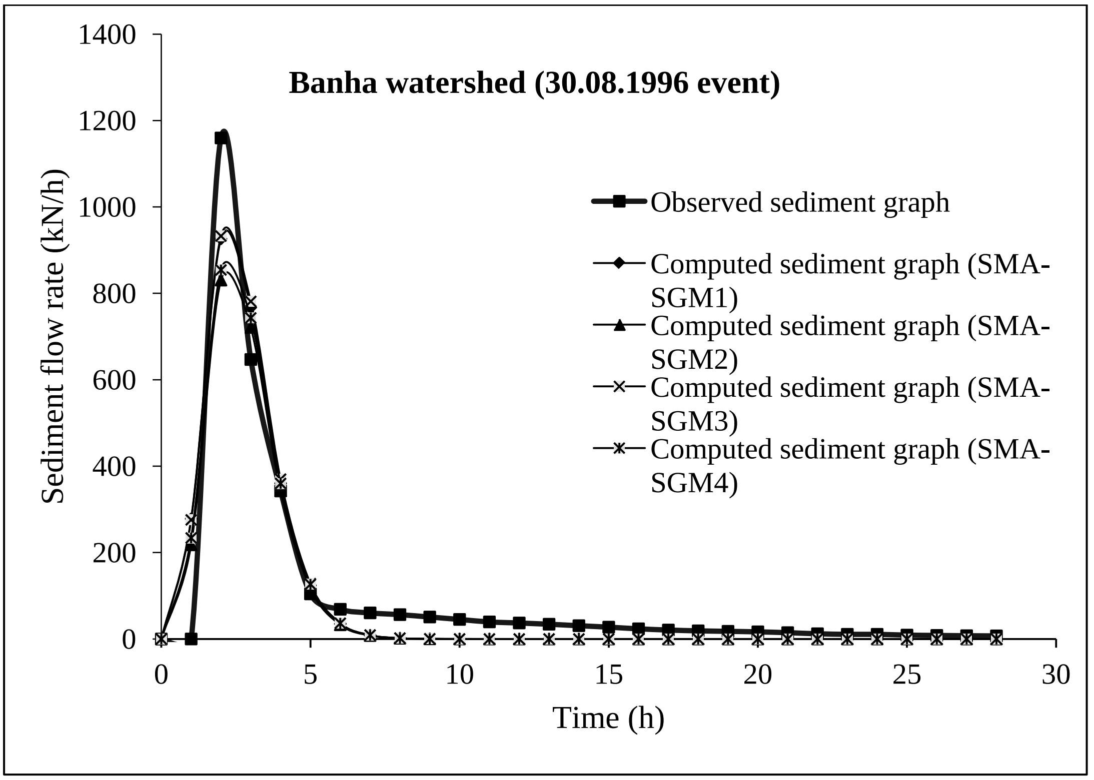


Figure-6.14: Comparison of observed and computed sediment graphs for validation of the models for Banha watershed (30.08.1996 event)

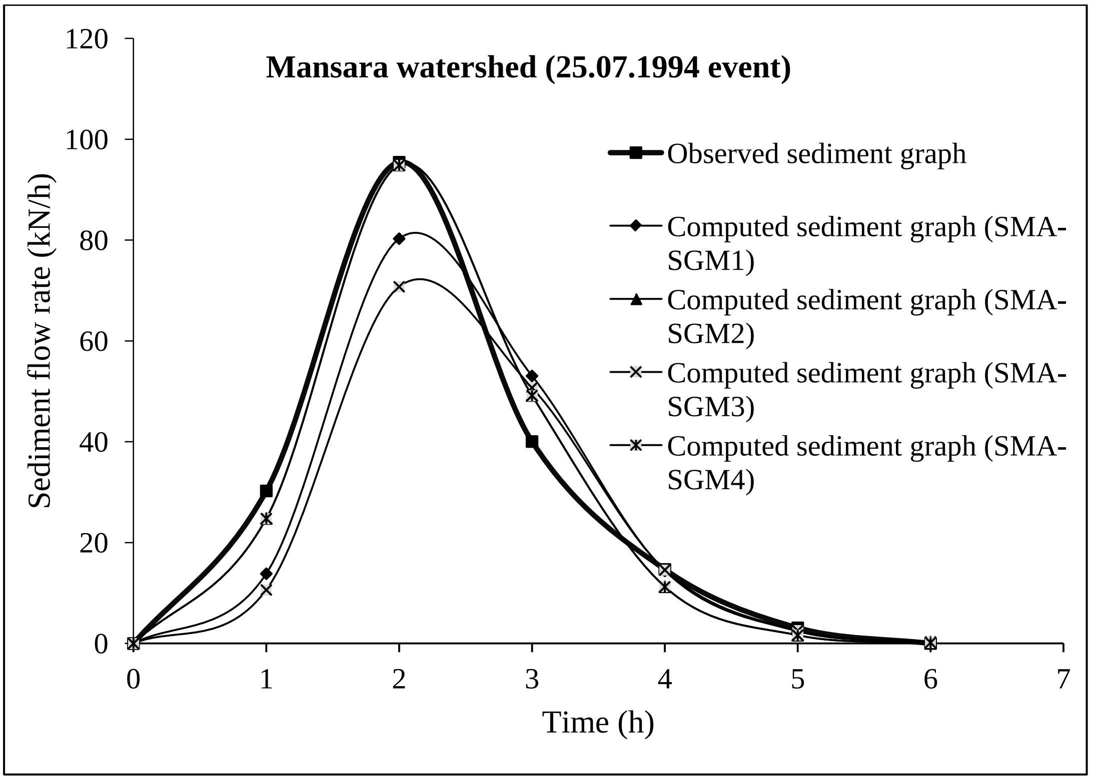


Figure-6.15: Comparison of observed and computed sediment graphs for validation of the models for Mansara watershed (25.07.1994 event)

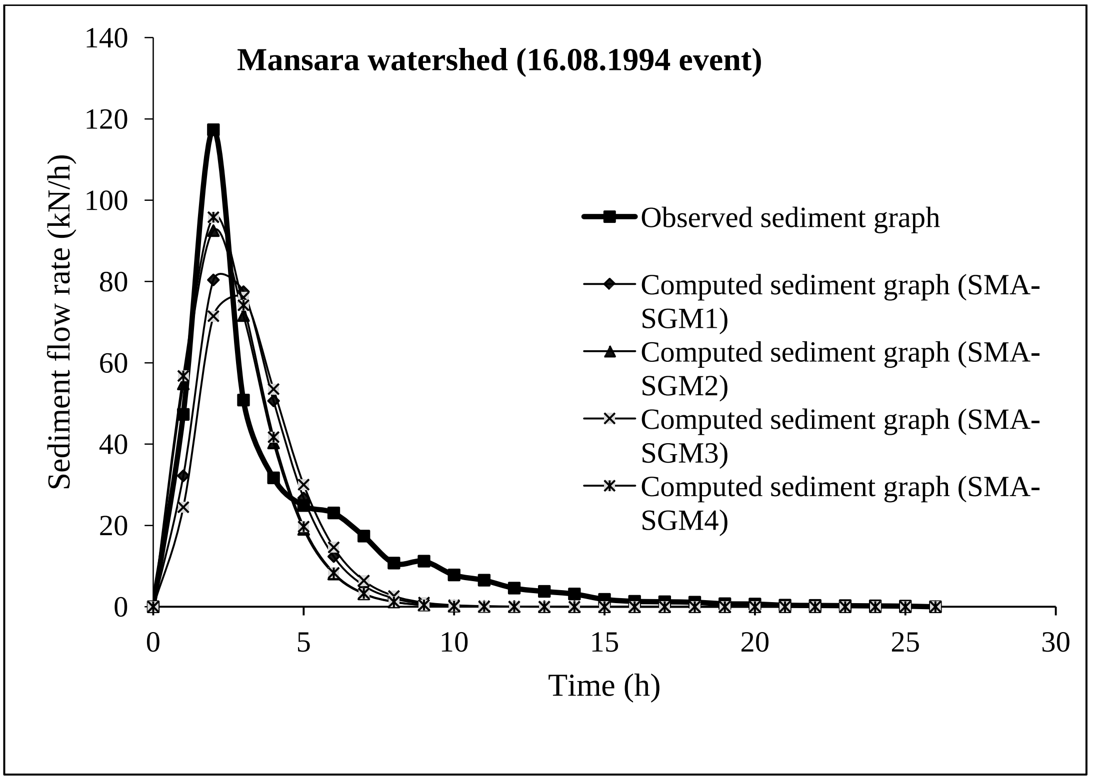


Figure-6.16: Comparison of observed and computed sediment graphs for validation of the models for Mansara watershed (16.08.1994 event)

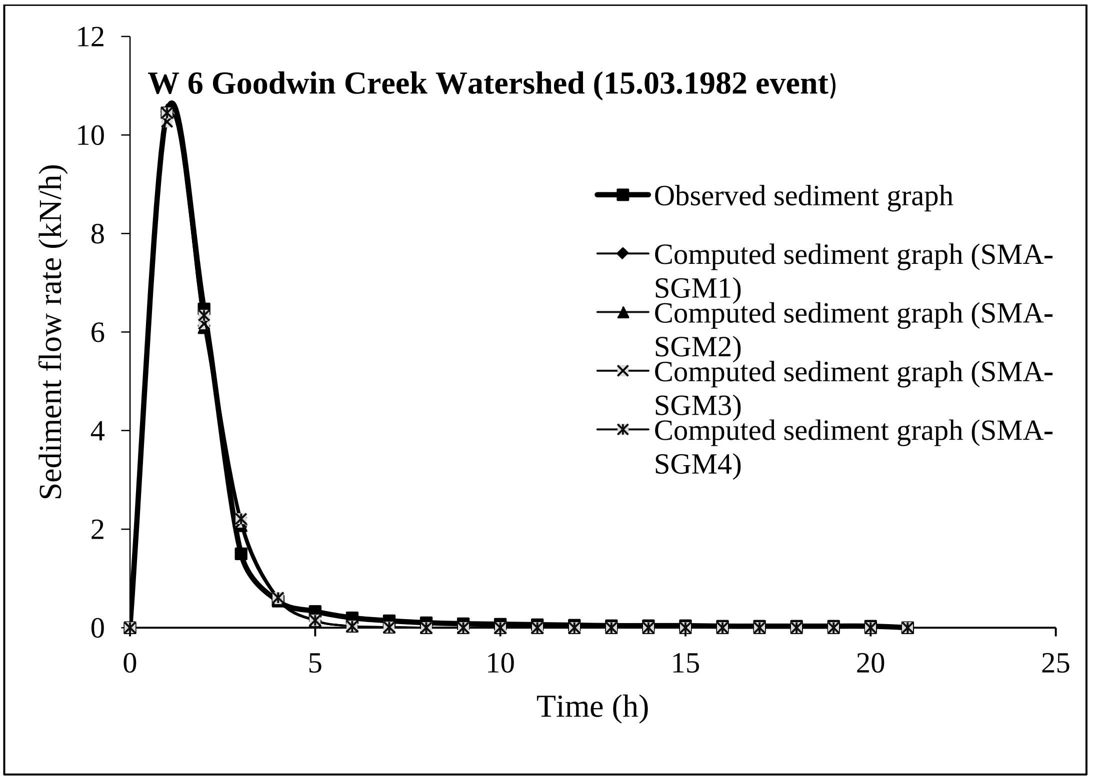


Figure-6.17: Comparison of observed and computed sediment graphs for validation of the models for W 6 Goodwin Creek watershed (15.03.1982 event)

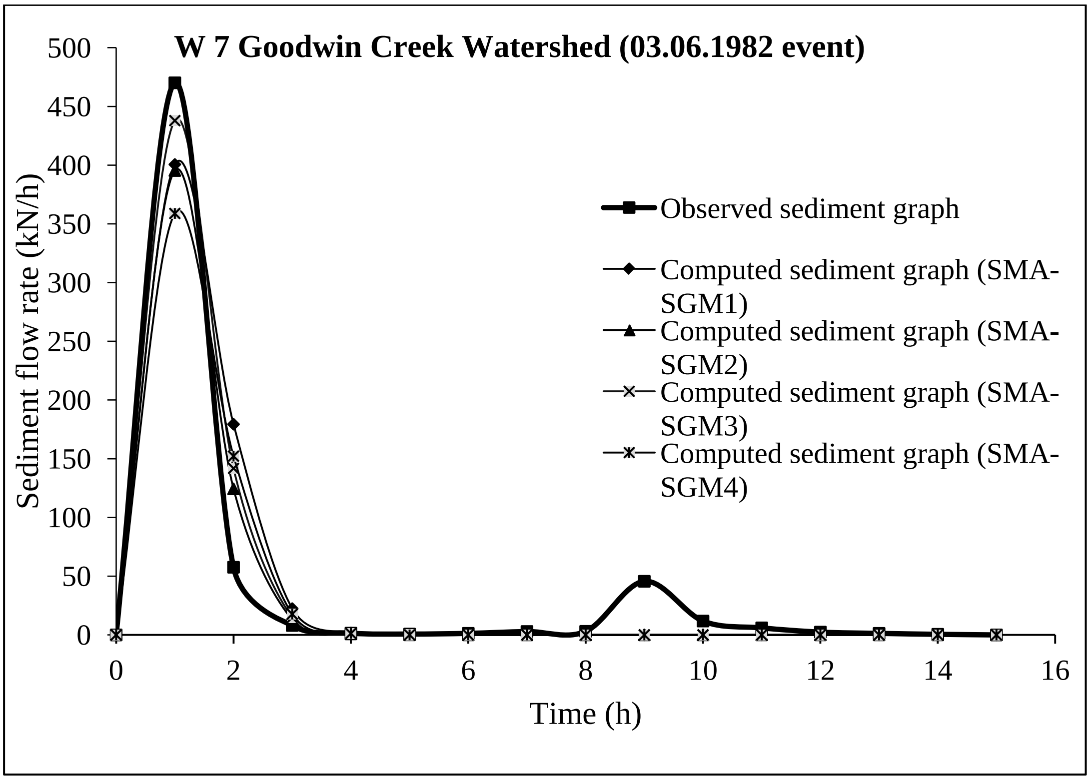


Figure-6.18: Comparison of observed and computed sediment graphs for validation of the models for W 7 Goodwin Creek watershed (03.06.1982 event)

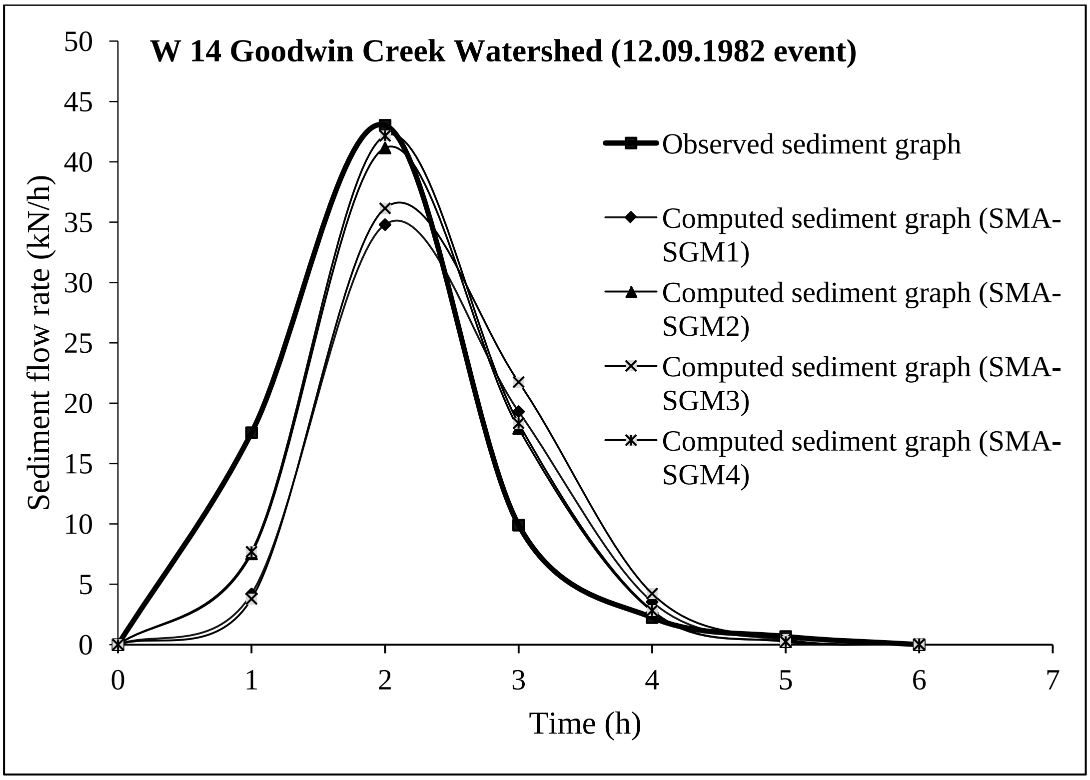


Figure-6.19: Comparison of observed and computed sediment graphs for validation of the models for W 14 Goodwin Creek watershed (12.09.1982 event)

6.5.5 Comparative Analysis between Proposed SMA-SGM and BJSM. (2010) Models

The comparative analysis of calibration and validation results between proposed SMA-SGM and Bhunya et al (BJSM). (2010) of observed and computed total sediment outflow (kN), observed and computed peak sediment flow rate (kN/h) and observed and computed time to peak sediment outflow (h) are shown in Tables 6.6 and 6.7. The visual representation between computed sediment flow rate (kN/h) and observed sediment flow rate from nineteen storm events are shown in Figs 6.20 to 6.38. It can be observed that the proposed SMA-SGMs in calibration events (Figs 6.1 to 6.10) compute higher sediment flow rate (kN/h) as compared to calibration events (Fig 6.30) of BJSM. (2010) model. These results of proposed SMA-SGMs are shows more hydrological sound and workable as compare to BJSM. (2010) model. The hourly observed and computed sediment graphs have been plotted along with corresponding BJSM. (2010) model as shown in Figs 6.20 to 6.38 (calibration and validation of the model). It is seen from the computation results of both calibration and validation event (Table 6.6) that the BJSM. (2010) model overestimate the total sediment flow rate and peak sediment flow rate for the Karso, Banha and Mansara watersheds and underestimates rest of the watersheds. Therefore it observed that from Table 6.6 the proposed SMA-SGM performs consistently better than BJSM model for all applications of the storm events. NSE statistical indices of BJSM model is lower than proposed SMA-SGM, similarly the RE of BJSM model is higher than proposed SMA-SGM as shown in Table 6.7. The sediment flow rate is varying according to several types of slopes, soil types, landuse/ landcover and hydrological condition of the watershed. Therefore sediment flow rate or sediment yield is gradually higher with an increase in slopes and low in less steep slopes. As in steep slopes, soil layer remain thin, therefore higher sediment yield results in more soil loss. In case of different soil types, the sediment yield is increasingly higher from clay to sandy loam soil again the proposed SMA-SGMs produce the higher sediment graphs as well as sediment yield as compare to BJSM. (2010) model. Clay soil has higher resistance to the sediment yield that covers maximum area than the other types of the soil therefore clay soil has less void ratio than the other soil types. The above discussion of the soil and landuse and hydrological condition of the watershed is the evidence that the proposed SMA-SGMs predict sediment flow rate or sediment yield from watersheds at higher accuracy as compare to BJSM. (2010) model.

6.7 SUMMARY

The proposed SMA-SGMs is based upon the simple and highly used models in hydrology for estimation of sediment graph as well as sediment yield. The proposed SMA-SGMs can be a simple or complex (four to seven parameters) models depending upon the number of parameters that are evolved. The uniqueness of the proposed SMA-SGMs is that it need only single input parameters for calibration and validation. At the present time, no sediment graph models based on soil moisture proxies is reported in any literature and text book. The proposed SMA-SGMs perform better then BJSM model on watersheds, supporting the significance of incorporating soil moisture proxies in analytical derivation of model formulation. The close agreement between observed sediment graphs and computed sediment graphs by proposed SMA-SGMs support the efficiency of the models. Results analysis and visual assessment of suggest that the proposed models suitable for field and as well as academic application. The proposed model is appropriate for ungauged watershed only if the hydrological condition and hydro-metrological condition are for a given watershed.

Table-6.6: Comparison between proposed SMA-SGM and BJSM. (2010) models

Name of Watershed	Event	Model	Proposed SMA-SGMs						Existing BJSM. (2010) model		
			Total sediment out flow (kN)		Peak sediment out flow rate (kN/h)		Time to peak sediment outflow (h)		Total sediment out flow (kN)	Peak sediment out flow rate (kN/h)	Time to peak sediment outflow (h)
			Q_S	Q_S (c)	Q_{ps}	$Q_{ps}(c)$	t_{ps}	$t_{ps}(c)$	Q_S (c)	$Q_{ps}(c)$	$t_{ps}(c)$
Karso	17.8.1991 (C)	SMA-SGM$_1$	2868.53	2174.87	650.81	472.68	6.0	6.0	3544.92	789.16	6.0
	28.7.1991 (C)	SMA-SGM$_1$	3180.34	2005.77	1076.44	607.29	2.0	2.0	2426.26	743.94	2.0
	14.6.1994 (V)	SMA-SGM$_1$	1218.74	1209.59	761.57	687.84	2.0	2.0	1174.41	721.86	2.0
	14.10.1994 (V)	SMA-SGM$_1$	1058.56	939.17	344.57	274.99	3.0	4.0	1294.59	367.74	3.0
Banha	31.8.1993 (C)	SMA-SGM$_1$	1229.08	1121.25	759.05	663.10	2.0	2.0	1083.13	660.36	2.0
	17.7.1996 (C)	SMA-SGM$_1$	1509.87	1289.07	1093.42	808.27	1.0	1.0	664.63	447.63	1.0
	14.6.1994 (C)	SMA-SGM$_1$	1191.44	3245.77	1191.44	1038.40	2.0	2.0	3245.77	1061.00	2.0
	20.8.1996 (V)	SMA-SGM$_1$	1256.03	953.26	244.00	163.65	3.0	4.0	953.26	163.65	4.0
	30.8.1996 (V)	SMA-SGM$_1$	2882.62	2502.36	1159.63	926.27	2.0	2.0	2497.35	926.55	2.0
Mansara	10.8.1994 (C)	SMA-SGM$_1$	182.65	162.18	54.96	44.83	3.0	3.0	173.69	50.45	3.0
	19.7.1994 (C)	SMA-SGM$_1$	154.78	150.02	63.11	58.16	3.0	3.0	239.21	95.06	3.0

Name of Watershed	Event	Model	Proposed SMA-SGMs						Existing BJSM. (2010) model		
			Total sediment out flow (kN)		Peak sediment out flow rate (kN/h)		Time to peak sediment outflow (h)		Total sediment out flow (kN)	Peak sediment out flow rate (kN/h)	Time to peak sediment outflow (h)
			Q_S	Q_S (c)	Q_{ps}	$Q_{ps}(c)$	t_{ps}	$t_{ps}(c)$	Q_S (c)	$Q_{ps}(c)$	$t_{ps}(c)$
	25.7.1994 (V)	SMA-SGM$_1$	183.58	164.32	95.46	80.29	2.0	2.0	173.90	88.32	2.0
	16.8.1994 (V)	SMA-SGM$_1$	368.64	288.25	117.34	80.39	2.0	2.0	265.61	79.38	2.0
W 6	2.1.1982 (C)	SMA-SGM$_1$	183.82	86.59	155.78	68.87	1.0	1.0	85.94	68.44	1.0
	15.3.1982 (V)	SMA-SGM$_1$	20.26	19.45	10.45	10.48	1.0	1.0	19.48	10.49	1.0
W 7	25.5.1982 (C)	SMA-SGM$_1$	517.07	461.53	383.45	296.26	1.0	1.0	278.84	191.61	1.0
	3.6.1982 (V)	SMA-SGM$_1$	612.86	604.08	470.09	400.58	1.0	1.0	472.87	334.09	1.0
W 14	16.6.1982 (C)	SMA-SGM$_1$	4.01	3.65	1.72	1.36	1.0	1.0	3.72	1.52	1.0
	12.9.1982 (V)	SMA-SGM$_1$	73.4	68.40	43.03	39.13	2.0	2.0	106.12	61.85	2.0

Note: C and V indicate the calibration and validation

Table-6.7: Model performance for the calibration and validation of proposed and existing BJSM. (2010) models from six watersheds

Name of WS	Event	Model	Proposed SMA-SGMs			NSE (%)	Existing BJSM. (2010) model			NSE (%)
			RE of total sediment outflow (kN)	RE of peak sediment outflow rate (kN/h)	RE of time to peak sediment outflow (h)		RE of total sediment outflow (kN)	RE of sediment outflow rate (kN/h	RE of time to peak sediment outflow (h)	
Karso	17.8.1991 (C)	SMA-SGM_1	24.18	27.37	0.00	83.44	-23.58	-66.95	0.0	33.55
	28.7.1991 (C)	SMA-SGM_1	36.93	43.58	0.00	70.37	23.71	-22.50	0.0	73.31
	14.6.1994 (V)	SMA-SGM_1	0.75	9.68	0.00	96.52	3.64	-4.95	0.0	97.12
	14.10.1994 (V)	SMA-SGM_1	11.28	20.19	-33.33	83.95	-22.30	-33.73	0.0	67.52
Banha	31.8.1993 (C)	SMA-SGM_1	8.77	12.64	0.00	85.26	11.87	0.41	0.0	87.15
	17.7.1996 (C)	SMA-SGM_1	14.62	26.08	0.00	92.42	55.98	44.62	0.0	61.26
	14.6.1994 (C)	SMA-SGM_1	-6.30	12.84	0.00	95.53	-6.30	-2.18	0.0	95.69
	20.8.1996 (V)	SMA-SGM_1	24.11	32.93	-33.33	67.89	24.11	0.00	-33.33	67.32
	30.8.1996 (V)	SMA-SGM_1	13.19	20.12	0.00	89.75	13.37	-0.03	0.0	89.73
Mansara	10.8.1994 (C)	SMA-SGM_1	11.21	18.43	0.00	91.15	4.91	-12.54	0.0	95.18
	19.7.1994 (C)	SMA-SGM_1	3.08	7.84	0.00	78.48	-54.55	-63.45	0.0	35.93

Name of WS	Event	Model	Proposed SMA-SGMs			NSE (%)	Existing BJSM. (2010) model			NSE (%)
			RE of total sediment outflow (kN)	RE of peak sediment outflow rate (kN/h)	RE of time to peak sediment outflow (h)		RE of total sediment outflow (kN)	RE of sediment outflow rate (kN/h	RE of time to peak sediment outflow (h)	
	25.7.1994 (V)	SMA-SGM_1	10.49	15.89	0.00	90.49	5.27	-10.00	0.0	95.40
	16.8.1994 (V)	SMA-SGM_1	21.81	31.49	0.00	80.10	27.95	1.26	0.0	83.50
W 6	2.1.19982 (C)	SMA-SGM_1	52.89	55.79	0.00	65.67	53.25	0.62	0.0	65.32
	15.3.1982 (V)	SMA-SGM_1	4.00	-0.29	0.00	99.56	3.85	-0.10	0.0	99.56
W 7	25.5.1982 (C)	SMA-SGM_1	10.74	22.74	0.00	93.76	46.07	35.32	0.0	70.65
	3.6.1982 (V)	SMA-SGM_1	1.43	14.79	0.00	89.09	22.84	16.60	0.0	87.59
W 14	16.6.1982 (C)	SMA-SGM_1	8.98	20.93	0.00	78.53	7.23	-11.76	0.0	80.53
	12.9.1982 (V)	SMA-SGM_1	6.81	9.06	0.00	82.14	-44.58	-58.06	0.0	46.95

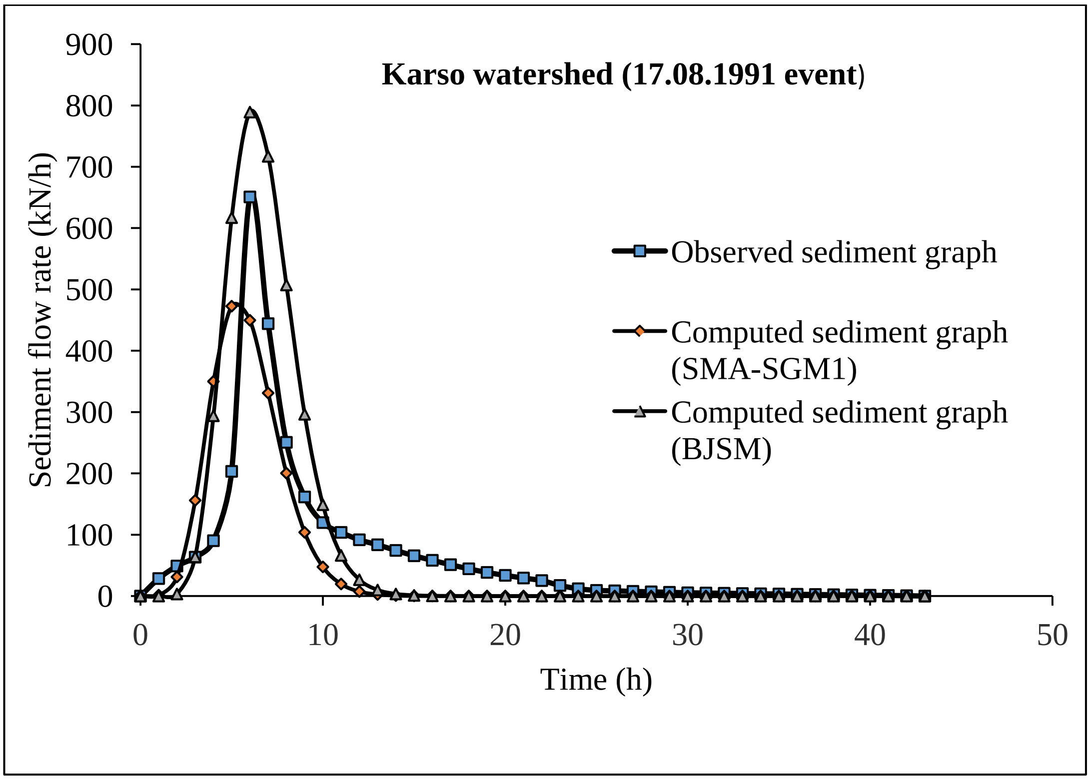
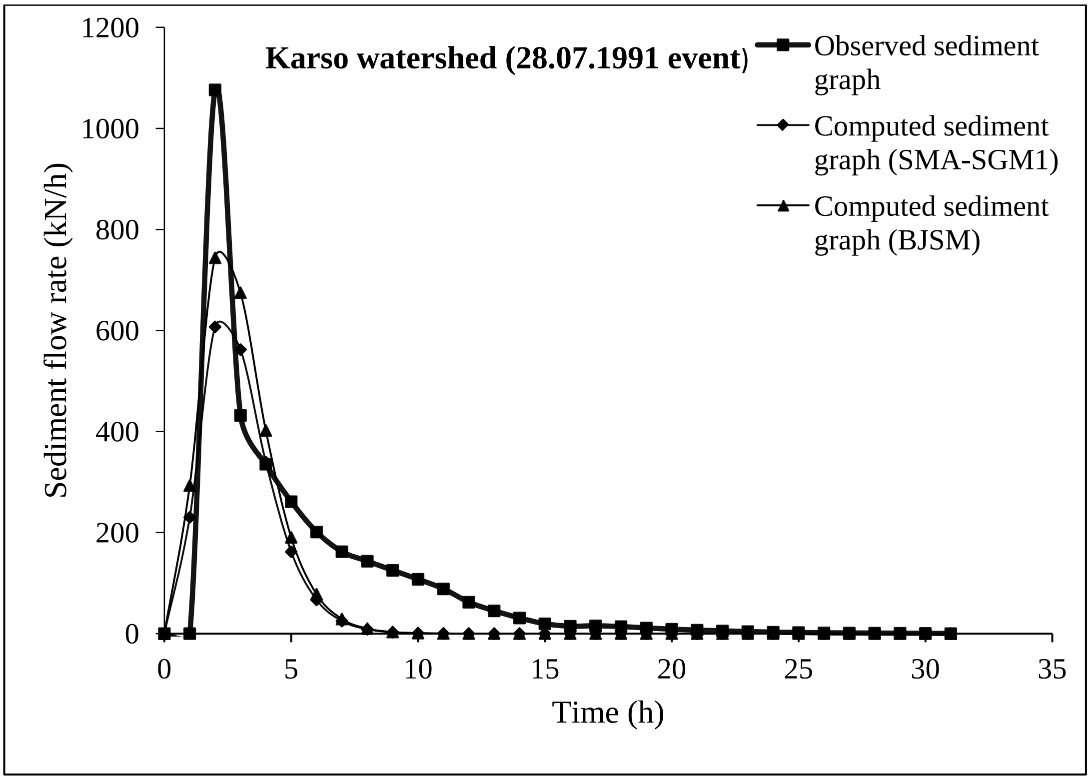


Figure-6.20: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for Karso watershed (17.08.1991 event)



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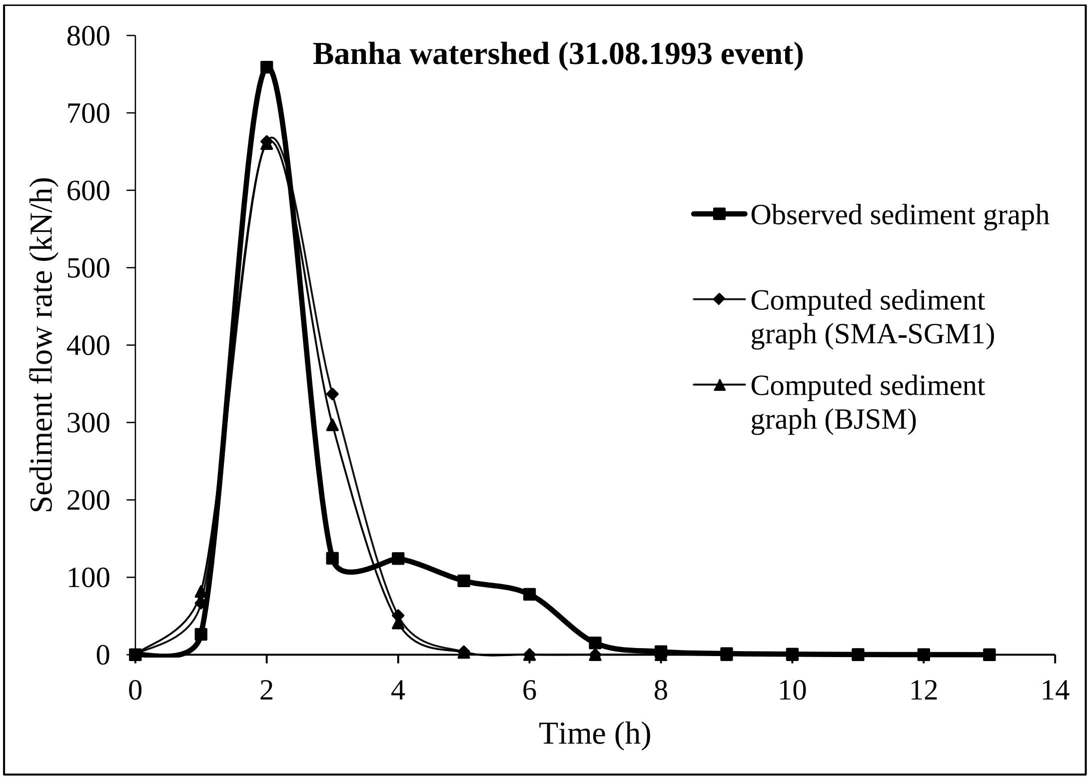


Figure-6.22: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for Banha watershed (31.08.1993 event)

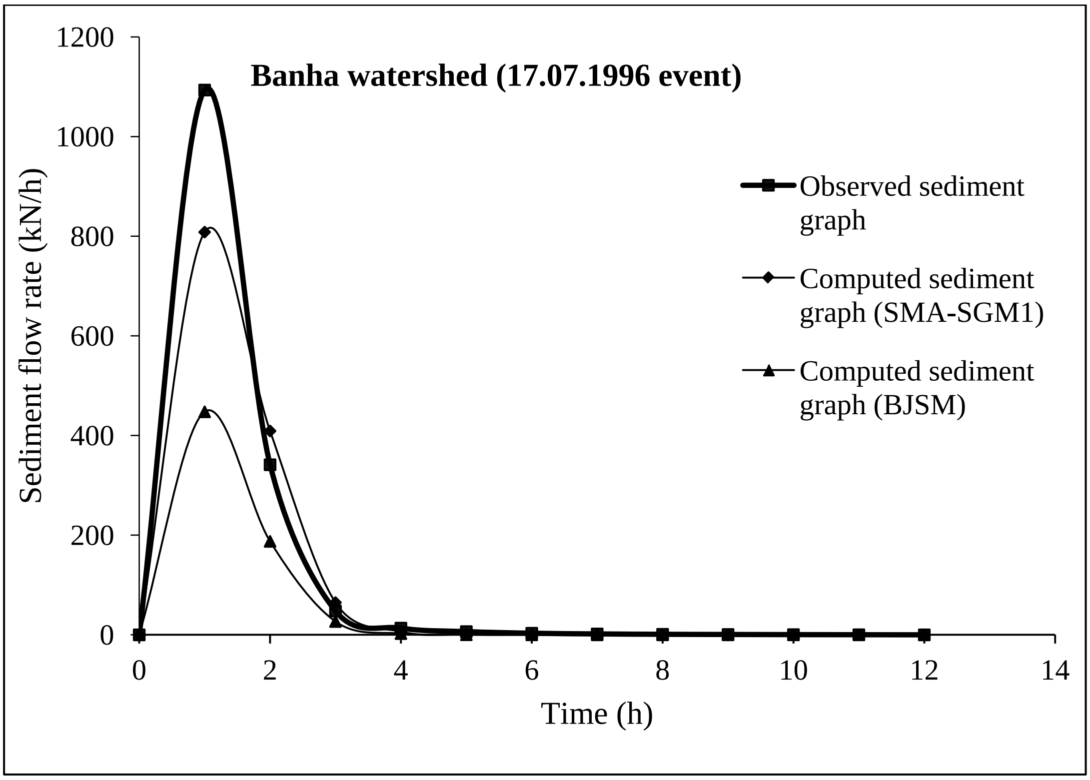


Figure-6.23: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for Banha watershed (17.07.1996 event)

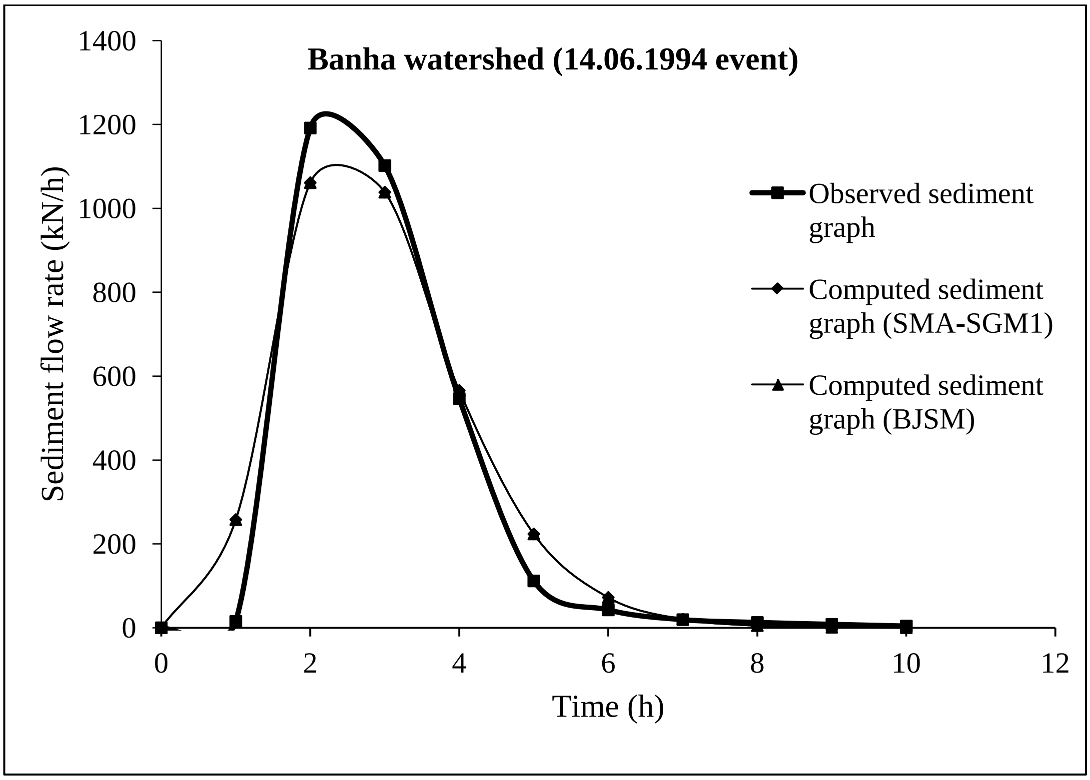


Figure-6.24: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for Banha watershed (14.06.1994 event)

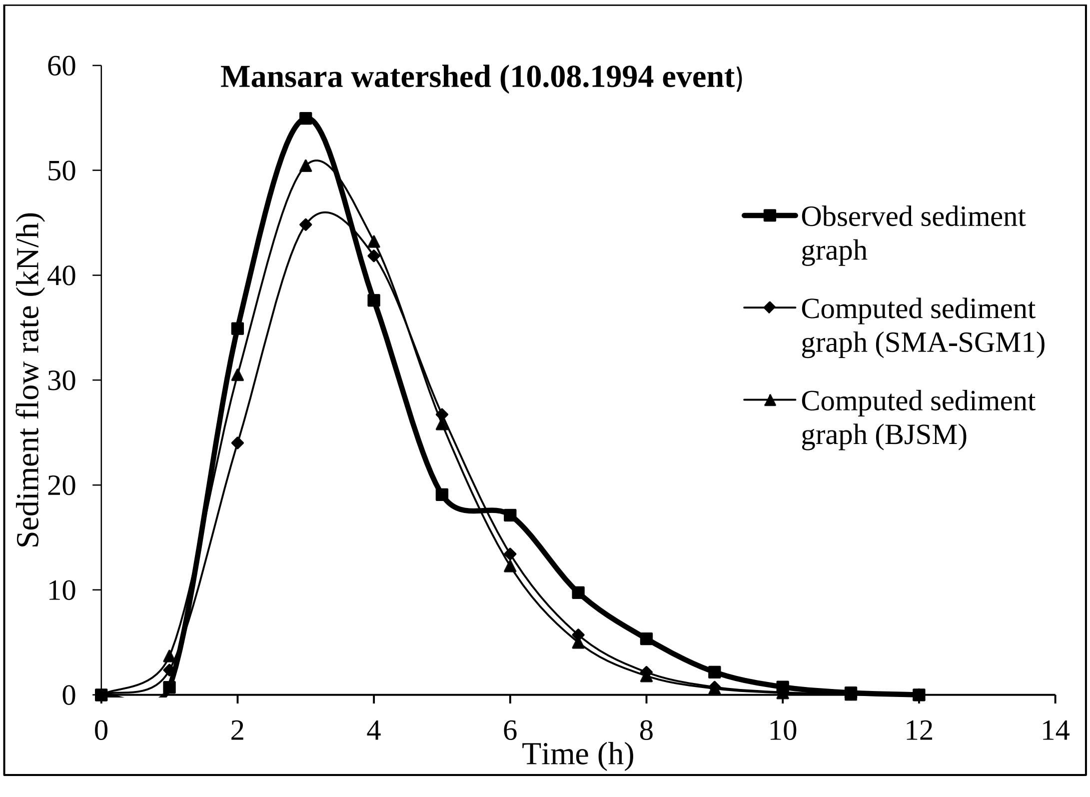
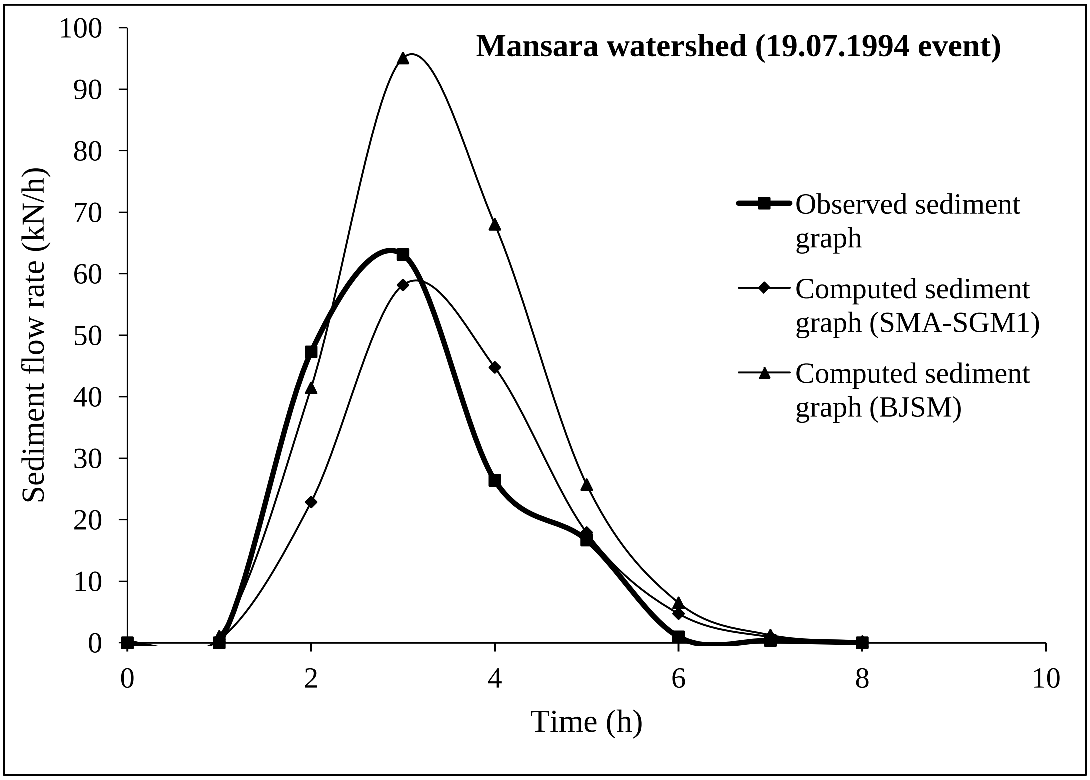


Figure-6.25: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for Mansara watershed (10.08.1994 event)



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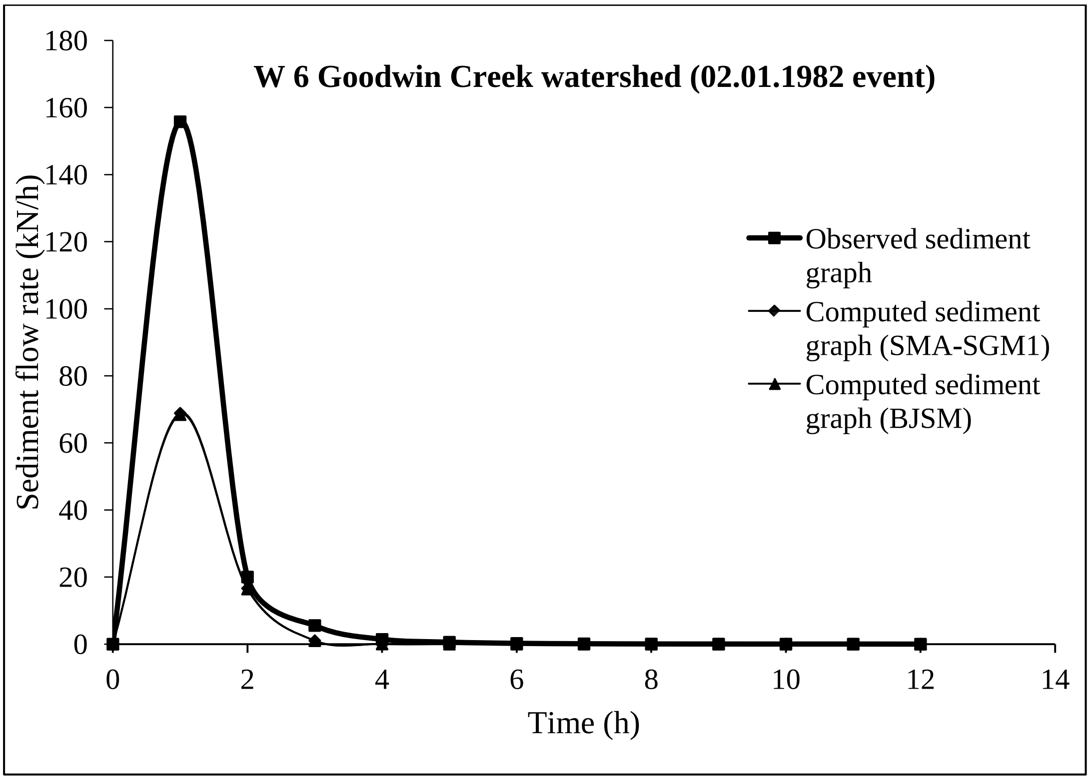


Figure-6.27: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for W 6 Goodwin Creek watershed (02.01.1982 event)

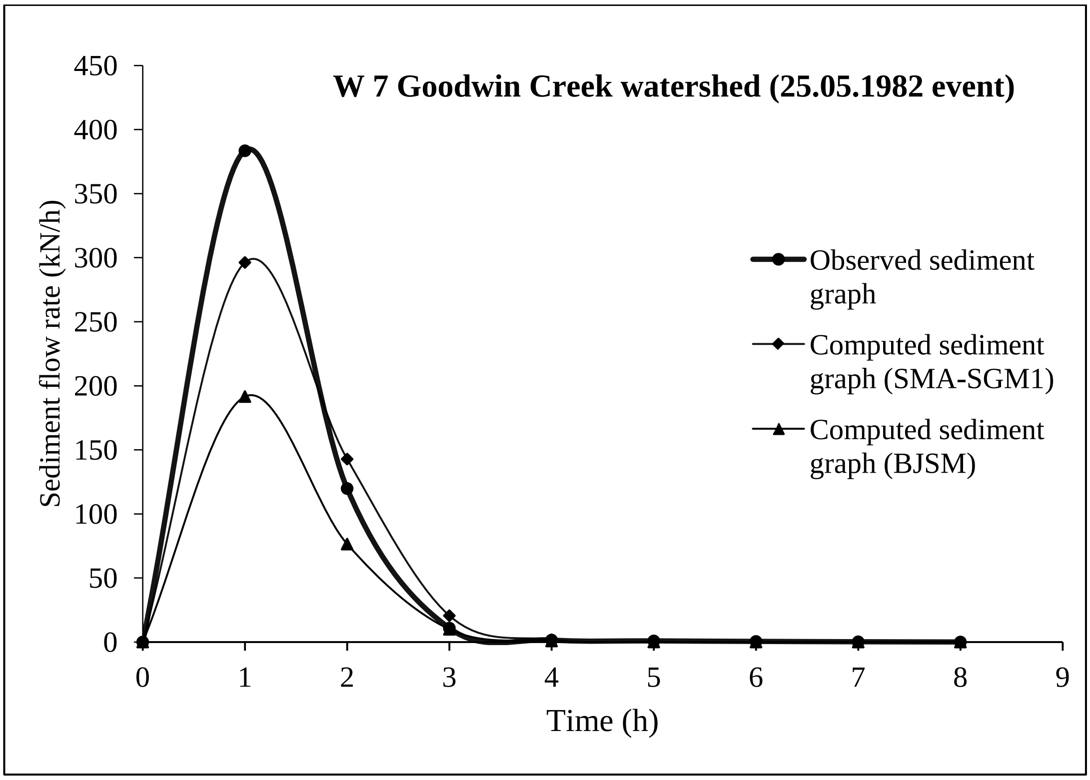


Figure-6.28: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for W 7 Goodwin Creek watershed (25.05.1982 event)

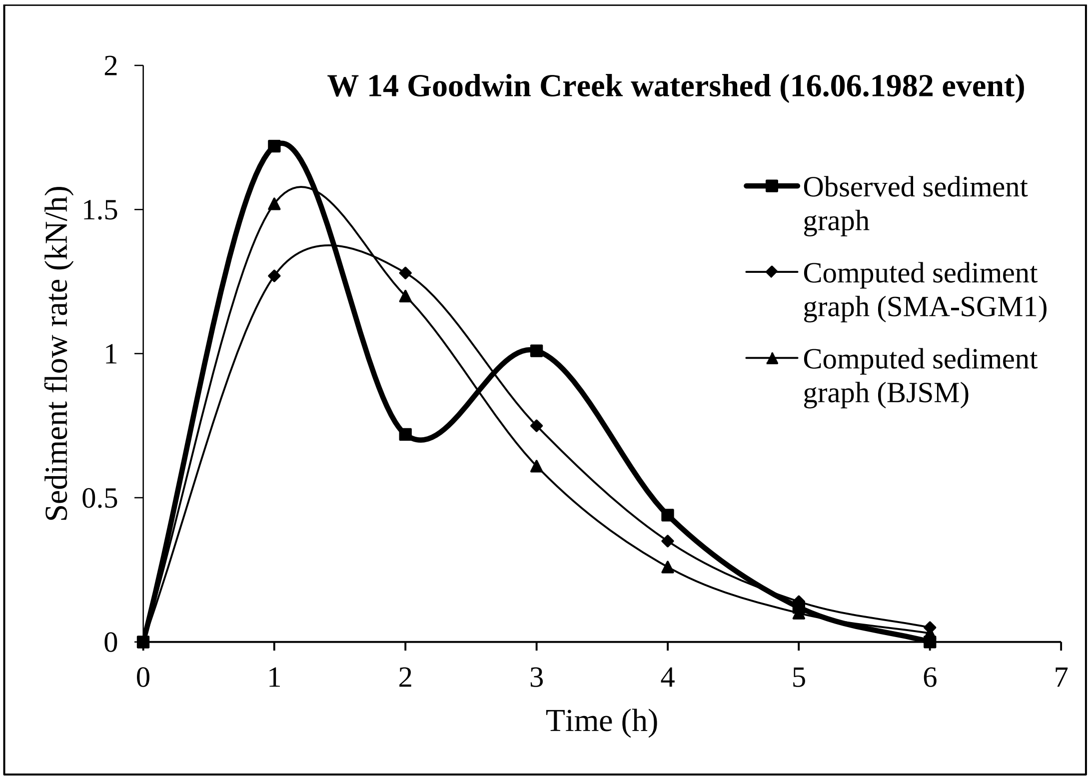


Figure-6.29: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for calibration of the models for W 14 Goodwin Creek watershed (16.06.1982 event)

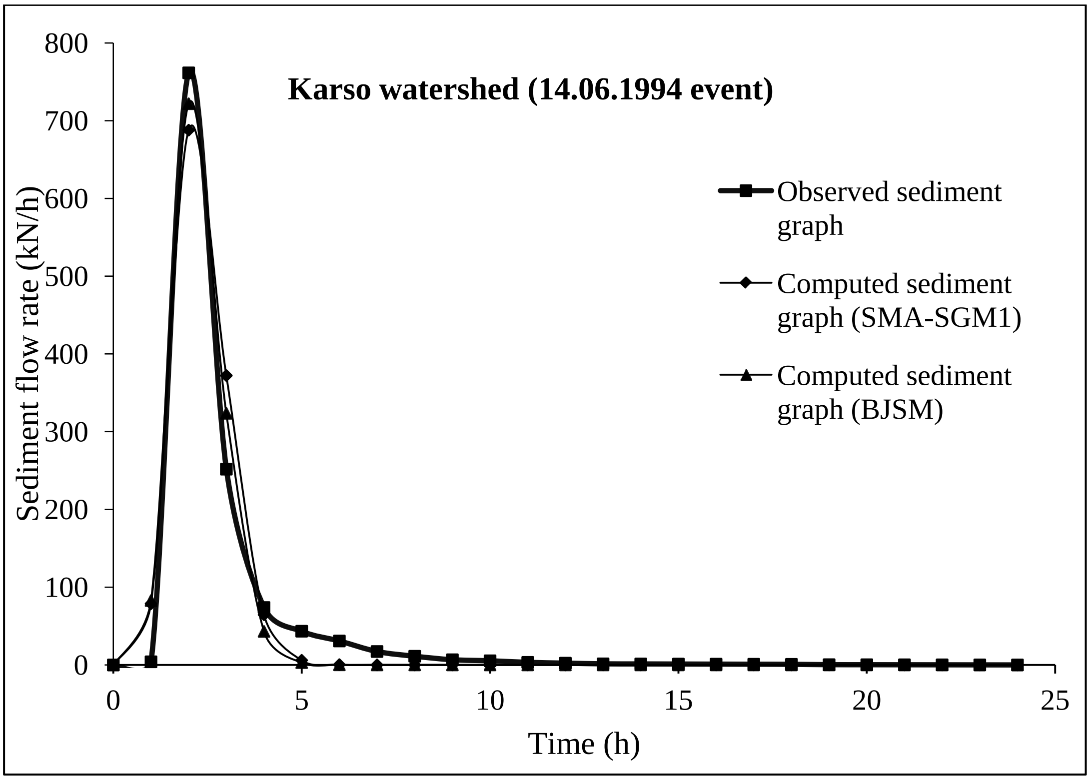


Figure-6.30: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for Karso watershed (14.06.1994 event)

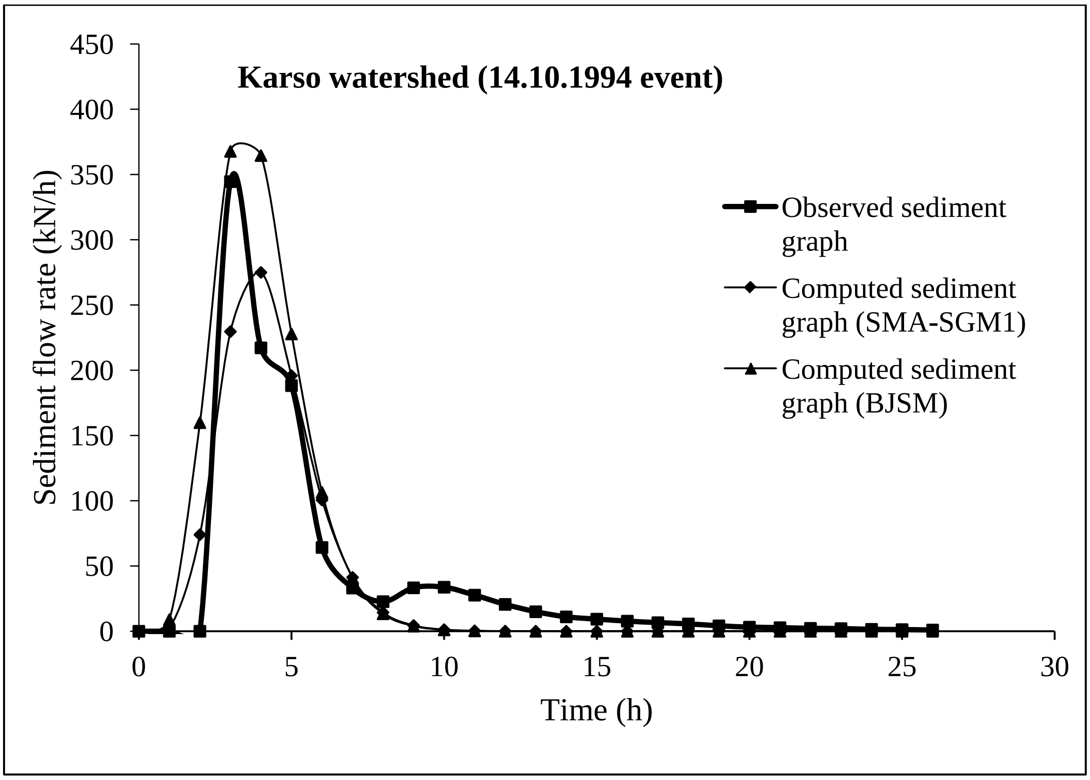


Figure-6.31: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for Karso watershed (14.10.1994 event)

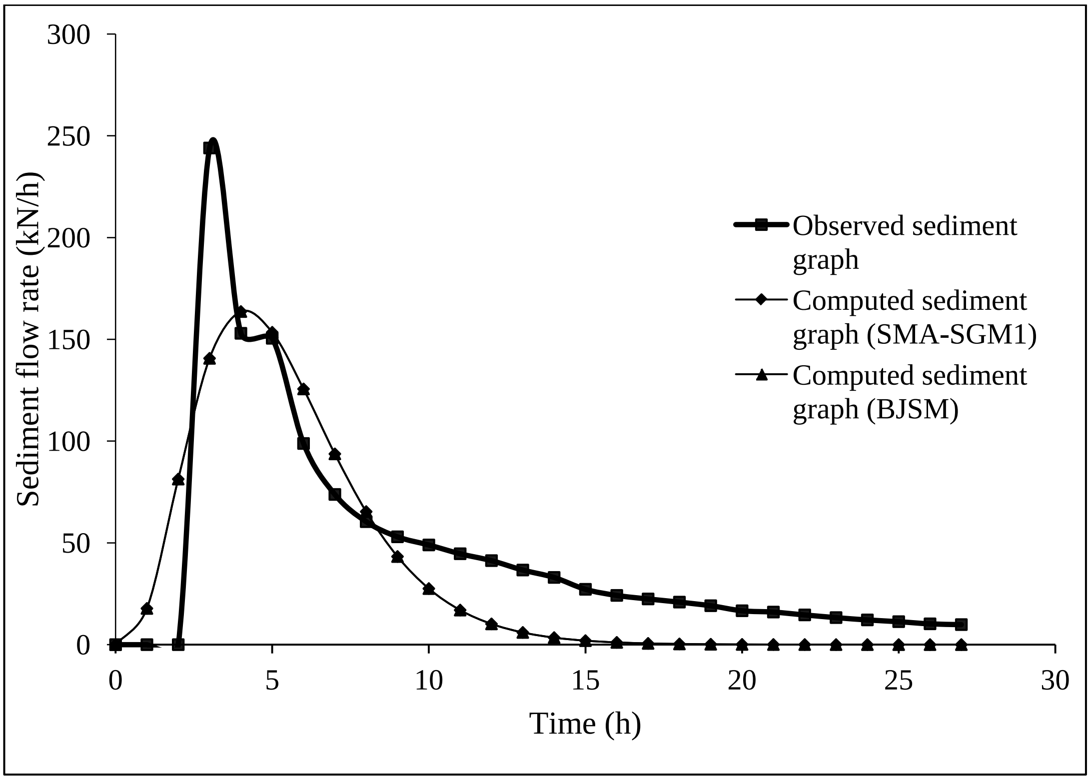
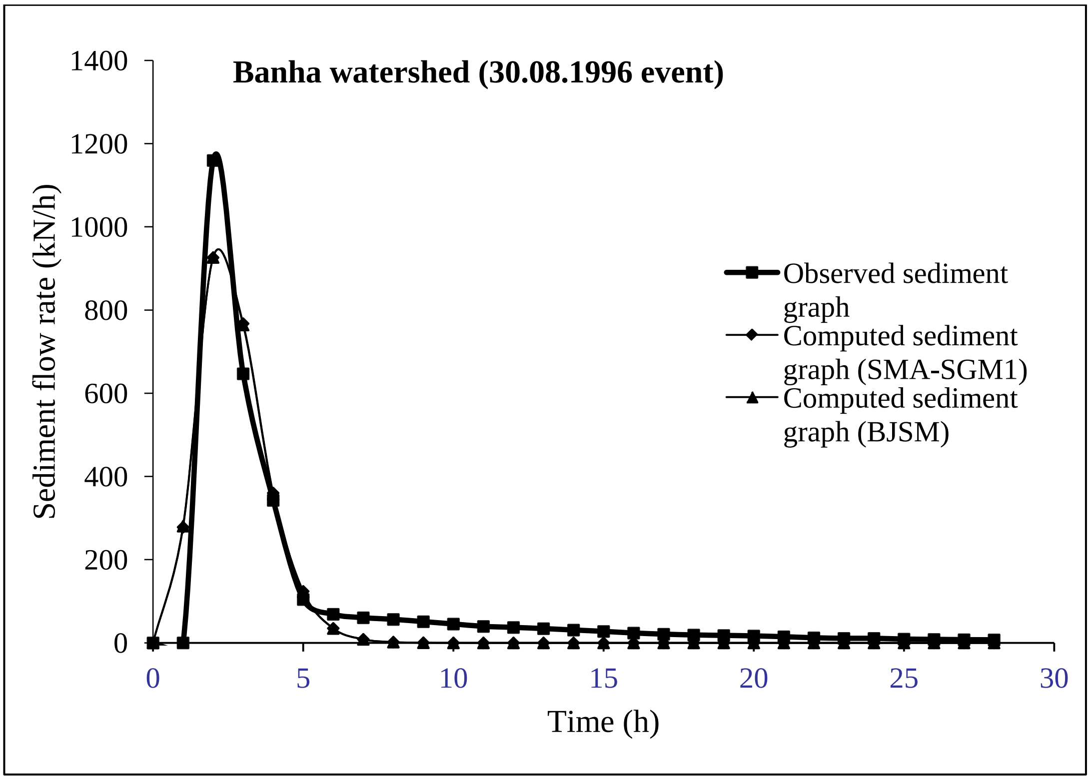


Figure-6.32: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for Banha watershed (20.08.1996 event)



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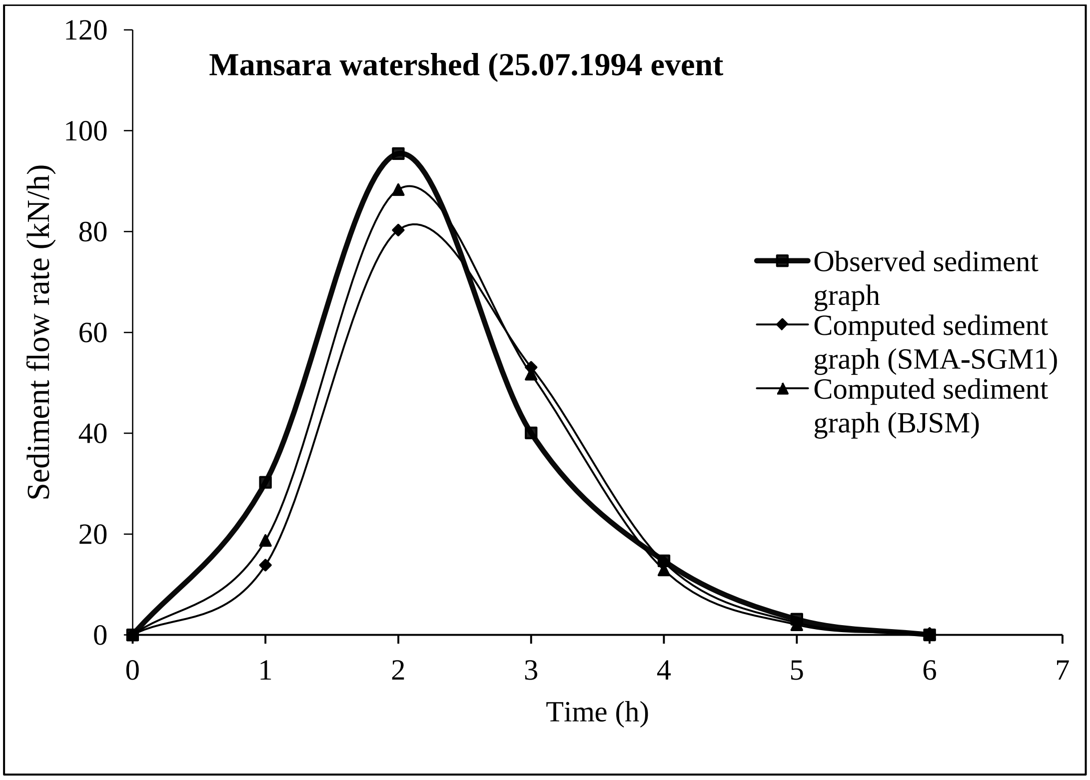


Figure-6.34: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for Mansara watershed (25.07.1994 event)

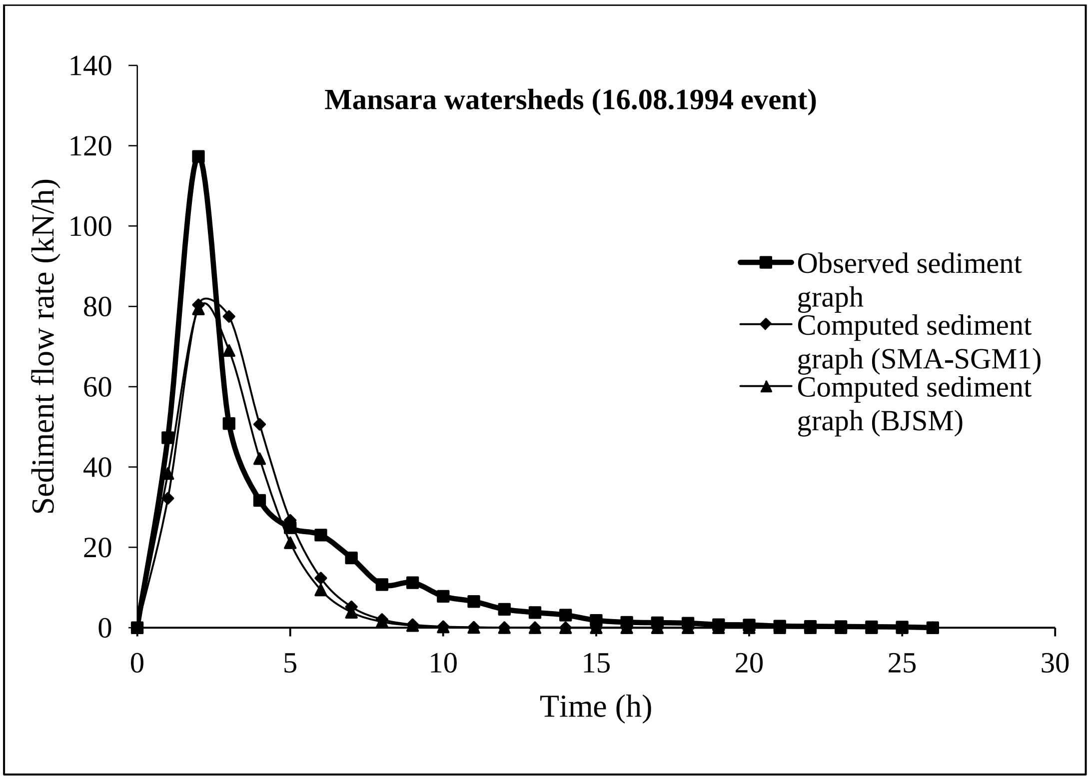


Figure-6.35: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for Mansara watershed (16.08.1994 event)

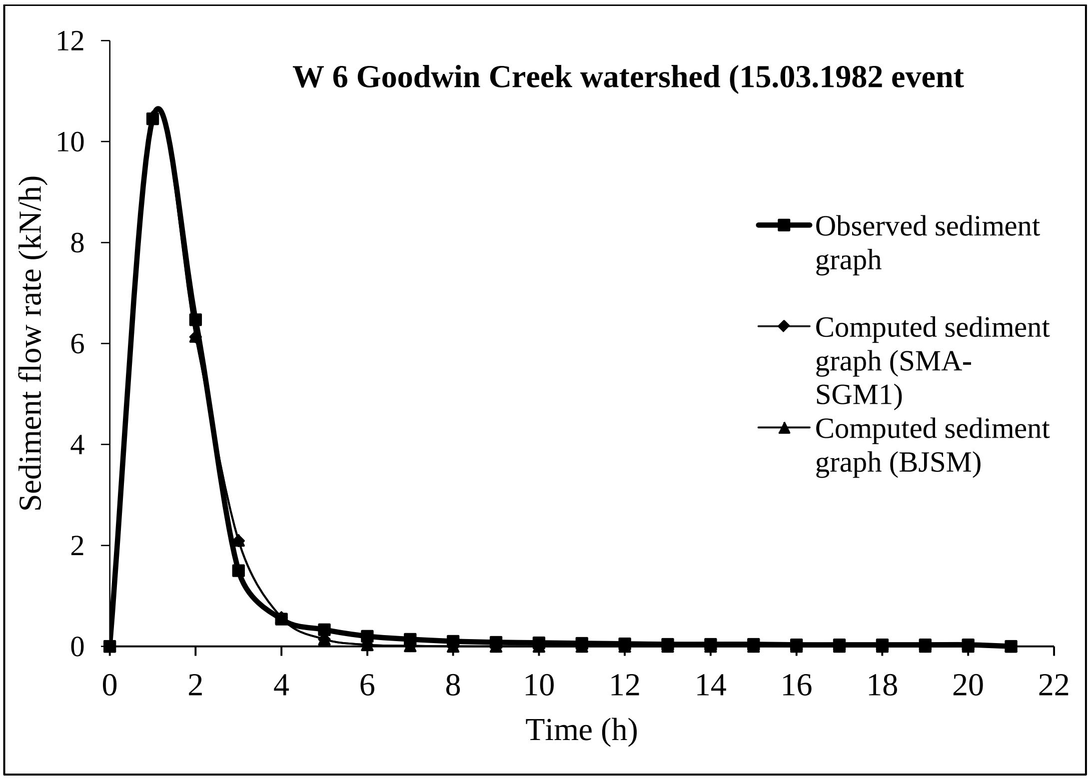


Figure-6.36: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for W 6 Goodwin Creek watershed (15.03.1982 event)

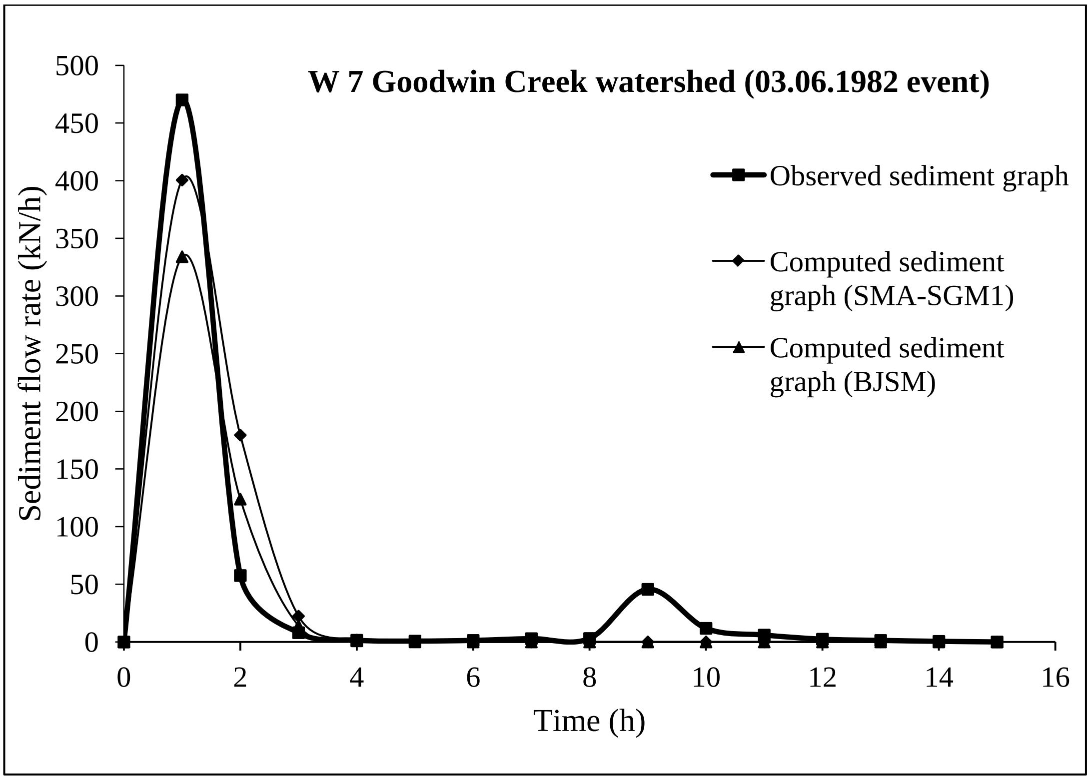


Figure-6.37: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for W 7 Goodwin Creek watershed (03.06.1982 event)

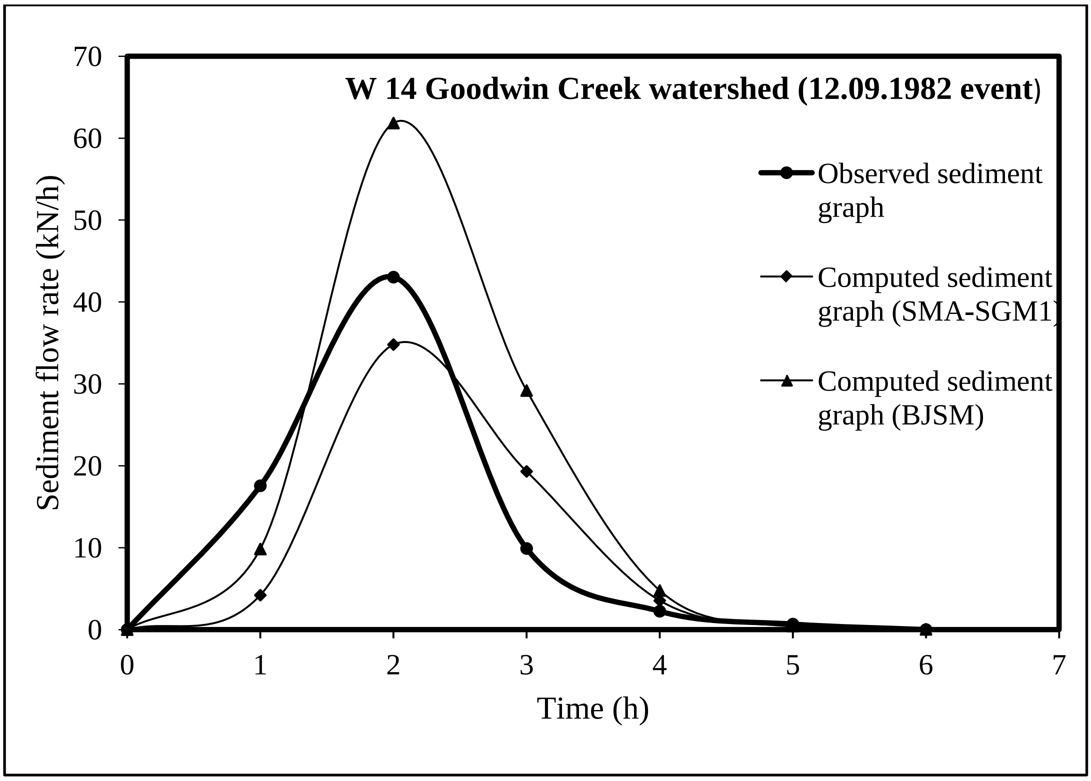
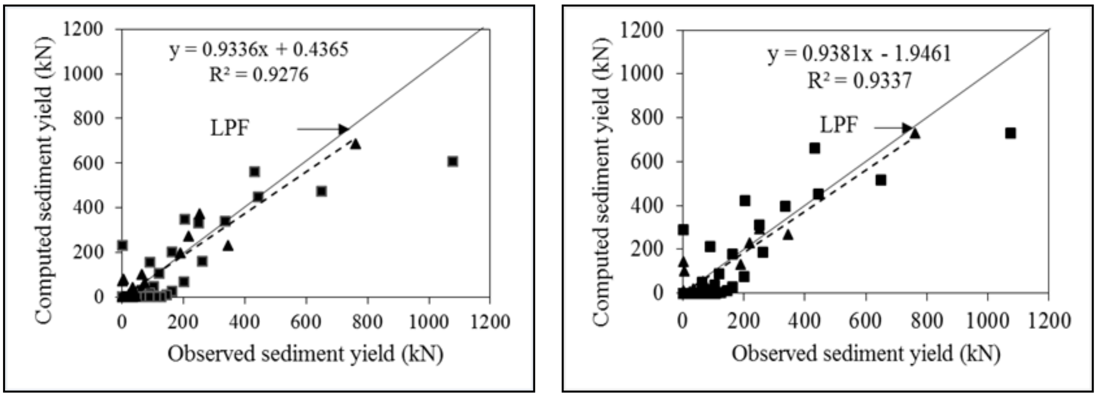
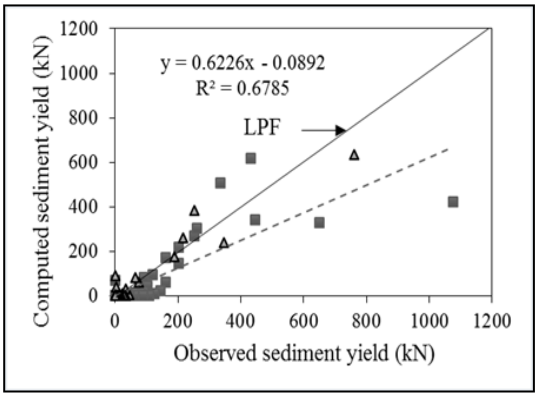


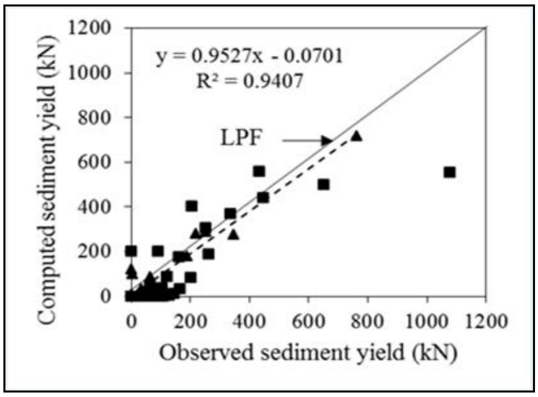
Figure-6.38: Comparison between SMA-SGM$_1$ and BJSM. (2010) models for validation of the models for W 14



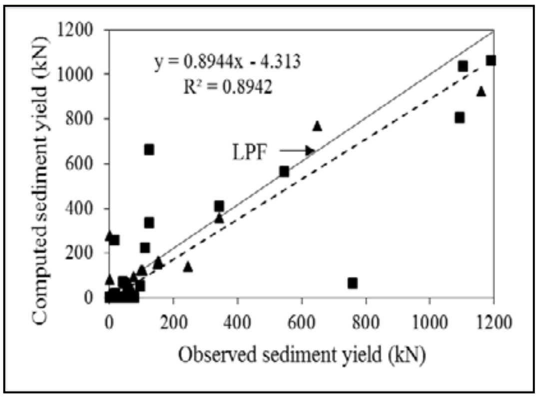
(a) Karso watershed (SMA-SGM$_1$) **(b) Karso watershed (SMA-SGM$_2$)**



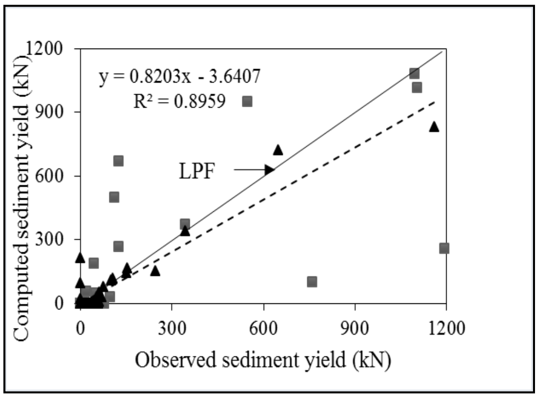
(c) Karso watershed (SMA-SGM$_3$)



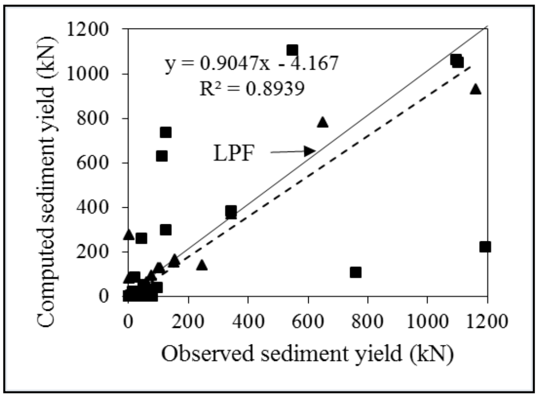
(d) Karso watershed (SMA-SGM$_4$)



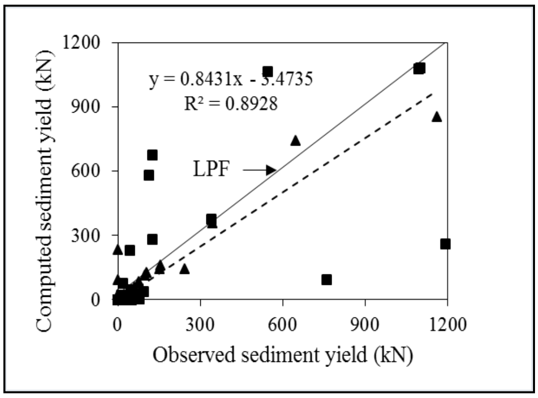
(a) Banha watershed (SMA-SGM$_1$)



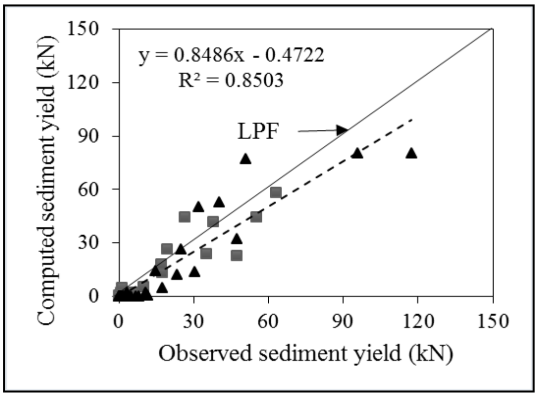
(b) Banha watershed (SMA-SGM$_2$)



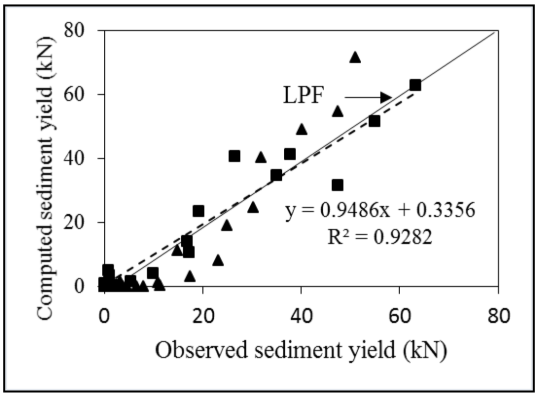
(c) Banha watershed (SMA-SGM$_3$)



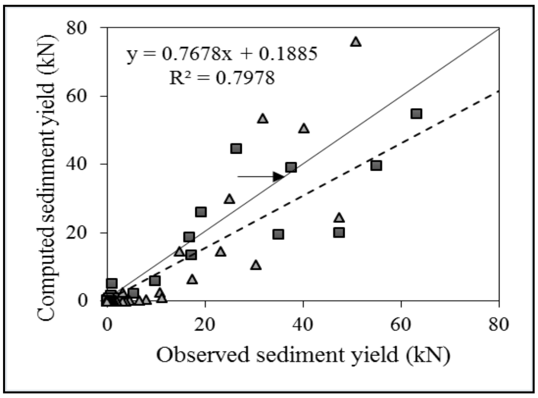
(d) Banha watershed (SMA-SGM$_4$)



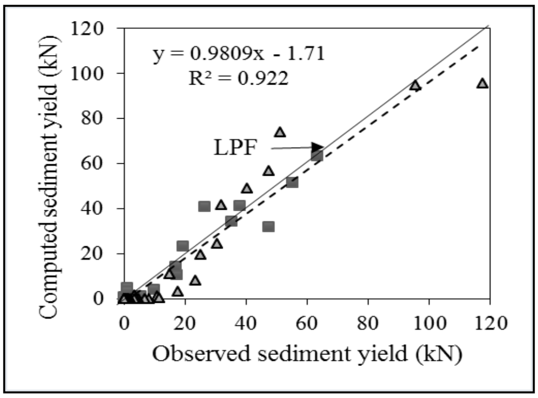
(a) Mansara watershed (SMA-SGM$_1$)



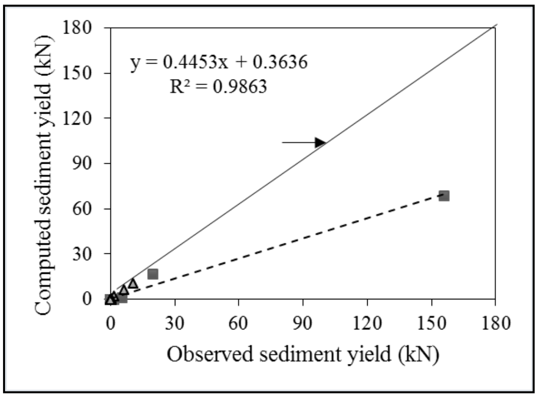
(b) Mansara watershed (SMA-SGM$_2$)



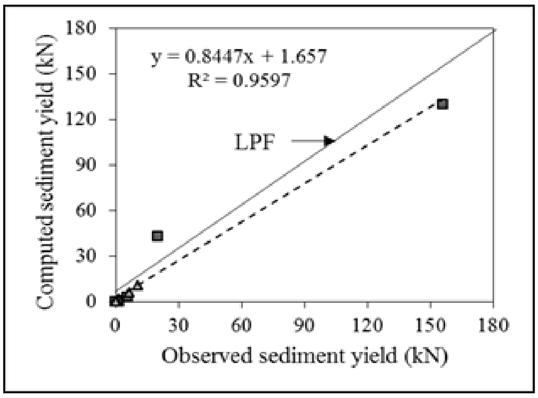
(c) Mansara watershed (SMA-SGM$_3$)



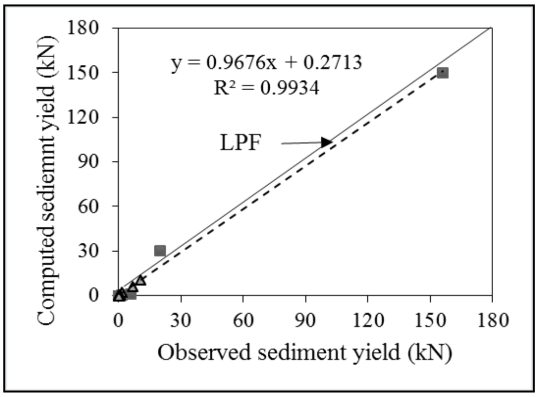
(d) Mansara watershed (SMA-SGM$_4$)



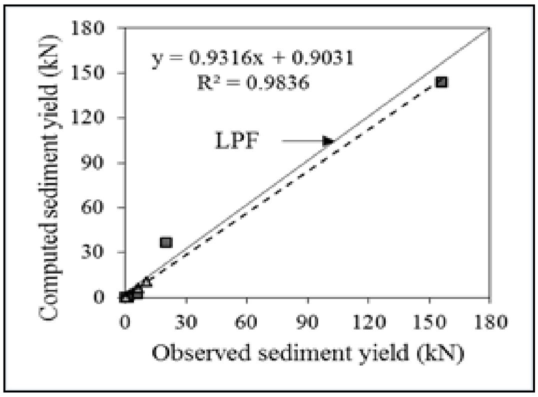
(a) W6 Goodwin Creek watershed (SMA-SGM$_1$)



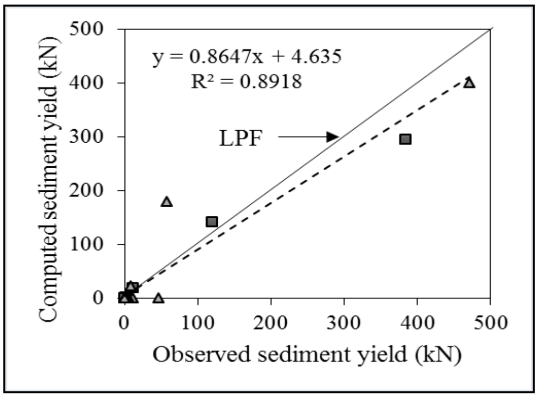
(b) W 6 Goodwin Creek watershed (SMA-SGM$_2$)



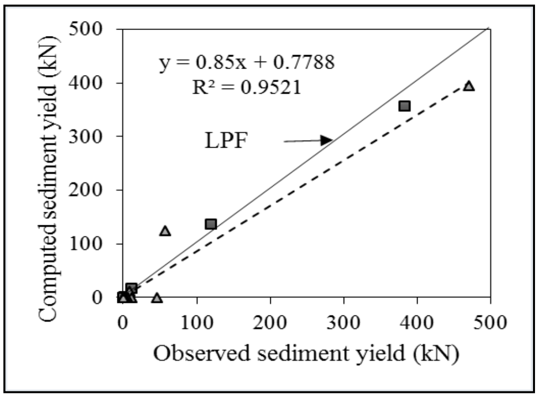
(c) W 6 Goodwin Creek watershed ($SMA-SGM_3$)



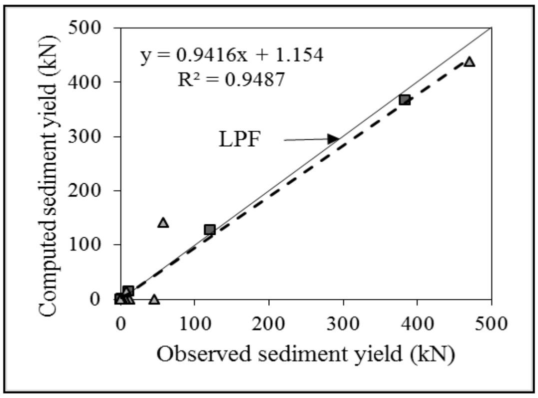
(d) W 6 Goodwin Creek watershed ($SMA-SGM_4$)



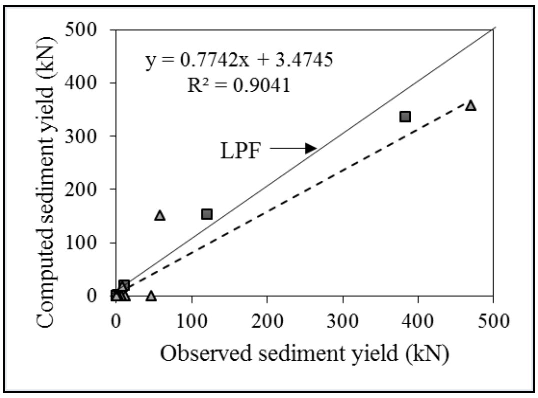
(a) W 7 Goodwin Creek watershed ($SMA-SGM_1$)



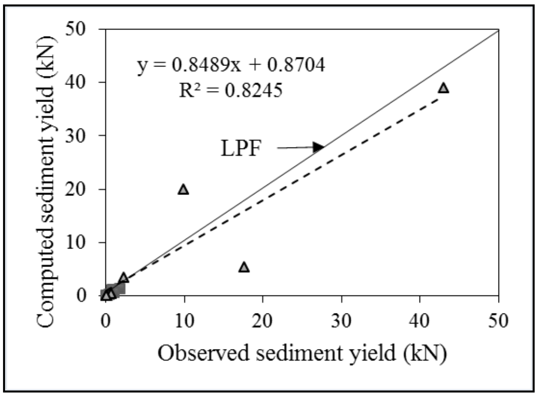
(b) W 7 Goodwin Creek watershed ($SMA-SGM_2$)



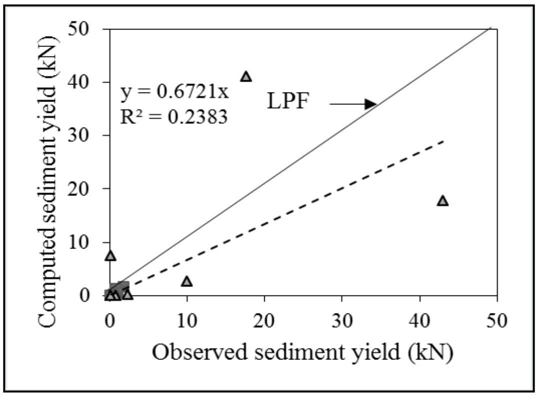
(c) W 7 Goodwin Creek watershed ($SMA-SGM_3$)



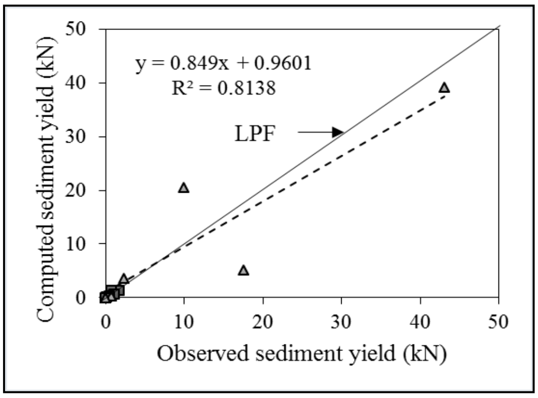
(d) W 7 Goodwin Creek watershed ($SMA-SGM_4$)



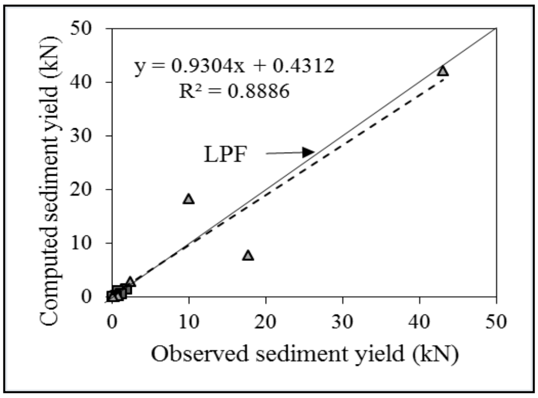
(a) W 14 Goodwin Creek watershed ($SMA\text{-}SGM_1$)



(b) W 14 Goodwin Creek watershed ($SMA\text{-}SGM_4$)



(c) W 14 Goodwin Creek watershed ($SMA\text{-}SGM_3$)



(d) W 14 Goodwin Creek watershed ($SMA\text{-}SGM_4$)

Figure-6.39: Comparison between computed and observed sediment yield for calibration of the model and validation proposed SMA-SGMs

CHAPTER 7
CONCLUSIONS

Sediment delivery is regarded as one of the most problematic off-site consequences of soil erosion is an extremely complex process. Many new and more sophisticated procedures have been developed for modeling sediment yield. Most of these models can be used only at the field scale and / or in small homogeneous watersheds. Physically based models are expected to provide reliable estimates of sediment yield. However, these models require a large number of input parameters and, therefore the practical application of such models is still limited. Keeping in view the scarce data availability for most of the watersheds in a developing country, simple models are needed for use in the field by water resource and conservation planners.

The models were developed using the well-accepted proportionality hypothesis of the SCS-CN method and SMA procedure were therefore extended to the sediment delivery ratio for developing the new sediment yield models. In developing the sediment graph models, the sediment yield was computed using the SCS-CN based SMA, IUSG and Nash's and Power law. In order to have confidence in its simulation ability, the models were first developed sediment yield model based on SMA for its performance in comparison with other existing Mishra et al. (2006) and Bhunya et al. (2010) models. The general applicability of the proposed sediment yield models were tested on the hydrologic and sediment yield data compiled from a number of watersheds located in India and USA. The summary of the research work, conclusions, major contribution of the study, recommendations and future scope of the study arrived at, are presented below

7.1 An Event Based Sediment Yield and Runoff Models Using Soil Moisture Accounting (SMA) Method

The new sediment yield and rainfall-runoff model coupling the SCS-CN method and SMA procedure for estimation of sediment yield and runoff for watersheds has been evolved and presented. The sediment yield model evolved uses the optimized parameters of static infiltration 'F_c' and potential maximum retention 'S' in the rainfall-runoff model for computation of runoff from the small watersheds.

The proposed sediment yield model the runoff coefficient equal to sediment delivery ratio this model applied to different hydro-meteorological data set. From the results and discussion and visual assessment show that the proposed model could be used both for field application and academic purposes. The salient features have discussed below:

1. An analytical development of sediment yield and runoff models were applied to a large set of rainfall-runoff and sediment yield data from 4 Indian watersheds and 8 USDA-ARS watersheds.
2. The proposed mathematical sediment yield (S2) and runoff (R2) models are based on SMA procedure therefore incorporating initial soil moisture and static infiltration.
3. The proposed sediment yield (S2) and runoff (R2) models predict the sediment yield and runoff, respectively with the NSE of 84.31 and 70.77 % for Karso, 74.55 and 70.86 % for Banha, 91.13 and 71.36 % for Nagwa, 80.03 and 92.48 % for Mansara, 89.40 and 66.43 % for Cincinnati, 83.46 and 78.44 % for W2, 80.54 and 82.44 % for W6, 80.32 and 58.28 % for W7, 87.97 and 64.46 % for W14, 79.05 and 64.82 % for 182, 88.42 and 55.23 % for 129 and 84.73 and 80.39 % for 123 watersheds respectively.
4. The proposed SMA based sediment yield (S2) and runoff (R2) models are simple and have only 3-parameters and 2-parameters models respectively. The computed parameters of sediment yield model of potential maximum retention (S) and static infiltration are utilized over proposed runoff model for estimation of direct surface runoff depth from all applications of the watersheds.
5. Therefore, proposed models computes higher NSE from all the watersheds as compared to other existing models.

7.2 Rainstorm-Generated Sediment Yield Model based on Soil Moisture Proxies (SMP)

The newly evolved sediment yield model is more applicable for estimation of sediment yield from small watersheds with the evidence of visual assessment and comparative analysis with Mishra et al. (2006) model. Therefore the advantage of proposed sediment yield model to reduce sudden jump of ‘CN’ for computation of sediment yield. Considering the integral effects of initial soil condition prior to rainfall and the initial abstraction after the rainfall and employing a new expression for continuous ‘S’ variation for each of the individual storms. In this thesis study identified the potential of soil moisture proxies an analytically derived sediment yield model that demonstrated encouraging results for the computation of sediment yield from all applications of the watersheds.

1. In the present study, the rainstorm-generated sediment yield model has been developed for quantification of sediment yield from small watersheds and found that it can be better interpreted by incorporating soil moisture proxies (SMP) in the lumped-based sediment yield model. It previous and after rainfall occurrence are utilized for model formulation.
2. The proposed sediment yield model computes higher sediment yield as compared to existing Mishra et al. (2006) model from small watersheds; the previous model overestimated the sediment yield.
3. The newly derived sediment yield model estimate the sediment yield which is in good agreement with the observed sediment yield from all application of the watersheds, based on all of the statistical indices as well as the visual assessment.
4. In this study, 4-parameters model has been proposed for computation of sediment yield based on SMP, therefore without soil moisture proxies the sediment yield model is undersized, as evidenced by comparatively higher PBAIS, nRMSE and lower NSE.

7.3 Sediment Graph Model based on Soil Moisture Accounting (SMA) Procedure

Coupling the SCS-CN method with the SMA, the time distributed model was developed for computation of sediment graph and sediment yield from a watershed. The coupling is based on SCS-CN method, SMA, Nash’s, IUSG and Power law. The proposed sediment graph models were applied to a large set of sediment yield data obtained from six watersheds of different land uses, size, climatic, physiographic and soil characteristics.

1. The analytical development of proposed sediment graph models incorporating simple and highly used models such as SMA, SCS-CN, Nash’s, IUSG, and Power law for computation of sediment graphs.
2. The proposed SMA-SGMs is conceptually and hydrologically sound for computation of sediment graphs as well as the total sediment yield from all applications of the watersheds.
3. The validation of the models the resulting NSE of proposed SMA-SGMs it varies from 67.89 to 99.56 %, 67.11 to 99.56 %, 67.57 to 99.52 % and 66.81 to 99.53 % for SMA-SGM_1 to SMA-SGM_4 respective models. Similarly the resulting NSE of calibration of the models it varies from 65.67 to 99.56 %, from 73.19 to 99.81 %, from 57.73 to 99.57 % and from 66.39 to 99.86 % for SMA-SGM_1 to SMA-SGM_4 models respectively.
4. Optimized parameters of the proposed SMA-SGMs are close to Mishra et al (2006), Singh et al. (2010) and Bhunya et al. (2010) models, therefore, the resulting peak sediment flow rate are overestimated during the validation events and rest of the underestimate from all storm events.
5. The proposed SMA-SGMs performs consistently better than BJSM model from all nineteen storm events. From statistical indices the NSE of BJSM model is lower than proposed SMA-SGMs, similarly, the RE of BJSM model is higher than proposed SMA-SGMs.

7.4 Major Contributions of the Study

The major contributions of the study can be summarized as follows:

1. Collection and compilation of hydrological and sediment yield data of twelve watersheds from different river catchments of India and USA that vary in size, physiographic, climatic, and land use characteristics. These data were collected from monitoring agencies, available literature and from internet resources.
2. Development of an event-based lumped sediment yield model and runoff model using soil moisture accounting (SMA) concept.

3. A simple procedure for estimating sediment yield using the soil moisture proxies (SMP) the input parameters before and after rainfall occurrences were utilized for model development.
4. Development of simple and conceptual, five, six, and seven parameters of sediment graph models based on SCS-CN method, SMA procedure, IUSG and Nash's and Power law for computing event sediment graphs.
5. Assessment of the applicability of the proposed sediment yields and sediment graph models on a number of watersheds varying in complexity and characteristics.

7.5 Recommendations

Following recommendation have been made based on the present study and given as below:

1. The combination of SCS-CN method and SMA/SMP can significantly improve the computation of sediment yield and runoff from the watershed. The SCS-CN method and SMA/SMP, can better interpreted for modeling of sediment yield.
2. In this study sediment yield and sediment graph models have been developed based on SMA/ SMP procedure insight into the behavior of the watersheds. These models can also be used on another watershed.
3. The proposed sediment yield and sediment graph models are conceptual basis for computation of sediment yield from all application of the watersheds. Hence two to seven parameters models have been developed in the present study.

7.6 Future Scope of the Study

The following suggestions are made for further scope of research and is listed as below:

1. Sensitivity analysis an important issue it's their role in rainfall-runoff and sediment yield modeling would provide a broader overview. In order to have broader overview the sensitivity analysis can also be carried out. Since rainfall-runoff-sediment yield modeling is complex this complexity increases further during monsoon period

2. Time distributed rainfall-runoff model based on Soil and Water Assessment Tool (SWAT), incorporating the SMP can be developed for enhancing the model capability.
3. Rainfall-Runoff and sediment yield models using Remote Sensing (RS) and Geographical Information System (GIS) technique with fine resolution data can also be develop for enhancing the model capabilities.

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Research papers

Soil Moisture Accounting (SMA) based sediment graph models for small watersheds

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Keywords:
Soil Moisture Accounting (SMA)
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ABSTRACT

The sediment graph models are useful for computation of sediment yield as well as total sediment out flow from watershed. In this study, the analytical development of proposed sediment graph models is based on Soil Moisture Accounting (SMA) procedure coupled Soil Conservation Service-Curve Number (SCS-CN) method, Nash's Instantaneous Unit Sediment Graph (IUSG)model and Power law. This coupling has led to the development of four sediment graph models (SGMs), i.e., SMA-SGM1, SMA-SGM2, SMA-SGM-3 and SMA-SGM4 depending on the four different hydrologic conditions as: (i) initial soil moisture (V_0) = 0 and initial abstraction (I_a) = 0, (ii) initial soil moisture (V_0) ≠ 0andinitialabstraction$I_a = 0$, (iii) initial soil moisture (V_0) = 0 and (I_a) ≠ 0, and (iv) initial soil moisture $(V_0) \neq 0$ *and* initial abstration $(I_a) \neq 0$, respectively. These models are applied on six natural watersheds with nineteen storm events having different land use/land cover, climatic condition (arid, semi-arid, humid and sub-tropical), rainfall and land slope conditions. The goodness-of-fit statistics is evaluated in terms of Nash Sutcliffe efficiency (NSE) and relative error (RE) between observed and simulated (calibrated and validated) sediment graphs. Further, the performance of these models is also compared with the sediment graph model of Bhunya et al. (2010) (BSGM) on all the six study watersheds. It is found that the proposed models perform very well in simulating sediment yield generation process for all the watersheds and show significant improvement over the BSGM model.

1. Introduction

Time-distributed sediment yield modeling has paramount importance in hydrology, water resources and environmental engineering. It has been recognized to be fundamental to a range of applications such as river morphology, natural resource conservation planning, land management, soil and water conservation and agricultural and water resource planning. The process of sediment yield generation is extremely complex and mainly consists of detachment and transport of sediment particles by raindrop and runoff (Tyagi et al., 2008). The sediment yield modeling is more complex as compared to other types of watershed modeling, as it arises from a complex interaction of several hydro-geological processes, and the knowledge of the actual process and extent of suspended materials is far less detailed (Bennett, 1974).

The sediment flow rate plotted as a function of time during a storm at a given location is known as sediment graph. Without a sediment graph, only the average sediment rate for the storm can be computed. The average sediment yield is not adequate for computing dynamic suspended sediment load and pollutants load during the storm (Raghuwansh et al., 1994). Rendon-Herrero (1978) developed a sediment graph model based on unit sediment graphs (USG) approach defined as the unit sediment graph generated from one unit of sediment for a given duration distributed uniformly over a watershed.

The sediment yield models can be classified into three groups: (1) lumped, (2) quasi-lumped and (3) distributed (Singh et al., 2015a, 2015b). Probably the most widely used lumped model for estimating sediment yield from small agricultural watersheds (agricultural, forest, and urban) is the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978). To apply USLE to large watersheds, the concept of sediment delivery ratio (ratio of sediment generated to the amount of erosion) has been incorporated. Another lumped sediment yield model was developed by Mishra et al. (2006a, 2006b) by coupling the Soil Conservation Service Curve Number (SCS-CN) method (SCS, 1956) and USLE. Later on, a sediment yield was developed by Tyagi et al. (2008) by utilizing the SCS-CN based infiltration model for computation of rainfall-excess rate and the SCS-CN-inspired

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An Event-Based Sediment Yield and Runoff Modeling Using Soil Moisture Balance/Budgeting (SMB) Method

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Abstract
The Soil Conservation Service Curve Number (SCS-CN) method is frequently used for the estimation of direct surface runoff depth from the small watersheds. Coupling the SCS-CN method with the Soil Moisture Balance (SMB) method, new simple 2-parameters rainfall-runoff model and 3-parametrs rainfall-sediment yield models are derived for computation of runoff and sediment yield respectively. The proposed runoff (R2) and sediment yield (S2) models have been tested on a large set of rainfall-runoff and sediment yield data (98 storm events) obtained from twelve watersheds from different land use/land cover, soil and climatic conditions. The improved runoff (R2) and sediment yield (S2) models show superior results as compared to the existing Mishra et al. (S1) and original SCS-CN (R1) models. The results and analysis justify the use of the proposed models for field applications.

Keywords Sediment yield model · Rainfall-runoff model · SMB · Watershed

1 Introduction

Estimation of runoff and sediment yield is of paramount importance in water resources, environmental engineering and hydrology. The estimates of these variables are mainly required for assessing the water resources, planning of soil and water conservation structures, and for assessing the impact of climate change on watershed output (Mishra and Singh, 1999). The

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