Impacts of the Geo-environmental setting on the flood vulnerability at watershed scale in the Jhelum basin.

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By

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M.Sc., NET (CSIR-UGC)

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Certificate

This is to certify that the M. Phil. Thesis entitled **"Impacts of the Geo-environmental setting on the flood vulnerability at watershed scale in the Jhelum basin."** is the original research work carried out by **Mr. Gowhar Meraj**, as a whole time M. Phil. research scholar in Environmental Science, University of Kashmir, Srinagar. This work has been carried out under our joint supervision and has not been submitted to this University or to any other University so far and is submitted for the first time to the University of Kashmir. It is further certified that this thesis is fit for the submission for the degree of ***Master of Philosophy in Environmental Science*** and the candidate has fulfilled all the statutory requirements for the completion of the M. Phil. Programme.

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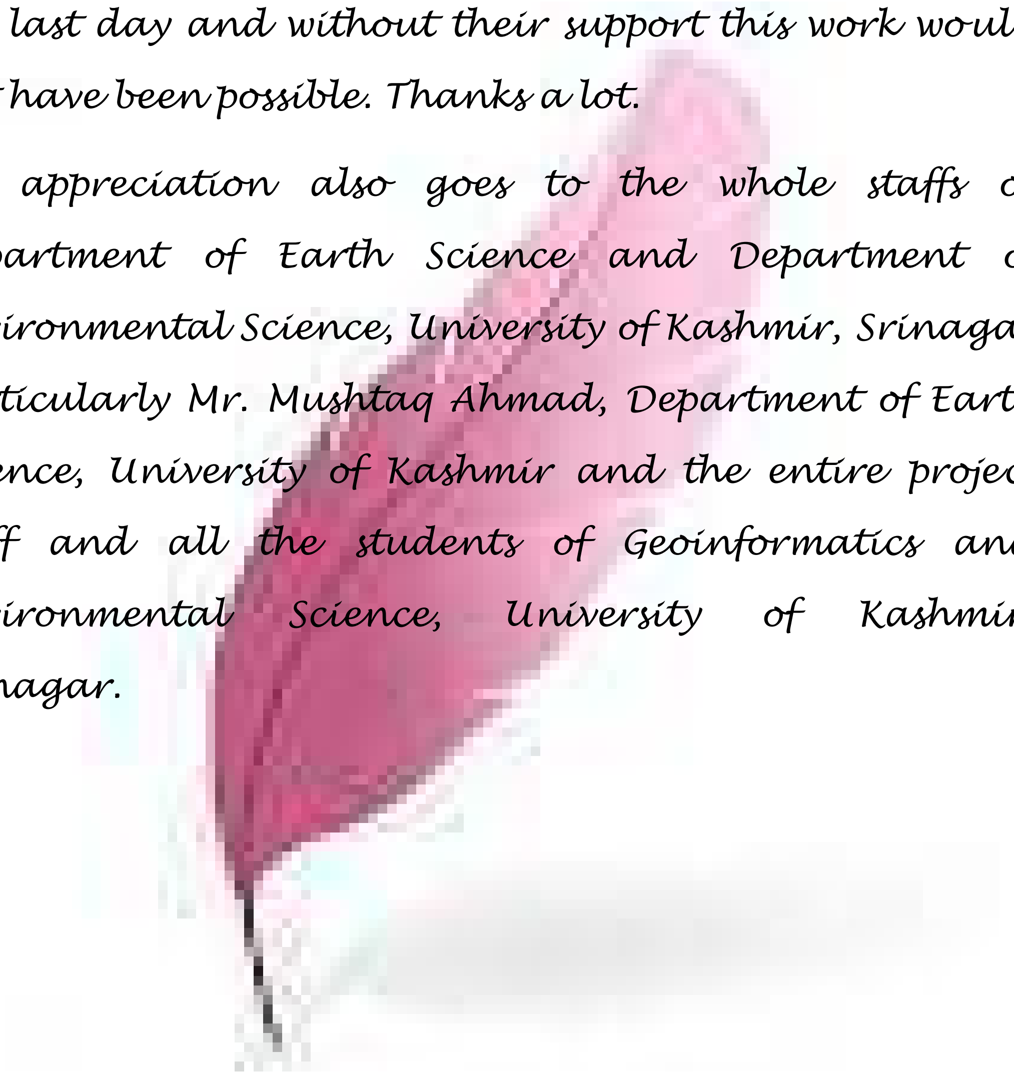

Gowhar Meraj

DEDICATED TO THE WHOLE
HUMANITY IN PARTICULAR TO
MY FAMILY

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Chapter: 1

Introduction

Man has always been overawed by the splendour of this universe. In ancient times, man would associate day to day processes of the nature to supernatural powers. In modern times an enormous amount of research has been undertaken to understand the overall mechanism of natural processes and the curiosity has not yet died down. However, as the unravelling of natural mechanisms with the help of technology is progressing leaps and bounds, so is increasing the occurrence of natural disasters across the globe. The consequent economic and human loss has pitched the inquisitiveness of modern-man against the massive forces of nature. Among these massive forces, floods pose the most serious threat to human life and property. The problem of flooding and the consequent famines and diseases, puts to risk the human lives and resources with its effect extending to vast stretches of the world. Ranging from minor disruptions to catastrophic consequences, experts have acknowledged the floods as the most impactful natural disaster. The impacts of flood-hazards on a global scale are enormous (Jonkman and Vrijling, 2008). Flooding is the single most destructive type of natural disaster that strikes humans and their livelihoods around the world (U.N., 2004). At global level, flooding constitutes a major and important component of the spectrum of hazards and increasing risks that mankind faces. Spatial and temporal dimensions of this threat have driven the current international and national concerns about the issue of flood hazards.

The main reasons for the increase observed in flood disasters include: An increase in the global temperature due to the effects of climate change (IPCC, 2007); greater susceptibility of river valleys to flooding; population growth and migration of population to coastal areas and river valleys; over exploitation of natural resources and deforestation; growing urbanization and uncontrolled land use change.

There are multiple layers of damage caused due to flooding such as environmental losses, economic damage and loss of life. The damage could be tangible and intangible, depending on whether or not the losses can be assessed in monetary terms. Another distinction is made between the direct damage, caused by physical contact with floodwaters, and the indirect damage, that occurs outside the flooded area (Merz et al., 2004).

India, where floods and other natural disasters are one of the serious geo-hazards, has witnessed alarmingly aggressive floods in recent times due to number of complex factors related to topography, geology, climate and human activity. About 40 million hectares or nearly 1/8th of India's geographical area is flood-prone (Bapalu and Sinha 2005). Among the physiographic divisions of India, the Himalayas have the greatest subaerial maximum relief, torrential rainstorms, frequent cloud bursts and a history of floods augmented by melting glaciers and river action. The floods thus pose a major physical threat to the sustainable development in the Himalayas (Jack Ives., 2004). Furthermore, unscientific human interference with the nature has compounded this problem, there-by posing risk to the life, economy and environment. The recent rains on 14 to 17 June, 2013 in the higher Himalayan reaches caused catastrophic floods and played havoc in the downstream area of Uttarakhand, Himachal Pradesh, Uttar Pradesh and Nepal causing widespread human suffering and sorrow in all these states.

The Himalayas is a vast water reservoir having three major drainage basins: the Indus, the Ganges and the Brahmaputra. The heavy deforestation of the Himalayas during the past 30 years has led to increasing erosion and flooding during the monsoon months. The available data suggests that during the period 1954-1990, more than 2700 billions of rupees were spent on the flood control measures in India, but the annual flood damage increased nearly 40 times and increasing flood affected areas 1.5 times in the period (Agarwal and Narain, 1996). These data emphasize the urgent need for a better understanding of the flood hazard mechanisms in India. The UNDP flood policy study has also called for enhancing research on river morphology, river training, mathematical modelling and land-water interactions so that a robust action plan is put in place to mitigate the flood damages in the country (UN, 2004).

1.1 River flooding

Flood is a consequence of climatological events such as excessive or prolonged rainfall, including snow and ice melt, cloud bursts, failure of dams and storm surges. Floods appear as peaks on hydrographs, when we plot stream discharge against time. These peaks can be intensified by factors associated either with the catchment itself or with the drainage network and stream channels (Ward and Robinson, 2000). As illustrated in the Figure 1.1, there are several causes of flooding in river basins and their influence may vary from basin to basin.

Both natural and human induced events can cause floods. Apart from the severe precipitation, there exist a number of factors that can further affect the process of flooding. Such factors can be human or physical or both, and will exert dominant controls to either intensify or ameliorate a flooding event.

Topography is recognized as a first-order control on the hydrological response of a catchment to rainfall (Brasington and Richards, 1998) and is a major determinant for flood inundation (Bates and De Roo, 2000).

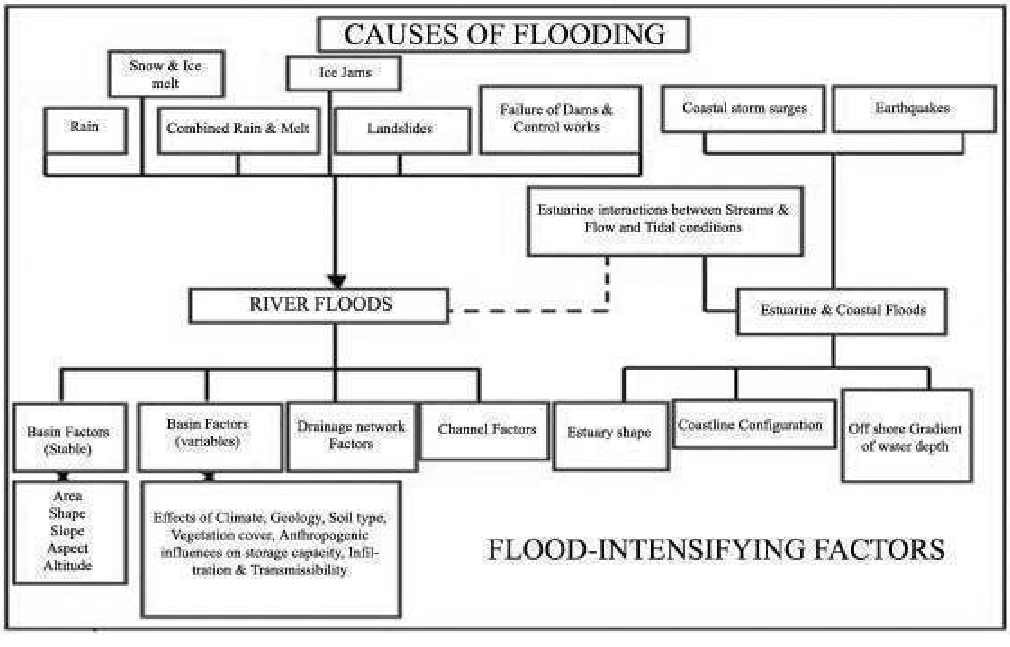


Figure 1.1 Showing causes of Floods and Flood-Intensifying factors (Ward and Robinson, 2000).

The shape of a drainage basin will have an important influence upon the flood hydrograph for a particular catchment. For example, as illustrated in Figure 1.2, basins A and C have extremely contrasting hydrograph shapes. Basin A, with a bifurcation ratio of 17, has only a short period of time, after the onset of a precipitation event, before the discharge increases, reaching its maximum soon after, and then reducing gradually over a long period of time. In contrast, catchment C, with a bifurcation ratio of 2.25, has a longer period after the onset of precipitation, until a peak flow is reached. This period of time is known as the lag, and can be clearly seen on the hydrograph. After a peak flow is reached, the discharge drops rapidly in comparison to that of catchment A, until a constant discharge is reached. The bifurcation ratio was proposed by Strahler (1964), and is a simple measure of basin shape and the internal arrangement of stream segments. Therefore, in elongated basins, such as A, with high bifurcation ratios and greatly unequal flow path lengths, a lower hydrograph peak is observed, but with a more sustained flow, and the opposite is true for basin C. Thus, basin shape and the arrangement of stream segments combine to influence the size and shape of flood peaks (Ward and Robinson, 2000).

1.2 Hydro- Geomorphology and flooding

The vital interest of engineers, geologists and land managers is the hydrology of river channels. The quantity of water that will pass through a given channel is a function of the storm event (precipitation), and the watershed characteristics (Vikrant and Sinha, 2003).

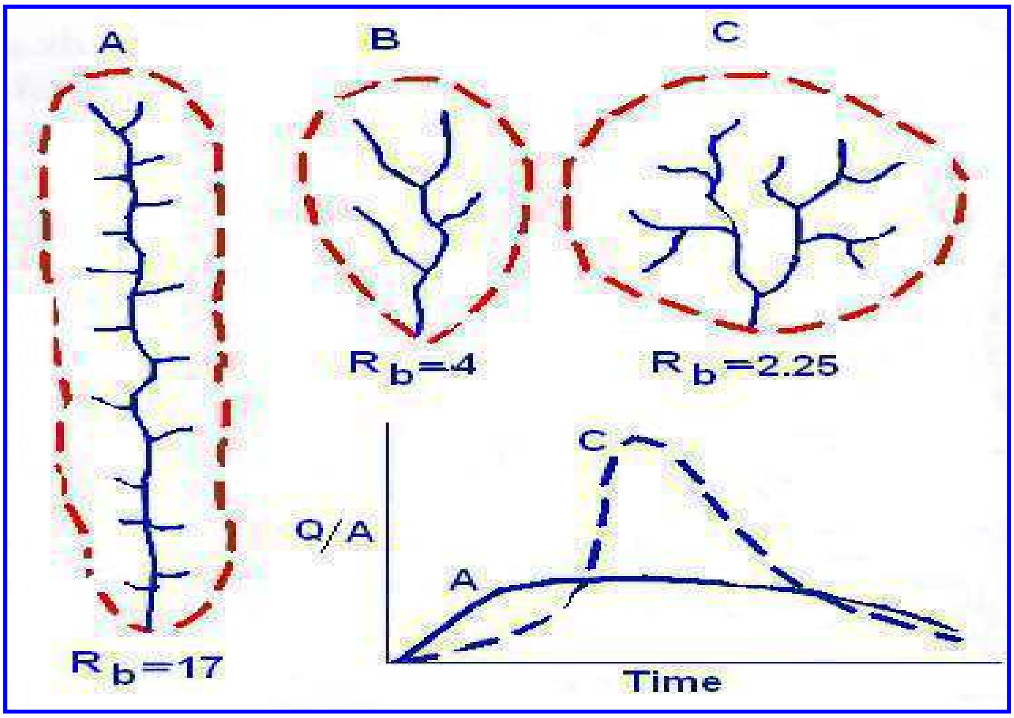


Figure 1.2 Showing relationships between catchment shape, bifurcation ratio (R_b) and shape of the flood hydrograph (Strahler, 1964).

However, how quickly the water passes through the channel is a function of the storm event (duration of the precipitation), as well as the channel and watershed geomorphology.

What actually is Geomorphology? In simple terms it is the quantitative analysis of surface landforms to help provide insight into the effects of channel network on flood mechanism and occurrence. Hence, it is important to quantify the geomorphic characteristics of a watershed accurately in order to aid in analyzing the hydrologic response of watersheds.

Morphological characteristics like stream order, drainage density, aerial extent, watershed length and width, channel length, channel slope and relief aspects of watershed are important in understanding the hydrology of the watershed (Chow, 1964). Runoff response of the watershed is different for different slopes, shapes, lengths, widths and areas of watershed. Response is also affected by the factors like drainage density, length of overland flow, stream frequency, relative relief and relief ratios. Computation of watershed morphological characteristics is therefore a prerequisite for detailed hydrological analysis of the watershed. Hydrologists have attempted to relate the hydrologic response of watersheds to watershed morphologic characteristics. Increasingly, studies have used the patterns of basin morphometry to predict or describe geomorphic processes; for example, it has been used to predict flood peaks, to assess sediments yield, and to estimate erosion rates (Gardiner, 1981).

The application of geomorphic principles to understanding and quantifying environmental hazards, such as flooding, has led to a significant amount of research focused on identifying the relationships between basin morphometry and stream flooding (Patton, 1988). Clearly, the shape and character of a stream flood hydrograph should be affected greatly by the manner in which a basin collects and routes water through its network. Stream hydrology, as defined by the flood hydrograph and by time elements such as flood frequency and lag, is significantly related to many components of basin and stream network morphometry. The interdependence of morphometry and hydrology is statistically real but does not necessarily indicate a cause and effect relationship; given two apparently related factors, i.e. one factor is not necessarily the cause of changes in the other. The high correlation probably exists because both factors vary in a consistent way with the same underlying climatic and geologic controls. All morphometric parameters, however, are themselves so complexly woven together that no single factor can be isolated as a completely independent variable.

1.3 Land use/ Land cover and flooding

It is not just topography and geomorphology that is needed for understanding the flood mechanisms, the land cover of a place is also vitally important influencing factor. The nature of vegetation, soil type and other geological traits has important controlling effects upon the characteristics of a catchment hydrograph. This is largely related to the permeability, transmissibility and water storage of the catchment. These are natural controlling influences, which can subsequently be influenced by human activity. Barry and Chorley (1998) state that Urbanization also change the physical characteristics of a catchment and in extreme cases may also influence the local climate.

Structural development has a significant effect on the hydrological system as the modified surface is often less permeable than the surfaces they replace (Ward and Robinson, 2000). Thus flood hydrograph peak responses are faster and higher (Robinson et al., 2000). Response time to flooding relates to the rate of surface runoff, therefore the reduction of friction due to the urbanised surface drastically reduces lag times. The difference between the urbanised and the natural catchment in terms of available soil moisture storage capacity is greatest during the summer, when soil moisture deficits are at their maximum, and urbanisation therefore tends to have a greater effect on the magnitude and frequency of summer floods (Arnell, 2002). However, urbanisation will tend to lead to flood hydrographs with both higher and earlier peaks, as well as increasing the downstream flood peaks and volumes (Ward and Robinson, 2000).

Deforestation, a major change in land use / land cover, has been known for an increased risk and magnitude of flood inundation. The major effect of deforestation is to increase the total amount of runoff (Bosch and Hewlett, 1982). The removal of trees reduces the amount of rainfall intercepted, and hence the amount evaporated back into the atmosphere, therefore more water will reach the ground surface at a faster rate (Arnell, 2002). The issues concerning land use lessen with increased rainfall magnitude, as storage capacity of a catchment becomes smaller relative to total precipitation. Therefore, determining the impact of land use and its change on the extent of flooding is an important area of research in hydrology (Hudson and Colditz, 2003).

1.4 Watershed characterization and Land surface processes - with special emphasis on morphometry.

Watershed is an area of surface whose major runoff is conveyed to the single outlet and is the appropriate unit to study several processes of the land surface. For example, watershed is considered a fundamental erosional landscape element, wherein conspicuous interaction of land and water resources takes place. Being fundamental units of fluvial terrain, considerable research focal point has been done on watershed geometric characterization such as stream network topology and quantitative narration of shape, pattern, and drainage texture (Abrahams, 1953). Hydrologic and geomorphic processes occur within the watershed, and morphometric characterization at the watershed scale reveals information regarding formation and development of land surface processes (Singh, 1992 and Dar et al., 2013) and thus provides a holistic insight into the hydrologic behaviour of a watershed. Basin travel time, time to hydrograph peak (basin lag time), and intensity of erosional processes operating at watershed scale can be predicted with better insight and accuracy from morphometric evaluation of a watershed. For unguaged watersheds wherein, in addition to hydrology, information regarding soil, geology, geomorphology, and so forth is also scarce, morphometric analysis provides a very good alternative to understand the underlying factors con-trolling the hydrological behaviour (Romshoo et al., 2013). Furthermore, there are a myriad of practical applications of quantitative morphometric analysis such as river basin evaluation, watershed prioritization for soil and water conservation, and management of natural resources. Watershed morphometric analysis dispenses a quantitative description of the drainage system and thus enabling a better characterization of watersheds (Strahler, 1964). The role of landform processes, soil physical properties, and erosional characteristics in shaping the idiosyncrasy of different watersheds can be best evaluated through juxtaposing their morphometric parameters (Dar et al., 2013). Using conventional techniques, morphometric characterization of many river basins and sub basins in different parts of the globe has been carried out (Strahler, 1964, Strahler, 1957 and Krishnamurthy et al., 1996). With the advancement in geospatial and computer technology, assessment of the drainage basin morphometry has been more accurate and precise. Nowadays, using Geographical Information System (GIS) technique, various terrain and morphometric parameters of the drainage basins are evaluated with more ease and better accuracy. Satellite data and GIS tools have been successfully employed to generate data on the spatial deviations in drainage characteristics thus providing an insight into hydrologic conditions necessary for developing watershed management strategies (Das and Mukherjee, 2005; Vittala et al., 2004 and Nag, 1998). GIS, being a powerful tool for the manipulation and analysis of spatial information, provides a flexible environment for morphometric analysis.

1.5 Jhelum Basin

The drainage system of Himalaya in general and that of Western Himalaya in particular is of recent geological origin owing to the mountain building movement of the late Tertiary age. The most important fact about the Himalayan rivers is that they are not consequent, i.e., the formation of these rivers was not consequent upon the physical features or the relief of the region. In other words, many of the Himalayan Rivers are older than the mountains they traverse (Hallet and Molnar, 2001; Oldham, 1893, 1907; Pascoe, 1919; Pligrim, 1919; Srivastava, 1978; Seeber and Grontiz, 1983; Rohtash et al., 1999).

The Himalayan drainage system consists of three major basins: the Indus, the Brahmaputra and the Ganges. The river Indus has a trans-Himalayan origin and its major tributaries like Sutlej, Ravi, Jhelum, Chenab and Beas rise from the southern side of the Himalaya. The catchment areas of these basins are not sharply demarcated; they may at places overlap each other. Table 1.1 summarizes the Himalayan drainage systems along with their salient hydrological characteristics.

The Jhelum basin is in an elongated basin with protrusions on NE, SW and NW sides. The basin is bounded between the Himalayas and Pir Panjal mountain ranges between 33.25^0 to 34.32^0 N and 74^0 to 75.30^0 E. River Jhelum passes largely along the middle of the Kashmir valley through the alluvium of its own deposition. The basin is the recipient of the entire drainage of the valley and is known in the Kashmir by the name “VYETH”. This is direct phonetic derivation of its ancient Sanskrit name “VITASTA”, which is mentioned among the river names of Rig-Veda. The river comprises of fairly developed streams as well as tiny rivulets with quite remarkable variations in the drainage and catchment characteristics.

Table 1.1 Showing summaries of the catchment areas of Himalayan drainage system (Roa, 1975).

Major basins	**Tributary**	**Basin area, km^2**	**% area in India**	**Discharge, Million m^3/Yr**
INDUS		**1,165,000**	**27**	207,800
	Jhelum	34,775	.	27,890
	Chenab	26,155	.	29,000
	Ravi	14,442	.	8,000
	Beas	20,303	.	15,800
	Sutlej	28,400	.	16,660
GANGA		**1,060,000**	**85**	459,040
	Yamuna	366,223	100	131,700
	Chambal	139,468	100	30,050
	Son	71,259	100	15,258
BRAHMAPUTRA	Gandak	45,800	10	52,200
	.	580,000	31	455,000

The encircling mountain ranges, with ridges and spurs and covered with snow almost throughout the year, provide ground for the development of a number of streams which have more or less established their own entities within valley. These drainage basins, together with the river Jhelum, constitute the drainage system of the Kashmir valley. The Jhelum basin has 24 tributaries and some of them drain from the slopes of the Pir Panjal range and join the river on the left bank, while others flow from the Himalayan range and join the river on the right bank. Consequently the Jhelum basin has 24 catchments and these have been sub-divided into 60 sub-catchments, further divided into hundreds of micro-watersheds.

1.6 Research Objectives

Even though there is growing interest in carrying out research on natural disasters among geoscientists, but there is still a significant gap in our understanding of the factors associated with flood hazard vulnerability (Beven, 1989). This research therefore addresses the fundamental scientific question of assessing the geologic and hydrological factors that make a drainage basin more or less prone to flooding. In this research, an integrated analysis of the hydrological, channel morphological (planform as well as cross-sectional morphology), and geomorphometrical (drainage network analysis) properties of Jhelum River basin facilitates a better understanding of the flooding problem and its associated processes. Remote Sensing data was used to generate up-to-date information about different hydrological and geomorphological parameters. Geo-spatial techniques were used to empirically simulate the hydrological processes and assess flood vulnerability. Thus, the findings can be of tremendous practical use in planning flood management and mitigation strategies. The specific objectives of the present research study were as follows:

1. Have a comparative analysis of the geo-environmental setting of Lidder (Greater Himalaya) and Rembiara (Pir Panjal-Lesser Himalaya) watersheds.
2. Assess the impact of differential geo-environmental setting on the hydrology of two watersheds.
3. Assess the flood vulnerability and the flood hazard zonation in the Lidder and Rembiara watersheds.

1.7 Importance of the Research - Flooding Scenario of Jhelum Basin and Need for Scientific Approach for Mitigation Measures.

Among the various hazard-prone Himalayan states of India, the state of Jammu and Kashmir is more vulnerable to almost all the hazards. The historical records reveal that the Kashmir Himalayan region has suffered heavy causalities and loss of properties due to earthquakes, landslides, floods, avalanches and other disasters. In the past, several floods have occurred in the Kashmir valley and damaged both the life and property. But the recurrent problem of flooding in the valley has become acute since the last fifty years due to unprecedented increase in the anthropogenic activities. An enormous amount of water flows into the valley and the only outlet for the water from the valley is the narrow gorge at Baramulla. Floods generally occur in the summer when heavy rain is followed by bright sun, which melts the snow. The Jhelum is the only river responsible for flooding in Kashmir valley. In ordinary times, it flows gently between its high banks, but in times of flood, it flows over the natural banks. Jhelum drainage basin is fed by numerous transverse streams traversing the Pir Panjal and Zanskar ranges. These streams join the axial river Jhelum. The hydrographic features and drainage characteristics of Jhelum river system show that the frequency of floods has been very high every since the valley assumed its present form. There have been more than 25 major floods, the mean expectancy being 1 in 4.3 years (Monis Raza, et al, 1975). The valley being saucer shaped with steep mountain slopes around, any heavy rain spell for a duration of 1-2 days can cause serious floods (Dhar, 1992). Precipitation falling on steep slopes, rushes to the valley as quick-runoff through these numerous tributaries of the Jhelum, causing serious inundation all along its course. The floods in the Jhelum can be serious if the runoff from these tributaries reaches the Jhelum almost the same time. Sometimes heavy precipitation, usually pouring down towards the end of summer monsoons and caused by the sudden cloud burst, often leads to flooding in Jhelum basin. During this period, the catchment areas of the river are already saturated and high run-off swells the river beyond its capacity with the result the river bunds and levees are breached and the whole valley is inundated (Monis Raza, et al, 1975). In general, the layout of Kashmir valley is such that it is highly prone to flooding. Also, the growth of human population and horizontal expansion of settlements and encroachments on the water courses, reclamation of low lying areas for agriculture, channelizing of rivers, construction of roads along river banks and urbanization of the flood plains, have aggravated the flood risk in the Jhelum basin.

As a result of these landscape modifications, in the basin, we are observing an increase in the frequency of floods. The flooding hazard is very dominating in the SW part of Kashmir Himalaya, particularly in Pulwama, Anantnag and Srinagar districts. These areas are settled on the flood plains of Jhelum river basin and are therefore vulnerable to the flood hazards. Flooding in this specific area is a result of a complex interaction of a number of factors, which vary in significance over space and time. The repetitive flooding is significantly more during summer monsoon periods, and has sometimes occurred in spring as well. The flooding has escalated ever since the reckless economic development along the flood plains of river Jhelum. Most of these floods coincide with incessant rainfall, and are controlled by the hydrological characteristics, geomorphic indices like basin shape, bifurcation ratio, and drainage density, elongation ratio compounded by weak and unconsolidated lithologies. The recent flood that occurred on 3-4 September 2006 inundated 4444 villages. 307 houses were completely damaged and over 93,000 hectares of land with standing crops also came under floodwaters.

There is an urgent need to minimize the losses of flood by adopting flood mitigation and prevention measures. It requires the development of an early warning system and near-real-time information of the floods. The advancement in the field of satellite Remote Sensing, Geographic Information System (GIS), simulation modelling and advanced field observation techniques have facilitated a better understanding of the geomorphological and geological influences on flooding. Remote sensing and GIS can play a vital role in flood mapping and analysis by accurate and repetitive coverage of large inaccessible areas and cost effectiveness. Similarly, geo-spatial analyses and simulation modelling facilitates the quantification of morphometry, hydrological processes and vulnerability assessment studies. The integrated use of these cutting edge technologies, together with the field observations, helps us to accurately understand the flooding mechanisms and thus identify the flood prone areas and communities at the basin scale.

The present study, therefore, demonstrates the integrated use of multi source data including Remote Sensing, geo-spatial modelling and field observations for assessment of flood hazard in the Jhelum river basin in general and sub-basins of Pir-

Panjal range in particular. This research provides some basic understanding of the causative factors of flooding in these sub-basins and the flood vulnerability is assessed in each of these watersheds at the village level.

STUDY AREA

The diverse geomorphological setup of the Kashmir drainage basin compounded with heterogeneous lithology and varied hydrological aspects render the basin all the more vulnerable to flooding. Keeping in view the above facts, two representative sub basins (Rembiara and Lidder catchments) of the Jhelum drainage basin on either banks of the axial river Jhelum have been chosen for the detailed studies involving land use/land cover generation, morphometry, hydrological characteristics and flood vulnerability analyses. The research was accomplished using an integrated approach based on Geographical Information System (GIS), Remote Sensing, Simulation modelling and extensive field observations. Figure 1.3 shows the location of the two representative sub-basins chosen for accomplishing the research objectives.

Jhelum Basin

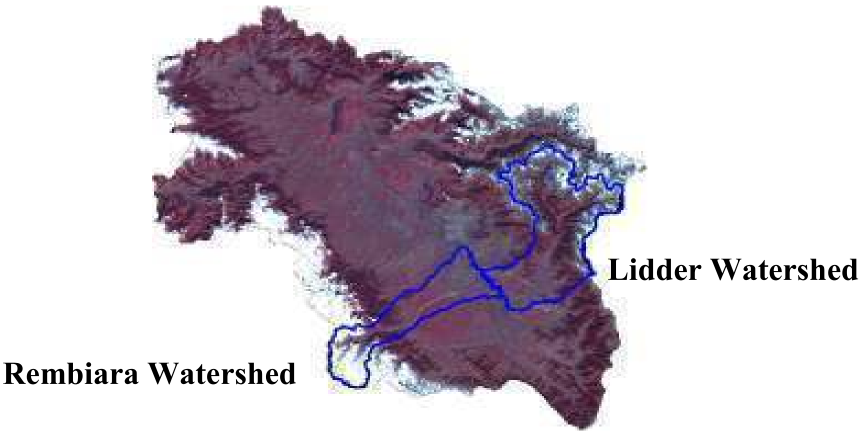


Figure 1.3 Showing location maps of Rembiara catchment and Lidder catchment of Jhelum drainage basin.

1.8 Physiography, Geology and Climate of the representative Study Areas

1.8 a Rembiara catchment

Watershed characteristics: The Rembiara rises in the Rupri ridge of the Pir Panjal range. Its headstreams originate from Dhaklar Peak (4660 m) and Bag Sar lake below Rupri pass (4085 m) on one hand and the Pir Panjal pass (3494 m) and the Naba Pir pass (4253 m) on the other hand. In Rupri, there occur a number of monor lakes which source water to the headstreams of the Rembiara. Below Hirpur, the river valley becomes narrower and deep. While debouching into the plain area near Shopian, the river gets divided into a large number of streams. Some of these branches migrate to the basins on either side and a few reunite to form the Wankaran Nala which merges with the Jhelum at village Kawain. The parent stream of the Rembiara meets the Jhelum at Sangam shortly after being joined by the Vishav. The total catchment area of the Rembiara is about 738.45 km^2. The Rembiara has a maximum length of about 73 km and flows in an east, southeast direction.

Geology: The study area falls in Pulwama district comprising of two geological formations of the Kashmir. The mountainous region belongs to Panjal trap formation and rest of the area belongs to Karewas group of formation. The brief detail of the geology/lithology of the Rembiara catchment is given below.

Panjal trap: Panjal trap lies on the top of the Agglomerate slates and almost forms the central axis of the Pir Panjal Range, where they attain a maximum thickness of about 100 m. The Traps are found in the upper catchment of the Rembiara river. Panjal traps consist mainly of basic rocks, and few intermediate and acidic rocks. Basic types are mainly basalt and andesitic basalt, while as acidic and intermediate rocks are represented by augite-andesite, trachyte, Keraphyre, rhyolite and acidic tuffs.

Karewa group of formation: The catchment mostly belongs to Karewa group of formations. The lower part of Karewa group is known as Hirpur formation. The lithological constituents of the group are clay, sandy clay, sand, conglomerate and lignite. The Nagum formation forms the low dipping to sub-horizontal part of the Karewa Group and constitutes only a small thickness of the Karewa succession. This formation combined with the top Dilpur Formation is commonly referred as ‘upper Karewa’

The Dilpur Formation consists exclusively of layers of brown silt, which vary from calcareous to apparently non-calcareous types. These silt layers show all shades of brown. The more calcareous silt layers are lighter in colour. The calcareous silt layers are harder than non-calcareous types and stand out on flat vertical surfaces. The non-calcareous silt layers are more prone to erosion and, therefore, form irregularly shaped vertical surfaces on erosion.

Climate: The catchment area receives precipitation both in the form of rain and snow. The mean annual precipitation, based on the analysis of 10 years record from 1989 to 1998 at Pulwama rain gauge station, is 499.1 mm. The highest rainfall of 779.7 mm was recorded during the year 1993 and the lowest of 271.3 mm during the year 1998. The analysis of the average monthly rainfall of 10 years shows that the area receives highest rainfall in the month of March (148.83 mm) and lowest in the month of November (10.77 mm). The season from April to October is pleasant while in the rest of the year, particularly winter, the study area experiences extreme cold and heavy snowfall. Figure 1.4 shows the mean monthly precipitation observed in the study area from 1989-1998.

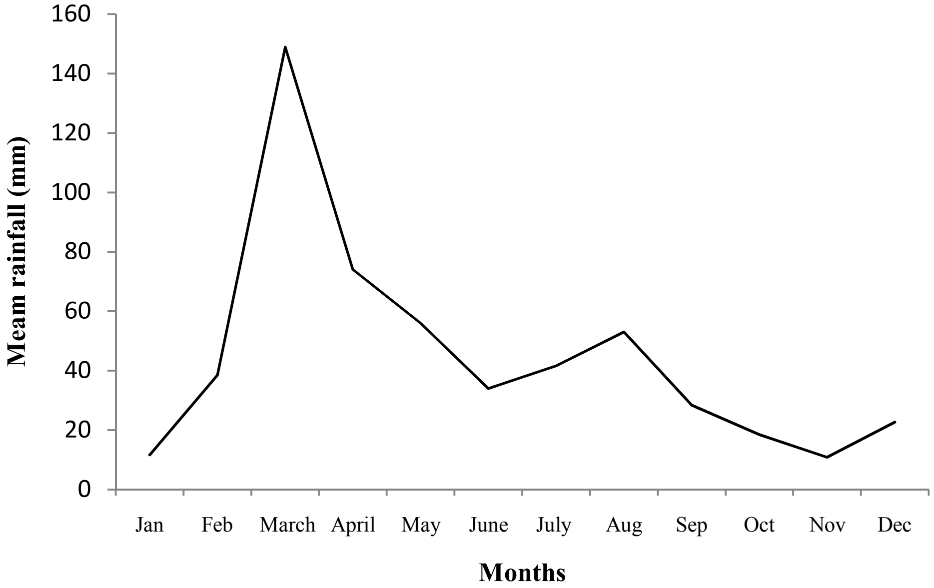


Figure 1.4 Showing monthly mean rainfall in Rembiara catchment (1989-1998).

Based on the time series analyses of the temperature data, the mean annual temperature is 12.8^0 C. The mean winter (December – February) and summer (April-June) temperatures are 5^0 C and 16.6^0 C respectively. The discharge data of ten years (1985-1994) of Rembiara River at Nayun gauge shows that the highest peak is observed in the month of May while as the lowest discharge is observed in the months of October and January. Since, the contribution is mainly from the snow melt runoff, the months of April, May and June show expectedly highest discharge in the year.

1.8 b Lidder catchment

Watershed characteristics: Lidder forms the first of the major right bank tributaries of the Jhelum. It is formed by the union of two major streams at Pahalgam, one is called the East Liddar and the other the West Lidder. The East Lidder drains the eastern Great Himalayan range of the Kashmir valley. It collects the snowmelt from the snow beds of Rabemarg, Astanmarg, Wahbal and Sonasar. It's main source lies in Shishiam Nag lake (alt. above 3500 m) and the Shishiam glacier (alt. above 4400 m). It traverses a course of about 21 Km. from Shishiam Nag (now called Sheesha Nag) before its merger with the West Lidder at Pahalgam.

The West Lidder drains a large area in the Kolahoi area. At Lidderwat, it receives an upland torrent from Tarsar. The West Lidder flows for a maximum length of about 35 km before its merger with the East Lidder. Below Pahalgam, the united Lidder passes through a narrow valley studded with massive boulders and overlooked by dense forests, till it debouches into a wide alluvial fan. From Pahalgam onwards, the Lidder receives a large number of small tributaries on either bank. At the head of its delta, the Lidder gets bifurcated into a number of channels, which spread out to form a wide alluvial plain. These streams merge with the Jhelum individually over a distance. However, the parent stream joins the Jhelum at Gur. The Lidder transports huge debris and contributes a significant quantity of water to the Jhelum. The total catchment area of the Lidder is about 1264 km^2.

Geology: The Lidder watershed falls in Anantnag district. It comprises of various geological formations of the Kashmir. Among all the watershed basins of Jhelum, Lidder basin is mostly bed rock river. The brief detail of the geology/lithology of this catchment is given below.

Shale slate greywacke: This is the oldest formation of the region and occupies considerable part of the localities of the Chaturgul, Gaurav and Hapatnar in the extreme southeastern part of the Lidder valley. The most common rock of the group is greywacke. The Shale-Greywacke formation is overlain by pale, pink or grayish colored quartzite near the localities of the Hapatnar, Shumal and Riatang.

Orthoquartzite-carbonate group: The Shale-Greywacke Group is overlain by the thick pile of Quartzites and Sandstone of various types intercalated with limestone beds. The exposures are observed in the localities of Nagbal, Driyan and the easternmost parts of the Kanjit, Gurdeman, Aishmaqam and Kolahoi-Basmi anticline. This group has two horizons, one comprising of Muth Quartzite and the other of Syringothyris Limestone. The rocks are mostly hard, compact and massive. Muth quartzite is overlain by thick,grey, hard,quartzites, sand stones and shale at Pindobal-ziral section.

Outer volcanic group: The orthoquartzic-carbonate group is conformably overlain by a set of rocks having complex petrological characters. They are pyroclastic in nature and are named as agglomeratic slates. The agglomeratic slates form the lower part of Panjal traps and underlying these series, are located the Fenestella shale.

Classic volcanic group (Panjal volcanic): Algometric slates are overlain by a thick homogeneous mass of lava, known as Panjal Volcanics. The rocks are green and cover a major portion of the northern part of the Lidder Valley. These are compact, thickly bedded and massive in nature. The Punjal volcanics forms the towering cliffs of the area.

Sandstone/Shale group: The formation lies directly over Panjal Volcanics. The exposures are observed along channel sites, in the localities of Burzulpatharner and Minmarnagar.

Limestone group: The next succeeding group overlaying the sandstone shales in the northern part of the Lidder Valley is the limestone group. It comprises of massive milestones, thinly bedded limestones and grayish shales, slates and thin limestones. These rocks are exposed nearly 3 kilometers north of Pahalgam near Dad War Mountains, Mundane and Poruspat Ridge

Glacial and fluvial alluvium group: These deposits occur in the form of older and newer alluvium. The older alluvium is deposited in the form of moraines, kames, and the scree and overlies the older rock groups from the Sheshnag to Ganishbal and Kola Hoi to Pahalgam along the valley sections of the east and west Lidder respectively. The recent alluvium is observed at the foot hills and along fans and is formed as a result of recent erosion and deposition in the area.

Climate: In Lidder catchment, the temperature varies between a monthly mean maximum of 19°C in July and a mean minimum of –1.7°C in January, with mean maximum of 25.5°C in July and mean minimum of -7.3°C in January. Temperature analysis for 26 years (1979-2004) at the Pahalgam station shows that the maximum temperature can rise above 30^0C and the minimum temperature can drop below –18 ^{0}C. The highest temperature of 32.2°C was recorded during the year 1990 in the month of August and the lowest temperature –18.6°C was recorded during the year 1986 in the month of January.

The study area receives precipitation in the form of both rain and snow. The mean annual precipitation (based on 26 years record from 1979 to 2004) at Pahalgam rain gauge station is 1267.2 mm. The highest rainfall of 1629 mm was recorded during the year 1994 and the lowest of 899.9 mm during the year 2000. The analysis of the average monthly rainfall of 26 years shows that the area receives highest rainfall in the month of March (208.8 mm) and lowest in the month of October (45.9 mm). The highest rainfall (544 mm) was in the month of March (1983) and the lowest (0 mm) rainfall was recorded in the month of December 1998 and 1999 (Figure 1.5). The season from April to October is pleasant while in the rest of the year, the study area experiences extreme cold and heavy snowfall, particularly at higher altitudes.

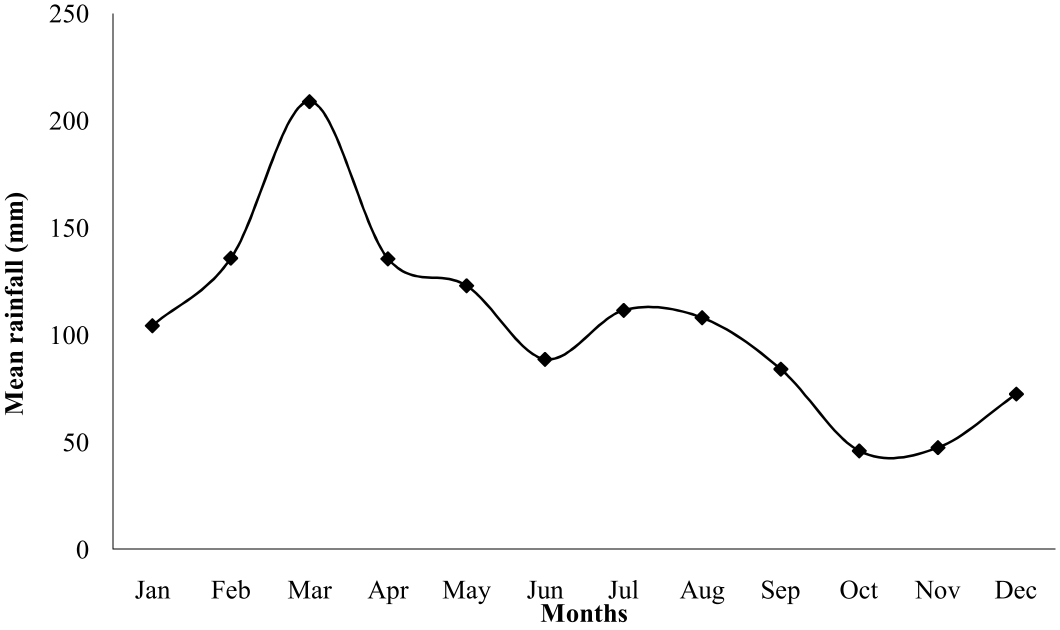


Figure 1.5 Showing monthly mean rainfall in Lidder catchment (1979-2004).

The average monthly discharge of Lidder at Odur shows that 74.9 % of the total annual runoff flows during the months of March to August and only 8.6 % of the total runoff flows during the winter months (Dec-Feb) and 16.8 % flows in September and November. The total yearly average (average of 16 years) discharge at Odur is 880.85 cusecs. The analysis shows that highest discharge is during the month of June (266.867 cusecs) and lowest discharge in the month of December (51.639 cusecs).

Chapter: 2

Literature Review

This chapter contains a review of the literature concerning research objectives of the current study. The chapter has been divided into six sections comprising of flooding mechanism, effect of geology on runoff, effects of geology on runoff generation, effects of land use on runoff generation, effects of geomorphology on runoff generation, use of remote sensing and GIS in flood studies and flood studies on Jhelum river basin.

2.1 Flooding mechanism

The flooding is caused by a number of contributing factors like geological, geomorphological and land use/ land cover accentuated by hydro-meteorological events. Flash floods, catastrophic rainfall and river avulsion are a regular affair in the Himalayas and other high ranges. The Himalaya, with the greatest relief and steep slopes on the earth, is an ideal place for study of low to high frequency and high magnitude floods (Das, 1983). Furthermore, economic development and dramatically expanding human populations in the Himalayan flood plains have forced the rivers to cause inundation. Aside from geomorphic, hydro-geological and oscillating climatic conditions, research on floods have been linked with other factors controlling flooding, including lithology, morphometry, and monsoonal precipitation.

It has long been recognized that the dominant runoff processes generating stream flow are strongly influenced by the physical characteristics of the catchment in question (Buttle, 1998; Beven, 2001). These will vary in different geographic environments, reflecting the catchment geology, topography, soils and vegetation (Dunne, 1978). These factors influence the landscape structure and spatial organisation of a catchment which, in turn, determine the distribution of water flow paths, the patterns of water storage and residence time distributions (McGlynn et al., 2003 and McGuire et al., 2005). The influence of catchment characteristics is acknowledged as being extremely important in determining spatial patterns of water flow paths and storage (Grayson and Western, 2001; Weiler and Naef, 2003). As catchment characteristics integrate the influence of parent material, topography, vegetation/land-use, and climate, they can act as a first order control on the partitioning of hydrological flow paths, residence time distributions and water storage (Uhlenbrook et al., 2004; Soulsby et al., 2004). In mountainous headwater catchments, such as those in the uplands, hydrological responses were traditionally assumed to be determined mainly by soil characteristics (Bell, 1972; Chappell et al., 1990; Billett and Cresser, 1992), as catchment geology was considered to be virtually impermeable. More recent research work has shown that groundwater in superficial drifts (Soulsby et al., 1998; Soulsby et al., 1999) and bedrock (Neal et al., 1997; Shand et al., 1999; Smart et al., 2001) also exert a strong influence on the hydrology and hydrochemistry of headwater streams. Process studies of hill-slope hydrology have often shown great heterogeneity at small spatial scales (Bonell, 1998); with soil water processes, groundwater recharge and hill-slope hydrological response, generally exhibiting marked complexity (Freer et al., 2002; McDonnell, 2003; Haria and Shand, 2004). This complexity, inherent in catchment systems, generally collapses at larger spatial scales as the averaging of processes often results in simpler emergent properties of systems behaviour (Wade et al., 1997; Kirchner et al., 2004). Kirchner et al. (2001) have recently called for a clearer theoretical basis for identification of fundamental processes in catchment hydrology.

2.2 Effects of geology on runoff generation

Geological approach to flood analysis is one of the most useful tools for flood frequency analysis which was first applied in confined bedrock canyons in which relatively small discharge variations produce relatively large changes in stage (Baker et al, 1979). It has been observed that the frequency of geomorphologically effective events is inversely proportional to the threshold of erosion. Given the high threshold conditions that characterise mixed bedrock–alluvial rivers, sediment transport and bedrock erosion is typically episodic and restricted to infrequent, high magnitude floods (Tinkler, 1971; Baker, 1977; Howard, 1987). It has been proved that geological or hydrological data conjugates effects to known geological and geomorphic processes for better understanding of the flood behaviour and to propose solutions to raise the long-term flood analysis. Concerning the climate change during the Quaternary (G´abris, 1998) and the unknown subsidence rate at a given place and time, the speed of the sedimentation also affects the flood frequency. Jansen and Brierley (2004) propose a late Holocene paleoflood history for Sandy Creek gorge based on stratigraphic analysis and radiocarbon dating of the pool-fill deposits in the lower gorge. Tectonic activity of the area can be traced by river planform analysis (Mike, 1970; Schumn et al, 2003). The Great Hungarian Plain and the Tisza River gives a nice example that recent vertical movements (based on either crustal processes or compaction) can significantly and quickly affect the flow characteristics of a river (Tim and R´acz, 2004). Drainage density is a fundamental property of the natural terrain, which reflects local geology, climatic condition, vegetation and soil (Ritter, 1986).

2.3 Effects of land use on runoff generation

The patterns of vegetation on the land surface determine its runoff generating characteristics. The vegetation cover, density, type and the spatial distribution will affect the discharge from the hill slope. As the vegetation density increases, the average infiltration rate will increase, thus leading to a reduction in discharge. However, as the vegetal cover becomes more fragmented, there are a greater number of pathways from the runoff source areas to the channel base. This increases in connectivity and consequently increases hill slope discharges (Ward & Robinson, 1990). Moreover, different land use types have different evapo-transpiration rates, because different plants have different cover density, leaf area index, root depths and albedo. During storms, interception rates are different for different land cover types. Although it is recognized, that interception losses represent a significant net addition to catchment evaporative losses (Ward & Robinson, 1990), the influence of interception is noticeable only during small storms and influences only surface runoff rates. For largest storm and flood events, the interception losses are of minor importance (Calder, 1993). Land cover also influences the infiltration and soil water redistribution process, because saturated hydraulic conductivity is influenced by plant roots and pores resulting from soil fauna (Ragab & Cooper, 1993).

The hydrological effects of land use changes have been thoroughly described by Ward and Robinson (1990) and Calder (1993). The major changes in land use and land cover that affect the surface hydrology are afforestation, deforestation, the intensification of agriculture, the drainage of wetlands, road construction, and urbanization. Of all the land use modifications, urbanization is by far the most significant land use/ land cover change, by which land is transformed from its natural state or from agricultural use to an economically developed or populating region. Urbanization results in numerous adverse effects on the water quality and quantity of surrounding terrestrial and aquatic ecosystems. The most significant of these effects is the alteration of the hydrological cycle and rainfall-runoff transformation of the watershed, including (1) changes in peak flow characteristics, (2) changes in total runoff, (3) changes in quality of water, and (4) changes in the hydrological amenities (Sharma, 1999; Dilip et al., 2000). As the watershed becomes more developed, it also becomes hydrologically more active, changing the stream flow components as well as the origin of flow. Additionally, urbanization tends to increase both the flood volume and the flood peak (Dilip et al., 2000).

2.4 Effects of geomorphology on runoff generation

Geomorphology is the quantitative analysis of surface landforms. Geomorphology reveals much about the effect of channel network on the way the flood hydrographs pass through a channel. Hence, it is important to quantify the geomorphic characteristics of a watershed accurately in order to aid in analyzing a hydrologic response of a watershed. However, how quickly the water passes through the channel is a function of the storm event (duration of the precipitation), as well as the channel and watershed geomorphology. Morphological characteristics like stream order, drainage density, aerial extent, watershed length and width, channel length, channel slope and relief aspects of watershed are important in understanding the hydrology of the watershed (Chow, 1964). Computation of watershed morphological characteristics is prerequisite to further detailed hydrological analysis of the watershed. Increasingly, studies have used the morphometry to predict or describe geomorphic processes; for example, it has been used to predict flood peaks, to assess sediments yield, and to estimate erosion rates (Gardiner, 1975 and Gardiner, 1981). Some researchers believe that basin morphometric studies may ultimately be extended to show the influence of basin characteristics on channel cross-sections and channel attributes.

Because basin area and peak discharge are highly correlative, we could expect that many other areal parameters will be similarly related to discharge. Every factor differs in its success as a predictor of discharge, but one parameter, i.e. drainage density, seems to have considerable value as a gauge of peak flow. Carlston (1963) observed a very close relationship between drainage density and mean annual flood. Notably, the basins in his sample had wide variations in relief, valley-side, channel slopes, and precipitation characteristics; yet none of these factors disrupts the flood magnitude-drainage density relationship. Similar relationships have been observed in experimental studies. Carlston (1963) suggests that the general capacity of a terrain to infiltrate precipitated water and transmit it through the underground system is the prime controlling factor of the density-mean annual flood relationship in basins up to 260 km^2 in area. In larger basins, channel transit time plays the dominant role in the flow character. The rate of base flow, found to be inversely related to drainage density, is also dependent on terrain transmissibility. Thus, as Horton (1945) concluded earlier, high transmissibility (as evidenced by infiltration capacity) spawns low drainage density, high base flow, and a resultant low-magnitude peak flood. In contrast, an impermeable surface will generate high drainage density and efficiently carry away the abundant runoff; base flow will be low and peak discharge high.

Patton and Bake (1976) demonstrated predictive relationships between several morphometric parameters and peak flood discharges for streams in several physiographic regions of the United States. They found that areal morphometric parameters such as drainage density and stream frequency accounted for much of a model’s ability to predict peak discharge, along with the relief measure known as ruggedness number (R) which is the product of relief and drainage density. These results were used to develop an index of flash flood potential (Beard 1975). Dingman (1978), however, warned that the relationship between drainage density and flow can be overridden by other effects in the basin such as floodplain or channel storage. In addition, where saturated overland flow is the major source of runoff, drainage density may not be related to the efficiency at which a basin is drained. Costa (1987) investigated the morphometry of basins associated with the largest historic floods in the United States. Although these flash flood basins did not uniformly possess the basin attributes expected from studies like that of Patton and Baker (1976), Costa was able to find some commonalties. Basins with flashy or peaked flood hydrographs generally contained significant area of exposed bedrock, occurred in semiarid to arid climates and had high relief.

In recent years, a large amount of research has focused on the development of more sophisticated models of runoff that are linked closely with geomorphic attributes of the basin and their impact on the production of floods. One of the predominant models is the geomorphic unit hydrograph (Rodriquez-Iturbe and Valdez, 1979; Allam and Balkhair, 1987). The success of modeling efforts have been mixed (Patton, 1988), partly because of our incomplete understanding of the complex interrelationships between rainfall-runoff events and the contributing basin networks. Further work using small, instrumented watersheds, as well as numerical analytical approaches that explore relationships between the geomorphic unit hydrograph and basin parameters (Gupta et al, 1980; Chutha and Doodge, 1990; Bhaskar and Devulapalli, 1991), will refine our understanding and perhaps lead to more reliable models for predicting flood using basin parameters.

In India, the application of morphometric techniques has been initiated long time back (Singh, 1982). The use of comparable morphometric variables in the classification of morpho-units of terrain has encouraged a host of scholars to apply morphometric symbols in their respective areas of study. Asthana (1967) has evaluated the land-form in Almora and its environs by the application of various morphometric techniques and classified it into morpho-units of various orders. Following the same approach, Kharakwal (1968) has classified the Kumaon Himalaya into morpho-units using its geo-morphogical characteristics. Later, Kharakwal (1971) has also carried out slope studies in the Himalyan terrain. Pal (1972) has provided a comprehensive scheme of classification of the morphometric methods of terrain. Later Pal (1973) has also studied the quantitative geomorphology of drainage basins in the Himalaya. Pradhan and Sinha (1973) have made a morphometric analysis of the Rapti valley in southern Nepal to identify the regions that could be brought under agriculture. Kumar and Singh (1978) have given a quantitative classification of land form regions of the Western Higher Plateau of Bihar. Mukhopadhayay (1980) has studied the Tista and Subernarekha basins in the light of advanced methods and techniques of morphometry. Singh (1982) has applied the morphometric techniques to classify Palamau Upland into morpho-units of various orders. Later Singh (1991) has carried out morphometric analysis of terrain in Manpur and its environs. Wagdany and Rao (1997) have investigated the relationship between the velocity parameter and climate as well as geomorphological parameters for the development of Exponential Distribution Geomorphological Instantaneous Unit Hydrograph model (ED- GIUH) using regression analysis. The authors found velocity parameter is depending on rainfall depth and basin slope and is not affected by run off characteristics and also found velocity is inversely proportional to the effective rainfall depth. The authors suggest that this method can be used to estimate the flow velocity of the ED-GIUH model and can be very useful for the estimation of flood hydrograph of the un-gauged watersheds. Nageshwar (1997) developed Geomorphological Instantaneous Unit Hydrograph (GIUH) using geomorphological characteristics of the watersheds and related it with Nash Instantaneous unit hydrograph for deriving its complete shape. The author found similarly between the models and observed results, and suggested that this type of physically based rainfall run off estimation methods are very useful and accurate than the traditional techniques for estimating flood using historical rainfall-run off data. Vikrant and Sinha (2003) highlight the importance of morphometric parameters in flood analysis and analysed the effect of individual parameters for the development of GIUH model. The authors found length of highest order and length ratio have maximum control on the hydrological response of a river basin.

Abrahams (1984) aptly summed up the difficulties in elucidating quantitative relationships in basin networks by noting that the apparent randomness arises largely from independent variation of a large number of factors such as lithology and microclimate. The possible interrelationships between hydrology and morphometry are seemingly infinite, and the parameters are so complexly related that simple equations will not explain all the variability. Still, the hydro-geomorphic approach has some advantages and can be abandoned in future research.

2.5 Use of remote sensing and GIS in flood studies

Remote sensing satellite data is highly useful for flood mapping and management in India (Bhaskar, 1992; Mohapatra and Singh, 2003; Jain et al., 2005; Chandran et al., 2006). Satellite data is an indispensable tool for vulnerability assessment of human settlements and disaster management (Gupta and Singh, 2005; Sanyal and Lu, 2005).

Nayak et al (1997), used satellite data for the monitoring of flood in a part of Gurgaon district, Haryana. The authors found that satellite data sets are very useful for such studies and suggested that information generated from satellite images on floods can be very useful for the flood control and relief measures. Jain et al. (2000) conducted the flood analysis of Gambheri dam catchment in Rajasthan using GIS supported GIUH model. The authors found that GIS has priority over manual methods, and suggested watershed characteristics based models are very accurate to analyse the floods than traditional models. Srinivasa et al.(2004) carried out detailed morphometric analysis of Pavagada area of Tumkur district, South India using Remote Sensing and Geographical Information System techniques. The authors found Remote Sensing and Geographical Information System efficient tools in drainage delineation and for morphometric analysis. Similar results were obtained by Aggarwal (1998); and Narendra & Nageswara (2006). Durga et al. (1999) conducted the flood risk analysis in a GIS environment for different return periods using the derived results for the assessing flood damage in this area. The authors suggested this type of the information is very useful for the planning for flood retention structures.

The use of Digital Terrain Models (DTMs) has often resulted in relatively simple topographic indices being used to model hydrological flow paths and runoff responses at larger catchment scales (Woods and Sivapalan, 1997; Peters et al., 2003). The limitations of such approaches in accurately translating process-dependent controls of landscape characteristics and organization on water movement are increasingly recognized (Beven, 2001and Bven, 2002). Thus, there remains a requirement to explore alternative tools that help integrate the insights from process studies with accessible descriptors of catchment characteristics to aid modeling and management decisions (Soulsby et al., 2003). Increased use of GIS has considerable potential in improving hydrological understanding at larger spatial scales. The use of Digital Terrain model is widespread and digitized catchment characteristics, such as geology, has been useful in improving hydrological understanding. This data base-has been used in hydrological modelling (Dunn and Lilley, 2001 and Dunn et al., 2003) and has considerable potential in developing process-based understanding of un-gauged basins (Uhlenbrook et al., 2004).

Flood vulnerability analyses would be very useful tool to reduce the damages (Badilla, 2002). The concept of vulnerability includes both physical, or structural vulnerability, as well as human or social vulnerability. The flood vulnerability of an area requires a proper integration of physical, socio-cultural, economic and demographic data. For this purpose, Geographical Information System (GIS) enable the planners to forecast flood conditions and manage the river environment. As data management and map representations tools of GIS helps in exploring new potions. Its integration with Remote Sensing, enhance the ability for preparing flood hazard map and forecasting. Besides its constraints like technological knowledge requirements, hardware and software requirements, thus GIS can be very useful to minimize flood hazard (Amit Kumar, 2005). Forte et al. (2006) has applied geographic information system (GIS) integrating with aerial photos and remote sensing techniques for flood vulnerability analysis in the Supersano-Ruffano- Nociglia Graben, southern Italy and found that these cutting edge technologies are very useful for analyzing the flood vulnerability of a flood prone area very accurately.

2.6 Flood studies on Jhelum river basin

A long history of floods and famines is obvious and a regular affair in the Himalayas and related river valleys. Among the earlier studies on flooding in the Himalayas are that of Bhan (1958), Parthasarthy (1959), Dhar (1962), IMD (1962), Dhar, and Narayanan (1965), Guilhati (1968), Vij and Shenoy (1968), Panchang (1970) and Rao (1975). While some of these studies discuss the floods in the overall Himalayan context, others refer to flooding in specific parts of the Himalayan mountain basin, using various techniques ranging from simple hydro-meteorological data to geo-spatial tools. The earliest report of floods comes from the Kashmir valley in the 9th century, when a solution to the complex problem of flood control in the valley had engaged the attention of several court men during the reign of King Awantiverman. The most notable measure adopted was by Suyya (engineer by profession) in the year 841 AD during King Awantiverman's reign (Stein, 1900). He (Suyya) changed the point of confluence of Jhelum and Sind, and also the course of their combined waters to the Wular Lake, so that the river entered the lake at a place which had natural and well defined boundaries. By doing so the absorption capacity of the lake was utilized to the maximum during the floods.

The studies so far carried out on floods in Jhelum river basin are of general nature, like discharge and precipitation analyses related to floods. Among the first to study the floods in the Kashmir basin was Bhan (1958) who studied rainfall of the upper Jhelum catchment using the time series of rainfall data of 5 stations in the Kashmir Valley. Gulhati (1968) in his paper, 'the Indus and its Tributaries' has given a brief description of the Jhelum and its hydrological features. Vij and Shenoy (1968) have discussed the rainfall and runoff characteristics of the river Jhelum. Parthasarthy (1959) studied the different meteorological situations, which caused the severe flood of July 1959 in the Jhelum. Rao (1975) has briefly touched upon various hydrological and hydropower aspects of the Jhelum. Dhar et al. (1982; 1990) have studied various aspects of rainfall distribution and the effects of Pir Panjal range over the monsoon rainfall distribution in Kashmir Valley. Ramaswamy (1987) while studying meteorological aspects of severe floods in India has made exhaustive study of associated meteorological situations that were responsible for causing severe floods in the Jhelum from 1923 to 1979.

In Kashmir valley, the only work on morphometric study is by Raza, et.al. (1978). He quantitatively studied the slope and the drainage network characteristics of the Kashmir valley, using morphometric techniques through manual methods based on topo-sheets of the Survey of India. In this study, the basic unit for analysis has been taken fairly large viz., 10.36 km^2. It is, therefore, a too generalized study. But still then, it represents the most commendable work on Kashmir valley. The rest of the land form studies, if any, are either restricted to some tributary basins of the Jhelum, for example, the morphometric study of the Sukhnag basin by Dar (1990). Recently Amin (2000) has done detailed morphometric analyses of Kashmir valley.

Various hydro-meteorological studies have been carried out by various researchers from time to time as discussed above, but a geomorphological study related to flooding has not yet been carried out in the Jhelum river basin. In this research, a step has been taken to understand the geomorphological and hydrological control on flood vulnerability of the two watersheds of Jhelum basin.

Chapter: 3

Material & Methods

The study of flooding is a complex problem that requires a multi-disciplinary understanding of hydrology, geomorphology and geology. Flood hazard assessment and vulnerability is very essential information required by geologists, engineers, planners, decision makers and others for a wide variety of objectives. One of the important objectives of understanding and assessing the flooding is the evaluation of flood vulnerability of places and people at the local level so that preventive and remedial measures are taken to minimize the economic and human loses of this recurring and most common natural disaster on the surface of earth. For accomplishing the research objectives set out for this research, a number of approaches were employed in an integrated manner at different spatial scales. For understanding the relationship between the morphometry, physiography, land use/ land cover (LULC), geology, geomorphology and soil on hydrology, a compound number evaluation approach was carried out on the seven watersheds. For the purpose of flood vulnerability assessment at watershed level, the two pilot watersheds of Jhelum basin (Lidder and Rembiara) were chosen as representative watersheds for detailed studies. Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) 30 m digital elevation model (DEM) of the area was used to get a basic idea about the overall physiography of the hilly and precipitous study area followed by a reconnaissance survey of the representative pilot study areas. In order to accomplish the research objectives outlined for this thesis, it is important to use a host of methods that includes the use of satellite remote sensing data, detailed field observations, digital elevation data, secondary/ancillary data, geo-spatial tools and 'compound value' evaluation. Figure 3.1 shows schematic flowchart detailing the methods employed to accomplish the research objectives. The chronological details of the methodology adopted for carrying out various tasks related to the research objectives are discussed in the following paragraphs.

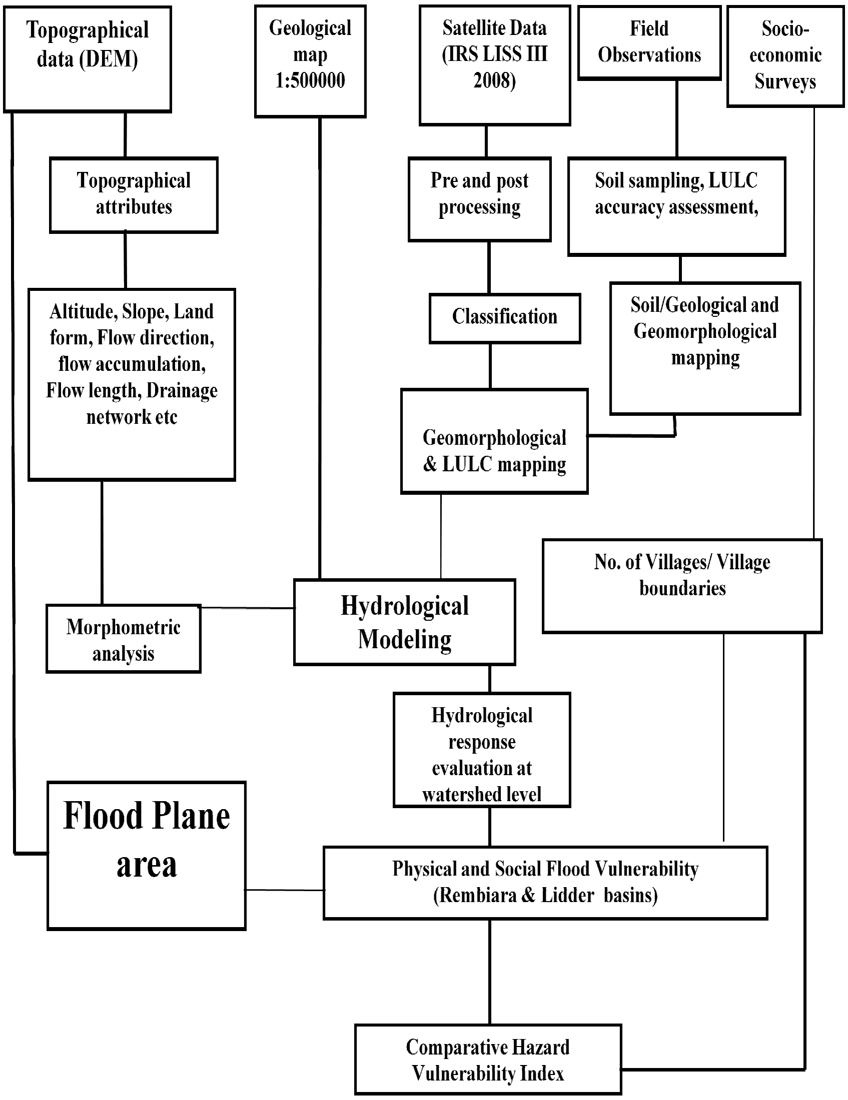


Figure 3.1 Showing flow chart of methodology used for accomplishing research objectives

3.1 Materials/ Datasets

The data sets used in this study are shown below against their respective purposes:

- Quantitative morphometry and Physiographic analysis: ASTER DEM 30 m
- Land use/ land cover classification and geomorphological mapping: IRS LISS III (dated 19 October 2008) with spatial resolution 23.5 m and Path/Row of 92/46
- Survey of India (SOI) topographical maps at 1:50,000
- Geological maps from Geological Survey of India at 1:500,000
- Soil maps from the National Bureau of Soil Sciences & Land Use Planning (NBSS & LUP) at 1:250,000 served as base line data

3.2 Methods

Objective 1: Have a comparative analysis of the geo-environmental setting of Lidder (Greater Himalaya) and Rembiara (Pir Panjal-Lesser Himalaya) watersheds

3.2.1 Morphometry

In order to understand the geomorphological influences on the flooding, it is essential to study the morphometry of the watersheds. Therefore, in the given watersheds a detailed morphometric analysis was carried out to understand the geomorphological and hydrological linkages. Computation of watershed morphological characteristics is a prerequisite for detailed hydrological analysis of the watershed. Hydrologists have attempted to relate the hydrologic response of watersheds to watershed morphologic characteristics (Rakesh, 2000). Morphometry is defined by Strahler (1969) as measurement of the shape, or geometry, of any natural form- be it plant, animal or relief features but in geomorphology, morphometry is defined as the measurement and mathematical analysis of the configuration of the earth's surface and of the shape and dimensions of its landforms (Clarke, 1966).

In fact, morphometry deals with the quantitative study of the area, altitude, volume, slope, profiles of the land and drainage watershed characteristics of the area concerned (Singh, 1972a; Singh, 1972b). Morphometric methods, though simple, have been applied for the analysis of area – height relationships, determination of erosion surfaces, slopes, relative reliefs and terrain characteristics as a whole since the beginning of the 20th century. But the vigorous application of statistical methods for the analysis of drainage watershed characteristics started after the publication of the classical research paper of Horton in 1945.

Morphological characteristics like stream order, drainage density, aerial extent, watershed length and width, channel length, channel slope and relief aspects of watershed are important in understanding the hydrology of the watershed (Chow, 1964). Runoff response of the watershed is different for different slopes, shapes, lengths, widths and areas of watershed. Response is also affected by the factors like drainage density, length of overland flow, stream frequency, relative relief and relief ratios.

However, it has been recognized that developing important watershed parameters using traditional techniques is labour intensive and tedious. The measurements have been made manually from medium and large scale maps. Other than a few parameters that can be easily measured like elevation and relief, measurement of more complex parameters, such as stream length, drainage density, mean watershed elevation, and channel gradient for streams of different orders, has been hampered by the amount of time that must be dedicated to extract these parameters. Therefore, digital elevation models (DEM) in Geographic Information System (GIS) environment can be used to compute these characteristics with greater efficiency and accuracy.

Technologies like Geographic Information systems (GIS), have gained significant importance over the last decade in their applications pertaining to drainage morphological characteristics. (Mark, 1983; Anderson, 2004; Band, 1986; Al-Wagdany and Roa, 1994; Tarboton, 1998 and Garbrecht and Martz, 1997). However, the user must be fully acquainted with the GIS being used for the generation of the morphologic characteristics. Since the mid 1980s digital elevation models (DEMs) have been used to delineate drainage networks, watershed boundaries, calculate slope characteristics; produce flow directions and watershed paths of surface runoff of the watersheds. The specific methods and steps followed for the generation of morphometric parameters is shown schematically in the Figure 3.2 and further elaborated and discussed in the following paragraphs:

I. Digital Elevation Model

Digital Elevation Model (DEM) is a representation of the continuous variation of relief over space that helps in assessing landscape characteristics along with topography and has a wide application in hydrological modeling (Mark 1983 and Tarboton, 1998). DEM is used to determine slope steepness, slope length, flow direction, areas, boundaries and outlets of watersheds. Over the past decade, numerous approaches have been developed for automated extraction of watershed structure from Digital Elevation Model (Tarboton 2001; Tarboton, 2003). Watershed morphometry was derived from Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) 30 m digital elevation model (DEM) using Arc Hydro tools (v 1.3; ESRI, Redlands, CA, USA) in Arc GIS 9.3 software. The Arc Hydro approach of drainage generation is more logical and consistent when compared to a manual approach. Since satellite based DEM is an image of the Earth's surface. Streams filled with water are normal surfaces just like land in a DEM. Arc Hydro manipulates DEM in order in corporate already existing streams and lakes. This function in Arc Hydro is termed as DEM manipulation. This function was performed by using digitized streams generated from SOI topo sheets.

II. DEM Processing For Morphometric Analysis

Various workers have used DEM for extracting stream network and other surface features (Mark, 1988; Band, 1986; Tarboton et al. 1991; Tarboton et al. 1992; Tarboton 1997; Tarboton and Ames 2001; Tarboton. and Shankar, 1998). For morphometric analysis, we followed the same methodology as shown in the Figure 3.2. The process involves the following steps:

- Filling the sinks in the DEM.
- Applying the flow direction function to the filled DEM.
- Applying the flow accumulation function on the Flow Direction grid.
- Applying a Threshold condition to the flow direction grid.
- Obtaining a stream grid from the threshold condition grid.
- Obtaining the stream links grid.
- Obtain watersheds grid from the streams grid.
- Vectorize the streams grid.
- Vectorize the watersheds grid.

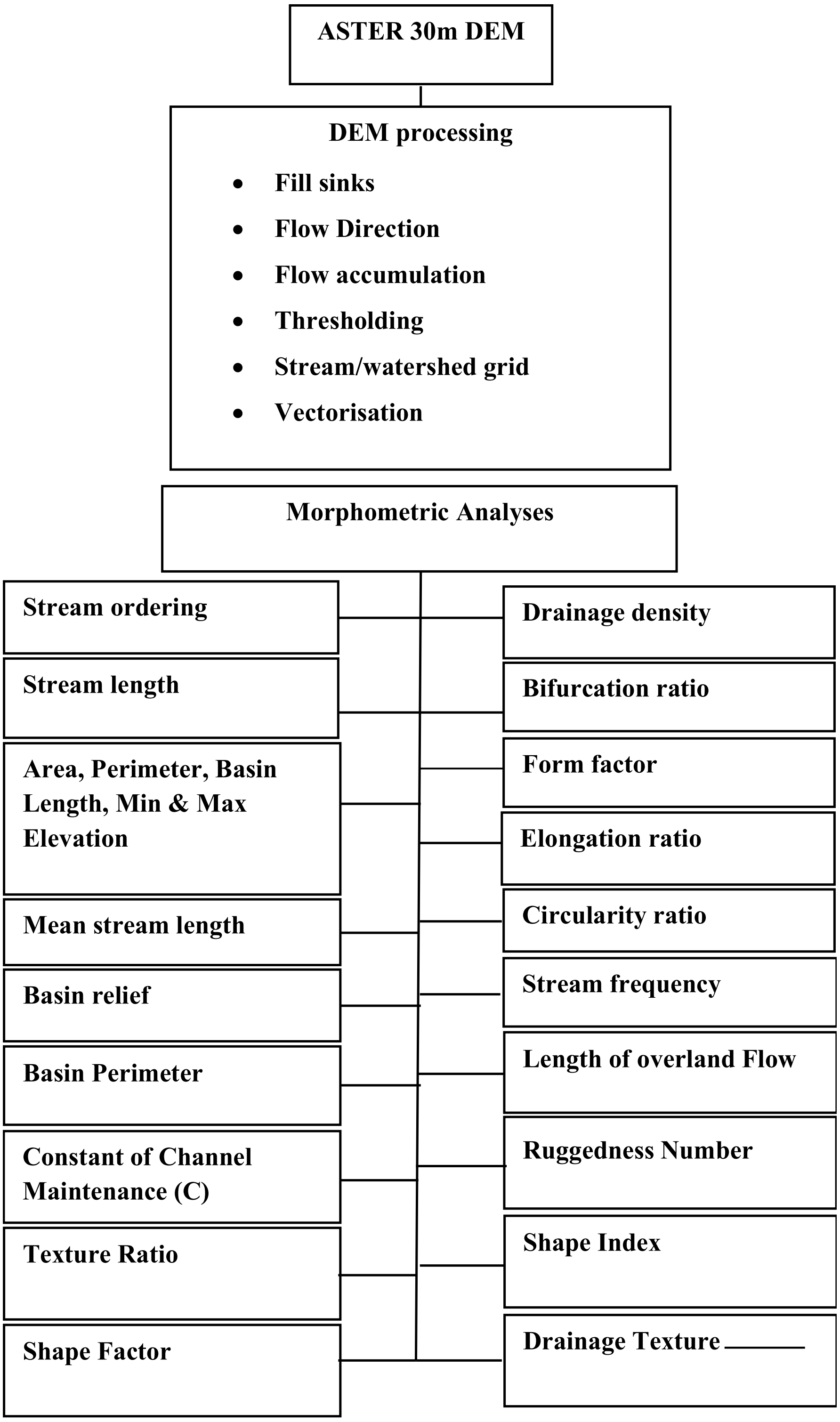


Figure 3.2: Showing flow chart of methodology used for morphometric analysis

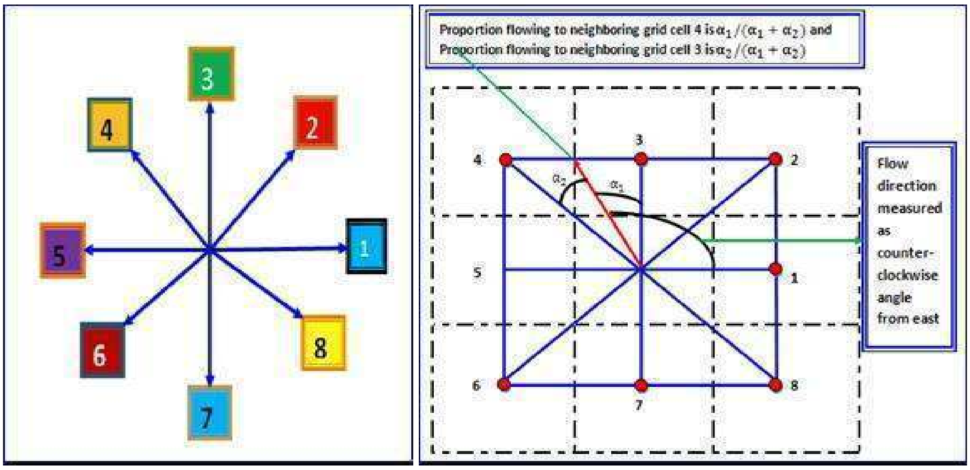


Figure 3.3: Showing flow direction defined as steepest downward slope on planar triangular facets on a block centered (Tarboton, 2000)

Filling up the DEM pits: This process identifies all pits in the DEM and raises their elevation to the level of the lowest pour point around their edge. Pits are low elevation areas in digital elevation models (DEMs) that are completely surrounded by higher terrain. They are generally taken to be artifacts that interfere with the routing of flow across DEMs, so need to be removed by raising their elevation to the point where they drain off the edge of the DEM. The pour point is the lowest point on the boundary of the "watershed" draining to the pit. This step may not be essential, if one has a reason to believe that the pits in the DEM are real. Also, if a few isolated pits are known, but others need to be filled, the isolated pits should have "no data" elevation values inserted at their lowest point. "no data" values serve to define edges in the domain, and elevations are only raised to where flow is off an edge, so an internal "no data" value will stop a pit from being filled, if, necessary.

Determining flow direction: The main purpose of this algorithm is again to ensure that the water always flows to lower elevations (Garbrecht and Martz, 1997). If we translate this into a finite cell system (the grid concept), we can say that the water that is stored in a determined cell is going to flow to the neighbor cell with lower elevation. But water in a cell based system has to choose just one path to get to the next cell that has the steepest slope as illustrated in the Figure 3.3.

There are numerous algorithms employed to determine flow direction from DEMs but, probably, the most common algorithm is the “D8” algorithm, where the flow direction for every cell within the watershed is determined by considering the surrounding eight neighboring cells. The local slope in each of the eight directions of these neighboring cells is calculated by taking the difference in elevation indicated by the DEM value at each of these eight neighboring locations and the value at the cell being examined. This difference in elevation is then divided by the center-to-center distance between these cells. The direction that yields the steepest downhill slope is the inferred direction of water flow. The determination of flow direction is very important because it allows for the inference of drainage areas, flow lengths, and the automated delineation of watersheds.

Determining flow accumulation: The next step is to define a grid in which each cell is going to store a value that is equal to the number of contributing cells upstream of it. When we obtain the flow direction grid, we can determine in each cell how many cells are pointing towards it and store this value as a number. When a cell, that has neighbouring cells pointing to it, is pointing towards another cell, its value is accumulated in the later one. This is what is defined as a flow accumulation grid. One can obtain the drainage area, if, we multiply the area of the cell by the number that is stored in it. Therefore, we can have basically a drainage area grid, from flow accumulation grid.

Applying threshold condition: With the flow accumulation grid, we know how much each cell is going to give or contribute, based on the cell's capacity of water storage multiplied by the drainage area contributing to the cell. Now, we need to determine how much drainage area is required in order to consider a certain cell as part of a river. This is a decision based on the hydrologic characteristics of the area. It is a function of the cell size and the selected drainage area.

Obtaining streams grid: This threshold number is applied as a condition in each cell to obtain a grid that is considered a stream/river and is identified by a number. The grids that do not satisfy the threshold criteria are not considered as streams/ rivers.

Generating stream links grid: Once we have identified the river grids these have to be linked. The best way is to break these rivers into their streams component. A stream has three characteristics: a ‘from node’, a ‘to node’ and an ‘ID’. These characteristics are use to link and name the streams. All the cells, that are part of the same stream, share the same ID.

Obtaining watersheds grid: Now, that every stream is well defined, we proceed to delineate the grids based on the links grid and on the flow direction grid. We are going to get one watershed per stream link. We also need to define the boundaries of each watershed, and for that, we need the flow direction grid. All the cells in a watershed should have a direction towards a certain stream. The cells that are flowing outside define the limit/boundaries.

Vectorizing streams grid: This procedure is used to convert the streams links grid into line vectors.

Vectorizing the watersheds grid: This step aims to create a polygon vector from the watersheds grid. The polygons vector defines an area that covers exactly the watershed grid. This function ensures that the area covers the cells with same value.

III. Quantitative morphometric parameters

Quantitative morphometric analysis of watershed and channel networks came into existence from a purely qualitative and deductive study subsequent to the valuable contributions made by R.E. Horton. Valuable contributions from further developments came from Strahler (1952a), Morisawa (1959), Melton (1957) and Leopold and Miller (1956). One of the advantages of quantitative analysis is that many of the watershed parameters derived are in the form of ratios or dimensionless numbers, thus providing an effective comparison irrespective of the scale (Krishnamurthy et. al.1996). Morphometric analysis provides a quantitative description of the watershed geometry to understand initial slopes or inequalities in the rock hardness, structural controls, recent diastrophism, geological and geomorphic history of the drainage watershed (Strahler 1964). Morphometric analysis requires measurements of linear features, the gradients of the channel network and contributing ground slopes of the drainage watershed (Nantiyal 1994). Remote sensing, with its varied advantages of spatial, spectral, and temporal availability of data covering large and inaccessible areas within a short time, has emerged as a powerful tool for analysing drainage morphometry. Image interpretation techniques are less time consuming than ground surveys, which if coupled with limited field checks yield valuable results (Rajiv et al. 2005). Linear and areal measurements form an important part of quantitative morphometric analysis by which different dimensionless ratios can be derived. Morphometric analysis of the watershed is considered to be the most satisfactory method because it enables (i) an understanding of the relationship of various aspects within a drainage watershed (ii) a comparative evaluation to be made of different drainage watersheds developed in different geomorphological and topographical regimes and (iii) the definition of certain useful variables of drainage watersheds in numerical terms (Krishnamurthy et al. 1996). Measurements of linear aspects such as stream orders, stream length and length of overland flow, as well as measurements for areal aspects such as drainage density, the constant of channel maintenance, stream frequency were made. Some useful and important shape factors and forms have also been calculated for the sub-watersheds. Overall above 20 parameters have been derived and some of them are explained below (Table 3.1):

Watershed shape factors and ratios

- Form factor, R_f

Quantitative morphometric expression of drainage-watershed outline form was made by Horton through a form factor R_f, which is a dimensionless ratio of watershed area A_u the square of watershed length L_b, thus $R_f = A_u / L_u^2$. Form factor, R_f has a direct relation to the stream flow and shape of the watershed. Low form factor R_f values indicate that the drainage watershed is elongated in nature and higher values indicate that the drainage watershed has developed a rectangular to circular shape.

- Circulatory ratio, R_c

Miller (1953) used a dimensionless circulatory ratio R_c defined as the ratio of watershed Area A_u to the area of a circle A_c having the same perimeter as the watershed, thus, $R_c = A_u / A_c$. Miller (1953) found that circulatory ratio R_c remained remarkably uniform in the range of 0.6 to 0.7. Low R_c values indicate strongly elongated and highly permeable homogenous geological materials while high values indicate low relief with impermeable surface.

- Elongation ratio, R_e

Schumms (1956) used an elongation ratio R_e, defined as the ratio of the diameter of circle of the same area as the watershed to the maximum watershed length. The ratio runs between 0.6 to 1.0 over a wide variety of climatic and geologic types, thus, $R_e = D_c / L_b$. Values near to 1.0 are typical of regions with very low relief, whereas values in the range of 0.6 to 0.8 are generally associated with strong relief and steep ground slopes (Miller 1953).

- Shape index, S_W

The shape of the watershed is equal to the square of the length of the watershed divided by the area of the watershed. W is the average width in km and A_u is the watershed area in km^2 (Horton 1945). The shape of the watershed is thus S_w=L/W=L^2 /A_u. The shape of the drainage watershed along the length and relief affect the rate of water and sediment yield.

- Texture ratio, T

Texture ratio is an important factor in the drainage morphometric analysis, which depends on the underlying lithology, infiltration capacity and relief aspect of the terrain. It is the ratio of the number of first order streams, $N_1$to the perimeter of the watershed, thus T=N_1/ P_u.

- Ruggedness number, R_n

The ruggedness number indicates the structural complexity of the terrain in association with the relief and drainage density. It also implies that the area is susceptible to soil erosion. It is the ratio of the watershed relief B_h to the drainage density of the watershed thus $R_n = B_h * D$.

- Shape factor, R_s

The shape factor is obtained by dividing the perimeter of the watershed P_u, by the perimeter of a circle Pc of same area as that of the watershed, thus, Rs = P_u/P_c.

- Stream frequency, F

Horton introduced stream frequency as the number of stream segments N_u per unit area A_u, thus,

F = S Nu/Au (expressed per km^2).

The detailed analysis made by Melton (1957) for studying the relationship between drainage density and stream frequency for 156 drainage watersheds covering a vast range of scale, climate, relief, surface cover and geologic type showed that a remarkably small scatter existed, indicating that the relationship between density and frequency tends to be conserved as a constant in nature.

Linear aspects

- Stream order and number, N_u

The first step for drainage-watershed analysis is designation of stream orders. In the present study a system introduced by Horton and modified by Strahler (Strahler 1952b, Schumns 1956, Singh 1980) has been adopted. Each segment of the stream was numbered starting from the first order to the maximum order present in each of the sub-watersheds. After numbering, the drainage-network elements are assigned their order numbers, the segments of each order are counted to yield the number N_u of segments of the given order u. The ratio of the number of segments of a given order N_u to the number of segments of the higher order N_{u+1} is termed the bifurcation ratio R_b, thus $R_b = N_u / N_{u+1}$. According to Horton’s law of stream numbers, a plot of stream order (abscissa) against stream numbers (ordinate) plotted on a semi-log sheet reveals a linear relationship. The average bifurcation ratio can be determined from the slope of the fitted regression of order Vs numbers of stream segments. Bifurcation ratios normally range between 3.0 and 5.0.

- Stream length, L_u

The mean length Lu of stream length segment of order u is a dimensional property, which reveals the characteristic size of components of a drainage network and its contributing watershed surfaces. Each of the channel lengths was measured using a digital curvimeter. According to Horton’s law of stream lengths, a plot of logarithm of stream length (ordinate) as a function of order (abscissa) will yield a set of points lying along a straight line. This indicates that the watershed evolution follows the erosion laws acting on geologic material with homogeneous weathering-erosion characteristics. Any deviation in the points may be due to structural control of the streams. A graph of stream order (abscissa) against stream length (ordinate) plotted on a semi-log sheet reveals a linear relationship.

- Length of overland flow, L_g

Surface runoff follows a system of down slope flow paths from the watershed perimeter to the nearest channel. During evolution of the drainage system, L_g is adjusted to a magnitude appropriate to the scale of the first-order drainage watersheds and is approximately equal to one-half of the reciprocal of the drainage density. Horton noted that the ‘length of the overland flow is one of the most important independent variables affecting both the hydrologic and physiographic development of drainage watersheds.' The shorter the length of the overland flow, the quicker the surface runoff will be.

Areal aspects

- Drainage density, D_u

As per Horton's definition drainage density is an important indicator of the linear scale of landform elements in stream-eroded topography and is simply the ratio of total channel-segment lengths L_u cumulated for all orders within a watershed to the watershed area A_u, thus,

D = summation Lu/Au (expressed in (km/km^2).

High drainage density is favoured in regions of weak or impermeable subsurface materials, sparse vegetation and mountainous relief. Low drainage density is favoured in regions of highly resistant or highly permeable subsoil materials under dense vegetation cover and where relief is low. On the basis of the drainage density, a drainage watershed can be classified into any of the five different textures as (i) very coarse (52), (ii) coarse (2–4), (iii) moderate (4–6), (iv) fine (6–8) and (v) very fine (48). Melton (5) found that drainage density varies directly with per cent of bare area and runoff intensity-frequency, but inversely with precipitation-effectiveness index and infiltration capacity, confirming Horton's infiltration theory of erosion.

- Constant of channel maintenance, C

The constant of channel maintenance is defined as the area of watershed surface needed to sustain a unit length of stream channel. Schumms (1956) used the inverse of drainage density to define the constant of channel maintenance, or C = A_u/Summation L_u (expressed in (km^2/km). The constant of channel maintenance depends not only upon the rock type and permeability, climatic regime, vegetation cover and relief, but also on the duration of erosion and climatic history. The constant is extremely low in areas of close dissection.

TABLE 3.1: Methodology adopted for computation of morphometric parameters

S. No.	Morphometric Parameters	Formulae	Reference
1	Stream Order (U)	Hierarchical rank (Strahler Scheme)	Horton, 1945
2	Stream Length (Lu)	Length of the stream	Strahler, 1964
3	Mean Stream Length (Lsm)	$Lsm = Lu/Nu$; Where, Lsm = Mean stream length; Lu = Total stream length of order 'u'; Nu = Total no. of stream segments of order 'u'	Horton, 1945
4	Stream Length Ratio (RL)	$RL = Lu/Lu\text{-}1$;Where, RL = Stream length ratio; Lu = The total stream length of order 'u'; $Lu\text{-}1$= The total stream length of its next lower order	Strahler, 1964
5	Bifurcation Ratio (Rb)	$Rb = Nu/Nu+1$;Where, Rb = Bifucation ratio; Nu = Total no. of stream segments of order 'u'; $Nu+1$= Number of segments of the next higher order	Schumms, 1956
6	Mean Bifurcation Ratio (Rbm)	Rbm = Average of bifurcation ratios of all orders	Strahler, 1957
7	Relief Ratio (Rh)	$Rh = H/L$; Where, Rh = Relief ratio; H = Total relief (Relative relief) of the watershed in Kilometre; Lb = Watershed length	Schumms, 1956
8	Drainage Density (D)	$D = Lu/A$; Where, D = Drainage density; Lu = Total stream length of all orders; A = Area of the watershed (km²)	Horton, 1932
9	Stream Frequency (Fs)	$Fs = Nu/A$; Where, Fs = Stream frequency; Nu = Total no. of streams of all orders; A = Area of the watershed (km²)	Horton, 1932
10	Drainage Texture (Rt)	$Rt = Nu/P$; Where, Rt = Drainage texture; Nu = Total no. of streams of all orders; P = Perimeter (km)	Horton, 1945
11	Form Factor (Rf)	$Rf = A/Lb^2$; Where, Rf = Form factor; A = Area of the watershed (km²); Lb^2= Square of watershed length	Horton, 1932
12	Circularity Ratio (Rc)	$Rc = 4*\pi*A/p^2$;Where, Re = Circularity ratio; π = 'Pi ' value i.e. 3.14; A = Area of the watershed (km²); P = Perimeter (km)	Miller, 1953

13	Elongation Ratio (*Re*)	$Re = 2/Lb \, sqrt(A/\pi)$; Where, *Re* = Elongation ratio *A* = Area of the watershed (km^2);π = '*Pi*' value i.e. 3.14; *Lb* = Watershed length	Schumms, 1956
14	Length of overland flow (*Lg*)	$Lg = 1/D*2$; Where, *Lg* = Length of overland flow; *D* = Drainage density	Horton, 1945
15	Constant Channel Maintenance (*C*)	$C = 1/D$; Where, *D* = Drainage density	Schumms, 1956
16	Texture Ratio (*T*)	$T = N1/P$; Where, *N1*= Total number of streams in 1st order; *P* = Perimeter of watershed	Schumms, 1956
17	Shape index (*Sw*)	$Sw=Lb^2/A$; Where, *Lb*= Watershed length; *A*= Area of watershed	Horton, 1945
18	Ruggedness number (*Rn*)	$R n = Bh * D$; Where, *Bh* = Watershed relief; *D* = Drainage density	Pareta, 2011
19	Shape Factor (*Rs*)	$Rs = P u /P c$; Where, *Pu* = Perimeter of circle of watershed area; *Pc* = Perimeter of watershed	Sameena, 2009
20	Drainage Intensity (*Di*)	$Di = Fs / Dd$; Where, *Fs* = Stream frequency; *Dd*= Drainage density	Faniran, 1968
21	Compactness coefficient (*Cc*)	$Cc = P c/P u$; Where, *Pc* = Perimeter of watershed; *Pu* = Perimeter of circle of watershed area	Suresh, 2004

3.2.2 Land use/ land cover data generation

Land use/Land cover data is very important input for the Cp evaluation scheme. The information about land use/land cover is vital for land surface processes including hydrological and climatic processes. Remote Sensing has a long and successful history of application in generating land use and land cover information on operational basis (Hausen et al, 1996 and Foody, 2002). For generating the land use/land cover information for the representative watersheds, we used IRS LISS III digital data. Figure 3.4 describes the flowchart methodology adopted for generating land use/ land cover information. Before using the satellite imagery for classification, the satellite image was pre-processed to rectify the geometric and radiometric corrections in order to improve its interpretability. The methodology for image processing of the satellite data is described here under:

Geometric correction: Remote sensing data are distorted by the earth curvature, relief displacement and the acquisition geometry of the satellites (i.e. variations in altitude, aspect, velocity, panoramic distortion). The purpose of geometric correction is to compensate for the distortions introduced by these factors so that the corrected image will have the geometric integrity of a map (Lillesand and Kiefer, 1987).

In the geometric correction process 90 Ground Control Points (G*CP*s) were taken from different part of the study area and were located both in terms of their two image coordinates on the distorted image and on the high accuracy image in UTM coordinate system with WGS 84 datum. These values were submitted to least square regression analysis to determine two coordinate transformation equation that was used to inter-relate the geometrically corrected image coordinates with distorted image coordinates. The next step was to find the corners of the rectified image to the distorted image; this was done using nearest neighbouring re-sampling method. This method has the advantage that pixel values are real as they are directly copied from the image and no interpolation algorithms are used. The final rectified image was obtained with Root Mean square error (RMSE) of 1.06.

Radiometric correction: Digital comparison of multi-sensor data requires further adjustment as the observations are made in sensor specified discrete spectral bands. The amount of energy received at the sensor from a particular earth feature is a function of received energy, reflectance, atmospheric propagation, sensor sensitivity, and the spectral bandwidth. The data that was made available for this research had already been radiometrically corrected. However, various image enhancement techniques were performed on the image for enhancing the visual interpretability of the data. Different filtering techniques were also used to enhance the quality of the data by reducing the noise.

Training data for classification: Training is a critical step in a supervised image classification. As the training samples should be representative of the land cover classes, they are collected from relatively homogeneous areas on the ground. Therefore, they are chosen subjectively and deliberately away from mixed pixels containing two or more classes. The size of the training samples is related to the number of wavebands. Training sites are necessary to define the classes that did not get classified uniquely during the unsupervised classification. Training sites were created by demarcating a polygon or area of interest for the known cover types. While demarcating the training sites various enhancement techniques were applied.

Best-suited enhancement techniques for particular feature identification were found out by trial and error procedure. In total, 120 training sites were collected, 10 for each land use/ land cover classes and were facilitated by the availability of ground truth information.

Signature Development: In signature development, training area statistics were gathered for each spectral band to be used in the final classification. Signature files were created from each training site. Signature files store statistics gathered from the training site, that are later applied to the entire image during the classification procedure. Care was taken to ensure that each class was well represented within the realm of natural variations that occur.

Classification: Data were classified using the Maximum likelihood classifier decision rule. The maximum likelihood (ML) procedure is a statistical approach for pattern recognition. The probability of a pixel belonging to each of a predefined set of classes is calculated and the pixel is then assigned to the class for which the probability is the highest.

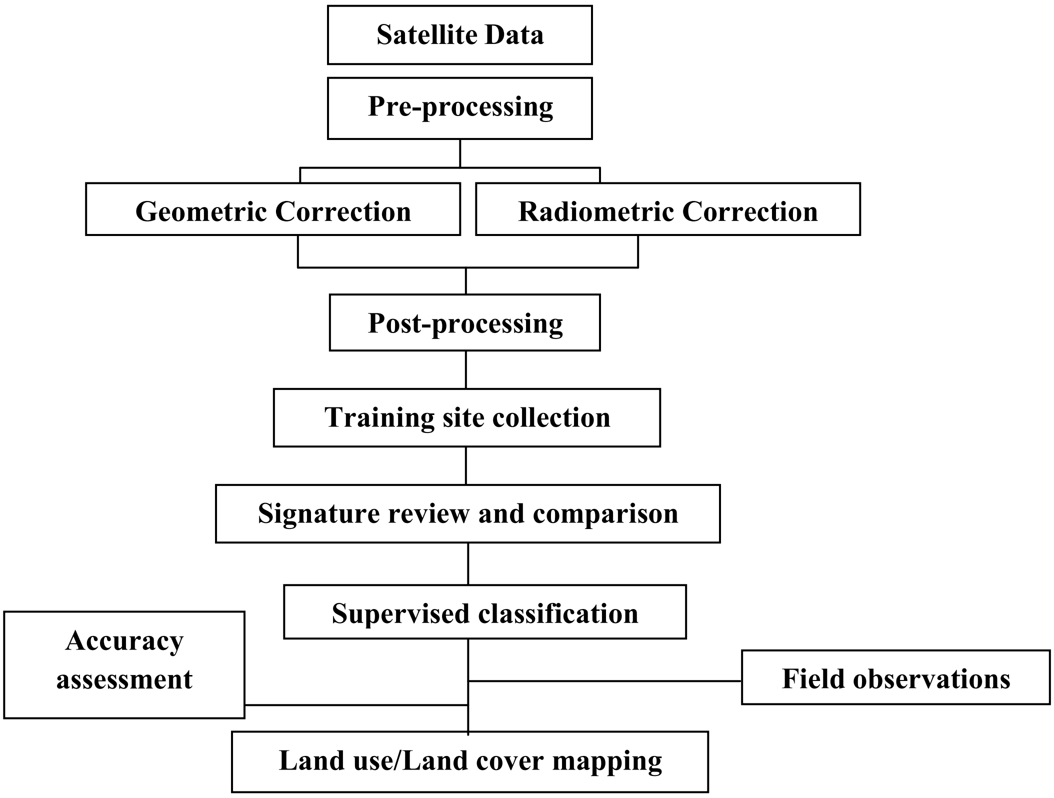


Figure 3.4 Showing Flow chart of methodology used for Land use/Land cover mapping.

Maximum Likelihood Classifier algorithm is defined by the following equation as suggested by Fu (1976):

where, g (x) = probability density

ρ (wi) = a priority probability

ρ (x / wi) = probability of ‘x’ for falling in class i

$$\mathbf{gi(x) = log\rho(wi) - \frac{-Nlog2\pi - log|\sum i\,|}{2} = \frac{1[\![(x - \mu i)t.\sum i - 1\mu i)]\!]}{2}}$$

$$\mathbf{i\ =\ 1, 2, 3 \ldots\ldots\ldots\ n}$$

For equal priority probability with Gaussian distribution, we have:

or simply,

$$\mathbf{gi(x) = -log\left|\sum i\right| - \frac{1long[(x - \mu i)t.\sum i - 1(x - \mu i)]i}{2}}$$

where,

|Σi| = determinant of variance-covariance matrix of class i

Σi-1 = inverse of variance of variance-covariance matrix

x = measurement vector, i.e. DN values of any pixel for all the channels

μi = mean vector for the ith class

t = transpose

Any measurement vector ‘x’ i.e. any pixel may be classified into ith class if gi (x) ≥ gj (x) for all i ≠ j.

The supervised classification of the satellite data using ML classifier resulted in a land use/land cover map of the pilot sites. Ground validation was carried out for all the land use classes identified in the study area. The necessary changes were incorporated and the final map was prepared.

Accuracy assessment: The accuracy estimation is considered to be one of the most important aspects of the study to assess reliability of the classified map. The quantitative approach is one such method through which the overall classification accuracy can be assessed. This is done by rationing the number of points found correctly on the classified image to that of total number of points checked in the field multiplied by hundred. This gives the total accuracy of the classified output in percentage. The confusion matrix between populations of pixels in a training set to that of its distribution among different classes would give over all accuracy of classification. Accordingly, the commission and omission errors could also be estimated to give percentage of accuracy each class. In addition, the Kappa Coefficient is also an important static used for describing the accuracy of the classified maps. . Errors of commission for each class were computed by summing up the number of pixels assigned to incorrect categories along each row and divide this number by total number of true pixels in this category. Errors of omission were computed by summing up the number of pixels assigned to incorrect categories along each column and dividing this number by the total number of true pixels in this category. The ideal numbers of points to be tested in the classification map were derived from the formula for binomial probability theory. The number of points (N) Selected was determined from the following formula (Jensen, 1986).

$$\mathbf{N} = \frac{4pq'}{E^2}$$

where, p = Expected percentage accuracy; q’ = 100 – p and

E = Allowable error.

To determine the accuracy of individual categories (p) in 95% confidence limit,

$$\mathbf{P} = \mathbf{p'} \pm \left(\frac{1.96\sqrt{p'\,q'}}{\sqrt{n}}\right) + \frac{50}{n}$$

where, p’ = Value of true per cent correct = $\frac{c}{n}$; q’ = 100 – p; c = No. of points correct; n = Number of points sampled.

The 95% one-tailed confidence limit for a binomial distribution was obtained from the following expression,

$$\mathbf{P} = \mathbf{p'} - \left(\frac{1.645\sqrt{p'\,q'}}{\sqrt{n}}\right) + \frac{50}{n}$$

where, p = overall accuracy

- **Kappa accuracy:** Kappa coefficient of agreement is a measure of agreement between classification and verification. The accuracy estimates as given above do not consider the distribution of error over the different categories. Kappa accuracy is determined from the error matrix, which not only gives the number of correctly classified units but also the errors of commission and omission. An error of omission occurs by erroneously excluding a unit from a category, when it belongs to the same class. An error of commission occurs by erroneously including a unit belonging to some other category. Error matrix can be generated for Level I and Level II land use / land cover classes. This statistic was introduced in remote sensing data by Congalton and Mead (1983). Kappa statistics is defined as follows.

$$\mathbf{k} = (\theta 1 - \theta 2) / (1 - \theta 2)$$

k gives an estimate of the overall accuracy.

$$\theta_1 = \sum \mathbf{xii} / \mathbf{N}$$

where i= 1 to r

$$\theta_2 = \sum \mathbf{xi} + \mathbf{x} + \mathbf{i} / \mathbf{N}^2$$

where i= 1 to r

where, r is the number of rows in the error matrix

xii is the ith diagonal element

xi is the marginal total of row i

x+i is the marginal total of column i

N is the total number of observations

Large sample variance of the kappa estimate is given as

$$\mathbf{var}\,(\mathbf{k}) = (\theta 1(1 - \theta)) / (1 - \theta 2)^2 + 2(1 - \theta 1)(2\theta 1\theta 2 - \theta 3) / (1 - \theta 2)^3$$
$$+ (1 - \theta 1)^2 (\theta 4 - 4\theta 2)^2)$$
$$/ (1 - \theta 2)^4$$

where, $\theta 3 = \sum \mathrm{Xii} + \mathrm{Xi}\,) / \mathrm{N}^2$ and i= 1 to r

$$\theta 4 = \sum \quad \mathrm{X\,ij}\,(\mathrm{Xj} + \; + \mathrm{X} + \mathrm{i}\,)^2 / \mathrm{N}^3\ \mathrm{i} = 1 \text{ to } \mathrm{r}$$

Kappa coefficient of 0.90 means that the classification is 90% accurate. Kappa coefficient is a coefficient of agreement as a measure of total map accuracy. A measure of overall agreement is computed for each matrix based on the difference between the actual agreement of the classification i.e. agreement between visual classification and reference data as indicated by the diagonal elements of the error matrix and the chance agreement which is indicated by the product of the row and column marginal elements.

There are two types of individual proportional accuracies involved. When the estimated individual accuracy includes the errors of commission, it is called the producer's accuracy and when it includes the errors of omission, it is called the user's accuracy.

3.2.3 Topography

The topography of a region is the fundamental tenet that will decide the impact of flooding. In this study following topographic features of the representative watersheds have been generated: elevation, slope and aspect. These features distinguish one watershed from other thereby creating unique characteristics for each. These watershed characteristics carved by nature are best studied in GIS environment. The elevation, slope and aspect details have been generated using the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) 30 m digital elevation model (DEM).

- **Elevation:** The DEM stores altitude above sea level for every pixel of the image. The elevation of the watersheds is classified into eight classes using the Arcview software.
- **Slope:** It shows the steepness or inclination of a line, determined from two points on a line. It is a measurement of steepness of terrain, the ratio of vertical rise to horizontal distance expressed in terms of percentage or degrees of an angle. A high slope value indicates a steeper inclination. The slope of an area is an important factor to be considered in geological and environmental studies. For the present study slope map was generated in Arc View 3.2 Model builder. The slope of each watershed is classified into ten classes based on the Canadian classification, which is found to best emulate and exhibit the natural topographic characteristics.

- **Aspect:** It determines the direction of maximum slope, also referred to as orientation. Using the ArcView software, both the watersheds were classified into nine aspects.

3.2.4 Geomorphology

Fluvio-Geomorphological mapping was carried out using the methodology described in the Figure 3.5. The different fluvio-geomorphologic units have been identified on the basis of various criteria as detailed as under:

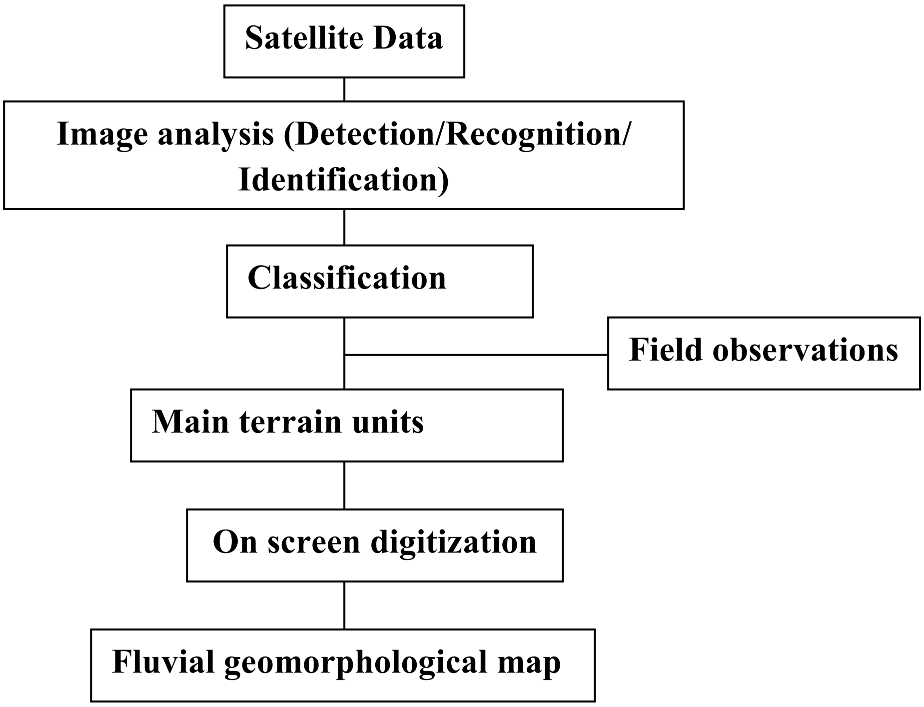


Figure 3.5 Showing flow chart of methodology used for generation of geomorphological map

Geomorphological classes

- *Active River Channel:* It reflects irregular topography with varying water content, erosion and linear shape.
- *Non Differential Alluvial plain:* Units recognized on the basis of the lighter tone, different type of vegetation cover, higher elevation than the flood plain.
- *Low Deppressional Areas (water logged):* Remarkable and irregular features incising in the uplands and showing dark tones related to their humidity content, although located higher than the floodplain.

- *Back Swamp:* Low lying geomorphic units with dark tone, high moisture content and marshy vegetation.
- *Temporary Lake:* Low deppressional areas with high moisture content and water logged during flooding period.
- Swamp: Low lying areas with some woody plants than found on a marsh land with high moisture content.
- *Lake:* Water body.
- *Inactive Alluvial Plain:* Areas slightly dissected, higher than the flood plain and showing different vegetation cover.
- *High Old terrace Deposits (higher remnant):* Located at topographically higher positions, well visible due to the higher reflectance of sandy material and never flooded (populated areas).
- *Low terrace deposits:* Areas slightly elevated than the floodplain, kind of transition zone, with some agricultural parcels but not in an exclusive way.
- *Non Differential Flood plain:* Small units towards the upper portions of the rivers, gently sloping and with different spectral reflectance, due to different vegetation cover type.
- *Former River Channel without Water (in filled):* Remarkable features, nearly flat, basically subject to silting up by fluvial accumulation and intensively used for agriculture purposes.
- *Old Flood Plain:* Older part of the flood plain with small patches of highlands, slightly undulated, intensively used for agriculture and some settlements, consistent tree and shrubs layer can also be found here.
- *Tributary River:* Water body.
- *Active Flood Plain:* One of the most active units of the system is characterized by the landform of recent meander system. Intensively used for agriculture with some scattered tree distribution.

3.2.5 Soil

The information about soil is very vital for estimating the hydrological response at the watershed scale.

The detailed methodology adopted for the generation of the soil data is schematic represented in the Fig. 3.6. The step-wise approach adopted for the generation of soil data input is described here under:

Satellite data analysis: Visual interpretation of IRS LISS III was carried out and different soil classes were identified on the basis of tone, texture, shape and associated land use/land cover.

Table 3.2 Showing soil classification on the basis of soil particle size (ISSS).

S. No.	Soil fraction	Diameter of the particles (mm)
1.	Coarse sand	0.2 – 2.0
2.	Fine sand	0.02 – 0.2
3.	Silt	0.002 – 0.02
4.	Clay	< 0.002

Soil class digitization: After visual identification of soil classes, digitization of individual classes were carried out using tonal variations, associations, patterns and various other image elements that aided soil interpretation. The base soil map was generated for the further analyses in GIS environment.

Field survey and soil sampling: A series of field trips were conducted for validation of identified soil classes from the satellite Image. Soil samples from each identified classes were collected for the soil texture analyses in the lab. Composite soil samples up to 15 cm depth were collected for each soil class identified by studying the tonal variations on the satellite image. 2-3 samples were collected for each sample location and 3-4 sample locations were taken for each identified soil class. The samples for each soil class from different sample locations were mixed and the lab analysis for soil texture was carried out for the mixed samples at Sheri Kashmir University of Agricultural Sciences and Technology (SKUAST), Shalimar, Kashmir.

Texture analyses: Particle size distribution is a fundamental property of soil and is an important distinguishing property characterizing different soils. According to size, there are three major size groups namely sand, silt and clay. These groups are called ‘soil separates’ and can be further sub-divided into smaller size classes. The International Society of Soil Science (ISSS) has grouped the soil particles into four soil classes as show in the Table 3.2.

Soil texture analysis was carried out by *pipette method*. This method involves two steps:

Dispersion: 20gms oven-dry soil was taken for analysis. The soil particles usually exist as floccules and are cemented together. In order to determine its texture, it is necessary to completely disperse soil particles. The dispersion of soil particles was achieved by inactivation or removal of cementing and flocculating agents viz. organic matter, oxides of iron and aluminium, calcium carbonate, soluble salts and ions, etc. The soil was chemically treated with hydrogen peroxide, hydrochloric acid, sodium phosphate and sodium hydroxide, and the final separation and hydration of the particles was accomplished by vigorous stirring of the soil water suspension using shaking tables.

Fractionation: It is based on the Stoke's law. The suspension was sieve-filtered after stirring. Coarse sand particles get separated and the rest of the suspension was collected in a 1000ml cylinder. Coarse soil particles are weighed and the percentage in relation to the total weight of the soil was calculated. The volume of the suspension in the cylinder was made 1 litre with distilled water. The temperature of the suspension was recorded and the required time for sampling against the temperature for silt+clay and clay was obtained from the sedimentation table provided by ISSS. The temperature of the suspensions of various soil samples was found to be 14ºC. Accordingly, the time required for the sampling was 5 minutes and 40 seconds for silt+clay and 9 hours and 20 minutes for clay alone. After shaking the suspension, 25ml of the suspension are pipetted out after waiting for the required time. The weight of the silt and clay were recorded and converted from per 25ml to per 1000ml. The percentages of silt and clay are then calculated. The remaining suspension was decanted and any particles settled at the bottom of the cylinder are weighed, which gives the fine sand content of the soil.

The texture of the soil is determined from the relative proportions of sand, silt and clay that it contains. Triangular classification suggested by ISSS. It makes use of an isolateral triangle whose area is divided into 12 compartments each representing a texture. For the determination of the texture of a soil, the clay and the silt percentages are located on the respective sides of the triangle. An inward line is drawn parallel to the sand axis in the former case and the parallel to the clay axis in the latter case. The compartment in which the two lines intersect is the texture of the soil.

GIS soil data base: All the spatial and non spatial information generated through the above described steps was integrated into a geospatial soil database. The data base model adopted for storing, accessing and querying the soil data is based on the relational data base management system (RDBMS).

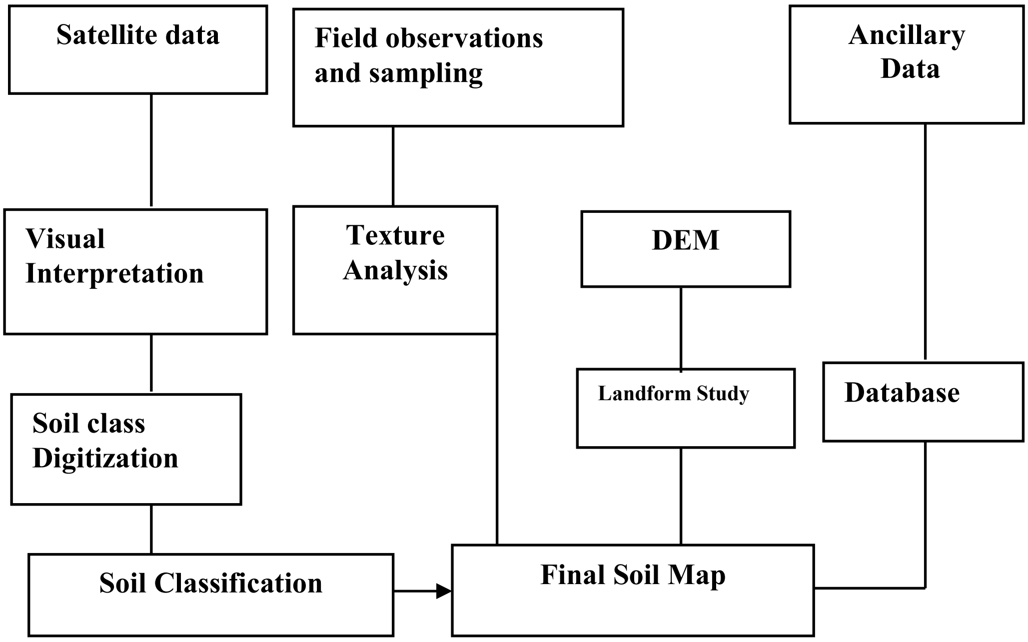


Figure 3.6 Showing flow chart of methodology used for generation of soil map

3.2.6 Geology

Geological maps from Geological Survey of India at 1:500,000 were co georeferenced with the topo sheets of the study area. The geological classes in the study area were digitized and a geospatial database of the existing geological maps was generated.

Objective 2: Assess the impact of differential geo-environmental setting on the hydrology of these watersheds

3.2.7 Empirically based hydrological modeling based on Compound Value (Cp) evaluation

In order to assess the impact of morphometry, LULC, topography, soil, geology and geomorphology on the hydrological response of the study area, an empirical hydrological modelling approach based on compound value method has been adopted (Javed et al, 2009). The method utilizes prioritization of watersheds to be done by taking the process of infiltration and runoff into consideration. For every class pertaining to any information layer, ranking has been done on the basis of their hydrological response. The total number of ranks to be assigned in *Cp* approach is based on the number of watersheds. Since there are two watersheds in the current study, therefore two ranks **one** and **two** were assigned to the values of every parameter of of morphometry, LULC, topography, soil, geology and geomorphology. Rank 1 is assigned in such a way that the value of the parameter depicts maximum contribution to the runoff processes and rank 2 is assigned in such a way that it reflects minimum contribution to runoff processes.

The ranks are then averaged to arrive at a common compound value (*Cp*) in order to prioritize the watersheds. Lower *Cp* value means that the watershed is dominated by the runoff processes and vice versa. Different criteria for different information layers used for ranking the classes have been discussed in detail below and the overall methodology for accomplishing this objective is shown in Figure 3.7:

Assigning ranks on the basis of LULC:

Higher percentage of plant cover and large amounts of root biomass generally increase the infiltration rate. The canopy of trees intercepts the precipitation which leads to stem flow. Thus, the rate of movement of water from canopy to ground decreases and water gets more time to infiltrate. The foliage of smaller plants intercepts the flow of water and thus increase the time of contact of water and soil leading to more infiltration. Due to the imbibitions and osmosis process, large amount of root biomass increase the infiltration process by holding and absorbing more water. Also, soils with good organic matter content have better ability of infiltration and this organic matter is more where plants are present. The land that is impervious either by their natural composition or by settlements created by humans will not contribute to any infiltration as the pores are blocked. So, the land use/ land cover plays very important role in determining the infiltration/ recharge zones in an area. The LULC varies in different areas due to difference in climate, temperature, geology, geomorphology, lithology, etc of these regions.

In this study, by adopting 'level I' LULC classification eight major classes have been identified and delineated which include agriculture, forests, waste-lands, impervious surface, pastures, shrubs, snow and water by using the satellite data IRS LISS III of 2008. Various LULC categories exhibit unique spectral image characteristics through their spectral signatures which are subsequently helpful for identification and delineation on the satellite data. Dense forests show dark red brown tone, variable texture due to variation in canopy cover; scattered pattern and association with high relief zones. Waste land exhibits light tone because of high reflectance, it shows irregular pattern with smooth texture. Water bodies appear dark on satellite images due to absorption of incoming IR radiations in the near infra red region, hence they are recognized by dark tone, smooth texture, well defined boundary outline and sharp contrast with other land uses. Impervious surface is characterized by greyish tone.

For the ranking process water bodies have been masked.

- Agriculture: The watershed with lower percentage of agricultural land has been given rank of 1, whereas the watersheds having higher percentage of agricultural land are assigned rank of 2. Agricultural land shows higher time to peak response due to the presence of crops and due to its coarse soil texture.
- Impervious surface*:* This constitutes exposed rocks or macadamized settlements characteristic of least infiltration. Therefore following the trend rank of 2 was given to the watershed having lower percentage of impervious surface, whereas the watershed having higher percentage was given a rank of 1.
- Forest: Rank of 2 has been given to watershed having higher percentage of forest cover and vice versa. The canopy and decaying leaves and twigs on ground helps infiltration.
- Wasteland: It may be described as degraded land which is currently unutilized. The upper part of the soil in such areas is usually very hard due to

inappropriate water and soil management. Therefore these areas behave more or less like impervious surfaces which halt the vertical movement of water. The watershed with higher percentage of waste land was thus given a rank of 1 and vice versa.

- Pastures: In pasture area, the infiltration is quiet high as in these areas the root biomass is very high which increases the water holding capacity of soil. Also the grass itself decreases the vertical water movement over land, thus, giving water more time to infiltrate. The rank of 2 was given to the watershed with maximum pasture area and vice versa.
- Shrub: The rank of 1 was given to the watershed with minimum shrub area and vice versa. Shrubs help in lowering the speed of water overland which cascading positively the process of infiltration.
- Snow: The perennial snow is present usually on exposed rocks of the watershed leading to minimum infiltration in these regions. Thus the watershed with higher percentage of snow cover was given a rank of 1and vice versa.

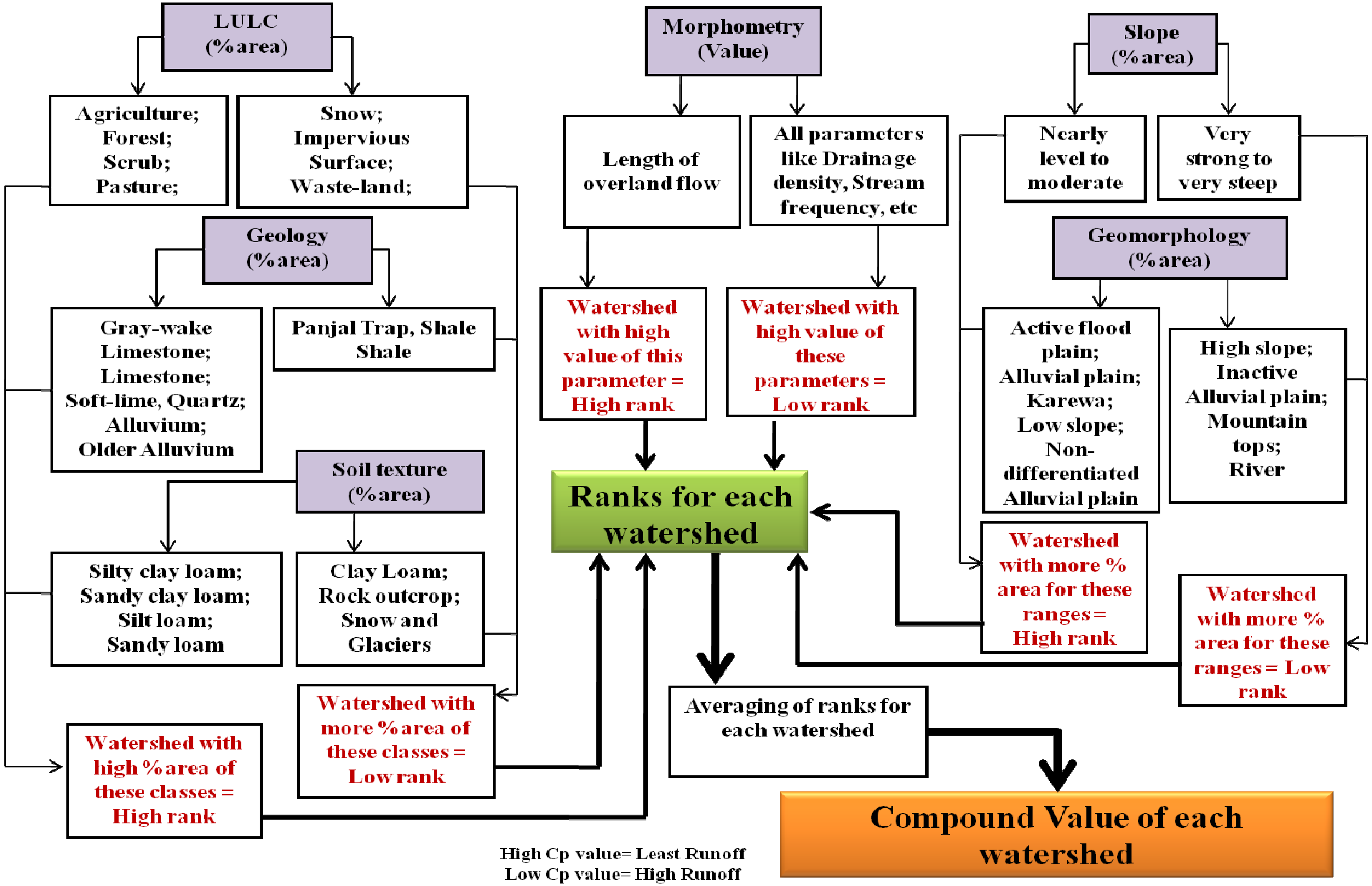


Figure 3.7 showing methodology adopted to assess the impact of differential geo-environmental setting on the hydrology of these watersheds

Assigning ranks on the basis of Morphometry:

Hydrological analysis based on morphometric parameters is very important for watershed planning since it gives an idea about the linkages between watershed characteristics in terms of geomorphology, hydrology, geology and land cover (Astras and Soulan Killin, 1992). Thus the morphometric analysis and prioritization was done to understand these linkages. Morphometry is factor of linear, shape and areal parameters of earth.

The application of geomorphic principles to understanding and quantifying environmental hazards as flooding has led to significant amount of research focussed on identifying relation between watershed morphometry and stream flooding. In order to understand geomorphological influence on flooding it is essential to study the morphometry and relate it to hydrology of the watershed. Therefore the watersheds with varied topographic, hydrologic, vegetation and physiographic setting were chosen for detailed morphometric analyses to understand geomorphologic and hydrological linkages. The bearing of geomorphology on hydrology is very significant and the relationship between the two is fairly complex. Geomorphologic properties of a drainage watershed represent its hydrologic behaviour. A strong mutual relationship exists between morphological variables and hydrological characteristics. Such realisation gave rise to quantitative geomorphology (Horton). Beven and Wood examined the dynamic nature of runoff contributing area and the relationship to the geomorphologic structure of watersheds. It has been shown that both runoff and flood frequency predictions are sensitive to assumption about nature of contributing area. According to the morphometric parameters the watersheds are ranked, based on their hydrological response; lowest rank assigned to the watershed with quickest time to peak i.e. a fast hydrological response (high runoff). After assigning rates to every parameter, the ranking for the two watersheds were averaged to arrive at a compound value (*Cp*).

Different criteria used for ranking of selected *linear morphometric parameters* have been discussed below:

- Drainage density: The higher values of drainage density indicates that the regions under these watersheds are composed of impermeable subsurface material, sparse vegetation and mountainous relief while as the lower drainage density of reveals that these watersheds are composed of permeable subsurface material, good vegetation cover and low relief which results in more infiltration capacity and can be the good sites for ground recharge sites. In general, the hydrology of a watershed changes significantly in response to the changes in the drainage density (Yildiz 2004). A high drainage density reflects a highly dissected drainage watershed with a relatively rapid hydrological response to rainfall events, while a low drainage density means a poorly drained watershed with a slow hydrologic response (Melton 1957). Carlston (1963) observed that there is a very close relationship between drainage density and mean annual flood. Accordingly, the watershed with higher drainage density is given a rank of 1 indicating quickest time to peak and vice versa.

- Stream frequency: Stream frequency is related to permeability, infiltration capacity and relief of watersheds (Montgomery and Dietrich, 1989, 1992). High stream frequency values indicate that watershed is having rocky terrain and has very low infiltration capacity reflective of early peak discharge that may result in flash floods. While the discharge from watersheds with low stream frequency would take time to peak because of low runoff rates. A rank of 1 is thus given to the watershed with highest stream frequency which is indicative of quickest hydrologic response due to higher runoff rates and vice versa.
- Mean bifurcation ratio: Because bifurcation ratio is indicative of structural complexity and permeability of terrain, whereby bifurcation ratio is negatively correlated with permeability. The high bifurcation ratio indicates early hydrograph peak with a potential for flash flooding during the storm events. Thus watershed with higher bifurcation ratio is given a rank of 1 demonstrating early time to peak due to lower infiltration and vice versa.
- Drainage texture: Horton recognized infiltration capacity as the single important factor which influences drainage texture. Regions of low infiltration capacity will give rise to higher drainage texture, leading to a quick hydrologic response hence given a rank of 1 and vice versa.
- Length of overland flow: Length of overland flow is one of the most important independent variables affecting both hydrologic and physiographic development of drainage watersheds. This factor relates inversely to the average slope of the

channel. The higher values of length of overland flow of watersheds indicate gentler slopes and longer flow paths and vice versa. The lower values thus indicate that runoff will take very less time to reach to out let hence given a rank of 1 and vice versa.

Shape parameters have a profound impact on the hydrological response from the watershed. Circular or fan shaped watersheds have high rates of run off when compared to other shapes because runoff from different points in the watershed are more likely to reach the outlet at similar times. High rates of runoff on small watersheds of this shape are short lived for long narrow (elongated) watersheds tributaries join the mainstream at intervals along its length. High flow rates from the downstream tributaries reach the outlet before high flows from the upper tributaries arrive, thus peak flow at the outlet is less than for a circular watershed but persists for a longer duration. Various parameters are indicative of the shape of the watershed and the hydrological response expected henceforth, these are discussed below:

- Elongation ratio: High elongation ratio is indicative of structurally controlled drainage, high to moderate relief and importantly the shape of the watershed tends to be more of circular in nature, resulting in higher peak flow of shorter duration. So the watershed with lower elongation ratio is ranked 2, while the watershed with highest elongation ratio will take least time to peak and also its peak flow will be higher, in other words a quick hydrologic response which is difficult to manage and given a rank of 1.
- Circularity ratio: Higher circularity ratio values are indicative of circular shape of the watershed along with moderate to high relief and impermeable surface. Low circulatory values indicate strongly elongated and highly permeable homogenous geological materials. The watershed with higher circularity ratio value is given rank 1as it will take lowest time to peak due to circular nature and higher infiltration capacity.
- Form factor: Smaller the value of form factor, more is the elongated nature of the watershed, thus more will be the infiltration capacity of the watershed. The watersheds with high form factors have high peak flows of shorter duration, whereas, elongated watershed with low form factors have lower peak flow of longer duration. So the watershed with higher form factor has quick, though

lower, hydrograph peak compared to the other watershed, hence it is given a rank of 1 while watershed with lower form factor is ranked 2.

- Basin shape: Higher the value of watershed shape, the watershed tends to have low infiltration capacity resulting in shorter lag time. Rank of 1 is thus given to the watershed with higher value of watershed shape as it will have quickest time to hydrograph peak.
- Compactness coefficient: The compactness coefficient of the watershed directly corresponds to infiltration capacity of the watershed so the watershed with higher value for compactness coefficient will have shortest watershed lag time or in other words will be showing a quicker hydrologic response hence given a rank of 1 and vice versa.
- Basin relief/ total relief: The elevation difference between the highest and the lowest points on the valley floor of a sub watershed is referred to as total relief. There is a strong correlation between hydrological characteristics and the watershed relief of a drainage watershed (Schumms, 1956). It is an index of overall steepness of a drainage watershed as well of intensity of runoff processes operating on the slopes of the watershed. Thus, the watershed with higher values was given a rank of 1 because steepness will be more and thus the time of contact between soil and water will be less.

- **Assigning ranks on the basis of slope:**

It shows the steepness or inclination of a line, determined from two points on a line. It is a measurement of steepness of terrain, the ratio of vertical rise to horizontal distance expressed in terms of percentage or degrees of an angle. A high slope value indicates a steeper inclination. The slope of any region is an important factor to be considered in geological and environmental studies. Slope plays very important role in studying rate of infiltration, erosion, sediment yield, etc. As the slope increases the infiltration decreases because the force of gravity overcomes the absorbance of soil. When there is storm event, water is more likely to move over land depending upon the other factors like LULC, soil, etc.

In this study, various standard slope classifications were used but the one that was found to be most suitable in our study area was the one given by "Agriculture and Agrifood Canada”. By adopting this classification, the highly undulating slopes in upper, middle and lower parts of watersheds were skilfully generated including certain geological features like ‘karewas’. The following slopes ranges were used: 0 – 0.3º (level); 0.3 – 1.1 º (nearly level); 1.1- 3 º (very gentle slope); 3 - 5 º (gentle slopes); 5- 8.5 º (moderate slopes); 8.5 - 16.5 º (strong slopes); 16.5-24 º (very strong slopes); 24-35 º (extreme slopes); 35-45 º (steep slopes); 45 - 90 º (very steep slopes).

For the ranking purpose, the watershed with higher percentage of area under 0 – 8.5 º slope i.e. level to moderate slopes was assigned a rank of 2 implying that the infiltration will be higher in these areas. The watershed with higher percentage of area under 8.5 - 90 º slope i.e. strong to very steep slopes were assigned a rank of 1 implying infiltration will be less in this watershed.

Assigning ranks on the basis of Geology:

Watershed with higher percentage of shale was given lower rank of 1 as the infiltration is least in shale. The watershed with higher percentage of alluvium, limestone and soft-lime was given higher rank of two as the infiltration will be higher in this as compared to other.

Assigning ranks on the basis of Geomorphology:

Watershed with higher percentage of active flood plain, alluvial plain, karewa, low slopes and non-differentiated alluvial plains was given rank of 2 as a runoff will be less due to more infiltration. While, the watershed with higher percentage of high slopes, inactive alluvial plain, mountain top and river was given a rank of 1 as infiltration will be least.

Assigning ranks on the basis of Soil:

The watershed with higher percentage of clay loam, rocky outcrop and snow/ glacier was given rank of 1 as these will show increased runoff. While, the watershed with high percentage of loam, silty clay loam, sandy clay loam, silt loam and sandy loam was given a rank of 2 as these amplify the infiltration process.

Objective 3: Assess the flood vulnerability and the flood hazard zonation in these watersheds

3.2.8 Delineation of flood plain

A flood plain is an area of land adjacent to a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls and experiences flooding during periods of high discharge (A. S. Goudie, 2004). It includes the floodway, which consists of the stream channel and adjacent areas that actively carry flood flows downstream, and the flood fringe, which are areas inundated by the flood, but which do not experience a strong current. The overall methodology for accomplishing this objective is shown in Figure 3.8.

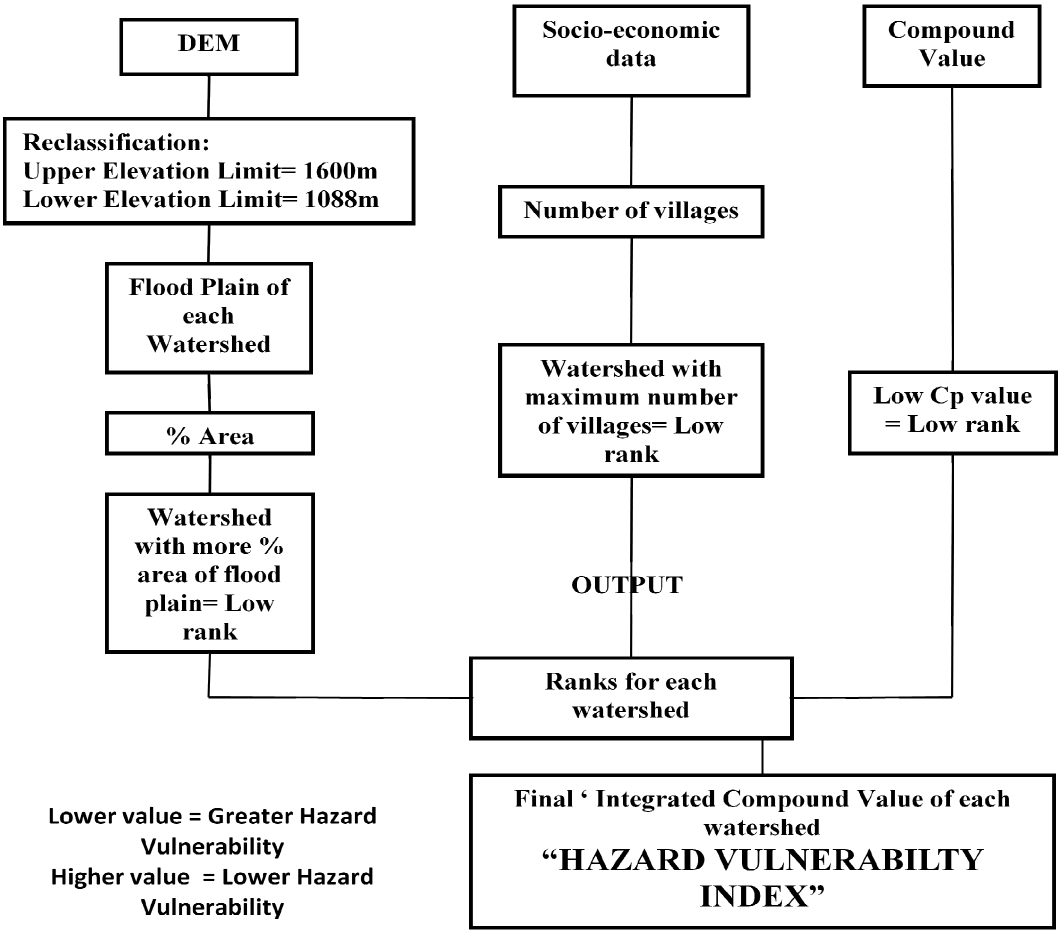


Figure 3.8 showing methodology adopted for the assessment of flood hazard zone and flood vulnerability

The flood plain was generated using spatial modelling tools in GIS environment. The elevation at the source (headwaters) and the mouth of river was used as input.

3.2.9 Assessment of flood hazard zone and flood vulnerability in study area by integrated compound value approach

One of the important tasks under this research was to assess the flood vulnerability and flood hazard zones of the places and people in the Jhelum watershed. Though a number of studies have been conducted to assess the physical vulnerability (Varnes 1984; Blaikie et al. 1994; Twigg 1998; Kumar, 1999; Kasperson 2001), but very few studies have been conducted to link the physical vulnerability to the social vulnerability. Physical vulnerability could be referred to as a set of physical conditions or phenomena, such as geology, topography, climate, land use and land cover etc. which renders a place and the people living there susceptible to disaster. The degree of danger or threat and the levels of exposure and resilience to threat are closely associated with location. Hence, spatial vulnerability is a function of location, exposure to hazards, and the physical performance of a structure, whereas socio-economic vulnerability refers to the socioeconomic and political conditions in which people exposed to disaster are living. A flood hazard zone is an area that has been identified by the government/ concerned agencies as being prone to floods by scientifically analysing the area and by taking past events into consideration. Delineation of these zones is very necessary to prevent/ mitigate socio-economic losses, to prepare agencies/ people for the future occurrence of such events, to go for ‘best management practices’ in these areas, etc.

The step-wise methodology adopted for the whole is discussed here under:

Step 1*:* In this study, flood hazard zones have been derived on the basis of generated flood plain. The flood plain clips of the watersheds were taken and the area of the same was calculated.

Step 2: The number of villages, area under flood plain and the compound values of the respective watersheds were used to generate integrated compound value (*ICp*). The latter is an index of flood hazard vulnerability. In case of compound value, lower rank of 1 was given to the watershed with lower *Cp* value which implies that compared to other watershed infiltration is least. In case of number of villages, lower rank of 1 was given to watershed with maximum number of villages, assuming that the socio-economic loss will be highest in this watershed in the event of flood if only this parameter is taken into consideration and in case of flood plain area, the watershed with highest flood plain area was given rank 1 implying that in the event of a flood, larger area of this watershed will get inundated and thus more devastation would take place. The ranks are then averaged and a final integrated compound value (*ICp*) was derived for each watershed. The watershed with low value *ICp* indicates that it is most vulnerable to flood and vice- versa. The detailed flow chart of the methodology for accomplishing the last objective is shown in Figure 3.8.

Chapter: 4

Results

In order to accomplish the research objectives set out for this research, various methods, based on multi-disciplinary approach, as detailed in the chapter 3, were used. The accomplishment of research objectives required the integrated use of satellite data, field observations, and geospatial analysis. The myriad of results obtained on geomorphology, hydrology, land use/land cover, geospatial analysis, flood vulnerability etc are documented in this chapter. The results/observations have been arranged systematically in order of the main objectives set for the study.

Objective 1: Have a comparative analysis of the geo-environmental setting of Lidder (Greater Himalaya) and Rembiara (Pir Panjal-Lesser Himalaya) watersheds.

4.1 Morphometry

I. Quantitative morphometric parameters

In the present study, morphometric analysis of 20 parameters has been carried out using the standard mathematical formulae given in the Table 3.2. The values of various basin characteristics required for calculating morphometric parameters are shown in Table 3.1. These parameters are derived by the help of software, which are then induced into various equations to derive other parameters. The comparative morphometry of both the watersheds is summed up in Table 4.2 (a, b) and drainage maps of both the watersheds are shown in (Figure 4.1 a-b).

- Stream order(U)

The stream order of Lidder watershed is 7 and that of Rembiara watershed is 5.

- Total number of streams (N)

The total number of streams present in Lidder is 7759 and that of Rembiara watershed is 307.

- Total stream length (Lu)

The value of the total stream length in Lidder watershed is 3689.16 km and in Rembiara watershed is 665.80 km.

- Average stream length ratio (RL)

The value of the average stream length ratio in Lidder is 1.81 and that of Rembiara watershed is 1.64.

- Mean Bifurcation ratio(R_{bm})

The value of the Mean bifurcation ratio of Lidder watershed is 4.74 and that of Rembiara watershed is 3.59.

- Drainage density (D_d)

The value of the drainage density in Lidder watershed is 2.92 km/km^2 and that of Rembiara watershed is 1.00 km/km^2.

- Stream frequency (F_s)

The value of the stream frequency in Lidder watershed is 5.34and in Rembiara watershed is 0.46.

- Length of overland flow (L_g)

Among the two watersheds, length of overland flow is highest in Rembiara watershed and equals 0.50 whereas in then Lidder watershed it equals 0.17.

- Form factor (R_f)

The form factor values of Lidder and Rembiara watersheds are 0.25 and 0.16 respectively as is shown in Table 4.2.

- Elongation ratio (R_e)

The elongation values of Lidder and Rembiara watersheds are 0.56 and 0.45 respectively as is shown in Table 4.2.

- Circularity ratio(R_c)

The value of circularity ratio of both Lidder and Rembiara watersheds is same and equals 0.27.

- Shape index (Sw)

The value of Sw for Lidder (3.94) is approximately half as that of Rembiara (7.14).

- Shape factor (Rs)

Shape factor for Lidder watershed and Rembiara watershed is 1.9 and 0.49 respectively.

- Compactness coefficient (Cc)

Compactness coefficient for Lidder and Rembiara is 1.91 and 2.05 respectively.

- Drainage texture(Rt)

The value of the drainage texture in Lidder watershed is 28.06 and that of the Rembiara watershed is 1.74.

- Relief Ratio (Rh)

The relief ratio for Lidder and Rembiara watersheds is 0.05 and 0.04 respectively.

- Constant Channel Maintenance (C)

Constant channel maintenance (C) for Lidder and Rembiara watershed is 0.34 and 1.00 respectively.

- Texture ratio (T)

Texture ratio (T) for Lidder and Rembiara watersheds is 28.06 and 1.34 respectively.

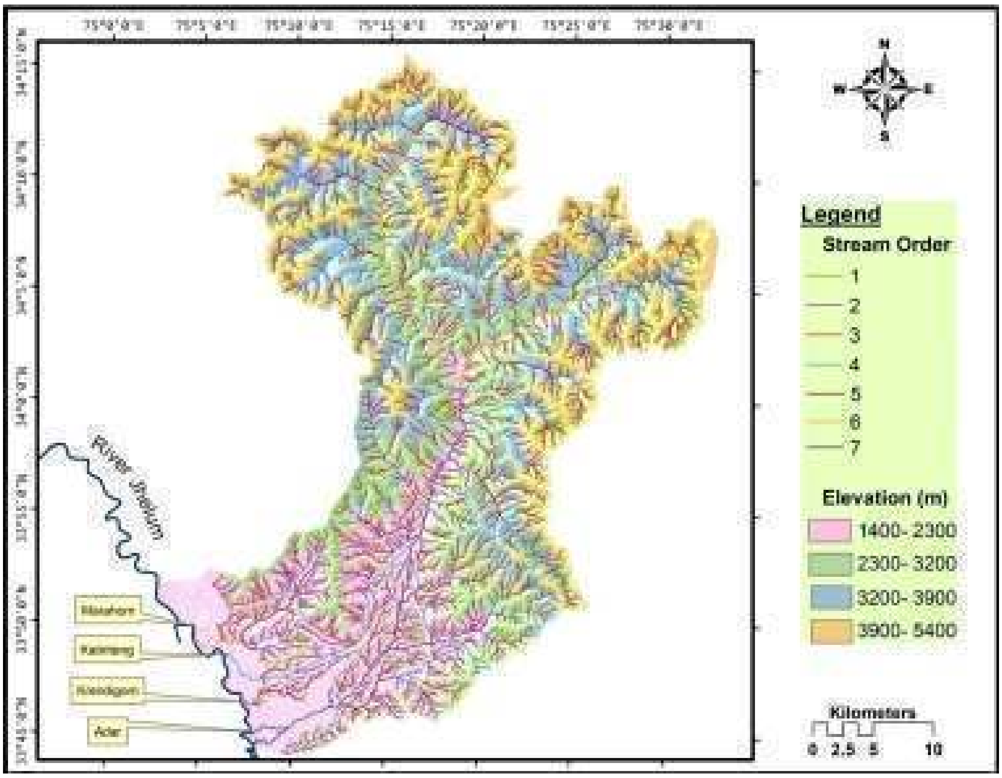
- Ruggedness number (Rn)

The ruggedness number for Lidder and Rembiara watersheds is 1.30 and 3.08 respectively.

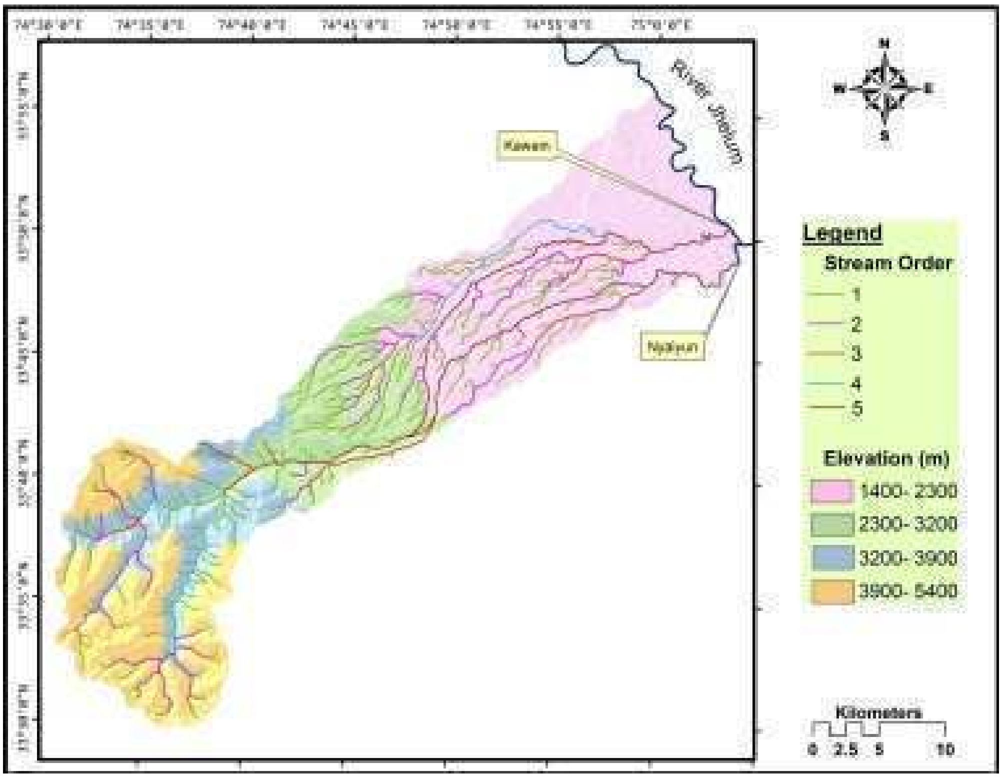
Table 4.1 Showing some Important Basin Characteristics of Watersheds		
Basin Characteristics	**Lidder**	**Rembiara**
Max. Elevation (km)	5.29	4.56
Min. Elevation (km)	1.48	1.48
Basin Relief (km)	3.81	3.21
Basin Perimeter(Km)	240.25	176.52
Basin Area (Km2)	1261.76	664.61
Longest Flow Path (Km)	78.25	83.75
Basin Length Lb(Km)	70.54	64.27

Table 4.2 (a) Showing Comparative Morphometry of Watersheds							
BIFURCATION RATIO Rb							
	1/2	2/3	3/4	4/5	5/6	6/7	Mean Bifurcation Ratio Rbm
Lidder	9.12	1.95	4.38	4.29	5.67	3.00	4.74
Rembiara	4.47	4.42	4.00	1.50	-	-	3.60
STREAM LENGTH RATIO							
	1/2	2/3	3/4	4/5	5/6	6/7	Average Stream length Ratio
Lidder	2.04	2.14	1.82	2.68	1.86	1.07	1.93
Rembiara	2.72	1.97	1.38	0.50	-	-	1.64
MEAN STREAM LENGTH LSM							
Stream Order	1	2	3	4	5	6	7
Lidder	0.33	1.49	1.36	3.28	5.26	16.00	44.90
Rembiara	1.43	2.35	5.29	15.30	46.34	-	-

Table 4.2 (b) Showing Comparative Morphometry of Watersheds			
S. No.	**Morphometric Parameter**	**Lidder**	**Rembiara**
1	Maximum Stream Order	7	5
2	Total Number of Streams	7759	307
3	Total Stream Length (Km)	3689.161	665.80
4	Mean Bifurcation Ratio	4.737	3.59
5	Average Stream Length Ratio	1.81	1.64
6	Relief Ratio (Rh)	0.054	0.04
7	Drainage Density (D)	2.92	1.00
8	Stream Frequency (Fs)	5.34	0.46
9	Drainage Texture (Rt)	28.06	1.74
10	Form Factor (Rf)	0.25	0.16
11	Circularity Ratio (Rc)	0.274	0.27
12	Elongation Ratio (Re)	0.56	0.45
13	Length of Overland Flow (Lg)	0.17	0.50
14	Constant Channel Maintenance (C)	0.342	1.00
15	Texture ratio (T)	28.06	1.34
16	Shape index (Sw)	3.944	7.14
17	Ruggedness number (Rn)	1.3021	3.08
18	Shape factor (Rs)	1.9075	0.49
19	Compactness coefficient (Cc)	1.91	2.05



(a)



(b)

Figure 4.1 Drainage maps of watersheds, a) Lidder; b) Rembiara

Land use/ Land cover (LULC**)**

Information about land use and land cover is very vital for assessing the land surface processes including hydrology (Quilbe et al., 2008, Fohrer et al., 2001). Using supervised classification on IRS LISS data, eight hydrologically important LULC classes were classified in each watershed, which include water, snow, wasteland, agriculture, forest, impervious surface, pasture and scrubs. A detailed area distribution of each class in these watersheds is shown in Table 4.3. Figure 4.2 a-b shows the LULC type distribution for each of these two watersheds. As can be seen from Table 4.3, in Lidder watershed the agriculture covers an area of 206.34 km^2, amounting to 16.35 % of the total area of the catchment, water body covers an area of 11.49 km^2 (0.91 %). Impervious surface occupies an area of 251.96 km^2 (19.97 %), shrub has an area of 176.4 km^2 (13.98 %), pastures have an area of 26.89 km^2 (2.13 %), waste land has an area of 53.26 km^2 (4.22 %), snow cover occupies an area of 105.94 km^2 (8.40 %) and the forest covers an area 429.47 km^2, amounting 34.04 % of the total area of the catchment. The study reveals that the major area is under forest and the least area is under water bodies land cover.

Again as can be seen in Table 4.3, in Rembiara, the agriculture covers an area of 238.09 km^2, amounting to 35.83 % of the total area of the catchment, water body covers an area of 22.61 km^2 (3.40 %). Impervious surface occupies an area of 36.9 km^2 (5.55 %), shrub has an area of 104.37 km^2 (15.71 %), pastures have an area of 7.19 km^2 (1.08 %), waste land has an area of 11.15 km^2 (1.68 %), snow cover occupies an area of 105.62 km^2 (15.89 %) and the forest covers an area 138.56 km2, amounting 20.85 % of the total area of the catchment. The study reveals that the major area is under agriculture and the least area is under pasture land cover.

5.2.1 Accuracy assessment

LULC maps derived from remote sensing data always have some sort of errors due to several factors which range from classification technique to satellite data type and methods employed for satellite data processing (Lillesand and Kiefer, 1987). In order to wisely use the LULC maps which are derived from remote sensing and the accompanying land resource statistics, the errors must be quantitatively explained in terms of classification accuracy. Whether the output meets expected accuracy or not is usually determined by the users themselves depending on the type of application the map product will be used latter. Accuracy levels that are acceptable for certain task may be unacceptable for others. Therefore, an accuracy assessment was done to finalize the land use/land cover maps of the two catchments that share a common boundary. A series of field expeditions were conducted to collect the ground truth information for both the catchments (Plates 1-16). Four hundred ground validation points were collected from the field in the two catchments. An error matrix of reference data collected and classification data was formed as given in the Table 4.4. Results from the Table 4.4 show that the overall accuracy of the land use and land cover classification is 95.25%. Kappa coefficient was also calculated as per the methodology given in the chapter 4. It has been found that Kappa coefficient of the land use and land cover classification is 0.89. The classification accuracy achieved here is quite encouraging and shall improve the quality of the hydrological simulations that use the land use and land cover type as one of the important input parameters (Foody, 2002).

Table 4.3: Showing area under different LULC **(km²)**

Class	Lidder		Rembiara	
	km^2	**% area**	**km^2**	**% area**
Agriculture	206.34	16.35	238.09	35.83
Impervious surface	251.96	19.97	36.9	5.55
Forest	429.47	34.04	138.56	20.85
Waste land	53.26	4.22	11.15	1.68
Pastures	26.89	2.13	7.19	1.08
Scrub	176.4	13.98	104.37	15.71
Snow	105.94	8.40	105.62	15.89
Water	11.49	0.91	22.61	3.40
Total	**1261.75**		**664.49**	

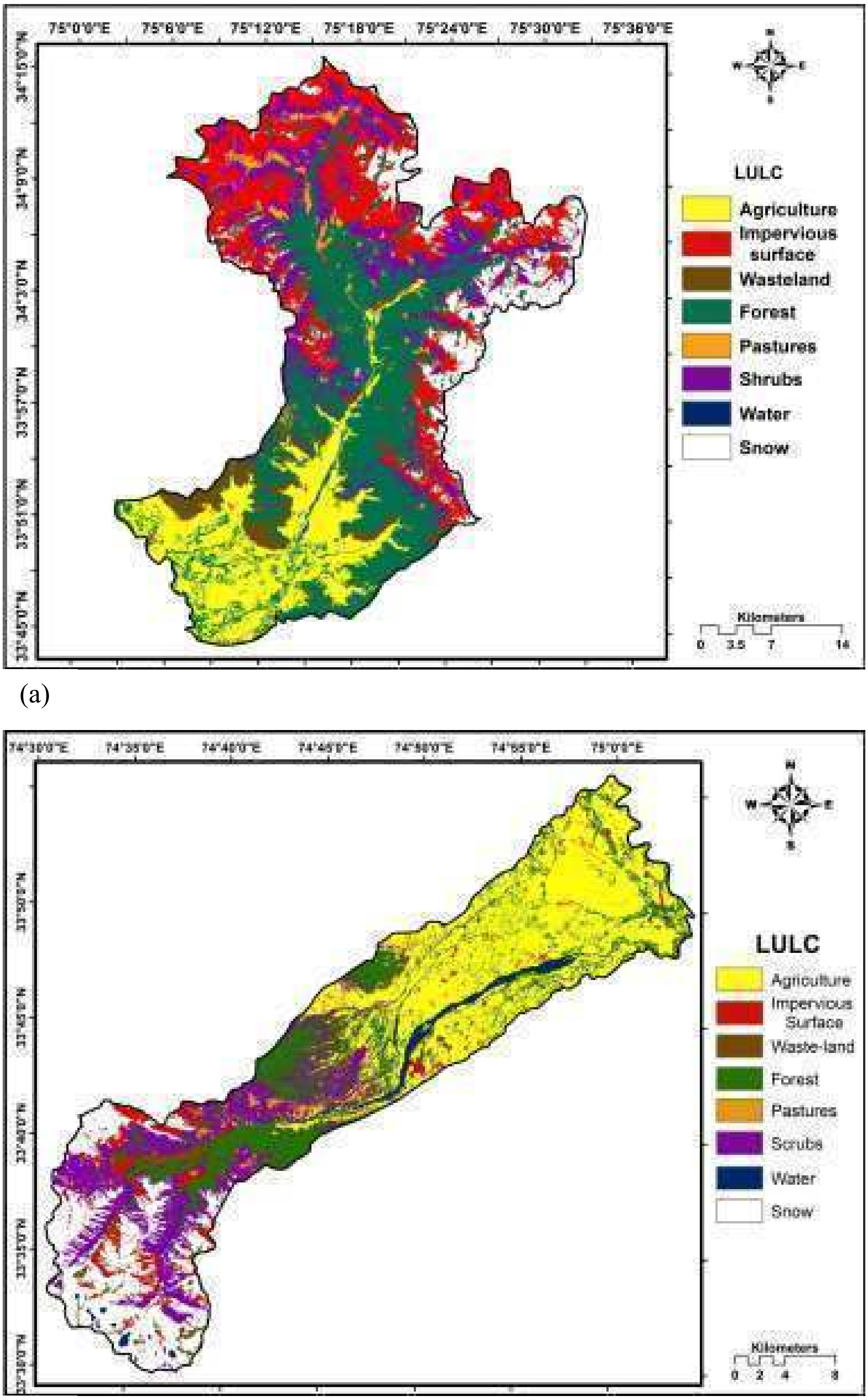


Figure 4.2: Showing LULC **maps of (a) Lidder (b) Rembiara**

Accuracy assessment

Extensive field survey was carried to check the generated land use/ land cover for accuracy assessment. A confusion matrix (error matrix) was generated to evaluate accuracy assessment indices i.e., kappa coefficient and overall accuracy. 400 ground truth sites were surveyed for this purpose (Table 4.4).

Table 4.4: Showing Error Matrix

Class	Agriculture	Water	Forest	Impervious surface	Scrubs	Pasture	Wasteland	Total	User's accuracy
Agriculture	**101**		3				2	**106**	95.28
Water		**46**	1	1				**48**	95.83
Forest	3	1	**68**					**72**	94.44
Impervious surface				**111**		1	2	**114**	97.37
Scrubs			2		**16**			**18**	88.89
Pasture			1			**20**		**21**	95.24
Waste-land	2						**19**	**21**	90.48
Total	**106**	**47**	**75**	**112**	**16**	**21**	**23**	**400**	
Producer's accuracy	95.28	97.87	90.67	99.11	100.00	95.24	82.61		

Sum of diagonals = 381

Total sum =400

- Overall Accuracy = 381/400*100= **95.25**
- $k = \mathrm{pr(a)} - \mathrm{pr(e)}\ /\ (1 - \mathrm{pr(e)}$= **0.89**
- The overall accuracy of the generated land use / land cover was 90.25 % and of kappa coefficient was 0.89 indicating very high accuracy.

4.3 Topography

Topographic characterization was carried out using 30 m spatial resolution ASTER DEM. Parameters generated were slope, elevation and aspect. These were generated in Arc View GIS software using model builder application.

4.3.1 Elevation Analysis

Rembiara and Lidder catchments have been divided into eight common elevation zones each based on the range of elevation as shown in the Table 4.5. Figure 4.3 (a, b) show the elevation maps of Lidder and Rembiara catchments respectively. Area statistics of following elevation zones were generated: 1400 m-1600 m, 1600 m-1650 m, 1650 m-1700 m, 1700 m-2300 m, 2300 m-2800 m, 2800 m-3300 m, 3300 m -3800 m, 3800 m-5400 m. The results of elevation analysis for each watershed are shown as under (Table 4.5)

It is observed that in the Lidder catchment the maximum area of 362.95 km^2 (28.77 % of total area) falls in zone 3800 m- 5400 m , while as minimum area of 26.83km^2 (2.13% of total area) falls in zone 1400 m- 1600 m (Table 4.5). These zones are also the lowest and highest elevation zones of the Lidder catchment.

In case of Rembiara, it is observed that the maximum area of 184.69 km^2 (27.79 % of total area) falls in zone 1700 m- 2300 m, while as minimum area of 32.84 km^2 (4.94 % of the total area) falls in zone 1650 m- 1700 m (Table 4.5).

Over all, Lidder catchment has more areas located at higher altitudes than the Rembiara catchment. In case of Lidder about 44% of the total area is having altitude greater than 3100 m while as the Rembiara has only about 30% area located at altitude higher than 3100m.

Table 4.5: Showing area under different elevation ranges				
Elevation (metres)	**Lidder**		**Rembiara**	
	Area (km²)	**% Area**	**Area (km²)**	**% Area**
1400- 1600	26.83	2.13	54.99	8.27
1600- 1650	50.05	3.97	70.65	10.63
1650- 1700	50.66	4.02	32.84	4.94
1700- 2300	241.31	19.12	184.69	27.79
2300- 2800	151.6	12.01	72.11	10.85
2800- 3300	154.03	12.21	51.23	7.71
3300- 3800	224.33	17.78	79.82	12.01
3800- 5400	362.95	28.77	118.28	17.8
Total	**1261.76**		**664.61**	

Table 4.6: Showing area under different slope ranges				
Slope (degrees)	**Lidder**		**Rembiara**	
	Area (km²)	**% Area**	**Area (km²)**	**% Area**
0 - 0.3	0.51	0.04	0.65	0.1
0.3 - 1.1	9.02	0.72	11.51	1.73
1.1 - 3	52.6	4.19	67.33	10.13
3 - 5	70.07	5.58	89.11	13.41
5 - 8.5	108.72	8.65	127.71	19.22
8.5 - 16.5	175.7	13.98	137.48	20.69
16.5 - 24	181.03	14.41	79.64	11.98
24 - 35	309.12	24.6	90.79	13.66
35 - 45	231.43	18.42	45.99	6.92
45 - 90	118.36	9.42	14.4	2.17
Total	**1261.76**		**664.61**	

Table 4.7: Showing area under different aspects				
Aspect	**Lidder**		**Rembiara**	
	Area (km²)	**% Area**	**Area (km²)**	**% Area**
Flat	0.51	0.04	0.65	0.10
North	131.55	10.43	98.45	14.81
Northeast	123.03	9.75	91.62	13.79
East	149.89	11.88	105.29	15.84
Southeast	153.48	12.16	95.49	14.37
South	170.74	13.53	72.25	10.87
Southwest	184.28	14.60	53.89	8.11
West	192.49	15.26	63.78	9.60
Northwest	155.79	12.35	83.19	12.52
Total	**1261.76**		**664.61**	

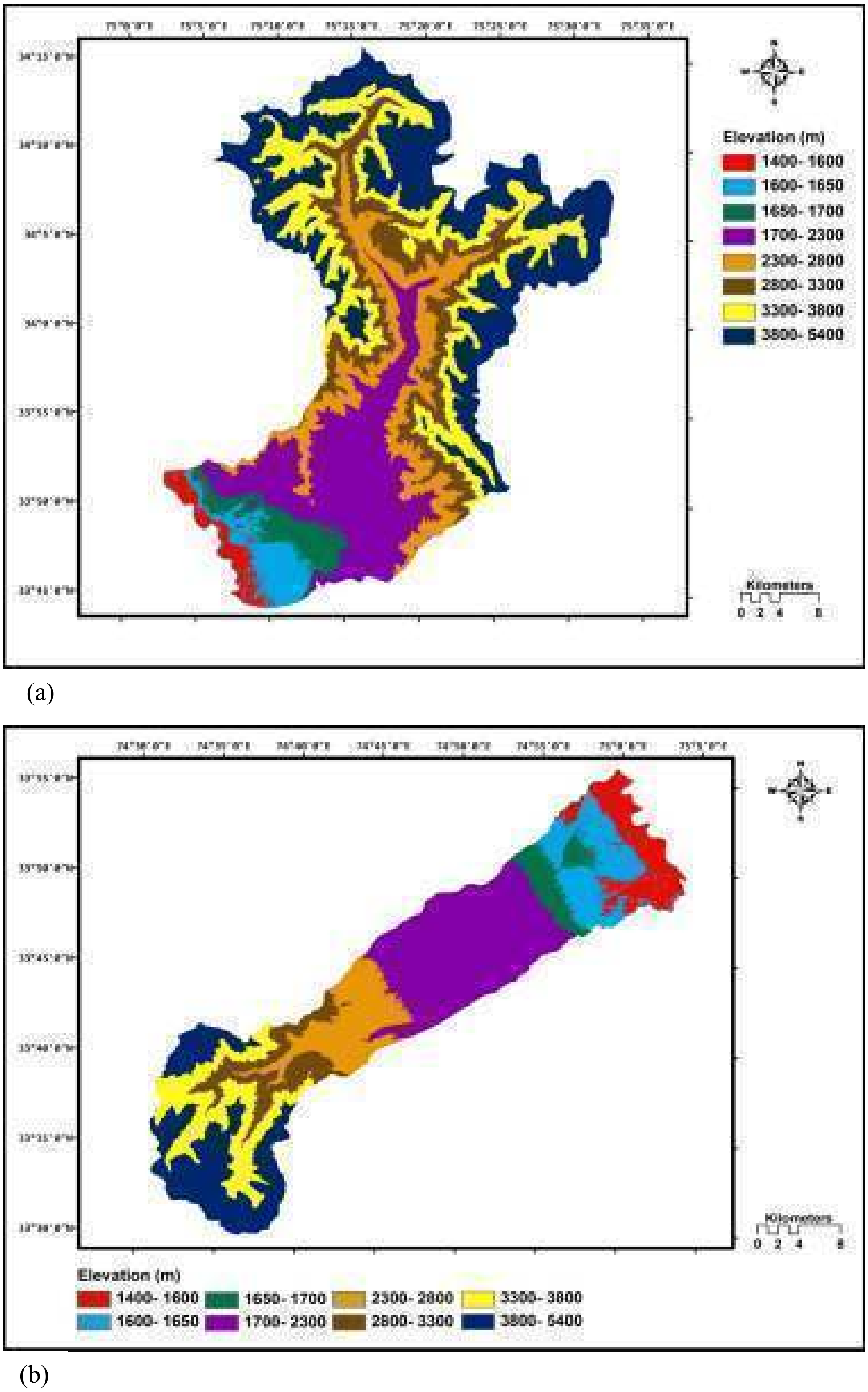
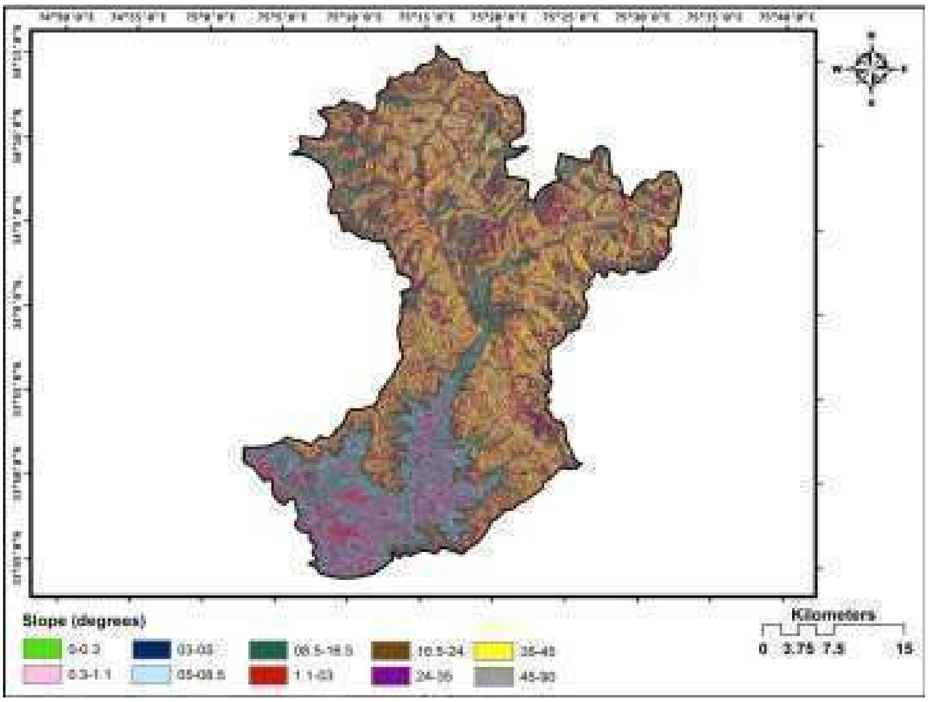


Figure 4.3: Showing elevation maps of (a) Lidder (b) Rembiara

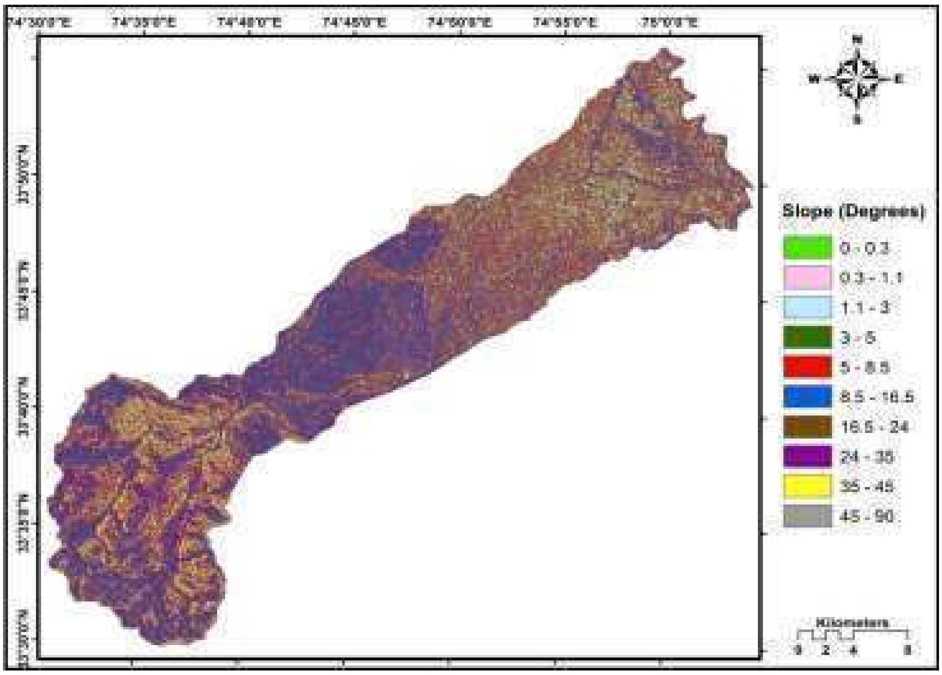
4.3.2 Slope Analysis

For achieving the objectives of this study, standard slope classification was adopted from “Agriculture and Agri- food Canada”. This classification establishes relationship between runoff and slope of an area. By adopting this classification, the highly undulating slopes in upper, middle and lower parts of watersheds were classified including certain geological features like ‘karewas’. Area statistics of the following ten slopes ranges were used: 0 – 0.3º (level); 0.3 – 1.1 º (nearly level); 1.1- 3 º (very gentle slope); 3 - 5 º (gentle slopes); 5- 8.5 º (moderate slopes); 8.5 - 16.5 º (strong slopes); 16.5-24 º (very strong slopes); 24-35 º (extreme slopes); 35-45 º (steep slopes); 45 - 90 º (very steep slopes). The results of slope analysis for each watershed are shown in Table 4.6.

Lidder catchment displays ten slope categories based on the range of slope angles that range from 0-90^0 (Figure 4.4 a). It is observed that maximum area of 309.12 km^2 falls in slope range of 24^0 - 35^0 while as minimum area of 0.51km^2 falls in slope range of 0^0 - 0.3^0 which indicates that only 0.04 % of total area of the basin is falling in lowest slope category of the catchment and 24.6 % of total area of the basin falls among the highest slope categories (Table 4.6). Similarly Rembiara catchment displays ten slope categories based on the range of slope angles that range from 0-90^0 (Figure 4.4 b). It is observed from the results that maximum area of 137.48 km^2 falls in slope range of 8.5^0 - 16.5^0 while as minimum area of 0.65 km^2 falls in slope range of 0^0 - 0.3^0 which indicates that only 0.01 % of total area of the basin is falling in level slope category of the catchment and 20.69 % of total area of the basin falls among the very strong slopes slope category



(a)



(b)

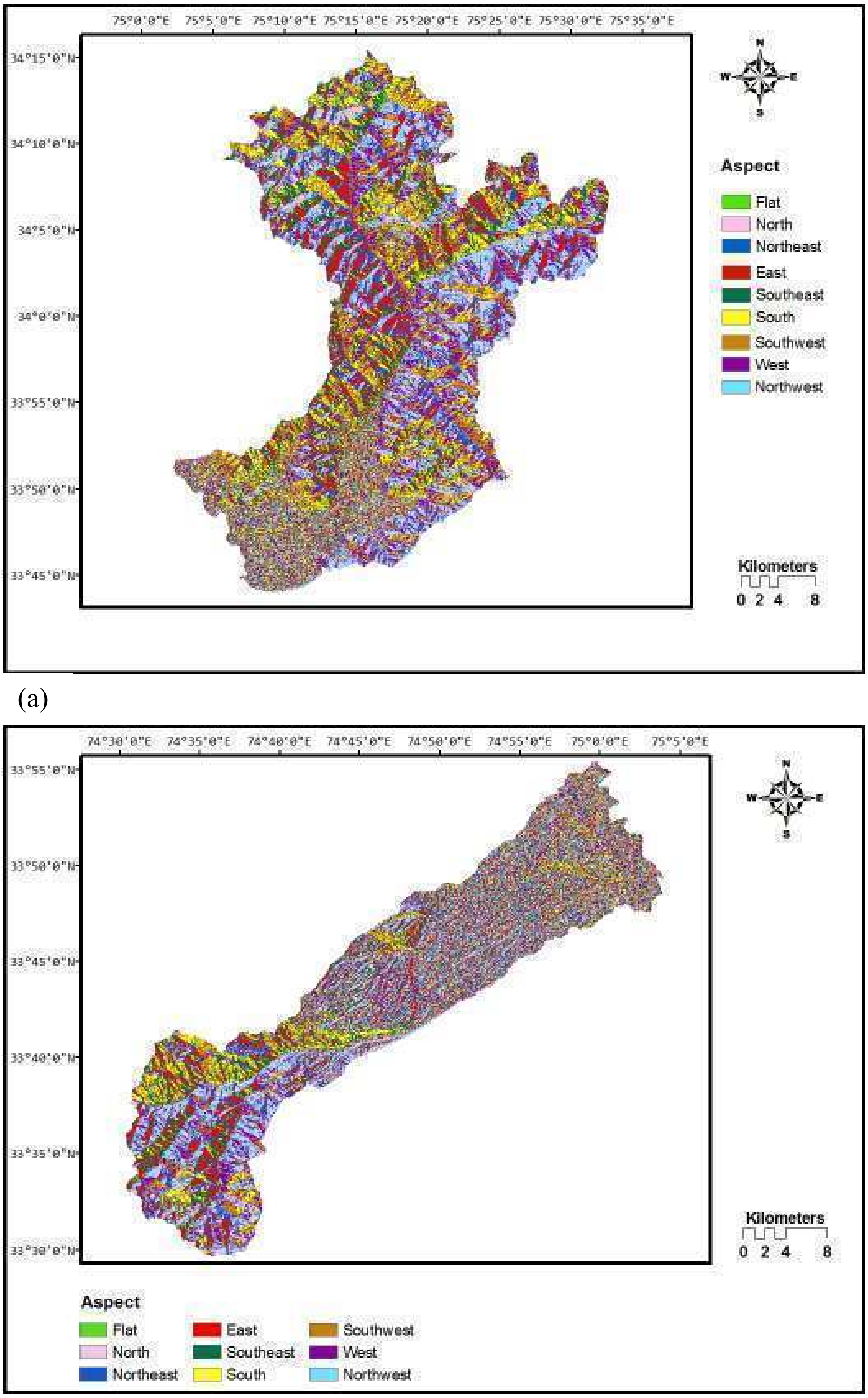
Figure 4.4: Showing slope maps of (a) Lidder (b) Rembiara

4.3.3 Aspect analysis

Area statistics of aspect analysis of each watershed on the basis of 9 aspects that is flat, north, northeast, east, southeast, south, southwest, west and northwest is shown in Table 4.7. The results of aspect analysis for each watershed are shown as under (Tables 4.7):

Out of the total 1261.77 km² of Lidder watershed, maximum area of about 192.49km² (15.26 %) falls under western aspect, while as only 0.51km² (0.04 %) is flat (Figure: 4.5, a).

Similarly, out of the total 664.61 km² of Rembiara watershed, the maximum area of about 105.29 km² (15.84 %) has Eastern aspect and the smallest area of about 0.65 km² (0.10 %) is flat (Figure: 4.5, b).



(a)

(b)

Figure 4.5: Showing aspect maps of (a) Lidder (b) Rembiara

4.4 Geomorphological analysis

Geomorphological mapping of terrain units was carried out on the basis of the interpretation of satellite data followed by field observations. Nine different geomorphological terrain units were identified and only eight were found in both the catchments namely active flood plain, alluvial plain, karewas, high slope, inactive alluvial plain, low slope, mountain tops, non differentiated alluvial plain, and river. Figure 4.6 show the geomorphological maps of both the catchments. In Lidder catchment, area occupied by different terrain units is given in the Table 4.8. The highest percentage of geomorphic terrain unit area is covered by mountain tops (40.08 %), while as the lowest terrain unit area is covered by river (0.94 %).

Table 4.8: Showing area under different geomorphological parameters

S. No.	Geomorphology	Lidder		Rembiara	
		Area (km^2)	% Area	Area (km^2)	% Area
2	**Alluvial Plain**	109.72	8.76	-	-
9	**River**	11.83	0.94	20.29	3.05
3	**Karewas**	-	-	37.65	5.66
8	**Non Differentiated Alluvial Plain**	25.47	2.03	41.87	6.30
1	**Active Flood Plain**	25.38	2.03	50.96	7.66
6	**Low Slope**	35.73	2.85	68.98	10.37
4	**High Slope**	462.01	36.88	104.87	15.77
5	**Inactive Alluvial Plain**	67.93	5.42	142.33	21.41
7	**Mountain Tops**	514.65	41.08	198.00	29.78
	Total	**1252.71**	**100.00**	**664.95**	**100.00**

In Rembiara catchment, Area occupied by different terrain units is given in the Table 4.8. Again in this catchment, the highest percentage of geomorphic terrain unit area is covered by mountain tops (29.78 %), while as the lowest terrain unit area is covered by river course (3.05 %).

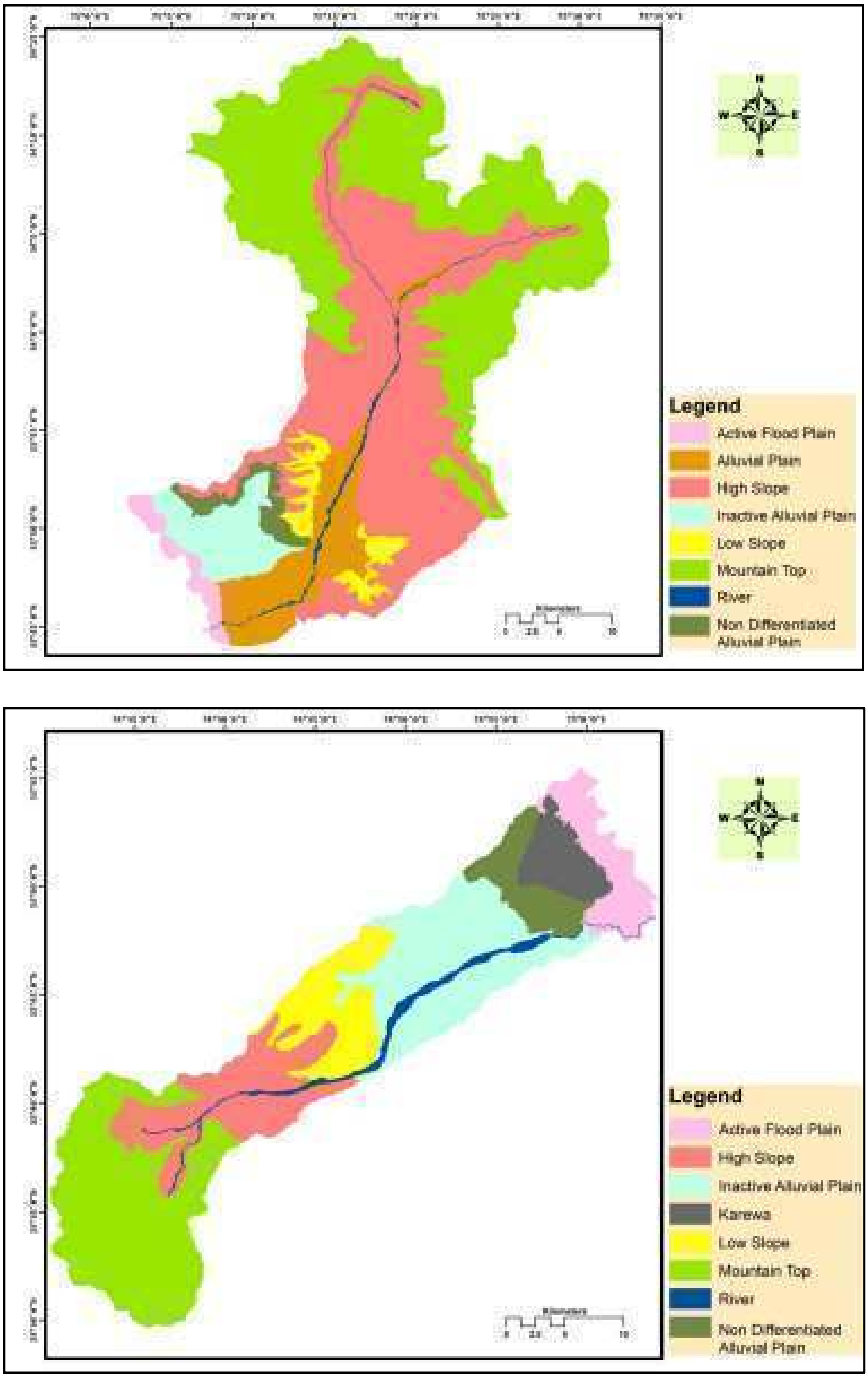


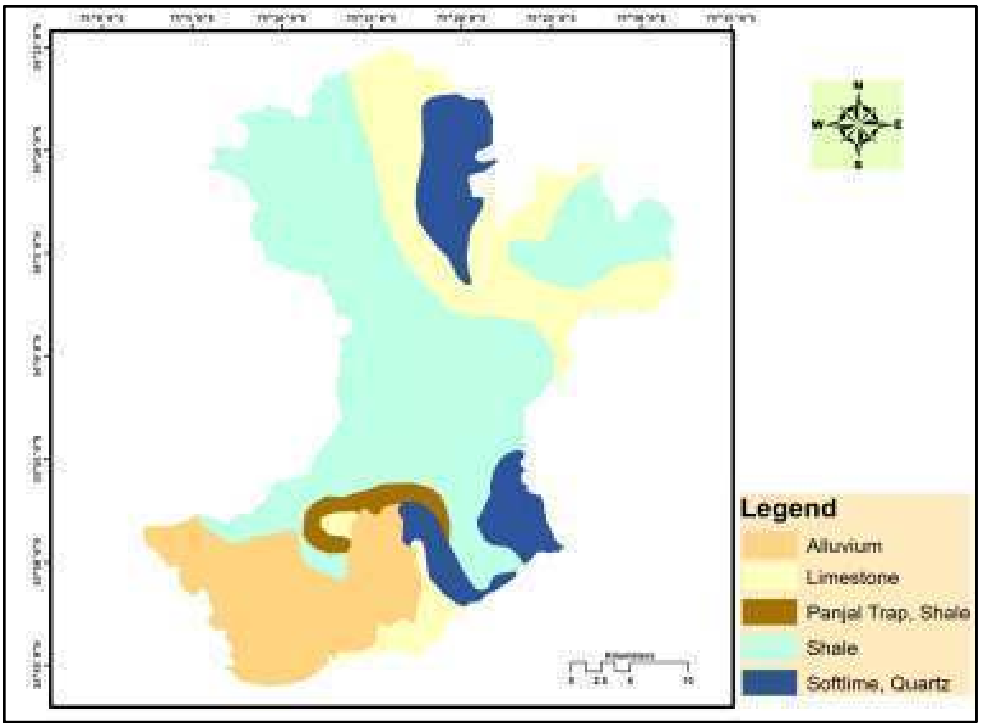
Figure 4.6: Showing geomorphological maps of (a) Lidder (b) Rembiara

4.5 Geological analysis

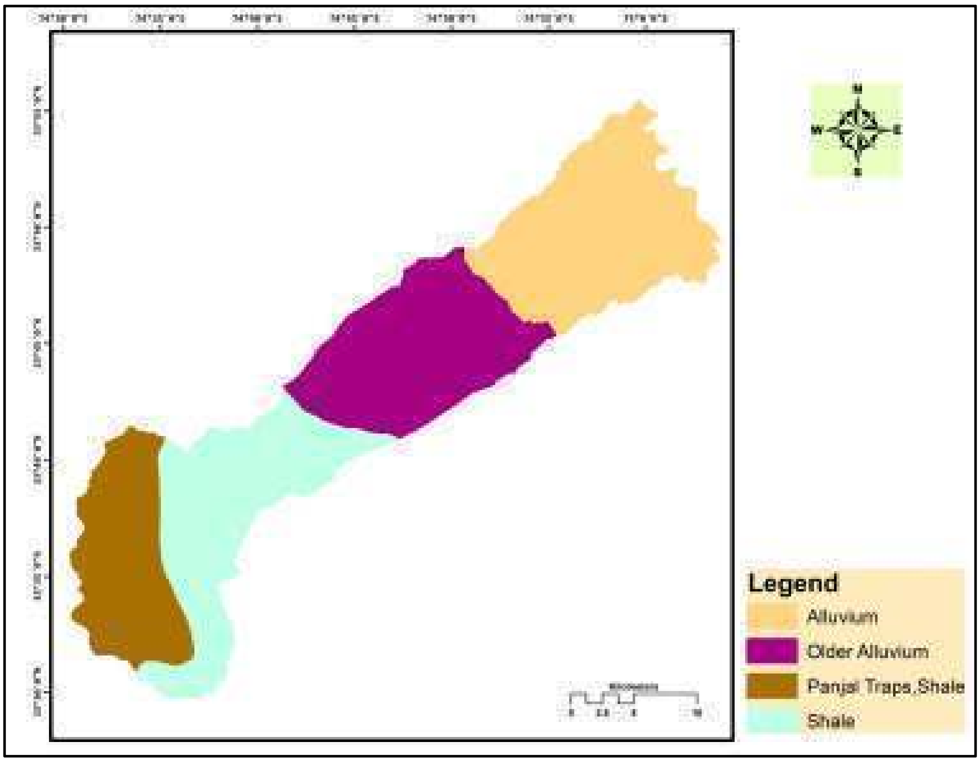
Most of the geological formations in both of the catchments are quaternary soils (Karewa deposits) and recent alluvium. However, the peripheries of these two catchments are dominated by hard rock lithology including panjal traps, Triassic limestone, fenestella shale and agglometric slates. The geological maps of the study areas show various lithologies and have been developed from existing literature (Figure 4.7 a, b). The data given in Table 4.9 show that Lidder watershed is dominated by shale (49.30 %) and Rembiara watershed is dominated by alluvium (29.74 %)

Table 4.9: Showing area under different geological parameters

S. No.	Geology	Lidder		Rembiara	
		Area (km^2)	% Area	Area (km^2)	% Area
1	**Panjal Trap, Shale**	29.93	2.39	121.86	18.33
2	**Shale**	617.65	49.30	171.89	25.86
3	**Alluvium**	213.87	17.07	197.70	29.74
4	**Older Alluvium**	-	-	173.22	26.06
5	**Gray-wake, Limestone**	23.45	1.87	-	-
6	**Limestone**	225.88	18.03	-	-
7	**Soft-lime, Quartz**	141.93	11.33	-	-
	Total	**1252.71**		**664.67**	



(a)



(b)

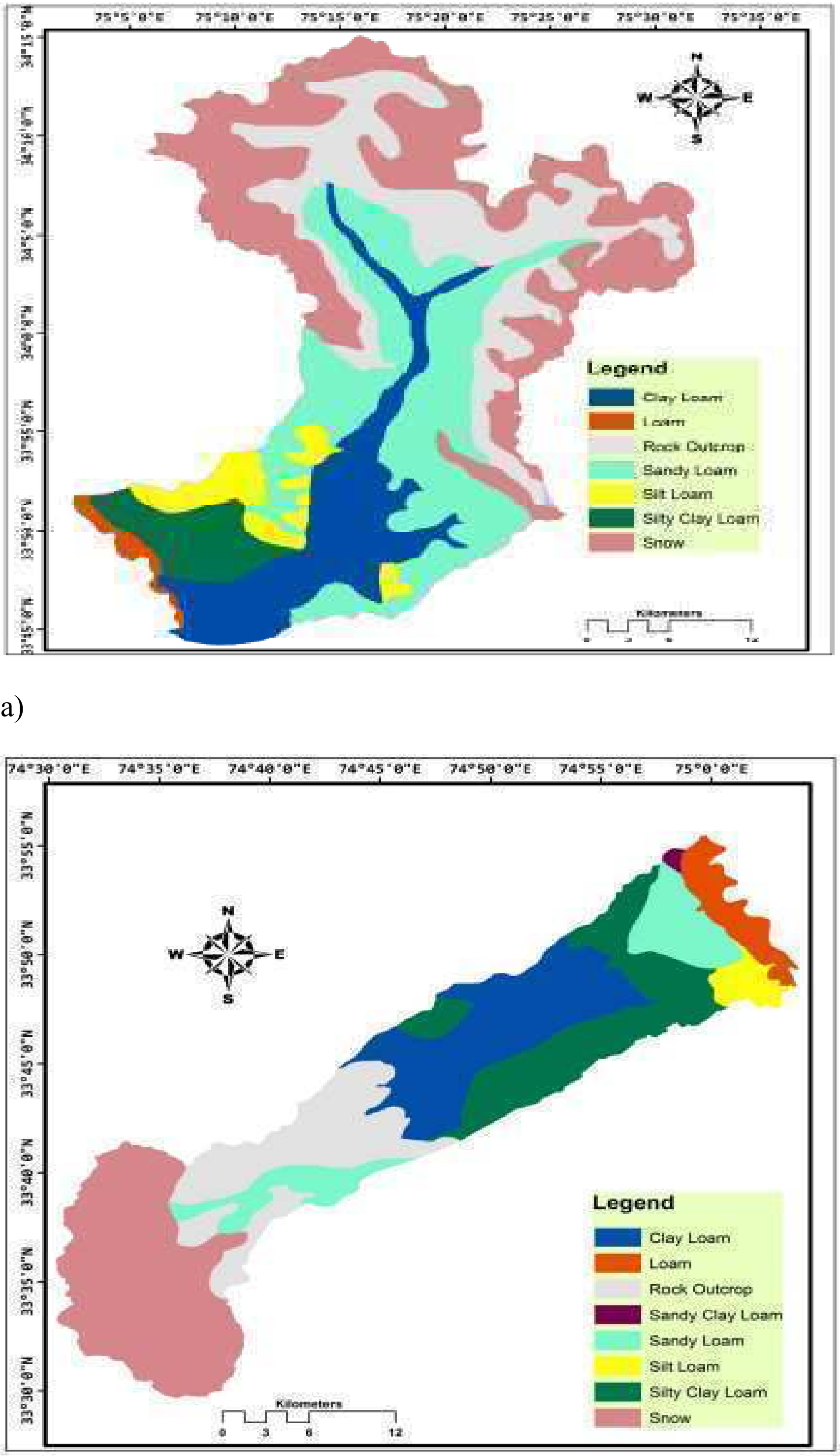
Figure 4.7 showing geological maps of (a) Lidder (b) Rembiara

4.6 Soil analysis

The soils of the both the representative catchments are diverse and vary with the topography and the geology. Figure 4.8 (a, b) show the spatial distribution of the soil types in the Rembiara and Lidder catchments respectively. The Lidder catchment comprises of six types of soils namely, Loam, clay loam, silty clay Loam, silt loam, sandy loam, and rock out crop. While as the Rembiara catchment comprises seven types of soils, i.e., loam, clay loam, silty clay loam, sandy clay loam, silt loam, sandy loam, and rock out crop. Permanent snow/glacier is also present in both the catchments. The Lidder catchment is dominated by snow/glaciers and rock outcrop, covering 29.27 % and 18.98 % of the total area respectively (Table 4.10). The loam, clay loam, silty clay Loam, silt loam, sandy loam, and rock out crop cover the 1.12 %, 14.93 %, 5.17 %, 4.57 %, 25.11 %, and 18.98 % of total area of the catchment respectively. The Rembiara catchment is dominated by snow /glaciers and rock out crop, covering 27.8 % and 17.92 % of the total catchment area respectively (Table 4.10), while the loam, clay loam, silty clay loam, sandy clay loam, silt loam, sandy loam, and rock out crop cover 4.78 %, 19.16 %, 17.98 %, 0.32 %, 2.45 %, 10.57 % and 17.92 % of total area of the catchment respectively.

Table 4.10: Showing area under different soil classes

S. no.	Soil texture	Lidder		Rembiara	
		Area (km^2)	% Area	Area (km^2)	% Area
1	**Loam**	14.12	1.12	31.71	4.78
2	**Clay Loam**	188.32	14.93	127.21	19.16
3	**Silty Clay Loam**	65.25	5.17	119.38	17.98
4	**Sandy Clay Loam**	-	-	2.12	0.32
5	**Silt Loam**	57.6	4.57	16.29	2.45
6	**Sandy Loam**	316.76	25.11	70.19	10.57
7	**Rock Outcrop**	239.43	18.98	113.39	17.92
8	**Snow and glaciers**	369.25	29.27	184.7	27.8
Total		**1250.73**		**664.99**	



(a)

(b)

Figure 4.8 showing soil map of (a) Lidder (b) Rembiara watersheds.

Objective 2: Assess the impact of differential geo-environmental setting on the hydrology of two watersheds.

In order to accomplish the objective of assessing the impact of differential geo-environmental setting on the hydrology of two watersheds, we followed an empirical hydrological modeling approach based on relative weightages given to each parameter of every information layer generated in the objective one. Compound value (*Cp*) evaluation methodology was adopted for ranking and weightage purposes as already detailed in chapter 3.

4.7 Empirically based hydrological model based on Compound value (*Cp*) evaluation

The Compound value (*Cp*) evaluation methodology was adopted ranks for all the land surface process layers generated in the objective one. In case of morphometry the higher values of the parameters among Lidder and Rembiara which enhance surface runoff were given a rank 1 and 2 for vice versa. In case of the other layers the greater percent areas among Lidder and Rembiara under those classes which enhance surface run off were given a rank of 1 and 2 for vice versa. These ranks were averaged to derive a compound value (*Cp*) for each watershed. Based on this *Cp* value, watersheds were prioritized taking the process of infiltration and runoff into consideration (Table 4.11). The results for different parameters are discussed below:

Assigning ranks on the basis of LULC:

As discussed earlier the water class was masked and the rankings of individual land use/ land cover category for each watershed were averaged so as to arrive at compound value (*Cp*) as discussed below:

- Agriculture: Agricultural land shows good infiltration capacity or conversely lower surface runoff. Since Lidder possesses comparatively lower percentage of agricultural land (16.35%) a lower rank of 1 was assigned to it. Accordingly the Rembiara with 35.83% of agricultural land was assigned a higher rank of 2.

- Impervious surface: Lidder with comparatively higher percentage of impervious surface (19.97%) was assigned a lower rank of 1 as in such a case among the two watersheds Lidder would be having comparatively quick surface runoff. The Rembiara is given a higher rank of 2 owing to the fact that the percent impervious surface in this case is comparatively lower which manifests itself in comparatively lower surface runoff.
- Forest: Lidder comparatively has a higher percentage of land under forests (34.04%) therefore it was assigned higher rank of 2 and the Rembiara, which has comparatively lower percent land under forests (20.85%) , was assigned a lower rank of 1.
- Waste-land: The rank of one was given to Lidder due to higher percentage of waste-land (4.22%) which under normal conditions is devoid of proper land use/cover, resulting in enhanced surface runoff. Due to comparatively lower percentage of waste-land in case of Rembiara (1.68%) it was given a higher rank of two.
- Pastures: Pastures are known to enhance infiltration and decrease run off, Lidder due to comparatively higher percentage of pastures (2.13%), is given the higher rank of 2. On the other hand the lower rank of one was given to Rembiara with 1.08 % pasture land.
- Shrubs: Shrub lands are known to have good infiltration capacities. Since in both catchments percent area of shrubs is almost same (13.98 % in case of Lidder and 15.19% in case of Rembiara) therefore both the watersheds are assigned a rank of 2.
- Snow: More snow was hypothesized to produce runoff. Thus higher rank of 2 was given to Lidder due to comparatively lower percentage of perennial snow (8.40 %). The comparatively higher percentage of snow in case of Rembiara (15.89 %) resulted in giving lower rank of 1 to it.

Assigning ranks on the basis of morphometry:

Except length of overland flow, all other morphometric parameters such as drainage density, stream frequency, bifurcation ratio, drainage texture, length of overland flow have a direct relationship with the time to peak after a storm event, i.e., higher the value of a morphometric parameter, higher is the runoff and vice versa. Hence among the two watersheds, the highest value of linear parameters was rated as rank 1, and comparatively lower value was rated as rank 2. Shape parameters such as elongation ratio, compactness coefficient, circularity ratio, basin shape and form factor have an inverse relationship with runoff (Nooka Ratnam et al., 2005).

- Drainage density: Lidder with comparatively higher drainage density is assigned a rank of 1 while as Rembiara is assigned a rank of 2.
- Stream frequency: Lidder with higher value for stream frequency is assigned a lower rank of 1 and Rembiara with a comparatively lower value of Fs is assigned higher rank of 2.
- Mean bifurcation ratio: Lidder with a higher value of Rbm is assigned a lower rank of 1 while as Rembiara with comparatively lower value of Rbm is assigned a higher value of 2.
- Drainage texture: Lidder with a higher value of drainage texture is assigned a lower rank of 1 while as Rembiara with comparatively lower value of drainage texture is assigned a higher value of 2.
- Length of overland flow: It also has a direct relationship with the runoff, the Rembiara watershed with the higher value of Lg is given lower rank while the watershed Lidder is given high rank.
- Circulatory ratio: Both Lidder and Rembiara have same circularity ratio. Therefore both were assigned a rank of 1.
- Elongation ratio: Lidder is assigned a lower rank of 2 due to higher value of elongation ratio (0.57). While as Rembiara is assigned a rank of 1 due to its comparatively lower elongation ratio (0.42).
- Form factor: Lidder is assigned a rank of 2 due to comparatively higher value of form factor (0.25), while as Rembiara is assigned a rank of 1 due to comparatively lower value of form factor (0.14).

- Compactness coefficient: Lidder is assigned a rank of 1 due to comparatively lower value of Cc (1.91), while as Rembiara is assigned a rank of 2 due to comparatively higher value of form factor (1.93).
- Shape index: Lidder is assigned a rank of 2 due to comparatively higher value of shape index (7.14), while as Rembiara is assigned a rank of 1 due to comparatively lower value of shape index (3.94).
- Basin relief: Since high values of basin relief indicate high steepness, Lidder since it has comparatively higher value of basin relief is assigned a rank of 1 while as Rembiara is assigned a rank of 2 due to its comparatively lower value of basin relief.

Assigning ranks on the basis of slope:

As discussed earlier, the watersheds with higher percentage of area under level to moderate slopes were assigned higher ranks and those with higher percentage of area under strong to very steep slopes were assigned lower ranks.

Based on the above fact, the maximum area under the slope ranges: 0 – 0.3° (level); 0.3 – 1.1 ° (nearly level); 1.1- 3 ° (very gentle slope); 3 - 5 ° (gentle slopes) and 5-8.5 ° (moderate slopes) has been reported from Rembiara, thus it was given higher rank of 2 for these ranges because the steepness in this watershed will be minimum. The minimum area of the same ranges has been calculated from Lidder, thus it was given the lower rank of one. Also, the highest area under the slope ranges: 8.5 - 16.5 ° (strong slopes), 16.5-24 ° (very strong slopes); 24-35 ° (extreme slopes); 35-45 ° (steep slopes) and 45 - 90 ° (very steep slopes) has been reported from Rembiara, thus it was given the lower rank as the steepness in this watershed will be maximum. The higher rank was given to Lidder with least percent area under these slope ranges.

Assigning ranks on the basis of geology:

Watershed with higher percentage of shale was given lower rank of 1 as the infiltration is least in shale. The watershed with higher percentage of alluvium, limestone and soft-lime was given higher rank of two as the infiltration will be higher and runoff lower in this case as compared to other.

Assigning ranks on the basis of geomorphology:

Watershed with higher percentage of active flood plain, alluvial plain, karewas, low slopes and non-differentiated alluvial plains was given higher rank of 1 as a delayed hydrological response will be present there due to low rate of overland movement of water. While, the watershed with higher percentage of high slopes, inactive alluvial plain, mountain top and river was given lower rank of 1 as infiltration of water will be least

Assigning ranks on the basis of soil:

The watershed with higher percentage of clay loam, rock outcrop and snow/ glacier was given lower rank of 1 as these will show increased runoff. While, the watershed with high percentage of loam, silty clay loam, sandy clay loam, silt loam and sandy loam was given higher rank of 2 as these support the infiltration process.

Tablee 4.11: Showing compound value evaluation

			Lidder	Rank	**Rembiara**	Rank
Morphometric parameters (**Values**)	Linear parameters	Drainage density	2.92	1	1.00	2
		Stream frequency	5.34	1	0.46	2
		Mean bifurcation ratio	4.74	1	3.59	2
		Drainage texture	28.06	1	1.73	2
		Length of overland flow	0.17	2	0.50	1
	Shape parameters	Circulatory ratio	0.27	1	0.27	1
		Elongation ratio	0.57	2	0.42	1
		Form factor	0.25	2	0.14	1
		Compactness coefficient	1.91	1	1.93	2
		Shape index	3.94	1	7.14	2
	Relief parameter	Basin relief	3.81	1	3.08	2
LULC **(% Area)**		Agriculture	16.35	1	35.83	2
		Imp. Surface	19.97	1	5.55	2
		Forest	34.04	2	20.85	1
		Waste land	4.22	1	1.68	2
		Pastures	2.13	2	1.08	1
		Shrub	13.98	2	15.71	2
		Snow	8.40	2	15.89	1
Geology **(% Area)**		Panjal Trap, Shale	2.39	2	18.33	1
		Shale	49.30	1	25.86	2
		Alluvium	17.07	1	29.74	2
		Older Alluvium	-	0	26.06	2
		Graywake, Limestone	1.87	2	-	0
		Limestone	18.03	2	-	0
		Softlime, Quartz	11.33	2	-	0
Geomorphology **(% Area)**		Active Flood Plain	2.03	1	7.66	2
		Alluvial Plain	8.76	2	-	0
		Karewa	-	0	5.66	2
		High Slope	36.88	1	15.77	2
		Inactive Alluvial Plain	5.42	2	21.41	1
		Low Slope	2.85	1	10.37	2
		Mountain Tops	41.08	1	29.78	2
		Non Differentiated Alluvial Plain	2.03	1	6.30	2
		River	0.94	2	3.05	1

Slope (degree) **(% Area)**	0-0.3	0.04	1	0.65	2
	0.3-1.1	0.72	1	11.51	2
	1.1-03	4.19	1	67.33	2
	03-05	5.58	1	89.11	2
	05-08.5	8.65	1	127.71	2
	08.5-16.5	13.98	2	137.48	1
	16.5-24	14.41	2	79.64	1
	24-35	24.60	2	90.79	1
	35-45	18.42	2	45.99	1
	45-90	9.42	2	14.40	1
Soil texture **(% Area)**	Loam	1.12	1	4.78	2
	Clay Loam	14.93	2	19.16	1
	Silty Clay Loam	5.17	1	17.98	2
	Sandy Clay Loam	-	1	0.32	2
	Silt Loam	4.57	2	2.45	1
	Sandy Loam	25.11	2	10.57	1
	Rock Outcrop	18.98	1	17.92	2
	Snow and glaciers	29.27	1	27.8	2
Compound value			**1.35**		**1.54**

Objective 3: Assess the flood vulnerability and the flood hazard zonation in these watersheds

4.8 Delineation of flood plain

Elevation at the source (at Sangam) of the Jhelum River and the point where it drains into Pakistan Administered Kashmir, i.e. around Uri gorge was recorded with the help of ASTER DEM and Topo sheets. Around the Uri gorge elevation recorded was1088m and at Sangam it was around 1600m. Using these as an input in to spatial analyst model flood plain area for the whole Kashmir valley was generated as is shown in Figure 4.9. Finally flood plain clips of the study area were extracted and are calculated for area as shown in Figure 4.10, a-b. Among the two watersheds flood plain area (Table 4.12) is minimum in Lidder (5.34 %) and maximum in Rembiara (8.86 %).

4.9 Assess the flood vulnerability and the flood hazard zonation in the Lidder and Rembiara watersheds.

Flood hazard zone of each watershed was derived on the basis of flood plain of each watershed. The area of flood plain under each watershed was calculated and designated as the flood hazard zone of the respective watershed as shown in Figure 4.10, a-b.

Using ranking system, the final three components (number of villages, % area in flood hazard zone and *Cp*) of the whole research were analyzed to extract the flood hazard vulnerable index for each watershed Table 4.12. The final results show that among the two watersheds, the watershed which is more vulnerable to flooding is Rembiara. (Figure 4.10, a- b).

Table 4.12: Showing evaluations for final Integrated Compound Value (*ICp*)

Watershed	***Cp***	**Rank**	**Flood plain km^2**	**Flood plain (% Area)**	**Rank**	**No. of villages within flood plain**	**Rank**	***ICp***
Lidder	1.35	1	67.65	5.34	2	38	2	1.66
Rembiara	1.54	2	14.04	8.86	1	51	1	1.33

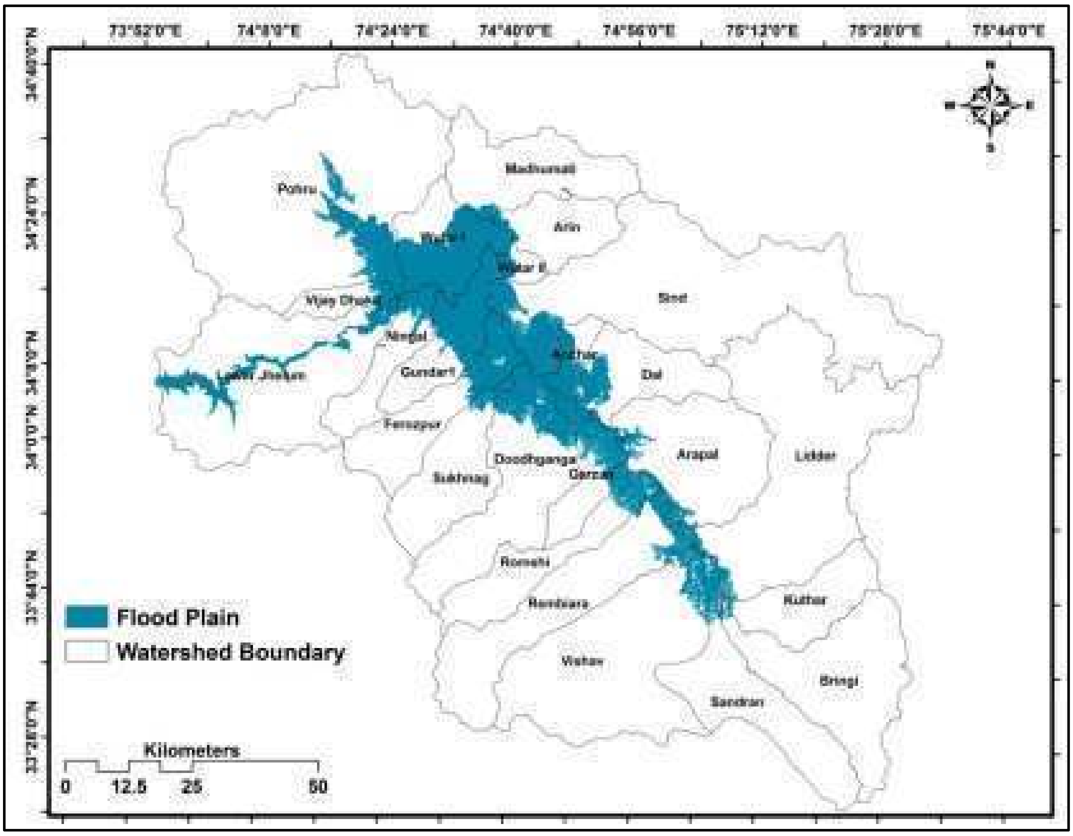


Figure 4.9: Showing flood plain of the Kashmir valley

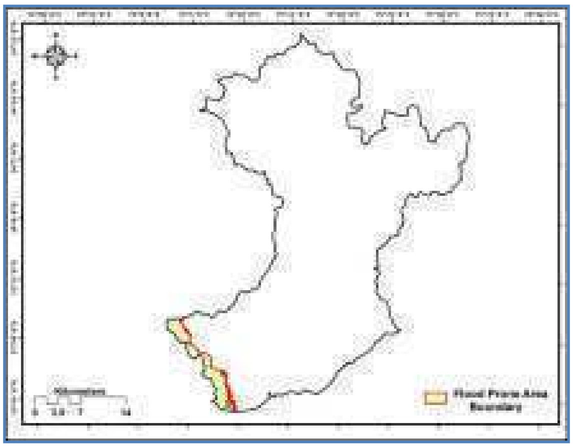


Figure 4.10: (a) Flood plain of Lidder watershed

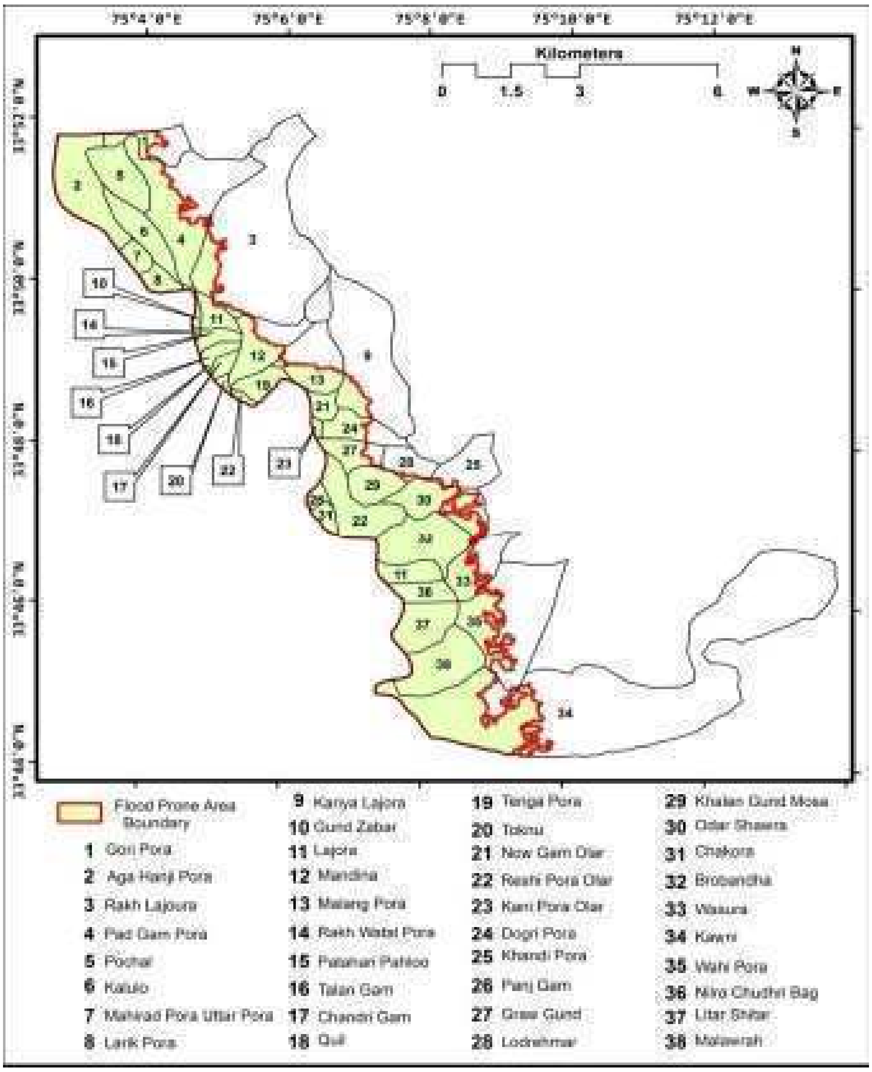


Figure 4.10: (a) Villages in Lidder flood plain

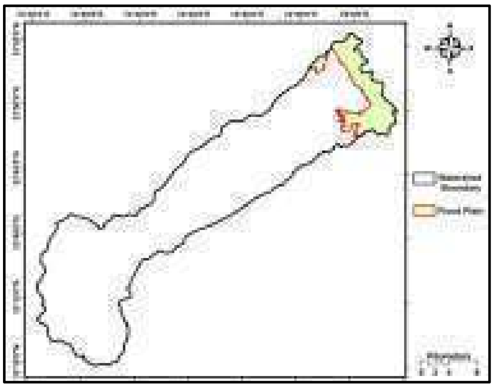


Figure 4.10: (b) Flood plain of Rembiara watershed

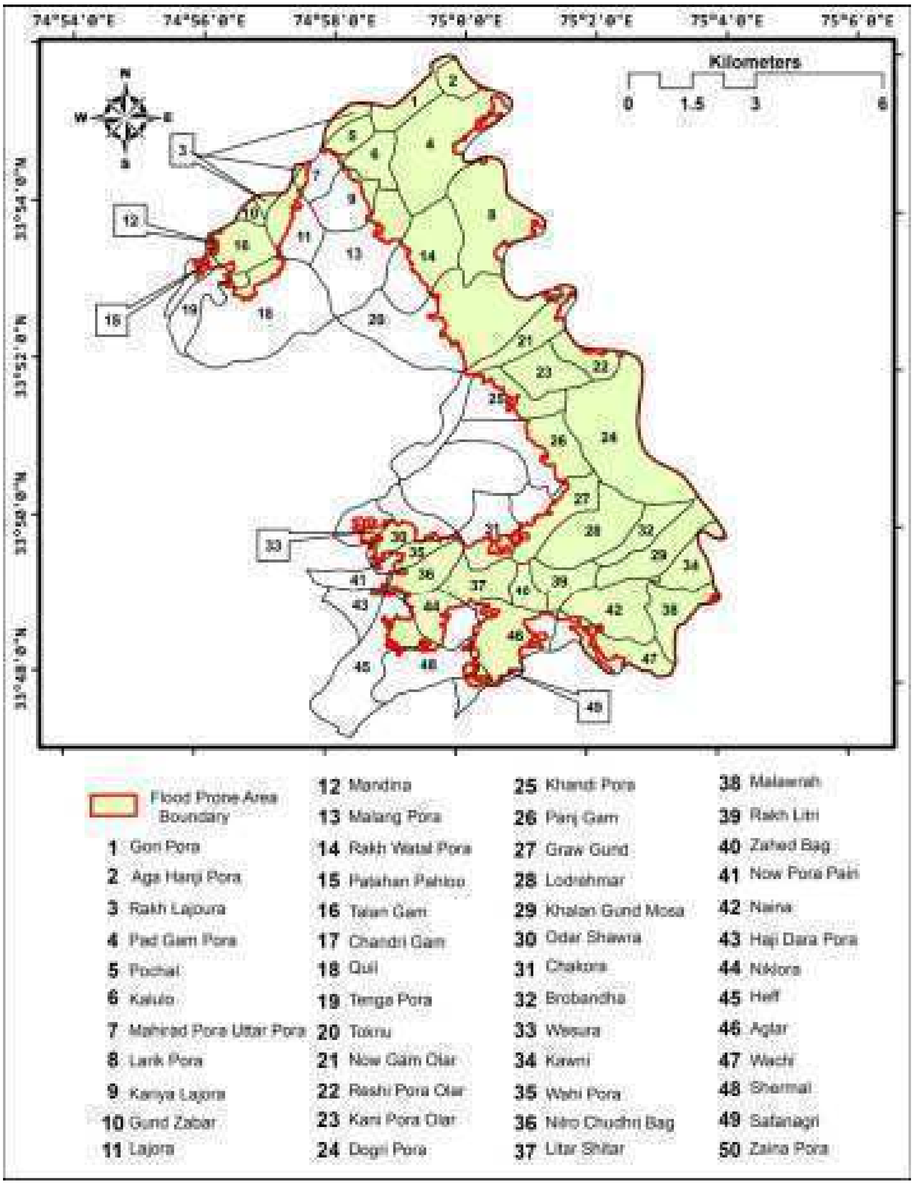


Figure 4.10: (b) Villages in Rembiara flood plain

Field Photographs

Plate 1: Kolahoi; Lidder watershed

Plate 2: Glacial valley

Plate 3: Soil sampling; Lidder watershed

Plate 4: Impervious area (settlements); Lidder watershed

Plate 5: Orchard field; Rembiara watershed

Plate 6: Karewa; Rembiara watershed

Plate 7: Pasture; Lidder watershed

Plate 8: Evergreen forests; Lidder watershed

Plate 9: Agricultural fields; Rembiara watershed

Plate 10: Agricultural fields; Rembiara watershed

Plate 11: Orchard field; Rembiara watershed

Plate 12: Rembiara nala; Rembiara watershed

Plate 13: River bed; Rembiara watershed

Plate 14: River bank; Rembiara watershed

Plate 16: Evergreen forests; Lidder watershed

Chapter: 5

Discussion

This chapter comprises the analysis and discussion part of the results of objectives covered under this research. The discussion is chronologically made under the headings of their respective objectives.

Objective 1: Have a comparative analysis of the geo-environmental setting of Lidder (Greater Himalaya) and Rembiara (Pir Panjal-Lesser Himalaya) watersheds.

5.1 Morphometric analysis

The various morphometric parameters estimated using the methods discussed in the chapter 4 are shown in the Table 4.2. Each of these parameters is discussed here under:

- Stream order (U)

Lidder watershed is a 7th order watershed whereas Rembiara is 5th order watershed. From these results it is evident that Lidder watershed contributes more surface runoff and sediment load into Jhelum River than Rembiara watershed. Further, the total number of stream segments decrease with stream order. This is referred to as Horton's law of stream numbers. Any deviation indicates that the terrain is typified with high relief and/or moderately steep slopes, underlain by varying lithology and probable uplift across the basin. In practice, when logarithms of the number of streams of a given order, are plotted against the order, the points lie on a straight line. Similar geometric relationship was also found to operate between stream order and stream numbers in both watersheds. It indicates that the whole area has uniform underlying lithology, and geologically, there has been no probable uplift in the basin (Figure 5.1).

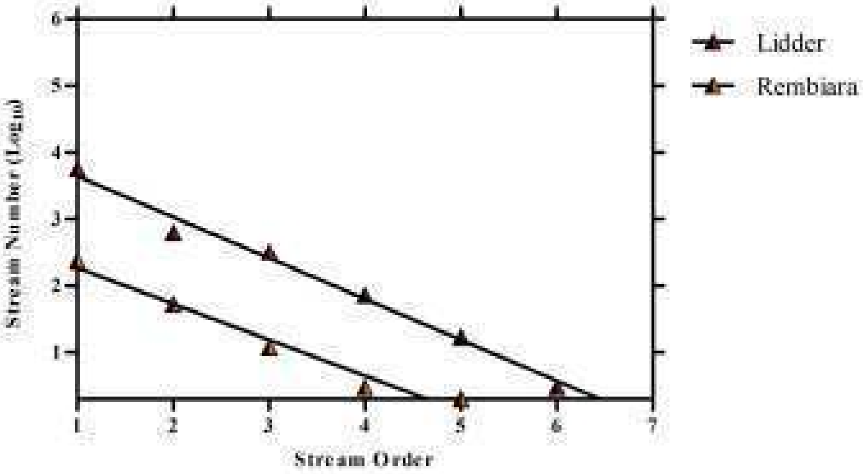


Figure 5.1 showing the comparative linear plots between stream order and logarithm of stream number in Lidder and Rembiara watersheds

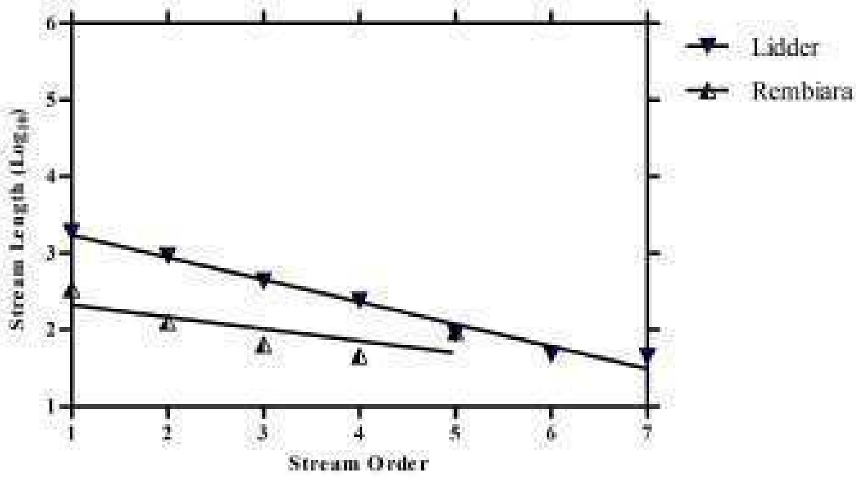


Figure 5.2 showing the comparative linear plots between stream order and logarithm of stream length in Lidder and Rembiara watersheds

- Stream Length (Lu)/Mean Stream Length (Lsm).

Analysis of the results showed that the total length of stream segments is the maximum in case of first order streams. It decreases as order increases in both the watersheds (Tables 4.2 a, b; Figure 5.2). The results reaffirm the fact that the area is underlain with uniform lithology with no probable basin upliftment. The observation demonstrates that watershed hydrology in these areas depends only on the drainage characteristics. Moreover, Table 4.2 indicates that Lsm in these sub watersheds range from a minimum of 0.33 km for stream order 1 in Lidder to a maximum of 46.34 km for the order 5 in Rembiara. According to the Horton's law of stream lengths, Lsm of any given order is greater than that of lower order. This geometric relationship can be seen in Figure 5.2. A comparative analysis of Lsm and stream length ratio RL of Lidder and Rembiara is shown in Table 4.2.

- Mean Bifurcation ratio (R_{bm})

Results show that the mean bifurcation ratios of Lidder and Rembiara watersheds are 4.73 and 3.59 respectively. The bifurcation ratio will not be precisely the same from one order to the next, because of possibility of variations in watershed geometry and lithology, but tends to be a constant throughout the series. The high bifurcation ratio in case of Lidder indicates early hydrograph peak with a potential for flash flooding during the storm events. (Rakesh et al., 2000)

- Drainage density (D_d)

The higher drainage density of Lidder watershed (2.92 km/km^2), indicate that this region is composed of impermeable subsurface material, sparse vegetation and mountainous relief while as the lower drainage density of Rembiara watershed (1.00 km/km^2) reveal that it is composed of permeable subsurface material, good vegetation cover and low relief. These characteristics imbibe Rembiara watershed more infiltration capacity. In general, the hydrology of a watershed changes significantly in response to the changes in the drainage density (Yildiz, 2004). A high drainage density reflects a highly dissected drainage basin with a relatively rapid hydrological response to rainfall events, while a low drainage density means a poorly drained basin with a slow hydrologic response (Melton, 1957).

- Stream frequency (F_s)

The results of the stream frequency of Lidder and Rembiara watersheds are shown in Table 4.2. Stream frequency is related to permeability, infiltration capacity and relief of watersheds (Montgomery and Dietrich, 1989, 1992). The high F_s value in case of Lidder (5.34) indicates that it is having rocky terrain and has very low infiltration capacity compared to Rembiara (0.46). Further, it is noted that F_s decreases as the stream number increases. Stream frequency of Rembiara reveals that it is covered by good vegetation and has very good infiltration capacity. Overall, the results of F_s reflect early peak discharge in case of Lidder watershed resulting in flashfloods while the discharge Rembiara watershed would take time to peak because of low runoff rates.

- Length of overland flow (L_g)

Length of overland flow is one of the most important independent variables affecting both hydrologic and physiographic development of drainage basins (Horton, 1932). From the Table 4.2, it can be seen that length of overland flow of Lidder and Rembiara is 0.17 and 0.50 respectively. The values of length of overland flow of Rembiara watershed indicate gentler slopes and longer flow paths than Lidder watershed. These values also indicate that runoff will take very less time to reach to out let in case of Lidder watershed. Thus it shall be more vulnerable to the flooding compared to the Rembiara watershed.

- Form factor (R_f)

The form factor values of Lidder and Rembiara watersheds are 0.25 and 0.16 respectively as shown in the Table 4.2. It indicates that Lidder watershed is more circular in shape characteristics with higher value of (0.25) where as Rembiara watershed is comparably elongated. This again reaffirms that Lidder will have quick, though lower, hydrograph peak compared to the Rembiara watershed. Watershed morphology has profound impacts on the watershed hydrology (Tucker and Bras, 1998)

- Elongation ratio (R_e)

Results of elongation ratio indicate that Lidder watershed is circular, whereas Rembiara watershed is comparatively elongated (Strahler, 1964). The impacts of varied watershed morphology on the hydrological response in this case shall be similar as that of the Form Factor discussed above.

- Circulatory ratio (R_c)

The circulatory ratio of Lidder and Rembiara watersheds is same (0.27) as shown in the Table 4.2. This excludes the role of circulatory ratio for understanding comparative hydrologic response in these watersheds.

- Shape index (Sw)

The value of Sw for Lidder (3.94) is approximately half as that of Rembiara (7.14). Rate of water and sediment yield along the length and relief of the drainage basin is largely by the shape. In terms of Sw only, Lidder will show the shorter basin lag time, while Rembiara will have the longer basin lag time.

- Shape factor (Rs)

Shape factor for Lidder and Rembiara is 1.9 and 0.49 respectively. This parameter is similar in interpretation to circularity ratio, elongation ratio, and form factor. It gives an idea about the circular character of the basin. The greater the circular character of the basin, the greater is the rapid response of the watershed after a storm event. Therefore, in terms of Rs only, Lidder has very short basin lag time, and Rembiara has long basin lag time.

- Compactness coefficient (Cc)

Compactness coefficient for Lidder and Rembiara is 1.91 and 2.05 respectively. Cc expresses the relationship of a basin with that of a circular basin having the same area. A circular basin yields the shortest time of concentration before peak low occurs in the basin. Cc = 1 indicates that the basin completely behaves as a circular basin. Cc > 1 indicates more deviation from the circular nature of the basin. Consequently, Rembiara watershed has the greatest deviation from the circular nature, and on the basis of this parameter alone, it will have the longest time of concentration before peak low occurs compared to Lidder watershed.

All the above shape related parameters significantly influence the hydrological response of the watersheds as basin shape and the arrangement of stream segments combine to influence the size and shape of flood peaks (Ward and Robinson, 2000). As such, Lidder watershed has high flood peaks than Rembiara.

- Drainage Texture (Rt)

From Table 4.2, Rt for Lidder is 28.05 and for Rembiara is very low 1.74. The reason for such a huge difference in these values is the very high number of streams in case of Lidder watershed (7759) than in Rembiara watershed (307). Rt is influenced by infiltration capacity. There are five different texture classes: very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8), and very fine (>8). According to this classification, Lidder watershed has very fine drainage texture whereas Rembiara has very coarse. Hydrologically very coarse texture watersheds have large basin lag time periods followed by coarse, fine, and very fine texture classes. This clearly indicates that Lidder watershed has shorter basin response time as compared to Rembiara watershed.

- Relief Ratio (Rh)

The Rh for Lidder and Rembiara watersheds is 0.05 and 0.04 respectively. Quantitatively, it is the measurement of the overall steepness of a drainage basin. Also, it is an indicator of the intensity of erosion processes operating on the basin slopes. Rh normally increases with decreasing drainage area and size of a given drainage basin. Higher values of Rh indicate that intense erosion processes are taking place. Thus Lidder watershed is more susceptible to erosion than Rembiara watershed if this parameter alone is considered for erosion intensity analysis.

- Constant Channel Maintenance (C)

Constant channel maintenance (C) for Lidder and Rembiara is 0.34 and 1.00 respectively. The reciprocal of the drainage density (D) is constant of channel maintenance and signifies how much drainage area is required to maintain a unit length of channel. Low values of C in case of Lidder watershed indicates that is associated with weakest or very low-resistance soils, sparse vegetation and mountainous terrain, while the Rembiara watershed is associated with resistance soils, vegetation and comparably plain terrain.

- Texture ratio (T)

Texture ratio (T) for Lidder and Rembiara is 28.06 and 1.34 respectively. T is one of the most important factors in the drainage morphometric analysis, and depends on the underlying lithology, infiltration capacity, and relief aspect. Hydrologically, it can be said that Lidder in terms of T alone will have the longest basin lag times during storm events and Rembiara will have the shortest.

- Ruggedness number (Rn)

The ruggedness number for Lidder and Rembiara is 1.30 and 3.08 respectively. Rn indicates the structural complexity of the terrain in association with the relief and drainage density. It also implies that the area is susceptible to soil erosion. In present study, Rn is minimum in case of Lidder and maximum in Rembiara as seen in Table 4.2 This indicates that Rembiara as a whole is comparably least susceptible to erosion than Lidder.

5.2 Land Use/Land Cover (LULC) Analysis

Land use/land cover data is very important for understanding hydrological response of the watersheds. LULC maps of Lidder and Rembiara watersheds have been prepared using the Remote sensing data in an image processing system. Keeping in view the objectives of this research only hydrologically significant LULC classes were generated. Results from Table 4.3 show that the Rembiara watershed is dominated by LULC classes which enhance infiltration and reduce surface run off. The type and distribution of land cover has profound impact on a number of hydrological processes (Quilbe et al., 2008, Fohrer et al., 2001, Matheussen et al., 2000).Moreover the accuracy assessment of the LULC product generated shows it is about 90 % accurate. This brings the more conviction when tangible results concerning flood vulnerability are to be sought using LULC. Therefore, Lidder watershed with comparatively lower percentages of infiltration favorable LULC's, shall generate more surface runoff compared to the Rembiara watershed.

The analysis of the LULC data reveals that, though same LULC are prevailing in both the watersheds but their proportion varies quite significantly. Table 4.3 provides a comparison of the area under each LULC type in the two watersheds. These LULC types have significant impact on the hydrological processes and the differences in their areal coverage shall significantly affect flooding patterns and magnitude in the two watersheds (Rosenqvist and Birket, 2002). For example the differences in the vegetal cover (agriculture, pasture, forest) shall, strongly affect the soil moisture, evapo-transpiration and interception process in the two watersheds (Choudhary et al. 1994). The differential area under the impervious areas and the barren lands in the two watersheds shall differentially affect the infiltration and evaporation (Arthur et al., 2003, Arthur et al. 2000). Similarly the varying river networks in the two watersheds shall have strong impact on the infiltration capacity and runoff of the two watersheds (Sharma et al., 2001).

5.3 Topographic analysis

The topographic parameters of Lidder and Rembiara watersheds have been calculated using the DEM (Tarboton, 1989). Table 4.5 and 4.6 provides the areas of these watersheds under different elevation and slope zones. The higher elevation and slope zones are an indication of quick runoff during rains or storm events (Tucker and Bras, 1998). The different elevation and slope categories of each watershed are shown in the Figure 4.3 a, b and Figure 4.4 a, b.

Watershed morphology and hydrology are strongly influenced by the hill slope processes (Tucker and Bras, 1998). Area/elevation analysis as shown in the Table 4.5 indicates that Lidder watershed has large areas under high elevation compared to the Rembiara watershed, which also reaffirms that the Lidder watershed has high runoff during rainfall events. From the slope analysis, it is evident that the Lidder watershed has more precipitous and topographically rugged terrain compared to the Rembiara watershed that has extensive areas with flat or near flat terrain. This will have tremendous influence on the flow regimes of the two watersheds and shall influence the hydrology and flooding in these two watersheds to a varying degree. The slope parameter influences the transport and flow of water and sediments from the watersheds depending upon the contributing area. Therefore, the understanding of the interacting hillslope, fluvial and hydrological processes are essential to simulate the hydrologic behavior of the watersheds (Howard, 1994, Willgoose et al., 1991, Kirkby, 1986). Lidder watershed is therefore highly prone to flooding as compared to Rembiara watershed. The differential topographic attribute distribution in the two watersheds is going to tremendous influences on the transport of water and sediments from these two watersheds (Tucker and Bras, 1998, Ijjasz and Bras, 1995). Consequently, the impacts on the flooding shall also vary that shall depend among other things on the amount and pattern of the precipitation.

There is a significant relationship between the slope and the contributing area (Willgoose, 1994). Area-slope analysis for each of these two watersheds, as shown in the Table 4.6 indicates that Lidder watershed has higher area percentages under the higher elevations compared to the Rembiara watershed. This again indicates that quick runoff may be generated from Lidder watershed that may result in flooding over prolonged rainy spell.

5.4 Geomorphological analysis

Information about geomorphology is essential to characterize the hydrological response of the watersheds (Knighton, 1984). From the results, as shown in the Figure 4.6 a, b and corroborated by the data in the Table 4.8, it is evident that Rembiara has much larger active flood plain (50.96 km^2) compared to Lidder watershed (25.38 km^2). Similarly, Rembiara watershed has 20.29 km^2 river course compared to 11.83 km^2 of the Lidder watershed. The Lidder watershed has much larger areas under mountain tops and high slopes compared to Rembiara watershed. All these geomorphological units shall strongly affect the hydrological regime and flooding pattern in these two watersheds.

5.5 Geological analysis

Geological analyses of the representative watersheds show that Rembiara watershed has high percentage of recent alluvium carried and deposited by the river action compared to the Lidder watershed. This indicates that Rembiara watershed may have witnessed several floods in the past that have left thick deposition of the alluvium in the flood plains. Sedimentological characteristics also point to the fact that Rembiara watershed has been hit by several flooding events compared to Lidder watershed in the geological history. Overall, it can be deduced from the geological setting of the two watersheds that geologically Rembiara watershed is more vulnerable to flooding than Lidder watershed. It has been shown that geological setting affects the geomorphic processes that control the behavior of flooding at the watershed level (Ritter, 1986).

5.6 Soil analysis

Soil maps of Lidder and Rembiara watersheds were generated as per the methodology described in the chapter 4. Figure 4.8 a, b shows the spatial distribution of the soil types in these watersheds. Table 4.10 indicates that both the watersheds share 7 common types of soils (Loam, Clay loam, Silty Clay Loam, Silt Loam, Sandy Loam, Rock Outcrop and Snow and Glaciers). Lidder watershed in addition to these also has a small percentage of sandy clay loam.

The Rembiara watershed is dominated by clay loam (19.16 %), silty clay loam (17.98%) and rock outcrop (17.92 %). On the other hand Lidder watershed is dominated by snow and glaciers (29.27%), sandy loam soil (25.11 %) and rock outcrop (18.98 %).

Soil types influence the hydraulic properties of the soils and that in turn affect a number of hydrological processes at the watershed scale including the lateral and horizontal movement of the sub-surface water (Entekhabi et al., 1999). Therefore, watershed with large areas under the barren and rocky outcrops shall contribute pre-dominantly to runoff without much infiltration capacity. Thus Lidder watershed shall contribute more towards runoff then Rembiara.

Similarly, the texture of the soil also determines to a large extent the moisture holding capacity of the soils and to a great extent affects the infiltration and evaporation processes that inter alia affect the surface runoff and hydrographs of the watersheds (Tansey and Millington, 2001). As a result, the two watersheds with varying proportions of the soil texture and cover shall respond hydrologically differently Therefore, Lidder watershed will have higher surface runoff compared to the Rembiara watershed because of their varying soil characteristics.

Objective 2: Assess the impact of differential geo-environmental setting on the hydrology of two watersheds.

One – third of the annual natural disasters and economic losses, and more than half of the respective victims are flood related. A burgeoning global population and growing wealth, particularly in the last two or three decades, have increased the risk and the demand for protection from flooding. Current challenge in flood damage research consists in developing a better understanding of the interrelations and social dynamics of flood vulnerability, leading to preparedness and flood management, and to take this into account in a modern design of flood hazard analysis and flood risk management. According to the definition “hazard" means the probability of occurrence within a specified period of time and within a given area of potentially damaging phenomena. Naturally the areas which have the greatest danger of flooding are the flood plain, the lower river terraces. This study aimed at estimating the severity of flood during periodic heavy rains in Jhelum basin is of prime socio-economic importance in the region.

The results under this objective are a manifestation of the differential geo environmental setting on the flood vulnerability.

5.7 Empirically based Hydrological Model based on Compound value (Cp) evaluation

The empirically based hydrological model based on Cp was set-up with all the input parameters generated from objective one. As per the Cp value generated, Lidder (1.35) it will show the quickest hydrological response evident as surface runoff as compared to Rembiara which has a Cp of 1.54. Conversely Rembiara watershed has a good infiltration capacity as compared to Lidder watershed. Although the difference between the Cp values of the two watersheds is very small (0.19) but statistically it is very significant since very large number of parameters were involved in its derivation. The results of the Cp for the two watersheds are in conformity with the individual information layers such as morphometry, LULC, soil etc. for these watersheds. Lidder watershed has a high drainage density compared to Rembiara, which imparts supercilious runoff characteristics to Lidder than Rembiara. Moreover Lidder has a high percentage of LULC and geomorphological classes which enhance runoff as compared to Rembiara (Table). Cp values for Lidder and Rembiara is a hand on information about the hydrological characteristics of the two watersheds. On the basis of Cp value it can be assumed that after a same intensity storm event Lidder will show quick surface runoff than Rembiara. Therefore, it is quite evident that the geomorphological and physiographic characteristics and geological setting of the watershed have significant impact on the hydrological response from the watershed. Therefore, geomorphological studies are a pre-requisite for understanding the hydrological response of the watersheds and can be used to predict flood peaks, sediment yield and water discharge (Gardiner, 1981, Chow, 1964).

These research outcomes show that the geo-morphometric characteristics of these watersheds have a strong influence on the hydrological characteristics and are direct and credible indicator to infer hydrological information including flooding and flood vulnerability of the watersheds (Patton, 1988). This integrated approach adopted here for characterizing the hydrological response of two watersheds with varied topography, land use/land cover, soils and geological setting emphasizes the strong relationship between the geomorphological, geological and hydrological setting of the watershed. These results are a significant scientific finding and needs to be tested in other watersheds in the Jhelum basin in order to develop a simple model relating the geomorphology with the hydrology in the Jhelum basin. Such an operational model, when realized, shall go a long way in mitigating and developing an early warning system for flood management in the Jhelum basin (Viera, 2003).

Objective 3: Assess the flood vulnerability and the flood hazard zonation in these watersheds

In order to accomplish the third and final objective of the research i.e., flood vulnerability and risk management for each location in two representative watersheds of the Jhelum drainage basin, two watersheds, namely Rembiara and Lidder have been selected. In-depth analysis of the geomorphological, geological, hydrological, land use/land cover and pedologic factors, controlling the flood vulnerability in these two basins have been conducted. These two watersheds are located on either sides of the river Jhelum having varied topography, geological setup and drainage characteristics. The discussion of the necessary geospatial analysis of the multi-source datasets, including field data, using a multitude of approaches as described in the Chapter 3and 4 is as under.

Integrated compound value (ICp) analysis in GIS environment was carried to analyze the physical and social vulnerability of the two representative watersheds as per the methodology discussed in the chapter 3. Figure 4.10 shows the flood prone areas under the two representative watersheds, Rembiara and Lidder. It has been found that an area of 67.65 Km^2 out of the total watershed area of 1261.75 km^2 falls under flood prone area of the Lidder watershed amounting to 12.75% of the basin area, while as Rembiara watershed has 14.04 km^2 of the total watershed area of 664.49 km^2 under flood prone area amounting to 2.12% of total area of Rembiara watershed as shown in the Table 4.17.

By analyzing the percent area under the flood plain, Cp and the number of villages within the flood plain in the two watersheds and following the ranking system wherein larger Cp implies more quick runoff, larger % flood plain implies lesser implications to life and property during flood event and more number of villages within the flood plain implies more risk to life and property, we have generated integrated compound value (ICp) which describes the physico-social vulnerability of the two watersheds (Table 4.12). Higher value means lesser vulnerability and vice versa.

Lidder, *ICp* of 1.66 denotes comparatively lesser physico-social vulnerability for this watershed while as Rembiara, *ICp*1.33 denotes greater -social vulnerability for this watershed.

Hazard zonation mapping is essential to understand and address risks that confront the community to tackle the flooding. Flood hazard mapping forms the foundation of any flood management action plan (Badilla, 2002). Apart from the natural factors and forces, human activity and socio-economic status can significantly impact the incidence and magnitude of the flooding at the watershed level. Therefore, flood hazard zonation mapping of both the watersheds, Rembiara and Lidder was carried out by integrating social vulnerability, physical vulnerability and elevation criteria obtained from the use of DEM of the flood prone areas the two watersheds. The hazard zonation maps for the study areas were obtained after giving the weightage as detailed in the Table 4.12 and integrated the relevant data in GIS using multi criteria analysis.

The integration of the physical and social vulnerability criteria adapted here for determining the overall vulnerability of the people and places in both the watersheds shall aid in developing and designing rural development schemes that aim at enhancing the social status of the communities living in these village and also taking up physical flood control measures to reduce the vulnerability of the communities living in the flood prone zones of these two watersheds to flooding. Particularly, the hazard zonation shall facilitate development of zonal and targeted plans in the flood prone areas of these two watersheds to develop robust strategy for mitigation and control of floods in the long run.

Chapter: 6

Summary and Conclusion

This chapter provides a concise summary of the findings and conclusions arrived at from the analysis of the results carried at various spatial scales as described in details in the preceding chapters. The basis for choosing different watersheds was that they should represent the overall physiographic, geological and hydrological setting of the Jhelum basins.

The pilot/test sites chosen varied in hydro-geomorphological settings in order to have a better understanding of the influences of the geomorphology and hydrology on the flooding in the Jhelum basin. For accomplishing the research objectives set out for this research, a number of approaches were employed in an integrated manner at different spatial scales. For understanding the relationship between the morphometry, physiography, land use/ land cover (LULC), geomorphology, soil, and geology on hydrology, a compound number evaluation approach was carried out on the two pilot watersheds. For the purpose of flood vulnerability assessment at watershed level, these two pilot watersheds of Jhelum watershed were chosen as representative watersheds for detailed studies i.e. Lidder, Rembiara. Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) 30 m digital elevation model (DEM) of the area was used to get a basic idea about the overall physiography of the hilly and precipitous study area followed by a reconnaissance survey of the representative pilot study areas. Some important findings/conclusions of the study are enumerated as under.

1. From the analysis of the results on the morphometry of the Lidder and Rembiara watersheds, it is concluded that the hydrology of a watershed changes significantly in response to the spatial variations in the morphometric parameters. Overall results indicated that Lidder watershed contributes much runoff to the Jhelum watershed than Rembiara watershed. Since there is a close relationship between the morphometric parameters and the mean annual flood (Carlston (1963), as such, Lidder Watershed is more prone to flooding compared to the Rembiara watershed.
2. From the analysis of the land use and land cover data of the two watersheds, it is concluded that Lidder watershed has a higher percentage of catchment under exposed rocks, while the Rembiara watershed has higher percentage of agriculture land. Since the type and distribution of land cover has profound impact on a number of hydrological processes (Quilbe et al., 2008, Fohrer et al., 200), Lidder watershed with comparatively lower percentage of infiltration favorable vegetation cover, shall generate more surface runoff compared to the Rembiara watershed.
3. Information about geomorphology is essential to characterize the hydrological response of the watersheds (Knighton, 1984). Geomorphological mapping of terrain units was carried out on the basis of the interpretation of satellite data followed by field observations. From these geomorphological analyses, it is evident that Rembiara has much larger active flood plain compared to Lidder watershed. The Lidder watershed has much larger areas under mountain tops and high slopes compared to Rembiara watershed. All these geomorphological units influence the hydrological regime and flooding pattern in the two watersheds.
4. Most of the geological formations in both of the watersheds are quaternary soils (Karewa deposits) and recent alluvium. However, the peripheries of these two watersheds are dominated by hard rock lithology including panjal traps, Triassic limestone, fenestella shale and agglometric slates. Geological analyses of the representative watersheds show that Rembiara watershed has high percentage of recent alluvium carried and deposited by the river action compared to the Lidder watershed. This indicates that Rembiara watershed may have witnessed several floods in the past that have left thick deposition of the alluvium in the flood plains. Sedimentological characteristics also point to the fact that Rembiara watershed

has been hit by several flooding events compared to Lidder watershed in the geological history. Overall, it can be deduced from the geological stetting of the two watersheds that geologically Rembiara watershed is more vulnerable to flooding than Lidder watershed as it has been shown that geological setting affects the geomorphic processes that control the behavior of flooding at the watershed level (Ritter, 1986)

5. From the results of hydrological model based o*n Cp*, Lidder watershed with *Cp* = 1.35 implies very fast hydrological response in terms of surface runoff as compared to Rembiara watershed wit*h Cp* = 1.54. From these results, it is concluded that during heavy rain spells Lidder watershed is more vulnerable to flooding than Rembiara watershed. The results on the hydrological response for Lidder and Rembiara watersheds are quite in agreement with those of the morphometric analysis. Therefore, it is quite evident that the geomorphological and physiographic characteristics and geological setting of the watershed have significant impact on the hydrological response from the watershed. Therefore, a geomorphological study can be used to predict flood peaks, sediment yield and water discharge (Gardiner, 1981, Chow, 1964).
6. The flood plain areas were delineated based on the geomorphology, drainage pattern and digital elevation model. The results showed that the Lidder watershed has 67.65 km^2 area under flood plain which accounts for about 5.34 % area of the whole watershed. Whileas Rembiara watershed has 14.04 km2 area under flood plain which accounts for about 8.86% area of the Rembiara watershed. Among the two watersheds Rembiara has the largest area under flood plain.
7. Integrated compound value *(ICp*) analysis in GIS environment was carried to analyze the physical and social vulnerability of the two representative watersheds. It was found that an area of 67.65 Km^2 amounting to 12.75% of the total watershed area of 1261.75 km^2 falls under flood prone area of the Lidder watershed , while the Rembiara watershed has 14.04 km^2 (2.12% of total area of 664.49 km^2) under flood prone area. By analyzing the percent area under the flood plain, *Cp* and the number of villages within the flood plain in the two watersheds and following the ranking system wherein larger *Cp* implies more quick runoff, larger % flood plain implies more implications to life and property during flood event and more number of villages within the flood plain implies more risk to life

and property, we have generated integrated compound value *(ICp)* which describes the physico-social vulnerability of the two watersheds. Higher value means lesser vulnerability and vice versa. Lidder watershed, with an *ICp* of 1.66 denotes comparatively lesser physico-social vulnerability than the Rembiara with an *ICp* 1.33

Challenges and limitations of this research

i) One way to validate the results of the current research is to simulate runoff regimes at watershed scale using physically based hydrological models and correlate the model simulations with the *Cp* value generated for that watershed. But the lack of the appropriate hydro-meteorological observation stations all over the Kashmir Himalayas hinders the characterization of the various hydrological processes and their validation. The availability of the discharge data is vital for validating and calibrating the hydrological simulation models. It is therefore of utmost importance that a network of hydro-meteorological and river discharge stations is established all over the basin to promote better prediction of the flooding mechanism in the basin.

ii) The assessment of the flood vulnerability conducted at the village level is not complete and it needs to be further strengthened from other socio economic parameters such as total population, sex ratio, literacy etc. so that a holistic community level vulnerability assessment could be promoted for the entire basin in order to formulate mitigation strategies which are focused at enhancing the socio-economic profile through various rural development schemes that are in vogue under various sectors in the state. Moreover the incorporation of the latest census data could improve the assessment of the social vulnerability to flooding at the village level. The availability of socio-economic data on disaster related facilities like availability of shelter houses, gunny bags, control rooms is required for better assessment of the flood vulnerability at the community level

iii) The availability of the high resolution satellite data, particularly for mapping the flood control features like levees, bunds is essential for developing a detailed Mitigation Action Plan for the Jhelum basin.

In light of these research findings, it is suggested that:

i) The reckless and unplanned urbanization of the flood plains and wetlands in the Jhelum basin need to be stopped forthwith. This practice is single most important reason responsible for enhanced flooding and water logging. We need to have some robust strategy for restoring the wetlands in the valley.

ii) The appropriate information about parameters of tremendous significance for the assessment of flood vulnerability need to be generated on priority. For example, the state of Jammu and Kashmir does not have any good soil and geological data basis at appropriate spatial resolution. The methodology used during the present study for soil mapping could be replicated to generate high resolution soil data for assessing the hydrological and other responses at watershed level. Similarly, we need to make efforts to generate credible and detailed geological maps for the entire state of Jammu and Kashmir.

iii) Similar studies need to be conducted in the other 22 watersheds of the Jhelum basin so that a complete understanding of the mechanisms controlling the flooding is established.

iv) Finally, it is recommended that the Flood Mitigation Action Plans may be developed for each of the 24 watersheds of the Jhelum basin.

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