Impact of Rainfall Variability on Reservoir Sedimentation

Thesis submitted to the Andhra University, Visakhapatnam in partial fulfillment of the requirement for the award of ***Master of Technology in Remote Sensing and GIS***

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CERTIFICATE

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TO

MY PARENTS

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ABSTRACT

Reservoirs are the key infrastructure for the socio-economic development of a country. The reservoir construction may prove to be a solution for remediation of highly erratic spatial and temporal availability of water. The growth in population and consequent developmental activities within a catchment area has shown to aggravate the problem of sedimentation which comprised of erosion, sediment transport and its deposition in reservoirs. Among all above mentioned, reservoir sediment deposition is most important as it reduces its useful life and impairs the purposes of these vast water resource. The volume of sediment deposited in a reservoir is usually quantified through hydrographic surveys, which are very expensive, cumbersome and time consuming. A comprehensive reservoir sedimentation study has been proposed in the present study, through modelling of reservoir catchment sediment yield. Major advances have been made in understanding the significance of factors involved in reservoir sedimentation. However effect of rainfall variability on reservoir sedimentation is not evaluated using spatially distributed sediment routing coupled soil erosion model. Rainfall variability mainly deals with the changes in kinetic energy and it is directly proportional to the rainfall intensity. Changes in rainfall intensity affect the runoff, detachment of soil particles, erosion, and transport, which affects the sedimentation yield of a stream. Due to the change of climatic condition there is an enormous effect on various parts of hydrological system such as decrease in number of rainy days, whereas increases in extreme events, leading to rise of erosion, consequently sediment transport increases.

Erosion assessment using Modified Morgan-Morgan-Finney model (2008) has not been operationally applied in reservoir sedimentation studies. In this study, this model will be used for evaluating sediment yield of a sub watershed which is close to Gobind Sagar reservoir (Satluj river basin). Estimation of total kinetic energy has been carried out in the present study, after estimation of the kinetic energy, by varying the intensity of erosive rain model will find out variation in the final sediment yield at the outlet. In sediment yield estimation model incorporates particle size selectivity in the process of erosion, transport and deposition. These processes are simulated separately for clay, silt and sand. This model also takes sediment routing into account, which increases sediment yield prediction accuracy and allows determination of sub-watershed contributions to the total sediment yield.

A set of factors as identified in the modified MMF model were studied & reviewed. These include land cover, soil, and topography. Each factor which consists of a set of logically related geographic features and attributes, which will be used as data input for analysis. The factor layers are collected from existing literature and data is extracted from ASTER – DEM, LULC maps (ISRO-GBP LULC project) and soil texture as well as soil parameters (NBSSLUP). Each of the above mentioned Modified MMF input parameters, with associated attributed data, will be digitally encoded in GIS database to eventually create input thematic layers for MMF model. Further work in this regards enumerates, Modified MMF model development in geospatial framework, sediment routing with pixel base soil erosion model to estimate actual sediment yield at the outlet, estimation of sediment yield of a part of Satluj river basin, and assessment of effect of rainfall variability on reservoir sedimentation. It has been noticed that with increase in rainfall intensity and decrease in rainy day would increase sedimentation rate of the reservoirs.

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LIST OF NOTATIONS

Notations	Description
R	Mean Annual Rainfall
Rf	Effective Rainfall
I	Rainfall Intensity
Nf	Particle Fall Number
*V*s	Fall Velocity
LIST OF VARIABLES USED IN A PYTHON CODE	
Variables	**Description**
fdr	Flow direction map
fac	Flow accumulation map
rf	Effective rainfall map
rc	Soil moisture storage capacity map
ro	Mean annual rain/rainy day map
R	Interpolated mean annual rainfall map
E	Evaporation map
LP	Lateral permeability map
sins	Sin of slope map
Q	Total runoff generated at the outlet map
Qe	Runoff generated at particular pixel map
IF	Interflow map
mx	Maximum value of flow accumulation map
arr	Array generated for various flow accumulation values
SLnew	Delivery of detached particles to runoff
DEP	Deposition maps for various textural class
Tcnew	Transport capacity maps for various textural class
SL	Total soil loss map
[a,b]	Pixel location of various maps

LIST OF ABBREVIATIONS

Abbreviations/Symbols	**Description**
MMF	Morgan-Morgan-Finney
USLE	Universal Soil Loss Equation
AGNPS	Agriculture Non-Point Source
LISEM	Limburg Soil Erosion Model
WEPP	Watershed Erosion Prediction Project
BBMB	Bhakra Beas Management Board
SJVN	Satluj Jal Vidyut Nigam
IDW	Inverse Distance Weighting
NBSS&LUP	National Bureau of Soil Survey and Landuse Planning
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
CE	Contributing Element
KE	Kinetic Energy
IF	Interflow
DEP	Deposition
TC	Transport Capacity

CHAPTER – 1
INTRODUCTION

1.1 Background

Balanced ecosystems including soil, water and plant environments are essential for the survival and welfare of mankind. However, in the past due to over exploitation in many parts of the world, including some parts of India the ecosystems have been distressed. The resulting imbalance in the ecosystem is revealed through various undesirable effects, such as soil surface degradation, frequent occurrence of intense floods etc. For example, the large scale deforestation which occurred in the Shiwalik ranges of the Indian Himalayas during 1960s caused the soil on the land surfaces to be directly exposed to the rains (Kothyari, 1996). This unprotected soil was readily removed from the land surface in the fragile Shiwaliks by the combined action of rain and resulting flow (Kothyari, 1996). It has also been reported that due to climate change, there is enormous effect on rainfall events (Kumar *et al.*, 2010). Because of rainfall variability, it has been seen that in last 10 -12 years, there were many extreme events have been occurred (Ghosh *et al.,* 2012). These extreme events are highly responsible for soil erosion and sedimentation process. A thorough knowledge and understanding of the different hydrological phenomena and soil erosion processes as a whole is required in studying the implications of these changes.

1.2 Types of Erosion

During the entire erosion process six types of erosion take place at different stages. It starts with splash erosion as the raindrops are falling from cloud at high velocities and detach the soil from surface. Once the raindrop hits the soil surface, it compact the soil directly under the drop and disperses the detached soil particles that are on the side. These soil particles can travel as far as 2-3 feet vertically and up to 5 feet horizontally. On a slopy surface over half of this material travels down the slope. Hence, as one can imagine in a heavy storm millions of these raindrops hit the slope and millions of soil particles moves towards downstream.

Detachment or losing of soil particles caused by raindrop impact begins to flow in the overland flow. As the rain continues, the raindrops continue to pummel the soil into smaller and smaller particles. If the particle size is smaller than the other, it moves faster in the runoff. Because of the raindrop splashes, particle transport downhill to result in the next stage of erosion. Effect of sheet erosion is relatively slow and uniform therefore it may go unnoticed.

After some time sheet erosion deteriorates to form small grooves on the slope, this starts a new type of erosion called rill erosion. Creation of small channels due to the runoff is called rills. As the runoff velocity increases, it's transport capacity increase. It means it can carry large amount of detached particles.

The next form of the erosion is gully erosion, which is an extremity of rill erosion. Large channels allow more amount of water to move swiftly and these large amounts of water can pick up even more soil.

When the runoff reaches the main channel, the erosion process does not stop and the next form of erosion starts. Erosion along the bank of the channel happens, because of which channels start meandering. The water cuts into the bank and erodes the soil.

The last stage of erosion is deposition of soil particles. Deposition usually happens in the lakes, reservoirs, ponds, estuaries and deltas. As the channels bed slope decreases, the velocity of the water decreases, this leads to the settlement of the soil particles. As the channel effectively decreases its own slope, then slower the water velocity, more the sediment deposits. This cycle intensifies the settling process.

Rates of soil erosion mainly depend upon the soil properties and its characteristics. Some soils are extremely vulnerable and sensitive to erosion while some are not. The main factor affecting the soil erosion is texture, organic matter content, structure, and permeability (Steiner, 1987). In the clay soil, the particles have the property to adhere to themselves in such a way that they reduce the erosion susceptibility. In general, smaller soil particles, travel longer distance than bigger one.

1.3 Soil Erosion Modeling

Soil erosion modeling is a mathematical representation of natural processes that influence primarily the movement of water and soil of a watershed. In general three types of models exist: Empirical or statistical, conceptual and physical based model.

Empirical models are generally the simplest models other than remaining. These models are primarily based on the analysis of observation and seek to characterize response from these data (Wheater *et al.,* 1993). Data requirement and computation for such models are usually less than from the conceptual and physical based models. Jakeman *et al.,* (1999) state that 'the feature of this class of models is their high level of spatial and temporal aggregation and their incorporation of a small number of causal variables', several empirical models are based on the analysis of catchment data using stochastic methods, and as such are ideal tools for the analysis of data in catchments (Wheater *et al.,* 1993). However, preferably empirical models are frequently used rather than the other models, as they can be implemented in situation with limited data and parameter inputs. This model is useful as a first step in identifying sources of sediment generation.

Conceptual models represent the catchments as a series of internal storages. These models incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure, as a series of storages these models representing flow paths in the catchment. Conceptual models lean towards to include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information (Sorooshian, 1991). With the help of these factors, conceptual models are provide an indication of the qualitative and quantitative effects of land use changes, without large amounts of spatially and temporally distributed input data.

Physically based models are based on the solution of fundamental equation describing various soil erosion processes like rainfall, runoff, detachment, deposition and associated sediment balance in a watershed. Standard equations used in such models are the equations of conservation of mass and momentum for flow and the equation of conservation of mass for sediment (Bennett, 1974). In theory all the input parameters for models are measurable and well known but in practice, the large number of parameters are involved and the heterogeneity of important characteristics in case of catchment are main factor, to overcome these problems parameters must often be calibrated against observed data (Beck *et al.,* 1995; Wheater *et al.,* 1993).

The fundamental objective of erosion modeling is to understand the causes, make predictions, and plan how to implement preventative and restorative strategies. Extraction of maximum amount of information from the available data, help user for decision making and model works better when correctly chosen and adjusted. Models are gradually used in hydrology to simulate changes in watershed management, to evaluate the impacts of natural influences (climate change and land cover change). They can be used to estimate discharge at ungauged sites, fill gaps in broken data with respect to longer records of rainfall. Complex spatially-distributed models are based on physical principles, but they need large data to be used effectively. There are many erosion and sediment yield models are available but skill is in selecting the right model for their job, efficient model calibration, and implementation for best outcome.

1.4 Geographical Information System and Soil Erosion Modeling

A Geographic Information System (GIS) is an arrangement of computer, hardware, software, and geographic data. GIS is a system that capture, store, integrates, analyzes, manages, and visualizes data that are linked to coordinates or location and it is a combination of statistical analysis, database and cartography that allows the user to identify geographic information, relationship, patterns and trends (Omar, 2010).

GIS provides representations of spatial features of the Earth, while soil erosion modeling is concerned with the flow of water and its constituents over the land surface and in the subsurface environment. GIS have been used in various environment applications since 1970s; however, extensive application of GIS to hydrologic, hydraulic modeling and flood mapping, management did not being until the early 1990s (Moore *et al.,* 1991; Vieux and Gauer, 1994; Maidment and Djokic, 2000).

Combining data of different types in a GIS has led to major increase in its use in soil erosion modeling. It also provides the opportunities to combine a data from different sources and different types. One of the typical applications is use of a digital elevation model (DEM) for extraction of hydrologic catchment properties such as elevation, basin boundary delineation, flow direction map, flow accumulation map, slope, aspect etc. For large scale, GIS coupled physically based distributed models are a most important tool for parameterization purpose. The extensive use of such models is increasing due to the significant development taking place in GIS domain. The primary limiting factor in soil erosion modeling is to provide the model parameters representing the flow environment accurately. The other factors which too affect are the ability to characterize erosion processes mathematically and to solve the resulting equations. The GIS will be an asset to overcome these limitations.

1.5 Remote Sensing and Soil Erosion Modeling

Satellite imageries are playing important role on soil erosion estimation efficiently. Remote sensing data has been used in soil erosion modeling such as land use land cover, DEM (Ustun, 2008; Gitas *et al.,* 2009). For the soil erosion estimation various model has been applied in hill slopes, field size scale, catchment scale and basin scale. In various erosion models user needs to define many input parameters such as temperature, rainfall, slope, aspect, soil type, drainage, and land use/land cover. These parameters can be derived from satellite imageries; this is the main advantage of remote sensing in the field of soil erosion modeling. In other way use of Multi temporal satellite imageries such as LANDSAT7 has been used to find out the input parameter for the selected model i.e. NDVI in different time scale for soil erosion risk mapping (Gitas *et al.,* 2009), rather than this LANDSAT8, LISS-III, LISS-IV imageries can also be used for better results. Remote sensing data give a better insight and understanding of erosion modeling in a respective study area and this facilitates the comparison of soil erosion at various locations very efficiently. Rainfall which is the prime input for soil erosion estimation, remote sensing data such as TRMM (Tropical Rainfall Measuring Mission) providing rainfall for a broad scale not for the point scale measurement as in the in-situ data. DEM is also obtained from remote sensing, this help user to define the pathways taken by flow, slope, and aspect (Sharma and Singh, 1995). The use of remote sensing techniques with the soil erosion model provides not only new possibilities for planning, but also new possibilities for predicting runoff and soil erosion at the various scale of the landscape.

1.6 Relevance of the Study Undertaken

Soil erosion and reservoir sedimentation process directly dependent upon each other. Sediment particles originating from the erosion processes in a catchment are propagating along with the river flow. When the reservoir comes on the path or river, the sediment settles in the reservoir and reduces its capacity. Thus assessment of sediment deposition becomes very important for the management and operation of such reservoirs. Developing simple methods, for assessment of erosion and sedimentation with the help of remote sensing and GIS is must. Relating to these issues (Jain el al., 2002), compared the rate of sedimentation assessed using the remote sensing and GIS based approach and the results obtained from the hydrographic survey.

The Satluj river basin covering major parts of Nari Khorsam region in Tibet, certain portion of China and remaining part of India (Himachal Pradesh) has been repetitively facing the adverse hydro- meteorological conditions such as cloud burst, land sliding, floods etc. in the recant times. A relationship between sediment yield and discharge has been established using three years daily discharge and sediment data at present study area (Jain *et al.*, 2003). The developed relationship was used to simulate the sediment yield for two different years. Generally USLE (Universal Soil Loss Equation), RUSLE (Revised Universal Soil Loss Equation), MUSLE (Modified Universal Soil Loss Equation) are used for erosion studies (Jones *et al.*, 1996; Di Stefano *et al.*, 2000; Ustun, 2008; Gitas *et al.*, 2009; Jain and Das, 2009). Even Morgan-Morgan-Finney model and modified MMF have been used (Morgan, 1982; Morgan *et al.*, 1998; Morgan, 2001) but there is a number of limitations in the previous models such as USLE applies only to sheet erosion since the source of energy is rain; so it never applies to linear or mass erosion, the relations between kinetic energy and rainfall intensity generally used in this model apply only to the American Great Plains, and not to mountainous regions (Kinnell and Risse, 1998). Estimation of soil erosion using RUSLE mainly affect by the individual locations because there is a change in the specific factors which have been used in RUSLE (Renard *et al.*, 1991). MUSLE model has been developed for estimating the sediment load produced by each storm, which takes into account not rainfall erosivity but the volume of runoff but it also has some limitation such as it is not incorporating detachment by runoff and raindrop impact (Arekhi *et al.*, 2012). However, for Satluj basin estimation of sedimentation rate in Bhakra reservoir has been carried out using remote sensing (Jain el al., 2002). It is only for the reservoir and no catchment study has been done Conventional method has been adopted for their work to identify the water pixels and computation of the capacity of the reservoir.

It has been seen that there is large variation in rainfall pattern in the basin of this sediment laden river. Therefore, it is necessary to study erosion, sediment yield and impact of rainfall variability on sediment yield of this basin. As most of the part of region is difficult to access, remote sensing technique may be very useful for the study. There is a need to identify suitable erosion and sediment yield model for the study. A detailed description on methodology adopted for carrying out this study is provided in the further chapter. In the present study, an attempt has been made to estimate erosion in catchment using Morgan-Morgan-Finney model (Morgan and Duzant, 2008). The model simulates the movement of water and sediment over the landscape from source to delivery to the river system. In this model the catchment has been divided into elements (pixel, grid) for routing procedure, each element being reasonably uniform in its soil type, slope and land cover. User needs to define the pathways taken by water and sediment from one element to another. For more complicated arrangements this model can be applied, whereby discharge is proportioned between two or more downslope elements and individual elements.

As compared to other soil erosion models, Modified MMF (Morgan and Duzant, 2008) model's distinguishing features are

- Modified MMF model incorporates effects of vegetation cover on erosion prediction and it can be expressed through measurable vegetation parameters.
- This model performs particle size selectivity in the processes of detachment, transport, and deposition. These processes are simulated separately for clay, silt and sand.
- In Modified MMF deposition is modeled through a particle fall number (Tollner, 1973) which takes into account of particle settling velocity, flow velocity, flow depth and slope length.
- There is no need to use a voluminous data in this respective model and it is very simple to couple with GIS, moreover it is always an ease to work with geospatial domain as the main perspective of the research.
- The aspect of routing of runoff and sediment has been performed via programming (PYTHON 2.6.5) which is further been used in the GIS environment.
- Modified MMF incorporates erosion due to rainfall and it has been observed that erosion and sedimentation varies with rainfall change. Using this model the effect of change in rainfall pattern and its probable effect on soil erosion and sedimentation can be find out.

1.7 Research Questions

In the present study there is a need to find out the answers of following questions:

- How to estimate actual sediment yield from pixel based erosion model?
- What will be the effect of rainfall variability on sediment yield as well as reservoir sedimentation?

1.8 Research Objectives

A number of studies have been applied for evaluating sediment in the reservoir. The associations of soil erosion modeling as well as reservoir sedimentation studies can be extremely useful in determining how much soil is being eroded, and what type of material is being eroded. This study will attempt to show how much as well as what types of particles are being eroded from the watershed and then transported and deposited in the associated reservoir. This entire study will be useful for watershed management and the reservoir in addition to predicting how much and what type of sediment will be trapped by the reservoir. The objectives of this research are as follows:

- To couple sediment routing with pixel based soil erosion model, to estimate actual sediment yield at the outlet.

- To evaluate the effect of rainfall variability on sediment yield as well as reservoir sedimentation.

1.9 Organisation of Report

Thesis is broadly divided into six different chapters each pertaining to an important theme of the research work. The introduction, providing an overview of the subject is discussed in the present chapter.

Second chapter deals with the review of literatures that is study of various papers, journals and books for the soul purpose of fulfilling the objectives. Review of literature is done for selecting an appropriate model for the present study and the model is related with rainfall variability.

The third chapter is the respective study area which gives the description of the region on which the present work is established.

Fourth chapter explains about the method applied to get the outputs as per the requirements. The detailed step by step explanation is discussed in this chapter.

Results and discussions are explained in the fifth chapter, where the outputs and the related discussion are mentioned in this chapter.

Conclusions and the future scope is the last chapter. This chapter concludes the complete work and provides recommendations for some future modifications and improvements.

CHAPTER – 2
LITERATURE REVIEW

This chapter delivers information related to soil erosion and sedimentation process, contributing factors of soil erosion, and erosion modeling. Initially, reviews of existing models are cited. Various soil erosion models are explained, and selection of an appropriate model structure for this study is established. In the interim a brief review of popular soil erosion and sediment yield model is done. There is a short description of the selected model. Whereas, role of remote sensing and GIS in soil erosion and sedimentation process have been reviewed extensively. Special attention is directed towards impact of rainfall variability on soil erosion and sediment yield of a watershed.

2.1 Soil Erosion and Sedimentation

It is believed that deposition of sediment in the reservoir, occur from watershed erosion. Soil erosion is a very complex subject, not only the mechanism is complex to determine but the process of erosion as well, because it depends upon several different criteria. As mentioned in Chapter- 1, there are several different types of erosion, those describe soil erosion and detachments of particles are depending upon the types of erosion. Various influencing factors contribute to soil erosion problem are rainfall pattern, topography, land cover conditions, erosion-prone soil properties, climate and inappropriate agricultural practices (Irvem *et al.,* 2007; Hessel and Jetten, 2007; Vrieling *et al.*, 2008) has described that soil erosion can occur in areas when the soil is erodible, the terrain is sloped and high-intensity rainfall coincides with limited vegetation cover. Sediment transport in a water bodies are a big threat for reservoirs and water storage structures which are present in that area, to overcome these problems many researches have been carried out the study of soil erosion mechanisms to develop methods that avoids sediment transport to water bodies (de Vente *et al.,* 2008).

2.2 Model Types

Soil erosion and sediment transport models exist in a wide range. These models differ in terms of complexity, process considered and the data required for model calibration and validation (Merritt *et al.*, 2003). Many researchers have been work on these models and conclude that there is no 'best' model for all applications. The most suitable model will depend upon the intended use and catchment characteristics. Other factors affecting the selection of model are as follows:

- Spatial and temporal variation of model input and output as well as data requirements of the model;

- Model assumptions, accuracy and validity;
- Model components (input parameters) and data availability;
- Scales at which model outputs are required, objective of the user including the ease of use of the model and
- Hardware requirements.

In general, there are three main categories, depending on the physical process simulated by the model, the model algorithms and the data dependence of the model:

- Empirical
- Conceptual
- Physical based model

2.2.1 Empirical Models

This is the simplest model among all type of models. Comparison of model types, general definition, model characteristics and data requirements have been discussed in Chapter- 1. Empirical models are frequently condemned for utilizing unrealistic assumptions about the physics of the catchment system by ignoring the heterogeneity imbibed in the catchment inputs and its characteristics, such as rainfall and soil types, as well as ignoring the inherent non-linearities in the catchment system (Wheater *et al.*, 1993). The overlaying criticism as insufficient meteorological networks and the spatial heterogeneities of soil infers that, there is a need for more complex and dynamic models which are no more superior to empirical models (Merritt *et al.*, 2003). These models are based on the assumption that underlying conditions remain unchanged for the duration of the study period. This assumption limits the potential for such models to be applied for prediction of the catchment changes. Empirical models has a limitation that, they are not event-responsive, ignoring the processes of rainfall-runoff in the catchment to be modeled.

However, these models are frequently used over more complex models as they can be implemented with limited data and input parameters, and useful in identifying sources of sediment generation. At the regional scale, ‘patterns of sediment delivery and sediment residence time remain poorly understood’ (Ian P. Prosser *et al.*, 2001). Hence, empirical methods which are applied uniformly in a region, is used for prediction of sediment delivery observation.

2.2.2 Conceptual Models

This model has lump representative processes over the scale at which outputs are simulated (Wheater *et al.*, 1993). Conceptual models which developed recently have provided outputs in a spatially distributed manner. Alternatively, lumped conceptual model may be applied in a semi-distributed form by dividing an entire catchment into linked sub catchments.

In this model parameter values have typically been obtained by calibration against observed data, such as stream discharge and concentration measurements (Abbott *et al.,* 1986). Calibration against observed data fulfill the requirement of that parameters, conceptual model suffers with the problem related to ability of identification of their parameter values (Jakeman *et al.,* 1999). Simple conceptual models have fewer problems associated with model identification then more complex models (Merritt *et al.,* 2003). Therefore, model identification problems can be minimized through limiting the parameters to be estimated through calibration and identifying additional parameters based on prior knowledge of the system (Kleissen *et al.*, 1990).

2.2.3 Physical Based Models

Physical based models depend upon the solution of the physical equation associated with stream flow, runoff generation, detachment, deposition and sediment balance. General description has been given in Chapter- 1. Limitation and working constrain have been described by various researchers. In several physics-based models there is a need to set numerous assumptions for describing individual process using mathematical expressions but that may not be relevant in many real world situations (Dunin, 1975). Generally, these equations are derived from related processes and required very specific physical conditions (Beven, 1989). But in practice, these equations are used in comparatively large scale and different physical conditions. The equation has been derived for use with temporal and spatial data, but the data used in practice is often point source data which represent an entire grid cell in the catchment. Use of this kind of physical based model is questionable (Beven, 1989).

Error accumulation is necessary to be controlled in various physical based models, which transfer output fluxes from one spatial element to the next as input. The finer the spatial scale of a model more number errors will increase in such transfers.

2.2.4 Selecting an Appropriate Model Structure

Each model type having a purpose and a particular model may not be more appropriate than others in all situations. Model suitability heavily depends upon the function that the model needs to serve.

From the literature review, the preferences of researchers for various model types over others, having two main views: working process of entire model or emphasis on the output. For example, Thorsen *et al.,* (2001) considered that ‘the predictive capability of empirical and conceptual models with regards to assessing the impacts of alternative agricultural practices is questionable, due to the semi-empirical nature of the process description’. However, other authors discuss that when simple conceptual models or empirical models, used within the developed framework, can be precise than models with more complicated structures (Ferro and Minacapilli, 1995; Letcher *et al.*, 1999). It has been noted that models having large number of input parameters yield a better fit to observed data during model calibration than other simple models. Simple models providing more stable performances than complicated models and tends to be more robust. In this way more complicated models with large numbers of processes, and associated parameters having an uncertainty associated with the model inputs, these uncertainties may avoid more realistic representation of the processes.

2.2.4.1 Distributed v/s Lumped Modeling

For categorizing the range of models it is necessary to identify the area where they applied; whether the model considers processes and parameters to be lumped or distributed. Usually, models have treated input parameters as lumped over the study area. Distributed approaches have become more feasible with the increasing in computing powers.

Distributed models show the spatial variability of various processes and outputs in the catchment. Distributed approaches are best fit for sediment transport modeling. In a catchment each sediment source is characterized by its travel time. The dependency of sediment delivery process on local factors, such as detachment, transport and flow transport travel time etc., for modeling this phenomenon there is a need to use a spatially distributed approach (Ferro and Minacapilli, 1995). While applying the spatially distributed criteria at the basin scale, the requirement for the sediment delivery process is both, a soil erosion model and a spatial disaggregation system. Parametric models are favored over the physical models as these models are data-intensive, and the scale of measurements are generally not at the scale of basin discretization for most model applications.

Semi- distributed models break a catchment down into a group of sub-watersheds / sub catchments and on the basis of other biophysical regions over the entire watershed, these properties help the user to compromise between distributed and lumped models. Finally the model selection between lumped and distributed depends on the preferred output and nature of parameters required.

2.2.4.2 Temporal Resolution

Timing of the events and time scale that the end user wants to predict is a key consideration in determining most suitable model for application. Sediment associated erosion models have been developed from two opposite point of view. For single storm event, event based models were developed. For each event, the time step is minutes to hours. These models were often developed for small plots or grid cell application in a catchment. Instead of a high temporal difference was used and models were used to identify broad trends over time to changes in, rainfall, land use land cover and vegetation. Third approach was to apply a continuous time step, generally daily, for example, recession of saturated zones can be estimated at this time step, however does not capture responses to intense rainfall and short duration events.

Many models originally developed for applying in a single event condition (e.g. AGNPS or ANSWERS) and they have undergone modifications and can now be applied as continuous imitations. Shifting of models from event based to continuous simulation causing problems.

2.3 Existing Model Reviews

A brief review of some popular soil erosion and sediment yield models being used is presented.

2.3.1 USLE and Modifications

The Universal Soil Loss Equation (USLE) is an empirical model and used for estimation of annual soil loss over the world, this model used widely within the United States. USLE developed in 1970s by USDA; many modifications have been made in USLE (Kinnell and Risse, 1998). The model has also been modified for taking into account additional information (RUSLE, Renard *et al.,* 1991). While developed for small hill slopes, USLE and its derivatives have been incorporated into many catchment scales for erosion and sediment transport modeling applications.

The USLE computes the average annual soil loss from:

$A= R\times K\times L\times S\times C\times P$

Where, A= estimated soil loss per unit area, R= rainfall erosivity factor, K= soil erodibility factor, L= slope-length factor, S= slope-steepness factor, C= cover-management factor, and P= conservation practice factor (Wischmeier and Smith, 1978).
The basic USLE is based on an empirical overland flow and sheet-rill erosion regression equation. These equations primarily based on observations. Models output types are spatially and temporally lumped. This is not only an event responsive model but providing an annual estimate of soil loss as well. This model avoids the processes of rainfall, runoff and effect of these processes on erosion, as well as variability in inputs such as soil types and vegetation cover. In this model input data requirements are low as compared to other models. Annual rainfall, soil erodibility factor, slope length, slope steepness, cover management factor, and conservation practice factor are main input for soil loss estimation; these can be taken from land cover map, soil map, and topographic information. The output from USLE is an annual estimation of soil erosion from hill slopes.
USLE has number of limitations. The model is not event based and didn’t develop for large-scale erosion estimation. Deposition of sediment is not considered and gully erosion and mass movement are ignored which usually occur in study area (Zhang *et al.,* 1995).

2.3.2 AGNPS

The Agricultural Non-Point Source model (AGNPS) developed by the US Department of Agriculture, Agricultural Research Service (USDA-ARS) in co-operation with the Minnesota Pollution Control Agency and the Soil Conservation Service (SCS) in the USA (Young *et al.*, 1989). It is a non-point source pollution model and has been developed to predict and analyze the water quality of runoff over catchments (5-20,000 hectares).
AGNPS has three main stages. Initial model includes estimation of upland erosion, overland runoff, pollutants from point source inputs, time taken by overland flow to become concentrated and the level of soluble pollutants in overland runoff. These calculations are made for each grid cell in a catchment. In the second stage, runoff leaving the cells bearing sediment yield for primary cells are calculated. The calculated sediments and nutrients are then routed through the remaining cells.

The main inputs data for AGNPS model are catchment morphology, landuse, and precipitation. For each grid cell, the input parameters are cell number (from), receiving cell number, SCS curve number, channel indicator that indicates the presence of a defined channel in a cell, slope, shape factor, slope length, channel side slope, Manning's roughness coefficient, soil erodibility factor, cover and management factor, support practices factor, surface condition constant, aspect, soil texture, fertilization level, fertilization availability factor, point source indicator, gully source level, COD factor, impoundment factor, and channel indicator.

Outputs for entire watershed include runoff volume, peak runoff rate, and the fraction of runoff generated in the cell. Outputs related to sediments are sediment yield, sediment concentration, sediment particle size and distribution, upland erosion, amount of deposition (%), sediment generated in the cell, enrichment ratios by particle size, delivery ratios by particle size etc.

AGNPS has a mixture of empirical and physical based components and both algorithms too. This model utilizes components of other existing models including the RUSLE (described earlier) for grid by grid soil prediction. The model is performing as a fully distributed model with surface runoff and sediment processes modeled for single grid, and outputs routed through individual grid to catchment outlet.

Limitations of AGNPS are greater data requirements and computational complexity as compared to other empirical models. Grid size selected by the model user was a major influencing factor for sediment yield calculation, this capabilities has been identified by Panuska et al. (1991). Therefore, user needs to know that when applying such model, the resolution chosen by them for modeling is adequate for the task or not. This statement is true for all distributed models that apply algorithms on a grid basis.

2.3.3 LISEM

The Limburg Soil Erosion Model (LISEM) (Roo and Jetten, 1999) is a physical based, spatially distributed hydrological and soil erosion model. This model has been developed by the Department of Physical Geography at Utrecht University and the Soil Physics Division at the Winard Staring Centre in Waneningen, the Netherlands. LISEM model is based on EUROSEM (Morgan *et al.*, 1998). LISEM is a data hungry model and includes number of different processes like interception, surface storage in depressions, infiltration, vertical movement of water through the soil, overland flow, and channel flow, detachment by rainfall and throughfall, detachment of overland flow and transport capacity of flow.
LISEM has a GIS nature and model simulation is in the form of GIS maps. For simulation using LISEM approximately 25 maps are required, including maps describing watershed morphology, leaf area index, roughness of the soil and fraction of the soil with crop cover. Point data of rainfall must also be input. Spatial distribution of rainfall intensity map can be generated by LISEM. Thus LISEM incorporates both type of rainfall variability (spatial and temporal). This is a main advantage of LISEM model for erosion and runoff modeling, with respect to variability in rainfall.

Runoff, sediment, infiltration and depression storage are the main outputs of LISEM model. Spatial distribution maps of soil erosion and deposition and overland flow at desired time intervals during simulation are also generated by LISEM. For a rainfall event sediment graphs and hydrographs also produced by LISEM.
Structure of the model simulation based on the solution of a various physical based equations which are describing water and sediment yield processes. Model has been developed to simulate runoff and erosion from individual rainfall events in agricultural catchments (0.01 km^2 to 100 km^2). This model is fully distributed, and has been completely incorporated GIS environment.

Application of LISEM model is having number of limitations, even though it is linked to a GIS. The detailed spatial and temporally variable representation is required for input data. There is an increasing trend to develop spatial databases, such as the United States Department of Agriculture (USDA) STATSGO soil database, but other than topography there is a limited data sets for variables. Performance of the model depends upon the resolution and quality of these GIS inputs. As the quality and resolution of these layers will increase, the value of fully distributed models will increase. However, this model suffers with the limited data availability.

2.3.4 SedNet

The Sediment River Network (SedNet) model is a steady-state model and it was developed for sediment generation estimation and deposition from hill slops, gullies and riverbanks in a river network (I.P. Prosser *et al.*, 2001). Land and water management issues are beautifully addressed by this model for the catchment. For example, model has been used to identify that in an entire watershed which sub-watershed supply much of the sediment to stream network, where deposition is occurring and delivery of the sediment to the stream network (Prosser *et al.*, 2001c).

Main input required to define the network of streams is a Digital Elevation Model (DEM) for SedNet. It also help user to calculate topographic attributes for the catchment and each river link. The hill slope model requires a grid of mean annual rainfall, soil erodibility, crop management factors, slope length and slope, and management practices. The gully erosion model needs a grid of gully density and a description of the mean characteristics for each link. SedNet requires in situ sediment data, river bank vegetation, and bank dimensions for modeling in-stream sediment generation and transport.

SedNet model has been coupled with GIS and provides spatial pattern of sediment, in stream sediment load and deposition.

The model having a large number of river links in the watershed, it makes model more complex. Much of these data are difficult to obtain for each link in a catchment. The high range of parameters are creating uncertainty for SedNet, thus limiting the confidence that can be placed in outputs.

2.3.5 WEPP

The Watershed Erosion Prediction Project (WEPP) is a physical model developed in the United States, collaboration between the Agricultural Research Service, the Soil Conservation Service, the Forest Service in the Department of Agriculture and the Bureau of Land Management in the US Department of the Interior (Laflen *et al.*, 1991; NSERL, 1995). The model has been widely use in US for hill slope study (Laflen *et al.*, 1991) and worldwide. Erosion, transport and deposition processes from the permanent channels, such as gullies and perennial streams do not consider by the model. Watershed version only developed for field areas that includes ephemeral gullies, and links with surface erosion processes to the channel network. The processed incorporated by WEPP can be broadly classified as erosional processes, hydrological processes, plant growth and residue processes, water use processes, hydraulic processes and soil processes (Laflen *et al.*, 1991).

The main inputs for WEPP are canopy cover, canopy height, above and below ground biomass of living and dead plant material, leaf area index (LAI) and basal area, and these thing are estimated on a daily basis (Laflen *et al.*, 1991). Plant information has influencing impact on erosion and hydrological processes, so that it has importance for model. Information regarding management practices and dates are essential inputs to the model. Information regarding hydraulic shearing forces, surface runoff, hydraulic roughness, and approximations of runoff duration and peak rate also requires. The final components is the soil processes module, which shows the changes in soil properties, and couple this with effect of management practices, weathering, consolidation, and rainfall on soil and surface variables (Laflen *et al.*, 1991). The watershed version of WEPP needs additional information to describe the watershed configuration and all the information of channel showing topography, soils type, channel management, and hydraulic characteristics.

Main outputs of WEPP are estimation of spatial and temporal distributions of soil loss, sediment yield, sediment size characteristics, runoff volumes and the soil water balance. It also considers sediment deposition occurring at the top of a hill slope to a channel. Others are runoff and erosion summary on a storm-by-storm, monthly, annual and average annual basis.

There are number of limitations of WEPP model. Firstly, large data requirement and computations these limit its applicability in catchments where there is few data available. Calibration of the model is required observed data creating problems with model identifiability and physical interpretability of parameters. Secondly, WEPP does not take care of erosion and permanent gullies. Watershed version of WEPP limited to large scale but in the small hill slops and catchment it is not applicable because complexity and large data requirement creating problem.

A number of erosion and sediment prediction models have been presented previously. Other than these models there are many more models have been developed and are in the literature, and give prediction of erosion and sediment yield, these models were summarized in this section. Other models deal with the processes of representation of temporal and spatial scales for which they were developed. However, the models have the potential to be, incorporated into catchment scale approaches. At the catchment scale, real situation is that a sediment associated model requires a number of components: rainfall-runoff module, a land surface erosion module, and an in stream module. Relatively Table 2.1 provides summery of these models and processes they have incorporated.

Table 2.1 Processes incorporated by the various models

Models	Rainfall-Runoff	Land Surface Sediment			Gully	In stream sediment			Sediment associated water quality	
		G	T	D		G	T	D	Land	In-stream
AGNPS	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
ANSWERS	Yes	Yes	Yes	Yes	No	No	No	No	No	No
CREAMS	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	No
EMSS	Yes	No	No	No	No	Yes	Yes	Yes	No	No
GUEST	Yes	Yes	Yes	Yes	No	No	No	No	No	No
HSPF	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
IHACRES-WQ	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
IQQM	Yes	No	No	No	No	No	No	No	No	No
LASCAM	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
LISEM	Yes	Yes	No	No	No	Yes	Yes	Yes	No	No
MIKE-11	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
PERFECT	Yes	Yes	No	No	No	No	No	No	Yes	No
SEDNET	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
SWRRB	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
TOPOG	Yes	Yes	Yes	Yes	No	No	No	No	No	No
USLE	No	Yes	No	No	No	No	No	No	No	No
WEPP	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No	No
Modified MMF (2008)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**No**

G, Sediment generation; T, Sediment transport; D, Deposition Source: (Merritt et al., 2003)

From the models have been reviewed in this section gives the idea regarding selection of an appropriate model for application to a small watershed and large catchment based study of erosion and sediment movement, yield studies. Two extreme model types can be identified: physical based models and conceptual complex models. Problem with the complex model is generally capable of on a continuous basis or in an event-based mode. Users need to decide between two extremes model.

This on-going research needs to develop a tremendous sediment routing module on annual basis and identification of an annual soil erosion prediction model for a sub-watershed scale. As well as this model has to be a capability to incorporate a geospatial environment for fast and accurate prediction of soil loss and sediment yield. Other than rainfall variability is a main impact factor for this study to find what will be the change in sediment yield of a sub-watershed scale with respect to kinetic energy of a rainfall and number of rainy days.

2.4 Modified MMF (Morgan and Duzant, 2008) Model

Morgan *et al.,* 1984 has developed a Morgan-Morgan-Finney model for predicting annual soil loss from field- sized area on hill slopes. Model has water phase and sediment phase. In the sediment phase process starts from the detachment of the soil particles by raindrop impact to their transport by runoff. Detachment of soil particles occur due to kinetic energy of rainfall and this factor helps to select this model for ongoing study; the changes in kinetic energy is directly related to the rainfall variability as well as changes in detachment, sediment delivery to the runoff and sediment yield of a stream at the outlet. Modification has been made by Morgan and other researchers in their basic version (Morgan *et al.,* 1984). A revised version has been presented by Morgan, (2001). Changes have been made in the process of detachment of soil particles by raindrop impact, which now takes account of plant canopy height and leaf drainage, and an additional component has been added in the process of detachment by runoff. This revised version was applied on two catchments by dividing them into number of elements and routing of runoff and sediment introduced for entire catchment (Morgan, 2001). This is an easy and time saving routing process in geospatial and GIS environment.

In between many changes have been made but in a year of 2008, Morgan and Duzant, (2008) proposed a predictive model approach for estimation of annual sediment yield and runoff, including effects of crop and vegetation cover. Modifications are made to the revised MMF model. Model enables the effect of vegetation cover in the erosion process, these vegetation cover to be expressed through measurable plant parameters. Changes are also made to the way of model deals with sediment deposition and in this version model deals with particle size selectivity (sand, silt, clay) in the process of erosion, transport and deposition. Deposition functioned through a particle fall number, which takes account of particle settling velocity, flow velocity, flow depth and slope length and detachment, transport and deposition of soil particles are simulated separately for clay, silt and sand (Morgan and Duzant, 2008).

2.5 Geographic Information System and Soil Erosion Modeling

GIS has been recognized as a very useful tool for environmental management since 1970s (Kim, 2006). Hydrologic and hydraulic modeling as well as flood mapping and management with the help of GIS only began about 20 years later (Kim, 2006). The Digital Elevation Model (DEM) is advancement in a field of geomorphological analysis because of its ability to identify the various factors features like elevation and topography etc. (Kim, 2006). The DEM is able to exhibit changes in landscape with time because of the repositioning of soil leading to the sediment deposition. This process naturally affects the various hydrological processes that occur within and over hill slopes (Kim, 2006). Firstly, interfacing GIS capabilities with the RUSLE aids a relatively fast analysis and visualization of likely sheet and rill soil erosion potential at diverse locations (Blaszczynski, 2001). This is highly useful because it allows simulation of large scale studies using voluminous amounts of data requiring only for a relatively short processing time (Blaszczynski, 2001). GIS acquires a spatial function that will perform the Georeferencing and spatial overlays in a very short span of time (Sharma *et al.*, 1996). Secondly, GIS also let you to perform the simulation of different scenarios from various changing land use conditions and management alternatives in space and time (Blaszczynski, 2001). This allows the evaluation of the potential effects of each management practice on soil erosion. GIS is also a sophisticated tool to animate sequences of model output images across time and space, can be displayed enabling the model output to be visualized from extensive perspectives (Tim, 1996). The catchment can also be modeled with more specific aspects and parameters as GIS enables the use of large catchments with various resolutions (de Roo, 1996). The integration of RUSLE and GIS is used as an automation tool to assist in the standardization of the application of the RUSLE to large areas of different feature class. The integration of RUSLE and GIS is further applied as an important procedure for other geomorphologic and hydrologic applications such as watershed condition analysis, water quality monitoring of environmental pollutants in soils, sediment loading of streams and rivers and non-point source pollution (Blaszczynski, 2001).

2.6 Rainfall Variability and Its Impact on Sediment Yield

Occurrence of erosion depends upon the rainfall intensity, kinetic energy of erosive rainfall and its variation in a particular time span. However, a considerable variation takes place in the shape and coefficients of the relationship between rainfall intensity and kinetic energy. It is well known that the amount of detached soil by a particular depth of rain is related to its intensity. It is the basic physics that soil splash rate is a combined function of rainfall intensity and some measure of raindrop fall velocity and results of many studies further suggested the same (Ellison, 1944). Product of mass and fall velocity of raindrops describe as a kinetic energy of rainfall and indicator of rainfall erosivity; the ability of rainfall to detach the soil particles (Mihara, 1951; Free, 1960). In the various research works and in this study also rainfall variability deals with the variation in the rainfall intensity and kinetic energy. Changes in the rainfall intensity caused enormous variation in the energy of rainfall. In this study formula derived by Kinnell, (1981) for kinetic energy has been used for estimation of total kinetic energy and variability shown by putting different observed values of rainfall intensity for different time scale for a catchment.

In MMF (Morgan and Duzant, 2008) model describes the kinetic energy of direct throughfall is a function of the intensity of erosive rain and the amount of direct throughfall. Since the relationship varies with drop-size distribution of the rainfall, relationship varies for different geographical regions of the world (Morgan, 2005). For Indian condition, (Kinnell, 1981) presented a relationship between kinetic energy and rainfall intensity. After that the detachment of soil particles by raindrop impact is a function of the kinetic energy of the effective rainfall, the detachability of the soil and the stone cover (Morgan and Duzant, 2008).

As described earlier variation in the rainfall intensity will increase or decrease the total kinetic energy of rainfall. Since, kinetic energy of direct throughfall is a product of kinetic energy and amount of direct throughfall so that, intensity will directly affect the kinetic energy of direct throughfall as well as total kinetic energy of the effective rainfall. The detachment of sand, silt and clay will vary according to the variation in the rainfall intensity and these factors directly affects the sediment yield of the catchment.

CHAPTER – 3
STUDY AREA

This chapter gives a brief overview of location and extent of study area, challenges faced by the basin regarding soil erosion and sedimentation issues, soil type of the area, climate. The brief description of reservoir and sedimentation aspects of the basin is also presented.

3.1 Location and Extent of the Satluj Basin

The geographical limits of Satluj basin lies between Latitudes 30^o N and 33^o N and Longitudes 76^o E and 83^o E up to Bhakra dam (Fig 4.1). Satluj basin is one of the major river basin of Indus system (Gosain *et al.,* 2011). It is a typical basin considered from geographical and geological point of view, covering major parts of Nari Khorsam region in Tibet, certain portion of China and remaining part of India (Himachal Pradesh). From Spiti valley, the river flows through moderate to high hilly terrain with elevation of 1525m to 3048m and has little rainfall but heavy snow. The catchment area of Satluj River up to Bhakra dam is about 56,876 km^2 out of which, about 36,900 km^2 falls in China and 19,975 km^2 in India. The total length of Satluj River is 1,448 km. It enters India at Shipkila and the altitude of this region is about 6,200 - 6,608 meters. Satluj flows in the South-Western direction through Kinnaur, Shimla, Kullu, Solan, Mandi and Bilaspur districts. Namgia, Kalpa, Rampur, Tattapani, Suni and Bilaspur are the prominent human settlements that have come on the banks of the Satluj River in Himachal Pradesh.

3.1.1 Gobind Sagar Reservoir

Gobind Sagar is one of the largest reservoir in India also known as Bhakra reservoir. Capacity of Gobind Sagar Reservoir is 9867.84x106 m^3, live storage is 7436.03 x 106 m^3 and Dead storage is 2431.81 x 106 m^3. The water-spread area of the Bhakra Reservoir, extends over 168.35 km^2 at full reservoir level (515.11 m) and its head touches a point about 12.87 km above Slapper village near Kasol (CBIP, 1990).

3.2 Challenges Faced by the Basin (Soil erosion and Sedimentation)

The Satluj River carries maximum amount of silt among the all Indian rivers (SJVN, 2006). The river has been affected by three floods which submerged the entire Satluj basin in 1997, 2000 and 2005. It is not only led to damages but the entire topography has been reported to have changed along with the catchment areas. The river banks eroded badly. The original plans that were made when the project was envisaged regarding silt contents (5,000 parts per million) had to be changed and are in the process of revision (SJVN, 2006). During last

12 years (1991-2003) nearly 36 major cloudbursts and flash floods have been recorded. An unprecedented cloudburst and flash flood of August 11, 1997 in the catchment area of Satluj caused extensive damage (CIA, 2006).

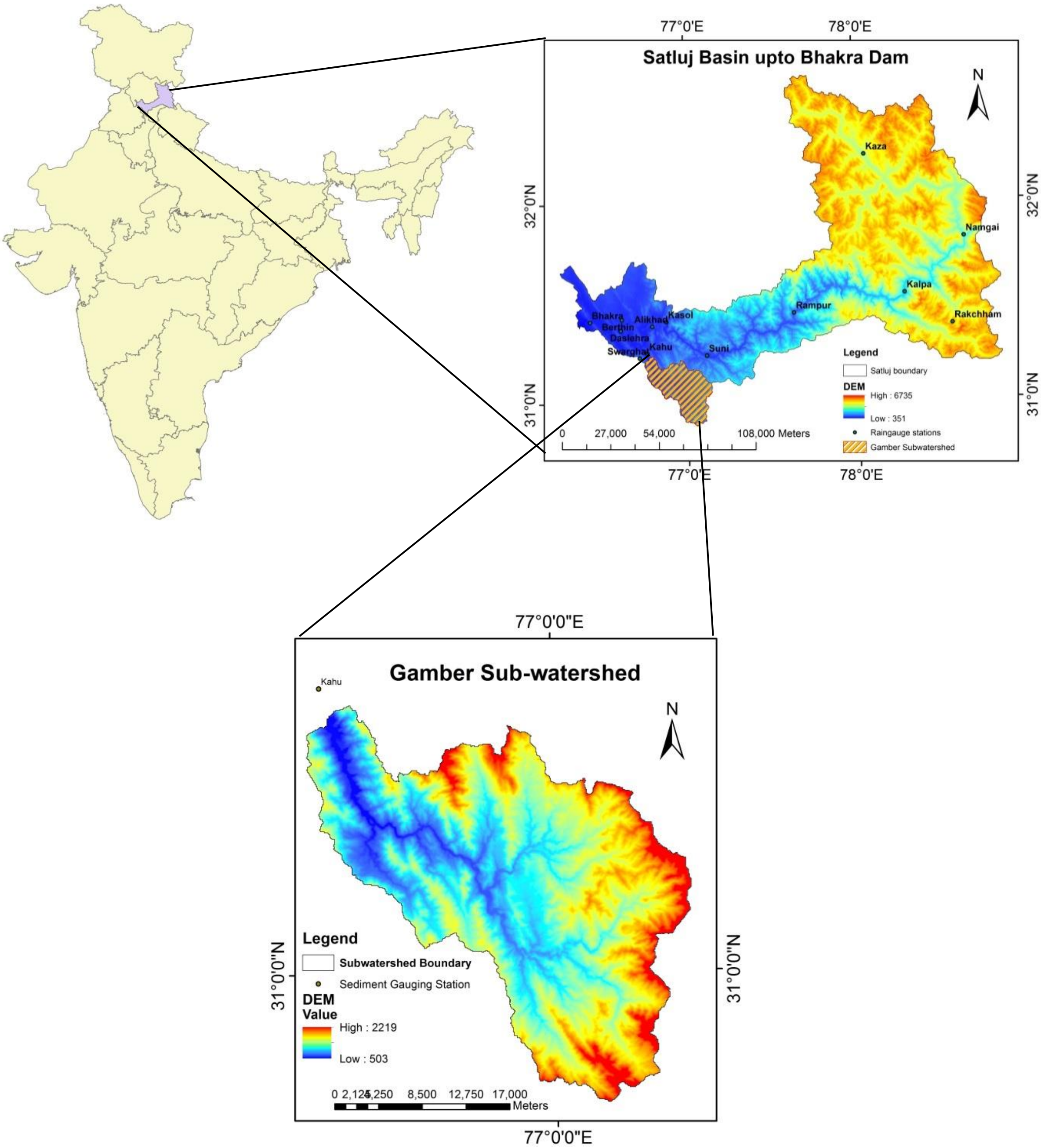


Fig. 3.1 Satluj river basin up to Bhakra Dam (Gobind Sagar reservoir) and location of Study area

3.3 Climate

In general, the climate of the entire region is temperate type but due to large variations in the altitude, there is a wide range of climatic variations, from the tropical climate of sub-mountainous areas at the bottom of the Satluj valley to the alpine in the upper reaches, parts of which are continuously under snow (SJVN, 2006).
Study area having mainly four types of distinct seasons (SJVN, 2006):

1. Severe cold winter during months of December to February,
2. Summer during months of April to June,
3. Monsoons during months of July to mid-September, and
4. Post monsoon/ autumn during months of mid-September to November.

3.4 Cloud Cover and Precipitation

The climate of Satluj valley shows a gradual change from a heavy monsoon in the outer Himalayas to the arid type with a winter snowfall practically in summer rains. The monsoon clouds advancing from the plains of India are encountered by the outer ranges of the hill, where most of the monsoon rain falls, so that the inner valley get a cloud cover but no steady precipitation during the monsoon months. The local aridity in the area is increased by the heating up of the enormous stretches of bare cliffs, making up the deep narrow gorge absolutely stifling under the summer sun. This results in a hot drying local wind, which beats up and down the main valley with great regularity. Thus, Rampur at 3000 ft. elevation, receives about 800mm rainfall, while Kotgarh at 8000 ft., almost in the same sector of valley receives about 1150 mm of rainfall showing the huge variation of the rainfall due to the arrangement, as per the Bhakra Beas Management Board (BBMB) sedimentation survey report (BBMB, 2003).

Due to western disturbances catchment area receives rainfall, these disturbances pass over the north western part of the country during the winter months. At higher altitude, significant precipitation in form of snow is received. In the valleys the rainfall is received during winter months. About 60 to 70 % of the annual rainfall occurs in the monsoon months (BBMB, 2003). At Gamber khad, the average number of rainy days in a year is about 84 to 86 days.

3.5 Soil type in the Study Area

In the selected sub-watershed mainly three soil types are present that is loamy, loamy skeletal and sandy soil. The soil texture has been identified from National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) map at 1:2,50,000 scale in the study of soil type, texture and composition of sand, silt, clay. In the present watershed area, the soil is usually shallow in depth, but soil depth is fairly deep where the vegetation cover is present. In this region, altitude above 1500 m. the soil is generally deep.

3.6 Sedimentation Aspects

BBMB has sited many sediment gauging stations in the entire Satluj basin, subsequently the Himachal Pradesh State Pollution Control Board had initiated a sediment sampling programme at several gauging stations in the Satluj River system. The mean annual sediment yield at Kahu gauging station for the year of 1994, 1996, 1998, 2000 & 2002 was 256680, 1764520, 1567360, 1263560 and 374480 tons (BBMB, 2003). Observation has been taken at the gauging stations in alternate years and rest of the years has been interpolated according to preceding year. The long time series and frequent sampling intervals have helped in various studies related to future impacts on the actual projects which are running there and reservoir sedimentation studies. Snowmelt and the related erosion processes (rapid mass wasting in combination with glacier runoff) are the major sediment sources. At the upper Satluj regions, the bed material is heterogeneous as a result of heavy floods or the catastrophic input from rapid mass wasting process. Both factors result in a rapid increase in bed-load transport that is reduced when the riverbed has been adapted to the new situation. It is therefore also pronounce difference between the rising limb and the falling limb of a flood event (CIA, 2006). In general, the runoff from the unprotected excavated borrow pits and muck disposal sites lead to increased soil erosion and therefore, increased sedimentation rate down-stream of the area.

It has been seen that there is large variation in rainfall pattern in the basin of this sediment laden river. Therefore, it is necessary to study erosion, sediment yield and impact of rainfall variability on sediment yield of this basin. As most of the part of region is difficult to access, remote sensing technique may be very useful for the study. There is a need to identify suitable erosion and sediment yield model for the study. A detailed description on methodology adopted for carrying out this study is provided in the next chapter.

CHAPTER- 4
MATERIALS AND METHODOLOGY

This chapter describes the various datasets used in this research work and elaborates the step by step methodology of sediment yield estimation of part of Satluj basin. Procedures for generating various input parameters and thematic layers for MMF model (Morgan and Duzant version) have been described. Model calibration and validation has also been mentioned.

4.1 Methodology and Data Used

The Morgan-Morgan-Finney model (Morgan *et al.*, 1984; Morgan, 2001) is an annual model that has been used in a various country by several researchers for soil erosion prediction and sediment yield estimation. This model has been used successfully at plot, hill slope, and small catchment scales in a wide range of environments including Malaysia (Morgan, 1982), Indonesia (Besler, 1987), Nepal (Shrestha, 1997), Kenya, Tanzania (Vigiak *et al.*, 2005), India (Behera *et al.*, 2005) and Nigeria (Ande *et al.*, 2009). However, Modified MMF (Morgan and Duzant, 2008) has been used in this study, it is semi distributed model, taking rainfall variability into account and incorporates particle size selectivity process i.e. clay, silt and sand in sediment yield estimation.

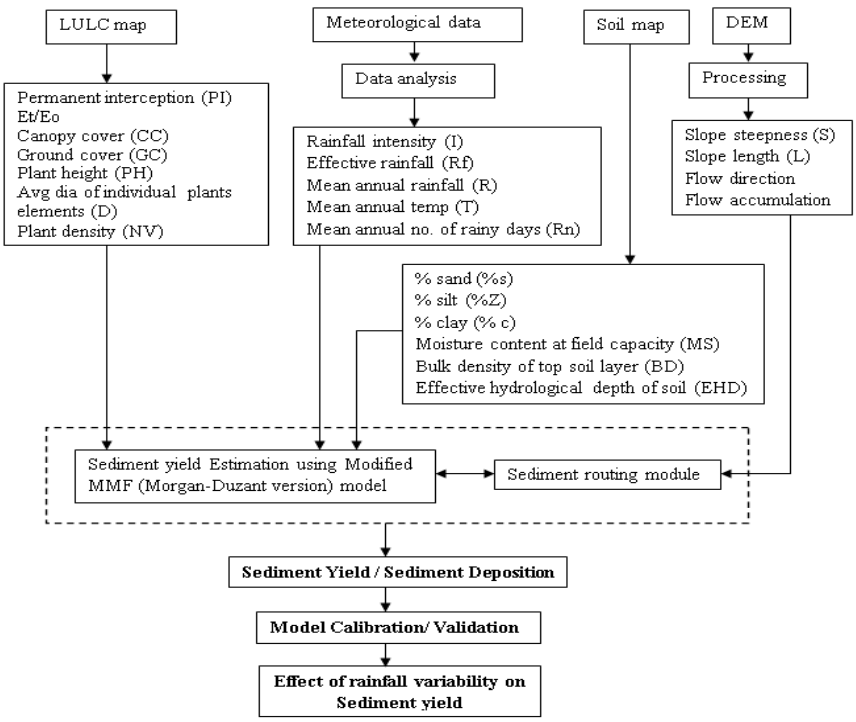


Fig.4.1 Overall Methodology of the Study

In the present study, the latest version of MMF (Morgan and Duzant, 2008 version) model has been developed for a watershed in geospatial environment, so the entire area has been divided in to number of elements and sediment yield estimation has been carried out on element basis, these elements are same as number of pixel for the area. The steps performed in the present study that is from the data acquisition till the end product is provided in the form of flowchart (Fig 4.1). In this study ASTER rescaled digital elevation model DEM (90m resolution) has been used as a major input. Entire study has been carried out at 90×90m grid size consequently DEM was taken as a base map.

4.2.1 Basin delineation and Sub-watershed Delineation

ASTER DEM shown in Fig. 4.2, having 30m resolution was downloaded from (http://gdex.cr.usgs.gov/gdex/) and is re-projected and rescaled up to 90m as required in the study using the software ERDAS Imagine 9.2. Basin boundary and sub-watershed boundary of watershed were derived by hydrology tool in ArcGIS 10.0 using ASTER rescaled DEM (90m resolution). Same DEM has been used to generate topographic parameters such as elevation and slope. The preprocessing was performed in Arc GIS 10.0 and followed by creation of input layers.

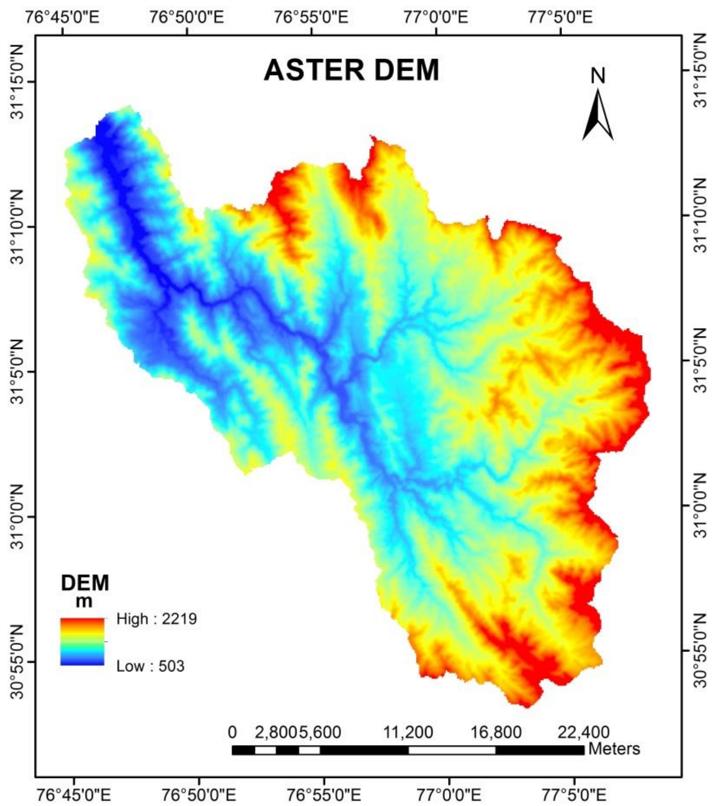


Fig. 4.2 Digital Elevation Model of Sub-watershed

Following operations were performed step by step:

- Fill Sinks
- Flow Direction
- Flow Accumulation
- Pour point Definition
- Watershed
- Raster to Polygon Conversion

In the first step, a Fill grid map is generated after correcting the DEM for sinks. Flow direction map is derived from this Fill sink map and subsequently a Flow accumulation map is derived from it. To extract the basin boundary, an outlet at the end of Gobind Sagar reservoir in the Satluj River basin was defined. Finally, a basin for the defined outlet is delineated along with the river network. It can further subdivide basin into desired number of sub-watersheds by specifying various outlets where the gauging station exists along the extracted drainage. In this study, a sub-watershed, Gamber Khad is chosen which have Kahu as a nearest gauging station from where the observed sediment yield data has been taken. The flowchart of sub-watershed delineation is illustrated in Fig 4.3.

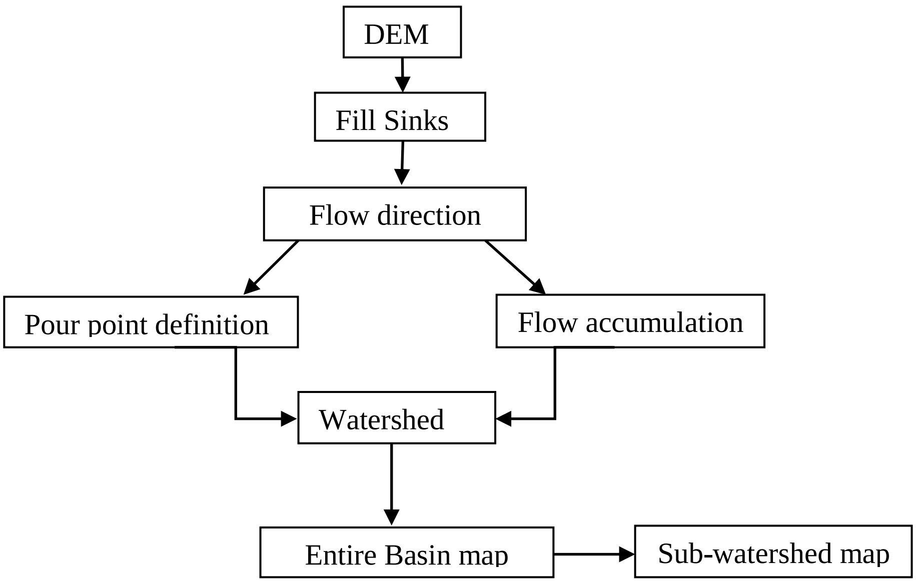


Fig 4.3 Flow chart showing Watershed delineation

4.2.2 Input Map Generation from Various Datasets

As it has been noticed in Fig 4.1, a large number of input parameters are required to estimate sediment yield using MMF (Morgan and Duzant, 2008 version). The list of input data required for each element to run MMF model (Morgan and Duzant, 2008 version) are given in Table 4.1.

Table 4.1 Input parameters for the MMF model (Morgan-Duzant version)

Factor	Parameter	Definition
	R	Mean annual rainfall (mm)
	T	Mean annual temperature (°C)
	Rn	Mean annual number of rain days
Climate	I	Typical intensity of erosive rain (mm h^{-1}). Use 10 for temperate climates, 25 for tropical climates and 30 for strongly seasonal climates (e.g. Mediterranean type or monsoon)
	%c	Percentage clay
	%z	Percentage silt
	%s	Percentage sand
Soil	ST	Percentage rock fragments on the soil surface
		Soil moisture at field capacity (% w/w)
	MS	Bulk density of the top soil layer (Mg m^{-3})
	BD	Effective hydrological depth of the soil (m)
	EHD	Roughness of the soil surface (cm m^{-1})
	S	Slope steepness (°)
Slope	L	Slope length (m)
	W	Slope width (m)
	PI	Permanent interception expressed as the proportion (between 0 and 1) of rainfall
	Et/E0	Ratio of actual to potential evapo-transpiration
	CC	Canopy cover expressed as a proportion (between 0 and 1) of the soil surface protected by the vegetation or crop canopy
Land cover	GC	Ground cover expressed as a proportion (between 0 and 1) of the soil surface protected by vegetation or crop cover on the ground
	PH	Plant height (m), representing the effective height from which raindrops fall from the crop or vegetation cover to the soil surface
	D	Average diameter (m) of the individual plant elements (stems, leaves) at the ground surface
	NV	Number of plant elements per unit area (number m^{-2}) at the ground surface

Land-use land-cover (LULC)

To couple the MMF model into geospatial environment user needs to generate various input maps for the steps which are presented in the Morgan-Duzant version of MMF. In this study, LULC prepared for ISRO Geosphere Biosphere Program under project entitled "Landuse/ Land cover Dynamics and Impact of Human Dimension in Indian River Basins" for year 1995 at a resolution of 1:2, 50,000 has been used to derive the layers of various LULC parameters.

In various stages of soil erosion estimation model requires, permanent interception, ratio of actual to potential evapo-transpiration, canopy cover, ground cover, plant height, average diameter of individual plant elements at the ground surface, number of plant per unit area (number m^{-2}) at the ground surface as given in Table 4.1. The guide values of these parameters used in this work. Selection of the appropriate class based upon the nearest class available in reference guide of Morgan and Duzant, 2008 (Table 4.2). Therefore, layers correspond to each parameter has been generated from LULC map. In Arc GIS 10.0 by using conversion tool each vector layer has been converted into raster map having 90×90 cell size and these layers have further been used for soil erosion estimation. LULC map of entire sub-watershed is shown in Fig 4.4.

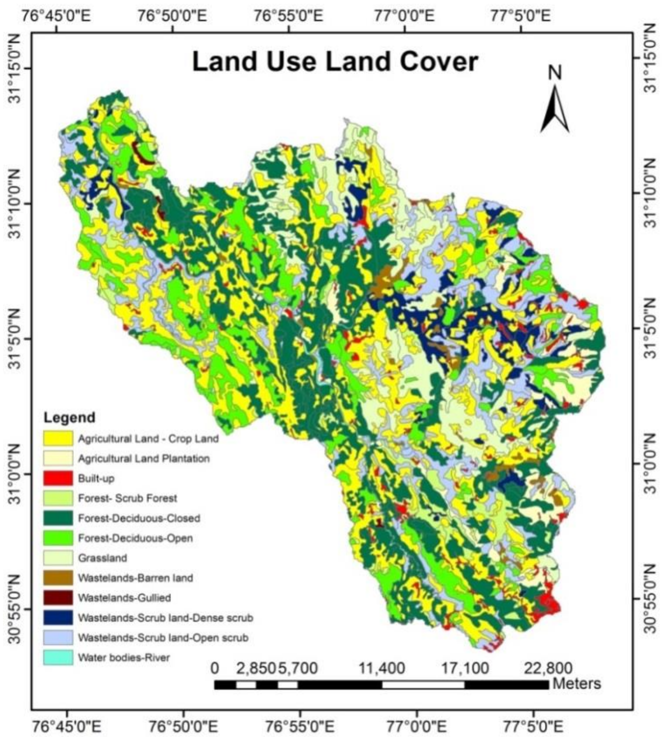


Fig 4.4 ISRO-GBP LULC map (1995) of Sub-watershed

Table 4.2 Parameters for land use land cover present in study region (Morgan and Duzant, 2008)

Land cover (present in study area)	**EHD (m)**	**PI (% fraction)**	**Et/Eo (% fraction)**	**CC (% fraction)**	**GC (% fraction)**	**PH (m)**	**NV**	**D (m)**
Agricultural Land Plantation	0.12	0.3	0.70	0.65	0.50	2.00	10.0	0.05
Agricultural Land-Crop Land	0.12	0.1	0.86	0.80	0.60	0.10	80.0	0.01
Built-up	0.01	0.5	0.05	0.00	0.00	0.00	0.0	0.0
Forest- Scrub Forest	0.15	0.25	0.70	0.98	0.40	4.00	0.2	1.5
Forest-Deciduous-Closed	0.20	0.3	0.95	0.98	1.00	30.00	0.6	2.0
Forest-Deciduous-Open	0.20	0.2	0.95	0.95	0.95	25.00	1.2	1.5
Grassland	0.12	0.3	0.86	0.80	0.50	0.10	100.0	0.04
Wastelands-Barren land	0.09	0.0	0.05	0.00	0.00	0.00	0.0	0.0
Wastelands-Gullied	0.09	0	0.05	0.00	0.00	0.00	0.0	0.0
Wastelands-Scrub land-Dense scrub	0.12	0.3	0.86	0.90	0.60	0.07	200.0	0.02
Wastelands-Scrub land-Open scrub	0.11	0.25	0.86	0.80	0.60	0.10	80.0	0.01
Water bodies- River	0.00	0.0	0.70	0.00	0.00	0.0	0.0	0.0

Soil map

The National Bureau of Soil Survey and Landuse Planning, Nagpur (NBSS&LUP) soil map at 1:2,50,000 scale (Fig. 4.5) was used for generation of soil texture related parameters namely % clay, % silt, % sand, soil moisture at field capacity, bulk density of the top soil layer, effective hydrological depth of the soil. Guide values have been taken for each parameter from (Morgan and Duzant, 2008). These values are presented in the Table 4.3. To derive the related layers, values have been given in the attribute of soil map and raster layer of 90×90 generated by vector to raster conversion in Arc GIS 10.0.

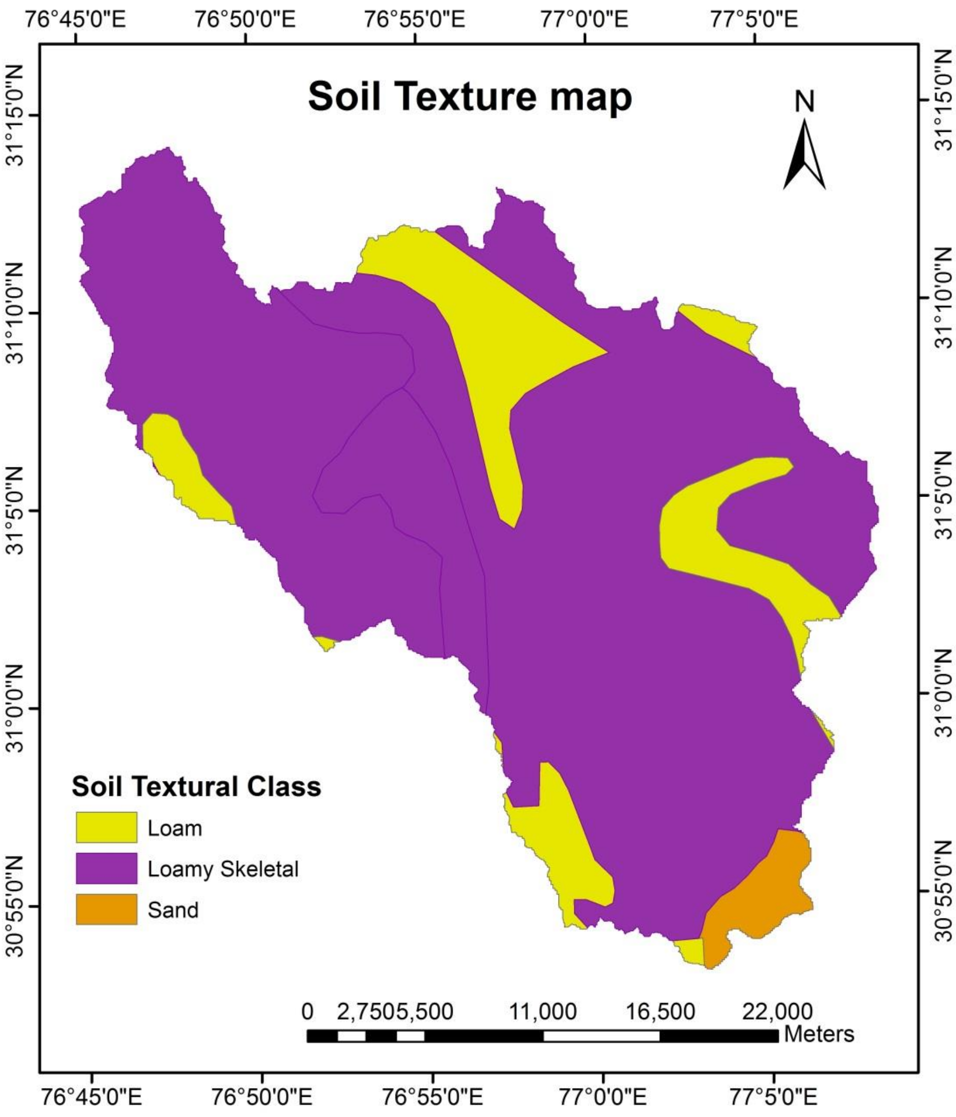


Fig. 4.5 NBSS & LUP soil map of Study area

Table 4.3 Typical values for soil parameters for the MMF model (Morgan and Duzant, 2008)

Soil type	**% clay**	**% silt**	**% sand**	**MS (%w/w)**	**BD (Mg m^{-3})**	**LP (m/day)**
Sand	4	4	92	0.08	1.5	230
Loamy sand	6	11	83	0.15	1.4	117
Sandy loam	10	25	65	0.28	1.2	50
Loam	20	35	45	0.20	1.3	25
Silt	5	89	6	0.15	1.3	20
Silt loam	15	66	19	0.35	1.3	14
Sandy clay loam	28	14	58	0.38	1.4	8
Clay loam	36	35	29	0.40	1.3	4
Silty clay loam	36	55	7	0.42	1.3	3
Sandy clay	42	5	53	0.28	1.4	2
Silty clay	48	45	7	0.30	1.3	2
Clay	64	18	18	0.45	1.1	1
Loamy Skeletal	10	43.96	46.04	0.20	1.5	25

Meteorological data

Rainfall data obtained from Bhakra Beas Management Board (BBMB) for 13 rain gauge stations (Fig. 4.6) present in the entire basin and the data of 1995, 1998, 1999 and 2002 has been processed to find mean annual rainfall and number of rainy days (Time period). To prepare rainfall distribution images, these station layers were subjected for Inverse Distance Weighting (IDW) interpolation technique by the rainfall values of all stations within the regional extent. The reason for selecting IDW technique for interpolation is that, it distributes the value in cells with an assumption that things that are more close to one another are alike than those that are farther apart. However, a station with the existence of data gaps was excluded in the interpolation. As the study watershed lie in lower Satluj basin region and it climate is tropical, the rainfall intensity was taken 25 mm/hr as suggest by Kinnell, (1981).

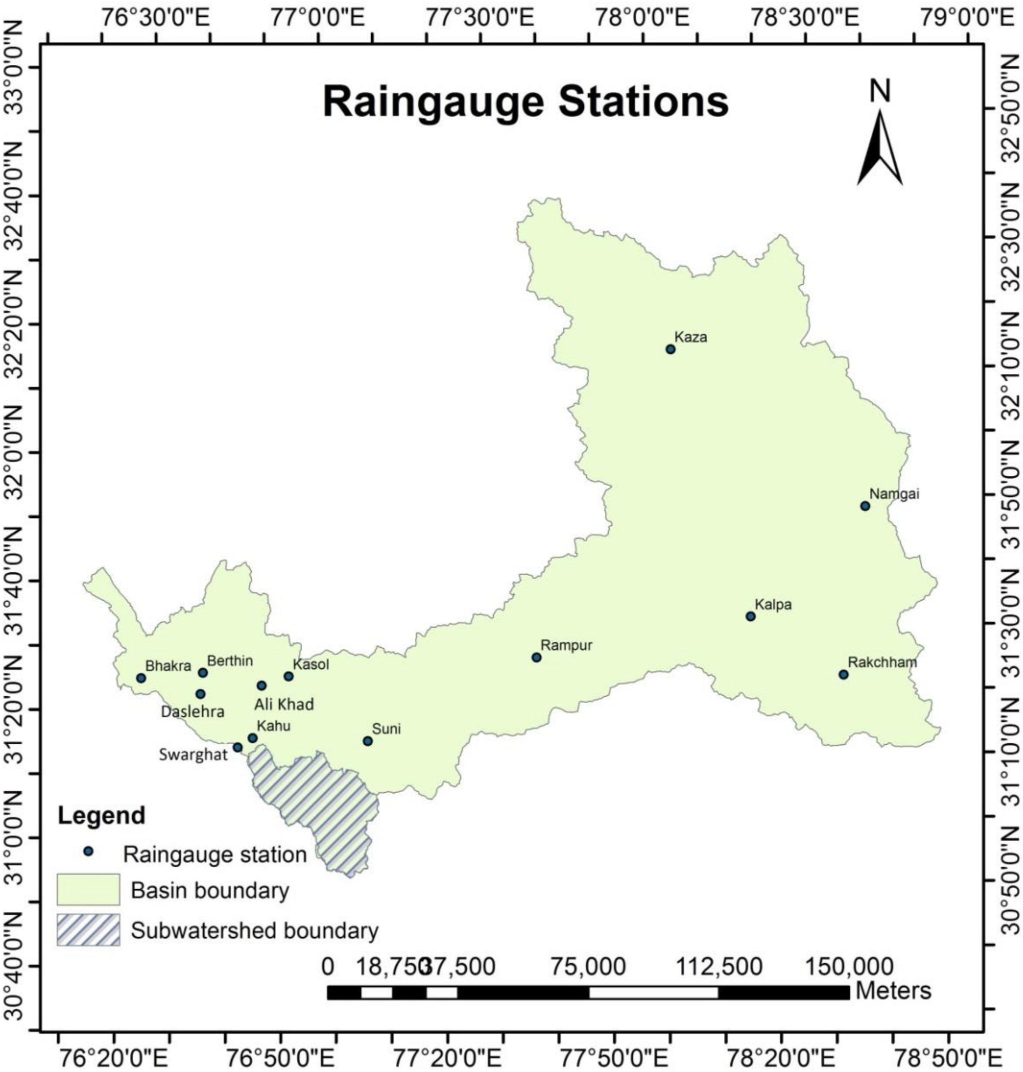


Fig. 4.6 Rain gauge stations in Satluj basin

4.3 Model Development

The model can be applied to a single slope element (Grid, Pixel) or many number of elements. However, in the present study, entire basin is sub-divided into number of elements (91523). These elements can be arranged in a logical sequence to reflect the direction of flow of runoff and sediment over the landscape. All layers have been inputted into the MMF model and processed further step by step. The main steps incorporated by the MMF model are:

1. Estimation of rainfall energy.
2. Estimation of runoff.

3. Detachment of soil particles.
4. Immediate deposition of detached particles.
5. Delivery of detached particles to runoff.
6. Transport capacity of runoff.
7. Sediment balance.

Estimation of rainfall energy

The model starts with rainfall energy estimation. The effective rainfall (Rf, mm) is calculated from the raster map of mean annual rainfall (R, mm) after allowing the permanent interception (PI, proportion between zero and unity) due to the vegetation cover. Slope (S, radian) is added on the quantity of the rain received per unit area for the profound effective rainfall estimation. All raster layers brought into the Raster calculator tool available in Arc GIS 10.0 and final Rf map has been derived.

$$Rf = R \times (1-PI) \times (1/\cos S) \qquad 4.1$$

The effective rainfall is divided into two sub categories that are direct throughfall (DT, mm) and leaf drainage (LD, mm). Direct throughfall is the amount of rainfall that reaches the soil surface directly through gaps in the vegetation cover, and similarly leaf drainage is that amount of rainfall reaching the soil surface as flow or drips from the leaves and stems of the vegetation. Leaf drainage is directly proportional to the amount of the effective rainfall which is intercepted by the canopy cover (CC). Canopy cover map is available in the form of raster layer and LD was derived by multiplying Rf and CC maps.

$$LD = Rf \times CC \qquad 4.2$$

Direct through fall then becomes the difference between the effective rainfall and the loss of rainfall water due to leaf drainage.

$$DT = Rf - LD \qquad 4.3$$

The kinetic energy (KE; J $m^{-2}mm^{-1}$) of direct throughfall is a function of the intensity of the erosive rain (I, mm h^{-1}), maximum kinetic energy content (KE_{max}; J $m^{-2}mm^{-1}$) and an amount of direct throughfall. The relationship between kinetic energy and rainfall intensity (I) varies with the drop-size distribution of the rainfall. In this study, formula developed by Kinnell, (1981) (for Indian condition) has been used.

$$KE(DT) = DT \times [KE_{max}\{1 - a \exp(-bI)\}] \qquad 4.4$$

Where, a and b are empirical constants and KE_{max} is the maximum kinetic energy. These three parameters have been obtained from work done by Van Dijk *et al.*, (2002). Guide values are basically used for the intensity of the erosive rain (I) according to geographical location. They are 10 mm h^{-1} for temperate climates, 25 for tropical climates and 30 for strongly seasonal climates. A value of 25 is suitable for the present study region (Kinnell, 1981).

Since the drop-size distribution of leaf drainage is reasonably uniform, regardless of the type of plant cover (Brandt, 1989), the kinetic energy of the leaf drainage is a function of the plant height (PH, m), which determines the height of fall of the raindrops. Based on the work of Brandt (1990), by giving the following condition in raster calculator KE (LD) map has been derived.

$$For\ PH < 0 \cdot 15,\ KE\ (LD) = 0 \tag{4.5}$$

$$For\ PH \geq 0 \cdot 15,\ KE\ (LD) = (15 \cdot 8 \times PH^{0 \cdot 5}) - 5 \cdot 87 \tag{4.6}$$

The above mentioned equation (4.5) is used to prevent the kinetic energy of the leaf drainage to becoming a negative value when Equation (4.6) is extrapolated to very low plant heights. The total kinetic energy of the effective rainfall is,

$$KE = KE\ (DT) + KE\ (LD) \tag{4.7}$$

Estimation of runoff

Development of Runoff routing module

This model is quite different from all other MMF models. It incorporates soil loss (sediment) routing as well as runoff routing. The model divides entire watershed in a number of elements, for this study ASTER DEM (90m, rescaled) has been taken as base map so that all input layers created in same resolution. Element size has been taken as same as pixel size (90×90) of base map (DEM). All the routing process has been carried out by coding developed in PYTHON 2.6.5. The input maps for the entire process are flow direction, flow accumulation, effective rainfall (Rf; mm), soil moisture storage capacity (Rc; mm), mean rain per rainy day (Ro; mm), mean annual rainfall (R; mm), evaporation (E; mm), lateral permeability of soil (LP; m/day) and slope map (s; radian). These layers have been taken as an input for python code and give total runoff map (Q; mm) as an output. The entire processes and algorithm used in runoff routing process shown in Fig. 4.7.

In this model runoff starts from the pixel where flow accumulation is zero because that pixel is not getting runoff from any other pixel. The total runoff generated on that pixel will now become contributing runoff for another which has flow accumulation greater than zero. The annual runoff generated on the pixel element (Qe; mm), which have no contributing pixel can be predicted from Kirkby (1976)

$$Qe = Rf\, exp\, (-Rc/R_0) \qquad 4.8$$

R_0 is the mean rain per rain day (i.e. R/R_n, where R_n is the mean annual number of rain days), Rf is the effective rainfall (from eq.4.1), *R*c (mm) is the soil moisture storage capacity of the soil, mainly depends upon the soil moisture content at the field capacity (MS, w/w), the bulk density of the soil (BD, Mg m^{-3}), the effective hydrological depth (EHD, m) which is defined as, the depth of soil within which the moisture store controls the starting of runoff, and the loss of water from the soil through evapo-transpiration, represented by the E_t/E_0 ratio of the land cover.

$$R_c = (1000MS \times BD \times EHD \times (E_t/E_0)^{0.5}) \qquad 4.9$$

The values of parameters have been used in eq. 4.9 are shown in Table 4.2 & Table 4.3. The runoff generated on the element having accumulation value zero will have some interflow. This volume of interflow can be estimated from formula given by Kirkby (1976).

$$IF = \frac{(R - E - Qe) \times LP \times \sin S}{356} \qquad 4.10$$

The amount of interflow generated on the element is simulated as a function of water balance, which incorporated rainfall (R), runoff generated on a particular pixel element (Qe) from eq. 4.8, evaporation (E), the saturated lateral permeability of the soil (LP; m/day) and the slope angle (S). The turc function (Turc, 1961) is used for annual evaporation (E):

$$E = \frac{R}{\sqrt{0.9 + \frac{R^2}{Z^2}}} \qquad 4.11$$

Where, $Z = 300 + 25T + 0.05T^2$. T is the mean annual temperature (°C).
This interflow will become contributing interflow for next element and subtract from initial soil moisture storage capacity of the soil, in this way new amount of soil moisture storage capacity will be

$$Rc = (1000MS \times BD \times EHD \times (E_t/E_0)^{0.5}) - IF\,(CE) \qquad 4.12$$

Now, this Rc has become input for equation 4.8, and the new runoff generated on the element, simulated along the flow direction map. Element, having higher flow accumulation than the previous one, will work as a runoff receiving element. In this way the total runoff (Q) generated on this element becomes

$$Q = (Rf + Q\,(CE))\, exp\, (-\mathbf{Rc}/R_0)\, (L/10)^{0.1} \qquad 4.13$$

This looping will continue for entire watershed, until the loop will not obtain the maximum value of flow accumulation (outlet). The total runoff calculated in equation (4.13) is appropriate for slopes about 10m long (Carson and Kirkby, 1972) and needs to be adjusted for the actual slope length (L; m). This is a very sensitive parameter for the entire model. Without slope length correction, very different results are obtained if a slope is simulated as a single element compared with dividing the slope into three or more elements.

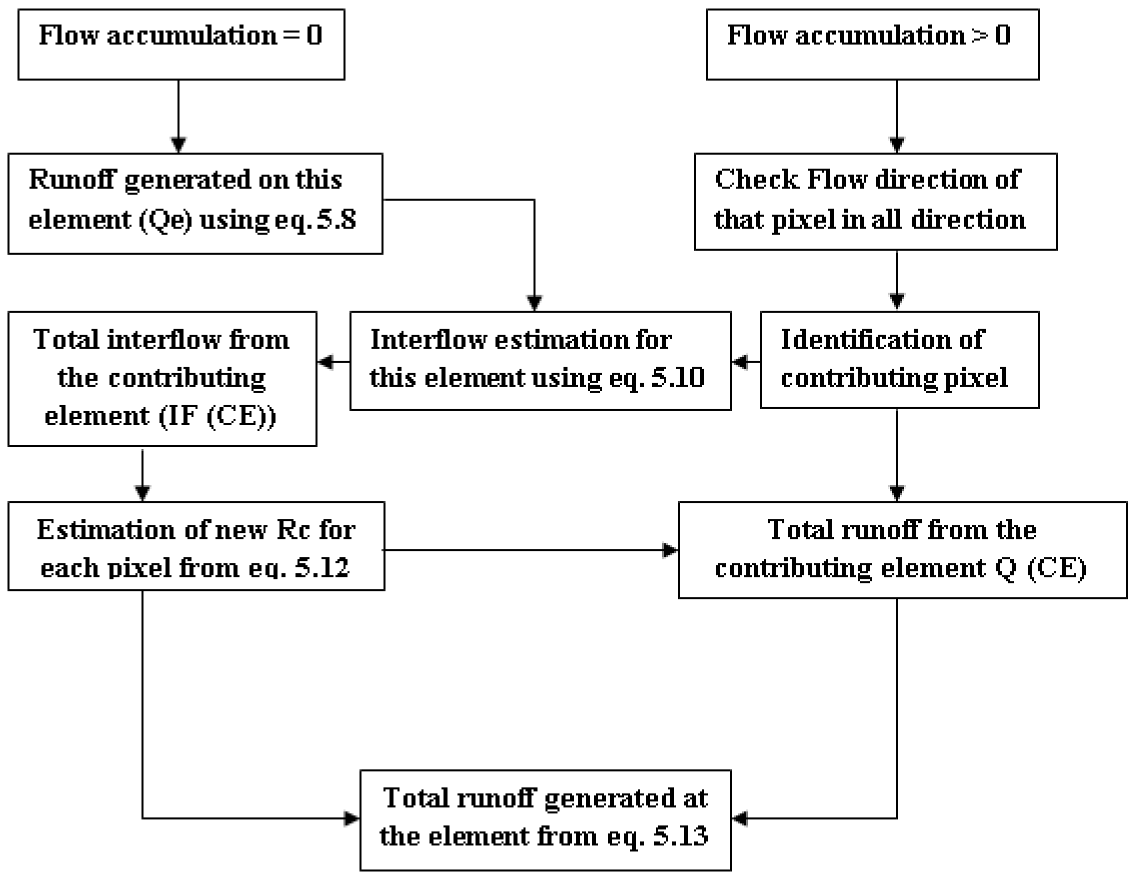


Fig. 4.7 Flow chart of estimation of total runoff

Detachment of soil particles

The detachment of soil particles by raindrop impact (F, kg m−2) is a function of kinetic energy of the effective rainfall (KE), the detachability of soil (K, J m−2) and the stone cover (ST, expressed as a proportion between zero and one). Stone cover can be omitted for this study region because major part of soil type containing sand silt and clay texture class. The kinetic energy of effective rainfall is proportioned according to the amount of clay (C), silt (Z), and Sand (S) particles in order to allow for the particle-size distribution in the soil. With the help of following equations detachment by raindrop impact estimated. Raster map of percentage clay, silt and sand map has been derived from soil map and KE map obtained from eq. 4.7.

$$Fc = Kc \times \%c/100 \times (1 - ST) \times KE \times 10^{-3} \qquad 4.14$$
$$Fz = Kz \times \%z/100 \times (1 - ST) \times KE \times 10^{-3} \qquad 4.15$$
$$Fs = Ks \times \%s/100 \times (1 - ST) \times KE \times 10^{-3} \qquad 4.16$$

Sensitivity analysis of the model is carried out by Morgan and Duzant, (2008). On the basis of that, higher values of Kc, Kz and Ks are taken respectively as 1·5, 5·15 and 4·15 g J^{-1}. The detachability of clay particles has a very high variability depending on the aggregate stability of the soil and the type of clay, both of which provides influence on soil cohesion. Total detachment by raindrop impact is,

$$F = Fc + Fz + Fs \qquad 4.17$$

The detachment of soil particles (H, kg m^{-2}) by runoff, is a function of volume of runoff (Q), the detachability of the soil by runoff (DR, g mm^{-1}), slope angle (S) and the proportion of the soil covered by vegetation (GC) and stones (ST). Q map obtained from eq. 4.13, ground cover (GC) raster map from LULC, and slope map derived from DEM.

$$Hc = DRc \times \%c/100 \times Q^{1\cdot5} \times (1 - (GC + ST)) \times \sin^{0\cdot3} S \times 10^{-3} \qquad 4.18$$
$$Hz = DRz \times \%c/100 \times Q^{1\cdot5} \times (1 - (GC + ST)) \times \sin^{0\cdot3} S \times 10^{-3} \qquad 4.19$$
$$Hs = DRs \times \%c/100 \times Q^{1\cdot5} \times (1 - (GC + ST)) \times \sin^{0\cdot3} S \times 10^{-3} \qquad 4.20$$

Total detachment by runoff is,

$$H = Hc + Hz + Hs \qquad 4.21$$

The calibrated values for DR are 2·0, 1·6 and 1·5 for the clay (c), silt (z) and sand (s) fractions respectively, based on data from sensitivity analysis (Morgan and Duzant, 2008).

Immediate deposition of detached particles

Only a part of the detached sediment will be delivered to the runoff for transport, the remainder will be deposited close to the point of detachment. The amount of detached soil delivered to the flow (G) is therefore the result of a balance between the amount of soil detached by raindrop impact (F), the amount of soil detached by runoff (H) and the amount of detached soil which is deposited (DEP).The deposition of soil particles is modeled as a function of the probability that is, a detached particle will fall to the soil surface instead of entrained in the runoff. This probability is related to a particle fall number (Nf, Tollner *et al.,* 1976), which depends upon the length of the element (l), the fall velocity of the particles (ν_s), the flow velocity (ν) and the flow depth (d).

Flow velocity calculations are made for four possible conditions:

a) A standard condition related to un-channeled overland flow over a smooth bare soil (ν_b).
b) The actual condition, which can take account of flow channeling into rills (ν_a).
c) A condition taking into account of the effects of the vegetation cover (ν_v).
d) A condition taking account of the roughness of the soil surface, as that result from tillage (ν_t).

Calculations are made only for those conditions that exist for the study region where the model is being applied. Thus, if there is no vegetation or crop cover, v_v can be omitted. In Gamber region tillage practices do not affect the sediment yield because crop acreage is less than hill slopes and forest therefore ν_t has been omitted from further calculation and first three velocities has been incorporated.

Considering the above said conditions and taking them into detail,

1. For the standard bare soil condition, flow velocity map is estimated from the Manning equation,

$$v_b = 1/n \; d^{0\cdot 67} S^{0\cdot 5} \qquad 4.22$$

   Where n is Manning's roughness coefficient and d is the flow depth (m) and slope(S) has been taken in m/m. Values of n = 0·015 and d = 0·005 are used.

2. For the actual flow velocity (v_a), the eq. 4.22 is used. If flow accumulation is >=50 the flow depth d = 0·005, it is showing un-channeled flow. If flow accumulation between 51 to 1000 flow depth d = 0·01 showing shallow rills and if flow accumulation greater than 1000 d will be 0·25 showing deeper rills. The equation used is,

$$v_a = 1/n \; d^{0\cdot 67} S^{0\cdot 5} \qquad 4.23$$

3. For the vegetated conditions, flow velocity is estimated as a function of slope map (S; m/m) and the density of the vegetation, the latter depends upon the diameter of the plant stems (D) and the number of stems per unit area (NV) (Jin *et al.*, 2000),

$$v_V = \left(\frac{2g}{D\ NV}\right)^{0.5} S^{0.5} \qquad 4.24$$

Raster layer of D and NV has been derived from LULC map and the values have been obtained from table 4.3. Now the particle fall number (N_f) map is determined separately for each soil particle class from,

$$Nf(c) = l \times Vs(c) \,/\, v \times d \qquad 4.25$$

$$Nf(z) = l \times Vs\,(z) \,/\, v \times d \qquad 4.26$$

$$Nf(s) = l \times Vs(s) \,/\, v \times d \qquad 4.27$$

Where length of the element (*l*) taken as 90m, ν is velocity for bare soil condition, vegetated condition or actual condition and d is the depth of flow used in eq. 4.23. Flow velocities have been taken from eq. 4.22, 4.23 and 4.24. Fall velocities are estimated from,

$$\nu_S = \frac{\frac{1}{18}\, x\, \delta^2(\rho_S - \rho)g}{\eta} \qquad 4.28$$

Where δ is the diameter of the particle, ρ_s is the sediment density (1240 kg m^{-3}), ρ is the flow density (typically 1100 kg m^{-3}) for runoff on hill slopes (Abrahams *et al.*, 2001), g is gravitational acceleration (taken as 9·81 m s^{-2}) and η is the fluid viscosity (nominally 0·001 kg m^{-1} s^{-1} but taken as 0·0015 to allow for the effects of the sediment in the flow). The above mentioned formula is applied to find out the particle velocity for clay, silt and sand. Particle diameter has been taken 0.000002 m for clay, 0.00004 m for silt and 0.0002 m for sand based on soil type classification and it gives respective v_s values of 0.000000203 m s^{-1} for clay, 0.00008130 m s^{-1} for silt and 0.002032593 m s−1 for sand. All the input for particle fall number is in the form of raster layer and derived from raster calculator tool in Arc GIS 10.0.
The percentage of the detached sediment that is deposited is estimated from the relationship obtained by Tollner et al. (1976) and is calculated separately for each particle size,

$$DEP(c) = 44{\cdot}1(Nf(c))^{0{\cdot}29} \qquad 4.29$$

$$DEP\,(z) = 44{\cdot}1(Nf(z))^{0{\cdot}29} \qquad 4.30$$

$$DEP(s) = 44{\cdot}1(Nf(s))^{0{\cdot}29} \qquad 4.31$$

These equations yield values of DEP layer > 100, but since it is physically not possible to deposit more material than detached, a maximum value is set at DEP = 100 by applying the condition in raster calculator, Arc GIS 10.0.

Development of Sediment routing module

This routing has been developed on same programming platform as used for runoff. Delivery of detached particles to runoff starts from the element having flow accumulation value zero, sediment flow starts from this pixel and correspondingly this will become contributing element for next pixels (Fig. 4.8). The predefined algorithm structured for the runoff is similarly used to estimate the soil loss by keeping the concept same but differentiating in the formulas and conditions. Fig. 4.8 shows the overall algorithm for estimation of total soil loss.

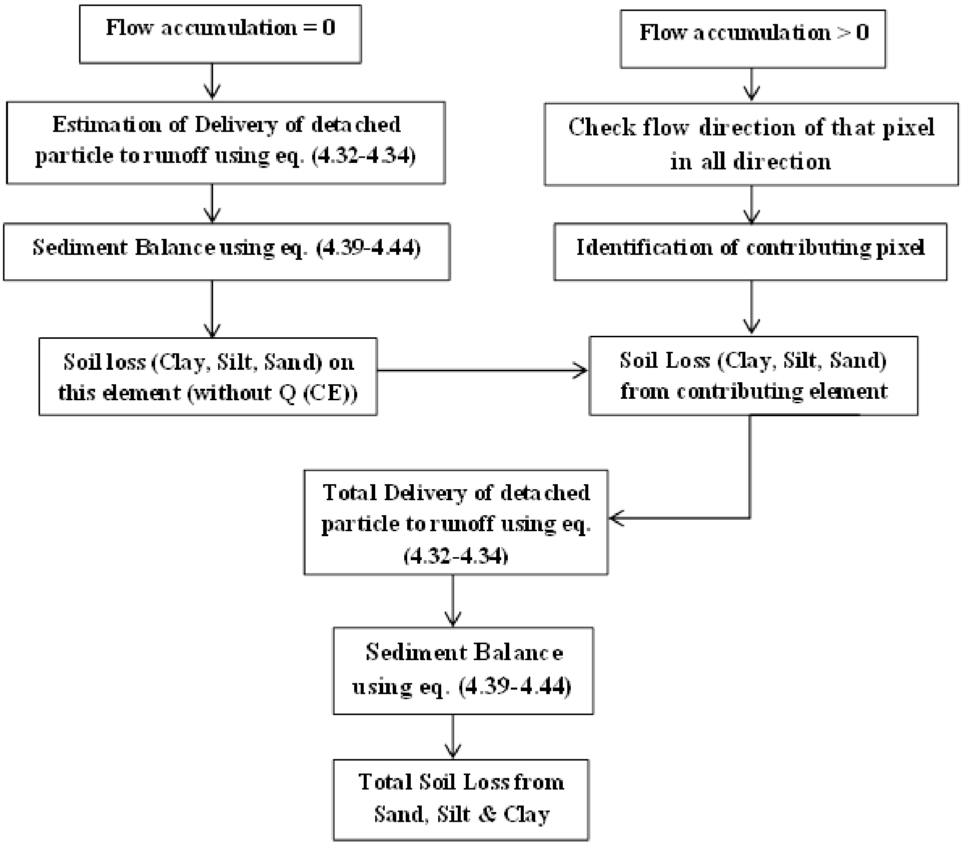


Fig. 4.8 Flow chart of estimation of total sediment yield

Delivery of detached particles to runoff

The number of detached particles (G) going into transport in the flow is calculated separately for clay, silt and sand, by taking into account detachment by raindrop impact (F), detachment by runoff (H) on the element which has been prepared earlier (eq. 4.14 -4.20), deposition of the detached material (DEP) on the element (eq. 4.29-4.31) and the input of detached sediment in the runoff from the upslope contributing element (SL (CE)). For the first pixel SL (CE) will be zero and G(c) will be calculated without SL (CE), after that with the help of flow direction map routing programme will find the location of contributing pixel and the contributed amount (G). This amount will be added to next pixel. In this way soil loss routing has been simulated.

$$G(c) = (F(c) + H(c)) \times (1 - (DEP(c)/100)) + (SL\,(CE)\,(c) \times W\,(CE)/W) \quad 4.32$$

$$G\,(z) = (F(z) + H(z)) \times (1 - (DEP(z)/100)) + (SL\,(CE)\,(z) \times W(CE)/W) \quad 4.33$$

$$G(s) = (F(s) + H(s)) \times (1 - (DEP(s)/100)) + (SL\,(CE)\,(s) \times W\,(CE)/W) \quad 4.34$$

Where W (CE) is the width of the upslope contributing element, in this case contributing element and receiving element both are having 90m width so the ratio becomes 1. The total detached material going into flow for transport:

$$G = G\,(c) + G\,(z) + G\,(s) \quad 4.35$$

Transport capacity of the runoff

After the delivery of detached particles to runoff, transport capacity decides the further movement of particles. The transport capacity of the runoff (TC, kg m^{-2}) is a function of the volume of runoff on the element (Q), the slope steepness (S; radian) and the effect of the plant cover (v_v) and estimated separately for clay, silt and sand.

$$TC(c) = (v_a \times v_v /vb)\ (\%c/100)\ Q^2 \sin S\ 10^{-3} \quad 4.36$$

$$TC\,(z) = (v_a \times v_v /vb)\ (\%z/100)\ Q^2 \sin S\ 10^{-3} \quad 4.37$$

$$TC(s) = (v_a \times v_v /vb)\ (\%s/100)\ Q^2 \sin S\ 10^{-3} \quad 4.38$$

Where, there is no vegetation or crop cover v_v can be omitted.

Sediment balance

Now the routing module compares the transport capacity (TC) with the amount of material available for transport (G). Two conditions are possible, which are:

1. If TC is greater than or equal to G, all of G is transported from the element and the soil loss (SL) from the element equals G.

$$If\ TC(c) \geq G(c),\ SL(c) = G(c) \quad 4.39$$

$$If\ TC(z) \geq G(z),\ SL(z) = G(z) \quad 4.40$$

$$If\ TC(s) \geq G(s),\ SL(s) = G(s) \quad 4.41$$

2. If the transport capacity (TC) is less than G, the material will need to be deposited from G, until the condition TC = G.

Deposition of excess sediment from the flow is therefore calculated by determining the particle fall number (Nf) from equations (4.25–4.27) using particle settling velocities for clay, silt and sand, calculating deposition (DEP) from Equations (4.29–4.31) and respectively applying the following equations to determine the sediment balance,

$$If,\ TC(c) < G(c),\ calculate\ G(c1) = G(c)\ (1 - (\%DEP(c)/100)) \qquad 4.42$$
$$If,\ TC\ (c) >= G(c1),\ SL(c)=TC(c);\ If,\ TC(c) < G(c1),\ SL(c)= G(c1)$$

$$If\ ,\ TC(z) < G(z),\ calculate\ G(z1) = G(z)\ (1 - (\%DEP(z)/100)) \qquad 4.43$$
$$If,\ TC\ (z) >= G(z1),\ SL(z)=TC(z);\ If,\ TC(z) < G(z1),\ SL(z)= G(z1)$$

$$If,\ TC(s) < G(s),\ calculate\ G(s1) = G(s)\ (1 - (\%DEP(s)/100)) \qquad 4.44$$
$$If,\ TC\ (s) >= G(s1),\ SL(s)=TC(s);\ If,\ TC(s) < G(s1),\ SL(s)= G(s1)$$

The total mean annual soil loss (SL, kg m^{-2}) from the element is,

$$SL = SL(c) + SL\ (z) + SL(s) \qquad \mathbf{4.45}$$

4.4 Model Calibration and Validation

Calibration of an erosion model is an iterative process of parameter evaluation and refinement, as a result of comparing simulated and observed values of interest. Validation is an extension of calibration process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations for periods separate from the calibration effort.

The evolution of sediment yield model behavior and performance is commonly made and reported through comparison of simulated and observed values at the outlet. In general eight model parameters of MMF model need to be calibrated. These parameters are slope length (L), detachability of clay particles by rain (Kc), detachability of silt particles by rain (Kz), Detachability of sand particles by rain (Ks), detachability of clay particles by runoff (DRc), detachability of silt particles by runoff (DRz), detachability of sand particles by runoff (DRs), and particle fall velocity (vs) for clay, silt and sand. In the present study MMF (Morgan and Duzant, 2008) model have been developed and calibrated for two years i.e. 1998 and 2002. Later, the calibrated MMF model for the study area has been validated for the year 1999, 1995. The reason for selection of these particular years is the observed data at gauging station (Kahu) was available for those two respective years (BBMB, 2003). The sediment gauging takes place for alternate years at the gauging station, so the year of 2000 was showing high variability with respect to preceding years and it has not been incorporated for model development. For the purpose of validation, year 1995 and 1999 has been chosen. The observed data was unavailable for these two years, since the interpolated data according to the preceding year was available (BBMB, 2003).

The following criteria were selected for model calibration:

- **Relative error (Er in percent)** between the simulated and observed annual sediment yield, defined as:

$$Er = (S_c - S_o) / S_o$$

Where, S_c and S_o are the simulated and observed annual sediment yield (tons).

4.5 Rainfall Variability and Its Impact on Annual Sediment Yield

After successful development of MMF model in geospatial environment, model needs to show the impact of rainfall variability on sediment yield. Gosain *et al.,* (2011) had studied the impact of precipitation and climate change over important river basin in India and concluded that rainfall may increase by 17-18 % by end mid and end of century respectively in Indus Basin. Satluj Basin which is a part of Indus system has shown high rainfall variability in past cumulative years (Source: BBMB). Hence, this scenario has been adopted for the current study. Due to climate change, there will be enormous effect on extreme events, which may occur in near future (Ghosh *et al.,* 2012). Therefore, to study the effect of rainfall variability on sediment yield, firstly rainfall intensity has been varied by increasing it by 10% and obtained various results. After that number of rainy days has been decreased by 10% and rainfall intensity increased by 10% and obtained another result. In this way developed MMF model for the study region has been applied for various rainfall intensities, mean annual number of rainy days and increased amount of sediment yield has been obtained.

There is a large spatial and temporal variability in the rainfall trends over India and strong intra-seasonal variability was analyzed for the majority of the sub divisions, regions and the whole of India by Kumar *et al.,* (2010). This variability increases the detachment of clay, silt and sand (Eq. 4.14 – 4.16) and sediment delivery to runoff (Eq. 4.32- 4.34). Finally increased amount of sediment yield has been obtained as discussed in subsequent chapter.

CHAPTER – 5
RESULTS AND DISCUSSION

This study attempts to estimate the sediment yield of a sub-watershed of Satluj river basin and assess rainfall variability impacts on mean annual sediment yield at the sub-watershed outlet. For this purpose, development of a sediment yield model (Morgan and Duzant, 2008) in geospatial framework for the year of 1998 and 2002 was carried out. Analysis of the changes in sediment yield and model validation has also been presented in this chapter. The trend of changes in mean annual sediment yield due to rainfall changes has been analyzed at the end of this chapter.

5.1 Basin Delineation and Sub-watershed Delineation

As discussed in the methodology, the preliminary step in sediment yield estimation is to delineate the respective watershed from ASTER DEM. Fig. 5.1(a-d) shows the step by step process of basin and sub-watershed delineation such as fill DEM, flow direction, flow accumulation and finally the delineated basin, sub-watershed boundary.

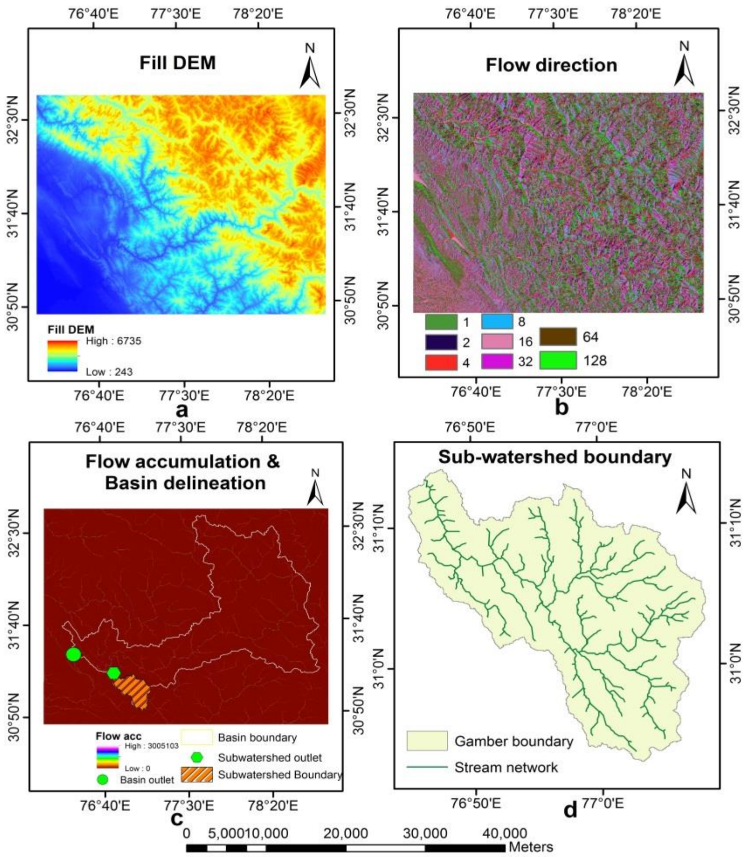


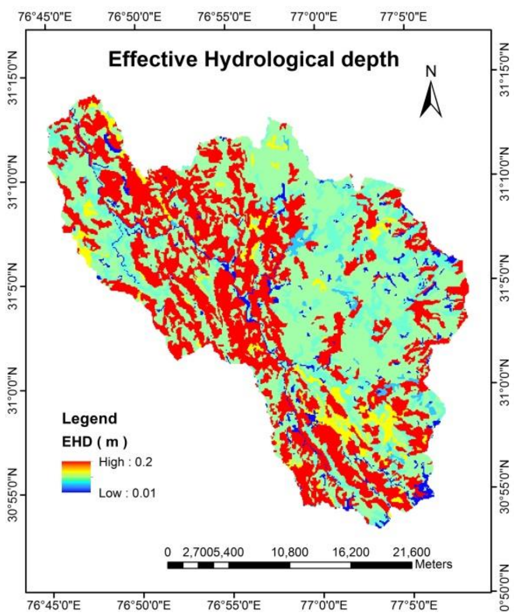
Fig. 5.1 Basin boundary and Sub-watershed delineation

The delineated sub-watershed of stream known as Gamber Khad covers around 750 km^2 of the entire basin. This region has sediment gauging station Kahu and gave observed sediment data for development and validation years. As explained in methodology a large number of input layers have been required, so the next step was input map generation for MMF model from various datasets.

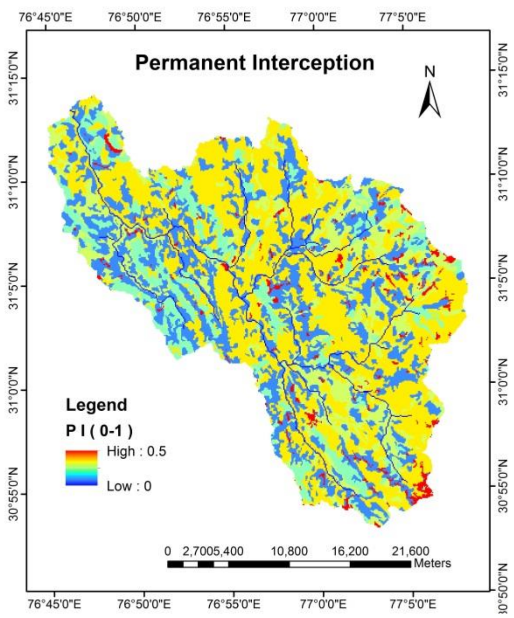
5.2 Input Map Generation

Land-use land-cover (LULC)

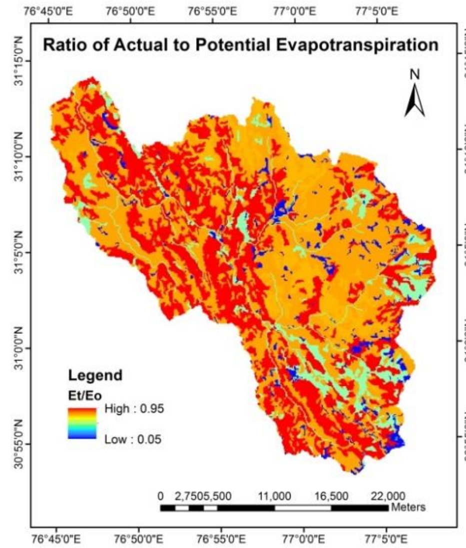
It is the important dataset for MMF model as most of the parameters were obtained from LULC. Since land use classes present in the study region were nearest matching, as used by Morgan and Duzant, 2008 in their work, selection of those classes and assigning parameter values in their attributes has been carried out. The thematic layers correspond to input parameters generated from LULC map for various classes are effective hydrological depth(m), permanent interception (between 0-1), ratio of actual to potential evapo-transpiration (Et/Eo), canopy cover (between 0-1), ground cover (between 0-1), plant height (m), plant density (number/m^2) and average stem diameter (m). Values for all the parameters were taken from Table 4.3 presented in previous chapter and assigned these values in the attribute of LULC subsequently raster layers have been derived separately for each parameter as shown in Fig 5.2 (a-h).

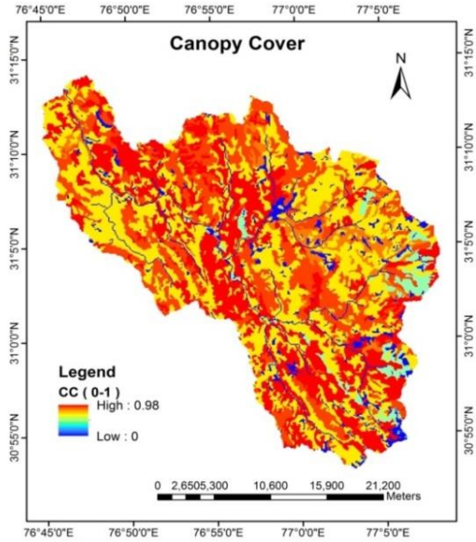


(a)

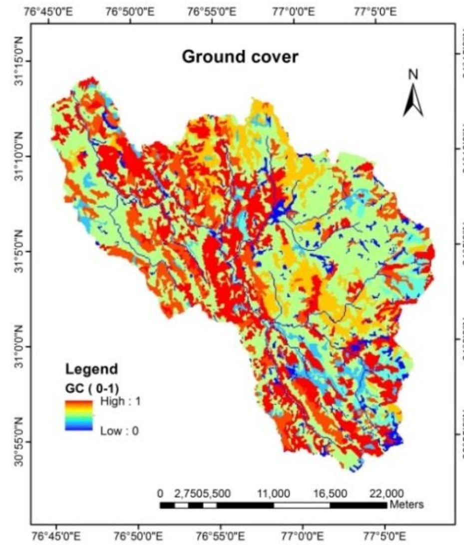


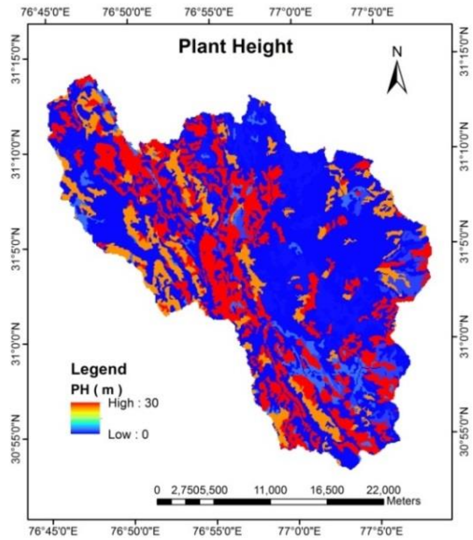
(b)



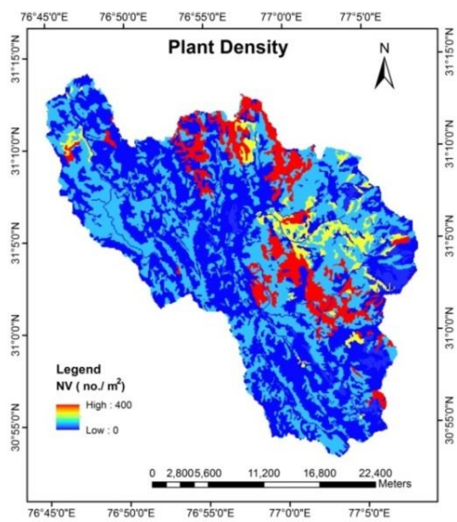


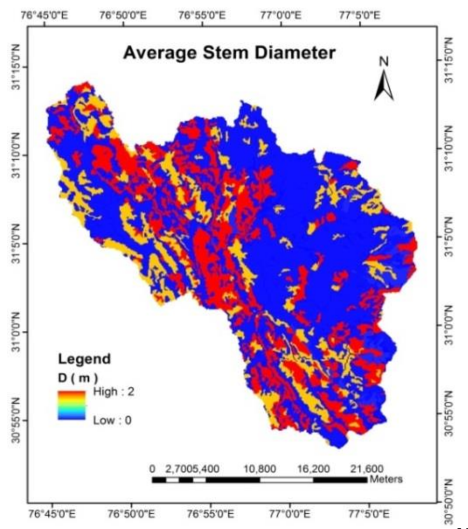
(c) (d)





(e) (f)



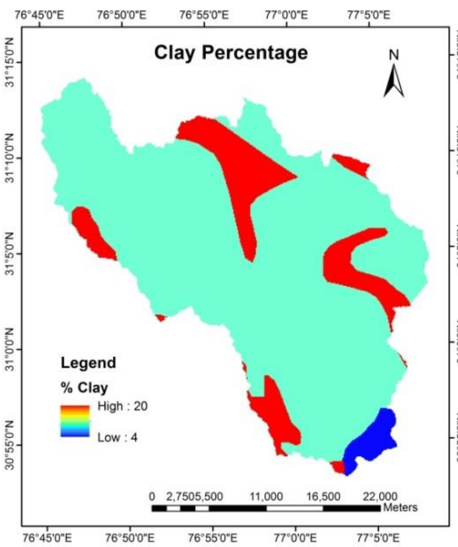


(g) (h)

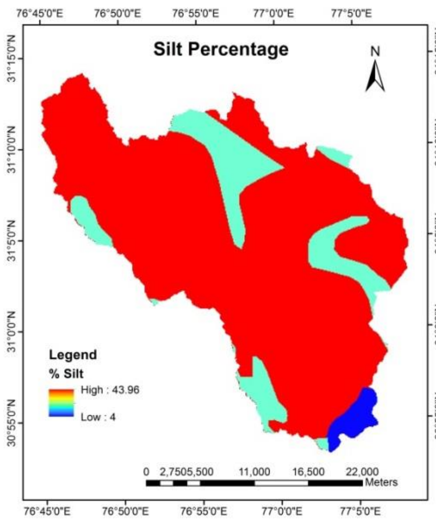
Fig. 5.2 Input parameter layers generated from LULC

Soil map

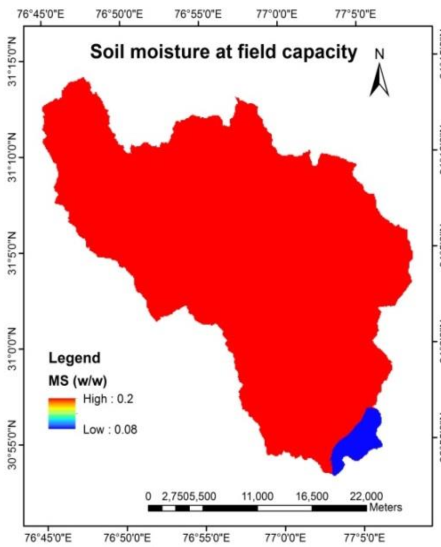
Soil map of an area provides information regarding soil type, texture and composition of sand, silt, clay. This information plays very significant role in sediment yield estimation using MMF (Morgan and Duzant, 2008 version), separately for each textural class. Mainly three types of soil exist in the selected sub-watershed; these are sandy, loamy and loamy skeletal. Composition of required parameter was shown in previous chapter (Table 4.2). Raster layer of necessary parameter has been generated by assigning these values into attribute of soil map; % clay, % silt, % sand, soil moisture at field capacity, bulk density and lateral permeability has been derived from soil map. Which are shown in Fig. 5.3(a-f).



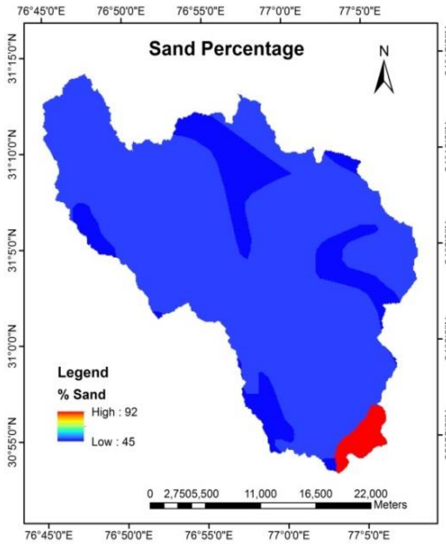
(a)



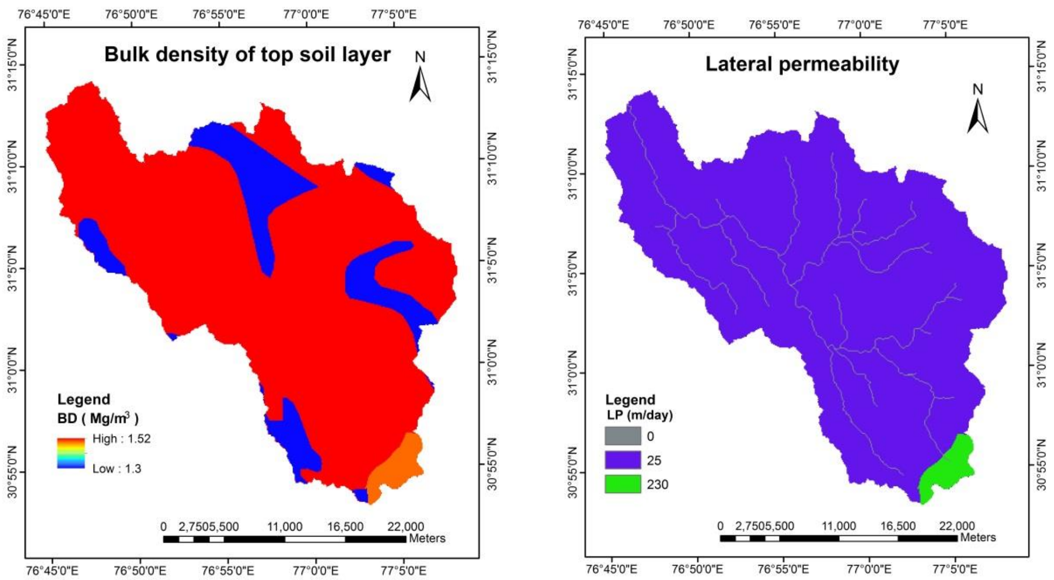
(b)



(c)



(d)



(e) (f)

Fig. 5.3 Input parameter layers generated from Soil map

The % clay ranges from 4 to 20%, % silt ranges from 4 to 44%, sand ranges from 45 to 92%, soil moisture at field capacity having maximum value of 0.2 in w/w, bulk density of top soil layer ranges from 1.3 to 1.52 in Mg/ m^3 and lateral permeability is 25 m/day in major areas. Modified MMF incorporates particle size selectivity process and estimate sediment yield separately for clay, silt and sand. These layers are needed to put in the model in various stages of sediment yield estimation. Clay, silt and sand maps are derived in percentage, soil moisture at field capacity map is in w/w, bulk density is in Mg/m^3 and lateral permeability is in m/day as required for the model.

Meteorological data

The Point data of mean annual rainfall and number of rainy days has been procured from BBMB for all the years under consideration. The mean annual rainfall has been interpolated by Inverse Distance Weighting (IDW) technique for entire basin and masked by sub-watershed area. These maps are showing distributed mean annual rainfall for entire sub-watershed and ranges from minimum to maximum annual rainfall. Second input for model development was mean rain per rainy day (Ro); it also has been derived from interpolated mean annual rainfall map by dividing the number of rainy days of a particular year. By decreasing the number of rainy days and increasing rainfall intensity, effect of rainfall variability has been analyzed and discussed in next chapter. Third input for model was annual evaporation of the selected region; this was derived from the interpolated rainfall map by applying the various formulas discussed in previous chapter. Since meteorological stations are situated outside the study region (at the outlet), IDW interpolation shows high value at the outlet and low values far from the station. The maps derived from meteorological data are mean annual rainfall, evaporation and mean rain per rainy days (Fig.

5.4). Model development has been performed for the year 1998 and 2002. Layers derived from meteorological data for these two years are shown in Fig 5.4 (a-c).

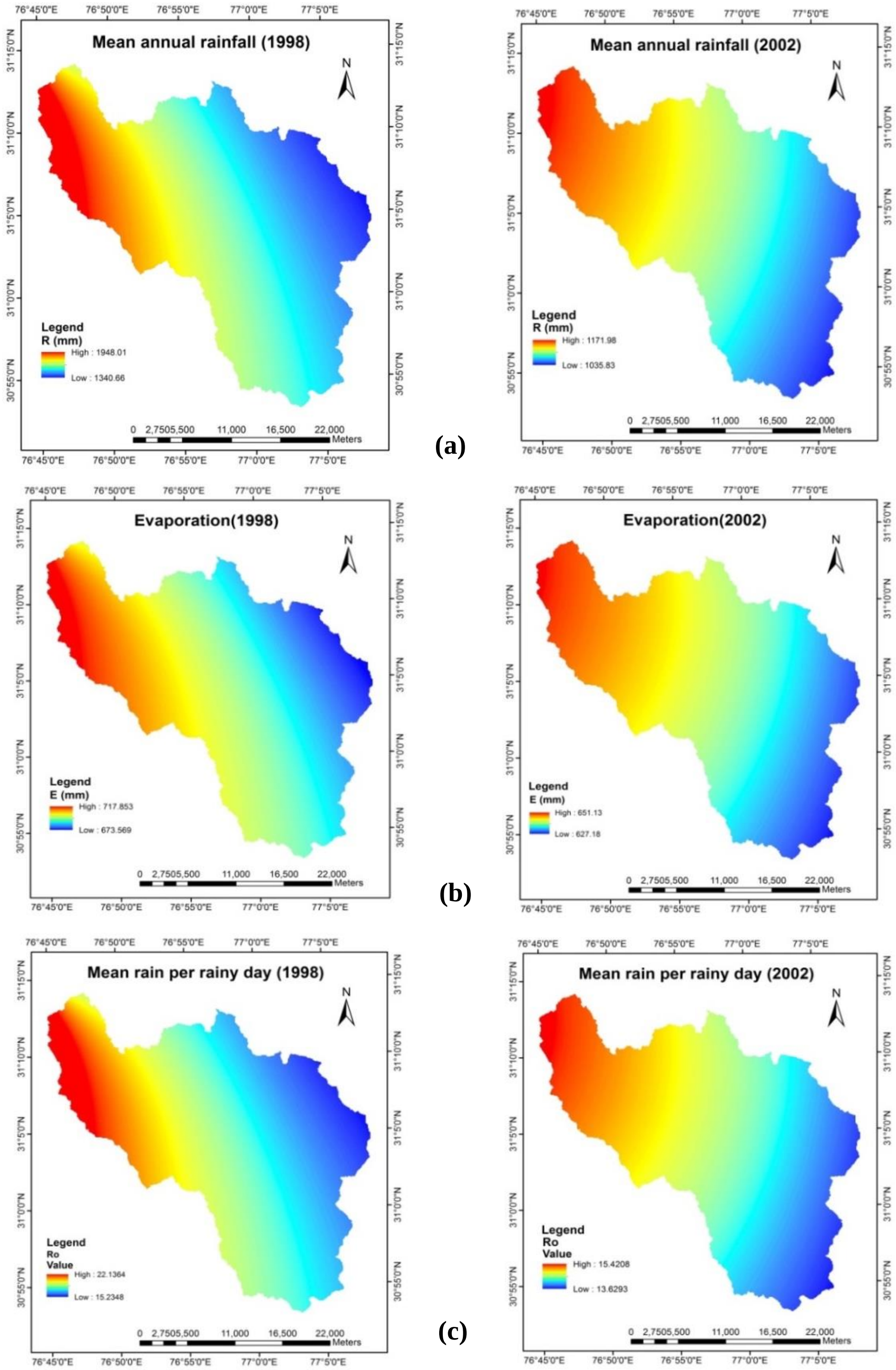


Fig. 5.4 Input parameter layers generated from Meteorological data

5.3 Model Development

The year 1998 and 2002 has been chosen for model development, since the observed data at gauging station (Kahu) was available for those two respective years. The sediment gauging takes place for alternate years at the available gauging station so that in the year of 2000 observed data of sediment yield was showing high variability with respect to preceding years and it has not been incorporated for model development. For the purpose of validation, year 1995 and 1999 has been chosen. The observed data was unavailable for these two years, since the interpolated data according to the preceding year was available (BBMB, 2003). Model development has been carried out for Gamber sub-watershed because its main stream finally goes to the Satluj River and fed to Gobind Sagar reservoir.

The input layers derived from various datasets have been used for model development. In general, this model deals with physical and empirical equations of erosion process and integrated with equations derived by various researchers (Morgan and Duzant, 2008). User needs to define the various constraints of processing and workspace, when routing of runoff and sediment couple with geospatial environment. In the previous work Morgan and Duzant divided the entire area in to the number of elements. In this work ASTER DEM has been taken as a base map and one assumption has been made that one pixel will behave like a one element. Total number of pixel available in the study region is 91523. In this way number of element has become 91523. Initially the model development has been performed for year 1998 & 2002 with following steps:

Estimation of rainfall energy

The layers derived from LULC, Soil map, Meteorological data and DEM are the inputs for this step. These layers are mean annual rainfall (mm), permanent interception (mm), slope (radian), canopy cover and plant height (m). These layers have been integrated into Arc GIS 10.0 and generated the total kinetic energy of effective rainfall (J/m^2) using Eq. from 4.1 to 4.7 discussed in previous chapter. Fig. 5.5 shows the total kinetic energy for the model development years.

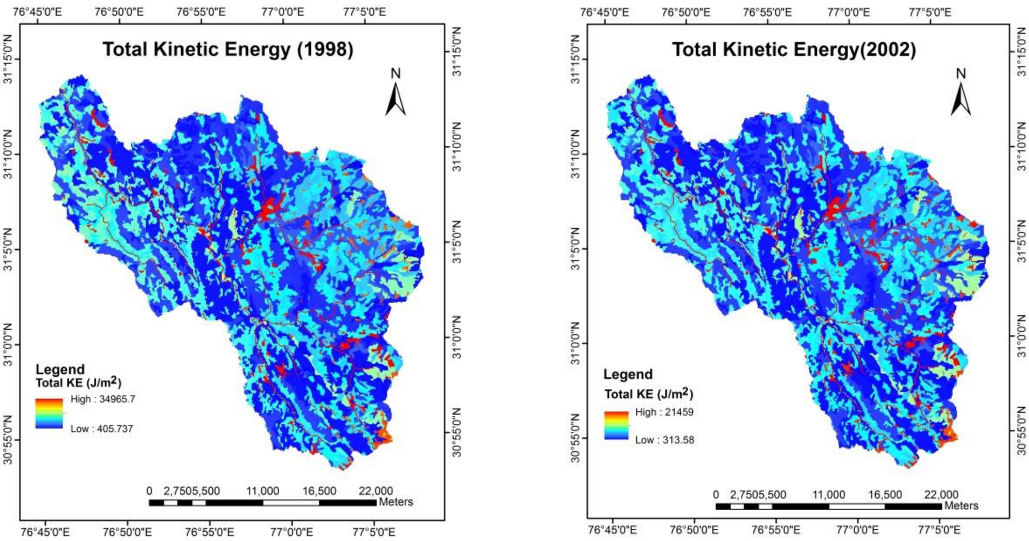


Fig. 5.5 Total kinetic energy of 1998 & 2002

The total kinetic energy is a summation of kinetic energy of direct throughfall and leaf drainage. Leaf drainage depends upon the plant height and minor change will be happen in that with respect to time. The formula of kinetic energy discussed by Kinnell, (1981) for tropical region is directly multiplying with the amount of direct throughfall. It means total kinetic energy directly depends upon the amount of direct throughfall and it will change according to rainfall received in a year. In the year of 1998 mean of interpolated rainfall was 1564 mm and for the year of 2002 it was 1098 mm, so that the high value of total kinetic energy (Fig. 5.5) is showing 34956.7 J/m^2, it is approximately 1.63 times greater than the total kinetic energy of 2002. It shows 3.18 times higher value of actual sediment yield estimated by model for year of 1998. It means, year which is getting high mean annual rainfall has higher kinetic energy and this will further effect the detachment of soil particles by raindrop impact and total sediment yield at the outlet.

Estimation of runoff

Requirement of the model demands an interactive programming code for a fast and efficient processing to estimate total runoff. The processing by code implements routing procedure for each pixel, by analyzing the contribution from surrounding pixels. This procedure continues from the pixel which inherits the beginning of flow to the pixel having maximum flow accumulation value.

Major input layer requires for the developed runoff routing module are flow direction, flow accumulation, soil moisture storage capacity, mean rain per rainy day, evaporation, lateral permeability of the soil, mean annual rainfall and slope. The developed code integrates all the input layers and internally calculates runoff generated on each pixel, interflow from each pixel and soil moisture storage capacity of each pixel after separating the generated interflow as given in Annexure I. Eq. 4.8-4.13 describe in a previous chapter has been used for the entire process. Fig. 5.6 shows the annual runoff generated at the outlet from the entire region for both year of 1998 and 2002.

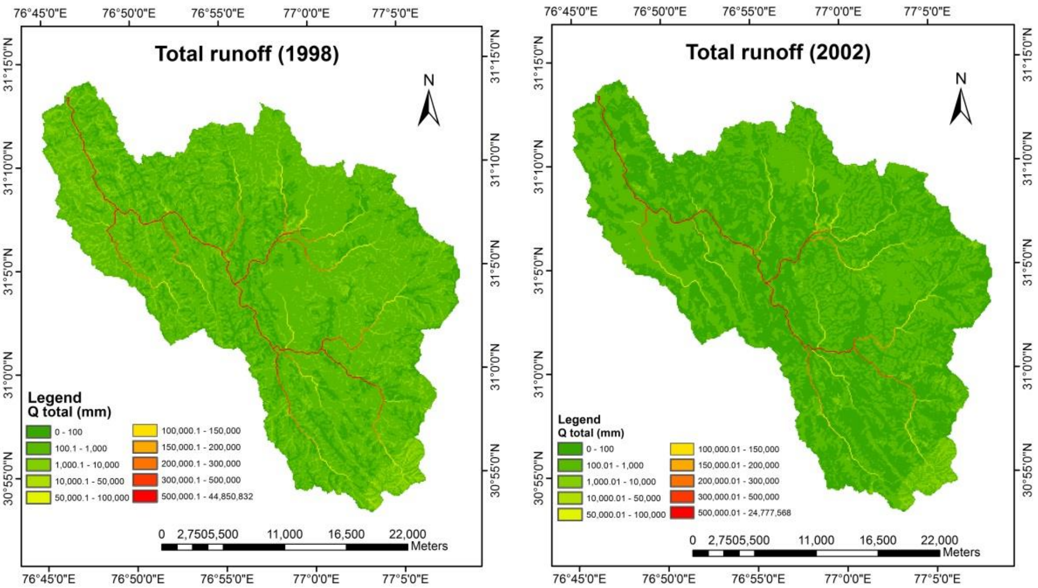
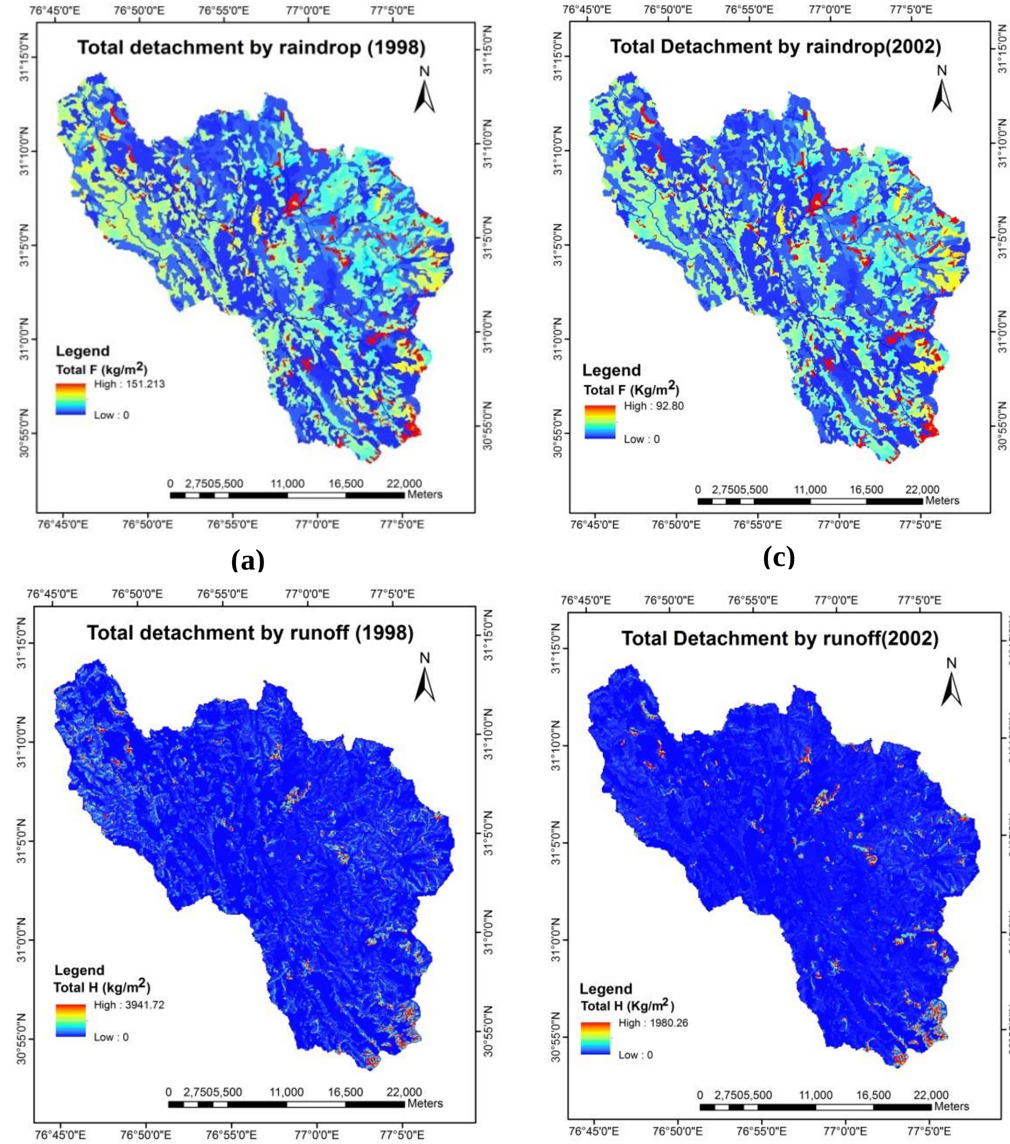


Fig. 5.6 Annual runoff generated from the Sub-watershed

The annual runoff generated at the outlet has been calibrated using the slope length as calibrating variable. This makes the model very sensitive to the number of pixels over which routing of runoff takes place. The value of slope length ranges from 10 to 50m as suggested by Morgan and Duzant, 2008 and for this region the calibrated value of slope length has been taken as 10.7 m. One assumption had been made in this process that was the total runoff is 20% of the mean of the interpolated rainfall. Routed runoff was calibrated against this assumption and slope length was fixed at 10.7 m for entire process. Fig 5.6 is showing the high variability between simulated runoff for selected years. Stream starts from hilly area and goes into the lower elevation; consistently increasing value of runoff towards outlet shows the accumulation of runoff. Since the mean annual rainfall of 1998 is higher than 2002, runoff map of 1998 showing high value 44850832 mm as compared to 2002 (24777568 mm).

Detachment of soil particle

The total kinetic energy obtained from first step and annual runoff derived from second step has been used for soil particle detachment in Kg/m^2. Model estimates detachment separately by raindrop and runoff impact. The total detachment by runoff and raindrop impact is shown in Fig 5.7 (a-d) for the selected year. From the analysis of derived output it is found that in year 1998 and 2002 mean values of detachment due to raindrop were 13.92 kg/m^2 and 9.89 kg/m^2, correspondingly the values of detachment due to runoff were 7.1 kg/m^2 and 2.1 kg/m^2 for the same.



(b) **(d)**

Fig. 5.7 Total detachment of soil particle

As discussed in the previous stages the year of 1998 having high mean annual rainfall as compared to 2002. Fig. 5.7(a) & Fig. 5.7(b) show the high detachment of soil in both conditions i.e. detachment due to raindrop and detachment due to runoff for the year of 1998. These detachments occur from the particular pixel. Bare soil, waste land, and open scrub land having high detachment due to raindrop. Open forest, barren land, and gullied wasteland having high particle detachment due to runoff.

Immediate deposition of detached particles

Detached particles which were estimated in the previous stage will go for transport but particle fall number of each pixel will decides that a detached particle fall to the soil surface rather than be entrained in the runoff. The particle fall number was estimated for each pixel of entire watershed. This estimation has been carried out from the raster layer of fall velocity (each soil textural class), velocity of each particle in bare soil and vegetated condition and the actual depth of flow. Fig. 5.8 shows the fall number for entire sub-watershed.

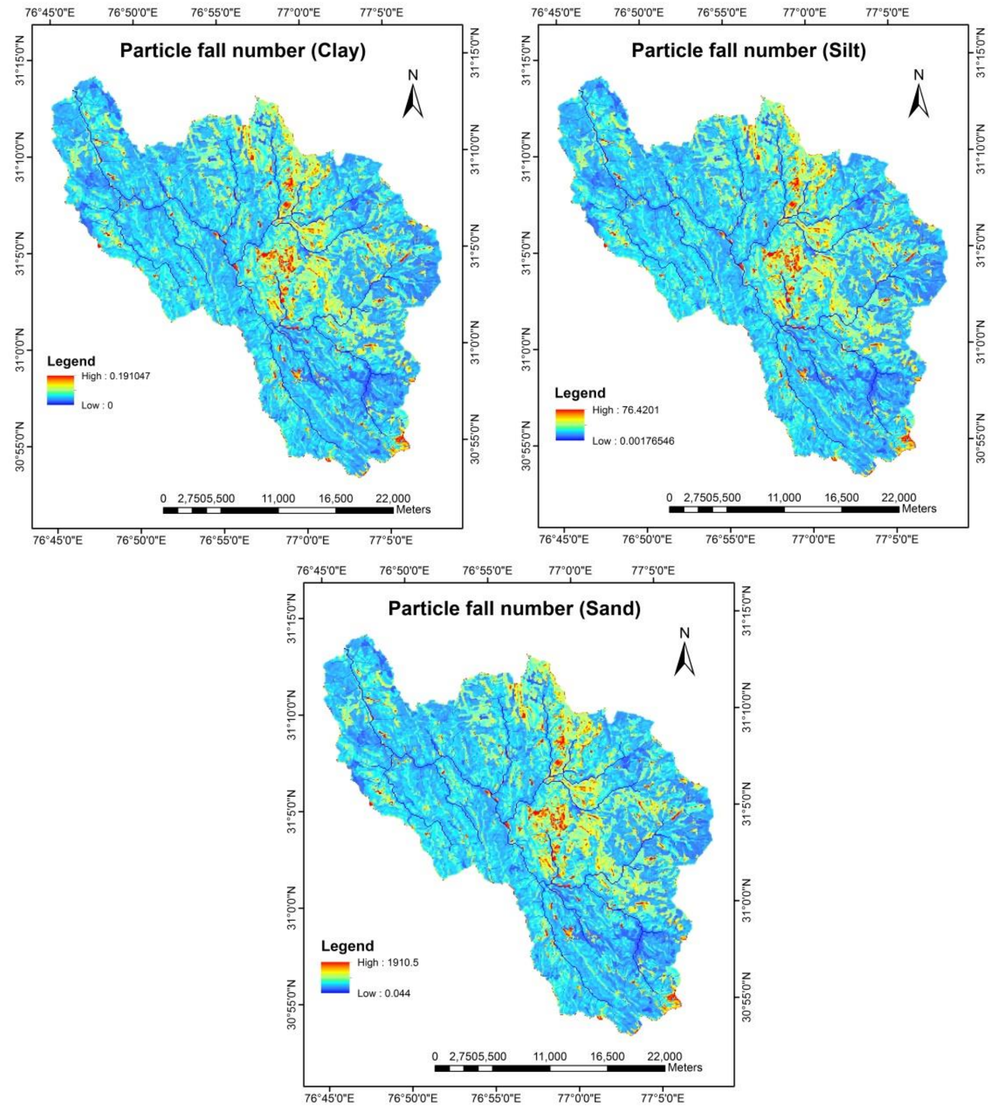


Fig. 5.8 Particle fall number for various textural class

High values of particle fall number of sand show that the sand particle tends to settle down faster than the silt and clay and it has the nature of immediate deposition. The particle with lower fall number values enters in the runoff for transport. Fig. 5.8 shows that the sand and silt particle having high fall number values as compared to clay, these values justified that the delivery of sand and silt will be less than the clay and most of the particle of silt and sand will deposit immediately. This is the main advantage of 2008 version of MMF model.

Particle fall number of clay, silt and sand has been used for further process and deposition was calculated separately for clay, silt and sand. Deposition equations yield DEP >100 % but since it is not physically possible to deposit more material that has been detached, by giving the condition in Arc GIS 10.0 (Raster calculator) a maximum value is set at DEP=100 when this occurs. Deposition maps of clay, silt and sand are shown in Fig. 5.9.

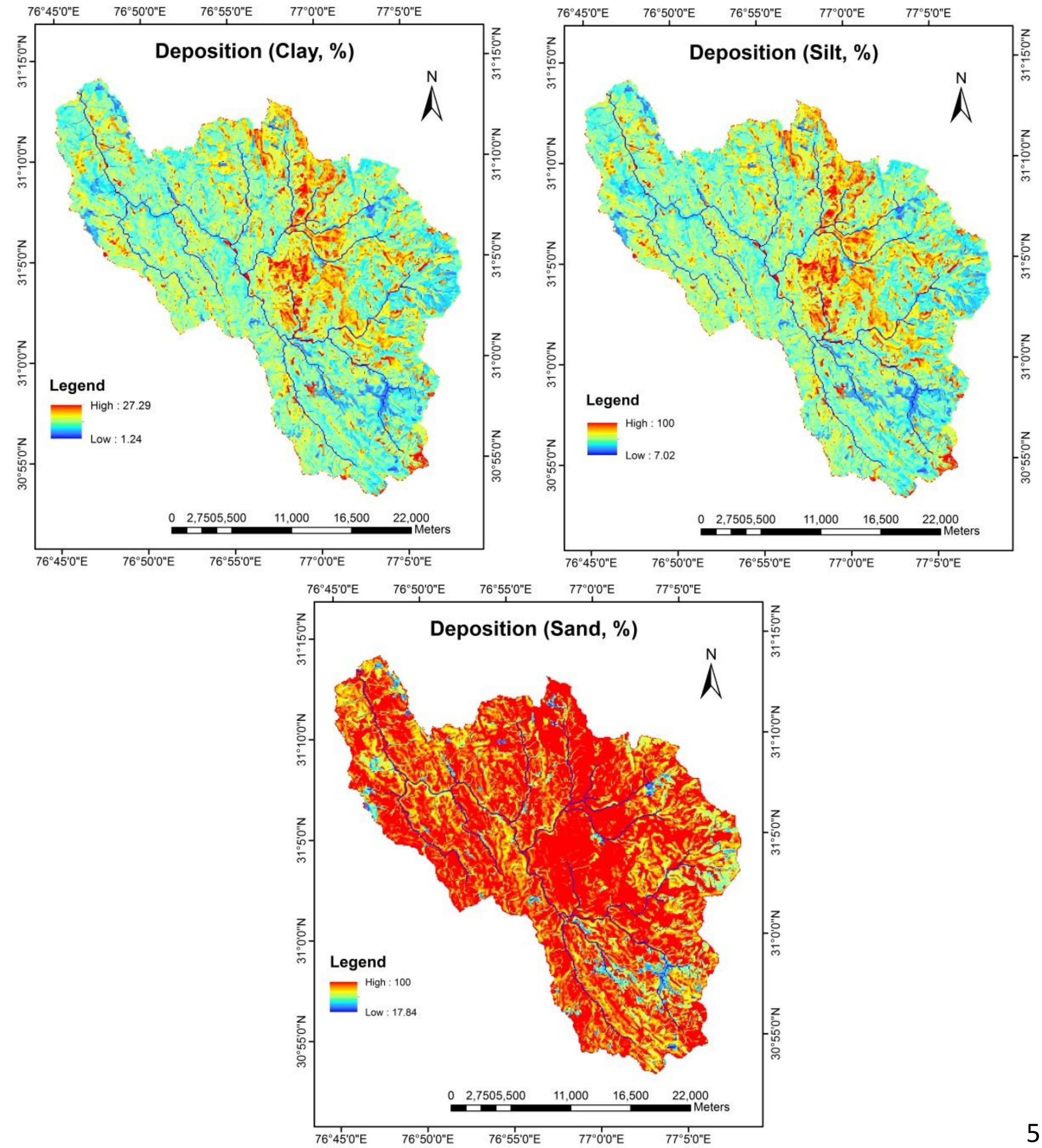


Fig. 5.9 Deposition maps of various textural class

Delivery of detached particles to runoff mainly depends on the process of deposition. Fig. 5.9 is showing the maximum deposition of clay particle which is 27.29%, but for sand it is 100% in most of the areas. By analyzing the histogram of deposition maps it has been observed that the average deposition of clay, silt and sand are found respectively as 7%, 40% and 95%. It shows that the large amount of sand particles deposited immediately and do not go for transport. In this way clay has lower deposition, silt has moderate deposition and sand has higher deposition.

Sediment yield estimation

This stage of model also demands an efficient programming code for a fast and efficient processing to estimate the mean annual sediment yield. The processing by code implements routing procedure for each pixel, by analyzing the soil loss contribution from surrounding pixels as given in Annexure II. This procedure continues from the pixel which inherits the sediment flow to the pixel having maximum flow accumulation value. Sediment routing has following steps:

1. Delivery of detached particles to runoff calculated for each pixel after that flow direction will decide the delivery of sediment from one pixel to another.
2. After detachment, immediate deposition of the particle has been taken place then sediment starts flow, now it will compare with transport capacity of runoff, if transport capacity is greater than the material available for transport, all the sediment will transport. If transport capacity is less than the amount available, again some part will be deposit and rest of the amount will transport.

For this routing user needs to define the input raster layer of detached particle (clay, silt, sand), transport capacity (clay, silt, sand) and deposition (clay, silt, sand). Module will calculate mean annual sediment yield separately for these three particles, after that the total mean annual sediment yield has been calculated. The transport capacity of the runoff for selected years is shown in Fig. 5.10.

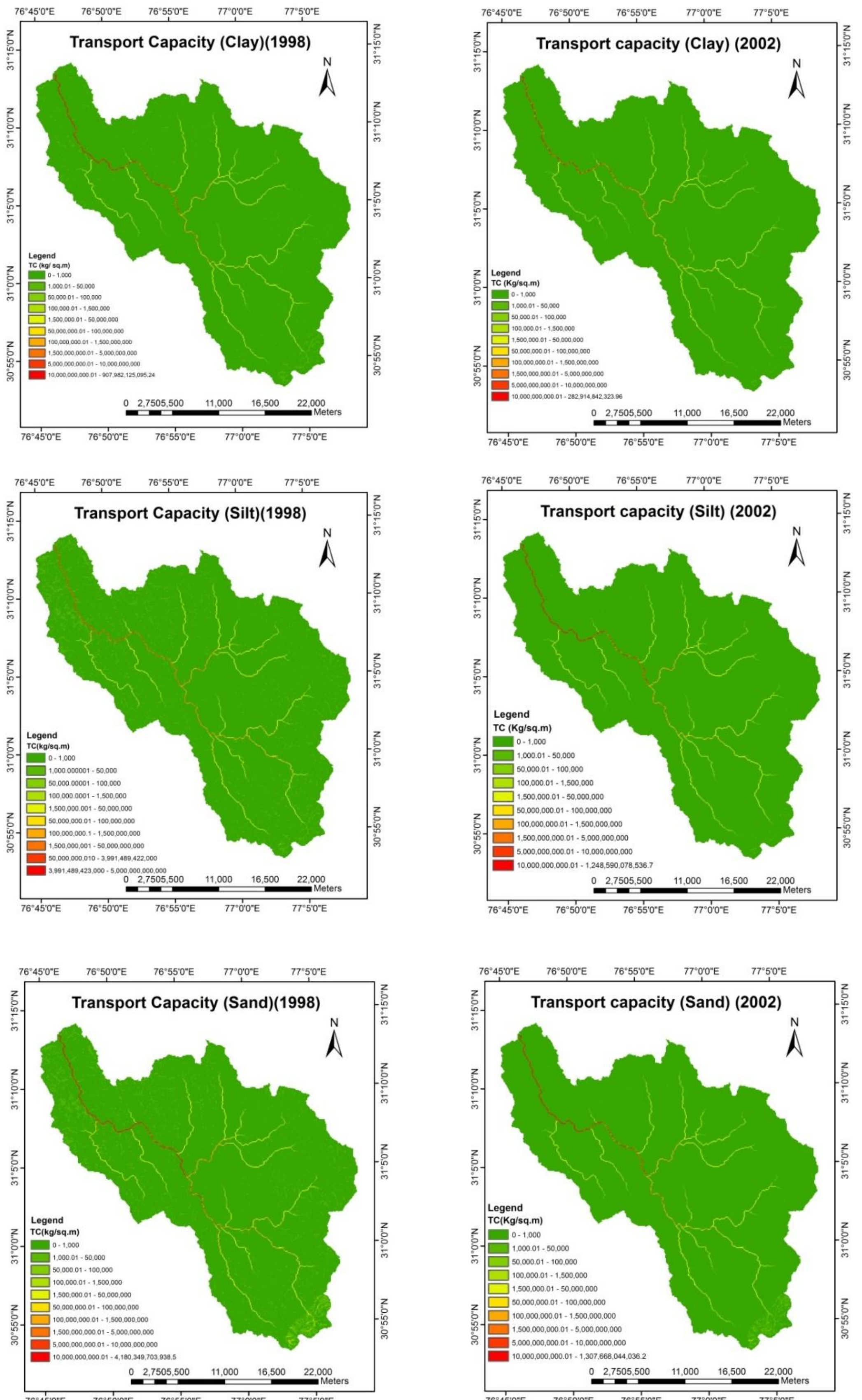


Fig. 5.10 Transport capacity of various textural classes

5.4 Model Calibration

Model calibration may be defined as the procedure of adjusting model parameters which cannot be determined exactly through available methods. Calibration of a sediment yield model is an iterative process which involves changing the values of sensitive model parameters to obtain best possible match between the observed and simulated values.

Before conducting the estimation of sediment yield, there was a need to calibrate the Modified MMF model to find out the reasonable sediment yield at the outlet. There are eight model parameters which were needed to be calibrated, these parameters are slope length (L), detachability of clay particles by rain (Kc), detachability of silt particles by rain (Kz), Detachability of sand particles by rain (Ks), detachability of clay particles by runoff (DRc), detachability of silt particles by runoff (DRz), detachability of sand particles by runoff (DRs), and particle fall velocity (vs) for clay, silt and sand. Parameter value ranges from low to high and each parameter having one base value as suggested by Morgan and Duzant, (2008) (Table 5.1). After calibration above mentioned parameters are assigned new values and the calibrated values are in the range of these parameters as shown in the Table 5.1.

Table 5.1 Calibration parameters for MMF model

Parameters	**Value Range**	**Base Value**	**Calibrated Value**
Slope length (L)	10-50 m	10 m	10.7 m
Particle fall velocity for clay (Vc)	-	0.000002 m/sec.	0.000000203 m/sec.
Particle fall velocity for silt (Vz)	-	0.002 m/sec.	0.000081 m/sec.
Particle fall velocity for sand (Vs)	-	0.02 m/sec.	0.00203 m/sec.
Detachability of clay particles by rain (Kc)	0.1-1.5 g/J	0.1 g/J	1.5 g/J
Detachability of silt particles by rain (Kz)	0.5-5.15 g/J	0.5 g/J	5.15 g/J
Detachability of sand particles by rain (Ks)	0.15-4.15 g/J	0.3 g/J	4.15 g/J
Detachability of clay particles by runoff (DRc)	0.02-2 g/mm	1 g/mm	2 g/mm
Detachability of silt particles by runoff (DRz)	0.016-1.6 g/mm	1.6 g/mm	1.6 g/mm
Detachability of sand particles by runoff (DRs)	0.015-1.5 g/mm	1.5 g/mm	1.5 g/mm

After simultaneous model development and calibration, output of the calibrated model for selected years are shown in Fig. 5.11a and 5.11b.

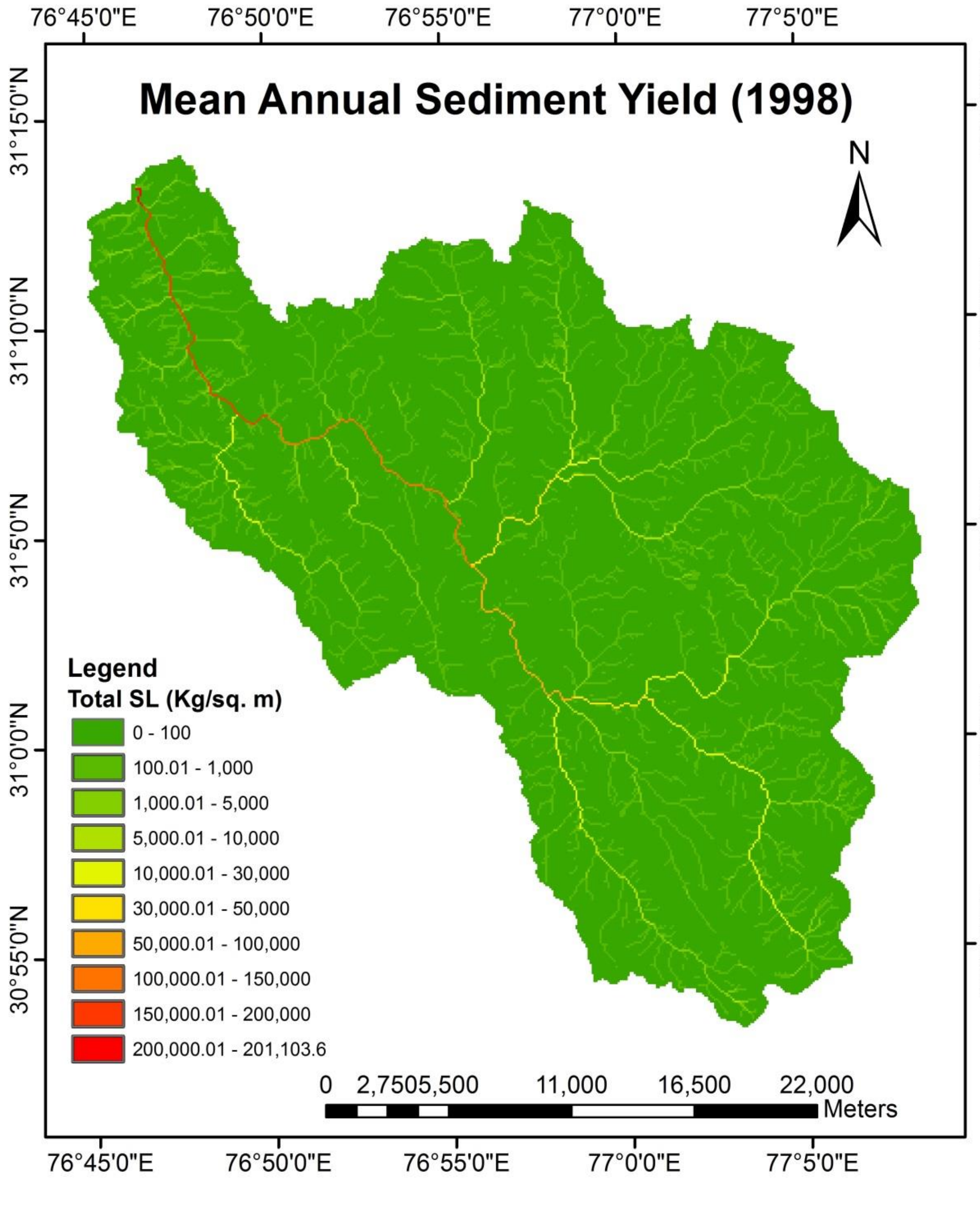


Fig. 5.11a Total mean annual sediment yield of 1998

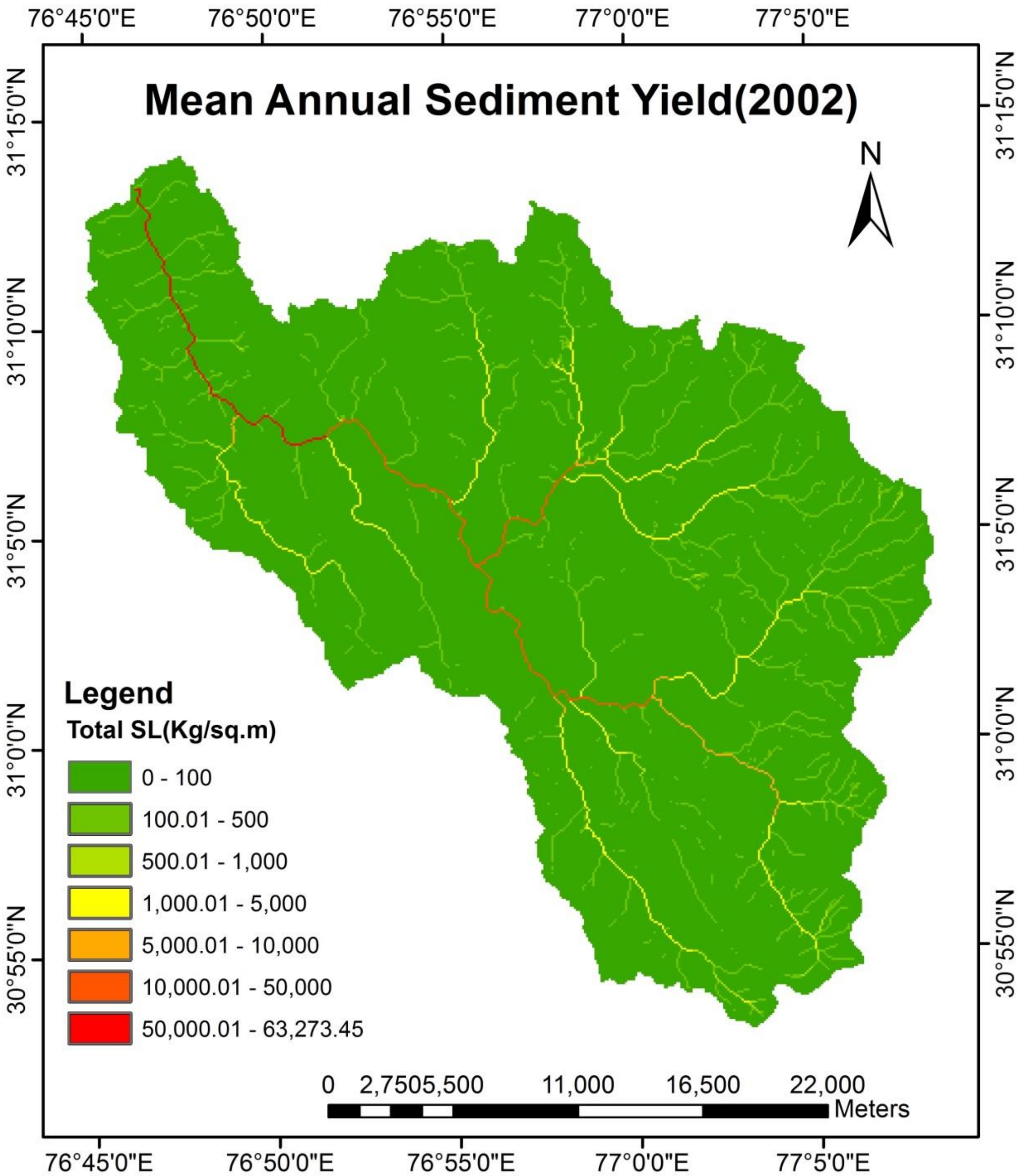


Fig. 5.11b Total mean annual sediment yield of 2002

Since the generated runoff for the year of 1998 was higher than 2002, the transport capacity of clay, silt and sand in 1998 showing higher values. These transport capacities (Fig. 5.10) and deposition (Fig. 5.9) inputted in the sediment routing module and mean annual sediment yield has been estimated for 1998 (Fig. 5.11a) and 2002 (Fig. 5.11b).

The land use, soil, slope steepness and parameters used for detachment and deposition are the main factors governing soil erosion potential at particular location to the erosive power of rainfall. The integration of detachment, transport and deposition maps in the developed python code are representing sediment yield potential of different grid cells (Fig. 5.11a & Fig. 5.11b). High values of this term indicate a higher potential of sediment generation in the cell and vice versa. The information shown in Fig. 5.11a and Fig. 5.11b could be utilized for identification of the sediment source areas of the sub-watershed.
On the other side detachment by raindrop impact plays an important role for assessing the effect of rainfall variability on actual sediment yield which has been estimated by MMF model (Fig. 5.11 & Fig. 5.11b). The equation used for the estimation of total kinetic energy for the study region (Eq. 4.4) in the previous chapter, works for range of rainfall intensity from 4-40 mm/hr in general condition of rainfall and 4-100 mm/hr for thunderstorm condition of rainfall (Van Dijk *et al.,* 2002). However, general condition of rainfall has been incorporated for the current study. This condition allows increase the rainfall intensity up to 40 mm/hr. for the study region. Therefore, intensity varies with 2.5 mm/ hr intensity interval to assess the impact of rainfall variability on actual sediment yield. Results obtained from this analysis have been discussed in next topic.

The model entirely developed in GIS framework. GIS helps to analyze the sediment yield of the study region in a distributed manner. As presented in the total sediment yield (Fig. 5.11a and 5.11b) it is observed that, low to high sediment zones are clearly visible. This can be further used for identification of high sediment yield contribution areas.

5.5 Model Validation

After simultaneous model development and its calibration, sediment yield estimation has been carried out for the year of 1995 and 1999. The estimated sediment yield for the year of 1995, 1998, 1999 and 2002 are shown in Table 5.2 and compared against the observed data (BBMB, 2003).

Table 5.2 Comparison between observed and estimated values of sediment yield

Name of gauging station	**Year**	**Mean Annual rainfall (mm)**	**Observed sediment yield (t)**	**Estimated sediment yield (t)**	**% Error**
Kahu(Gamber Khad)	1995	1226	1085000	710981	34.47
	1998	1564	1567360	1628931	-3.93
	1999	1213	806000	709953	11.92
	2002	1098	374480	511372	-36.56

It is seen from Table 5.1 that the percentage of error in the estimated sediment yields from the observed values varies in the range of (-) 36.56% (over prediction) to (+) 34.12% (under prediction). For the year of 1995 and 1999 the mean annual rainfall was nearly same but in the observed sediment yield, it is showing larger variation (Table 5.1) and is ascribed to probable uncertainties in observations. Other source of uncertainty could be attributed to large spatial and temporal variability in rainfall, dynamic nature of vegetation which influence generally transport capacity, effective hydrological depth and interflow generated from the particular element and need to be further investigated in future studies. As seen from Table 5.1, for most of the years, the error between observed and computed sediment yield lie within ±36.5%. This % of error indicating acceptable results and reasonable accuracy in computation of sediment yield (ASCE 1975; Foster 1982; Hadley *et al.*, 1985; Wu *et al.*, 1993; Wicks and Bathurst 1996).

5.6 Rainfall Variability and Its Impact on Annual Sediment Yield

During the model development for the year of 1998, number of rainy days has been taken as 88 and rainfall intensity has been taken as 25mm/hr. For the analysis of rainfall variability on annual sediment yield, initially the rainfall intensity has been changed for the year of 1998 and other parameters have been remaining constant. Simultaneously calibrated model has been run for the entire watershed and following results have been obtained for year 1998 (Table 5.3).

Table 5.3 Comparison between Rainfall intensity and Sediment yield

Rainfall (mm)(1998)	Intensity (mm/hr)	Annual Sediment yield (Tons) (1998)	% Increase in Sediment yield
1564	25	1628931	Base value
1564	27.5	1636794	0.48
1564	30	1642742	0.84
1564	32.5	1653979	1.53
1564	35	1660468	1.93

The actual value of rainfall intensity has been taken for this study is 25 mm/hr and to assess the impact of rainfall variability, it has been increased by 10% from the initial value as shown in Table 5.3. When rainfall intensity increased by 10% it directly affects the process of detachment due to rainfall and the total detachment also increases. Finally this amount of detached particles deliver to the runoff and increased amount of annual sediment yield has been obtained at the outlet.

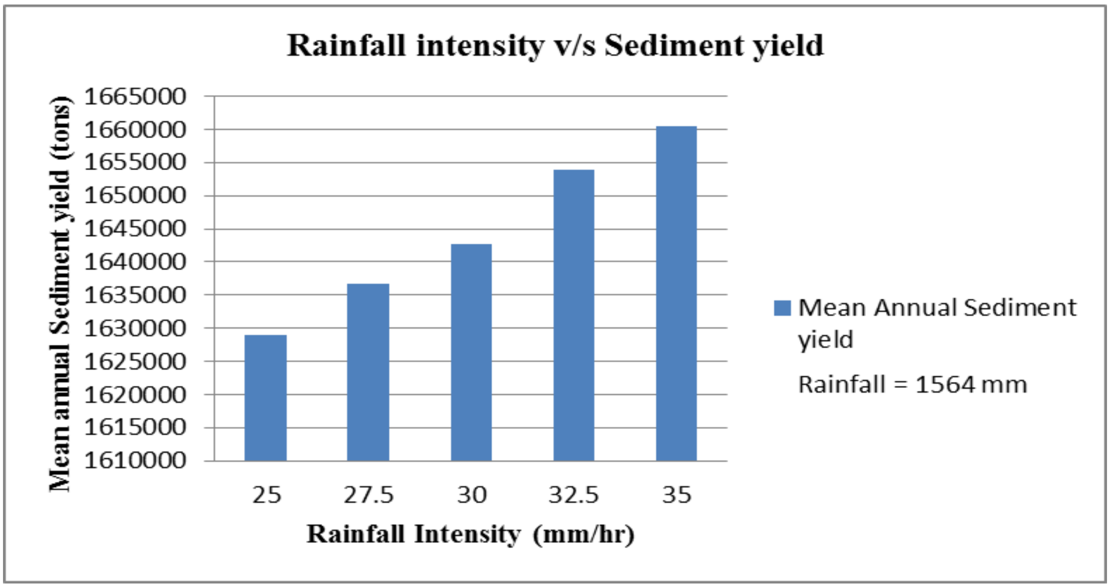


Fig. 5.12 Plot showing relation between various Rainfall intensities v/s Sediment yield

From Fig. 5.12 it is observed that when there is an increase of rainfall intensity by 2.5 mm/hr, there is a consistent increase of amount of sediment at the outlet of the selected region. Table 5.3 describes the % increase in the sediment yield with respect to rainfall intensity. In several studies, it has been observed that future rainfall events will be occurring with high rainfall intensity. Therefore, this work must be helpful for spatially distributed soil erosion and sediment yield modeling in near future.

During the model development for the year of 1998, number of rainy days has been taken as 88 and rainfall intensity has been taken as 25mm/hr. After that to assess the impact of rainfall variability on actual sediment yield according to the future climate scenario, number of rainy days have been decreased and rainfall intensity has been increased by 10% and other parameters have been remaining constant. Simultaneously calibrated model has been run for the entire watershed and following results have been obtained for year 1998 (Table 5.4).

Table 5.4 Comparison between Rainfall intensity, Number of rainy days and Sediment yield

Rainfall (mm) (1998)	Number of Rainy days	Intensity (mm/hr.)	Annual Sediment yield (Tons) (1998)	% Increase in Sediment yield
1564	88	25	1628931	Base value
1564	79.2	27.5	1810196	11.12
1564	70.4	30	2026020	24.37
1564	61.6	32.5	2299168	41.14
1564	52.8	35	2712609	66.52

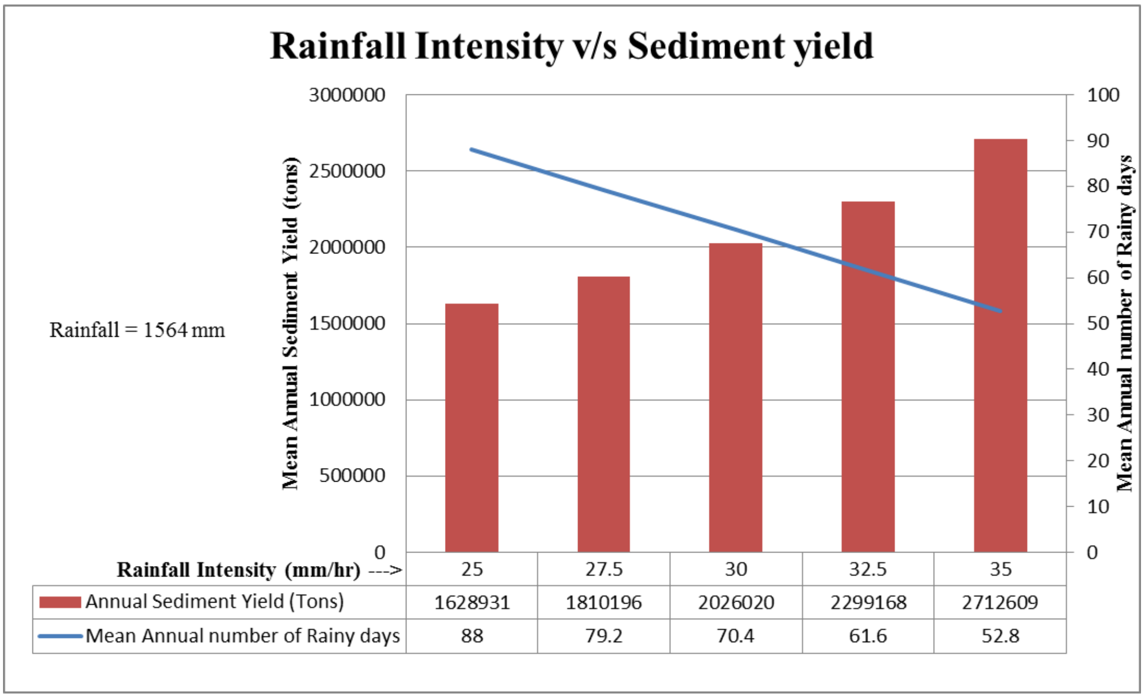


Fig. 5.13 Plot showing relation between various Rainfall intensities, Mean annual number of Rainy days & Sediment yield

From Fig. 5.13 it is observed that when there is an increase of rainfall intensity by 2.5 mm/hr and decrease in mean annual number of rainy days by 10% of actual value i.e. 8.8, there are a consistent increase of sediment yield at the outlet of the selected region. Table 5.4 describes the % increase in the sediment yield with respect to rainfall intensity and mean annual number of rainy days. In several studies, it has been observed that future rainfall events will be occurring in the form of heavy storms and having high rainfall intensity. Therefore, this work must be helpful for spatially distributed soil erosion and sediment yield modeling in near future.

CHAPTER – 6
CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion and Summary

Scientific management of soil and water is very important to arrest erosion and enhancing the reservoir storage capacity. Deterioration of soil resources in the study area can be controlled effectively by adopting watershed treatment measures if spatial distribution of soil erosion is known. Various thematic layers representing different factors of Modified MMF (Morgan and Duzant, 2008 version) were generated and overlaid to compute spatially distributed detachment, deposition, transport and gross sediment yield maps for the Gamber sub-watershed (Satluj Basin, India). The concept of effective rainfall, detachment by raindrop and runoff, deposition of soil particles, transport capacity were used in ArcGIS for generating such maps. Total runoff and gross sediment yield were routed to the watershed outlet using hydrological drainage paths resulting in generation of total runoff and mean annual sediment yield maps with the help of developed programming code. Such maps provide the amount of runoff and sediment flowing from a particular grid in spatial domain. A comparison of the observed and computed sediment yield reveals the proposed method to compute sediment yield with reasonable accuracy. Further deposition maps of various soil particles were shows the deposition grids.

Further work in this regards enumerates the change in rainfall intensity by constant interval and observe the variation in sediment yield. For this purpose to estimate the rainfall kinetic energy equation suggested by Kinnell, (1981) has been used for the study region. Since the rainfall intensity value can be kept from 4-100 mm/ hr, this equation can works in a general rainfall conditions as well thunderstorm and provide sovereignty to apply the Modified MMF (Morgan and Duzant, 2008 version) model even in extreme events.

Requirements of the study was to estimate the actual sediment yield at the outlet from various soil type (clay, silt, sand), totally distributed soil erosion and sediment yield estimation model, estimation of runoff, detachment, transport and deposition at a distributed manner, takes in to account of future climatic condition and compatibility of the entire study with remote sensing and GIS. All the requirements have been fulfilled by Modified MMF (Morgan and Duzant, 2008 version) model and have proven very capable and efficient.

The specific conclusions of the study are given as below:

1. Proposed kinetic energy equation for computation of total kinetic energy can be used to compute spatially distributed value of total kinetic energy for entire sub-watershed whereby the effect of variation of rainfall intensity on sediment yield is accounted.
2. Areas showing higher transport capacity associated with steep slope and channel areas in the watershed and smaller transport capacity values are mainly coincide

with the overland regions, high vegetation areas, overland regions that surround the confluence of the main stream with just smaller order streams.

3. For the entire watershed routing has been done separately for runoff and sediment yield estimation with the developed programming codes. This is very much efficient and time saving and yielded reasonable amount of sediment and runoff.
4. This study has been carried out for the impact of rainfall variability on sediment yield and reservoir sedimentation. Proposed model taking into account of rainfall intensity to show the effect of rainfall variability on sediment yield with respect to future climate scenario.
5. The proposed Model produces satisfactory estimates of sediment yield from sub-watershed with ±36.5% deviation from observations.
6. By changing the rainfall intensity it is observed that there is an enormous effect on sediment yield and it has been increased by 0.48%, when intensity increased by 2.5 mm/ hr for the same year.

6.2 Recommendation for Future Work

Since Modified MMF (Morgan and Duzant, 2008 version) model was designed as a small catchment scale model which could also be applied to simple hill slopes from crest to the stream line. If the number of elements will be higher in count, over estimation can be occurred in the estimation of runoff and total sediment yield.

When applying models to conditions for which they were not designed, it is not uncommon to require the addition of fudge factors i.e. slope length, detachability etc. to get them to work. However there are some uncertainties for applying under different condition.

For runoff and sediment routing the developed code require processing time because of large area and many number of elements. It is suggested that if the number of elements present in the area will less, the time taken by the routing process will be less and more accuracy can be obtained in runoff and sediment yield estimation.

To show the proper effect of vegetation cover on the sediment yield, it is suggested that landuse land cover preferred to be of same year as the year of analysis.

DEM playing very important role in sediment and runoff routing, it has been observed that from the present study DEM errors may create problem for deposition and transport. It is suggested that error less DEM should be used for further studies.

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Annexure I

PYTHON 2.6.5 code for runoff routing.

Estimation of runoff.py - C:\Users\sony\Desktop\MMF CODE FINAL\Estimation of runoff.py

File Edit Format Run Options Windows Help

```
Q=numpy.zeros((row,col),numpy.float)
Qe=numpy.zeros((row,col),numpy.float)
IF=numpy.zeros((row,col),numpy.float)

mx= 91088                                        ##input flow acc max value
print "new maximum is " +str(mx)

l1 = sum(1 for line in open("G:\\Test\\fac_arr.txt")) ##input txt
arr= numpy.zeros(l1, numpy.int)

n=0
crs = open("G:\\Test\\fac_arr.txt", "r")         ##out txt
for columns in ( raw.strip().split() for raw in crs ):

    arr[n]=int(columns[0])
    n+=1

value=0

for v in range(len(arr)):
    for a in range(1,row-2):
        for b in range (1,col-2):

            if rf[a,b]>0.0 and rc[a,b]>=0.0 and ro[a,b]>=0.0:
                if fac[a,b]==arr[v] and arr[v]==0:
                    Qe[a,b]=rf[a,b]*(math.exp((-rc[a,b])/(ro[a,b])))
                    Q[a,b]=rf[a,b]*(math.exp(-rc[a,b]/ro[a,b]))
                    IF[a,b]=IF[a,b]+((((R[a,b])-(E[a,b])-(Qe[a,b]))*(LP[a,b])*(sins[a,b]))/365)
                    if IF[a,b]<0:
                        IF[a,b]=0.0

                elif fac[a,b]==arr[v] and arr[v]>0:


                    if fdr[a,b-1]==1:
                        if rf[a,b-1]>0.0 and ro[a,b-1]>=0.0 and rc[a,b-1]>=0.0:
                            if IF[a,b-1]<0:
                                IF[a,b-1]=0.0

                            Q[a,b]=Q[a,b]+Q[a,b-1]
```

Annexure II

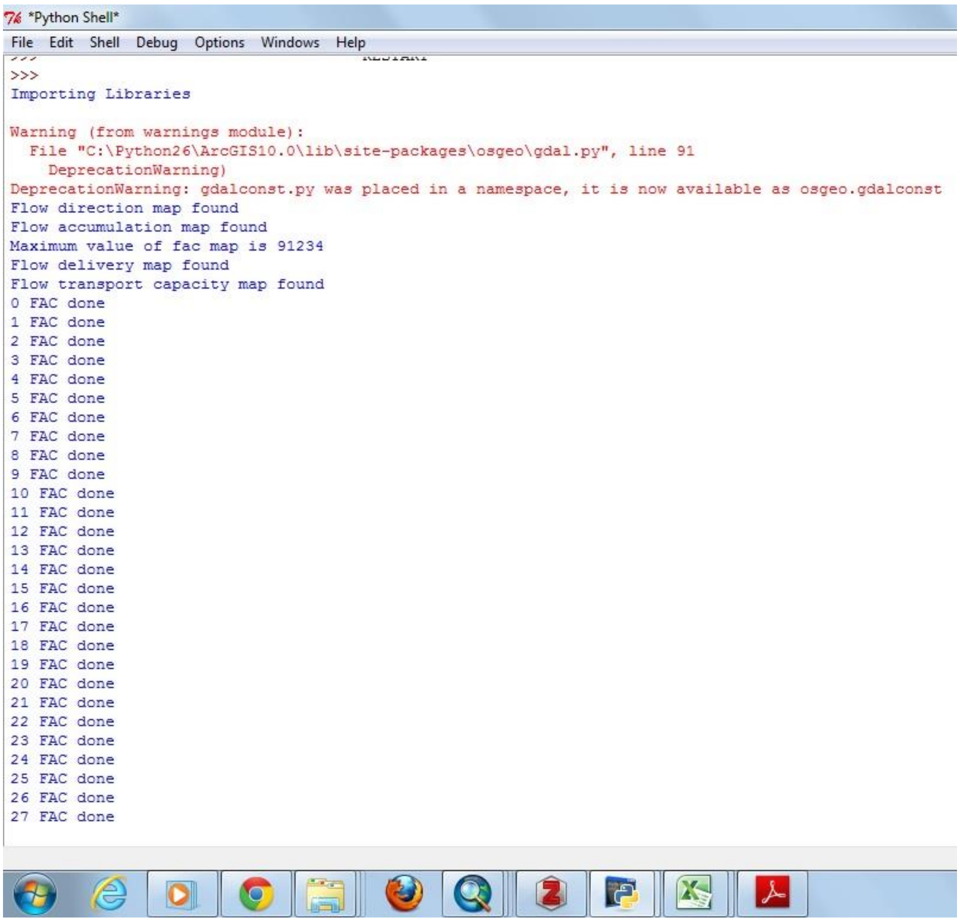
PYTHON 2.6.5 code for sediment routing.

Estimation of soil loss.py - C:\Users\sony\Desktop\MMF CODE FINAL\Estimation of soil loss.py

File Edit Format Run Options Windows Help

```
from osgeo import gdal
from gdalconst import *



fn1 = r'G:\Test\Full_image\fdr.img'                    ##input FDR DO NOT CHANGE
ds1 = gdal.Open(fn1, GA_ReadOnly)
if ds1 is None:
    print 'Could not open ' + fn1
    sys.exit(1)
col = ds1.RasterXSize
row = ds1.RasterYSize
driver=ds1.GetDriver()
fdr = ds1.ReadAsArray()

fn2 = r'G:\Test\Full_image\fac1.img'                    ##input FAC DO NOT CHANGE
ds2 = gdal.Open(fn2, GA_ReadOnly)
if ds2 is None:
    print 'Could not open ' + fn2
    sys.exit(2)
fac = ds2.ReadAsArray()
maxf= fac.max()
print "Maximum value of fac map is " +str(maxf)

fn3 = r'G:\Endru\1999\Delivery of detached particles to runoff\g_s.img'                        ##input G
ds3 = gdal.Open(fn3, GA_ReadOnly)
if ds3 is None:
    print 'Could not open ' + fn3
    sys.exit(2)
SLnew = ds3.ReadAsArray()
SL1new= ds3.ReadAsArray()

fn4 = r'G:\Endru\1996\deposition_factor\dep_s.img' ##input DEP DO NOT CHANGE path, change img only
ds4 = gdal.Open(fn4, GA_ReadOnly)
if ds4 is None:
    print 'Could not open ' + fn4
    sys.exit(2)
DEP = ds4.ReadAsArray()

fn5 = r'G:\Endru\1999\Transport capacity\tc_s.img'                                             ##input TC
ds5 = gdal.Open(fn5, GA_ReadOnly)
```

Starting of the routing programme



End of the routing programme