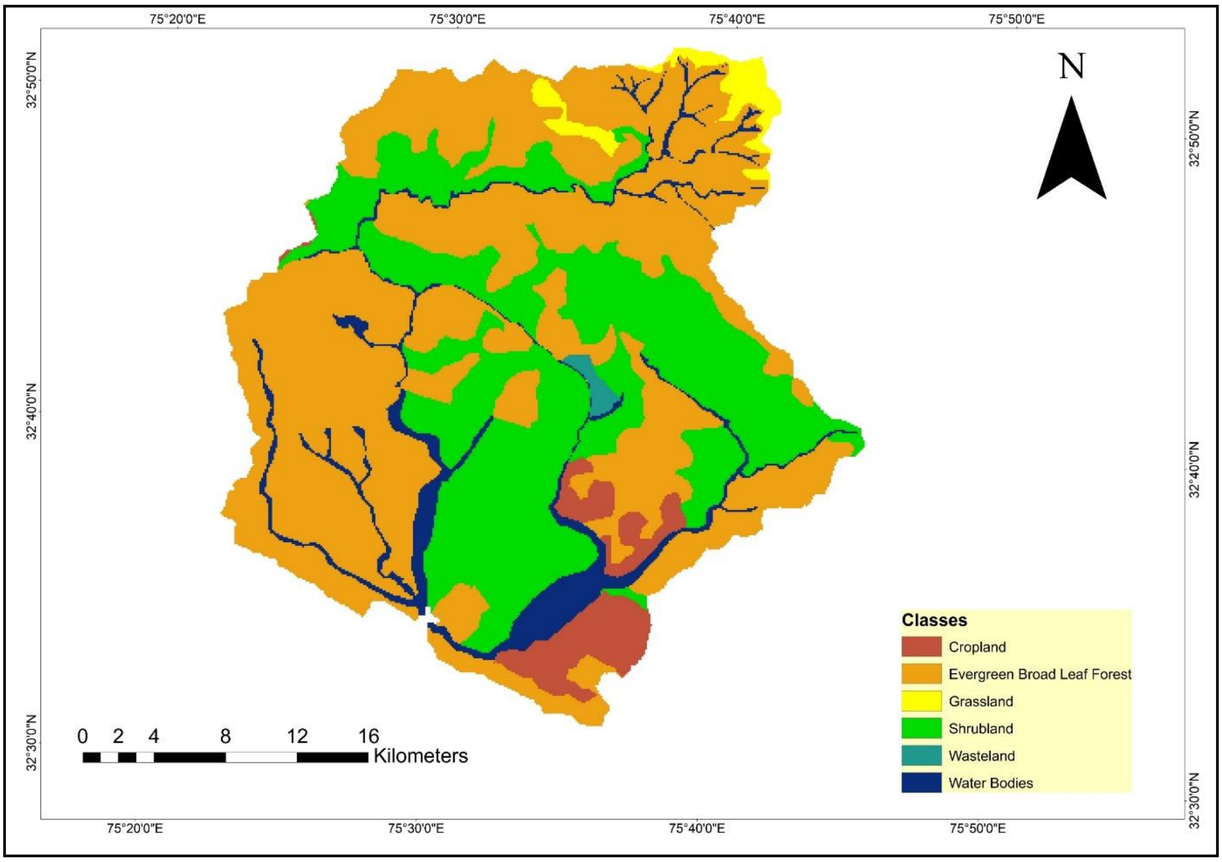
FINAL REPORT

Assessment of Hydrological Characteristics of a Western Himalayan River – A case study on River Ujh



NATIONAL INSTITUTE OF HYDROLOGY

Western Himalayan Regional Centre, Jammu

October, 2020

Assessment of Hydrological Characteristics of a Western Himalayan River – A case study on River Ujh

NATIONAL INSTITUTE OF HYDROLOGY

Western Himalayan Regional Centre, Jammu

October, 2020

Director	:	**Dr. J. V. Tyagi**
Head & Co-ordinator	:	**Dr. M. K. Goel**

STUDY GROUP

Principal Investigator (PI)	:	**Drona Khurana, SRA, WHRC, Jammu**
Team (Co-PIs)	:	**Dr. P. G. Jose, Scientist 'D', WHRC, Jammu** **Dr. S. S. Rawat, Scientist 'D', WHRC, Jammu** **Dr. R. V. Kale, Scientist 'D', WHRC, Jammu** **Er. D. S. Bisht, Scientist 'B', WHRC, Jammu**

Contents

List of Figures

List of Tables

CHAPTER - 1
INTRODUCTION

1.1 Background

Land and water are two important natural resources and have been the source of sustenance for any civilization. In scientific terminology this Land-Water-Human relationship is encompassed by the unit called "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 vital goods such as food, fodder, fibre 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 of ever growing populace. However, today these limited resources are under increasing pressure due to their non-sustainable exploitation. Thus, watershed planning and management has become the 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.

Flow regime of a river is an important component of project hydrology, on the basis of which development of water resources of a river for various beneficial uses is envisioned and conceptualized. In recent decades, concerns about the impacts of changing patterns of land use associated with deforestation and agricultural transformation on water resources have created social and political tensions from local to national levels. Consequences of land use change on water supply and demand and downstream hydrological hazards, and for biodiversity conservation cannot be ignored. Moreover, land use changes may alter the amount of infiltration into the groundwater system and can affect the quality of water discharged from a watershed. The groundwater flow regime is significantly impacted due to a reduction in recharge. Since recharge can be the driving force of groundwater flow, not only can this reduction change flow magnitude and direction, it can reduce the hydraulic heads of the system, affect the surface-water groundwater interaction and reduce the volume of water available for withdrawal. Reduced recharge can affect the ability of the system to serve as a reliable water supply. Pollutants that accumulate on impervious surfaces during dry periods are flushed into streams, rivers, lakes, and reservoirs during rainfall events and can degrade water quality. This can increase the maximum pollutant loads that the receiving natural systems eventually have to assimilate. Vegetation is sometimes completely stripped from the land during site development and the bare soil is exposed to the erosive forces of rainfall which in turn increase the sediment loads in runoff during storm events. If the groundwater and surface water systems are hydrologically adjacent and interact dynamically, the pollution of one can affect the quality of the other.

It can be concluded that climatic variability and land use change are the most important factors affecting the changes in the hydrologic regime of a river, and is accentuated by increased competition for water. Therefore, it is important to study and understand catchment characteristics pertaining to flow behaviour of water and how land use/cover changes affect the flow characteristics and in turn the flow regime of the river.

1.2 Problem Statement

Ujh River has a very high social impact as it along with its 4 tributaries are the chief source of water for the district of Kathua and adjoining villages. Its water is utilized for drinking, agricultural and irrigation needs. A multipurpose project is also coming up on this river. Two canals proposed under the multipurpose project will provide irrigation to Kathua, Hiranagar and Samba tehsils. The area is encountering change in Land Use and Land cover patterns with growing populations and resettlements in the towns of Bani, Bhilwar, etc. The Ujh River causes heavy flash floods during monsoons in Kathua district causing substantial losses to the exchequer in rehabilitation and protection works and devastate sizeable hectares of cultivable area downstream. The land on both the banks of the River is subjected to severe erosion and submergence. The main objective of the present study is to assess catchment response, geometry and probable maximum sediment loss from the catchment of River Ujh using well established empirical formulae and methods based on a morphometric approach and using GIS tools. The study also aims to assess the land use land cover changes in the region and to develop a rainfall-runoff model for the catchment using hydrological modelling techniques.

1.3 Study Objectives

- Morphometric analysis of Ujh river basin
- Assessment of Land use and Land cover change in Ujh basin
- Modelling of the flow characteristics (Rainfall-Runoff) of the basin using HEC-HMS model

CHAPTER – 2
Study Area

2.1 Origin and Location

River Ujh, is one of the main tributaries of River Ravi. It originates from the Domal Structure of Seojdhar of the middle Himalayan ranges near the hills of Bhaderwah in Jammu Division of the UT of Jammu & Kashmir, with its head waters in the Kailash mountains at an altitude of 4,300m. It is joined by other four tributaries Suterkhad, Dunarikhad, Bhini and Talyan at Panchtirthi viz. confluence of five streams. This sub-himalayan catchment with a hilly and rugged terrain and altitude ranging from 526 m to 4319 m. receives its major contribution from South-West monsoon with a minor share from Western disturbances mostly in the form of rain, while a very small portion of the catchment receives snowfall.

The Ujh catchment lies between 32.52 N and 32.86 N latitude and 75.37 E and 75.75 E longitude, and passes through Ramkot side of Jammu and through Kathua, flows for a distance of nearly 100km before it joins Ravi below Nainkot in West Pakistan.

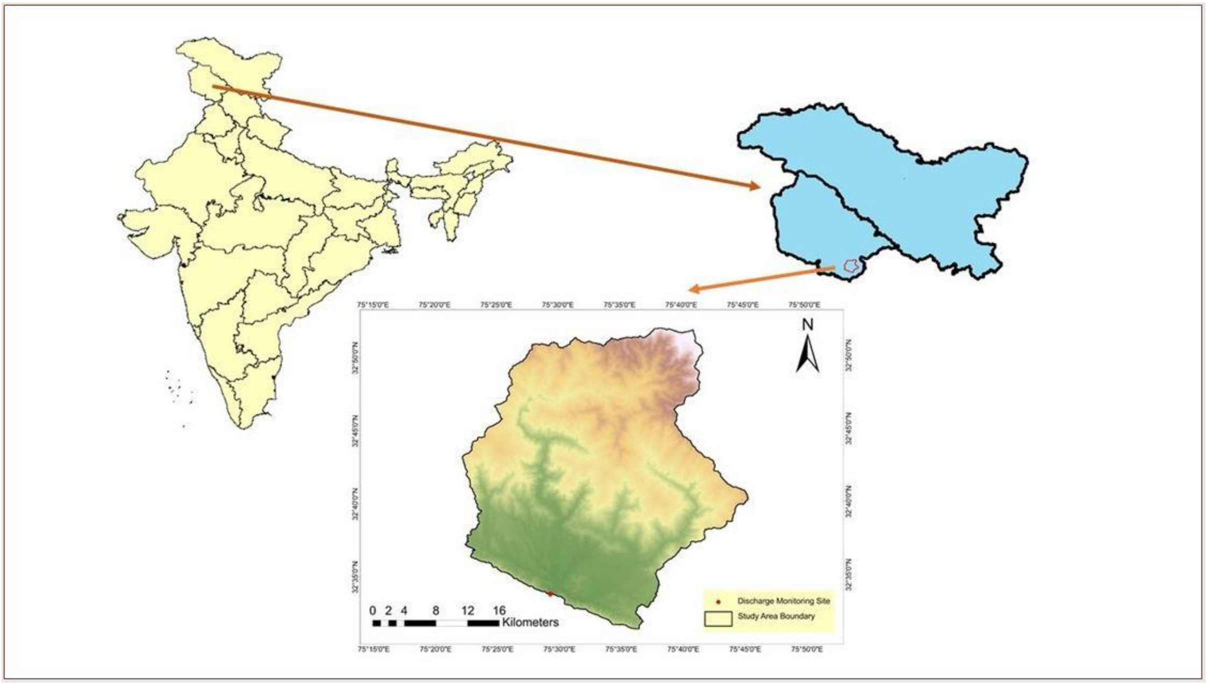


Fig. 1.1 – Location of Ujh catchment

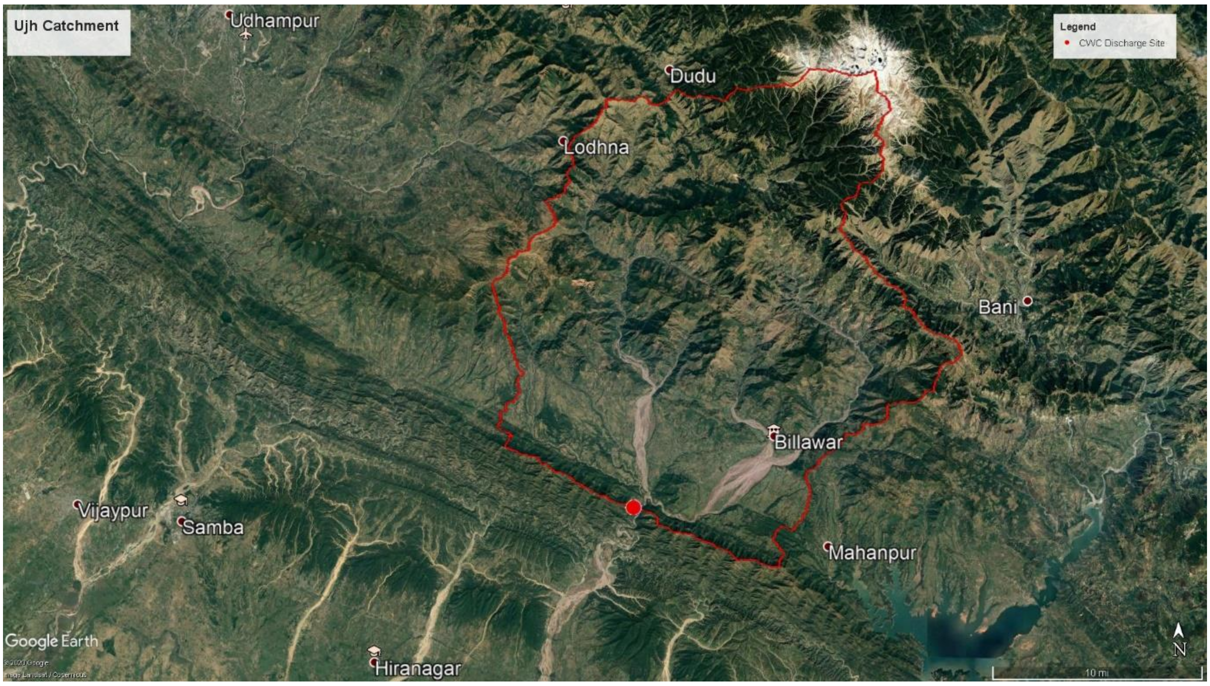


Fig. 1.2 – Location of Ujh catchment

2.2 Tributaries

River Ujh is one of the major rivers of Jammu region and the second most important river of Kathua District. It is a branch of Ravi river. Naaz and Bhinni Nallahs of Billawar are the two main tributaries of the Ujh River. The length of the river in the district is 65 kilometres (40 mi) and the average width is about 1.2 kilometres (0.75 mi). The River Ujh is joined by other four tributaries Sutarkhad, Dunarikhad and Talyan at a place called Panchtirthi. Ujh and Bhini are perennial streams while other streams flow during rainy season only. While Ujh River water is mainly utilized for drinking purposes, it also feeds a number of small canals and Khuls for irrigating the agriculture land of the district.

2.3 Topography

The catchment is hilly, mountainous and rugged, and sloping towards the south from the northern hilly terrain varying in altitude from 526 m to 4319 m as revealed by the Digital Elevation model (DEM) of the Ujh catchment (Fig. 2). Areas having an altitude of 2000 m and above which constitute about 20% of the catchment are generally snow bound for most of the winter. From origin to outfall the longitudinal section of the river exhibits wide variation. The gradient changes from very steep at upper part to concave and flat in the lower part of the river.

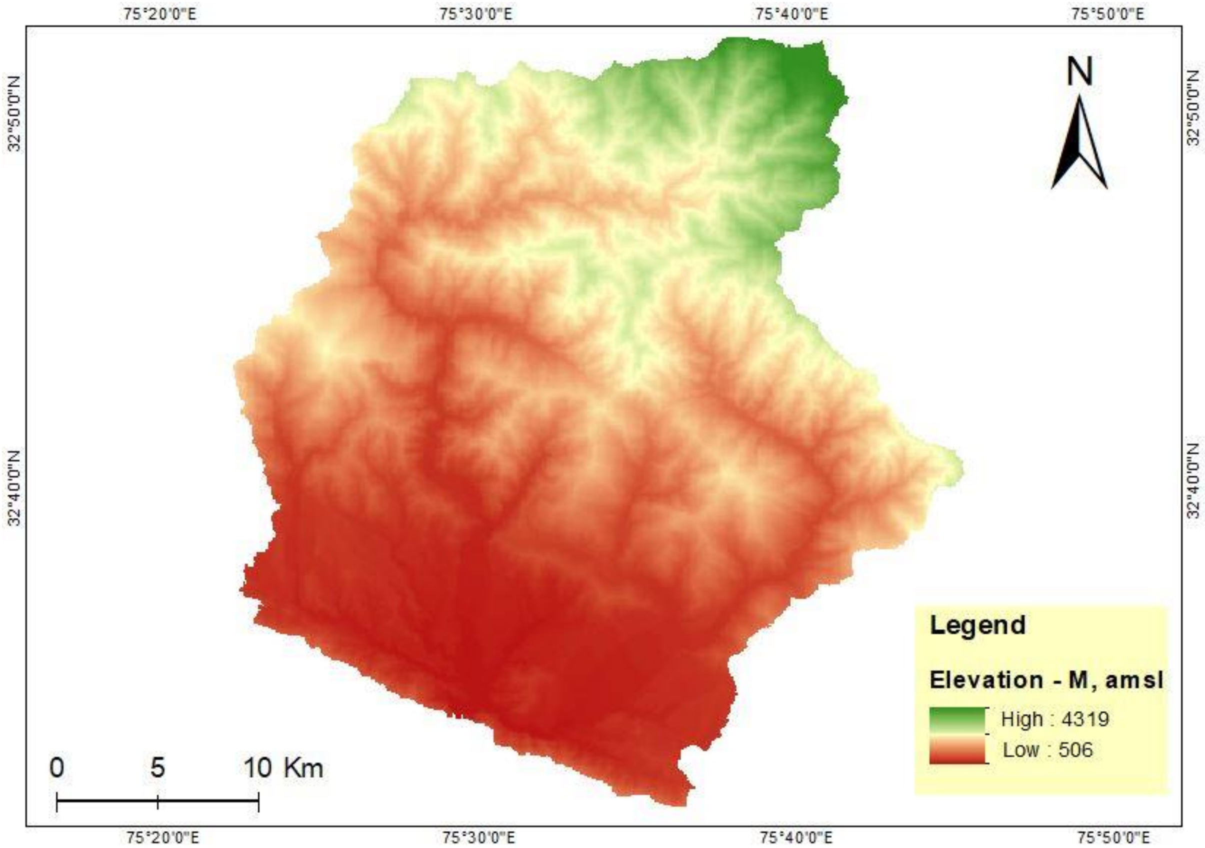


Figure 2 - Digital Elevation Model (SRTM) of Ujh catchment

2.4 Climate

The climatic conditions of the catchment vary from semi-arid to humid from south to north. Altitudinal variation within the catchment gives rise to temperature differences between the plains (Kathua and Hiranagar) and hilly areas (Basohli and Billawar) of the catchment. The summer temperatures rise as high as 48 degree Celsius in the plains, while sub-zero winter temperatures are encountered in the upper hilly areas. The mean annual temperature of the southern part of the catchment is 23^{o}C and that of the eastern portion of the catchment is 16^{o}C.

2.5 Precipitation

The catchment experiences rainfall during winter and early summer primarily from western disturbances and monsoon rains from second week of July onwards. The hilly areas receive more rains than the plains. Most of the higher areas in the Basohli and Billawar Tehsils experience snowfalls for most part of the year. The annual rainfall in the entire district of Kathua is approximately 1672 mm. About 85% of the total rainfall is received during monsoon season viz. July to September, while the rest occurs during December to February.

2.6 Land use

The major land use /land cover in the Ujh catchment is shown in the Fig. 3 below :-

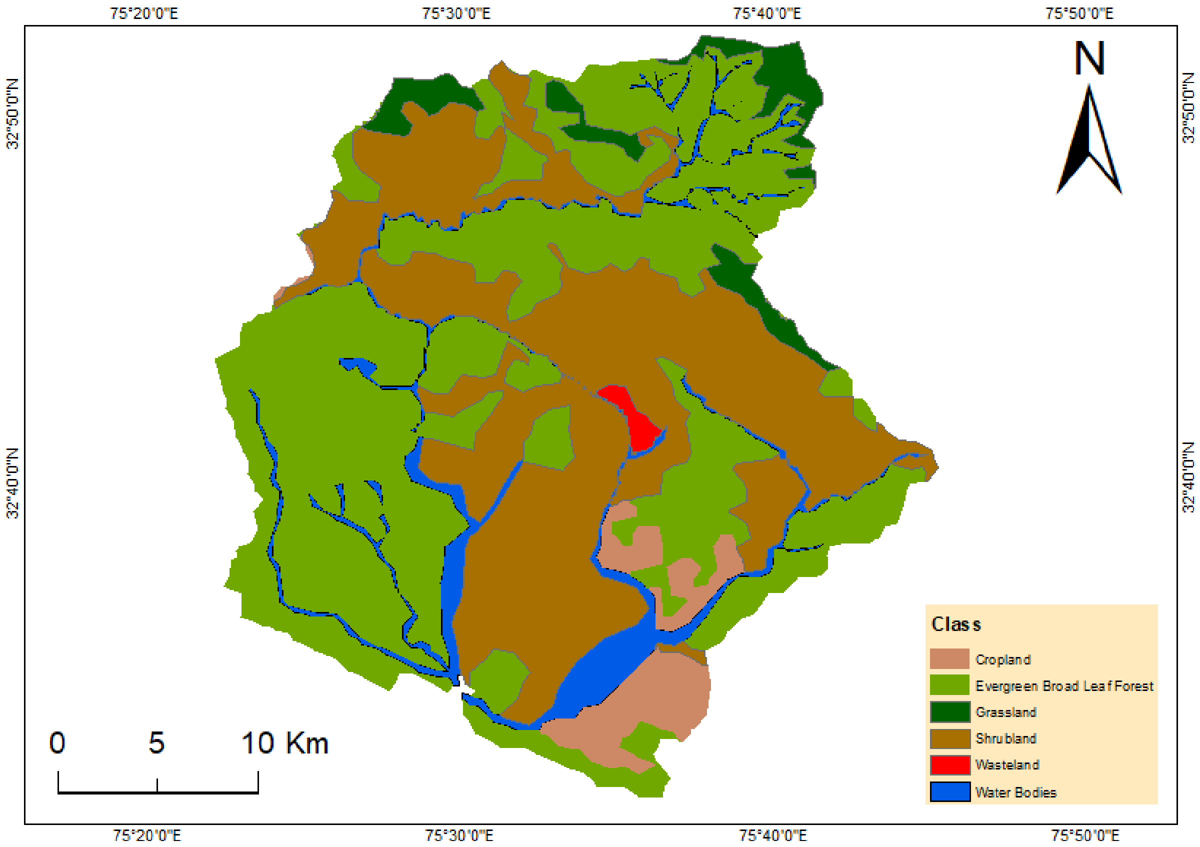


Fig. 3 Land use/Land cover in Ujh Catchment

CHAPTER – 3

Literature Review and Methodology

3.1 Morphometric Analysis and Prioritization of Catchment

3.1.1 Literature Overview

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 the linear relationships exhibited between number of streams, length of stream segment and area drained by streams when plotted in successive Strahler orders and these are popularly known as Horton's ratio in the field of hydrology. These morphometric parameters have been linked with hydrological behaviour 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.

Morphological parameters have been recurrently used to assess the hydrological response of a watershed. Due to a strong mutual correlation between the runoff characteristics and the terrain of a watershed the method is significantly popular especially in an un-gauged catchment. Morphometry is the measurement of earth's configuration pertaining to various features such as surface, shape and dimension of its landforms in a way that they can be interpreted mathematically for further deliberation [Agarwal CS (1998); Clarke JI (1996); Obi Reddy GE, Maji AK, Gajbhiye KS (2002)]. Linear, aerial, gradient and relief of channel network and contributing ground slope are measured for morphometric analysis [Nag SK, Chakra borty S (2003); Nautiyal MD (1994)]. In recent years, Geographical Information System (GIS) and Remote Sensing (RS) have proven to be very effective and time-saving in analysing any basin, due to ease of availability through open source imagery programmes such as SRTM, ASTER etc. This data in conjunction with well-defined surveyed sheets such as geo-referenced Survey of India (SOI) toposheets, can prove to be a very effective and frugal method of accurate watershed response assessment.

Since most of the morphometric parameters are in the form of ratios, the scale does not limit their applicability while comparing different watersheds. Due to lack of observed data, these simple morphometry based approaches are still popular in characterization of sub-watersheds with reference to their susceptibility towards hydrological response behaviour. Estimating the geomorphologic parameters has always been challenging for field engineers. Regional methodologies have seldom been developed for analysis of hydrological problems where sufficient data is unavailable and gauging is absent. With the advancement in the field of geospatial technologies like GIS and RS, geomorphological parameters can be easily extracted from the digitized toposheets. It has been accepted widely that morphological parameters of the drainage basin are a clear reflection of geological and geomorphological evolution of an area over time, as substantiated in various morphological studies. Drainage lines of an area give an insight about the three-dimensional geometry of the region and are a clear manifestation of the evolution process [Singh KN (1980)]. Besides, it is important to analyse a watershed quantitatively to highlight its important hydrological aspects and their impact. Morphometric analysis based on observation of hydrologic and geomorphic processes at watershed scale reveals information regarding formation and development of land surface processes [Dar RA, Chandra R, Romshoo SA (2013); Singh S (1992)]. It has been concluded widely that crucial drainage system parameters such as flow intensity and surface runoff can be estimated on the basis of geomorphic features associated with morphometric parameters [Ozdemir H, Bird D (2009)].

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 were prioritized using mean values of the four morphological parameters as an index. This index was related to the severity of soil erosion. Severest erosive sub catchment was 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 was 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 was finally used to rank the sub catchments. The standard deviation of morphological parameters was 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 analyse runoff, soil erosion and sediment delivery ratio etc. Morphological parameters along with land use information were 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 an integrated map to explain the conditions 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 and 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) estimated the morphometric parameters pertaining to 10 sub-watersheds of Tarai development project area and used it in the estimation of sediment production rate.

The sediment production rate in the study area varied between 2.45 to 11.0 ha-m/100 km^2/year. The remote sensing data was utilized for generating land use/land cover data which is an essential prerequisite for land and water resource planning and development. They concluded that 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 modelling.

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 values of index indicate severe erosion and vice versa. SYI values and morphological parameters based ranking together resulted in better prioritization of micro watersheds as well as 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 brought out relationships among various attributes of the morphometric aspects of the watershed and helped in understanding their roles 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. The study revealed 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. The 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 subwatersheds using Landsat imageries and topographical maps and concluded that the development of stream segments was affected by slope and local relief. The mean bifurcation ratio indicated that the drainage pattern was not significantly influenced by geological structures. The drainage densities of the sub-watersheds suggested that the general nature of rocks was impermeable.

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) 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) examined 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 greatly influence on the sediment yield.

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 and for optimum utilisation of 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 when these rivers enter the plains. However, the major sources of sediment are the upstream areas and carried-out by small mountainous tributaries which are unfortunately un-gauged. Process of sedimentation 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 cannot be a justification to identify the actual source areas of sediment within the watershed. To overcome such limitations, 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 comparing different watersheds. Due to lack of observed data, these simple morphometry 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 capable of handling spatial and temporal data and morphometric parameters can be updated in real time (Apaydin et al., 2006).

Therefore, based on the foregoing discussions substantiating a clear relationship between the geomorphology and hydrologic response of the watershed, the present study has carried out analysis of morphological parameters of eight sub-watersheds of Ujh watershed and to prioritize these sub-watersheds based on a morphometry based compound index. In this study sediment production rate from different sub-watersheds have also been computed using geomorphological parameters to assess the susceptibility to erosion in different sub-watersheds of catchment.

3.1.2 Material and Methods

In the present study, Ujh River catchment and its drainage network has been delineated and extracted using ArcHydro Tools. By following the Strahler (1964) method, stream ordering has been carried-out for the entire Ujh catchment and it was found to be sixth order catchment. According to the extracted drainage network, entire drainage area of 867.27 sq. km was subdivided into eight sub-watersheds (Fig. 4), having areas ranging from 30 sq. km (SW6) to 207 sq. km (SW1) for better understanding with morphometric parameters and finding their correlation with hydrological response and consequent soil erosion of the catchment. The drainage networks of eight different sub-watersheds were analyzed as per Horton's (1945) laws in ArcHydro module of ArcGIS. All sub-watersheds have been 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), circulatory 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 Ujh catchment. The formulae for computation of the morphometric parameters are shown in Table 1.

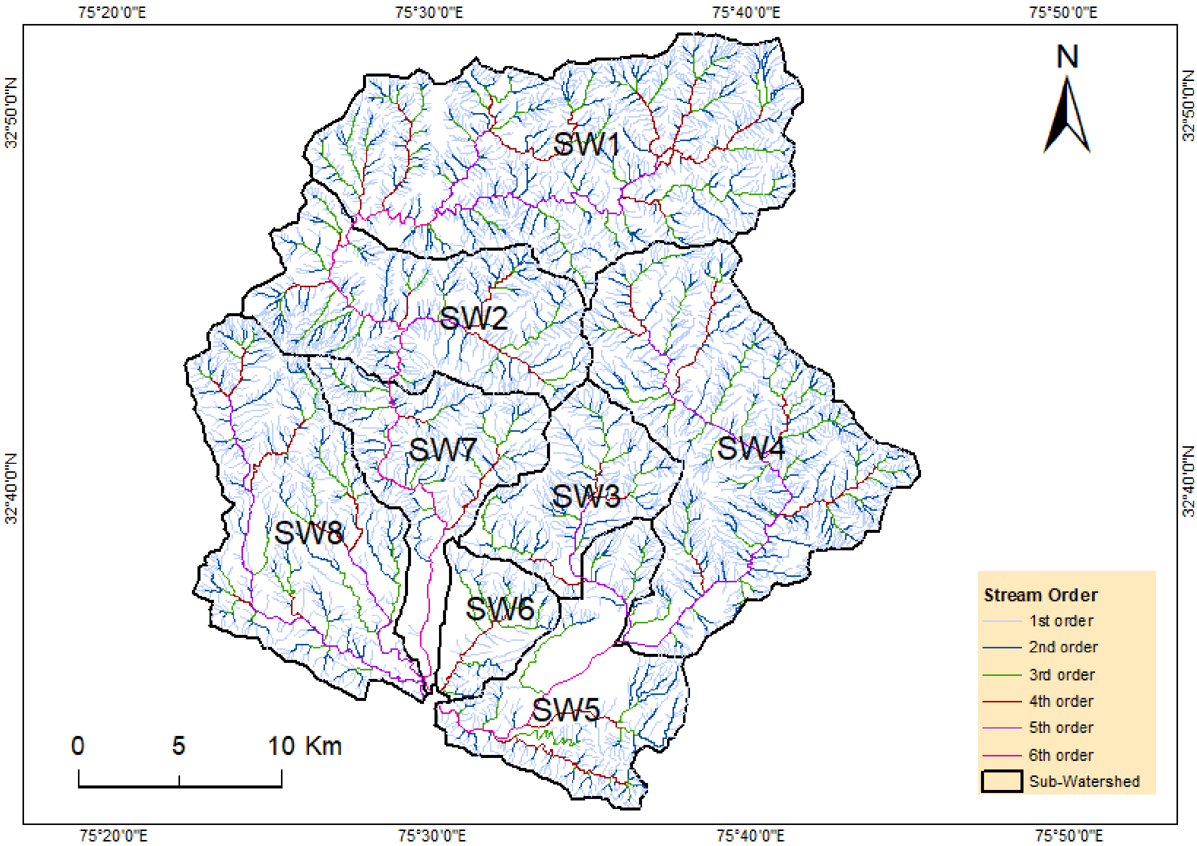


Fig.4 Delineated Sub-Watersheds of Ujh Catchment and their drainage network according to stream order

Table 1: Different Morphometric Parameters used in the Study and their standard formulae

	Morphometric Parameter	**Formula**	**Reference**
Linear	Stream order (u)	Hierarchical rank	Strahler (1964)
	Basin Length (L)	$L=1.312*A^{0.568}$ 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, Rb=Bifurcation ratio Nu=Total no. of stream segments of order 'u', N_u+1=Number of segments	Schumm(1956)

		of the next higher order	
	Mean bifurcation ratio (R_{bm})	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)	$F_f=A/L^2$ Where F_f=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 the 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 A=Area of the basin (km^2) P=Perimeter(km)	Miller (1953), Strahler (1964)
	Compactness Coefficient (C_c)	$C_c=0.282L_p/A^{0.5}$, where L_p=perimeter of the basin, A=area of the basin	Horton(1945)
	Length of overland flow (L_o)	$L_g=1/(2XD_d)$, 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)

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:

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

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

3.2 Land Use/ Land Cover (LULC) Change Assessment

3.2.1 Literature Overview

Land use is influenced by economic, cultural, political, and historical factors at multiple scales and refers to human activities and the various uses which are carried out on land. Urbanization is inevitable, when pressure on land is high, agriculture incomes are low and population increase rate are excessive, as is the case in most of the developing countries of the world. In a way urbanization is desirable for human development. However, uncontrolled urbanization has been responsible for many of the problems our cities experience today, resulting in substandard living environment, acute problems of drinking water, noise and air pollution, disposal of waste, traffic congestion, etc. To improve these environmental degradations in and around the cities, the technological development in relevant fields have to solve these problems caused by rapid urbanization, only then the fruits of development will reach most deprived sections of the society.

The growing population and increasing socio-economic necessities creates pressure on land use/land cover. This pressure results in unplanned and uncontrolled changes in LULC. The LULC alterations are generally caused by mismanagement of agricultural, urban, range and forest lands which lead to severe environmental problems such as landslides, floods, etc. Remote sensing and Geographical Information Systems (GIS) are powerful tools to derive accurate and timely information on the spatial distribution of land use/land cover changes over large areas. Past and present studies conducted by organizations and institutions around the world have mostly concentrated on the application of LULC changes. GIS provides a flexible environment for collecting, storing, displaying and analysing digital data necessary for change detection. Remote sensing imagery is the most important data source for GIS. Satellite imagery is used for recognition of synoptic data of earth’s surface. Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data have been broadly employed in studies towards the determination of land cover since 1972, the starting year of Landsat program, mainly in forest and agricultural areas. The rich archive and spectral resolution of satellite images are the most important reasons for their use.

The aim of change detection process is to recognize LULC on digital images that bring out changes in features of interest between two or more dates. There are many techniques developed in literature using post classification comparison, conventional image differentiation, using image ratio, image regression, and manual on-screen digitization of change principal components analysis and multi date image classification. A variety of studies have concluded that post-classification comparison was found to be the most accurate procedure and presented the advantage of indicating the nature of the changes. In this study, change detection comparison (pixel by pixel) technique was applied to the Land use/Land cover maps derived from satellite imagery.

3.2.2 Data Set

To detect LULC change in the Ujh catchment data prepared by Oak Ridge National Laboratory, National Aeronautical Space Administration (NASA) under NASA's Land Use/Land Cover change programme has been used. This data set provides land use and land cover classification products at 100-m resolution for India at decadal intervals for 1985, 1995 and 2005. The data were derived from Landsat 4 and 5 Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Multispectral (MSS) data, India Remote Sensing satellites (IRS) Resourcesat Linear Imaging Self-Scanning Sensor-1 or III (LISS-I, LISS-III) data, ground truth surveys, and visual interpretation. The data has been classified according to the International Geosphere-Biosphere Programme (IGBP) classification scheme.

This data set utilized satellite imagery to generate national level LULC maps for India at decadal intervals for 1985, 1995 and 2005. The process includes classification, visual interpretation, and data verification of the 2005 imagery (using ground truth data) to produce a 2005 LULC map. The 1995 Landsat images were overlaid onto the 2005 map and polygons were traced where LULC change had occurred. The process was applied to the 1985 imagery using the 1995 map as the starting reference. On-screen image interpretation was used to assess the mapped data. The minimum mapping unit was 2.5 hectares. In preparation of this data the accuracy of the 2005 data was evaluated using pre-determined field sample points. A total of 12,606 stratified random samples to were selected to assess the accuracy of the map with the help of ground truth data (Biodiversity Information System, 2014; Roy et al., 2012). The confusion error matrix was created with the mapped and ground reference points to determine the users' accuracy and Cohen's kappa accuracy. Most of the LULC classes showed accuracies of more than 90% except for plantation, wasteland, and barren land. However, the accuracies of these three later classes are also within the acceptable limits. An overall mapping accuracy was achieved of 94.46% and the Kappa accuracy of 0.9445 for 2005 (Roy et al., 2015).

The migration of classes (LULC change) from one category to another between different years (1985 to 2005) was found to be only 10.36% of total geographical area, of which it was 5.74% between 1985 and 1995, and 8.55% between 1995 and 2005. Field surveys and other information (existing land and revenue records) were used in 5% of the noted change areas to ascertain the nature of change, and the extent and direction of change. It can be assumed that the mapping and Kappa accuracies of the 1995 and 1985 maps are similar to that of 2005 (Roy et al., 2015).

This data set utilizes the following satellite products and sensors:-

Table 2. Satellite remote sensing data used for the LULC mapping

Period	Satellite	Sensor	Resolution
1984-85	Landsat 4	MSS	80 (resampled to 60 m)
1994-95	Landsat 5 & IRS-1B	Thematic Mapper (TM), Enhanced Thematic Mapper (ETM +), Linear Imaging Self-Scanning Sensor – 1 (LISS I)	30 and 72 m (resampled to 56 m) respectively
2004-05	Landsat 5 & Resourcesat	ETM+, LISS-3	30 and 23.5 m respectively

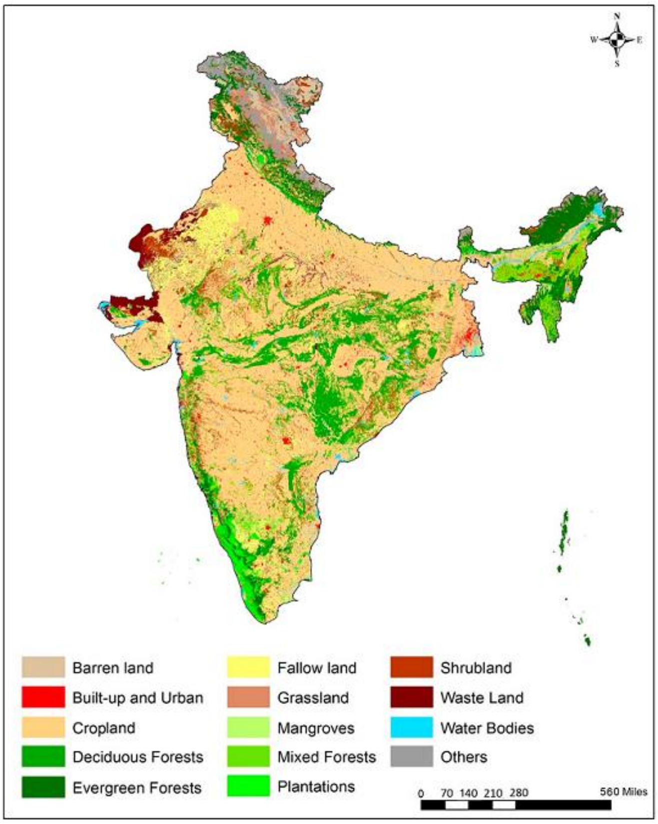


Fig. 5 - Land use and land cover map of India for 2005

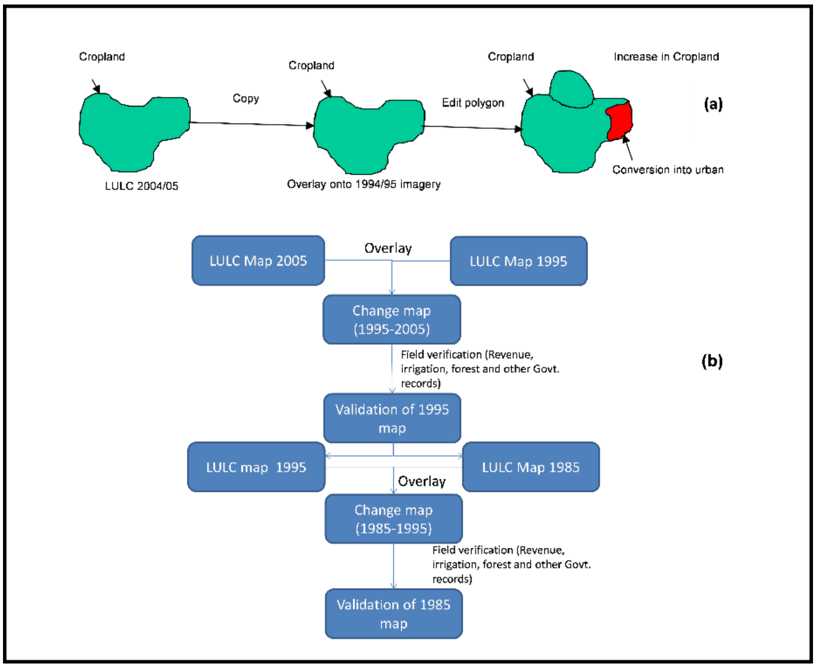


Fig. 6. Methodology for LULC maps of 1995 and 1985 to maintain continuity of accuracy as in 2005

3.3 Hydrological Modelling (Rainfall-Runoff Modelling)

Reliable measurements of various hydrological parameters including runoff and sediment yield are also a tedious and difficult task in remote and inaccessible areas. Studies are needed in Western Himalayan region for rigorous assessment of flow in rivers. This necessitates simulation of runoff from river basins through hydrological modelling. A multitude of hydrological models that range from empirical to physically based distributed models have been developed by researchers in the past. However, the accuracies in the results of these models completely rely on the availability and veracity of the available data. In river basin modelling the three main types of data, employing which the calibration and validation of the model can be done are discharge; i.e. flow data, sediment data, and nutrient data.

3.3.1 HEC-HMS model for flow simulation

HEC-HMS (Hydrologic Engineering Center and Hydrologic Modeling System) model was developed by the US Army Corps of Engineers (Feldman, 2000) that could be used for many hydrological simulations. The HEC-HMS model can be applied to analyse urban flooding, flood frequency, flood warning system planning, reservoir spillway capacity, stream restoration, etc. (U.S. Army Corps of Engineers, 2008). The proliferation of personal computers and the development of the HEC-1 model of the U.S. Army Corps of Engineers in 1998 to a GUI (graphical user interface) based user-friendly HEC-HMS model is available in the public domain, have come as another useful tool to the field hydrologists. Unfortunately, the HEC-HMS model, or any of the many watershed models for that matter, has not found many takers due to the uncertainty involved in the estimation of parameters of the models. But, parameter estimation on a regional scale at least may be possible to switch over to watershed models like the HEC-HMS and take advantage of the high speed computer programs rather than spread sheet exercises (Kalita, 2008). The HEC-HMS contains four main components:

1. An analytical model to calculate overland flow runoff as well as channel routing,
2. An advanced graphical user interface illustrating hydrologic system components with interactive features,
3. A system for storing and managing data, specifically large, time variable data sets, and
4. A means for displaying and reporting model outputs (Bajwa and Tim, 2002). This model is not calibrated and validated for the Krishna basin and need reliable data inputs to check the suitability of the model for the study location and purpose. Calibration of rainfall-runoff models with respect to local observational data is used to improve model predictability. When model

results match observed values from stream-flow measurement, users have greater confidence in the reliability of the model (Muthukrishnan et al., 2006)

3.3.2 SCS loss method

A total of nine different loss methods are provided in HEC-HMS and some of these methods are designed primarily for simulating events, while others are intended for continuous simulation. Gridded Loss Methods and Soil Moisture Accounting Loss Methods are not preferred for the simulation studies because they require a high number of parameters. Among the remaining loss methods, the SCS Loss method is selected for the event based simulation studies. The method is simple and practical because it requires only two input parameters such as CN number and impervious area (10 %). The SCS CN method implements the curve number methodology for incremental losses. Originally, the methodology was intended to calculate total infiltration during a storm. The program computes incremental precipitation during a storm by recalculating the infiltration volume at the end of each time interval. Infiltration during each time interval is the difference in volume at the end of two adjacent time intervals.

The SCS CN method requires percentage land use pattern of the catchment and the sub catchments, total length of the river and the elevation of the catchment area. SCS CN model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use and antecedent moisture content (Feldman, 2000). The maximum retention and watershed characteristics are related through an intermediate parameter, the curve number. The CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates. The CN were taken as a weighted value based on different land uses in the study area. Calculation of weighted curve number (WCN) is shown by Equation 1,

$$\mathrm{WCN} = \frac{\sum_{1}^{n} CNi * Ai}{\sum_{1}^{n} Ai}$$

Where, WCN is weighted curve number, Ai is area for i_{th} land use type and CN_i is curve number for i_{th} land use type. Curve numbers were taken from standard curve number tables (Schwab et al., 2005). Calculated weighted curve number was used in the calibration of the model. The area of the sub-basin which is impervious (%) needs to be specified as a portion of total area. No loss calculations are carried out on the impervious areas where all the precipitation on such portions become excess precipitation and subjected to direct runoff.

3.3.3 SCS unit hydrograph method

A total of seven different transformation methods are provided in HEC-HMS. Some of these methods are complicated requiring many inputs that are not available for most of the ungauged catchments. SCS unit hydrograph method has been applied successfully to simulate stream flows elsewhere. This method requires Lag time (min) and curve number as input. The transformation of precipitation excess into direct surface runoff by SCS hydrograph method requires lag time and type of graph for transformation. The lag time is calculated using curve number of the watershed, slope and area of the basin length of the river as input. The time of concentration (hr) which is the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet is calculated by equation 2. Lag time is then calculated from the Tc using the relation as shown in the equation 3 below.

$$L = 0.6T_c$$

$$T_c = \frac{L^{0.8} * (S + 1)^{0.7}}{1140 * Y^{0.5}}$$

3.3.4 Trend Test

3.3.4.1 Mann-Kendall trend test

Two widely used non-parametric tests (Bisht et al. 2017; Dhage et al. 2016; Jena et al., 2014; Pingale et al., 2014; Taxak et al., 2014; Duhan and Pandey, 2013; Kumar and Jain, 2011; Basistha et al., 2009; Partal and Kahya, 2006) namely, Mann-Kendall and Theil-Sen's estimator, were used for detecting trend and change in magnitude in rainfall time series, respectively.

Mann-Kendall (Mann 1945; Kendall 1948) is a rank based test. MK test statistics is defined as;

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(X_j - X_i) \quad (1)$$

Where, n is the length of data set, X_i and X_j represent data points in time series i and j, respectively ($i < j$).

$$\mathrm{sgn}(X_j - X_i) = \begin{cases} -1, & \text{if } X_j - X_i < 0 \\ 0, & \text{if } X_j - X_i = 0 \\ +1, & \text{if } X_j - X_i > 0 \end{cases} \quad (2)$$

It has been documented that for $n \geq 10$, statistics S is normally distributed with

$$E(S) = 0 \quad (3)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \quad (4)$$

Where $E(S)$ is the mean, $V(S)$ is the variance of S, m is the number of tied groups and t_i is the size of ith tied group. The standard normal test statistics Z is given by,

$$Z = \begin{cases} \frac{S+1}{\sqrt{V(S)}}, & \text{if } S < 0 \\ 0, & \text{if } S = 0 \\ \frac{S-1}{\sqrt{V(S)}}, & \text{if } S > 0 \end{cases} \quad (5)$$

Positive Z score indicates an increasing trend and vice versa. If $|Z| > Z_{1-\alpha/2}$, null hypothesis H_0 for 'No Trend in time series' is rejected and a significant trend exists.

3.3.4.2 Theil–Sen's estimator

Theil-Sen approach (TSA) (Theil 1950; Sen 1968) is used to determine the magnitude of change. TSA slope β is defined as;

$$\beta = \text{median}\left(\frac{X_j - X_i}{j-i}\right) \quad (6)$$

Where, X_i and X_j represents data points in time series i and j, respectively ($i < j$). Positive value of β indicate an upward trend and vice versa.

Change magnitude as percentage of mean (ΔX) for the period of study is computed as following Yue and Hashino (2003);

$$\Delta X = \frac{T.\beta}{E(X)} \quad (7)$$

Where, T is the length of year and $E(X)$ is corresponding mean.

To identify the trend in discharge values, the Mann-Kendall test has been employed by a number of researchers (Yu et al., 1993; Douglas et al., 2000; Yue et al., 2003; Burn et al., 2004, Singh et al., 2008a, b, Bisht et al, 2018). In the present study also, the commonly used nonparametric Mann- Kendall test estimator was applied to determine monotonic trends and change in different variables.

CHAPTER - 4
RESULTS AND DISCUSSIONS

4.1 Morphometric Analysis and Prioritization

The various morphometric parameters of the Ujh river catchment in the present study are summarized in Tables 3 to 6. The basic parameters of all the sub-watersheds of Ujh catchment are shown in Table 3 and other parameters pertaining to linear aspects, areal aspects and relief aspects are described in subsequent sections.

Table 3. Basic Parameters of different sub-watersheds of Ujh River Catchment

SW Name	Basin Area(Km^2)	Perimeter(Km)	Basin Length(Km)
SW1	207.4	69.36	34.72
SW2	105.7	51.3	13.76
SW3	56.16	35.16	11.44
SW4	176.9	67.87	34.26
SW5	84.78	50.16	16.16
SW6	30.42	23.71	9.16
SW7	74.49	52.56	23.73
SW8	131.5	57.09	27.9

4.1.1 Linear Aspects

4.1.1.1 Stream ordering

Stream ordering is the first step to extract the geomorphological parameters of a catchment. Ujh river basin was adjudged sixth order basin according to the Strahler (1964) hierarchical rank. The drainage map of the Ujh catchment with stream order is shown in Figure 4. As the stream order increases the total number of streams decreases as suggested by Strahler (1957) and shown in Table 4. 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). Ujh catchment contains two types of drainage patterns viz. parallel and dendritic. In parallel drainage system, primary and secondary streams flow parallel to each other and meet the main channel at about same angle. Such drainage patterns follow the regional slope and normally start from the water divide of the watershed. In SW1, SW3, SW6 and SW7 sub-watersheds parallel drainage pattern is the dominant drainage pattern. However, dendritic drainage pattern is found frequently in SW2 and SW4 sub-watersheds and some parts of other sub-watersheds also. Dendritic type of drainage pattern indicates homogeneity in texture, lithology and lack of structural control.

Table 4: Extracted streams 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	1053	209	49	8	2	1	-	-	4.28
	Stream Length(km)	517.56	123.94	70.41	41.39	22.69	6.63	-	-	
	Bifurcation ratio	5.04	4.26	6.12	4.00	2	-	-	-	
SW2	No. of Stream	500	96	26	5	1	1	-	-	4.02
	Stream Length(km)	272.59	70.99	31.41	14.71	3.33	11.9	-	-	
	Bifurcation ratio	5.21	3.69	5.2	5	1	-	-	-	
SW3	No. of Stream	204	47	9	3	1	-	-	-	3.89
	Stream Length(km)	135.71	32.20	16.58	8.09	4.46	-	-	-	
	Bifurcation ratio	4.34	5.22	3.00	3.00	-	-	-	-	
SW 4	No. of Stream	880	187	40	8	3	1	0	-	3.51
	Stream Length(km)	492.04	114.24	60.63	25.62	28.80	0.38	-	-	
	Bifurcation ratio	4.71	4.68	5.00	2.67	3.00	1.00	-	-	
SW 5	No. of Stream	267	62	15	3	1	1	-	-	3.49
	Stream Length(km)	145.87	42.46	24.80	14.76	3.26	12.1	-	-	
	Bifurcation ratio	4.31	4.13	5.00	3.00	1.00	-	-	-	
SW 6	No. of Stream	90	21	7	1	-	-	-	-	4.76
	Stream Length(km)	49.210	12.18	12.83	6.15	-	-	-	-	
	Bifurcation ratio	4.28	3.00	7.00	-	-	-	-	-	
SW 7	No. of Stream	268	58	14	2	1	1	0	0	3.75
	Stream Length(km)	153.76	41.11	17.35	7.22	0.11	20.0	0	0	
	Bifurcation ratio	4.62	4.14	7.00	2.00	1.00	-	-	-	
SW8	No. of Stream	505	111	29	7	2	-	-	-	4.01
	Stream Length(km)	279.22	69.97	42.25	18.70	32.74	-	-	-	
	Bifurcation ratio	4.55	3.83	4.14	3.5	-	-	-	-	

4.1.1.2 Stream Length

Numbers of stream of various orders in all sub-watersheds were counted and their lengths from mouth to drainage divide were measured with the help of GIS software and depicted in Table 4. Generally, the total lengths of stream segments are highest in first order streams and decreases as the stream order increases (Table 4). However, in case of SW1, SW4, and SW8 sub-watersheds the stream segments of first orders are proportionately very high as compare to general observation (Table 4). This change may indicate flowing of streams from high altitude, lithological variation and converging terrain (Singh and Singh, 1997).

4.1.1.3 Bifurcation Ratio (R_b)

It is the ratio of the number of streams of given order u to the number of streams of next higher order. In general, lower value of R_b is characteristic of a watershed that has suffered less structural disturbances and whose 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 are in the middle range and vary from 3.5 to 4.8 (Table 4). The minimum and maximum value was found to be 3.51 and 4.76 for sub-watershed SW4 and SW6, respectively. It can be witnessed from Table 4, the bifurcation ratios between the first order, second order and third order streams are higher than the other higher orders in all sub micro-watersheds indicating that the catchment falls under areas of active gullies and ravines, hence, higher erosion rates.

4.1.2 Areal Aspects

Areal aspects include different morphometric parameters, like drainage density (D_d), stream frequency (F_s), drainage texture (T), form factor (R_f), infiltration number (I), circulatory ratio (R_c), elongation ratio (R_e) and length of the overland flow (L_o) and compactness coefficient (C_c). The values of these parameters were calculated and results have been given in Table 5.

4.1.2.1 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 in the basin to the area of basin. It reflects the land use 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, whereas high drainage density is prevalent in region of weak, impermeable sub-surface material which is sparsely vegetated and has high relief (Strahler, 1964). Drainage density in the study area varies between 2.64 (SW6) and 4.08 (SW4) indicating medium to high drainage density (Table 5). High drainage density of 4.08 in SW4 sub-watershed may be resultant of weak or impermeable subsurface material, high mountainous relief and fine drainage texture. However, low drainage density in SW6, SW5 and SW2 sub-watersheds indicate areas of highly resistant on permeable subsoil material, low relief and coarse drainage texture.

4.1.2.2 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 Ujh sub-watersheds varies from 3.91 to 6.37. Sub-watershed SW1, SW2, SW4 and SW8 are associated with high stream frequency, while sub-watersheds SW6 has low stream frequency. Drainage density and stream frequency has a similar measure of stream network of a drainage basin. Table 5 shows close correlation between drainage frequency with drainage density indicating the increase in stream population with respect to increase in drainage density.

4.1.2.3 Drainage Texture

Drainage texture is a depiction of the relative spacing of drainage lines; it acts as a significant geomorphologic parameter of a watershed which underlines features such as lithology, infiltration capacity and relief aspects of the watershed terrain. Drainage texture (D_t) is the ratio of the total number of stream segments of all orders to the perimeter of that area (Horton, 1945). Smith (1939) classified five different categories of D_t namely very coarse (<2), coarse (2 to 4), moderate (4 to 6), fine (6 to 8) and very fine (>8). The drainage textures of the eight sub-watersheds vary from coarse to very fine. The sub-watershed located in the downstream part of Ujh catchment (SW5, SW6, SW7 and SW8) possess coarse drainage texture; however, sub-watersheds of upstream part or hilly region (SW1,SW3 and SW4), comprise moderate to very fine texture. The more finer the texture, more is the dissection, leading to 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.

4.1.2.4 Form Factor (R_f)

Form factor is a dimensionless property and is used as a quantitative expression of the shape of basin form. The values of form factor of the sub-watersheds in the present case are in between 0.13-0.56. According to form factor, SW1, SW4, SW7 and SW8 are relatively more elongated due to low values of form factor, while SW2, SW3, SW5 and SW6 are have higher values of form factor and hence are less elongated. The basins with high form factors have high peak flows of shorter duration, whereas, elongated drainage basins with low form factors have lower peak flow of longer duration.

4.1.2.5 Infiltration Number

The infiltration Number is defined as the product of Drainage Density (D_d) and Drainage Frequency (F_s). Sub-watershed SW6 has the lowest infiltration number of 10.34, while the Sub-watershed SW4 has the highest infiltration number of 25.81 among all sub-watersheds in Ujh catchment. Higher the infiltration number, lower will be the infiltration and consequently higher will be the 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 for SW1, SW2 and SW4 reveal that these sub-watersheds are of impermeable lithology and higher relief.

4.1.2.6 Circulatory Ratio (R_c)

The circulatory 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 (for a line) to 1 (for a circle). The Circulatory ratio for all sub-watersheds is in the range of 0.34 to 0.68. It is clear from the Fig. 4 that SW7 is elongated and hence attributed to low value of circulatory ratio (0.34), however, SW6 is circular in nature and hence associated with higher value of circulatory ratio (0.68).

4.1.2.7. Elongation Ratio (R_e)

It is defined as the ratio between the diameter of a circle with the same area as 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 Ujh catchment area SW1, SW4, SW7, SW8 have high relief (consisting high average slope) and hence associated with low values of elongation ratio.

4.1.2.8 Length of Overland Flow (L_o)

The term length of overland flow 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. Overland flow lengths range from 122.56 meters to 189.22 meters in Ujh sub-watersheds. SW4 has the highest relief among all sub-watersheds and hence has low length of overland flow i.e. 122.56 meters. Smaller the length of overland flow, quicker the surface runoff will enter streams, indicating a well-developed drainage network with higher slope. In such watersheds a significant amount of surface runoff is contributed to the stream discharge for even a low amount of rainfall.

4.1.2.9 Compactness constant (C_c)

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 standpoint because it will yield the shortest time of concentration before peak flow occurs in the basin. The values of C_c in the eight sub-watersheds of Ujh catchment varies from 1.21 to 1.72 showing variations across the watersheds. It can be shown from the Fig. 4 that SW6 is somewhat circular in shape with a low compactness coefficient (close to unity). However, SW5 and SW7 have higher values of C_c due to their elongated shape.

Table 5 : Aerial Aspect of the Ujh River Catchment

Sub-Watershed	D_d (km/km^2)	F_s (no./km^2)	I	R_c	R_f	R_e	T	L_o (m)	C_c
SW1	3.77	6.37	24.05	0.54	0.17	0.47	19.06	132.50	1.36
SW2	3.83	5.95	22.80	0.50	0.56	0.84	12.26	130.52	1.41
SW 3	3.51	4.70	16.49	0.57	0.43	0.74	23.08	142.50	1.32
SW4	4.08	6.33	25.81	0.48	0.15	0.44	32.66	122.56	1.44
SW5	2.87	4.12	11.81	0.42	0.32	0.64	6.96	174.23	1.54
SW6	2.64	3.91	10.34	0.68	0.36	0.68	5.02	189.22	1.21
SW7	3.22	4.62	14.86	0.34	0.13	0.41	6.54	155.44	1.72
SW8	3.37	4.97	16.75	0.51	0.17	0.46	11.46	148.46	1.40

4.1.3 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 analyse 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, relief aspect includes the analysis of total relief, relief ratio, relative relief and average slope of all eight sub-watersheds of the Ujh catchment.

4.1.3.1 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). SW1 is characterized by high relief i.e. 3164 m, while SW2, SW3, SW4, SW5, SW7 and SW8 comprise medium to high relief i.e. 1809 m, 1514 m, 2623 m 1033 m, 1472 m, and 1667 m respectively. However, SW6 is characterized by low relief i.e. 425 m. Most of the sub-watersheds are associated with medium to high relief and hence are prone to generation of significant runoff and consequent soil erosion.

4.1.3.2 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 is that it removes the size effect by dividing the total relief by the basin length. In Ujh watershed relief ratio varies from 46.39 m/km (SW6) to

132.34 m/km (SW3) (Table 6). Significantly high relief ratio especially in SW3 indicates the steepness of the principal flow path which can severely erode the bank of the stream.

4.1.3.3 Relative Relief (R_r)

Relative Relief 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 8 sub-watersheds of Ujh catchment varies from 17.92 m/km (SW6) to 45.61 m/km (SW1), indicating the terrain of Ujh catchment is highly undulating. High values of R_r for SW1 and SW3 sub-watershed indicates that these are highly susceptible to soil erosion.

4.1.3.4 Average Slope (S_a)

Average slope of the watershed, S_a has direct influence on the erodibility of the watershed. It has been proved generally observed that more the percentage of slopes more are the erosion, if other factors remain unchanged. The average slope for different sub-watersheds varies between 12.37% (SW6) to 48.12 % (SW1) (Table 6). It was observed that high relief ratio and relative relief sub-watersheds are characterized by high slopes and vice versa.

Table 6. Relief Aspect of the Ujh River Catchment

Sub-Watershed	H (m)	R_h (m/km)	R_r (m/km)	S_a (%)
SW1	3164	91.12	45.61	48.12
SW2	1809	131.46	35.26	40.89
SW 3	1514	132.34	43.06	31.94
SW4	2623	76.56	38.64	40.58
SW5	1033	63.92	20.59	16.01
SW6	425	46.39	17.92	12.37
SW7	1472	62.03	28.00	33.86
SW8	1667	59.74	29.20	23.42

4.1.4 Prioritization of Sub-watersheds using Morphological Parameters

Morphological parameters (linear, aerial and relief) for all sub-watersheds were calculated separately and shown in Table 4-6. For prioritization, all eight sub-watersheds are ranked based upon their corresponding morphological parameter values. Morphological parameters like drainage density, stream frequency, bifurcation ratio, infiltration number and texture ratio have direct relationship with erosivity. Therefore, the sub-watershed having highest numerical value of these individual parameters was assigned rank first and next higher was second and so on. Similarly, aerial parameters like elongation ratio, circulatory ratio, form factor and compactness coefficient having an inverse relationship with erosivity. Therefore, the sub-watershed having lowest value of these individual parameters was assigned rank first and next lower was second and so on. Similarly, sub-watersheds were ranked according to relief aspect as it has direct relationship with erosivity. Finally, based upon all individual ranking, a compound ranking was calculated for each sub-watershed and depicted in Table 7. It is evident from the Table 7 that SW1 has the first priority (lowest value of compound parameter i.e. 3.15) and SW6 has the least priority (highest value of compound parameter i.e. 6.1). The highest priority indicates the greater degree of erosion in the particular sub-watershed making it a potential candidate for applying soil conservation measures. Thus, in order to check soil erosion, treatment has to be started from SW1 and then on to others depending on their priority. The priority map of Ujh catchment is shown in Figure 7.

Table 7: Prioritization of Sub-watersheds of Ujh 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	3	3	8	2	6	3	4	3	3	1	3	1	1	3.1538	1
2	4	2	6	3	4	8	8	4	5	3	2	4	2	4.2308	3
3	5	4	4	5	7	7	7	2	2	5	1	2	5	4.3077	4
4	6	1	7	1	3	2	2	1	6	2	4	3	3	3.1538	2
5	8	7	2	7	2	5	5	6	7	7	5	7	7	5.7692	7
6	1	8	1	8	8	6	6	8	1	8	8	8	8	6.0769	8
7	7	6	3	6	1	1	1	7	8	6	6	6	4	4.7692	6
8	2	5	5	4	5	4	3	5	4	4	7	5	6	4.5385	5

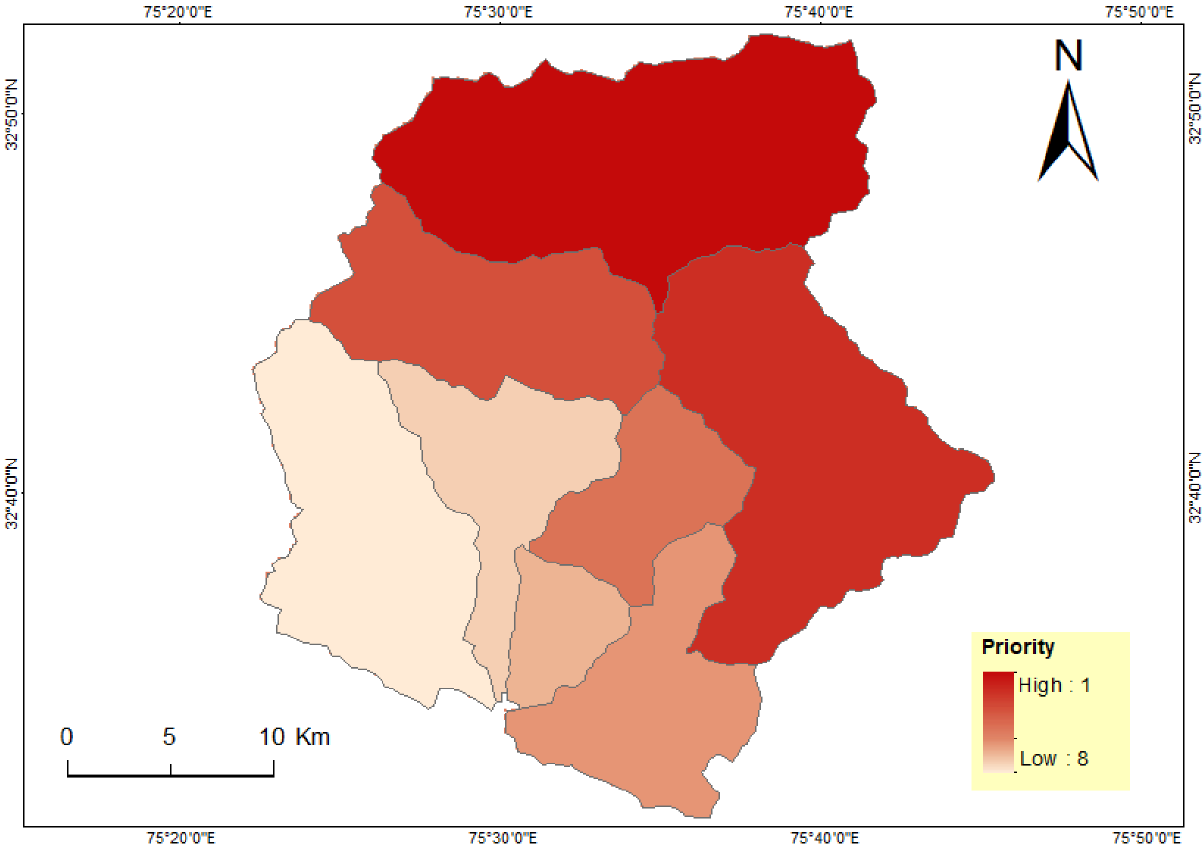


Fig. 7 : Sub-watershed wise priority map of Ujh catchment

4.2 Estimation of Sediment Production Rate (SPR) using morphological parameters

Sediment production rate (SPR) for various sub-watersheds was estimated using equation described in the literature and tabulated in Table 8. From this analysis, the highest SPR was found to be 3.96 ha-m/100 sq.km/yr for SW1, indicating that the sub-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-Nangal on Satluj and Ramganga in Uttarakhand. It was found that the SPR_s estimated for different sub-watersheds using this method is concurrent with the priority as listed in Table 7. Sediment Production Rate (SPR) calculated in this study for an un-gauged catchment not only plays a key role in fixing the priority of watershed but also is vitally important in deciding the volume of the conservation measures to reduce the SPR at certain level. Moreover, priority classification based on standardized SPR gave a better distribution of sub-watersheds between various priority categories.

Table 8 : Estimated Sediment Production Rate (SPR) for different Sub-Watersheds of Ujh Catchment

Particulars	Sub-watershed of Ujh Catchment							
	SW1	**SW2**	**SW3**	**SW4**	**SW5**	**SW6**	**SW7**	**SW8**
SPR (ha-m/100 sq. km./year)	3.96	2.28	2.65	3.79	1.78	2.34	1.18	3.77
SPR (tonne/hectare/year)	5.55	3.19	3.71	5.31	2.49	3.28	1.65	5.27

However, as these values are computed on empirical methods they may be considered as probable maximum values of Sediment production rate from various sub-catchments.

4.3 Land Use/Land Cover (LULC) Change Assessment

LULC change was computed employing the NASA Oak Ridge National Laboratory data set for the year 1985 and 2005 to compute the land use change. The thematic maps have been prepared considering the six major LULC classes prevailing in the study area i.e. Crop land, Evergreen Broad Leaf Forest, Grass Land, Shrub Land, Waste Land and Water Bodies as shown in the table below. It was observed that no major change has taken place in the land use pattern over the time period for which change was assessed. The catchment is a virgin catchment with population confined to small urban and semi-rural pockets of Bani, Bhilwar, etc. which is a very small area in comparison to the catchment. Evergreen broadleaf forest has been found to be reduced by around 4.6%; this change can be attributed to the increase in area of grasslands which are shown to have grown by 95%. Not much change is identified in other classes on account of the catchment being virgin in nature with very less inhabited area.

Table 9 – LULC change in Ujh catchment from 1985 to 2005

Land Use Classes	1985		2005		Area Change	Area Change
	Area (Sq.Km)	%Area	Area (Sq.Km)	%Area	(Sq.Km)	(%)
Water Bodies	57.87	6.67	57.81	6.67	-0.06	-0.10
Grassland	17.94	2.07	35.03	4.04	17.09	95.25
Evergreen Broad Leaf Forest	434.60	50.12	414.51	47.81	-20.09	-4.62
Cropland	41.27	4.76	41.43	4.78	0.16	0.40
Shrubland	311.40	35.91	314.33	36.25	2.93	0.94
Wasteland	3.99	0.46	3.95	0.46	-0.03	-0.84
Total	867.06	100.00	867.06	100.00		

4.4 Hydrological modelling (Rainfall-Runoff modelling) using HEC-HMS model and Trend Analysis

HEC-HMS model has been employed for Rainfall-Runoff modelling in the catchment. Streamflow data (daily) was requested from Central Water Commission, Indus Basin Organization from the year 1984 to 2018 for the discharge site at the Ujh Dam. However, daily discharge data for a period of only 5 years (2010-2015) could be obtained. Upon analysing the data, it was found that the data was not continuous and had prevailing data gaps, while majority of values were found to be non-conforming to the general rainfall pattern prevailing in the Western Himalayan region (Figure 8). This made it difficult to employ the data for modelling purpose as employing this data would not yield any meaningful results. Small duration of the data set and gaps in the data also made it difficult to follow the standard calibration validation procedure of hydrological modelling. Therefore, in view of all the restrictions being posed due to the inadequate data, it was decided to use manual calibration and validation technique to match the peak events and set up the model for the period between 2010-2011 which had reasonably continuous stream discharge data.

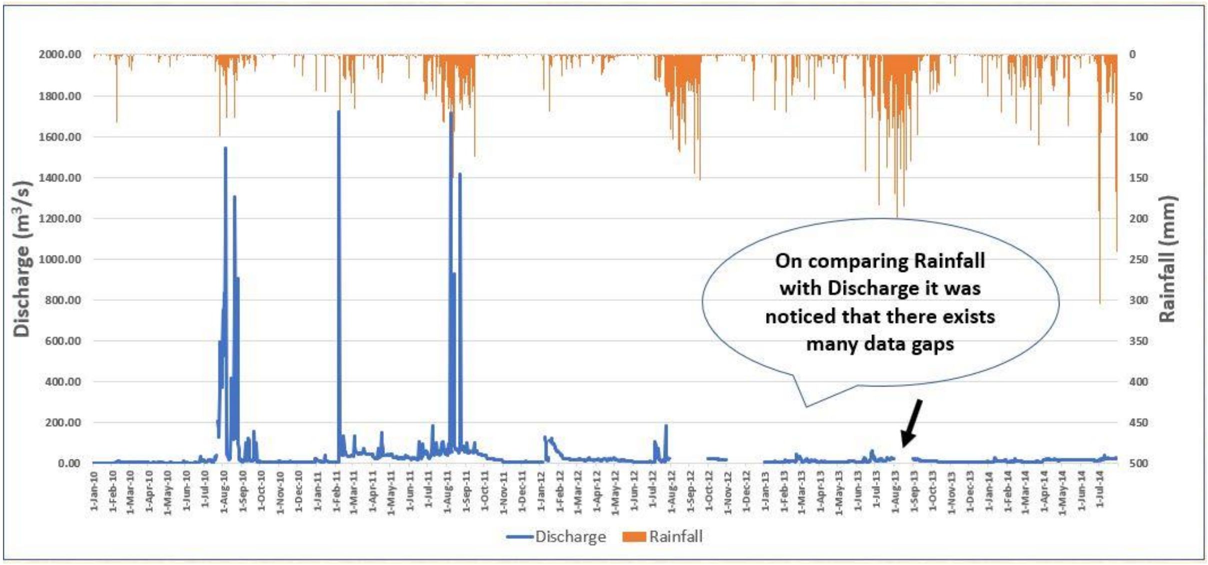


Fig. 8 - IMD gridded rainfall data Vs Discharge data of Ujh

Two gridded rainfall datasets namely, India Meteorological Department (IMD) gridded rainfall product and Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) have been used to compute the rainfall-runoff characteristic and both have been employed separately in the HEC-HMS model using manual calibration technique. It was noticed that for the study area both the data sets exhibited comparable values of rainfall.

4.4.1 Preparation of Input Data for HEC-HMS model

For setting up the HEC-HMS model a variety of data are required, mainly the climatic forcing, hydrologic data, terrain data etc. The source, scale, period of the various data used in the study are depicted in the following table.

Table 10 : Type of data used

Data	**Source**	**Scale**	**Period**	**Description**
Topographic Data	SRTM	30 m	-	Digital Elevation Model
Hydrological Data	CWC	Daily	2010-11	Discharge
Meteorological Data	IMD	Daily, 0.25° spatial resolution	1951-2011	Gridded Precipitation and Temperature
	APHRODITE	Daily, 0.25° spatial resolution	1951-2011	Gridded Precipitation

SRTM – Shuttle Radar Topography Mission
CWC – Central Water Commission
IMD – India Meteorological Department
APHRODITE – Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources

Although the catchment area of Ujh is approximately 870 km^2 it has only one discharge measuring point at Ujh Dam site which has been considered as the outlet of the catchment and the entire study is focused upto this point. The details for preparation of the data are described below:

4.4.1.1 Digital Elevation Model

The digital elevation model (DEM) of Ujh catchment was generated using Shuttle Radar Topography Mission (SRTM) data. The Shuttle Radar Topography Mission is an international project spearheaded by the U.S. National Geospatial-Intelligence Agency (NGA) and the U.S. National Aeronautics and Space Administration (NASA). The Shuttle Radar Topography Mission (SRTM) is an international research effort that obtained digital elevation models on a near-global scale from 56° S to 60° N, to generate the most complete high resolution digital topographic database of Earth prior to the release of the ASTER GDEM in 2009.

The elevation models derived from the SRTM data are used in geographic information systems. They can be downloaded freely over the Internet, and their file format (.hgt) is widely supported. The GDEM's pre-production accuracy estimates were 20 meters at 95% confidence for vertical data, and 30 meters at 95% confidence for horizontal data. For this study, grids covering the study areas were downloaded from internet and DEMs of the study areas were prepared (Figure 9).

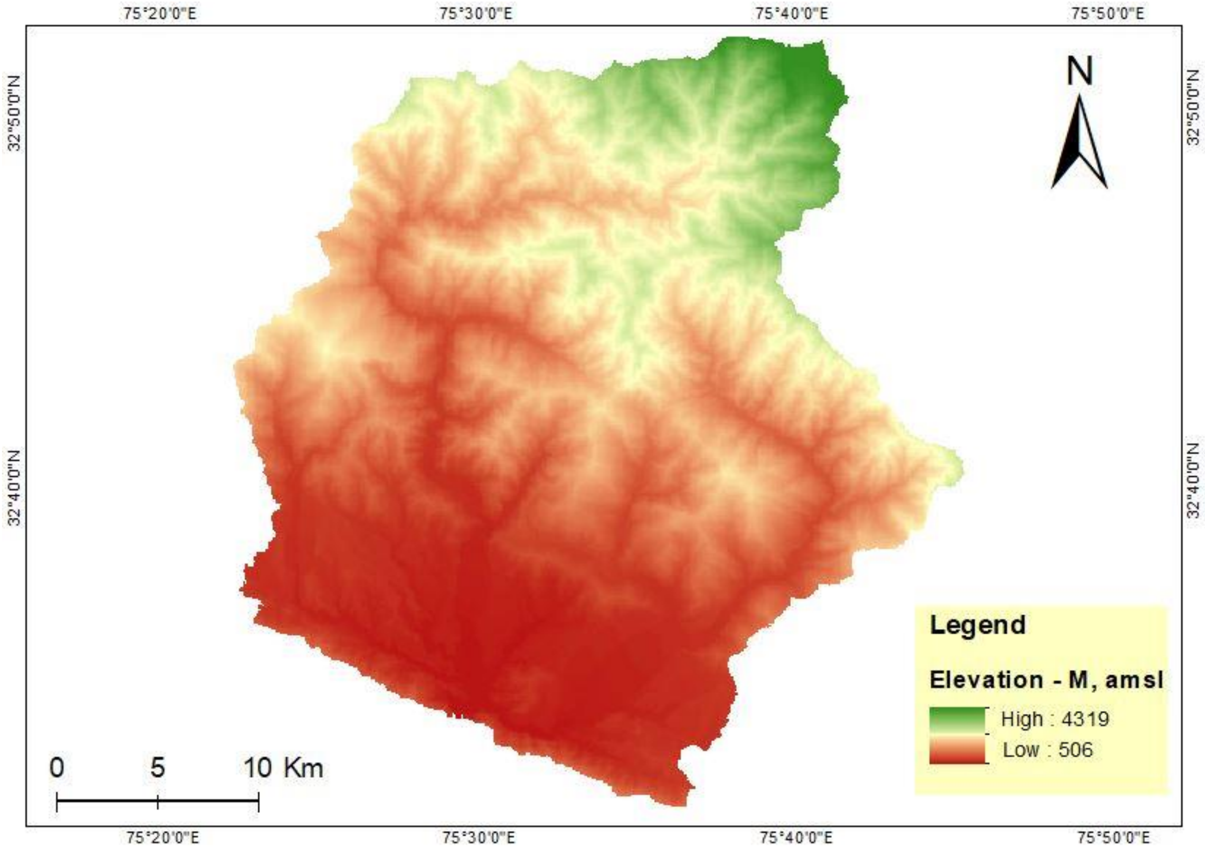


Fig. 9 – DEM of Ujh river catchment

4.4.1.2 Hydrological Data (Streamflow Discharge)

The daily discharge data monitored by CWC at Ujh dam site gauging site was utilized in the study. This gauging site was established for the multipurpose project and was closed in 2015. The data for the years from 2010-2015 for Ujh dam gauging site was procured, processed and utilized. The data from 2010-11 has been employed for running the HEC-HMS model.

4.4.1.3 Meteorological Data

Gridded rainfall datasets from IMD and APHRODITE at 0.25^{o} spatial resolution has been utilised to obtain precipitation and temperature values for the period of study i.e., 2010-11. IMD rainfall has been widely used in a variety of studies (Mishra et al., 2014; Deshpande et al., 2016; Beria et al., 2017; Bisht et al., 2017; 2018; Meher et al., 2017; Sharma and Mujumdar, 2017; Smitha et al., 2018). IMD rainfall data were developed utilizing the daily rainfall observations with varying periods of records of 6,955 stations after quality control. Owing to an extensive number of rain gage stations used in the preparation of the data set and high spatial resolution, it captures the rainfall climatology, spatial distribution, and orographic effects with reasonable accuracy; readers are encouraged to refer Pai et al. (2014) for further details. IMD gridded temperature data was developed using quality control records of 395 stations and has been used in a range of studies published in the recent past (Kumar et al., 2013; Deshpande et al., 2016; Beria et al., 2017; Chakraborty et al., 2017; Sharma and Mujumdar, 2017; Paul et al., 2018; Smitha et al., 2018). To ensure the consistency in spatial resolution of the data set, gridded temperature record was remapped from 1^o to 0.25^o spatial resolution using bilinear interpolation following Sharma and Mujumdar (2017). Model has been set up separately for both the data sets and results from both the data sets have been analysed separately. APHRODITE data has been reported to give better results in the Western Himalayan Region. The climate over the western Himalayas is colder and drier than that of other Himalayan regions, and therefore, the daily temporal resolution of APHRODITE allows detection of precipitation events that are missed at the monthly time resolution of other data sets (Dimri et al., 015). Therefore, it was employed to see whether there is any variation between the results obtained from IMD datasets or whether they are in conformity with each other.

4.4.1.4 Calculation of Time of Concentration (T_c)

To assess the catchment response behaviour, time of concentration (T_c) was computed using Kirpich Equation (1940). Length of longest flow path and Straight line path were determined using GIS tools (Figure 10). The time of concentration for the catchment was found to be **5.10 hours**. This computation gives an idea about the lag between rainfall/storm event and stream discharge peaks. Time of concentration were also computed for the individual sub-basins in the model which was given as an input value.

Kirpich Equation (1940)

$$T_c = 0.01947 * (K^{0.77})$$

Time of Concentration (T_c) = 0.01947 times K raised to power 0.77

Where,

$$K = \sqrt{\frac{L^3}{\Delta H}}$$

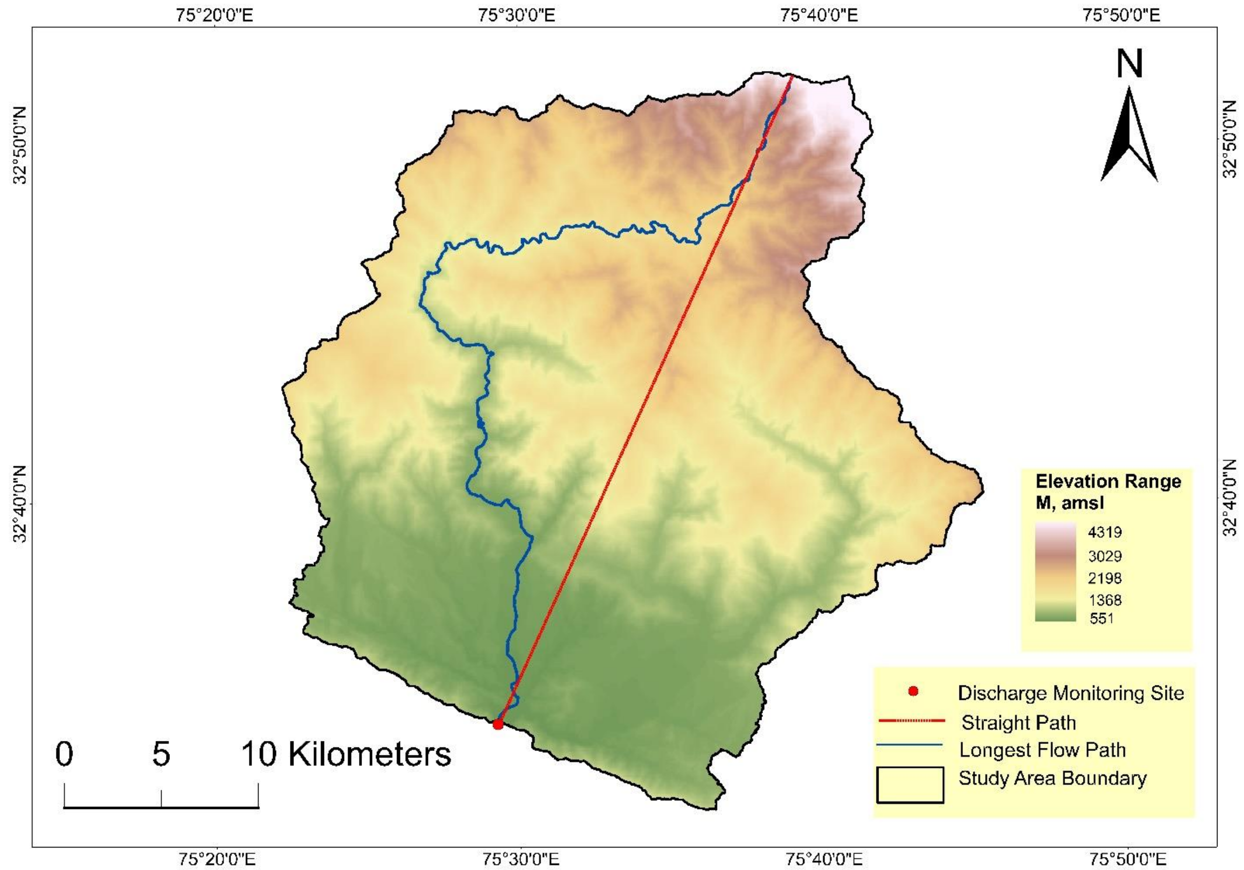


Fig. 10 – Longest flow path and Shortest flow path in Ujh Catchment

4.4.1.5 Redistribution of Gridded Rainfall

Area weighted rainfall was also calculated using the below mentioned formula for both IMD and APHRODITE gridded rainfall datasets for further employing into the HEC-HMS model (Figure 11&12).

$$P_w = \frac{P_1A_1+P_2A_2+P_3A_3+\ldots PnAn}{A1+A2+A3\ldots An}$$

Where P1 – Rainfall value of Grid 1

A1 – Area of Sub Basin lying in that grid

P2 – Rainfall value of Grid 2

A2 – Area of Sub Basin lying in that grid & so on

In the absence of hourly of sub-daily rainfall data, time distribution coefficient for the region to distribute the daily rainfall values in hourly time steps are often used (Bisht et al., 2016). Gridded rainfall values in present study were redistributed using **Time Distribution Coefficients of Cumulative Hourly Rainfall for Zone 7** (CWC,1994) on the daily gridded precipitation values to distribute the rainfall on hourly basis into 6h, 7h, 8h, 9h, and 10h events. These synthetic rainfall distributions were employed in HEC-HMS to identify which distribution corresponds towards a best match for the observed peak flow discharges. It was observed that the hourly synthetic rainfall redistribution into a 9h event produces the best results for the river basin. This process was adopted individually for both IMD and APHRODITE gridded precipitation datasets.

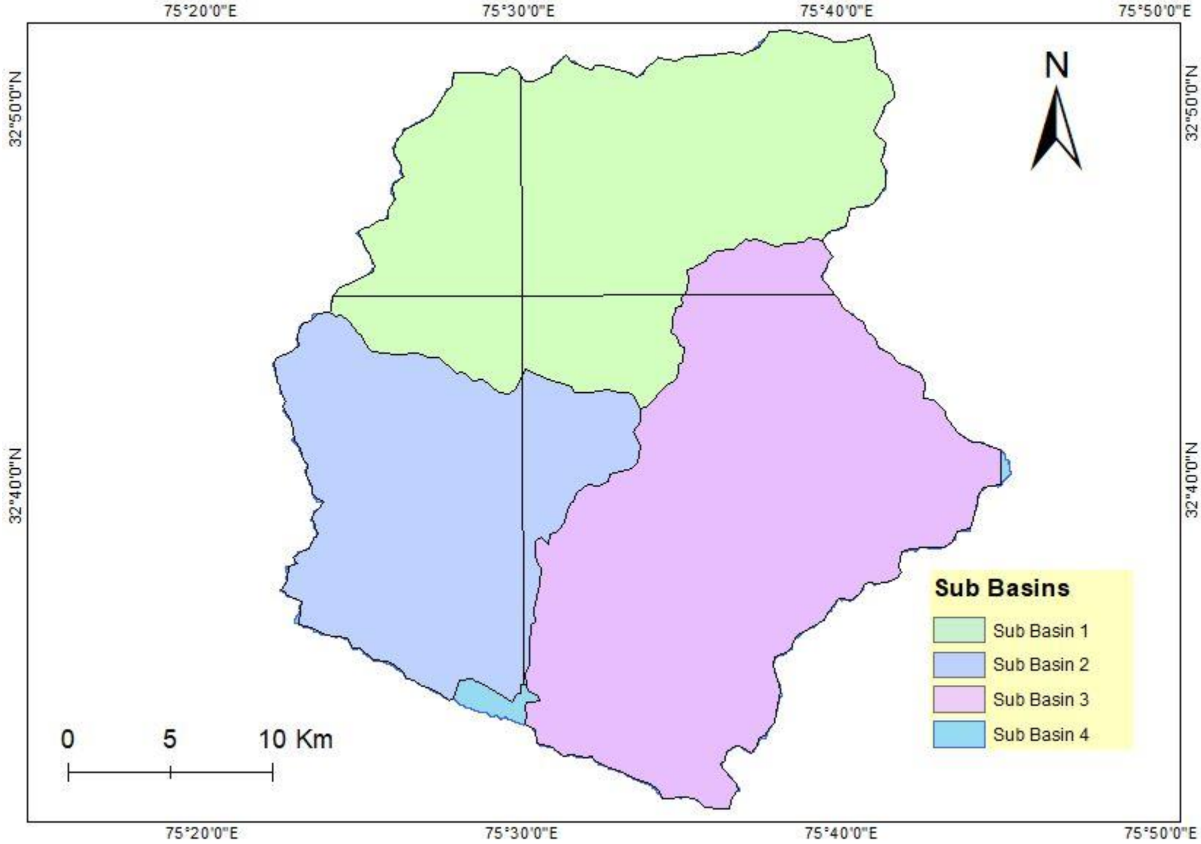


Fig. 11 – Overlap of Sub-Basins over APHRODITE Grids for Weighted Area distribution

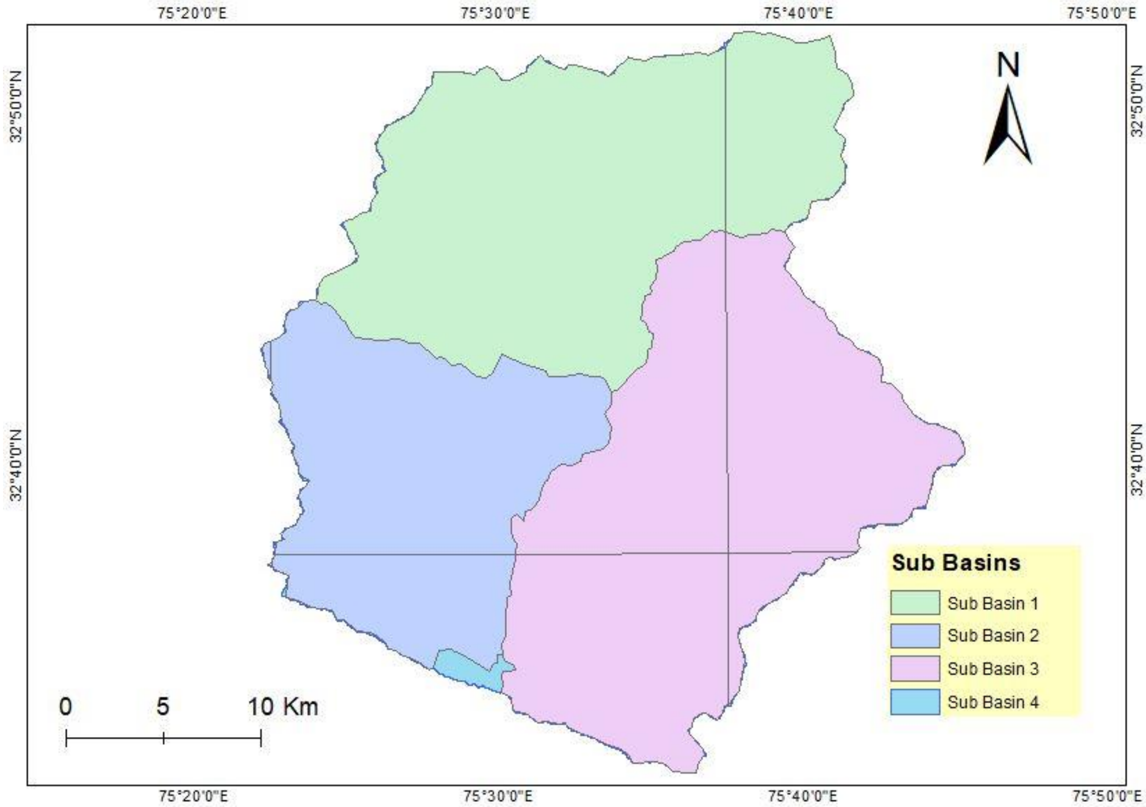


Fig. 12 – Overlap of Sub-Basins over IMD Grids for Weighted Area distribution

4.4.2 Application of HEC-HMS model

4.4.2.1 Model Setup

HEC-HMS model was set up for Ujh river catchment up to the discharge site located at Ujh dam site. A digital elevation model (DEM) was imported into the HEC-HMS model. A masking polygon was loaded into the model in order to extract the area of interest, delineate the boundary of the watershed and digitize the stream network in the study area. Although, observed discharge data was available only at the outlet of the basin, still 3 sub-basins were made in accordance with the terrain of the catchment for a better understanding of the catchment response. The gridded daily data of rainfall, minimum and maximum temperatures were imported into the model separately for IMD and APHRODITE and employing both the data separately to run the model.

SCS Curve Number method has been employed as 'Loss method' and SCS Unit Hydrograph as 'Transform method'. Initial values of Curve Number for sub-basins have been kept realistic and in line with the general values observed in the Western Himalayan region. Muskingum method has been employed for channel flow routing. Manual calibration has been done by trial and error method to match the peak discharge and flows for the said period in the best possible way as the data was scarce for automatic calibration and validation.

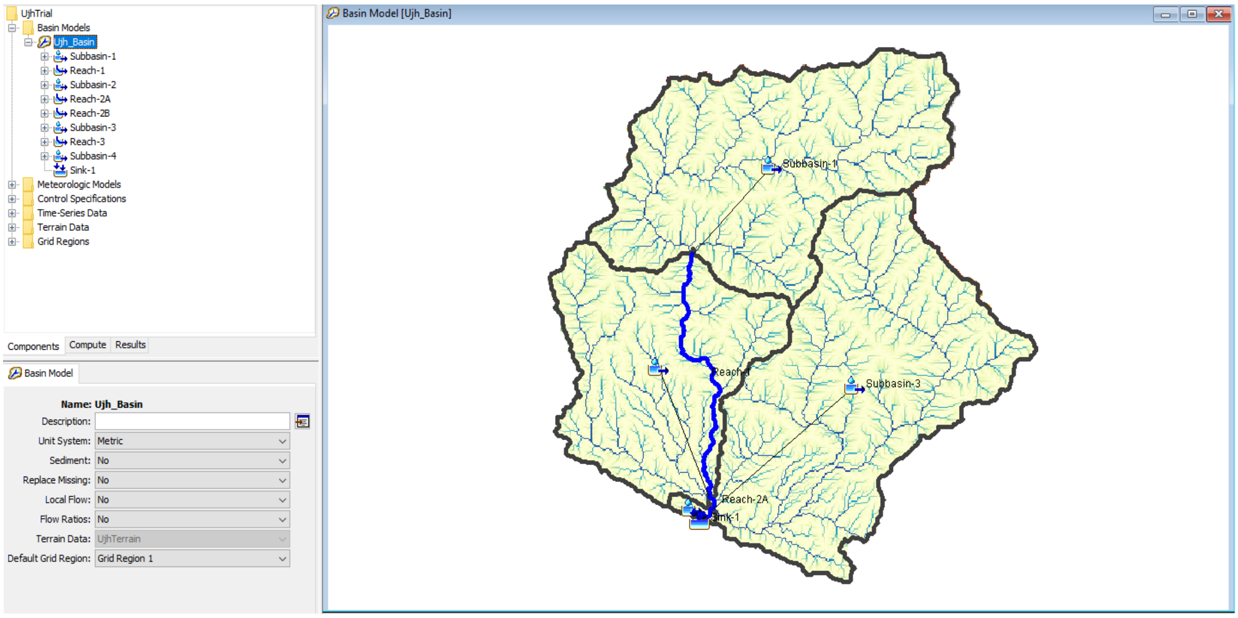


Fig. 13 – Basin model in HEC-HMS

4.4.2.2 Modelling Output

The model was setup separately for both IMD and APHRODITE datasets for the period of 2010-2011 and manually calibrated to simulate observed discharge peaks in the best possible way. The simulated discharge in both the cases are shown in Fig. 14 and Fig. 15. It is evident from the Fig. 14 and Fig. 15 that observed record has may data gaps as not much discharge is observed in the monsoon season contrary to ground reality. It is further important to note that only few peak events are found to be recorded in the observed time series. The reason behind missing data can be attributed to lack of man power and infrastructure to measure continuous discharge as well as to the general understanding that for various design consideration the engineers are chiefly interested in annual maximum values. Despite, unavailability of the continuous time series an attempt was made to calibrate the model against the recorded peaks using trial and error approach. It was found that the calibrated model could capture the recorded peaks with considerable accuracy using IMD and APHRODITE rainfall dataset as shown in Fig. 14 and Fig. 15. Both the rainfall products also yield similar results and infer towards the occurrence of rainfall which should have been translated into considerable runoff contrary to the information extracted from the observed discharge time series.

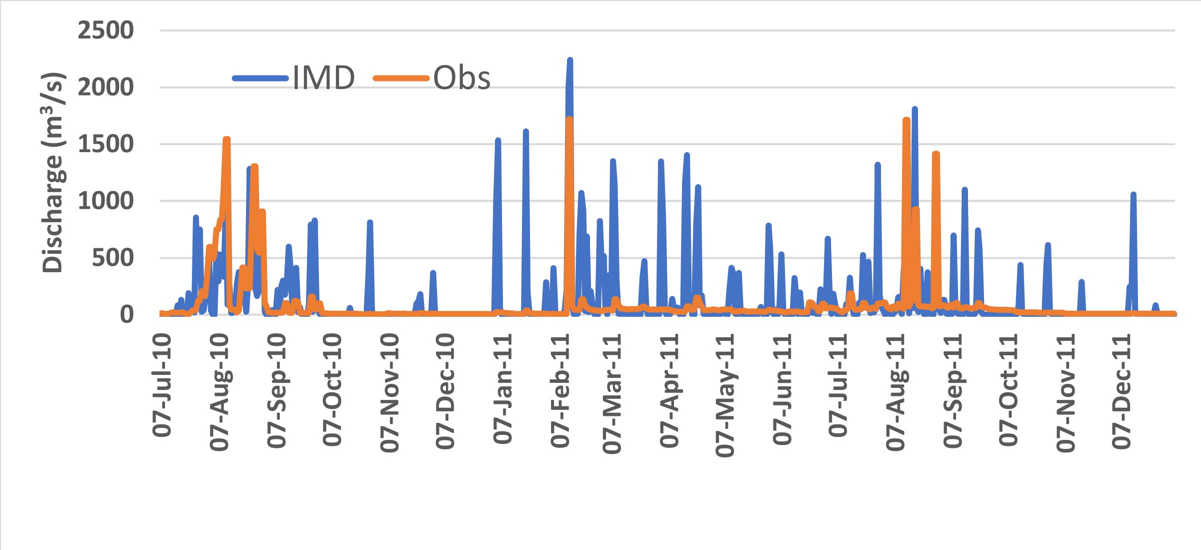


Fig. 14- Simulated Vs Observed discharge data from July 2019- Dec 2011 employing IMD gridded dataset

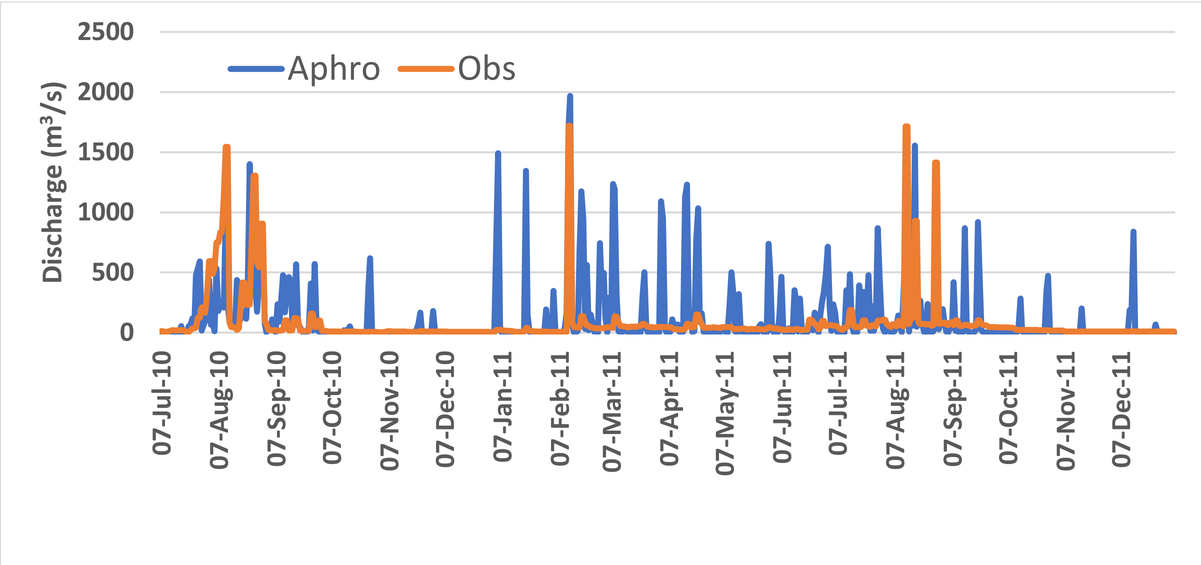


Fig. 15- Simulated Vs Observed discharge data from July 2019- Dec 2011 employing APHRODITE gridded dataset

4.4.2.3 Trend Analysis

The river flow regime was analysed to detect any trend in the maximum discharge of Ujh River. For this the simulated time series were studied in the following two fashions

i. Annual time scale, considering all 12 months

ii. Seasonal time scales, by considering the months (a) when the rainfall is dominated by South-West monsoon, i.e. June to September and (b) when the rainfall is dominated by western disturbance i.e., October to November

Considering above, the time series of maximum simulated discharge values using IMD and APPHRODITE data were extracted from annual time series, from the time period of South-West monsoon, and Western Disturbances. In this way, a total of six time series were prepared. Before applying the test, these time series were examined for serial correlation and significance of autocorrelation was tested using Anderson correlation bounds at 10% significance level. It was found that there is no auto-correlation in the time series. Thereafter, the MK test was applied on to detect the trend in the time series and Thiel-Sen's estimator was used to estimate the magnitude of change. Except the simulated maximum discharge using APHRODITE in western disturbance which was found to be increasing at 5% significance level none of the trend was found to be significant at 10% significance level. It is to be noted that both IMD and APHRODITE showed the increase in the maximum simulated discharge during Western disturbance. Interestingly, for South-West monsoon simulated maximum discharge using either dataset showed a downward trend which was not statistically significant. Contrary to seasonal flows, the diametric, though not statistically significance, trends were observed for annual maximum discharge wherein the IMD simulated discharge showed a downward trend whereas the APHRODITE simulated discharge showed an upward trend.

Table 11 : Trend analysis of discharge in Ujh river catchment

Season	**Z Value**	**Trend**	**Statsitical Significance**	**Percent_Change**
		IMD		
Annual	-0.86	(-)	Not Significant	-11.3
WD	**1.29**	**(+)**	Not Significant	21.4
SW	-1.57	(-)	Not Significant	-34.3
		APHRODITE		
Annual	0.91	(+)	Not Significant	13.4
WD	**2.05**	**(+)**	Significant at 5% significance level	37.6
SW	-0.42	(-)	Not Significant	-8.3

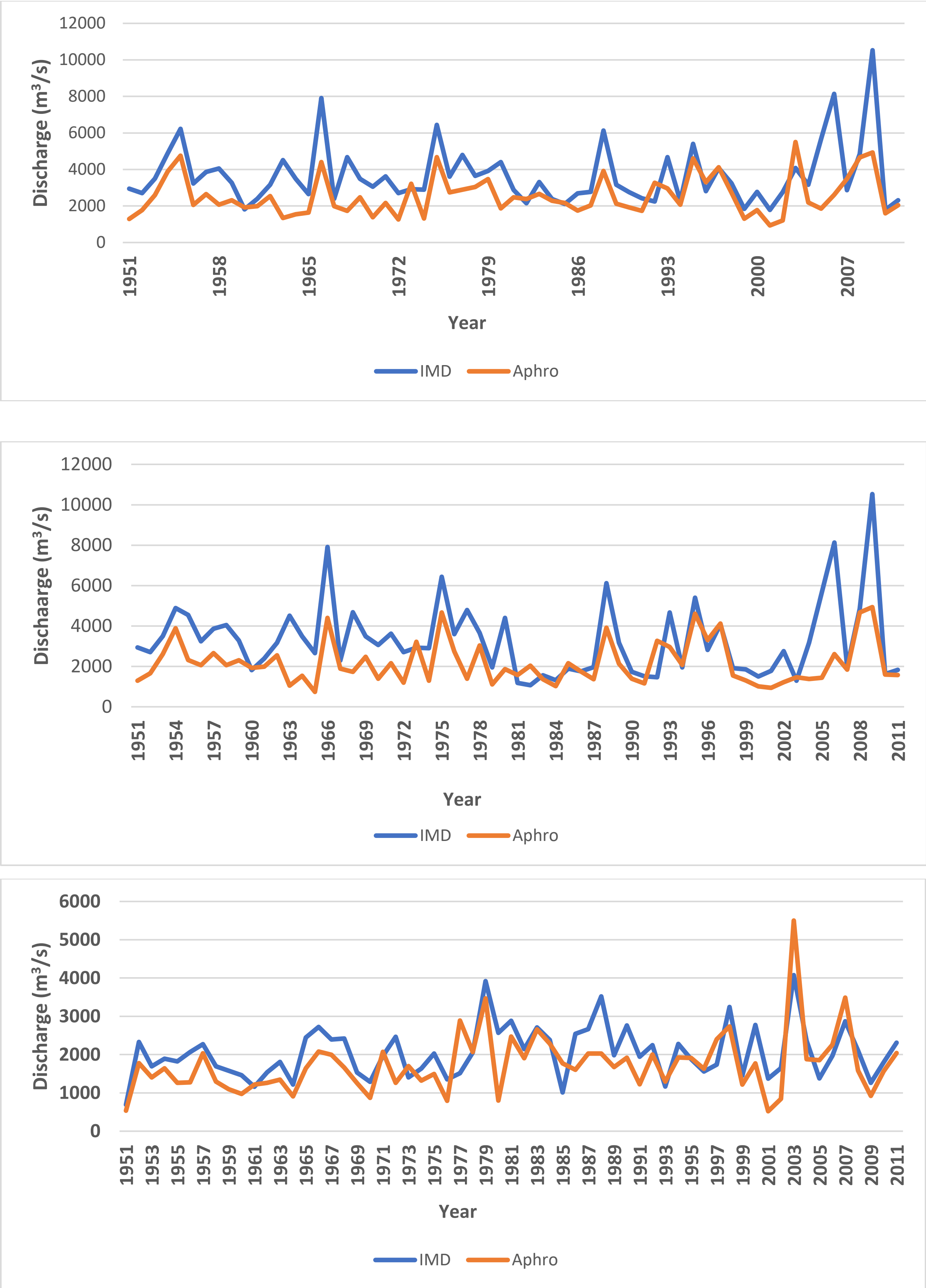


Fig. 16 – Trends in Average Discharge in Annual, South-West and Western Disturbance season

SUMMARY AND CONCLUSION

The present study was envisaged to cover three hydrological aspects of River Ujh, a Western Himalayan River: (i) Morphometric Analysis and prioritization of catchment; (ii) Assessment of the Land Use and Land Cover change (LULC) in the Ujh catchment; (iii) To set up hydrological model using HEC-HMS for Ujh catchment. The summary of the study and conclusions drawn with respect to these three aspects have been elaborated in the following sections:

5.1 Morphometric Analysis and prioritization of catchment

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 to a large extent. In a developing country like India where availability of data is a major constraint, to prepare a fruitful project plan, a morphological parameters based methodology as discussed in this study has high practical utility. 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 data used in the study are freely available, the proposed approach is parsimonious in terms of funds and also time saving. The vulnerability of the watersheds once identified, would help in facilitating investment decision and making best use of the available resources. The proposed approach is not only fixing the priority but it also quantifies the erosivity in terms of SPR values within the catchment, which is helpful in apportioning the treatment activities in proportion to the erosivity values. Moreover, it can be helpful to allocate the budget for treatment in different watersheds within the catchment. In the present study, as there was no sediment data available at any of the sub-basin outlets, sediment production rate (SPR) estimated for different sub-watersheds of Ujh catchment cannot be compared quantitatively with the sediment yield data at the watershed outlet.

5.2 Assessment of LULC Change

The LULC maps have been obtained for the years 1985, 1995 and 2005 and data prepared by Oak Ridge National Laboratory, National Aeronautical Space Administration (NASA) under NASA's Land Use/ Land Cover change programme has been used. The thematic maps have been prepared considering the six major LULC classes prevailing in the study area i.e. Crop land, Evergreen Broad Leaf Forest, Grass Land, Shrub Land, Waste Land and Water Bodies as shown in the summary table below. It was observed that no major change has taken place in the land use pattern over the time period for which change was assessed. The catchment is a virgin catchment with population confined to small urban and semi-rural pockets of Bani, Bhilawar, etc. which is a miniscule area in comparison to that of the catchment. Evergreen broadleaf forest has been found to be reduced by around 4.6%; this change can be attributed to the increase in area of grasslands which are shown to have grown by 95%. Not much change is identified in other classes on account of the catchment being virgin in nature with very less inhabited area.

Land Use Classes	**1985**		**2005**		**Area Change**	**Area Change**
	Area (Sq.Km)	**%Area**	**Area (Sq.Km)**	**%Area**	**(km^2)**	**(%)**
Water Bodies	57.87	6.67	57.81	6.67	-0.06	-0.10
Grassland	17.94	2.07	35.03	4.04	17.09	95.25
Evergreen Broad Leaf Forest	434.60	50.12	414.51	47.81	-20.09	-4.62
Cropland	41.27	4.76	41.43	4.78	0.16	0.40
Shrubland	311.40	35.91	314.33	36.25	2.93	0.94
Wasteland	3.99	0.46	3.95	0.46	-0.03	-0.84
Total	867.06	100.00	867.06	100.00		

5.3 Runoff simulation through HEC-HMS and Trend Analysis

One of the objectives of the study was to model the rainfall-runoff process of the catchment and simulate flows. HEC-HMS model has been employed for simulation of flows in this study. The data required for the model set up has been procured, processed and digitized using ArcMap software package and GIS capabilities in-built in the HEC-HMS model. Due to scarcity and paucity of the discharge data obtained from CWC, the model has been manually calibrated for the period 2010-11 using trial and error method to simulate and match the peak discharge. The model was able to simulate the observed peak discharges and under the restrictions posed by data availability, it is assumed that the parameter has been calibrated and the model is set up for the catchment. To analyse the streamflow regime over a period of time, the maximum discharge over the last 60 years was analysed using two non-parametric tests, Mann-Kendal test and Theil-Sen's estimator. Except for the simulated maximum discharge during the Western Disturbance dominated season using APHRODITE data, none of the trends was found to be statistically significant. Due to the limited calibration of model in the absence of good quality data, these results require further investigation, which can be achieved in subsequent studies wherein adequate data availability for model calibration and validation is ensured.

References

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"NordicHydrol.37(2),129-142(2006).
4. Anbazhagan S, Ramasamy SM (2005) Evaluation of areas for artificial groundwater recharge in Ayyar basin, Tamil Nadu, India through statistical terrain
5. Bajwa, H.S., Tim, U.S., 2002. Toward immersive virtual environments for GIS based oodplain modeling and visualization. In: Proceedings of 22nd ESRI User Conference, San Diego, TX, USA.
6. 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.
7. Beria, H., Nanda, T., Singh Bisht, D. and Chatterjee, C. (2017) Does the GPM mission improve the systematic error component in satellite rainfall estimates over TRMM? An evaluation at a pan-India scale. Hydrology and Earth System Sciences, 21(12), 6117–6134. https://doi.org/10.5194/hess- 21-6117-2017.
8. Bisht DS, Chatterjee C, Kalakoti S, et al (2016) Modeling urban floods and drainage using SWMM and MIKE URBAN: a case study. Nat Hazards 84:749–776. https://doi.org/10.1007/s11069-016-2455-1
9. Bisht, D.S., Chatterjee, C., Raghuwanshi, N.S. and Sridhar, V. (2017) An analysis of precipitation climatology over Indian urban agglomeration. Theoretical and Applied Climatology, 133, 421–436. https://doi.org/10.1007/ s00704-017-2200-z.
10. Bisht DS, Chatterjee C, Raghuwanshi NS, Sridhar V (2018) An analysis of precipitation climatology over Indian urban agglomeration. Theor Appl Climatol 133:421–436. https://doi.org/10.1007/s00704-017-2200-z
11. Bisht DS, Chatterjee C, Raghuwanshi NS, Sridhar V (2018) Spatio-temporal trends of rainfall across Indian river basins. Theor Appl Climatol 132:419–436. https://doi.org/10.1007/s00704-017-2095-8
12. Central Water Commission (1994), Flood Estimation Report for Western Himalayas – Zone 7
13. 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.

14. Deshpande, N.R., Kothawale, D.R. and Kulkarni, A. (2016) Changes in climate extremes over major river basins of India. International Journal of Climatology, 36(14), 4548–4559. https://doi.org/10.1002/joc.4651.

15. 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.

16. Dimri, A.P., D. Niyogi, A.P. Barros, J. Ridley, U.C. Mohanty, T. Yasunari and D.R. Sikka (2015), Western Disturbances : A review. Rev. Geophys., 53, 225-246, doi: 10.1002/2014RG000460.

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

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

19. 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.

20. Feldman, A.D., 2000. Hydrologic Modeling System HEC-HMS, Technical Reference Manual. U.S. Army Corps of Engineers, Hydrologic Engineering Center, HEC, Davis, CA, USA.

21. 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.

22. 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

23. 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.

24. S. Grauso, G. Fattoruso, C. Crocetti, A. Montanari. Estimating the suspended sediment yield in a river network by means of geomorphic parameters and regression relationships. Hydrology and Earth System Sciences Discussions, European Geosciences Union, 2008, 12 (1), pp.177-191.

25. 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,

26. Hack, J.T. (1973) Stream-Profiles Analysis and Stream-Gradient Index. Journal of Research of the U.S. Geological Survey, 1, 421-429

27. 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

28. 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.

29. Jose CS, Das DC (1982) Geomorphic prediction models for sediment production rate and intensive priorities of watersheds in Mayurakshi catchment, in Proceedings of the international symposium on hydrological aspects of mountainous watershed held at School of Hydrology, No. 4–6, vol. I (University of Roorkee, 1982), pp 15–23

30. Kalita, D.N., August 2008. A study of basin response using HEC-HMS and subzone reports of CWC. In: Proceedings of the 13th National Symposium on Hydrology. National Institute of Hydrology, Roorkee, New Delhi.

31. Kumar, K.N., Rajeevanb, M., Pai, D.S., Srivastava, A.K. and Preethi, B. (2013) On the observed variability of monsoon droughts over India. Weather and Climate Extremes, 1, 42–50. https://doi.org/10.1016/j.wace.2013.07.006.

32. Mishra, V., Shah, R. and Thrasher, B. (2014) Soil moisture droughts under the retrospective and projected climate in India. Journal of Hydrometeorology, 15, 2267–2292. https://doi.org/10.1175/JHM-D-13-0177.1.

33. Muthukrishnan, S., Harbor, J., Lim, K.J., Bernard, A.E., 2006. Calibration of a simple rainfall-runo_ model for long-term hydrological impact evaluation. Urban and Regional Information Systems Association (URISA) Journal 18 (2), 35-42.

34. 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).

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. 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.

37. Pai, D.S., Sridhar, L., Rajeevan, M., Sreejith, O.P., Satbhai, N.S. and Mukhopadyay, B. (2014) Development of a new high spatial resolution ($0.25^o \times 0.25^o$) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam, 65(1), 1–18.

38. Pakhmode, V., Kulkarni, H., and Deolankar, S.B (2003): Hydrological drainage analysis in watershed programme planning: A case study from the Deccan basalt, India. Hydrogeology Journal, 11:595 – 604.

39. 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

40. 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.

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

42. Roy, P.S., P. Meiyappan, P.K. Joshi, M.P. Kale, V.K. Srivastav, S.K. Srivasatava, M.D. Behera, A. Roy, Y. Sharma, R.M. Ramachandran, P. Bhavani, A.K. Jain, and Y.V.N. Krishnamurthy. 2016. Decadal Land Use and Land Cover Classifications across India, 1985, 1995, 2005. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1336

43. 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.

44. Schumm SA (1956) Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geol Soc Am Bull 67:597–646

45. Schwab, G.O., Fangmeier, D.D., Elliot, W.J., Frevert, K.R., 2005. Soil and Water Conservation Engineering, fourth ed. John Wiley and Sons, New York, p. 508.

46. Schumm SA (1963) Sinuosity of alluvial rivers in the great plains. Bull Geol Soc Am 74:1089–1100

47. Sharma, S. and Mujumdar, P. (2017) Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India. Scientific Reports, 7, 15582. https://doi.org/10.1038/s41598-017-15896-3.

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

49. Smitha, P.S., Narasimhan, B., Sudheer, K.P. and Annamalai, H. (2018) An improved bias correction method of daily rainfall data using a sliding window technique for climate change impact assessment. Journal of Hydrology, 556, 100–118. https://doi.org/10.1016/J.JHYDROL.2017.11.010.

50. 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.

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

52. U.S. Army Corps of Engineers, 2008. Hydrologic Modeling System (HEC-HMS) Applications Guide: Version 3.1.0. Institute for Water Resources, Hydrologic Engineering Center, Davis, CA.

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

54. Zernitz, E.R. (1932) Drainage Patterns and Their Significance. Journal of Geology, 40, 498-521. http://dx.doi.org/10.1086/623976