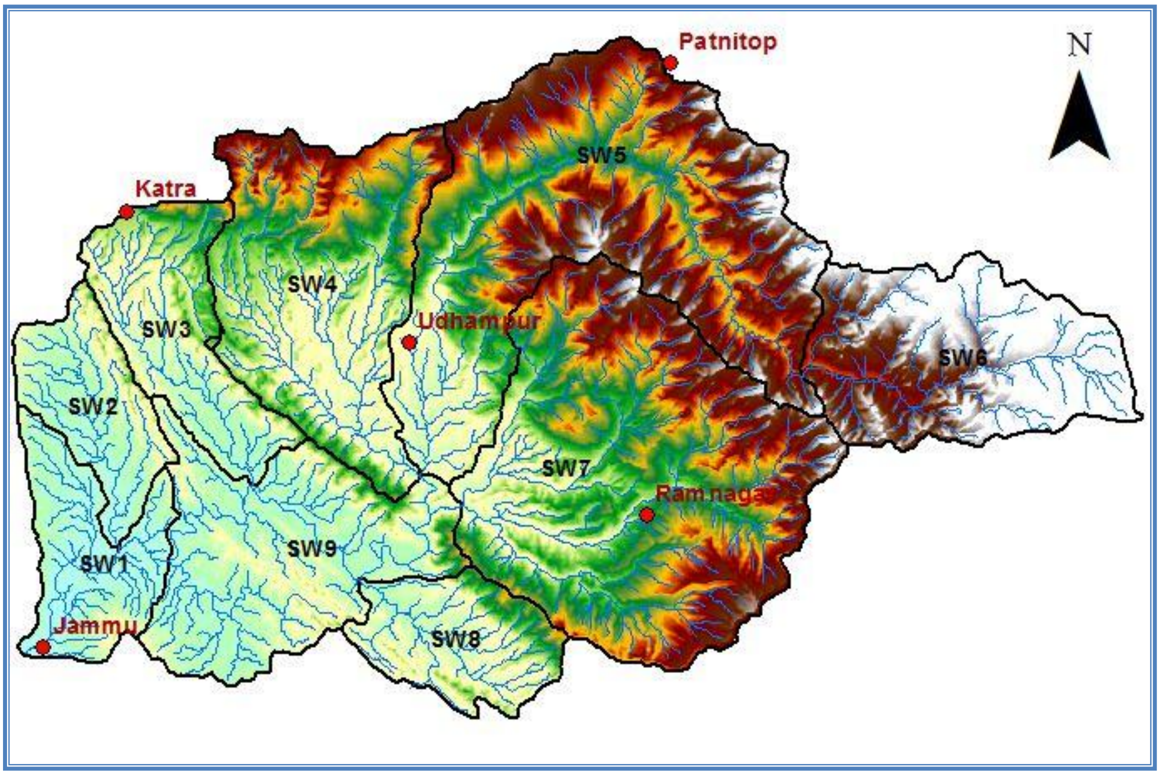
FINAL REPORT

"Estimation of Sediment Yield and Identification of Areas Vulnerable to Soil Erosion and Deposition in a Western Himalayan Catchment"



NATIONAL INSTITUTE OF HYDROLOGY

Western Himalayan Regional Centre, Jammu

MARCH 2017

FINAL REPORT

"Estimation of Sediment Yield and Identification of Areas Vulnerable to Soil Erosion and Deposition in a Western Himalayan Catchment"

NATIONAL INSTITUTE OF HYDROLOGY

Western Himalayan Regional Centre, Jammu

MARCH 2017

Director	**:**	**Sh. R. D. Singh**
Co-ordinator	**:**	**Dr. Sharad K. Jain**
Head	**:**	**Dr. M. K. Goel**

STUDY GROUP

Principal Investigator (PI)	**:**	**Dr. Soban Singh Rawat, Sci.-D**
Team (Co-PIs)	**:**	**Dr. Pradeep Kumar, Sci. - C**

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER - 1

INTRODUCTION

1.1 Background

Eighty percent of the sediment material delivered to the world's oceans each year comes from Asian rivers, and amongst these, Himalayan rivers are the major contributors (Stoddart 1969). The Himalayan and Tibetan regions cover only about 5% of the earth's land surface but supply about 25% of the dissolved load to the world ocean (Raymo and Ruddiman 1992). The Himalayas is the youngest mountain range on the earth, and it is the origin of world's three major river systems viz. the Indus, the Ganges, and the Bhrahmaputra. In spite of the hydrological importance of the region, a few studies have been reported on rainfall induced soil erosion/sediment yield modelling. Depending on the model algorithms which describe erosion, transportation processes, and the data requirement, several models ranging from simple empirical to complex physically based have been developed. Simple popular empirical models such as USLE and its derivatives perform very well at the plot scale. However, there use at catchment scale is problematic. Therefore various physically based models such as Water Erosion Prediction Project (WEPP) (Nearing at al., 1989), Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) (Beasley and Huggins, 1980), Agricultural Nonpoint Source Pollution Model (AGNPS) (Young et al., 1989), and Soil and Water Assessment Tool (SWAT) (Arnold et al., 1993), and many others have been developed and theses have proved very useful as research tools. However, these are of limited use in field, especially in developing countries, because they require skill and large amount of data. Therefore, an emphasis should be given to develop models that are less complex than the physically based models but yield precise results compared to those due to USLE or its derivatives (Aksoy et al., 2005).

In developing country like India, where rural population is often more than 65%, assessment of erosion focuses mainly towards on-site effects of erosion. On site erosion strongly affects crop yield, undermines the long term sustainability of farming system, and repeat a major threat to the livelihood of the farmers and rural communities. In the present era of industrialization, more attention is being paid to the society at large, viz., in flood prevention, water reservoir preservation, and water pollution control (Garen et al., 1999). Whether the main concern of soil and water conservation planning is towards prevention of onsite or off-site effects of erosion, there is a growing need for tools that enable to define the spatial distribution of erosion within a catchment, i.e. to identify sources of sediment erosion. Indeed, the location of sediment sources and sinks is more important than the quantification of soil losses, as it is more cost effective than over-dimensioned erosion control measures. Therefore, modelling should be focused on spatial distribution of sediment within the watershed as well sediment yield at the outlet of the watershed.

1.2 The Problem Definition

River , a major River in Jammu region is the left bank tributary of river Chenab originating from the lapse of Kali Kundi glacier in Bhaderwah, flows through some parts of Doda district in Udhampur and then reaches Jammu from where it finally merges into Chenab in Pakistan.The length of river from its originating point to Jammu is about 150 km. The important role of River for sustaining the most populous cities in the region, Jammu and Udhampur has been considered while selecting the basin. The River has a very high social impact as it is the only major source of water for drinking, agricultural and industrial needs and serving to the almost 20% population of the whole J&K State. However, this heavy population load causes the ecological degradation (Change in the land use pattern, deforestation and low growth rate of vegetation, construction of new roads and bridges) which has accelerated the severe erosion in the catchment. Very high sediment yield has been experienced by the field engineers during monsoon season in river. This huge debris ultimately gets deposited in the surface of the river channel when enters in the plain area. Consequently, the channel capacity reduces significantly and river gets overflow. The flood of last September might be the result of this heavy sediment load deposition. Therefore, a study is being proposed hereby for accurate estimation of sediment yield in channel of river and also identify the sources of soil erosion and deposition in its catchment so that treatment measures can be prioritized accordingly.

1.3 Objectives

The present investigation is taken up with the following objectives:

- To prepare comprehensive digital geo-database of study area.

- To develop a grid based spatially distributed sediment yield model for better understanding of the sediment flow through complex slop of the hills

- To categorize the catchment on the basis of soil erosion and deposition prone areas for prioritizing the watershed treatment measures.

CHAPTER - 2

REVIEW AND LITERATURE

In developing country like India, where rural population is often more than 65%, assessment of erosion focuses mainly towards on-site effects of erosion. On site erosion strongly affects crop yield, undermines the long term sustainability of farming system, and repeat a major threat to the livelihood of the farmers and rural communities. In the present era of industrialization, more attention is being paid to the society at large, viz., in flood prevention, water reservoir preservation, and water pollution control (Garen et al., 1999). Whether the main concern of soil and water conservation planning is towards prevention of onsite or off-site effects of erosion, there is a growing need for tools that enable to define the spatial distribution of erosion within a catchment i.e to identify sources of sediment erosion. Indeed the location of sediment sources and sinks is more important than the quantification of soil losses, as it is more cost effective than over-dimensioned erosion control measures. Therefore, modelling should be focused on spatial distribution of sediment within the watershed as well sediment yield at the outlet of the watershed.

The main objective of the present research work is to prioritize a catchment in terms of their susceptibility for the erosion. As per the review and literature cited, studies on prioritization of watershed can be divided into two categories (i) which deals with a ungauged watershed, and (ii) the methods or models developed for a gauged watershed. Accordingly, the review and literature part is divided into two parts..

2.1 Studies on Sediment yield for Un-gauged Watersheds

Watershed planning and management in an un-gauged catchment has been always remaining a challenging task for scientist, policy makers and field departments. In absence of soil erosion or sediment data, decision to list the priority of sub-watersheds is vital important issue and success of watershed treatment project largely depends in the correct fixation of priority. Research work has shown that a number of morphological parameters together influence a particular watershed characteristic for example permeability is influenced by drainage density, drainage frequency, length ratio and constant of channel maintenance. A Catchment can be prioritized based on different morphological parameters of different watersheds existed within the catchment. Some researcher had developed the indices like Morphological Index of Erodibility (MIE) for connivance in characterization and comparative study especially when large number of small watershed.

2.1.1. Morphological Parameters and Watershed Prioritization

Morphological parameters have been studied by researchers for erosion assessment and for determining relation between different morphological parameters. An important advantage of morphological analyses is that many of its parameters are in the form of ratios or dimensionless numbers thus providing an effective comparison of different watersheds regardless of scale.

Agarwal and Chakraborty (1994) carried out morphometric analysis in part of Mussoorie Syncline using remote sensing. Low value of drainage density indicated high permeability of sub soils and low value of bifurcation ratio indicated lack of geological control on the development of drainage pattern.

Lokesh et al. (1996) estimated morphological parameters using planimetric measurements of Pangala river watershed which is situated in Dakshina Kannada district of Karnataka. Study revealed that bifurcation ratio is about 4.0 indicating mature stage of watershed development and geological structures have least influence on the drainage pattern.

Chaudhary and Sharma (1998) carried out morphological analysis for Giri river catchment located in North Western Himalayas. Morphological parameters such as drainage density, relief ratio, and drainage texture and bifurcation ratio were computed for 36 sub catchments of Giri watershed. Sub catchments have been prioritized using mean value of the four morphological parameters as an index. The index is related to the severity of soil erosion. Severest erosive sub catchment is found to have highest value of the index.

Goel (2003) used morphological parameters for prioritization of 32 sub catchments of Soan river situated in lower Shivaliks Hills in Una district of Himachal Pradesh. The ranking of priority have been fixed on the basis of individual values of morphological parameters which are directly associated with the soil erosion. Individual parameters were then used to obtain an averaged priority index which is finally used to rank the sub catchments. The standard deviation of morphological parameters is also used to assess similarity of the sub catchments.

Regression analysis among morphological parameters suggested that drainage density has good correlation with the slope and drainage texture.

Singh et al (2003) estimated morphological parameters of sub watersheds of Nana Kosi watershed from Kumaun lesser Himalayas. Various morphological parameters were used to analyze runoff, soil erosion and sediment delivery ratio etc. Morphological parameters along with land use information have been used in the ranking process for resource management.

Pandey et al. (2004) estimated various morphological parameters of sub watersheds of Karso watershed which is situated in Damodar Barakar catchment. Morphometric parameters were coupled with the land use and soil cover to obtain the integrated map to explain condition of runoff and soil loss in the sub watersheds. Integrated map layers reflecting hydrological and geological conditions were used for delineation of areas for soil and water conservation measures.

Reddy (2004) studied drainage morphometry of basaltic terrain (Deccan traps), Nagpur district, Maharashtra, Central India. Study found that sub watersheds associated with high drainage density, stream frequency and texture ratio show very severe to severe erosion. The analysis revealed that the influence of drainage morphometry is significant in understanding the landform processes, soil physical properties and erosional characteristics.

Suresh et al., (2004) have estimated the morphometric parameters pertaining to 10 sub-watersheds of Tarai development project area and used in the estimation of sediment production rate. The sediment production rate in the study area varies between 2.45 to 11.0 ha-m/100 km^2/year. The remote sensing data has been utilized for generating land use/land cover data which is an essential prerequisite for land and water resource planning and development. The remote sensing data can especially play significant role in collection of real time information from remote areas of river basins for generation of parameters required for hydrologic modeling.

Nookaratnam et al. (2005) used morphometric analysis and sediment yield index (SYI) for prioritization of Tarafeni watershed in Midnapur district, West Bengal. Total 82 micro-watersheds from Tarafeni watershed were analyzed for estimation of various morphological parameters. Morphological parameters of micro-watersheds have been ranked on the basis of relationship with soil erosion. A combined parameter of priority has been estimated by averaging the ranks of various morphological parameters of micro-watershed. Low value of index indicates severe erosion and vice versa. SYI values and morphological parameters based ranking together resulted in better prioritization of micro watersheds and to find suitable check dam positioning.

Sreedevi et al. (2005) analyzed various aspects of morphometric characteristics of Pageru River watershed. The elongated shape of the watershed is mainly due to the guiding effect of thrusting and faulting. The erosion processes of fluvial origin are predominantly influenced by the subsurface lithology of the watershed. The analysis indicates relationships among various attributes of the morphometric aspects of the watershed and helps to understand their role in sculpturing the surface area of the region. The importance of such analyses is emphasized in the utilization of its results, for locating sites for artificial recharge. It is noticed that stream segments up to 3rd order traverse parts of the high altitudinal zones, which are characterized by steep slopes, while the 4^{th}, 5^{th} and 6^{th} order stream segments occur in comparatively flat lands. These are important locations for constructing check dams.

Hodgkinson et al. (2006) worked on the relationship between geological fabric and drainage patterns in the 81.8 km^2 Laceys Creek sub-catchment of the North Pine River catchment, southeast Queensland, Australia. Study revealed the evidence of the evolution of drainage network and the extent to which geological fabric controls the drainage pattern. Large-scale geological structures and palaeo-controls are likely to be the dominant influences on highest order streams; the middle-orders are mainly controlled by the structural grain and lithological fabric; and the lowest orders not yet incised to bedrock may be influenced initially by neotectonism and exogenic controls. Study also concluded that assessment of the influence of rock architecture on drainage patterns is strongly affected by the scale of analysis.

Mesa (2006) carried out morphometric analysis of Lules River watershed and its watersheds using land-sat imageries and topographical maps. Study concluded that the development of stream segments is affected by slope and local relief. The mean bifurcation ratio indicates that the drainage pattern is not much influenced by geological structures. The drainage densities of the sub-watersheds suggest that the general nature of rocks is impermeable.

Jaiswal et al. (2007) carried out morphometric analysis of Gorna and Baghari watershed of Son river of Shahdol district, Madhya Pradesh. Gorna watershed has high drainage density (2.05 km/km^2) due to presence of hills, high percentage of slopes and rock subsurface compared to Baghari watershed which has low drainage density (1.69 km/km^2) due to devoid of hills and presence of gentle slope. It was observed that low constant channel maintenance (0.49 km^2/km) of Gorna watershed characterized by lineaments guided drainage network compared to constant channel maintenance (0.59 km^2/km) of Baghari watershed. Comparatively high values of average stream length, bifurcation ratio and drainage density of Gorna watershed are indicative of more erosion, less stable topography, high runoff potential and poorer ground water occurrence.

Pareta and Pareta (2012) have computed more than 53 morphometric parameter of all aspects for a watershed of Ravi river basin in Himachal Pradesh. The study reveals that remotely sensed data i.e. CartoSAT-1 DEM and GIS based approach in evaluation of drainage morphometric parameters and their influence on landforms, soils and eroded land characteristics at river basin level is more appropriate than the conventional methods Based on all morphometric parameters analysis; that the erosion development of the area by the streams has progressed well beyond maturity and that lithology has had an influence in the drainage development. This study is very useful for planning rainwater harvesting and watershed management.

Ahmed and Rao (2015) were estimated sediment production rate (SPR) and run-off rate of Tuirini watershed (drainage area 420 sq. km) The mean bifurcation ratio indicates strong structural control over the drainage development. The values of drainage density and texture ratio indicate that the area is composed of impermeable rocks associated with very fine drainage texture. The analysis of shape and relief parameters shows that watershed is having elongated shape and structurally complex with high relief. The estimated value of SPR and run-off rate suggests that the watershed produces moderate amount of sediments annually with high discharge of runoff due to high relief with steeper slopes.

Zhang et al. (2015) examine how watershed complexity affects sediment yield in terms of rainfall and geomorphic characteristics. They developed a co-relation matrix between 29 watershed characteristics and sediment yield. The results showed that watershed shape and relief parameters have large influences on the sediment yield.

2.2 Study on Sediment Yield for Gauged Watershed

The process of soil erosion involves the processes of detachment, transportation, and accumulation of soil from land surface due to either impact of raindrop, splash due to rain impact, shearing force of flowing water, wind, sea waves or moving ice. Erosion due to water is an area of interest to hydrologists and sedimentologists. Various forms of soil erosion due to water are inter-rill, rill, gully and stream channel erosion. Rain drop plus sheet erosion jointly causes inter-rill erosion. The concentrated flow causes rill erosion. Gully erosion is an advanced stage of rill on account of head cutting at the gully head. Apart from rainfall and runoff, the rate of soil erosion from the area is also strongly dependent upon its soil, vegetation, and topographic characteristics. During the process of erosion and transportation to downstream side, some part of the eroded material may get opportunity to deposit. The net amount of sediment flowing through the watershed is termed as sediment yield.

Deposition of sediment transported by a river into a reservoir reduces the reservoir capacity, thereby adversely affecting the water availability for power generation, irrigation, domestic and industrial use. Sediment deposition on river bed and banks causes widening of flood plains during floods. Control of upland erosion does not always reduce the sediment yield immediately, because of the increased erosivity of channel flow in the downstream. Soil erosion is a serious problem in lower Himalayas and foothill ecosystem. Sustainable use of mountains depends on conservation and potential use of soil and water resources. High population growth has placed a demand on limited natural resources present in the hills. High rainfall coupled with fragile rocks, and high relief conditions in Himalayas are conducive to soil erosion. It is a prime threat to sustained land use for crop production in Himalayan ecosystem. Rapid increase in the developmental activities, mining and deforestation etc. are major factors contributing to soil erosion and thus leading to land degradation.

2.2.1 Popular Soil Erosion and Sediment Yield Models

A multitude of models are available in hydrologic literature for estimation of soil erosion and sediment yield from watersheds. Most of these models can be grouped into three broad categories, viz., (i) empirical models-those based on empirical equations generally derived based on analysis of field data, for example, the equation of Musgrave (1947), Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) or Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991); (ii) conceptual soil erosion models, for example, the models of Johnson (1943), Rendon-Herrero (1978), Williams (1978), Kalin et al. (2004); and (iii) physically based model, for example, the models of WEPP (Water Erosion Prediction Project) (Nearing et al., 1989), European Soil Erosion Model (EUROSEM) (Morgan et al.,1998), sediment component of SHE (SHESED) (Wicks and Bathurst, 1996) and Chemicals, Runoff, and Erosion from agricultural Management Systems (CREAMS) (Kinsel, 1980), Areal Non-point Source Watershed Response Simulation (ANSWERS) (Beasley et al., 1980)

2.2.1.1 Empirical Erosion Models

Models based on empirical equations are generally derived from field data and are commonly termed as empirical models. Some of the empirical soil erosion/sediment yield models are as follows:

USLE: Soil erosion is most frequently assessed by using Universal Soil Loss Equation (USLE) since early 1960's. The equation was designed for inter-rill and rill erosion (Wischmeier and Smith, 1978; Renard et al., 1991). Although the equation is described as universal, its database, though extensive, is restricted to slopes (normally) 0 to 17°, and to soils with a low content of montmorrilonite. It is also deficient in information on erodibility of sandy soils. In addition to the limitation of its database, there are theoretical problems with the equation. Soil erosion cannot be adequately described merely by multiplying together six factor values (E = RKLSCP). There is considerable interdependence between variables (Morgan, 1995). Despite all, it is most commonly used throughout the globe.

MUSLE: is the modified version of the USLE. In MUSLE (Williams. 1975), the rainfall erosivity factor was replaced by runoff. The runoff factor includes both total storm runoff volume and peak runoff rate. Compared to USLE, this model is applicable to individual storms and it eliminates the need for sediment delivery ratios, because the runoff factor represents energy used in detaching and transporting sediment. The main limitation is that it does not provide information on time distribution of sediment yield during a runoff event.

RUSLE: is a revised version of USLE intended to provide more accurate estimates of erosion (Renard et al., 1991). It contains the same factors as USLE, but all equations used to obtain factor values have been revised. It updates the content and incorporates new material that has been available informally or from scattered research reports and professional journals. The major revisions occur in the cover management factor, C, support practice factor, P, and slope length gradient factor, LS, factors. C is now the product of four sub factors: prior land use, canopy cover, soil surface cover and surface roughness.

MMF Model: Morgan-Morgan-Finny model (Morgan et al., 1984) was developed to predict annual soil loss from field size areas on hill slopes. The model has the simplicity of the universal soil loss equation and yet it covers the advances in understanding of the erosion process. This model is physically based empirical model and needs less data than the most other erosion predictive models. This model divides soil erosion processes into two phases including a water phase and a sediment phase. In water phase determines the energy of rainfall available to detach soil particles, and in the sediment phase soil partial detached by the rain is estimated. The MMF model can be easily applied in raster based geographic information system (Shrestha, 2007). The MMF model was further refined by adding the erosion by the flow (Morgan, 2001). However, the flow component in the model is not very realistic since there is no transfer of flow down slope to other pixels.

SLEMSA Model: The Soil Loss Estimator for Southern Africa (SLEMSA) (Elwell. 1978; Stocking, 1981) was developed largely from data from Zimbabwe to evaluate the erosion resulting from different farming systems so that appropriate conservation measures could be recommended. Generally, the model looks like USLE and it has the same limitations as USLE.

SEDD: The SEdiment Delivery Distributed (SEDD) model, which is based on the empirical USLE model, was proposed by Ferro and Porto (2000). Monte Carlo technique was used to test the effect of uncertainty in the model parameters on sediment yield computations, similar to the study by Biesemans et al. (2000) on the RUSLE.

2.2.1.2 Conceptual Models

Conceptual models tend to include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information (Sorooshian, 1991). This allows these models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed input data. The conceptual models lie somewhere between empirical and physically based models.

Johnson (1943) was perhaps the first to derive a distribution graph for suspended sediment concentration employing the hypothesis analogues to that embodying in the unit hydrograph. Rendon-Herrero (1978) extended the unit hydrograph method to directly derive a unit sediment graph (USG) for a small watershed. The sediment load considered in the USG is the wash load only. Williams (1978) extended the concept of an instantaneous unit hydrograph (IUH) to instantaneous sediment graph (IUSG) to determine the sediment discharge from an agricultural catchment. The concept of USG has been also employed by Singh et al. (1982), Chen and Kuo (1986), Kumar and Rastogi (1987), Raghuwanshi et al., (1994), Banasik and Walling (1996), among others, for the purpose of estimating the temporal variation of sediment yield. Kalin et al. (2004) developed a modified unit sedimentograph approach for identification of sediment source area within the catchment. The catchment was portioned into a number of elements. The sediment flux response of the elements at the basin outlet was computed by characterizing the rainfall event by the pulse of rainfall excess depths. The application of these methods requires considerable input data for their calibration, but the models inherit the limitations of unit hydrograph theory.

Viney and Sivapalan (1999) coupled a continuous (daily time interval) conceptual sediment generation and transport algorithms, to an existing water and salt balance model, LASCAM. LASCAM was originally developed to predict the effect of land use and climate change on the daily trends of water yield and quality in forested catchments in Western Australia. The developed sediment transport algorithm does not discriminate between sediment size classes. It was found that the amount of runoff and sediment produced by the model matched well in monthly and daily time intervals.

2.2.1.3 Physically based Models

The other category of models which use theoretical description of processes involved in the form of mathematical equations are termed as physically based models. These models are intended to represent the essential mechanisms controlling erosion and they incorporate the laws of conservation of mass and energy. Most of them use particular differential equations and generally require more input parameters than empirical models.

Numbers of the physical based models are developed in recent past.

AGNPS: The Agricultural Non-Point Source model (AGNPS) is an event-based model developed by the US Department of Agriculture, Agricultural Research Service (USDA-ARS) in cooperation with the Minnesota Pollution Control Agency and the Soil Conservation Service (SCS) in the USA (Young et al., 1989). AGNPS simulates runoff, sediment, and nutrient transport from agricultural watersheds. The model divides the watershed into square cells uniformly distributed over the watershed. The erosion and sediment transport components are based on estimating the upland erosion by the USLE and routing it by the steady-state continuity equation of sediment. The model produced comparable results for runoff and sediment (Young et al., 1989). Panuska et al. (1991) identified that the grid size selected by the model user was a major factor influencing sediment yield calculations. Consequently, care needs to be taken when applying such a model to ensure that the resolution chosen for modeling is adequate for the task.

ANSWERS: Areal Nonpoint Source Watershed Response Simulation (ANSWERS) model (Beasley et al., 1980) is an event based, distributed parameters watershed model to simulate the runoff and sediment yield from agricultural watershed and to evaluate the effect of various management practices on the runoff and sediment response of the watershed. ANSWERS-2000 (Dillaha et al., 2001), a recent version of the ANSWERS model is capable of simulating the runoff and sediment yield on continuous basis. Preparing input data file for ANSWERS is rather complex (Norman, 1989) as it is the case for many physically-based hydrological and erosion and sediment transport models. The applicability of ANSWERS is limited in many catchments by the large spatial and temporal input data requirements of the model. Given the lack of such data in most catchments, parameters may need to be calibrated, raising problems with model identifiably and physical interpretability of model parameters.

LISEM: The LImburg Soil Erosion Model (LISEM) (De Roo and Jetten, 1999) is a spatially distributed, physics-based hydrological and soil erosion model developed by the Department of Physical Geography at Utrecht University and the Soil Physics Division at the Winard Staring Centre in Waneningen, the Netherlands, for planning and conservation purposes. LISEM (De Roo et al., 1996) is one of the first models that use GIS. In the soil erosion part, the model accounts also for roads, wheel tracks and channels. Approximately 25 maps are required for simulation, including maps describing catchment morphology, leaf area index, random roughness of the soil, and the fraction of the soil with crop cover. LISEM does not simulate concentrated erosion in rills and gullies, rather it simulates sediment detachment by flows in the ponded area only. Additionally, regardless of how well constructed or sophisticated a model is, the performance of a model such as LISEM ultimately is constrained by the resolution and quality of these GIS inputs.

CREAMS: Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS), a physically based daily simulation model, maintains the elements of USLE, but includes the sediment transport capacity of flow. The sediment transport component of CREAMS analyzes the inter-rill area and rill separately. Detachment on both rill and inter-rill area is determined by the modified USLE. The procedure allows parameters to change along the overland flow profile and along waterways to describe spatial variability (Foster et al., 1981). An advantage of CREAMS is that it accounts for gully erosion and deposition, in addition to overland erosion sources, erodability factor to be updated from one runoff event to the next (Govers and Loch, 1993). The model applies to field-sized catchments of approximately 40 ha, although it can be used on scales up to 400 ha (Lane et al., 1992).

WEPP: Water Erosion Prediction Project (WEPP) (Nearing et al., 1989) is a continuous simulation (field or watershed) scale model that incorporates new erosion prediction technology developed by USDA. The model requires input data of rainfall amount and intensity, soil texture, plant growth, residue decomposition, effect of tillage implements on soil properties, slope shape, steepness, and orientation, and soil erodability parameters. The watershed version of WEEP routes runoff and sediment from fields and incorporates channel scour based on the work of Foster and Meyer (1972), and Knisel (1980). The model was found reliable (Zhang et al., 1996) in predicting long term averages of soil loss under cropped conditions. The ability of WEPP to accurately predict where detachment and deposition will occur will be useful in establishing appropriate conservation or management practices. Despite the process-based nature of the model, WEPP still contains a degree of empiricism and care should be taken when applying the model to new sites.

EUROSEM: The EUROpean Soil Erosion Model (EUROSEM) (Morgan et al., 1998) is a model for predicting soil erosion by water from fields and small catchments. The model was designed as an event-based model, for it was assumed that erosion was dominated by only a few events per year. EUROSEM is a dynamic erosion model and is able to simulate sediment transport, erosion and deposition by rill and inter-rill processes over the hillslope. The model provides total runoff, total soil loss, storm hydrograph and storm sediment graph.

KINEROS: KINematic EROsion Simulation (KINEROS) (Smith, 1981; Woolhiser et al., 1990) is composed of elements of a network, such as planes, channels or conduits, and ponds or detention storages, connected to each other. KINEROS is an extension of KINGEN, a model developed by Rovey et al. (1977), with incorporation of erosion and sediment transport components. The sediment component of the model is based on the one dimensional unsteady state continuity equation. Erosion/deposition rate is the combination of raindrop splash erosion and hydraulic erosion/deposition rates.

2.3 REMARKS

It is evident from the literature, based on processes considered, complexity, accuracy, scale (space and time), and ultimately input data requirement, a wide range of models exist for modeling sediment yield and soil erosion. Use of physically based models, assumed most accurate, is limited to research use due to their complexity and non-availability of data required for use. Therefore, the morphological based approach has been still widely used in ungauged watershed due to it's up to the mark performance as per literatures. The major problem with the conceptual model is lack of uniqueness in parameters obtained in calibration from the observed data Therefore, empirical models are more commonly used in field application and modelling for data scarce regions. However, these are based on inductive logic and generally applicable only to those conditions for which the parameters have been calibrated. Overall, there is not a single model valid for all applications. Therefore, there exists an urgent need to develop such models which describe the complex physical process of sediment erosion/deposition in simple manner as USLE and at the same time, output is close to reality as far as possible in space and time. As per above literature in the present study firstly, the morphological based watershed prioritized method will be applied for catchment assuming it as un-gauged and secondly a simple low data requirement model will be developed by using the available sediment data at the outlet of catchment for prioritizing the entire catchment.

CHAPTER - 3

PRIORITIZATION OF CATCHMENT USING MORPHOLOGICAL PARAMETERS

3.1 Introduction

Land and water are two important natural resources since our relationship with them directly reflects the success of civilization. In scientific terminology this Land-Water-Human relationship has been bounded by the term "Watershed". Watershed is the basic unit for development and planning of resources for the welfare of the communities. India has been delineated into 3237 watersheds ranging from 200 sq. km to 3000 sq. km. As these watersheds are the source of goods such as food, fodder, fiber and fuel wood and services like water for the local population, their scientific management is essential for sustainable development and to meet the increasing demand for larger biomass. However, today these limited resources are under rising pressure due to their non-sustainable exploitation. Which consequences are huge devastation occurred due to flood in one part of the globe which claimed huge losses of government and private properties whereas the same time drought hit the several lives in other part of the globe. Thus, watershed planning and management has been become top priority to mitigate such consequences. Furthermore, Watershed planning and management schemes play a vital role in ensuring efficient use of land and water resources in terms of quantity and quality to meet the present and future demands for the stakeholder.

Morphology is a scientific parameterization of configuration of earth's landforms which provides a quantitative description of fundamental units of surface drainage system (Strahler, 1964) of a piece of land or watershed. Horton (Horton, 1945) was the first who expressed that linear relationships exhibited between number of streams, length of stream segment and area drain by streams when plotted in successive Strahler orders and theses are popularly known as Horton's ratio in the field of hydrology. These morphometric parameters have been linked with hydrological behavior of an ungauged watershed through popular GIUH theory, (Rodriguez-Iturbe et al., 1979; Gupta et al., 1980), stream profile analysis (Hack, 1973), prioritization of sub-watersheds for their vulnerability of soil erosion (Mishra, 1980; Goel, 2003; Pandey et al., 2004; Nookaratnam et al., 2005; Jaiswal et al., 2015; Grauso et al., 2008), estimation of sediment production rate (Jose and Das, 1982; Suresh et al., 2004; Grauso et al., 2008; Rymbai and Jha, 2012; Ahmed and Rao, 2015) identification of artificial recharge locations (Ghayoumian et al., 2005; Saraf and Chaudhary, 1998; Ghayoumian et al., 2005) permeability of underlying geological formation (Pakhmode et al., 2003; Anbazhagan et al., 2005) and many more.

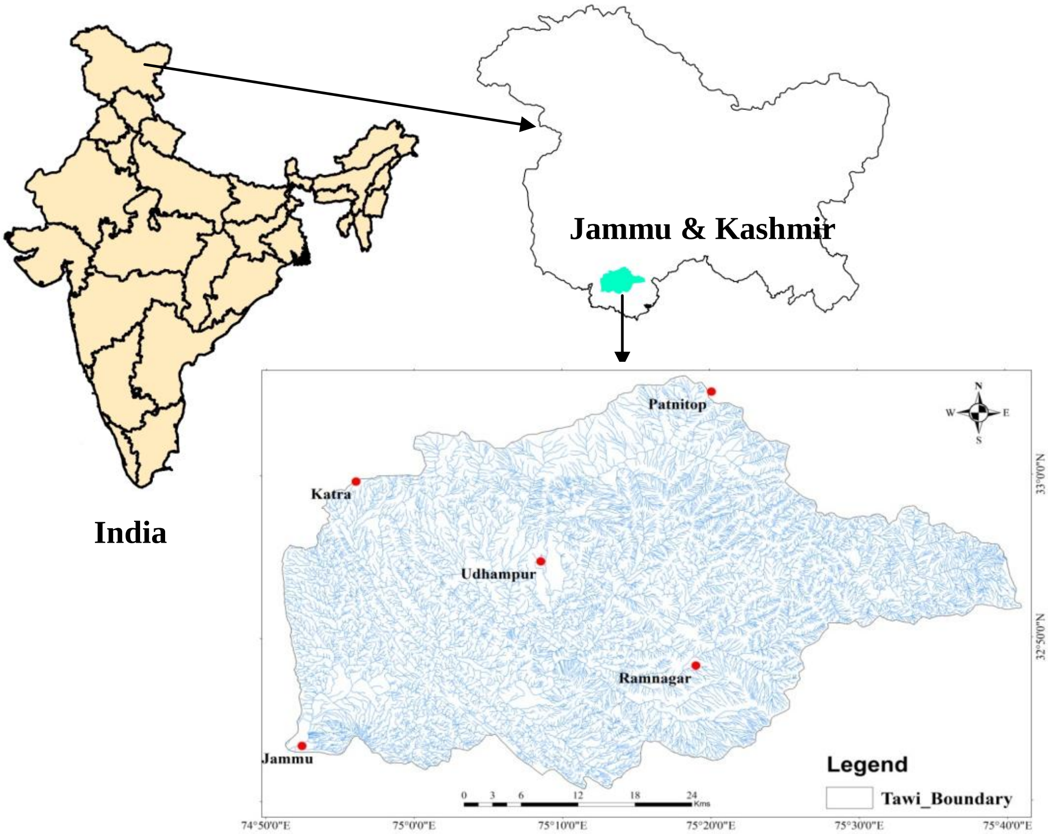
The response to soil and water conservation measures for alleviating erosion would be different for different parts of a catchment due to their physiographical variability throughout the catchment or in other words exhibit different physiographical setting in the sub-watersheds of a same catchment. Thus it is not only necessary to know the state of erosion of the watershed but it is equally important to quantify the rate of erosion from different watershed to optimize the project outcome from the funds. In developing countries like India, observations of discharge and suspended sediment yield are usually gauged only at the outlet of large watersheds normally while these rivers entered in the plain areas. However, the major sources of sediment are the upstream areas and carried-out by small mountainous tributaries which are unfortunately un-gauged. Process of sediment is exclusively influenced by erosion, deposition and transportation sub-processes which are continuously taking place at every place of sediment flow path within the watershed. Therefore, using sediment data of large watershed could not be justified to identify the actual source areas of sediment within the watershed. To overcome such circumstance, various morphometric parameters (drainage density, drainage frequency, form factor, length of overland flow, elongation ratio, circulatory ratio, compactness coefficient, drainage texture, bifurcation ratio etc) have been correlated with surface and sub-surface features of the watershed which are responsible for runoff and consequent erosion from the watershed. Since, most of the morphometric parameters are in form of ratio, scale does not limit their application while compare for different watersheds. Due to lack of observed data, theses simple morphometrical based approaches are still very relevant in characterization of sub-watersheds in reference to their susceptibility towards soil erosion and accordingly prioritizing of soil and water conservation measures within the watershed.

Manual estimation of geomorphologic parameters is a tedious and cumbersome process and often discourages the field engineers from developing regional methodologies for solving various hydrological problems of the un-gauged catchments or in limited data situations (Singh, 1998; Kumar et al., 2001; Singh et al., 2003). With the advancement in the field of geo-spatial technologies like GIS and Remote Sensing (RS), geomorphological parameters can be easily extracted from the digitalize toposheets (Tarboton et al., 1991; Moore et al., 1992; Maathuis, 2005; Hengl et al., 2006; Nookaratnam et al., 2005). Nevertheless, GIS tools are cable to handle spatial and temporal data and morphomtric parameters can be updated while any change occurs (Apaydin et al., 2006).

Therefore, based on the foregoing discussions and the intermittency between the geomorphology and hydrologic response of the watershed, the present study was carried out analysis of morphological parameters of nine sub-watersheds of watershed and to prioritize sub-watershed based on morphometric based compound index. In this study sediment production rate from different sub-watershed are also quantify using geomorphological parameters to decide the amplitude of the treatment activities in different areas or sub-watersheds of catchment.

3.2 Study Area

In present study river watershed located in Jammu division of Jammu and Kashmir State of India (Fig. 1) is selected for detail morphometric analysis. River , a major River in Jammu region is the left bank tributary of river Chenab originating from the lapse of Kali Kundi glacier in Bhaderwah, flows through some parts of Doda district, Udhampur reaches Jammu from where it finally merges into Chenab in Pakistan. The length of river from its originating point to Jammu is about 150 Km. The important role of River for sustaining the most populous cities in the region, Jammu and Udhampur has been considered while selecting the basin. The River has a very high social impact as it is the only major source of water for drinking, agricultural and industrial needs and serving to the almost 20% population of the whole J&K State. However, this heavy population load causes the ecological degradation (Change in the land use pattern, deforestation and low growth rate of vegetation, construction of new roads and bridges) which is accelerated the severe erosion in the catchment. The average annual rainfall of the study area is 1000 mm. A very high average sediment yield is reported to be of the order of 65 lacs MT per years in river. This huge debris ultimately gets deposited in the surface of the river channel when enters in the plain area. Consequently, the channel capacity reduces significantly and river gets overflow. The flood of September 5-6, 2014 might be best example of this heavy sediment load deposition. Since, study area is of eight order having geographical area of 2163 square km, entire area was subdivided in nine sub-watershed (Fig. 2) for greater understanding with morphometric parameters and their correlation with hydrological response and consequence soil erosion.



Tawi catchment

Fig 3.1: Location of catchment in the map of India

3.3 Material and Methods

3.3.1 Data Sources and Analysis

In the present study Tawi River catchment and its drainage network were delineated from toposheets obtain from the Survey of India (SOI). Total eight toposheets of 1:50,000 scale viz., 43O4, 43O8, 43L13, 43P5, 43P9, 43L14, 43P2 and 43P6 were first geo-referenced in ArcGis 10.2 followed by digitalization of stream network. By following the Strahler

(1964) method, stream ordering was carried-out for the entire catchment and it was found to be eight order catchment. According to drainage system nine different sub-watersheds area ranging from 97 sq. km to 487 sq. km. were delineated in catchment and depicted in Fig 2. The drainage networks of different nine sub-watersheds were analyzed as per Horton's (1945) laws in ArcHydro module of ArcGIS. In case of morphometric analysis, all sub-watersheds were examined from all dimensional aspects i.e., linear aspect indicates one dimensional view of the watershed, aerial aspect shows two dimensional, however, relief aspect explored three dimensional characteristics of the watersheds. Linear aspect comprises the study of stream order (N_u), stream length (L), and bifurcation ratio (R_b) whereas aerial aspect deals with drainage density (D_d), stream frequency (F_s), texture (T), form factor (R_f), circularity ratio (R_c), elongation ratio (R_e), compactness coefficient (C_c) and length of overland flow (L_o), however, total relief (H), relative relief (R_r), relief ratio (R_o) and average slope (S_a) was explored under the relief aspect of morphometric characterization of the catchment. The formulae for computation of the morphometric parameters are shown in Table 1.

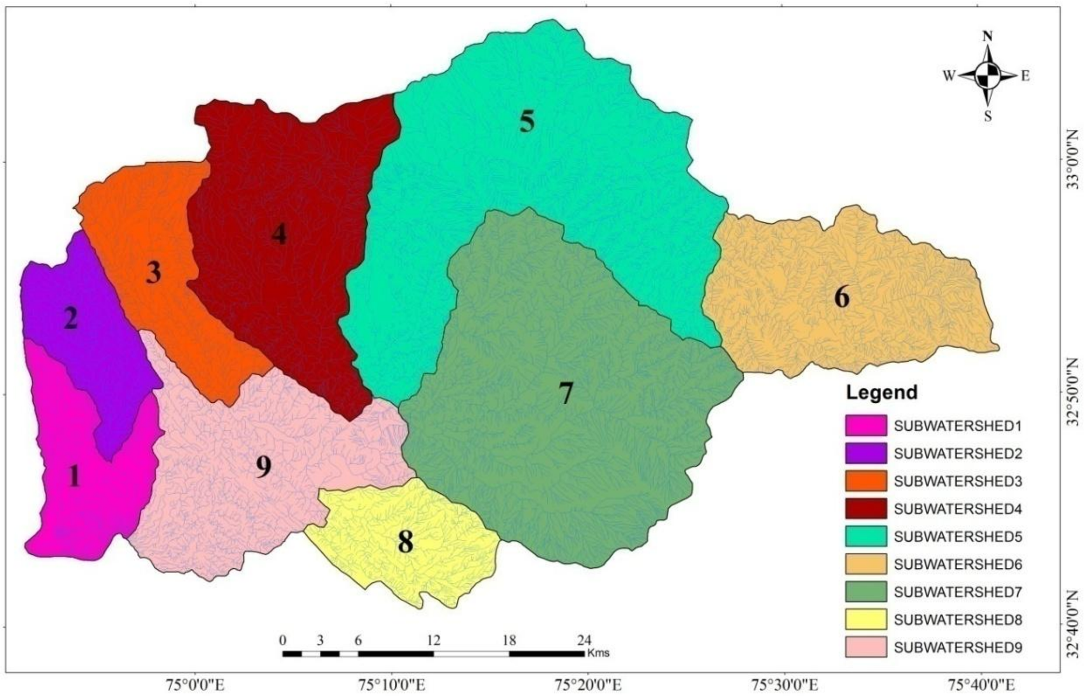


Figure 3.2. Delineated sub- watersheds of catchment

Table 3.2: Different morphometric parameters used in the study and theirs standard formulae.

	MorphometricParameters	Formula	Reference
Linear	Stream order(u)	Hierarchical rank	Strahler(1964)
	Basin Length(L)	$L=1.31*2A^{0.568}$ Where L=Basin length(km)A=Area of the basin (km^2)	Nookaratnam et al.(2005)
	Stream length(L_u)	Length of the stream	Horton(1945)
	Mean stream length(L_{sm})	$L_{sm}=L_u/N_u$ Where L_{sm}=Mean stream length L_u=Total stream length of order 'u', N_u=Total no. of stream segments of order 'u'	Strahler(1964)
	Bifurcation ratio (R_b)	$R_b=N_u/N_{u+1}$ Where,R_b=Bifurcation ratio N_u=Total no. of stream segments of order'u',N_{u+1}=Number of segments of the next higher order	Schumm(1956)
	Mean bifurcation ration (Rbm)	R_{bm}=Average of bifurcation rations of all orders	Strahler(1957)
Areal	Drainage density (D_d)	$D_d=L_u/A$ where, D_d= drainage density, L_u= total stream length of all, A= Area of the basin	Horton(1945)
	Form factor(R_f)	$Ff=A/L^2$ Where Ff=Form factor A=Area of the basin(km^2)L=Basin length(km)	Horton(1932, 1945)

	Stream frequency (F_s)	$F_s=N_u/A$ where, F_s=stream frequency, N_u=total no. of streams of all orders, A=area of the basin	Horton(1945)
	Drainage texture (T)	$T=N_u/L_p$, where N_u=total no. of streams of all orders, L_p=perimeter of th basin	Horton(1945)
	Elongation ratio(R_e)	$Re=1.128xA^{0.5}/L$ A=Area of the basin (km^2) L=Basin length(km)	Schumm(1956)
	Circularity ratio(R_c)	$R_C=4\pi A/P^2$ Where R_C=Circularity ratio π=3.14 A=Area of the basin (km^2)P=Perimeter(k m)	Miller(1953), Strahler(1964)
	Compactness Coefficient (C_c)	$C_c=0.282L_p/A^{0.5}$, where L_p=perimeter of th basin, A=area of the basin	Horton(1945)
	Length of overland flow (L_g)	$L_g=1/(2XD_d)$, where D_d= drainage density	Horton(1945)
Relief	Total Relief (H)	H= Difference between maximum and minimum elevation of the watershed	Schumm(1956)
	Relative Relief (R_r)	$H_R=H/L_p$ where, H=total relief, L_p=basin perimeter	Schumm(1956)
	Relief Ratio (R_o)	$H_{RR}=H/L$ where, H=total relief, L=basin length	Schumm(1956)

3.3.2 Morphological Index of Erodibility (MIE)

The concept of morphological index of erodibility was introduced to identify the area which are severely degraded and where soil has disappeared or lost most of its fertility. The combined effect of climate and continuous use of erosive land for agriculture prevents the soil from forming or recovering its fertility and the erosion continues (Fairbridge, 1968). Formation of degraded land gets activated through several processes such as head cutting in gully, scouring, selective erosion transport of sediment (Kirkby and Bull 2000). Degraded land formation exhibits particular land topography and stream morphology, which determine the rate of development of degraded land (Smith and Bretherton, 1972; Howard and Kerby, 1983). The subject of gully expansion and degraded land formation has been widely attempted in various parts of the world. In this study a morphological index of erodibility is to be evolved for comparing severity of erosion or degradation in different sub-watersheds of the catchment.

Linear parameters ($D_{d,}$ $R_{f,}$, T and R_h) favour erodibility of watersheds whereas shape parameters (R_c, R_e, and R_f) have inverse relationship with erodibility. Biswas et al., (1999) and Nookaratnam et al., (2005) used ranking system to compare degradation of watersheds. Ranking system is thus useful for prioritization of watershed within a specified area. However it cannot be used as a measure of morphological influence on erodibility. Comparison of watersheds in terms of large number of parameters is usually complicated and confusing. In the present study a morphological index of erodibility (MIE) has been also proposed for assessing combined influence of several morphological parameters on erodibility.

$$MIE= (D_d \times D_f \times T \times R_o)/ (R_c \times R_e \times R_f) \quad (1)$$

3.3.3 Estimation of Sediment Production rate (SPR)

Sediment production rate is the volume of sediment produced per unit watershed area per unit time. The sediment production rate of the watershed has been estimated based on the model suggested by Jose and Das (1982) and is expressed by the following equation:

$$\text{Log (SPR)} = 4919.80 + 48.64 \log (100 + R_t) – 1337.77 \log (100 + R_c) – 1165.64 \log (100 + Cc) \quad (2)$$

where, SPR is sediment production rate in ha-m/100 sq. km./year, R_t is Rotundity factor, R_c is circulatory ratio and Cc is compactness coefficient.

3.4 Results and discussion

The various morphometric parameters of the River basin area were determined and are summarized in Tables 2 to 4. The basic parameters of sub-watersheds of Tawi catchment have shown in Table 2.

Table 3.2. Basic Parameters of different sub-watersheds of Tawi River Catchment

Sub-watershed name	Basin Area(km^2)	Perimeter(km)	Basin Length(km)
SW1	108.4	62.4	18.78
SW2	96.92	49.55	17.63
SW3	136.5	62.83	21.42
SW4	276.3	83.64	31.96
SW5	486.9	128.5	44.10
SW6	229.9	70.6	28.80
SW7	483	94.89	43.89
SW8	104.1	47.25	18.36
SW9	237.9	88.5	29.36

3.4.1 Linear Aspects

Linear aspect i.e. number and length of different stream order stream and corresponding bifurcation ratio has given in Table 3.

3.4.1.1 Stream ordering

Stream ordering is the first step to extract the geomorphological parameters of a catchment. river basin was adjudged eight order basin according to the Strahler (1964) hierarchical rank. The drainage map with stream order of the catchment is shown in Figure 3. As the stream order increases the total number of streams decreases as suggested by Strahler (1957) and shown in Fig. 4 while stream orders and number of streams are plotted on a semi-log graph paper. The drainage pattern of an area reflects the nature of slope, geological structure and lithologic controls of the underlying rocks (Zernitz, 1932 and Easterbrook, 1969, Nag and Chakraborty, 2003). Study area comprises three kind of drainage pattern viz., trellis, parallel and dentritic. In trellis type drainage pattern primary or secondary tributaries meet the main stream at about right angle. Such patterns are developed in the areas of folded sedimentary rocks of various resistances to erosion. In sub-watersheds SW5 and SW6, trellis is the dominant drainage pattern. However, SW7, SW3 and SW1, parallel drainage pattern is the dominant drainage pattern. In parallel drainage system primary and secondary stream flow parallel to each other and meet main channel at about same angle. Such drainage pattern are pertaining the regional slope and normally start from the water divide of the watershed. However, dentritic drainage patter is found frequently in SW4, SW2 SW8 and SW9 sub-watersheds and some part of other sub-watersheds. Dendritic type of drainage pattern refers to the homogeneity in texture, rock and lack of structural control.

Table 3.3: Extracted stream of different orders and their bifurcation ratios.

Sub-watershed	Parameter	Stream Order								Mean Bifurcation ratio (R_b)
		I	II	III	IV	V	VI	VII	VIII	
SW1	No. of Stream	370	75	18	3	2	0	0	1	4.15
	Stream Length(km)	197.9	71.2	50.1	8.0	5.2	0.0	0.0	17.8	
	Bifurcation ratio	4.93	4.2	6.0	1.50	-	-	-	-	
SW2	No. of Stream	369	81	18	6	1	0	0	0	4.51
	Stream Length(km)	189.4	64.6	34.1	37.8	20.7	0	0	0	
	Bifurcation ratio	4.6	4.5	3.0	6.0	-	-	-	-	
SW3	No. of Stream	418	96	19	7	2	1	0	0	3.52
	Stream Length(km)	236.8	86.4	46.5	24.0	9.6	13.6	0.0	0.0	
	Bifurcation ratio	4.4	5.05	2.71	3.5	2.0	-	-	-	
SW 4	No. of Stream	709	158	37	9	3	1	0	0	3.77
	Stream Length(km)	484.1	144.9	83.5	34.4	28.9	10.5	0.0	0.0	
	Bifurcation ratio	4.49	4.27	4.11	3.00	3.00	-	-	-	
SW 5	No. of Stream	1809	363	74	19	3	1	0	0	4.62
	Stream Length(km)	1051.3	276.4	126.2	61.7	8.2	61.9	0.0	0.0	
	Bifurcation ratio	4.98	4.90	3.89	6.33	3.0	-	-	-	
SW 6	No. of Stream	1110	207	45	11	2	1	0	0	4.31

	Stream Length(km)	617.4	139.2	71.0	43.9	29.6	0.9	0.0	0.0	
	Bifurcation ratio	5.36	4.6	4.09	5.5	2.0	-	-	-	
SW 7	No. of Stream	1849	370	84	20	6	2	1	0	3.66
	Stream Length(km)	1072.3	290.5	143.8	56.7	58.0	24.1	0.2		
	Bifurcation ratio	4.99	4.40	4.2	3.33	3.0	2.0	-	-	
SW 8	No. of Stream	446	89	24	8	1	0	0	0	4.92
	Stream Length(km)	239.9	60.0	42.7	27.1	13.1	0.0	0.0	0.0	
	Bifurcation ratio	5.01	3.7	3.0	8.0	-	-	-	-	
SW 9	No. of Stream	881	183	44	11	2	3	2	1	3.23
	Stream Length(km)	462.6	139.9	96.9	41.1	9.8	0.4	5.9	41.8	
	Bifurcation ratio	4.81	4.15	4.0	5.5	0.66	1.5	2.0	-	

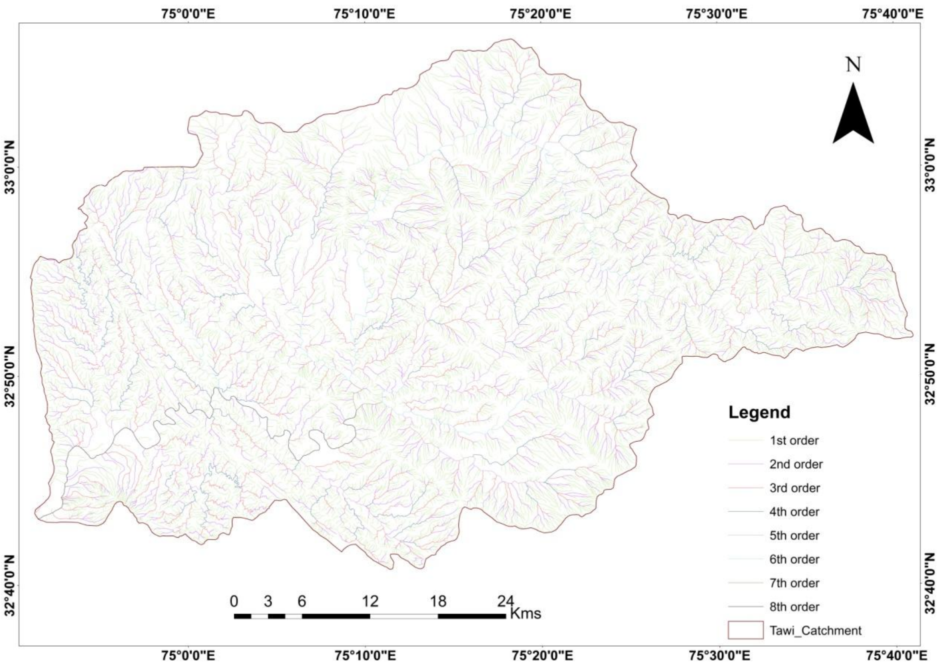


Figure 3.3: Drainage network map of catchment.

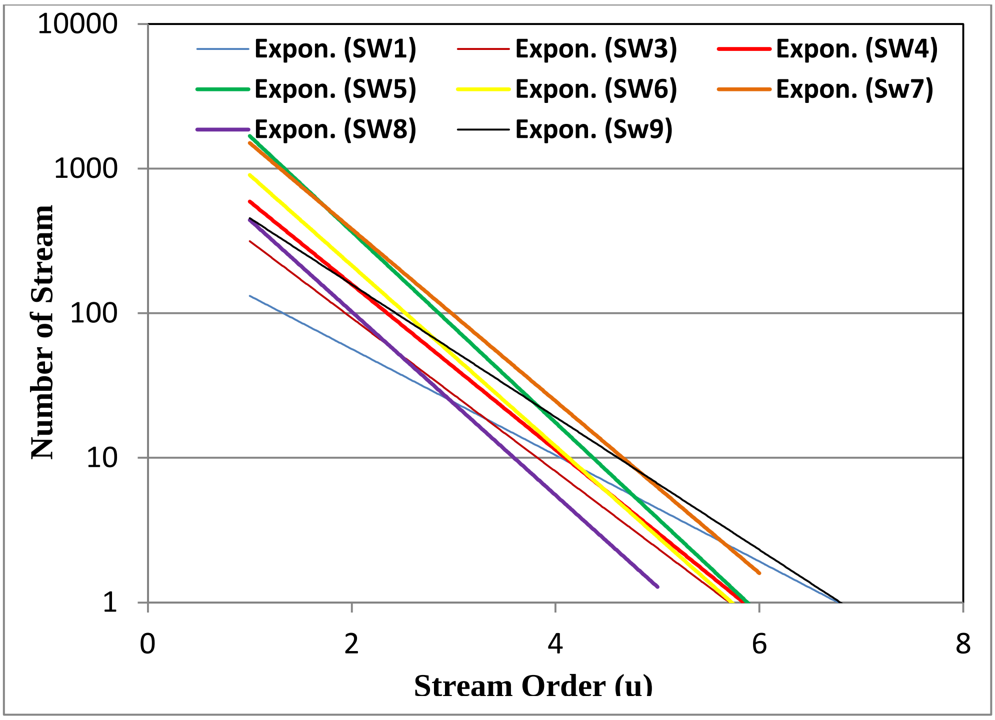


Figure 3.4: Variation of number of stream with respect to stream order for sub-watersheds of catchment

3.4.1.2 Stream Length

Number of streams of various orders in a sub-watershed are counted and their lengths from mouth to drainage divide are measured (Table 2) with the help of GIS software. The stream length (Lu) corresponding to different stream orders have been computed based for all 9 sub-watersheds (Table 3). Generally, the total lengths of stream segments are highest in first order streams and decreases as the stream order increases. However, in case of SW5, SW6, and SW7 sub-watersheds the stream segments of first orders are proportionately very high as compare to general observation (Table 3). This change may indicate flowing of streams from high altitude, lithological variation and converging terrain (Singh and Singh, 1997).

3.4.1.3 Bifurcation Ratio (R_b)

It is the ratio of the number of streams of given order u to the number of streams of higher order u+1. In general, lower value of R_b is characteristics of watershed which has suffered less structural disturbances and the drainage pattern has not been distorted by structural disturbances (Nag and Chakroborty, 2003). Abnormally high value of R_b might be expected in region of steeply dipping rock strata. The value of R_b is also indicative of shape of the basin. An elongated basin is likely to have high R_b, where as a circular basin is likely to have a low R_b. In the study area, the values of R_b in the middle range and varies between 3.0 to 5.0 (Table 3). The minimum and maximum value was found to be 3.23 and 4.93 for watershed SW9 and SW8, respectively. It can be witnessed from Table 3, the bifurcation ratios between the first and second order streams are higher than the higher orders in all sub micro-watersheds indicating that the catchment fall under areas of active gullies and ravines, hence, higher erosion rates.

3.4.2. Areal Aspects

Areal aspects include different morphometric parameters, like drainage density (D_d), stream frequency (F_s), form factor (R_f), circulatory ratio (R_c), elongation ratio (R_e) and length of the overland flow (L_o). The values of these parameters were calculated and results have been given in Table 4.

3.4.2.1 Drainage Density (D_d)

Drainage density is one of the important indicators of the linear scale of land form in stream eroded topography, and is defined as the ratio of total length of the streams of all order of basin to the area of basin. It reflects the landuse and affects infiltration and the basin response time between precipitation and discharge. It is also of geomorphological interest particularly for the development of slopes. Drainage basin with high D_d indicates that a large proportion of the precipitation runs off. The drainage density, expressed in km/km^2, indicates closeness of spacing of channels, thus providing a quantitative measure of the average length of stream channel for the whole basin. Further, it also gives an idea of the physical properties of the underlying rocks. Low drainage density occurs in regions of highly resistant and permeable sub soil materials with dense vegetation and low relief, where as high drainage density is prevalent in region of weak, impermeable sub-surface material which is sparsely vegetated and has high relief (Strahler1964). Drainage density in the study are varies between 2.84 (SW4) and 3.92 (SW6) indicating medium to high drainage density (Table-4). High drainage density in SW6 sub-watershed may be resultant of weak or impermeable subsurface material, high mountainous relief and fine drainage texture. However, low drainage density in SW4, SW1 and SW3 sub-watersheds indicate areas of highly resistant on permeable subsoil material, low relief and coarse drainage texture.

3.4.2.2 Stream frequency /Drainage Frequency (F_s)

Stream frequency is the number of streams per unit area of the basin. It mainly depends upon the lithology of the basin and reflects the texture of the drainage network. Stream frequency of sub-watersheds varies from 3.32 to 5.98. Sub-watershed SW6, SW8 associated with high stream frequency while sub-watersheds SW4 and SW3 having low stream frequency. Drainage density and stream frequency has a similar measure of stream network of a drainage basin. Table 4 shows close correlation between drainage frequencies with drainage density indicating the increase in stream population with respect to increase in drainage density.

3.4.2.3 Drainage Texture

Horton (1945) defined drainage texture is the total number of stream segments of all order in a basin per perimeter of the basin. It is important to geomorphology which means that the relative spacing of drainage lines. Drainage texture depends on the underlying lithology, infiltration capacity and relief aspect of the terrain. The drainage texture of entire 9 sub-watersheds are of coarse to very fine. The sub-watershed located in the downstream of catchment (SW1, SW2, SW3, SW4 and SW9) consist coarse drainage texture however, sub-watersheds of upstream part or hilly region (SW5, SW6 and SW8), comprise moderate to very fine texture. More finer is the texture more will be dissection and leads more erosion.

Several studies (Reddy 2004; Jaiswal et al., 2007) revealed that sub watersheds associated with high drainage density, stream frequency and texture ratio show very severe to severe erosion.

3.4.2.4 Form Factor (R_f)

It is dimensionless property and is use as a quantitative expression of the shape of basin form. The value of form factor is in between 0.2-0.3. According to form factor SW5, SW7 and SW4 are relatively more elongated due to low values of form factor. However, SW2, SW8 and SW1 are relatively having high values of form factor and hence less elongated. Smaller the value of form factor, more elongated will be the basin. The basins with high form factors, have high peak flows of shorter duration, whereas, elongated drainage basin with low form factors have lower peak flow of longer duration.

3.4.2.5 Infiltration Number

The infiltration Number is defined as the product of Drainage Density (Dd) and drainage Frequency (Fs). Sub-watershed SW4 has the low infiltration 9.44 and the SW6 has the higher infiltration number of 23.48. The higher the infiltration number the lower will be the infiltration and consequently, higher will be run off. It gives an idea about the infiltration characteristics which play vital role in transformation of rainfall into the runoff. High value of infiltration number SW6 and SW8 reveal that the sub-watersheds are impermeable lithology and higher relief.

3.4.2.6 Circulatory Ratio (R_c)

The circularity ratio is a similar measure as elongation ratio, originally defined by Miller (1953), as the ratio of the area of the basin to the area of the circle having same circumference as the basin perimeter. The value of circularity ratio varies from 0 (in line) to 1 (in a circle). The Circulatory ratio for all basins is in the range of 0.35 to 0.67. It is clear from the figure that SW5 is elongated and hence attributed to low value of circulatory ratio (0.37), however, SW7 is circular in nature and associated with higher value of circulatory ratio(0.674).

3.4.2.7. Elongation Ratio (R_e)

It is defined as the ratio between the diameter of a circle with the same area that of the basin to the maximum length of the basin. The elongation ratio ranges from 0.0 to 1.0 over a wide variety of climatic and geological environments. High Value (nearing 1) of elongation ratio is typical of regions of low relief, whereas low values are generally associated with strong relief and steep ground slopes. In cathment area SW4, SW5, SW6, SW7 are having high relief (consisting high average slope) and hence associated with low values of elongation ratio. Elongated basin with high bifurcation ratio like SW5 yields a low but extended peak flow (Verstappen, 1983).

3.4.2.8 Length of Overland Flow (L_o)

The term length of overland is used to describe the length of flow of water over the ground before it becomes concentrated in definite stream channels. Horton (1945) expressed it as equal to half of the reciprocal of drainage density (D_d). This factor relates inversely to the average slope of the channel and is quite synonymous with the length of sheet flow at a large degree. The length of overland flow ranges from 127 meter to 176 meter in sub-watersheds. SW6 has highest relief among all sub-watersheds and hence has lowest length of overland flow i.e. 127 meter. However, Smaller the value of overland flow the quicker surface runoff will enter the streams represents well developed drainage network with higher slope. In such watersheds a significant amount of surface runoff contributed in the stream discharge for even a low amount of rainfall.

3.4.2.9 Compactness constant

Compactness coefficient is used to express the relationship of a hydrologic basin with that of a circular basin having the same area as the hydrologic basin. A circular basin is the most hazardous from a drainage stand point because it will yield the shortest time of concentration before peak flow occurs in the basin. The values of Cc in the nine sub-watersheds of catchment varies from 1.22 to 1.69 showing variations across the watersheds. It can be shown from the fig that SW7 is almost circular in shape which tends to low value of compactness coefficient (close to unity). However, SW1, SW5, SW9 having higher values of Cc due to their elongated shape.

Table 3.4: Aerial Aspect of the River Catchment

Sub-Watershed No.	D_d (km/km^2)	F_s (no./km^2)	R_c	R_f	R_e	T	L_o (m)	C_c
1	3.232	4.328	0.350	0.307	0.626	7.516	155	1.69
2	3.576	4.901	0.496	0.312	0.630	9.586	140	1.42
3	3.054	3.977	0.434	0.298	0.616	8.643	164	1.52
4	2.846	3.318	0.496	0.270	0.587	10.964	176	1.42
5	3.257	4.660	0.370	0.250	0.565	17.653	154	1.64
6	3.923	5.984	0.579	0.277	0.594	19.489	127	1.31
7	3.407	4.828	0.674	0.251	0.565	24.575	147	1.22
8	3.675	5.454	0.586	0.309	0.627	12.020	136	1.31
9	3.356	4.737	0.382	0.276	0.593	12.735	149	1.62

3.4.3 Relief Aspects

Relief aspects of drainage basin relate to the three dimensional features of the basin involving area, volume and altitude of vertical dimension of landforms wherein different morphometric methods are used to analyze terrain characteristics. Because many landscape processes are driven by gravity and relief properties are frequently used as indicators of erosion potential and denudation rates. In this study, thus, relief aspect includes the analysis of total relief, relief ratio, relative relief and average slope of all nine sub-watersheds of the catchment.

3.4.3.1. Total Relief (H)

It is the maximum vertical distance between the lowest and highest point of the watershed. It is also known as maximum watershed relief. Watershed relief controls the gradient of drainage lines within the watershed and hence significantly influences the soil erosion of the watershed (Patton et al., 1988 and Ozdemir and Bird, 2009). SW5, SW6, and SW7 are attributed by high relief i.e. 2737 m, 2704 m, 2157 m, respectively and SW3, SW4, SW8 and SW9 comprise medium relief i.e. 1469 m, 1967 m, 1215 m and 1012 m, respectively. However, SW1, SW2 are comes under low relief i.e. 457 m and 561 m, respectively. Most of the watersheds are associated with high relief and hence more prone to soil erosion.

3.4.3.2. Relief Ratio (R_h)

The relief ratio defined as the ratio between the total relief of a basin and the longest dimension of the basin parallel to the main drainage line (Schumm,1956). The advantage of relief ratio over the total watershed relief as it removes the size effect by dividing the total relief by the basin length. In watershed relief ratio varies from 19.19 m/km (SW2) to 82.74 m/km (SW6) (Table 5). Significant high relief ratio especially in SW6 indicates the steepness of the principal flow path which eventually severally eroded the bank of the stream.

3.4.3.4. Relative Relief (R_r)

It is the ratio of the maximum watershed relief to the perimeter of the watershed. The Relative relief represents actual variation of altitude in a unit area with respect to its local base level. It enumerates that the steeper the slope the higher is the surface above its base. The values of the relative reliefs for 9 Sub-Watershed of catchment varies from 7.32 m/km to 38.3 m/km, indicating the terrain of catchment is highly undulating. Very High values of R_r for SW6 sub-watershed indicates that it is highly susceptible to soil erosion.

3.4.3.3 Average Slope (S_a)

Average slope of the watershed, S_a has direct influence on the erodibility of the watershed. It has been proved by researcher that more the percentage of slopes more are the erosion, if other factors remain unchanged. The average slope for different sub-watersheds varies between 10.35% (SW1) to 44.44 % (SW6) (Table 5). It was observed that high relief ratio and relative relief sub-watersheds are characterized by high slopes and vice versa.

Table 3.5. Relief Aspect of the River Catchment

Sub-Watershed No.	H (m)	R_h (m/km)	R_r (m/km)	S_a (%)
1	457	19.55	7.32	10.35
2	561	19.19	11.32	15.38
3	1469	51.17	23.38	19.37
4	1967	61.87	23.52	24.05
5	2737	42.21	21.30	35.16
6	2704	82.74	38.30	44.44
7	2157	68.19	22.73	30.77
8	1215	61.21	25.71	20.23
9	1012	0.022	0.011	20.33

3.4.4 Prioritization of Sub-watersheds

3.4.4.1 Based on Morphological Parameters

Morphological parameters (linear, aerial, relief) for all sub-watersheds were calculated separately and shown in Table 3-5. For prioritization, all nine sub-watersheds are ranked based upon their corresponding morphological parameters value. Linear parameters like drainage density, stream frequency, bifurcation ratio and texture ratio have direct relationship with erosivity. Therefore, the sub-watershed having highest numerical value of these individual parameters was assigned ranked first based and next was second and so on. Similarly, aerial parameters like elongation ratio, circulatory ratio, form factor and compactness coefficient having the inverse relationship with erosivity. Therefore, the sub-watershed having lowest value of these individual parameters was assigned rank first and next was second and so on. Similarly sub-watersheds are ranked according to relief aspect as it has direct relationship with the erosivity. Finally, based upon all individual ranking, a compound ranking was calculated for each sub-watershed and depicted in Table 6. It is evident from the Table 6 that SW6 has the first priority and SW1 has the least priority. The highest priority indicates the greater degree of erosion in the particular sub-watershed and it becomes a potential candidate for applying soil conservation measures. Thus, soil conservation measures can be first applied to SW1 and then to others depending on their priority. The priority map of catchment is shown in Figure 5.

Table 3.6: Prioritization of Sub-watersheds of catchment according to morphological parameters.

Sub-Watershed No.	Morphological Parameter													Compound Parameter	Final Ranking
	R_b	D_d	F_s	I	R_c	R_f	R_e	T	C_c	H	R_h	R_r	S_a		
1	5	7	7	7	1	7	7	9	9	8	8	9	9	7.2	9
2	3	3	3	3	5	9	9	7	6	9	9	8	8	6.3	8
3	8	8	8	8	4	6	6	8	4	5	5	4	7	6.2	7
4	6	9	9	9	6	3	3	6	5	4	3	3	4	5.4	5
5	2	6	6	6	2	1	5	3	8	1	6	6	2	4.2	3
6	4	1	1	1	7	5	1	2	3	2	1	1	1	2.3	1
7	7	4	4	4	9	2	2	1	1	3	2	5	3	3.6	2
8	1	2	2	2	8	8	8	5	2	6	4	2	6	4.3	4
9	9	5	5	5	3	4	4	4	7	7	7	7	5	5.5	6

3.4.4.2 Based on Morphological Index of Erodibility (MIE)

Nine Sub-watersheds (SW1 to SW9) of catchment (Figure 6.1) have been selected for analysis of erodibility. Proposed morphological index of erodibility has been computed using equation (1). Sub-Watershed SW6, MIE value 396712, is found to be highly degraded whereas SW1, MIE value 30615, has the least degradation. MIE of watershed number SW6 is about 13 times more than the SW1 which indicates large variation in the degraded land in cathment. Therefore, SW6 need to be taken under immediate watershed treatment programme. Coincidentally, SW6 is the origin of the river and also source of the major sediment load in the river according to the morphological based index of erodibility.

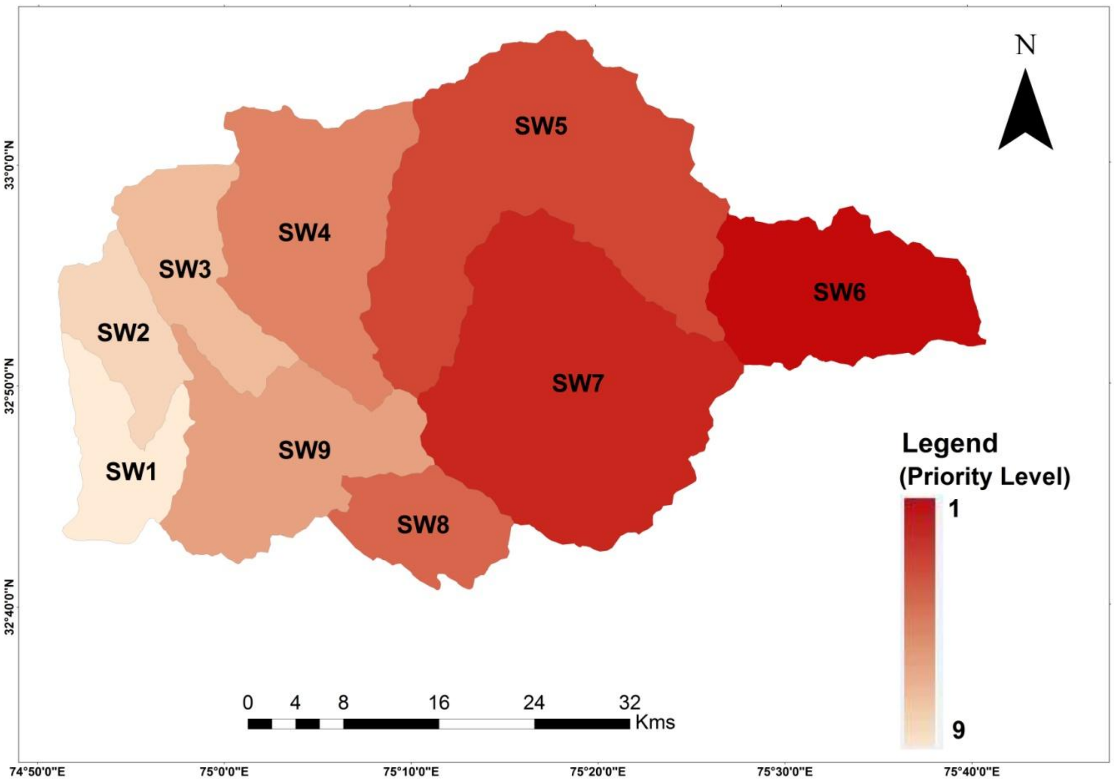


Figure 5: Su-watershed wise priority map of catchment.

3.4.4.3 Based on Sediment Production Rate (SPR)

Sediment production rate (SPR) for various sub-watersheds were to be estimated using Eq 2. and tabulated in Table 6. From this analysis, the highest SPR was found to be 3.07 ha-m/100 sq.km/yr for SW6, indicates that the watershed produces significant amount of sediment load annually. Estimated SPR value is also close to the design SPR values (4.3 ha-m/100 sq.km/yr) for major river valley projects in Western Himalayan region viz. Beas in Himachal Pradesh, Bhakra-Nagal on Satluj and Ramganga in Uttarakhand. Sediment Production Rate (SPR) is useful in deciding the methods of soil conservation practice and for fixing the priority of watershed for adopting conservation measures. Lowest SPR was found for SW1 which is also accomplished by lowest MIE. Priority classification based on standardized SPR gave a better distribution of sub-watersheds between various priority categories.

Table 3.7: Morphological Index of Erodibility (MIE) and Sediment Production Rate (SPR) for different sub-watersheds of catchment.

Particulars	**Sub-watershed of Catchment**								
	SW1	**SW2**	**SW3**	**SW4**	**SW5**	**SW6**	**SW7**	**SW8**	**SW9**
MIE	30615	33097	67497	81380	216118	396712	288790	130059	71254
SPR	0.82	2.62	1.98	2.78	1.18	3.07	2.75	2.93	1.29

3.5 Conclusion

Prioritization is to be the first and primary step for any watershed management and planning project and the success of project depends upon the accuracy in prioritization at large extent. In developing country like India where availability of data is major constraints, to prepare a fruitful project plan, such morphometric based methodology as discussed in this report are very relevant. The proposed methodology for prioritization of a catchment using morphological parameters in GIS environment is easy to use and very useful for an un-gauged catchment. Since, most of data used in the study are freely available; the proposed approach is parsimonious in terms of funds and also time saving. Once identify the criticality of these watersheds using morphological based approach would help in facilitating investment decision and making best use of the available resources. The proposed approach is not only fix the priority but it also quantify the erosivity with in the catchment which also helpful to divide the treatment activities in proportionate to the erosivity. Moreover, it can be helpful to allocate the budget for treatment in different watershed within the catchment. In the present study rainfall intensity and volume and its variation within the watershed has not considered, therefore, sediment production rate (SPR) estimated for different sub-watersheds of catchment cannot be compared quantitatively with the sediment yield data at the watershed outlet. In addition to this data of prevailing land use pattern and their spatial and temporal variation and existing soils within the catchment are also significantly affect the soil erosion within the watershed and need to be considered in the future study.

CHAPTER 4

GIS-SUPPORTED SPATIALLY DISTRIBUTED SEDIMENT YIELD MODEL

4.1 INTRODUCTION

The processes of sediment generation, transport, and deposition have been well described elsewhere (Rose, 1993; Haan et al., 1994; Govindaraju and Kavvas, 1991). On the basis of the experiment conducted on 10000 plots of USA, Wischmeier and Smith (1965) first proposed an equation popularly known as USLE to estimate the soil erosion. Subsequently, the equation was modified by the researcher as Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) or Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991), and frequently used for estimation of surface erosion (Williams and Berndt, 1972; Griffin et al., 1988; Ferro et al., 1998; Jain and Kothyari, 2000; Jain and Goel, 2002; Kothyari et al., 2002; Mishra et al., 2006). It is well known that all the soil eroded at a place does not reach at the outlet of the catchment. In reality, it depends on several parameters responsible for the soil detachment and the transport capacity of the path followed by the sediment to reach the outlet. However, the linking on-site soil erosion rate within a basin to the sediment yield at the basin outlet is often problematic because of the lack of detailed input data at a river catchment scale (100-100000 km^2) (Van Rompaey et al., 2001). To this end several researchers (Roehl, 1962; Vanoni, 1975; Walling, 1983; Ferro and Minacapilli, 1995; Klaghofer et al., 1992; Bazoffi et al., 1996) used a sediment delivery ratio (SDR) approach to link the soil erosion within a basin to the sediment yield at outlet. However, the SDR-based sediment yield estimation approach is empirical lumped approach (Walling, 1983; Atkinson, 1995; Bazoffi et al., 1996; Verstraeten and Poesen, 2001) and hence performs well on the data of catchment belonging to inherent region.

Nevertheless, the sediment control management policy should not only concentrate to those areas which directly contribute the sediment to river channels, however more emphasis should be on the areas which are major contributor of the sediment (Verstraeten et al., 2007). In this context, the lumped SDR based approach is not helpful in prioritization of watershed management/treatment activities within a river basin/catchment. Prosser and Rustomji (2000) found the problem in defining the spatial pattern of sediment in hilly catchments due to lack of hydrological model for hillslope.

Despite the development of a range of physically based soil erosion and sediment transport models, sediment yield predictions at a watershed or regional scale are at present achieved mainly through simple empirical models such as USLE and its derivatives. However, the popular soil erosion model USLE, MUSLE, RUSLE and its derivative are generally developed for plot size area and hence do not perform very well when applied to a large area or catchment. It has been observed that USLE over-predicts combined length-slope value (LS) at higher slope and longer slope-lengths. In reality, the term λ used in estimation of LS factor in USLE is only applicable to 2-D non-converging and non-diverging hill slope. Therefore, the equation can not be extended for real 3-D landscape. Furthermore, both of these quantities, viz., the surface erosion and sediment yield are found to have large spatial variability in a catchment due to the spatial variation of rainfall and catchment heterogeneity. The technique of Geographical Information System (GIS) is well suited for quantification of heterogeneity (not only in space but also in time) in the topographic, cover type, and drainage features of a watershed by partitioning the watershed into small homogenous grids (Jain and Kothyari, 2000; Gosain and Sandhya, 2004; Jain et al., 2004, 2005; Onyando et al., 2005; Wu et al., 2005; Eldho et al., 2006; Naik et al., 2009).

Keeping all the above discussion in view, a simple distributed sediment yield model has been proposed in the present study which is parsimonious in terms of data, time, and funds. The accuracy of the developed model has been verified by the historical sediment data of a hilly catchment belonging to Western Himalayan region of India, i.e. catchment. Furthermore, the spatial capability of the proposed distributed sediment model has been cross-checked with the observed sediment yield data at the outlet of the study catchment i.e. Jammu. Most of the model parameters are extracted from the geospatial data which is most update, easily available, and probably free of cost throughout the globe.

4.2 MODEL DEVELOPMENT

The proposed model comprises of three major components (1) the assessment of seasonal gross soil erosion for each grid cell; (2) the assessment of seasonal transport capacity for each grid cell; and (3) a transport limited accumulation algorithm for routing sediment from each of the discretized grid cell to the outlet of the catchment by taking into account the local transport capacity of each grid cell.

4.2.1 Estimation of Gross Soil Erosion

Universal Soil Loss Equation (USLE) has been found to produce realistic estimates of surface erosion over small size areas (Wischmeier and Smith, 1978; Ferro et al., 1998; Jain and Kothyari, 2000; Kothyari et al., 2002; Jain and Goel, 2002; Lee, 2004; Onyando et al., 2005; Pandey et al., 2007, Jain et al., 2009). Although USLE is a lumped empirical model, this equation has been a part of several spatially distributed process-based models. This is possible due to the discretization of heterogeneous catchment into small homogeneous unit/cell. In the present study, USLE is used to estimate gross soil erosion from each of the discretized cells. The USLE for estimation of gross soil erosion within a cell is expressed as:

$$GSE_i = RK_i LS_i C_i P_i \qquad (4.1)$$

where GSE_i = gross amount of soil erosion in cell *i* (MT ha^{-1} $year^{-1}$); R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$); K_i = soil erodibility factor in cell *i* (MT ha h ha^{-1} MJ^{-1} mm^{-1}); LS_i = slope steepness and length factor for cell *i* (dimensionless); C_i = cover management factor (dimensionless) and P_i = supporting practice factor for cell *i* (dimensionless).

4.2.2 Sediment Transport and Outflow

Use of Eq. (4.1) produces the estimate of gross soil erosion in each of the discretized cell of the catchment. Gross amount of soil erosion for each cell area during a season can be generated by multiplying the term KLSCP with the R-factor for the corresponding season. The eroded sediment from each cell follows a defined drainage path as shown in Fig. 8.1 for a particular cell to the catchment outlet. The rate of sediment transport from each of the discretized cell depends on the transport capacity of the flowing water (Meyer and Wischmier, 1969).

The sediment outflow from an area is equal to soil erosion in the cell plus contribution from upstream cells if transport capacity is greater than this sum. However, if transport capacity is less then the amount of sediment available, sediment load equal to transport capacity is discharged to the next downstream cell and amount of sediment excess of transport capacity gets deposited (Wischmeier and Smith, 1969).

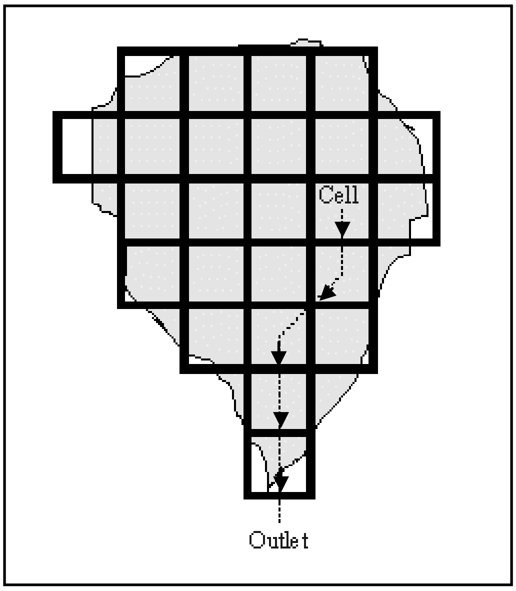


Fig. 4.1: Schematic diagram showing a drainage path.

(a) Mean annual sediment transport capacity

Desmet and Govers (1995) and Van Oost *et al*. (2000) considered the mean annual transport capacity to be directly proportional to the potential rill (and ephemeral gully) erosion:

$$TC = K_{TC} E_{PR} \qquad (4.2)$$

where TC is the transport capacity (kg m^{-2} $year^{-1}$); K_{TC} is the transport capacity coefficient; and E_{PR} is the potential for rill erosion (kg m^{-2} $year^{-1}$). Van Rompaey et al. (2001) estimated E_{PR} in terms of potential inter-rill erosion (E_{PIR}) and potential total erosion E_{PT} as follows:

$$E_{PR} = E_{PT} - E_{PIR} \qquad (4.3)$$

E_{PT} can be estimated from USLE by assuming the erosion from completely barren land without any conservation measures. However, E_{PIR} can be estimated by the equation proposed by McCool et al. (1989) as follows:

$$E_{PIR} = aRK_{IR}S_{IR} \qquad (4.4)$$

where 'a' is a coefficient, K_{IR} is the inter-rill soil erodibility factor (kg h MJ^{-1} mm^{-1}) and S_{IR} is the inter-rill slope gradient factor. Due to non-availability of data, Van Rompaey et al. (2001) assumed K_{IR}=K and arrived at the expression of transport capacity as follows:

$$TC = K_{TC} RK\left(LS - aS_{IR}\right) \tag{4.5}$$

From Eq. 8.5, it is clear that transport capacity does depend on the same topological variable as gross soil erosion depends (Eq. 8.1). Van Rompaey et al. (2005) found poor performance (R=0.25, for mountainous part) when the model was applied to the Italian catchments following the stratified calibration procedure whereby a distinction was made between mountainous and non-mountainous parts of the catchment. In reality, the topography of hilly areas is such that flow converges at some points, generally at the junction of the steep slope and valley floor (or toe of the slope). Theses points are generally the end point of the steep slope or where sudden flattened in the slope is observed. However, these points represent high flow accumulation values. Theoretically, the smaller transport capacity of such points due to low slope gradient (according to Eq. 4.5) is not capable to transport the huge amount of sediment that comes from the steep slopes or upland areas resulting in large amount of sediment deposition in theses areas and hence model underestimate the sediment yield at the outlet of the watershed. To overcome this problem an upslope contributing area factor is incorporated which represents the actual flow accumulation of any cell and the equation for transport capacity for i^{th} cell can be written as:

$$TC_i = K_{TC} RK_i S_i^{\beta} A_{si}^{\gamma} \tag{4.6}$$

where A_{si} is the upslope contributing area for cell *i*. The major advantage of this equation is to solve the problem of deposition of huge amount of sediment at the flow convergent point (normally at the toe of the slope) which frequently occurred in the hilly catchment. Using Eq. (4.6), transport capacity of such points will be sufficiently high, even having low slope gradient to carry the sediment coming from the steep slopes. However, similar equation has been used by Verstraeten (2007) for the computation of sediment transport capacity for an Australian catchment named Murrumbidgee basin. The value of exponent of upslope area (γ) and slope gradient (β) is taken as 1.4 for both exponent (Prosser and Rustomji, 2000).

(b) Transport limited accumulation

Eroded sediment from each cell follows a definite path defined by direction of flowing water. The amount of sediment outflow from one cell to its downstream cell depends on local sediment transport capacity for a cell. If the local TC is smaller than the sediment flux, then sediment deposition is modeled. This approach assumes that sediment transport is not necessarily restricted to a transport limited system. If the TC is higher than the sediment flux, then sediment transport will be supply limited. Thus, by introducing the K_{TC}, transport capacity coefficient, a more realistic representation of overland flow sediment transport can be simulated. The model produces different maps of erosion, sediment transport, and sediment deposition rates. For cell-based discretization system transport limited accumulation can be computed as:

$$T_{out_i} = \min(GSE_i + \sum T_{in_i}, TC_i) \tag{4.7}$$

$$D_i = GSE_i + \sum T_{in_i} - T_{out_i} \tag{4.8}$$

where GSE_i = annual gross soil erosion of cell *i*, TC_i = transport capacity, $T_{in\,i}$ = sediment inflow from upstream cells, $T_{out\,i}$= sediment outflow from the cell *i*. D*i* = deposition in cell *i*. The flow chart of the proposed model is shown schematically in Fig. 4.2.

4.3 FORMATION OF INPUT DATABASE

As discussed in Chapter 3, sixteen years seasonal (June-September) rainfall-sediment yield data belonging to a western Himalayan catchment i.e. catchment were used for modelling of sediment. However, the other input parameters were extracted from different maps prepared in GIS environment. It is worth emphasizing here that the result of a spatially distributed model greatly depends on the spatial and temporal quality of the input dataset. Therefore, proper care should be taken in preparation of error free digital elevation model (DEM), appropriate classification of land use and soil map, realistic schematization of drainage network of the watershed, and finally, more important is to provide adequate value of different input parameters for each cell. In the following text, the input data required for the above developed model are being described in detail.

4.3.1 Extraction of Drainage Network and Watershed from DEM

In this study SRTM derived DEM (Fig. 4.3) is used to generate different maps such as slope, gradient, length-slope factor, drainage network, and finally delineation of watershed boundary. Drainage and catchments are extracted from SRTM DEM using ARC HYDRO module (ARC/INFO Window; version 9 2005).

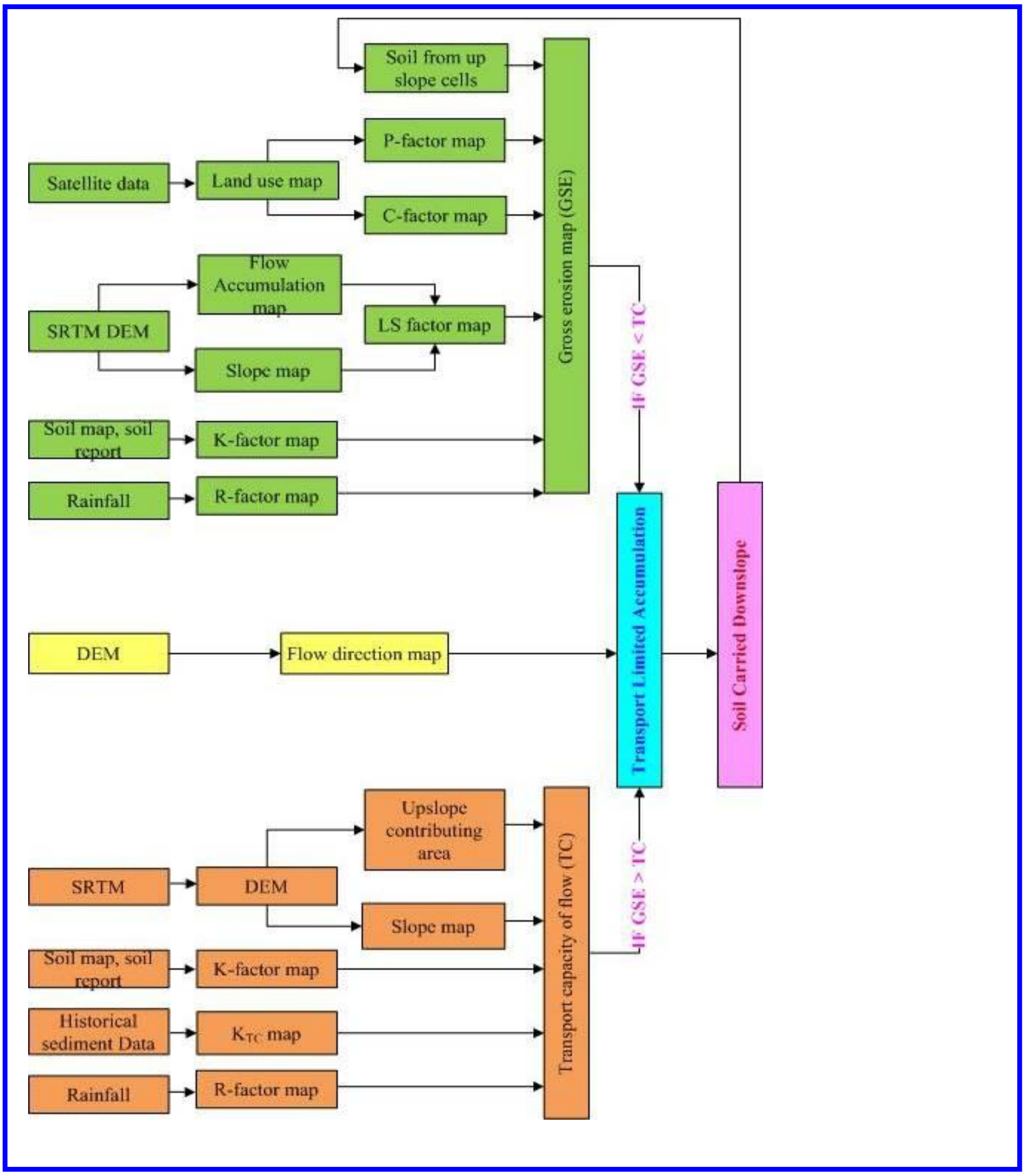


Fig. 4.2: Flow chart of the proposed sediment yield model.

In this sequence, the first step is to FILL SINKS of raster DEM which are the pixel of no data value or local depression. The physical significance of this step is to avoid the discontinuation of drainage line or local drainage. Using FLOW DIRECTION tool, we determine in which neighboring pixel, the water from any central pixel will flow naturally. Then the FLOW ACCUMULATION in each pixel is determined, which represents a cumulative count of the number of pixels that are contributing at any pixel. The stream generation threshold or channel initiation threshold is a numerical value, pixels having flow accumulation value less than channel initiation threshold are termed as overland flow pixels and those having higher flow accumulation value than channel initiation threshold are termed as channel/stream pixels (ESRI, 1994).

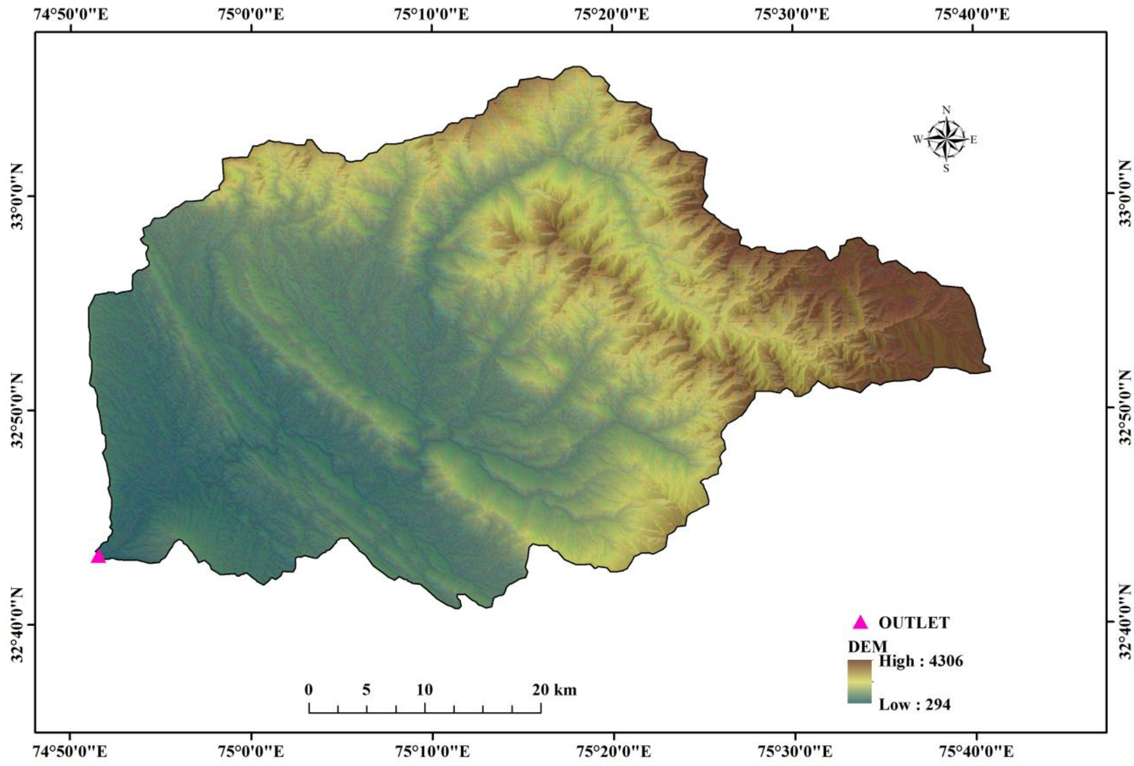


Fig. 4.3: Extracted DEM of the study area from SRTM data.

The threshold has to be chosen in such a way that the total stream length generated using threshold and channel network seen in satellite data and SOI Toposheet (digitized in vector form) should be equivalent (Jain and Kothyari, 2000). Accordingly, a channel initiation threshold value of 0.24 km^2 is adjudged appropriate to define channel cells. The extracted drainage of the catchment from SRTM data is depicted in Fig. 4.4. Finally, the watershed boundary is extracted by supplying the location of outlet of the watershed in the WATERSHED option of the ARCHYDRO module.

4.3.2 Rainfall Erosivity (R)

The R-factor expresses the erosivity of rainfall at a particular location. An increase in the intensity and amount of rainfall results in an increase in the value of R. Realistic estimation of monthly or annual rainfall erosivity values requires long-term pluviographic data at 15 minutes intervals or less (Wischmeier and Smith, 1978). In many parts of the world, especially in developing countries, spatial coverage of pluviographic

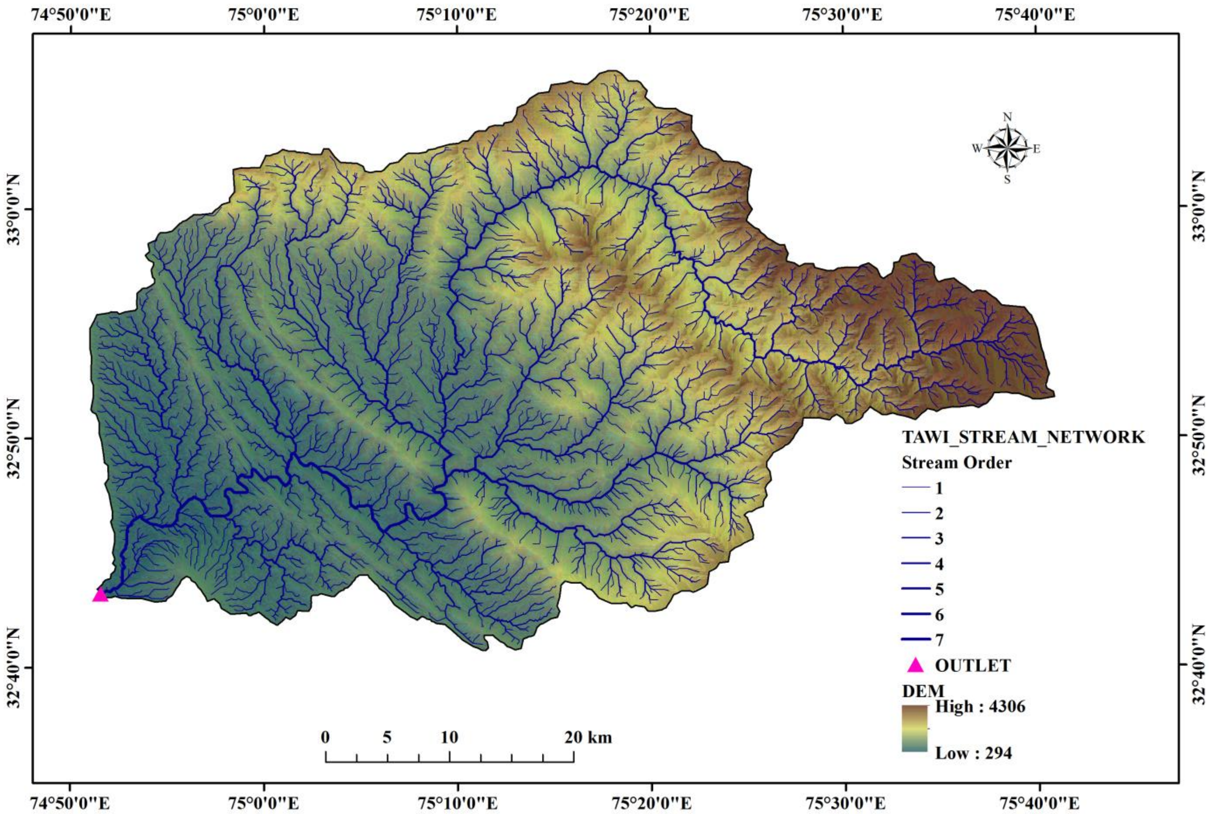


Fig 4.4: Extracted drainage network of the Tawi watershed from SRTM data.

data are often difficult to obtain (Yu et al., 2001; Cohen et al., 2005; Shamshad et al., 2008). Wischmeier (1959) found that the product of kinetic energy of the storm and the 30 minutes intensity (EI_{30}) is the most reliable single estimate of rainfall erosion potential. Rainfall erosivity estimation using rainfall data with long time intervals have been attempted by several researchers for different regions (for example, Morgan, 1995; Millward and Mersey, 1999; Mati et al., 2000; Grimm et al., 2003; Natalia, 2005; Shamshad et al., 2008). Using the data for storms from several raingauge stations located in different zones, linear relationships were derived between average annual/seasonal rainfall and computed EI_{30} values for different zones of India, and iso-erodent maps were drawn for annual/seasonal EI_{30} values (Babu et al., 2004). In this study, rainfall erosivity was calculated by the relationship developed by Babu et al. (2004) for this particular zone and presented as:

$$R = 71.9 + 0.361\,P \quad (r = 0.91, \text{ for } 293 \leq P \leq 3190) \tag{4.9}$$

where P is the average seasonal rainfall in mm. In the present study, Eq. 4.9 is used to compute seasonal values of R-factor by replacing P with observed seasonal rainfall of a particular year.

4.3.3 Soil Erodibility (K)

The soil erodibility factor K expresses inherent erodibility of the soil or surface material. The value of "K" depends on the particle-size distribution, organic-matter content, structure, and permeability of the soil or surface material. To this end, soil map of the watershed was digitized from soil survey report prepared by National Bureau of Soil & Landuse Planning (NBSS&LUP, 2004) using ArcGIS®. The digitized polygon map of Tawi watershed is then rasterized at 90 m grid cells by using GIS Arc Vector to Raster tool and the same is depicted in Fig. 4.5.

Details such as fraction of sand, silt, clay and organic matter and other related parameters information for different mapping units are taken from NBSS&LUP (2004) for catchment. K-values for mapped soil categories are then calculated for each of the mapping units using Haan et al. (1994) procedure, and the results are given in Table 4.1.

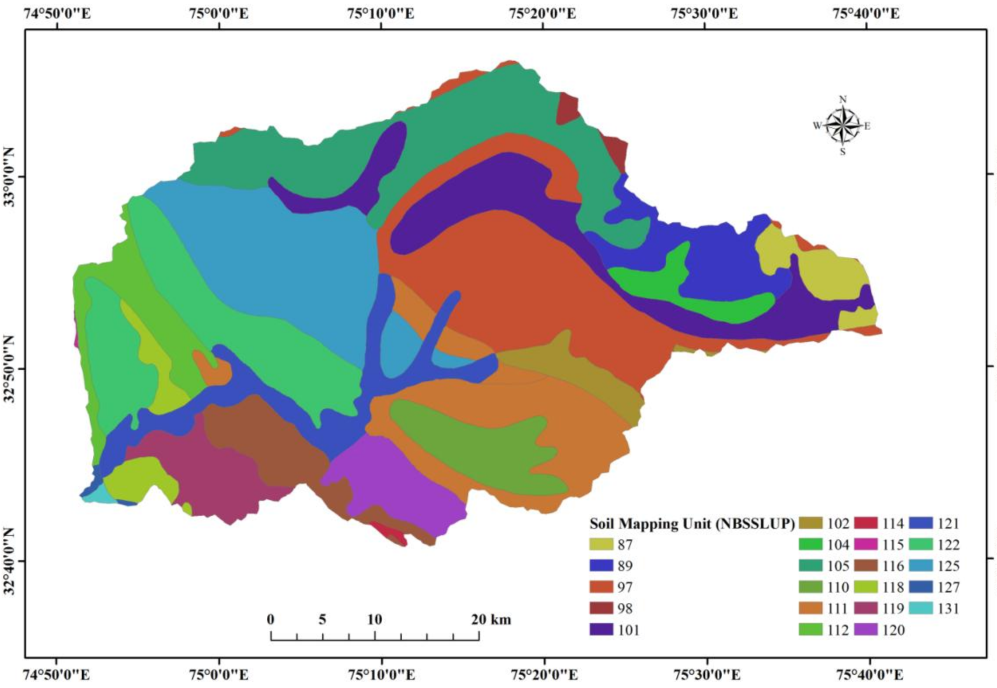


Fig. 4.5: Soil map of catchment.

Table 4.1: Soil characteristics of catchment.

Soil Map Unit	Depth	Erosion	Texture	Surface	Drainage	Soil Taxonomy
112	Medium deep	severe erosion	coarse-loamy soils	loamy surface	excessively drained	Dystric Eutrochrepts
101	Medium deep	severe erosion	coarse-loamy soils	loamy surface	somewhat excessively drained	Dystric Euthrochrepts
131	Deep,,with and	slight erosion	fine-loamy soils	loamy surface	well drained	Fluventic Ustochrepts
127	Medium deep	moderate erosion	sandy soils	sandy surface	somewhat excessively drained	Udic Ustochrepts
116	Shallow	severe erosion	fine-loamy soils	loamy surface	well drianed	Typic Udorthents

115	Shallow to medium deep	severe erosion	loamy-skeletal soils	loamy surface	excessively drained	Typic Udorthents
111	Deep	slight erosion	fine-loamy soils	loamy surface	excessively drained	Typic Udorthents
118	Medium deep	moderate erosion	fine-loamy soils	loamy surface	well drained	Dystric Euthrochrepts
122	Medium deep	moderate erosion	fine-loamy soils	loamy surface	well drained	Typic Udorthents
119	Shallow	severe erosion	fine-loamy soils	loamy surface	well drained	Dystric Euthrochrepts
120	Shallow	moderate erosion	loamy-skeletal soils	loamy surface	well drained	Dystric Eutrochrepts
114	shallow	severe erosion and slight stoniness	coarse loamy soils	loamy surface	somewhat excessively drained	Dystric Eutrochrepts
125	Deep	moderate erosion	coarse-loamy soils	loamy surface surface	well drained	Typic Udorthents
121	Deep	slight erosion	fine-silty soils	loamy surface	well drained	Dystric Euthrochrepts
110	Deep	slight erosion	fine-loamy soils	loamy surface	well drained	Typic Udorthents
98	Medium deep	moderate erosion	fine - loamy soils	loamy surface	excessively drained	Typic Eutrochrepts
105	Deep	moderate erosion	fine-loamy, calcareous	loamy surface	well drained	Typic Euthrochrepts

			soils			
97	Shallow	severe erosion	fine-loamy soils	loamy surface	somewhat excessively drained	Lithic Hapludolls

4.3.4 Length-Slope Factor (LS)

The LS factor expresses the effect of topography, specifically hillslope length and steepness, on soil erosion. An increase in hillslope length and steepness results

in an increase in the LS factor. It is well known that the combined length-slope (LS) factor in the Universal Soil Loss Equation (USLE) is a measure of the sediment transport capacity of overland flow and can also be derived from the DEM of the study area. There are many relationships available for estimation of the LS factor (Wischmeier and Smith, 1978; Moore and Burch, 1986a, b; McCool et al., 1989; Moore and Wilson, 1992; Desmet and Govers, 1996). Among these, the one that is best suited for integration with the GIS is the theoretical relationship proposed by Moore and Burch (1986a, b) and Moore and Wilson (1992) based on unit stream power theory, given as:

$$LS_i = \left[\frac{A_{si}}{22.13}\right]^n \left[\frac{\sin\theta_i}{0.0896}\right]^m \tag{4.10}$$

where A_{si} is the specific area at cell i defined as the upslope contributing area for overland grid (A_{up}) per unit width normal to flow direction; θ_i is the slope gradient in degrees for cell i. It has been shown that the values of $n = 0.6$, $m = 1.3$ give results consistent with the RUSLE LS factor for slope lengths <100 m and slope angles <14 degrees (Moore and Wilson, 1992). Exponent n and m can also be obtained through calibration if data are available for a specific prevailing type of flow and soil conditions.

In original equation of LS factor, the slope length (λ) is defined as the distance from the point of the origin of overland flow to the point where either the slope gradient decreases enough that deposition begins or runoff water enters a well-defined channel (Wischmeier and Smith, 1978). In the present study the slope length (L) is replaced by the unit upslope contributed area at which formation of channel is started and taken as channel/stream threshold (Jain and Kothyari, 2000). The main aim of the replacement of slope length by upslope contributing area is to incorporate the effect of converging and diverging terrain on soil erosion and hydrological aspect of the watershed. Consequently, a new theme has been prepared which represent the grids as a channel whose flow accumulation is greater than threshold value for channel initiation. However, the grids having the flow accumulation values less than or equal to channel initiation still remain in overland region. The LS factor for a cell area is computed with Eq. 4.10 in ArcGIS® using upslope contributing area and slope gradient computed from DEM of the study watershed. Fig. 4.6 represents the LS map for the entire watershed.

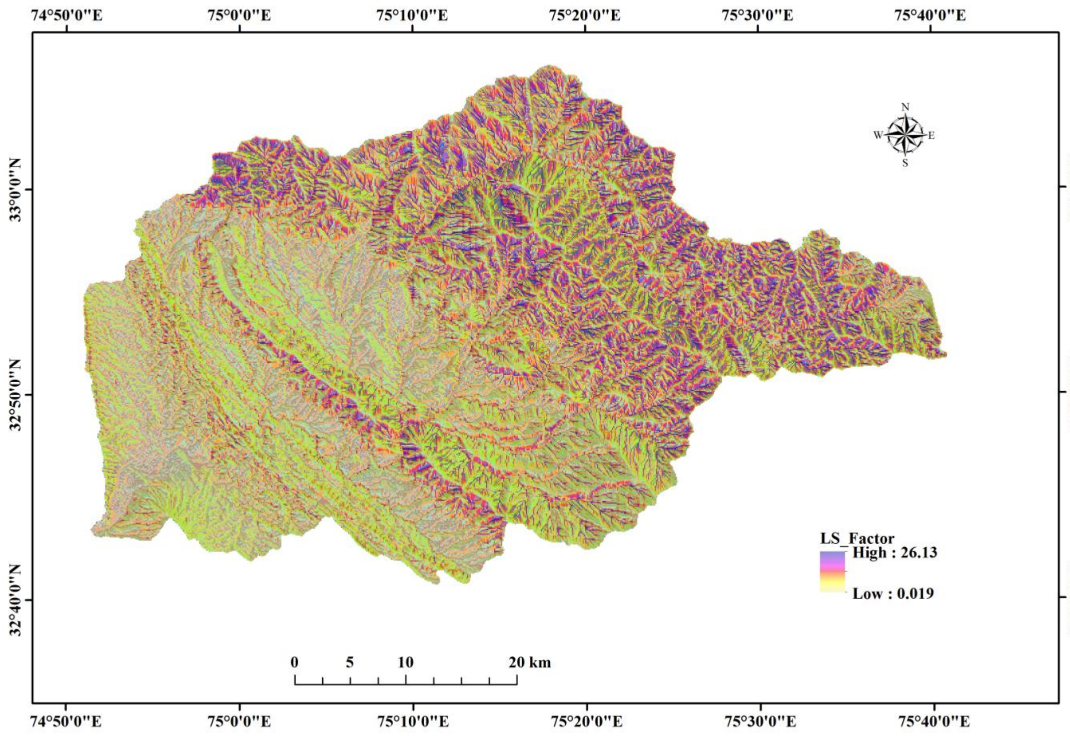


Fig. 4.6: Length-Slope factor map of catchment.

4.3.5 Crop Management Factor (C)

The crop management factor is used to express the effect of plants and soil cover. Plants can reduce the rainfall erosivity and runoff velocity and protect surface pores. The C-factor measures the combined effect of all interrelated cover and management variables, and it is the factor that is most readily changed by human activities. Vegetation cover and cropping systems have a large influence on runoff and erosion rates. Soil erosion can be controlled with proper management of vegetation, plant residue and tillage. The crop management factor can be determined with the use of land cover data. A lower C value represents a cover type that is more effective at defending against soil erosion. C factor map of the study area is prepared using land use map. Hence land use/land cover map is prepared first using the LANDSAT TM satellite data corresponding to November 1st, 1992 (path 140 to 141 and Row 43 to 44) downloaded from GLCF site. The geometrically corrected image is analyzed using image processing software ERDAS Imagine™ (ERDAS 2005). To discriminate the vegetation from other surface cover types, the Tassel Cap transformations (TCT), Vegetation Index (VI), Water Index (WI) are performed in ERDAS. Then a stratified supervised classification using Maximum Likelihood Method is carried out to generate the land use/land cover map for the watershed. The classified image is further verified for locations and extensions of various lands cover classes using limited ground truth information, Google Earth image and Survey of India topographic maps. Finally, a land use map of desired classes, viz., forest, agriculture, wasteland, grassland and water is generated. However, one more class i.e. builtup is incorporated in the map by digitizing the urban area with the help of Toposheet and Google Earth images. Generated land use/land cover map of the watershed is depicted in Fig 4.7

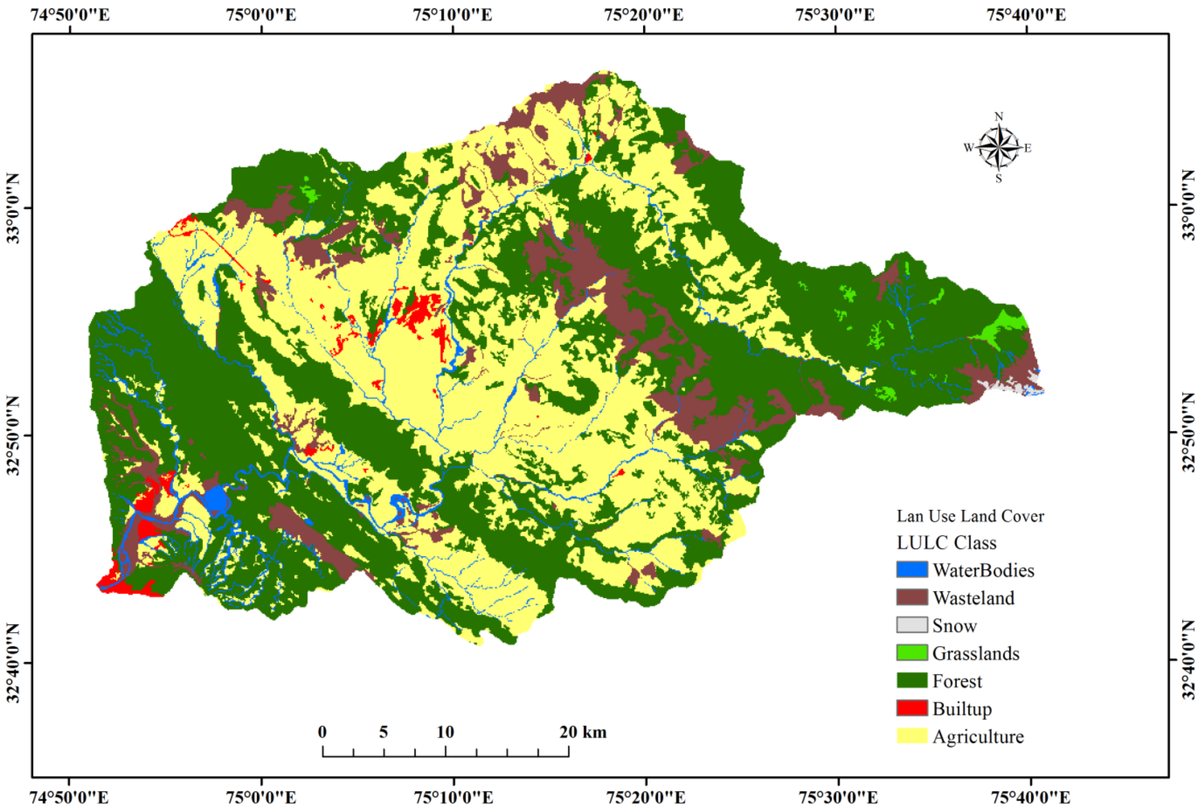


Fig. 4.7: Land use/land cover map for catchment.

Based on the land cover categories, the attribute values for the C-factor are assigned to individual cells from the tabulated values suggested by Wischmeier and Smith (1978), Singh et al. (1981, 1992), Haan et al. (1994).

4.3.6 Management Practice Factor (P)

The P-factor is the support practice factor. It expresses the effects of supporting conservation practices, such as contouring, buffer strips of close-growing vegetation, and terracing on soil loss at a particular site. A good conservation practice may result in reduced runoff volume, velocity, and less soil erosion. The management practice factor, P by definition is the ratio of soil loss from any conservation support practice to that with up and down slope tillage. It is used to evaluate the effects of contour tillage, strip cropping, terracing, subsurface drainage, and dry land farm surface roughening. A bare fallow land surface causes maximum soil erosion especially when it is cultivated up and down the slope or in other words, cultivated across the contours of the land surface. When a sloping land is put under cultivation, it needs to be protected by practices that will attenuate the runoff velocity, so that much less amount of soil is carried away by the runoff water. P is always $\leq$ 1.0. Based on experimental investigations, values for P-factor have been tabulated for many management conditions (Haan et al., 1994). The P-factor was taken equal to 0.9 for agricultural lands as mostly contour cultivation and 0.6 for cultivated land without contour are followed on agricultural lands, and unity for other land use/land cover types. P-factor values are added in the attribute field of land use Map, and depicted in Fig. 4.8.

4.3.7 Generation of Erosion Potential Maps

The land use, soil, slope steepness and management practices are the main factors governing soil erosion potential at particular location to the erosive power of rainfall. Assessment of gross soil erosion (GSE) of Tawi watershed has been done using ArcGIS Raster Calculator. The layers of topographic factor (LS), crop management factor C, soil erodibility factor K, and support practice factor P were overlaid. Then evaluated values of

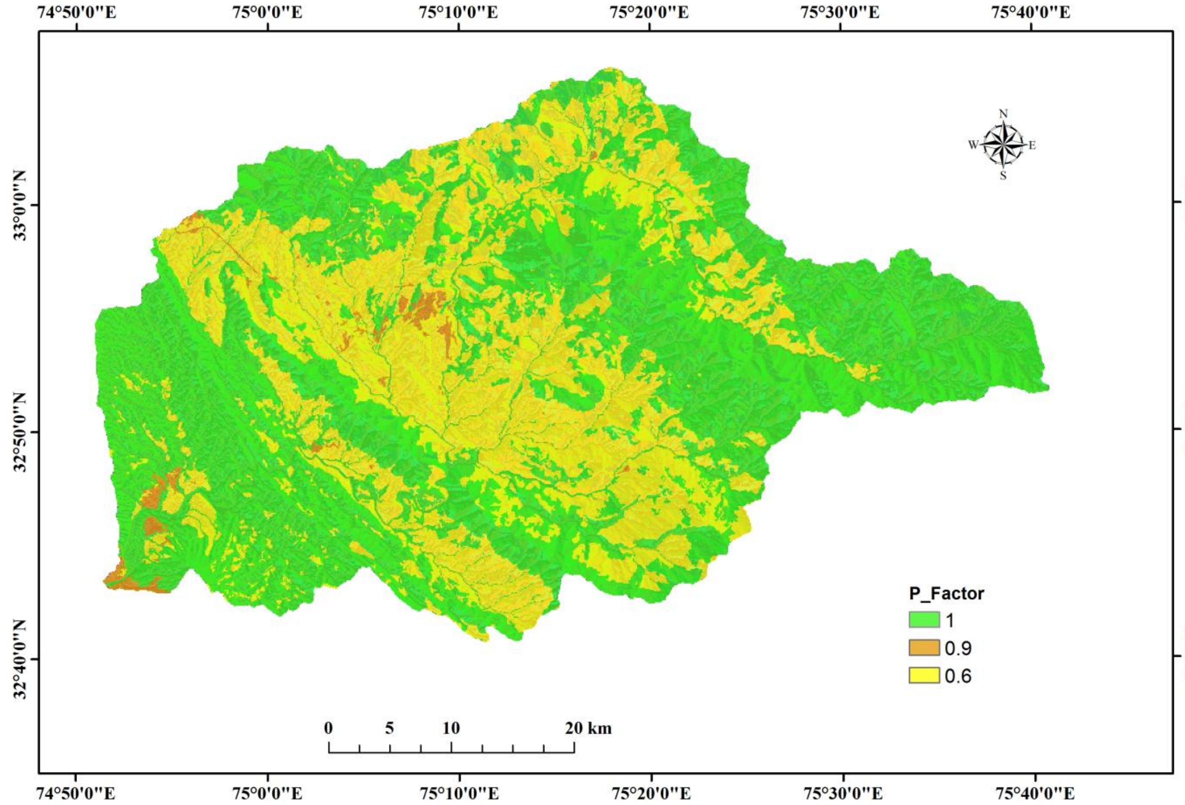


Fig.4.8: Management practice (P) factor map of catchment.

LS, K, C and P maps are multiplied by values of R, rainfall erosivity factor for respective year, to estimate the gross soil erosion in tons per annum/season for the catchment. Multiplication of R-factor into KLSCP factor map resulted in maps of gross erosion for different years (season). Fig. 4.9 presents gross soil erosion for the year of 1977.

4.4 MODEL APPLICATION AND DISCUSSION

4.4.1 Sediment Routing

Gross soil erosion and transport capacity of each pixel/Grid is estimated using raster calculator tool of ArcGIS, but as on today there is no ready to use tool available in GIS, which estimates the sediment transport from one pixel to next (sediment routing). The basic principle of overland flow routing is applied to generate a tool for sediment routing. The programme for this is developed in Interactive Data Language (IDL), a general purpose scientific computing package, sold by ITT Visual Information Systems,

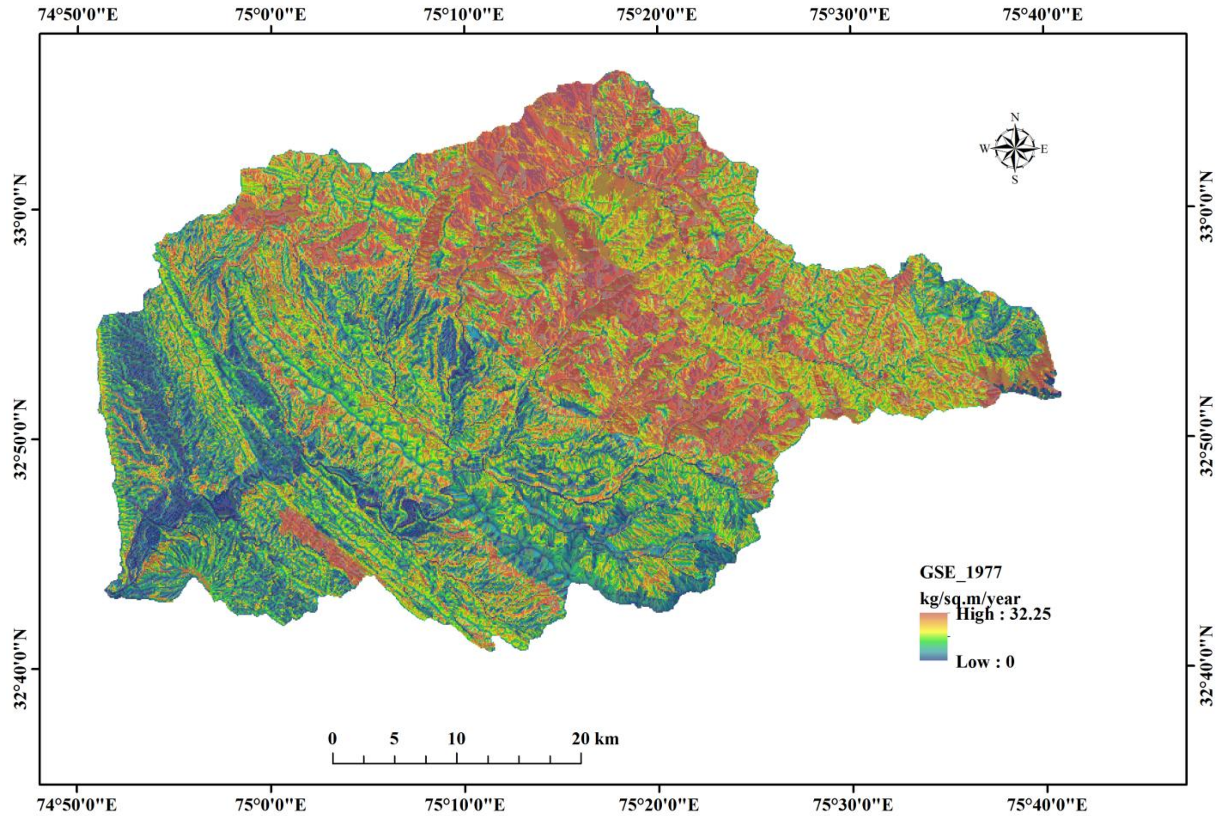


Fig. 4.9: Gross soil erosion map of Tawi watershed for year 1977.

which provides a suite of mathematical functions, data analysis tools, as well as some scientific visualization and animation tools. The developed tools/programme estimate the sediment transport for each pixel using flow direction, flow accumulation, gross soil erosion, and transport capacity maps. The generation of all these maps is discussed in previous section, but care was taken to have same spatial reference, extent, and pixel size in all the maps. The programme starts the estimation of sediment transport from ridge pixels (i.e. Flow Accumulation = 0). The tool compares the gross soil erosion (total soil ready to move out of a particular pixel) and transport capacity of the flow in that pixel, if transport capacity is equal or greater than gross soil erosion then entire eroded soil will be transported into the next pixel. The destination of this transported soil/sediment is determined using flow direction map. In overland flow pixels the total soil ready to move out of particular pixel is summation of gross soil erosion of that pixel and sediment inflow from upstream area. If the transport capacity of any pixel is less than total soil ready to move out of particular pixel, the tool will assign the difference between transport capacity and the total soil ready to move out, as amount of sediment deposited in that pixel. Batch processing option is given in programme to process temporal data and to save time in repeated operations/process. The tool provides the output maps of total sediment yield at any pixel in tons, deposition per pixel in tons, and net erosion from each pixel in raster format (Geo TIFF). The spatial reference, extent and pixel size of the output map is kept as same as input maps.

4.4.2 Generation of Transport Capacity Maps

Transport capacity of overland flow is calculated for each season and each pixel from the relationship stated in Eq. (4.6) by multiplying the R factor of each year in ArcGIS. The parameter K_{TC} appearing in Eq. (4.6) is taken as unity at the beginning and then its value is calibrated by minimizing error between observed and computed values of five years sediment data (1979-83) by varying K_{TC} values. To find the optimum value of K_{TC} for Tawi watershed two statistical criteria, viz., Model Efficiency (ME), (Nash and Sutcliffe 1970) and Relative Root Mean Square Error (RRMSE) are used in calibration. Model efficiency (ME) can be calculated as follows:

$$ME = 1 - \frac{\sum \left(Y_{obs} - Y_{pred}\right)^2}{\sum \left(Y_{obs} - Y_{mean}\right)^2} \tag{4.11}$$

where Y_{obs} observed seasonal sediment (tons), Y_{pred} is predicted seasonal sediment (tons), Y_{mean} is mean of the observed sediment (tons). Value of ME ranges from -∞ to 1, the value close to 1 indicated that model performed very well. However the negative value of ME implies the inefficiency of the model in prediction. Relative Root Mean Square Error is estimated by the following formula:

$$RRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_{obs} - Y_{pred})^2}}{\frac{1}{n}\sum_{i=1}^{n} Y_{obs}} \tag{4.12}$$

where Y_{obs} and Y_{pred} are the same as above and *n* is the number of data points. It is evident from Fig 4.10 that at K_{TC} value of 0.06, ME is the highest (0.97) and RRMSE is at the lowest (0.10). Changing the K_{TC} value from 0.06, RRMSE and ME increased and decreased, respectively. Transport capacity maps are generated using calibrated K_{TC} value for all years (1977-94). Transport capacity map for year 1977 is presented in Fig. 4.11 as illustration. It is evident from this figure that the ridges and the flattened area near the channel, generally

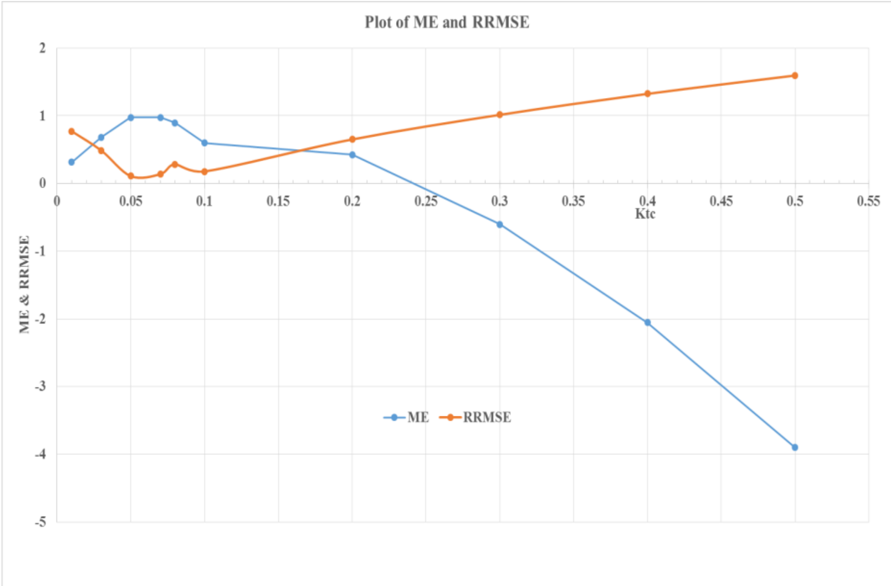


Fig. 4.10: Calibration of K_{TC} for Tawi watershed using five years (1979-83) seasonal rainfall-sediment yield data.

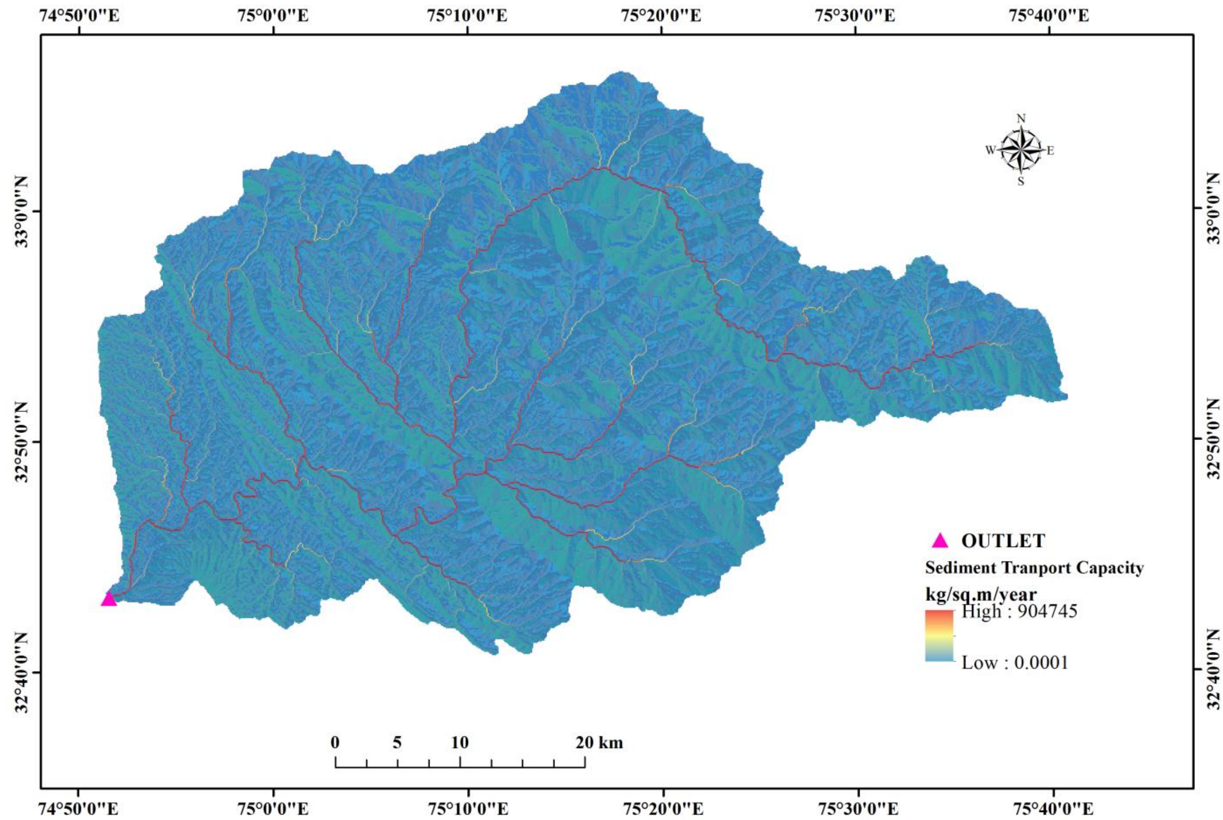


Fig. 4.11: Transport capacity map of Tawi watershed for year 1977.

cultivated are the areas possessing low transport capacity. However, transport capacity is high in channel areas and the steep head water areas especially where the slope plane curvature is convex in nature.

4.4.3 Computation of Transport Limited Sediment Accumulation and Outflow

As reported earlier, all erosion produced in a grid cell does not find opportunity to get transported to the outlet. Therefore, to convert gross erosion into spatially distributed sediment yield, transport limited accumulation concept is applied. Using Eq. (4.7), the gross erosion from each cell is routed following drainage path to generate map of accumulated sediment yield and deposition by considering the transport capacity of each cell. This process is repeated for all sixteen years (1977-94) of data used in the analysis. Such maps provide the amount of sediment transported from the system at every cell and are useful for determination of sediment flowing out of the watershed at any location. Figure 4.12 depicts the sediment yield map for the year 1977 as illustration.

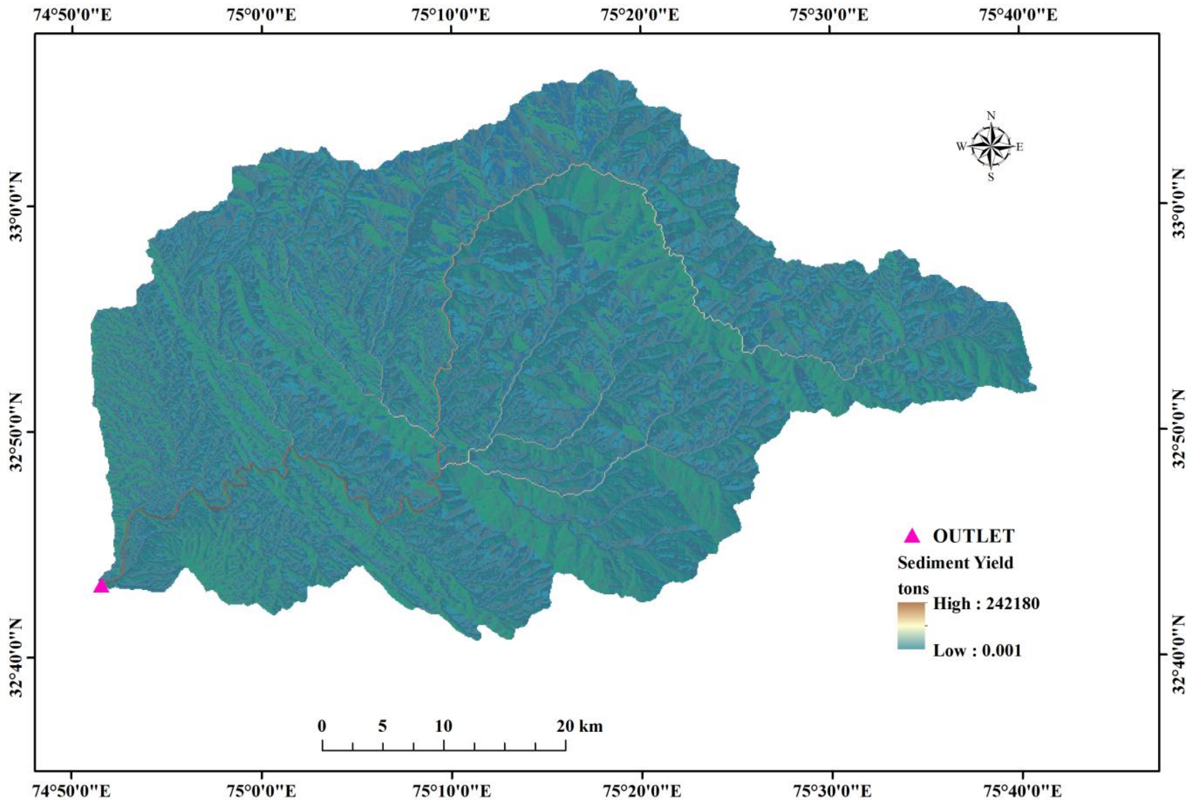


Fig. 4.12: Sediment outflow map of catchment for year 1977.

The pixel value of the sediment outflow map denotes the amount of sediment leaving the current cell to the next downstream cell. Comparison of predicted sediment yield with the observed sediment yield for all years from 1979 to 1994 is shown in Table 4.3. As discussed earlier, the years 1977 to 1981 were used for calibration, and the rest twelve years data (1982-94) for validation. It is evident from Table 4.3 that the average errors in validation period are 44% which is acceptable in sediment yield modelling. In reality, the large errors may be attributed to probable uncertainties in observations and/or model formulation. It can be seen from Table 4.3 that the large errors are mostly negative (over-prediction of model), which is probably attributed to large temporal variability in sediment yield that influenced the observation of sediment data at outlet greatly. Nevertheless, the spatial and temporal variability in rainfall, dynamic nature of vegetation which influence greatly transport capacity and crop management factor for overland regions may be other reason of large error and can be studied in future.

Table 4.3: Year wise comparison between observed and predicted sediment yield at different gauging sites.

Year	Rainfall (mm)	Observed Sediment Yield (tons)	Predicted Sediment Yield (tons)	%Error
1977	1207	241418.1	242180.3	0.315711
1978	810.1	140343.7	173822.8	23.85504
1979	714	164330.7	157272	-4.29538
1980	469.2	127603.7	115110.7	-9.79042
1981	769.6	155362.6	166847.9	7.392532
1982	504.5	54515.5	121190.6	122.3048
1983	569	93696.74	132298.9	41.19907
1985	1098.4	258383.9	223475.8	-13.5102
1987	638.5	139340.5	144269.1	3.537081
1988	883.2	2004628	186412.6	-90.7009
1989	382	490906.6	100092.5	-79.6107

1990	981.9	927405.1	203412.1	-78.0665
1991	574.7	129675.7	133280.6	2.779969
1992	815.1	522292.6	174684.6	-66.5543
1993	746.7	745466.1	162904	-78.1474
1994	1320	1658002	261642.2	-84.2194
Average Error (%)				**44.14%**

Moreover, considering all data points, the accuracy obtained is considered good because even the more elaborate process-based soil erosion models are found to produce results with still larger errors (ASCE, 1975; Foster, 1982; Hadley et al., 1985; Wu et al., 1993; Wicks and Bathurst, 1996).

4.4.5 Generation of Net Erosion/Deposition Maps

Using Eq. (4.8), maps for deposition of sediment can be obtained. When sediment deposition map superimposed over gross erosion map, a net soil erosion/deposition map is produced. Such maps are helpful in identifying areas vulnerable to silt deposition and sediment erosion in the watershed area. Fig. 4.13 depicts net soil erosion/sediment deposition map for year 1987 as illustration. As can be seen from Fig. 4.13 that deposition of sediment resulted at side of some of the stream reaches where transport capacity is low. It is possible to identify the critical areas delivering most of the sediment to the river system. Notably, these areas are not necessarily the same as those producing most erosion, as most of the eroded sediment is deposited within the catchment, before reaching the river system. The net erosion estimated on a cell basis for the watershed is grouped into the following scales of priority: Slight (0 to 5 t ha^{-1} $year^{-1}$), Moderate (5 to 10 t ha^{-1} $year^{-1}$), High (10 to 20 t ha^{-1} $year^{-1}$), Very High (20 to 40 t ha^{-1} $year^{-1}$), Severe (40 to 80 t ha^{-1} $year^{-1}$) and Very Severe (> 80 t ha^{-1} $year^{-1}$) erosion classes as per the guidelines suggested by Singh et al. (1992) for Indian conditions. Such a categorization of net soil erosion as illustrated in Fig. 4.13 and it can be of immense significance in deciding the priority levels for implementation of the suitable measures (biological or engineering) for watershed treatment.

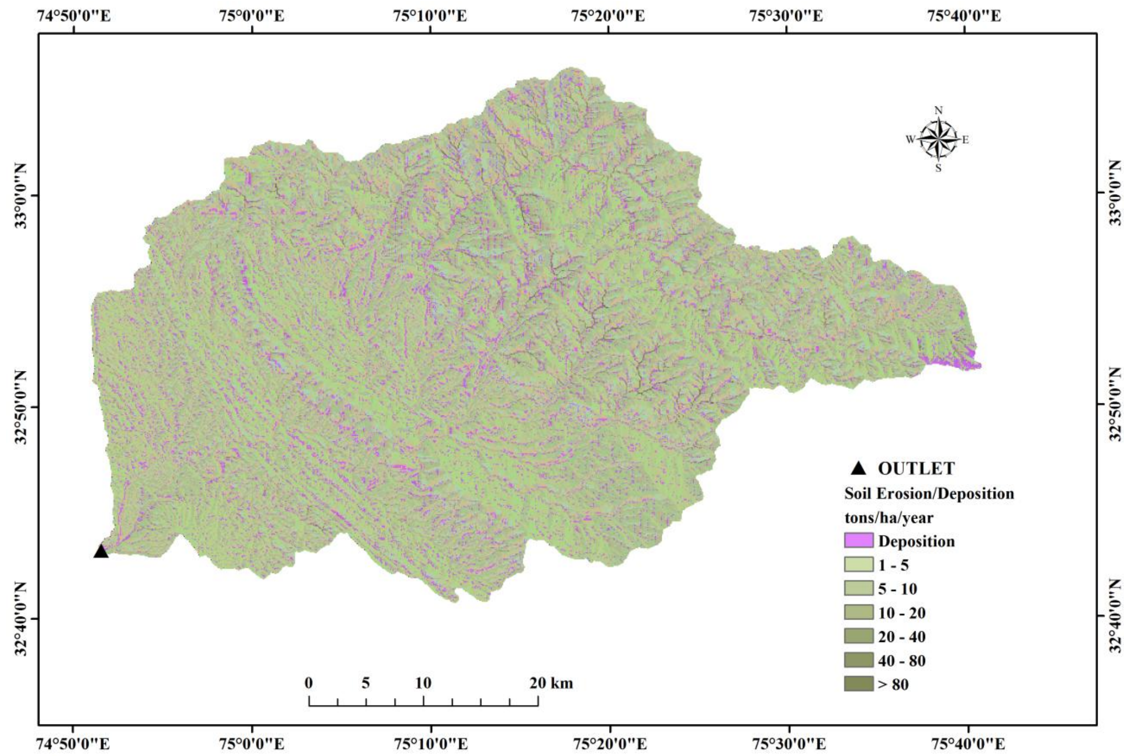


Fig. 4.13: Net erosion/deposition map for year 1987 of Tawi watershed.

4.5 SUMMARY

A simple model involving only elementary processes of soil erosion/sediment deposition is used to predict the sediment delivery by surface runoff from hill slopes to watershed outlet. Model application is in principle not restricted by the size of the watershed on condition that digital elevation data and land use data are available. Various thematic layers representing different factors of USLE are generated and overlaid to compute spatially distributed gross soil erosion maps for watershed using recorded rainfall for 16 years of the Himalayan watershed. A concept of transport limited accumulation is formulated and used in ArcGIS for generating maps for transport capacity. Gross soil erosion is routed to the catchment outlet using hydrological drainage paths resulting in generation of transport capacity limited sediment outflow maps. Transport capacity coefficient is calibrated using five year observed rainfall-sediment yield data, value of K_{TC} (0.05) is found. Very low calibrated value of parameter K_{TC} indicates good vegetation cover which reduces transport capacity. An average error (44%) in prediction of sediment yield are observed when model was applied for three-year data of validation period of the same watershed. Superimposition of sediment deposition map over gross erosion map resulted in identification of areas vulnerable to soil erosion and deposition. According to recommended range of net soil erosion for Indian conditions, the entire watershed is categorized. The values of net soil erosion/deposition (upto a small unit i.e. a pixel) are described through maps for their use in field for implementation of suitable protection measures.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Estimation of sediment yield is basic to design of a wide variety of hydraulic structures, environmental impact assessment, evaluation of the impact of climatic change, irrigation scheduling, flood forecasting, planning of tactical military operation, augmentation of runoff records, pollution abatement, and watershed management and so on. To this end, several sediment load estimation techniques were developed to mimic the process from plot to catchment scale, however research is still ongoing largely by linearizing different components of rainfall-runoff-sediment yield process.

In developing country like India, where rural population is often more than 65%, assessment of erosion focuses mainly towards on-site effects of erosion. On site erosion strongly affects crop yield, undermines the long term sustainability of farming system, and repeat a major threat to the livelihood of the farmers and rural communities. In the present era of industrialization, more attention is being paid to the society at large, viz., in flood prevention, water reservoir preservation, and water pollution control (Garen et al., 1999). Whether the main concern of soil and water conservation planning is towards prevention of onsite or off-site effects of erosion, there is a growing need for tools that enable to define the spatial distribution of erosion within a catchment i.e to identify sources of sediment erosion. Indeed the location of sediment sources and sinks is more important than the quantification of soil losses, as it is more cost effective than over-dimensioned erosion control measures. Therefore, modelling should be focused on spatial distribution of sediment within the watershed as well sediment yield at the outlet of the watershed.

The main objective of the present research work was to model the erosivity of an Himalayan catchment using the hydrological techniques which were simple in structure, easy to use, even by a field worker, and simultaneously parsimonious in data, time, and funds. A summary of the research work and the conclusions arrived at are presented below in sequence of development of models.

5.1 MORPHOMETRY BASED CONVENTIONAL TECHNIQUE

- The vulnerable areas for erosion have been identified in a Western Himalayan catchment using conventional as well spatially distributed modeling approach

- In developing countries like India where availability of observed data is a major constraint, to prepare a fruitful project plan, the morphological parameters based methodology has high practical utility.

- Morphological parameters based methodology is capable to assess the response of a catchment towards erosivity by partitioning the catchment into small sub-watershed. However, the technique does not suitable to identify the erosion prone area within small watershed. Estimation of sediment quantity is another limitation of morphological based conventional technique.

5.2 SPATIALLY DISTRIBUTED SEDIMENT YIELD MODEL

- Gross soil erosion and transport capacity for catchment were calculated by overlaying the different thematic layers prepared in GIS environment, and depicted in the forms of maps for easy use. Considering the transport capacity of each pixel, the concept of transport limited accumulation was formulated and used in ArcGIS for generating sediment outflow from each cell and finally up to the outlet.
- The proposed GIS-based spatially distributed model estimates the sediment yield with high accuracy, accompanying a low error in validation period. Since SRTM data, satellite images, and soil map (input of the proposed model) are easily available throughout the globe, the model can be easy to apply to hilly watersheds.
- Deposition of sediment resulted at the sides of some stream reaches in valley due to low transport capacity. Such sites are not suitable for the hydro-based multipurpose projects due to high degree of sedimentation, which may result in rapid reduction in reservoir capacity.

5.3 MAJOR RESEARCH CONTRIBUTIONS OF THE STUDY

- A simple spatially distributed sediment yield model based on the concept of erosion-deposition process is proposed. It is more rational, and pragmatic than the lumped Sediment Delivery Ratio (SDR) approach. The proposed cell-based Transport Limited

Accumulation (TLA) approach is used to route the sediment up to the outlet by considering the transport capacity of each pixel.

5.4 SCOPE FOR FUTURE RESEARCH

- The present study deals with the spatial distribution of soil erosion/sediment deposition with the assumption that land use/land cover and other parameters remain constant with time. However, several parameters change with time/season. Therefore, incorporation of variability of these parameters with time/season in GIS environment may form to be a scope for future study.

BIBLIOGRAPHY

1. Agarwal, C. S., Chakraborty, B. (1994). Morphometric Analysis in part of Mussoorie Syncline, Hydrology Journal, XVIII, (1&2), 54-57.

2. Aksoy, H., and Kavvas, M.L., (2005). A review of hillslope and watershed scale erosion and sediment transport models. Catena, 64, 247– 271.

3. Apaydin, H., Ozturk, F., Merdun, H. & Aziz, N.M., "Determination of the drainage basin characteristics using vector GIS"Nordic Hydrol. 37(2),129-142(2006).

4. areta K., Pareta U. (2012). Quantitative Geomorphological analysis of a watershed of ravi river basin, H.P. India. International journal of remote sensing and GIS, Vol. 1(1), 47-62

5. Arnold, J.G., Engel, B.A., and Srinivasan, R. (1993). Continuous-time, grid cell watershed model. In: Proceedings of the Conference, Spokane, WA, June 18–19, pp. 267–278.

6. Arnold, J.G., Engel, B.A., and Srinivasan, R. (1993). Continuous-time, grid cell watershed model. In: Proceedings of the Conference, Spokane, WA, June 18–19, pp. 267–278.

7. Beasley, D.B., Huggins L.F., and Monke, E.J. (1980). ANSWERS - a model for watershed planning. Transactions of American Society of agricultural Engineers, 23: 938–944.

8. Choudhary, R. S. and Sharma, P.D. (1998). Erosion hazard assessment and treatment prioritization of Giri river catchment; north-western Himalaya. Indian J. Soil Cons., 26(1), 6-11.

9. De Roo, A.P.J., and Jetten, V.G. (1999). Calibrating and validating the LISEM model for two data sets from the Netherlands and South Africa. Catena, **37**(3-4), 477–493.

10. De Roo, A.P.J., Wesseling, C.G., and Ritsema, C.J., 1996. LISEM: a single-event physically based hydrological and soil erosion model for drainage basins: I. Theory, input and output. Hydrological Processes, **10**, 1107– 1117.

11. Dillaha, T.A., Wolfe, M.L., Shirmohammadi, A., and Byne, F.W. (2001). ANSWERS-2000. In: Parsons, J.E., Thomas, D.L., Huffman, R.L. (Eds.), Non-Point Source Water Quality Models: Their Use and Application. Final Report of USDA-CSREES Southern Region Research Project S-273, Development and Application of Comprehensive Agricultural Ecosystems Models, 200 pp.

12. Elwell, and H.A. (1978). Modelling soil losses in southern Africa. Journal of Agricultural Engineering Research, **23**: 117–127.

13. Ferro, V., and Porto, P. (2000). A sediment delivery distributed (SEDD) model. J. Hydrol Engng ASCE, **5**(4), 411-422.

14. Foster, G.R., Lane, L.J., Nowlin, J.D., Laflen, J.M., and Young, R.A. (1981). Estimating erosion and sediment yield on field-sized areas. Transactions of the ASAE, pp. 1253– 1262.

15. Garen, G., Woodward, D., and Geter, F. (1999). A user agency's view of hydrologic, soil erosion and water quality modelling. Catena, **37**: 277-289.

16. Ghayoumian J, Ghermezcheshme B, Feiznia S, Noroozi AA (2005) Integrating GIS and DSS for identification of suitable areas for artificial recharge, case study, Meimeh Basin, Isfahan, Iran. Environ Geol 47(4):493–500

17. Ghayoumian, J., Ghermezcheshme, B., Feiznia, S. and Noroozi, A.A. (2005) Integrating GIS and DSS for Identification of Suitable Areas for Artificial Recharge, Case Study, Meimeh Basin, Isfahan, Iran. Environmental Geology, 47, 493-500.

18. Goel, A. K. (2003). Geo-morphological studies in Soan river catchment in north-west Himalayas of India. Indian J. Soil Cons., 31(2), 120-126.

19. Gupta, V.K., Waymire, E., and Wang, C. T. (1980). A representation of an instantaneous unit hydrograph from geomorphology. Water Resour. Res., **16**(5), 863–870,

20. Hodgkinson, J. H., McLoughlin, S. and Cox, M. (2006). The influence of geological fabric and scale on drainage pattern analysis in a catchment of metamorphic terrain, Laceys Creek, southeast Queensland, Australia. Geomorphology, 81(2&3), 394-407.

21. Horton R.E. (1945). Erosion development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin, 56(3): 275

22. Jaiswal, R. K. and Krishnamurthy, J. (2007). Role of landform and topography in the development of drainage network Hydrology Journal, 30(1-2), 1-13.

23. Jose C.S., Das D.C. (1982). Geomorphic prediction models for sediment production rate and inter soil erosion properties of watersheds in Mayurakshi catchment. Proc. Int. Symp. Hydrol. Univ. Roorkee, 1: 15-33.

24. Kalin, L., Govindaraju, R.S., and Hantush, M.M. (2004). Development and application of a methodology sediment source identification. 1: Modified unit sedimentograph approach. Journal of Hydrologic Engineering, ASCE **9**(3): 184–193.

25. Knisel, W.G., (1980). CREAMS: a field-scale model for chemical, runoff and erosion from agricultural management systems. Conservation Research Report No. 26, South East Area, US Department of Agriculture, Washington, DC.

26. Kumar, S., and Rastogi, R.A. (1987). Conceptual catchment model for estimation of suspended sediment flow. J. Hydrol., 95, 155–163.

27. Lokesh K. N. and Shenoy K. N. (1996). Geomorphological and Hydrogeochemical studies of Pangala river basin, (D.K). Karnataka. Hydrology Journal, XIX (1), 33-43.

28. Mesa, L. M. (2006). Morphometric analysis of a subtropical Andean basin (Tucuma´ n, Argentina). Environ.Geol., 50, 1235-1242.

29. Miller, V. C., A quantitative geomorphic study ofcdrainage basin characteristics in the clinch mountain area, Virgina and Tennessee, Proj. NR 389-402, Tech. report 3, Columbia University, Department of Geology, ONR, New York, (1953).

30. Morgan, R.P.C., Morgan, D.D.V., and Finney, H.J. (1984). A predictive model for the assessment of erosion risk. Journal of Agricultural Engineering Research, **30**, 245–253

31. Morgan, R.P.C., Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D., and Styczen, M.E. (1998). The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms **23**(6): 527–544.

32. Musgrave, G.W. (1947). The Quantitative Evaluation of Factors in Water Erosion- A First Approximation. Journal Soil Conservation, 321-327, UK.

33. Nag S. K. and Chakroborty S., Influence of rock types and structures in the development of drainage networks in hard rock area, J. Ind. Soc., Rem. Sens., 31(1), 25-35, (2003).

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

35. Nooka Ratnam, K. (2005). Check dam positioning by prioritization of micro-watershed using SYI model and morphometric analysis-Remote sensing and GIS perspective. J. of the Indian Soc. of Remote Sensing, 30(1), 39-61.

36. Norman, S.E. (1989). An evaluation of ANSWERS, a distributed parameter watershed model. Thesis submitted in partial satisfaction of the requirements for the degree of master of science in Water Science in the Graduate Division of the University of California, Davis, California.

37. Norman, S.E. (1989). An evaluation of ANSWERS, a distributed parameter watershed model. Thesis submitted in partial satisfaction of the requirements for the degree of master of science in Water Science in the Graduate Division of the University of California, Davis, California.

38. Ozdemir, H. and Bird, D. (2009) Evaluation of morphometric parameters of drainage networks derived from topographic maps and DEM in point of floods, Envi. Geo/. 56: 1405 - 1415.

39. Pandey, A., Chowdary V. M., and Mal, B.C. (2004). Morphological analysis and watershed management using GIS. Hydrology Journal, 27(3-4), 71-84.

40. Panuska, J.C., Moore, I.D., and Kramer, L.A. (1991). Terrain analysis: integration into the agricultural nonpoint source (AGNPS) pollution model. J Soil Water Cons 46(1):59–64

41. Patton, P. C. (1988) Drainage basin morphometry and floods, In: Baker, V. R., Kochel, R. C., Patton, P. C. (Eds), Flood geomorphology, Wiley, USA, pp 51-65

42. Raghuwanshi, N.S., Rastogi, R.A., and Kumar S. (1994). Instantaneous unit sediment graph. J. Hydraulic Engineering, 120(4), 495-503.

43. Reddy, G. P. O., Maji, A. K. and Gajbhiye, K. S. (2004). Drainage morphometry and its influence on landform characteristics in a basaltic terrain, Central India – a remote sensing and GIS approach. International Journal of Applied Earth Observation and Geoinformation, 6, 1-16.

44. Renard, K.G., Foster, G.R., Weesies, G.A., and Porter, J.P., (1991). RUSLE: revised universal soil loss equation. Journal of Soil and Water Conservation, 30–33 (January–February).

45. Rendon-Herrero, O. (1978). Unit sediment graph. Water Resourc. Res., 14(5), 889-901.

46. Rodriguez-Iturbe, I., and Valdés, J.B. (1979). The geomorphologic structure of the hydrologic response, Water Resour. Res., 15(6), 1409– 1420.

47. Rymbai P N and Jha, L K. (2012) estimation of sediment production rate of the Umbanium Micro-watershed, Meghalaya, Indai. Journal og geography and regional planning, Vol. 5(11), pp293-297.

48. Saraf, A.K. and Choudhury, P.R. (1998) Integrated Remote Sensing and GIS for Groundwater Exploration and Identification of Artificial Recharge Sites. International Journal of Remote Sensing, 19, 1825-1841.

49. Shrestha, D.P. (2007). Lecture notes on Soil degradation assessment and modelling. Department of Earth System Analysis, ITC, Enschede.

50. Singb, S. and Singh, M.C. (1997). Morphometric Analysis of Kanhar River Basin. National Geographical. J. of India, 43(1): 31-43.

51. Singh R. K, Bhatt, C. M., and Prasad, V. H. (2003). Morphological study of a watershed using remote sensing and GIS techniques. Hydrology Journal, 26(1-2), 55-66.

52. Smith, R.E. (1981). A kinematic model for surface mine sediment yield. Transactions of the ASAE, 1508– 1514.

53. Sorooshian, S., (1991). Parameter Estimation, Model Identification, and Model Validation: Conceptual-Type Models. In: Recent Advances in the Modelling of Hydrologic SystemsI, D.S. Bowles and P.E. O'Connell (eds.). Kluwer Academic Publishers, Netherlands, pp. 443–467

54. Sreedevi, P. D., Subrahmanyam, K. and Ahmed, S. (2005). The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain. Environmental Geology, 47, 412-420.

55. Stocking, M. (1981). A working model for the estimation of soil loss suitable for underdeveloped areas, University of East Anglia, Development Studies Occasional Paper, 15.

56. Stoddart, D.R. (1969). World erosion and sedimentation in water. In: Chorley, R.J., (Ed.), Water, Earth, and Man, Methuen, London, pp. 43–64.

57. Stoddart, D.R. (1969). World erosion and sedimentation in water. In: Chorley, R.J., (Ed.), Water, Earth, and Man, Methuen, London, pp. 43–64.

58. Strahler A.N. (1964). Quantitative geomorphology of drainage basins and channel networks. Section 4-11 in Handbook of Applied hydrology(Ed. By V. T. Chow), Mc Graw Hill , New York.

59. Strahler, A. N. (1957). Statistical analysis in geomorphic research. J Geol 62, 1–25.

60. Suresh, M., Sudhakar, S., Tiwari, K. N. and Chowdary, V. M. (2004). Prioritization of watershed using morphometric parameters and assessment of surface water potential using remote sensing. Indian Journal of Remote Sensing, 32, 259-260.

61. Verstappen, H. Th. (1983) Applied geomorphology. Geomorphological surveys for environmental development, Elsevier, Amsterdam, pp I -437.

62. Viney, N.R., and Sivapalan, M. (1999). A conceptual model of sediment transport: application to the Avon River Basin in Western Australia. Hydrological Processes, **13**: 727–743.

63. Wicks, J.M., and Bathurst, J.C. (1996). SHESED: a physically based, distributed erosion and sediment yield component for the SHE hydrological modelling system. J. Hydrology, 175: 213-238.

64. Williams, J.R. (1975). Sediment routing for agricultural watersheds. Wat. Resources, Bull. 11, 965-974.

65. Williams, J.R. (1978). A sediment graph model based on an instantaneous unit sediment graph, Water Resour. Res., 14(4), 659-664.

66. Wischmeier, W.H., and Smith, D.D. (1978). Predicting rainfall erosion losses. Agricultural Handbook no.537, US Dept of Agriculture, Science and Education Administration.

67. Young, R.A., Onstad, C.A., Bosch, D.D., and Anderson, W.P. (1989). AGNPS: a non-point source pollution model for evaluating agricultural watersheds. Journal of Soil and Water Conservation, 168–173 (March–April).

68. Zhang H Y, Shi Z H, fang N F, and Guo M H (2015) linking watershed geomorphic characteristics to sediment yield. Geomorphology, 234, 19-27.

Publication from the Project

1. **Rawat SS**, Kumar P and Jose PG. 2016. Assessment of Areas Vulnerable to Soil Erosion and Deposition in a Himalayan Watershed. *Indian* Journal of Ecology, 43 (Special Issue-1), pp: 15-20. **NAAS Rating: 4.93**

2. **Rawat, SS**, M.K. Jain, K.S. Rawat, B. Nikam and S.K. Mishra (2017).Vulnerability Assessment of Soil Erosion/Deposition in a Himalayan Watershed using a Remote Sensing and GIS Based Sediment Yield Model. *International Journal of Current Microbiology and Applied Sciences,* Volume 6 Number 3 (2017). **NAAS Rating: 5.38**

3. **Rawat, SS**, P. Prashar, K.S. Rawat, B.R. Nikam, and P. Kumar (2017) Prioritization of sub-watersheds of a western Himalayan catchment employing morphologically based compound index and sediment production rate. Accepted in Journal of Agricultural Physics. **NAAS Rating: 4.31**

4. **Rawat, SS**, Kumar P and Jose PG (2016). Identification and quantification of Areas Vulnerable to Soil Erosion and Deposition in a Himalayan Watershed using Remote Sensing and GIS', Proceedings of the Indian Ecological Society : International Conference "Natural Resource Management: Ecological Perspectives", Vol. 1, pp. 97. (Presented and extended abstract published).

5. **Rawat, SS**, P. Prashar, P. Kumar, R. V. Kale and P. G. Jose (2017). Prioritization of Sub-Watersheds of a Western Himalayan Catchment Using Morphological Parameters. 1st Asian conference on water and land management for food and livelihood security (WLMFLS-2017) organized by IGKV, Raipur and Soicity of Soil and Water Conservation, India during January 20-22, 2017 Raipur, Chhattisgarh, India

6. **Rawat, SS**, P. Kumar(2016) Interim Report of the Internal Project "Estimation of Sediment Yield and Identification of Areas Vulnerable to Soil Erosion and Deposition in a Western Himalayan Catchment.