FLOOD RISK ANALYSIS AND MAPPING OF A HIMALAYAN RIVER

A DISSERTATION

Submitted in partial fulfillment of the

Requirement for the award of the degree

of

MASTER OF TECHNOLOGY

in

WATER RESOURCE DEVELOPMENT

By

AVINASH THAKUR

WATER RESOURCE DEVELPOMENT AND MANAGEMENT DEPARTEMENT

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

ROORKEE – 247667

MAY 2016

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled **"Flood Risk Analysis and Mapping of a Himalayan River",** submitted in the partial fulfilment of the requirement for the award of the degree of **Master of Technology** in **Water Resource Development** and submitted in the **Water Resource Development and Management Department** of the **Indian Institute of Technology, Roorkee** is an authentic record of my own work carried out during the period June 2015 to May 2016 under the supervision and guidance of **Dr. M.L. Kansal, Professor**, **IIT Roorkee**.

Date: May 02, 2016

Place: Roorkee **AVINASH THAKUR**

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dr. M.L. Kansal
Professor
WRDM, IIT Roorkee

ACKNOWLEDGEMENT

I would like to articulate my deep gratitude to **Dr. M.L. Kansal** who has always guided and motivated me for carrying out the dissertation **"Flood Risk Analysis and Mapping of a Himalayan River".** His constant inspiration and effort made this evaluation report a great success. I am thankful to him for his contributions in completing this evaluation report. I am also thankful to **Mr. Sandeep Shukla** for his guidance and help. An assemblage of this nature could never have been attempted without help and inspiration from all faculty members, research scholars and staff of **Water Resource Development and Management Department, Indian Institute of Technology, Roorkee**. I acknowledge my indebtedness to all of them.

May, 2016

Roorkee Avinash Thakur

ABSTRACT

In the present work flood risk analysis for Mandakini River, a tributary of river Ganga has been done by hydraulic modeling. Flood plain inundation mapping has been done by integrated use of ArcGIS and HEC RAS. Geometric data for hydraulic model has been created in ArcGIS using HRC GeoRAS (an extension to ArcGIS) and then sediment transport and flow simulation for different value of floods have been done in HEC RAS. Simulation results are then exported back to ArcGIS and analyzed for flood risk analysis and flood plain mapping. Further the sites for flood risk management are prioritized as 'hotspots' using Choosing By Advantages (CBA) method.

Cloudbursts also occur in upper Himalayan reaches during monsoon which can further add to the volume of flood in the rivers. So, a detailed study has been carried out to find suitable method for estimation of flood hydrograph characteristics for cloudburst events and necessary modification and corrections for coefficients has been suggested considering the characteristics of the catchment and the results has been used as an input for simulation of flood plain inundation.

Flood plain inundation mapping and sediment transport analysis has been done for flow values ranging between 1500 and 3000 cumecs based on which detailed flood risk analysis report has been prepared. Flood risk analysis considered all the major elements (social, economic and ecological) in the flood affected areas. Detailed analysis of some identified sites has been done and they are ranked in order of the flood risk using CBA technique.

CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

SYMBOLS & NOTATIONS

t_p = basin lag In hours.

C_t = a regional constant representing watershed slopes and storage effects.

t_r = standard duration of effective rainfall

L= basin length measured along the water course from basin divide to gauging station in km.

L_{ca} = distance along the main water course from the gauging station to a point opposite to watershed centroid in km

Q_{ps} = peak discharge for unit hydrograph of standard duration

C_p = a regional coefficient

t_R = actual duration of effective rainfall

Q_p = peak discharge for actual unit hydrograph

t_p' = basin lag in hours for effective rainfall of t_R hours.

T_b = time base

W_{50} = width of unit hydrograph at 50% peak discharge

W_{75} = width of unit hydrograph at 75% peak discharge

S= basin slope

C_{tl} = basin constant

n = regional constant (0.38 for study of catchments in USA).

t_c = time of concentration

CBA- Choosing by Advantages

GIS- Geographic Information System

HEC- Hydraulic Engineering Center

LULC- Land Use Land Cover

TOPSIS- Technique for Order Preference by Similarity to Ideal Solutions

CHAPTER 1
INTRODUCTION

1.1 General

Floods are one of the potential disasters occurring in the Himalayan region that accounts for huge losses of life and property. Flood may be defined as "a relatively high flow in a river, markedly higher than usual and thus inundating lowland. It is a body of water, rising, swelling and over flowing land, not usually thus covered"**.** Floods may be normal riverine floods or the flash floods. Normal riverine floods can be predicted to some extent, as they offer some time and opportunities for preparation and avoidance of losses. But flash floods are sudden, usually unexpected, and allow little time to react. Individual flash floods may have their base time from several minutes to several days and may happen anywhere, but are more common in mountain catchments. They consist of a very strong surge of water that can carry rocks, soil, and other debris usually along a riverbed. Although areal extent of flash floods is generally smaller than riverine floods, their unexpected and intense nature may pose a significant risk to people and infrastructure. The Himalayan region is particularly vulnerable to flash floods because of the steep slopes, high rate of surface erosion, and intense seasonal precipitation, particularly during the monsoon season. Changing land use-land cover and climatic conditions further increase this vulnerability.

Floods can be caused by a variety of factors. Floods in the Himalayan region are mainly caused by intense rainfall, rapid melting of snow, landslide dam outbursts, glacial lake outbursts, and failure of artificial structures such as dams and levees. Cloudbursts, stationary monsoon troughs, or monsoon depressions are the general cause of intense rainfall. Landslides and debris flows are generally caused by intense monsoon rainfall in the region of weak geological formations and rugged topography. Large amounts of debris from a landslide can temporarily block a river, leading to development of a temporary reservoir or lake upstream of the landslide dam. Failure of unstable dam may occur either as a result of hydrostatic pressure, or overtopping. Sometimes debris from the secondary landslides may fall into the reservoir leading to a combination of pressure and overtopping resulting in sudden outburst of water. Such catastrophic failures are generally random and difficult to predict precisely. Glacial lakes due to the retreat of glacier leave behind the debris mass at the end that are known as the end moraine exposed. This moraine wall acting as a dam can trap the water melted from the glacier and form a lake. The moraine dams can eventually break, leading to a catastrophic glacial lake outburst flood. The glaciers in the Himalayan region are in a general state of retreat; thereby increasing the threat of an outburst. Consequences of flooding depend on a number of factors such as depth of water, velocity of flow, duration, amount of debris and boulders carried along with water, wave-action effects, water quality and the vulnerability of receptors, nature, presence and reliability of mitigation measures etc. Floods may result in a worst disaster that not only causes economic losses in terms of damage to houses, critical infrastructure, industries and property but also human and animals lives are lost. Increasing trend has been observed in frequency and impacts of flood events in recent past e.g. Kedarnath (2013) and Srinagar (2014). This has raised the need for policy making and preventive measures for disaster management in Himalayan region.

It is neither technically nor financially feasible to avoid all the losses occurring from flooding. So, flood risk analysis and mapping is required for management strategies to be employed to optimize flood protection benefits and minimize harm. Floodplain mapping is highly specialized area of expertise that depends mainly on geographical data processing and hydraulic modeling. Risk analysis consists of characterizing the area; determining the likelihood and intensity of a flood; assessing the extent of damage and its vulnerability; and assessment of the overall risk using this information Flood risk is generally expressed as a combination of the likelihood of flooding and the potential consequences. The analysis indicates the kind of management needed and can be used to plan, prioritize, and implement management measures. In the present work, flood risk analysis and mapping for Mandakini river has been done using Arc GIS and HEC RAS software and then hotspots for flood hazard have been identified to aid the decision making process.

1.2 Objectives of the Study

The objectives of the dissertation work are as follow:-

1. To understand different methods of peak flood estimation and suggest the suitable method (with appropriate changes in equations and coefficients) for peak flood estimation for a cloudburst event in Himalayan region.
2. To carry out flood risk analysis of Mandakini river using HEC RAS and Arc GIS software.
3. To identify and prioritize the hotspots for flood risk management.

1.3 Study Area

Dissertation work is focused in the western Himalayan region. According to Central Water Commission (CWC, 1994) classification this area comes under hydrological zone 7. Case study for flash flood induced by cloudburst event has been done for Leh region of state of Jammu and Kashmir. And the flood risk analysis has been carried out for the Mandakini River (Fig. 1.1) from its origin near Kedarnath to the confluence near Rudraprayag where it merges with river Alaknanda. Vasukiganga, Mandani, Kali and Madhyamaheswar rivers are the important tributary rivers of Mandakini which are also considered in the study area. Kedarnath, Sonprayag, Ukhimath, Rudraprayag are the important towns in the region. This is a fragile mountainous ecosystem in the state of Uttarakhand, India which is prone to extreme natural disturbances such as intense rainfall and earthquake.. The study area is confined to latitude 30°12'58.132" N to 30º48'27.642" N and longitude 79°02'58.649" E to 79°02'00.952" E and covers a total area of 1645 sq.km. Altitude in the area varies from 615 m to 6749 m. Huge devastation was caused in Kedarnath in 2013 due to flash flood induced by heavy rains and cloudburst.

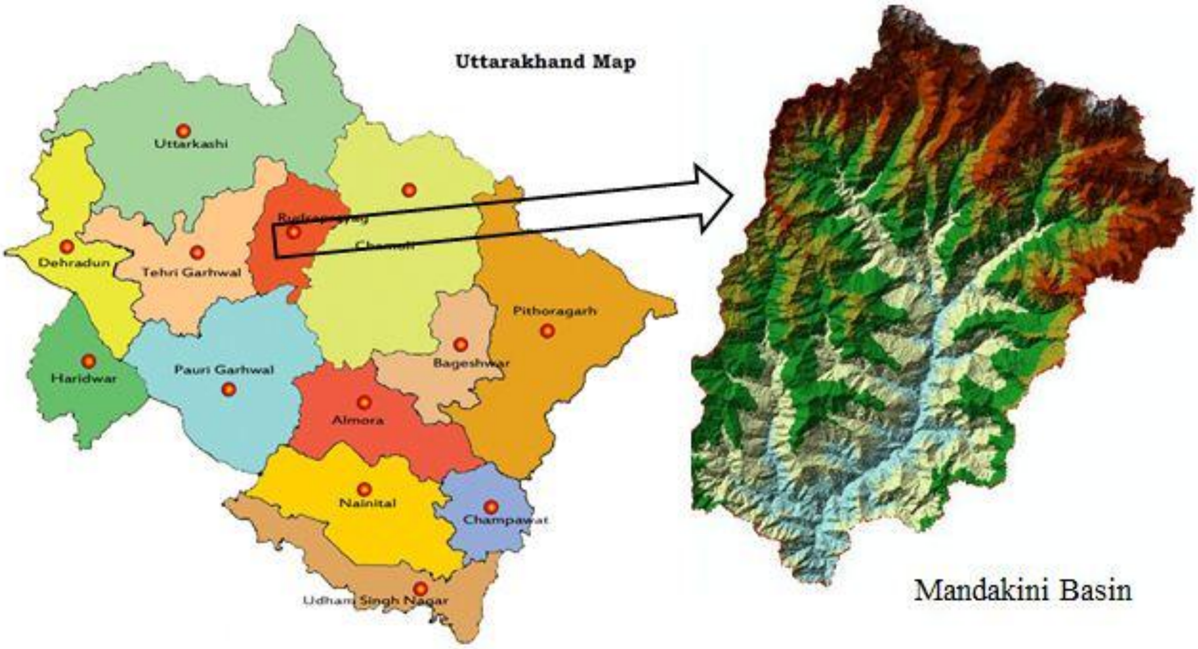

Figure 1.1: Catchment area of Mandakini River

Mandakini river has a length of about 80 km with an average slope of 42.0m per km. the famous shrine of Kedarnath is also located in Mandakini river basin. This is a low volume river in winters but it is unpredictable during monsoon period when all the rivers are swollen.

1.4 Scope of the Work

The scope of the present work is limited to the flood risk analysis and mapping of Mandakini River based on flood plain mapping and sediment transport analysis for river model in HEC RAS and analysis of results in Arc GIS. Flood risk analysis has only been done for main river reach but main tributaries of river have also been modeled to some distance from confluence so as to obtain more realistic results for inundation. River model is completely based on the cross section obtained from DEM of the basin and no existing protection measures and bridges have been included in the model. Flood plain maps have been generated for different flows ranging between 1500 and 3000 cumecs. Along with flood risk analysis for the area the hotspots for flood hazard have also been found using Choosing By Advantage (CBA) technique considering social, economic and ecological elements.

CHAPTER 2
CLOUDBURST INDUCED FLASH FLOODS

2.1 Introduction

Western Himalayan region is prone to a number of natural disasters due to its inherent geographical climatic conditions. Most common hazards in this area are earthquakes, floods or flash flood, landslides and glacial lake outbursts. Out of these floods and flash floods are the most frequently experienced and the frequency of these events has rapidly increased in near past. Cloud burst is one of the reasons of flash flood in hilly regions. Due to the severity of the damages caused by cloudbursts, they are often termed as 'Himalayan Tsunami'. Such events are related to extreme hydro-meteorological conditions that lead into debris flow, landslides and boulder movement along with shooting velocity of water in hilly areas. This results in huge change of momentum and hence the large force. This force along with flood movement causes heavy loss of life and property. The worst considered flood disaster of northwest India in the past century i.e. Alaknanda flood of 1970 was also a flash flood triggered by a cloudburst The flash floods of Bhagirathi (1978), Sutlej (1993 and 2000) and Teesata (1968) are some more examples of such events in northwest Himalayas.

Cloudburst is a sudden aggressive rainstorm of small duration (few minutes to few hours) with rainfall intensity of more than 100 mm/hr (Das et al. 2006).Some of the extreme rainfall events recorded in India range from 900 mm/day to 1,040 mm/day (Dhar et al. 1998). Cloudbursts in Himalayan region represent the rapid convective lifting of moist air mass under the conditions of steep orography and thermodynamic instability. The warm and humid air moves uphill due to orography of the area. As this air mass continues to rise up, it forms large clouds. Lack of upper air at such great heights prevents the dissipation and water concentration in the cloud keeps on increasing which finally result in sudden localized downpour of water (Fig. 2.1). Generally, cloud-burst is a localized weather phenomena concentrated over a small area (not exceeding 20–30 km^2). Researchers have attributed the cloud burst phenomena to the increased anthropogenic activities and the climate change. Generally, it occurs in the monsoon season (June to September). The cloudbursts are mesoscale and least known of all the weather systems. Most of the Himalayan streams flow through narrow gorges having moderate to steep slopes. As the rivers flow towards plains the valley starts becoming relatively wider and less steep. The flash floods that occur particularly in narrow river valleys are one of the most-dangerous and feared consequences of cloudbursts, landslides or glacial lake outburst. Deposition of boulders and debris along the constricted course of the rivers due to cloudburst or landslide lead to ponding of the river flow, which results in in the formation of temporary lakes, which can last from a few days to a few decades. When the hydrostatic pressure caused by backwater of the lake exceeds the retention capacity of the barrier, the accumulated water flows downstream with high velocity and discharge thus inundating otherwise safe settlements.

Often, these events are associated with very small areal extent, less duration of storm and remoteness of location. It is difficult to predict the location and impact of cloud burst particularly when most of these hilly areas are ungauged. Therefore, such events sometime go unnoticed and even the events which are reported, have scanty data due to the poor ground monitoring mechanism or sometimes even these also get washed away. Only data which remain available for such events is the flood water scars on the banks of streams, uprooted trees, and visual observations by the local people. These large number of eye witnesses provide crucial and reasonably accurate information of flood timing (Gourley et al. 2010).

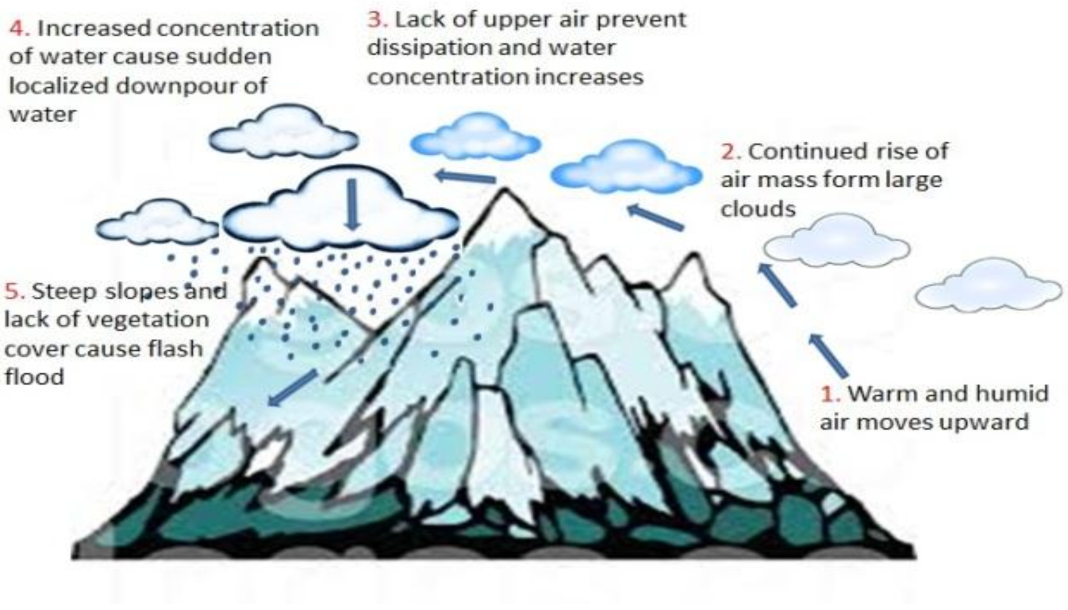

Figure 2.1: Schematic diagram of cloudburst and flash flood generation

Some of the recent cloud burst events occurred in the state of Uttarakhand in India and their estimated impact are as follows:

1. On July 6, 2004 - At least 17 people were killed and 28 injured when three vehicles were swept into the Aleksandra River by heavy landslides triggered by a cloudburst that left nearly 5000 pilgrims stranded near Badrinath shrine area in Chamoli district.
2. On August 7, 2009 - 38 people were killed in a landslide resulting from a cloudburst in Nachni area near Munsiyari in Pithoragarh district.
3. On August 5 2010- A cloudburst was reported in Leh region of Jammu and Kashmir. The flash floods affected 52 villages in the area, covering around1, 420 hectares of land and destroyed 1,749 houses.

4. On September 15, 2010 - Cloud burst in Almora drowned away two villages leaving a few people alive.
5. On September 14, 2012 - Rudraprayag district experienced a cloudburst which resulted in death of 39 people.
6. On June 17, 2013 - A cloudburst was reported in Kedarnath and Rambada region in Kedar valley, of Himalaya'. Over 10000 people died and more than 100,000 got affected with extensive loss of life and property. Figure 2.2 shows the damage caused near Kedarnath temple due to flash flood.
7. On September 6, 2014- A cloudburst occurred in Kashmir valley killing more than 200 people. Centre for Science and Environment (CSE) mentioned heavy and unchecked development aggravated the development in the region.

Keeping the importance of cloud burst in mind and its role in flash flood, it is desired to assess the quantum of flood caused by such an event in an ungauged catchment. So a case study has been done to estimate the flood hydrograph characteristics of the flash flood caused by cloudburst. This study focuses on Synthetic Unit Hydrograph approach for the north Himalayan regions of India. The suggested approach is validated through one of the cloud burst event. In future the proposed methodology can be extended to other regions and its reliability can be improved with availability of more data.

Figure 2.2: Damage caused by cloudburst induced flash flood near Kedarnath temple

2.2 Methods of Flood Estimation

Quantum of flood in a catchment can be assessed in terms of peak, peak time and the time distribution of flow in terms of flood hydrograph. Flood estimation can be studied under following categories of methods:

1. Empirical method
2. Rational method
3. Flood frequency analysis
4. Unit hydrograph method.

2.2.1 Empirical Method

Empirical method uses regional formulae based on correlation between discharge and catchment characteristics. Almost all the empirical formulae represent discharge as a function of catchment area. These formulae are regionally valid and give approximate results when applied to other catchments. For example, Dicken's formula (CWC, 1972) is widely used in India as the first approximate value of peak flood in a catchment, which is given as:

$$Q_p = C_d . A^{\frac{3}{4}} \tag{1}$$

where

Q_p= peak discharge (m^3/s);

C_d = coefficient of runoff that varies from 6 to 30 (11.5 for northern India);

A=catchment area (km^2).

2.2.2 Rational Method

Rational method another semi-empirical formula used for peak flood estimation in small catchments. It considers a rainfall of uniform intensity occurring over small catchments such that duration of rainfall is greater than the time of concentration for catchment. Runoff is assumed to increase gradually to a peak value at the time of concentration or time of peak and stay at the peak as long as the rainfall continues. Mathematically, flood peak and peak time (Kirpich equation) are represented as:

$$Q_p = \frac{1}{3.6} C(i_{cp}) A \tag{2}$$

$$t_c = t_p = 0.01947 \left(L^{0.77} S^{-0.385} \right) \tag{3}$$

where

Q_p= peak discharge (m^3/s);

C=coefficient of runoff = (runoff/ rainfall);

i_{cp}= mean intensity of precipitation (mm/h) for duration t_c;

A=catchment area (km^2);

t_c= time of concentration (minutes);

t_p= time of peak (minutes); S = slope.

2.2.3 Flood Frequency Analysis

In flood frequency method, one uses the observed maximum annual flow values and estimates the statistical parameters of the probability distribution. The values of successive annual maximum discharge from a given catchment area for a large number of years constitute a hydrologic data series. This information is for estimation of likelihood of flood as a function of recurrence interval. The data are arranged in decreasing order and the plotting position is calculated by formula:

$$P = \frac{m}{N+1} \qquad (4)$$

where

m= order of the event

N = total number of events in data

The recurrence period T is calculated as:

$$T = 1/P \qquad (5)$$

But as this method is based on the analysis of the historical data, it cannot be used in case of cloudburst event as there is very scanty or almost no historical data available for such events.

2.2.4 Unit Hydrograph Method

A unit hydrograph represents the lumped response of catchment to a unit rainfall excess of D-hour duration to produce direct runoff hydrograph. The factors that affect the shape of unit hydrograph have been studied under two categories i.e. physiographic factors and storm characteristics. Physiographic factors include basin characteristics (shape, size, slope, nature of the valley, drainage density, elevation etc.), infiltration characteristics (land use and land cover, lakes and other storages, soil type and geological conditions) and channel characteristics (cross-sections, roughness, storage capacity etc.). Storm characteristics include precipitation, intensity, duration, magnitude and movement of storm. The effect of various factors on hydrograph is as follow:

1. The shape of basin influence the time of concentration i.e. the time taken for water from the remotest part of catchment to reach the outlet. Fan shaped catchments gives high peak and narrow hydrographs while elongated catchments give narrow peaked and broad hydrographs.
2. Size of a basin affects its behavior. In small catchments channel flows are predominant by overland flows. Hence intensity of rainfall and land use has greater impact on peak flood. In larger catchments channel flow is more predominant. Time base for larger catchments will be larger as compare to corresponding hydrographs for smaller catchments.
3. Slope of the stream controls the velocity of flow in channel. Slope has significant effect on recession limb of hydrograph as it represents the depletion of storage. The basin slope for smaller catchments is more important where overland flow is predominant. Steeper slopes result in larger peak discharges.
4. Ratio of total channel length to total drainage area is known as drainage density. Large drainage density results in quick conduction of water down the channel that reflects as pronounced peak discharge. In basins with small drainage densities, the overland flow is more predominant and hence the resulting hydrograph is squat with a slowly rising limb.
5. Vegetal cover offers resistance to the flow of water and increases the infiltration and storage capacities of soil. This results in reduced peak of hydrograph. This effect is very pronounced for catchments with smaller areas.
6. Intensity, duration and direction of storm movement are the most important climatic factors that affect the shape of a flood hydrograph. Peak and volume of surface runoff are directly proportional to intensity of rainfall for a given duration. Duration of a storm of given intensity also has direct proportional effect on volume of runoff. There will be quicker concentration of flow if a storm moves from upstream end of catchment to downstream end. This results in high peak flood. This effect is further attenuated by shape of catchments. Hydrographs for long and narrow catchments are most sensitive to direction of storm movements.

Detailed information about rainfall and resulting flood hydrographs is not available for all catchments, especially in remote and small catchments. To construct unit hydrographs for such catchments empirical relationships of regional validity has been given by a number of researchers (Singh et al. 1988). A number of methods are reported in literature for developing synthetic hydrographs. But these methods being based on empirical relationships have regional limitations and they should not be considered as general relationships for all regions.

Central Water Commission (CWC) has classified India in seven hydro-meteorologically homogenous zones (Fig. 2.3). Each zone is described by a different set of relationships for the synthetic unit hydrograph. For example, western Himalayan region lies in the zone 7.

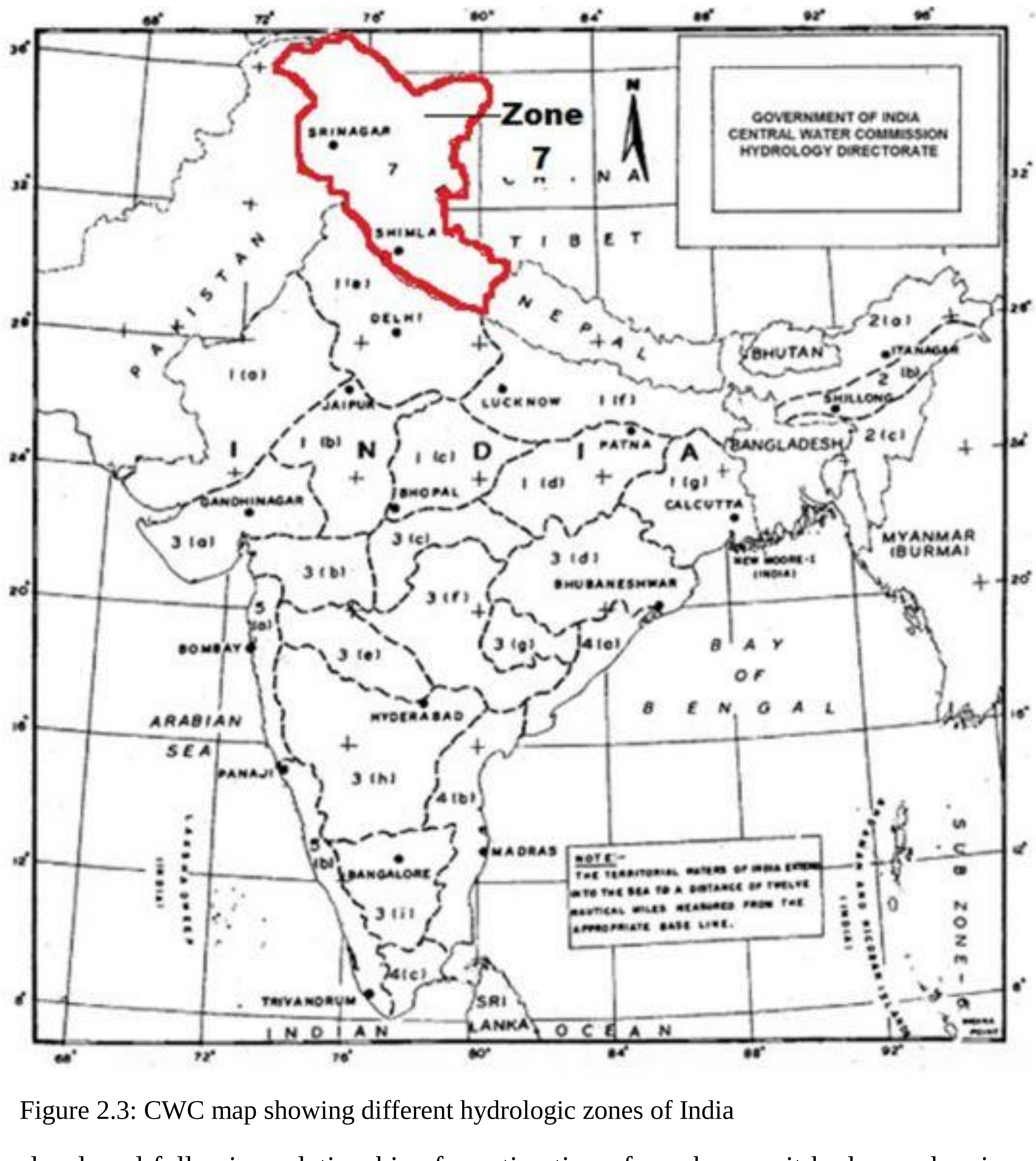

Figure 2.3: CWC map showing different hydrologic zones of India

CWC has developed following relationships for estimation of one hour unit hydrograph using the principle of least square error in regression analysis that are recommended to be used for estimation of parameters of 1-hour synthetic hydrograph :

$$t_p = 2.498 * (L * L_c / S)^{0.156} \qquad (6)$$

$$q_p = 1.048 * (t_p)^{-0.178} \quad (7)$$

$$W_{50} = 1.954 * (L * L_c / S)^{0.099} \quad (8)$$

$$W_{50} = 0.972 * (L * L_c / S)^{0.124} \quad (9)$$

$$WR_{50} = 0.189 * (W_{50})^{1.769} \quad (10)$$

$$WR_{75} = 0.419 * (W_{75})^{1.246} \quad (11)$$

$$T_B = 7.845 * (t_p)^{0.453} \quad (12)$$

$$Q_p = Q_p * A \quad (13)$$

However, the recommended synthetic unit hydrograph is only useful for catchment area greater than 25 km² (CWC, 1994). Therefore, it cannot be used for derivation of unit hydrograph for cloudburst events as it is a localized and restricted to area less than 25 km^2.

Snyder (1938) developed a set of empirical equations for synthetic unit hydrograph based on the study for a large number of catchments in USA. These equations are as follow:

$$t_p = C_t (LL_{ca})^{0.33} \quad (14)$$

$$t_r = \frac{t_p}{5.5} \quad (15)$$

$$Q_{ps} = \frac{2.78 C_p A}{t_p} \quad (16)$$

$$t_p' = t_p + \frac{t_R - t_r}{4} \quad (17)$$

$$Q_p = \frac{2.78 C_p A}{t_p} \quad (18)$$

$$T_b = 5\left(t_p' + \frac{t_R}{2}\right) \quad (19)$$

$$W_{50} = \frac{5.87}{q^{1.08}} \quad (20)$$

where

$$q = \frac{Q_p}{A} \quad (21)$$

$$W_{75} = \frac{W_{50}}{1.75} \quad (22)$$

where

t_p = basin lag (hours);

L = basin length measured along the water course from basin divide to gauging station (km);

L_{ca} = distance along the main water course from the gauging station to a point opposite to watershed centroid (km);

C_t = a regional constant representing watershed slopes and storage effects;

t_r = standard duration of effective rainfall;

Q_{ps} = peak discharge for unit hydrograph of standard duration (m^3/s);

C_p = a regional coefficient;

t_R = actual duration of effective rainfall (hours);

Q_p = peak discharge for actual unit hydrograph (m^3/s);

t_p = basin lag in hours for effective rainfall of t_R hours;

T_b = base time (hours);

W_{50} = width of unit hydrograph at 50% peak discharge;

W_{75} = width of unit hydrograph at 75% peak discharge.

Value of C_t in Snyder's study ranged from 1.35 to 1.65 but many other studies have shown that its value depends on the region under study. Wide variation in the value of C_t (0.3-6.0) has been reported (Skolov et al, 1976). Value of C_p is considered to be a representation of retention and storage capacity of catchment and ranges from 0.56 to .69 for Snyder's study. But depending on the region under study these coefficient may have values outside these ranges also. Linsley et al, (1958) have suggested modified formula for basin lag as:-

$$t_p = C_{tl}\left(\frac{LL_{ca}}{\sqrt{S}}\right)^n \tag{23}$$

where,

S= basin slope;

C_{tl} = basin constant;

n = regional constant (0.38 for study of catchments in USA).

US Soil Conservation services (SCS) has suggested equation to estimate the value of peak discharge Q_p and time of peak T_p which is very popular method used in watershed development activities especially in small catchments. The equations that are developed based on the study of large no of catchments are as follow:-

$$t_p = 0.6t_c \tag{24}$$

$$T_p = \left(0.6t_c + \frac{t_r}{2}\right) \quad (25)$$

$$Q_p = 2.98\frac{A}{t_p} \quad (26)$$

$$T_b = 2.67T_p \quad (27)$$

where

t_c= time of concentration (hours);

t_r= duration of effective rainfall (hours);

t_p= lag time (hours);

T_p= time of peak (hours);

Q_p= peak discharge (m^3/s);

A= area of catchment (km^2).

SCS dimensionless unit hydrograph facilitates the construction of unit hydrograph. In this ordinate is Q/Q_p that is the discharge Q expressed as the ratio to peak discharge Q_p and the abscissa is t/t_p which is the time t expressed as the ratio of time to peak t_p (Table 2.1). This unit hydrograph has same percentage of volume on rising side as the SCS triangular unit hydrograph.

Table 2.1: Coordinates of SCS Dimensionless unit Hydrograph

t/T_p	q/Q_p	t/T_p	q/Q_p
0	0	1.4	0.75
0.1	0.02	1.5	0.66
0.2	0.08	1.6	0.56
0.3	0.16	1.8	0.42
0.4	0.28	2	0.32
0.5	0.43	2.2	0.24
0.6	0.6	2.4	0.18
0.7	0.77	2.6	0.13
0.8	0.89	2.8	0.1
0.9	0.97	3	0.07
1	1	3.5	0.04
1.1	0.98	4	0.02
1.2	0.92	4.5	0.01
1.3	0.84	5	0

Since most of the Himalayan catchments facing cloudbursts are very remote and of smaller areal extent, they are generally ungauged. There is no single recommended method for flood estimation of such events. Therefore, in this study, applicability of these methods is examined for the assessment of flood hydrograph and its characteristics by using empirical, Rational, Snyder's Synthetic Unit Hydrograph and SCS method.

Various coefficients that represent the catchment characteristics in these methods are based on normal conditions before the occurrence of a storm. However, in case of cloudburst, generally the soil is fully saturated and depressions are already full. This causes a significant rise in the peak of outflow hydrograph and decreases the time of peak. Also, a major part of precipitation appears as surface runoff because the initial abstractions are very less. So the coefficients for runoff are higher as compare to those in normal cases. Further, considering steep slopes, small size of catchment, lack of vegetation, very small initial abstraction and saturation of soil make it imperative to select different coefficients.

2.3 Case Study for Cloudburst Induced Flash Flood

Cloud burst is one of the reasons of flash flood in hilly regions. Such events have caused heavy loss of life and property due to its devastating nature in terms of landslides and boulder movement along with shooting velocity of water which results in heavy change of momentum and hence the force. Often, these flash floods are associated with very small areal extent, less duration of storm and remoteness of location. It is difficult to predict the location and impact of cloud burst particularly when most of these hilly areas are ungauged. Therefore, such events sometime go unnoticed and even the events which are reported, have scanty data due to the poor ground monitoring mechanism. In India, there are 3 major states (Jammu and Kashmir, Himachal Pradesh, and Uttarakhand) in North and 7 states (Meghalaya, Assam, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh) in north-east which are termed as 'Himalayan states'. As a case study, cloud burst event which occurred in Leh (J & K State in north Himalaya) during night of 5th August 2010. During the last few years, these states have experienced a number of cloud burst events which may be attributed to the increased anthropogenic activities and the climate change phenomena. Keeping this in mind, the present study aims at estimating the outflow flood hydrograph at the outlet of an ungauged Himalayan catchment using Synthetic Unit Hydrograph. Some of the historical cloudburst events in Northern Himalaya are studied and accordingly the runoff and basin lag corrections are suggested. The results are compared with the previous study reported in literature. Such study is expected to help in disaster preparedness. Further, it highlights the need for comprehensive data base of such events over the entire Himalayan range for effective disaster management in the region.

In India, there are 3 major states (Jammu and Kashmir, Himachal Pradesh, and Uttarakhand) in North and 7 states (Meghalaya, Assam, Tripura, Mizoram, Manipur, Nagaland and Arunachal Pradesh) in north-east which are termed as '*Himalayan states*'. During the last few years, these states have experienced a number of cloudburst events.

3.3.1 Study Area

India has been classified in seven hydro-meteorological homogenous zones with different sub-zones. The Western Himalayan belt falls under zone 7 (Fig. 2.4). which covers the states of Uttarakhand, Himachal Pradesh and Jammu & Kashmir. There is very less of no vegetation in such areas to offer resistance to flow. Also the land surface in these catchments generally has less infiltration index. So the flood hydrographs for these catchments are generally high peaked and narrow with very less time of peak. In this study, Leh cloudburst (2010) has been discussed and obtained results for the same have been compared with results of Renoj et al.(2012). Leh is a small town in Ladhakh region of the state of Jammu and Kashmir. Ladhakh covers 52.6% area of state of Jammu and Kashmir (Renoj et al. 2012) and shares India's northern boundary with Pakistan and China. The area has a long history of glaciations, and every subsequent glaciations in the region was smaller than the previous one (Owen et al. 2006).

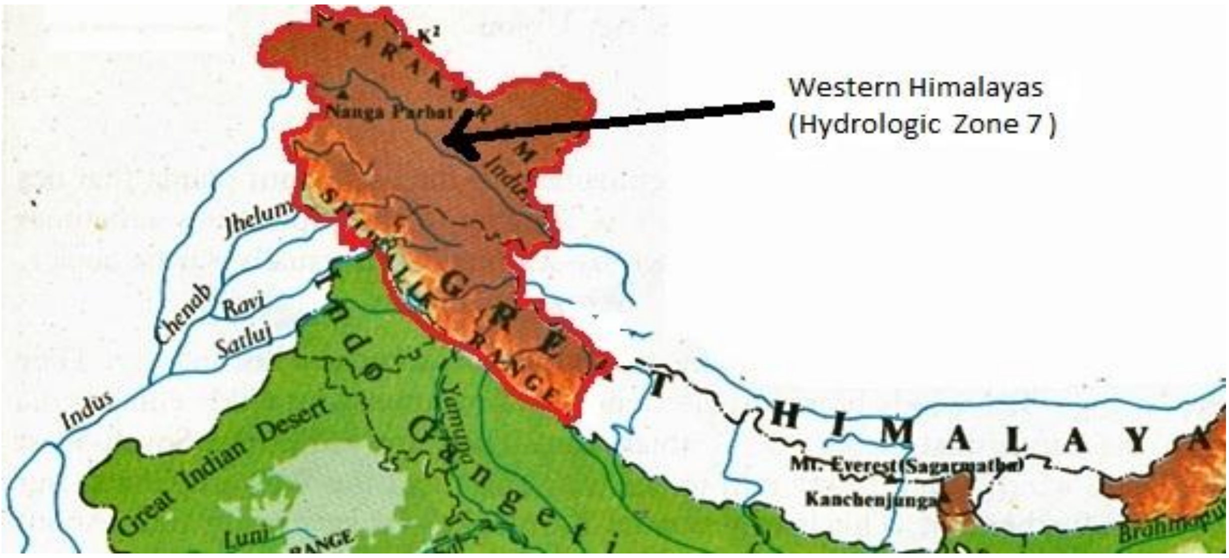

Figure 2.4: Western Himalayan States (Zone – 7).

Due to adverse climatic conditions in the region, the settlements are sparsely situated. District Leh is situated roughly between 32 to 36 degree north latitude and 75 to 80 degree East longitude and altitude ranging from 2300 m to 5000 m above sea level. District Leh with an area of 45,100 km^2 makes it second largest district in the country after Kutch (Gujrat) with an area 45,652 km^2 in terms of area. The district is bounded by Pakistan occupied Kashmir in the west and china in the north and eastern part and Lahul-Spiti of Himachal Pradesh in the south east. Ladhakh lies on the rain shadow side of the Himalayan, where dry monsoon winds reaches Leh after being robbed of its moisture in plains and the Himalayas mountain the district combines the condition of both arctic and desert climate. Therefore Ladhakh is often called "COLD DESERT". There is a wide diurnal and seasonal fluctuation in temperature with –40°C in winter and +35°C in summer. Precipitation in this region is very low with annual precipitation of 10cm mainly in form of snow. Air is very dry and relative humidity range from 6-24% (LADHC, Leh).

Topography of western Himalayas (Zone-7) is dominated by high peaks, K-2 (8611m) being the highest peak in the region. In addition to this there are so many snow clad peaks within 8000 m. Extreme northern and north eastern areas of this zone have elevations ranging between 6000m and 7500m. The elevation decreases southwards and ranges between 4500m and 6000m in the central portion of zone. Elevation ranges between 600m and 4500m in areas near river banks and further decreases to 300m in plain area s of U.P. and H.P.

Skeletal soils along with alkali and saline soils are found in northern part of the zone. Mountain meadow soils are found near the Indus River. Brown hill soil is found in southern areas while central northwest to northeast area have sub mountain soils.

Most of the area in north, south east and north east of the zone is waste. Scrubs are found in small pockets towards south and south west of the zone. Forests are located in some area of north east and south east and remaining part of the zone is dominated by agricultural activities.

This zone is fed by both rain and snow. A good percentage of flow is contributed by snow and glaciers. Glaciers form a potential reservoir that accumulates the snow in winters and melts to form surface runoff in summers. Glaciers are located at an elevation of 5500m while the Permanente snow line is at an elevation of 4500m. However seasonal snowline dips up to 1800m during winters (CWC, 1994). The depth of snow precipitation increases from south to north and east to west.

2.3.2 Methodology

As a case study, cloud burst event which occurred in Leh (J & K State in north Himalaya) during night of 5th August 2010. Gridded rainfall data of India Meteorological Department (IMD) suggested the storm intensity of 120 mm/day on 5th August, 2010, whereas Kumar et al. (2012) suggest occurrence of 70 mm precipitation in 3 hours on 5th August. Area of catchment is about 0.842 km^2 and length of main channel till the outlet of the catchment area is about 1.25

km. This event is analyzed by Renoj et al (2012). This event is analyzed by various methods and the flood hydrograph characteristics thus obtained are compared with the flood hydrograph characteristics suggested by Renoj et.al (2012) for the same cloudburst event.

Value of Dicken's coefficient for northern India is taken as 11.5. Considering this value, the peak flood for Leh catchment for unit rainfall is estimated to be 10.11m^3/s.

Attempt has been made to use the different values of runoff coefficient, slope and time of peak and the flood is estimated using Rational method. Further, in India, it is a recommended common practice to increase the peak flood by 25% for cloudburst event. The results are shown in Table 2.2.

Characteristics of unit hydrograph using Snyder's SUH approach have been derived for different sets of C_t and $C_p$with $C_t$ranging from 0.15 to 0.30 and C_p ranging from 0.75 to 0.95 as shown in Table 3.3. SCS triangular Unit hydrograph method is used to estimate peak flood and peak time for the catchments and then the hydrograph (Fig. 2.3) is constructed by SCS dimensionless unit hydrograph method using the peak food and base time. Same equation has been used for time of peak (t_p) as given by Snyder's method. Peak flow is estimated to be 7.429m^3/sand time of peak as 0.236 hours. Base time for the hydrograph is estimated to be 1.28 hours.

Table 2.2: Peak flood and time of peak for various values of runoff coefficient and slope estimated using rational method.

Slope	Runoff Coefficient	t_p	Q_p
		Hr	m^3/s
0.1	0.85	0.25	4.98
0.1	0.9	0.25	5.26
0.1	0.95	0.25	5.55
0.07	0.85	0.3	4.96
0.07	0.9	0.3	5.26
0.07	0.95	0.3	5.55
0.05	0.85	0.33	4.98
0.05	0.9	0.33	5.26
0.05	0.95	0.33	5.55

The results obtained from above three methods are checked for the compliance with requirements of unit hydrograph and then compared with the results reported by Renoj et al.(2012) estimated using atmospheric and hydrological modeling approach.

Table 2.3: Unit hydrograph characteristics for various value of C_t and C_p

C_t	C_p	Qp	t_p	T_b
		m^3/s	Hours	hours
0.3	0.75	5.49	0.32	2.09
0.3	0.8	5.86	0.32	2.09
0.3	0.85	6.23	0.32	2.09
0.3	0.9	6.59	0.32	2.09
0.3	0.95	6.96	0.32	2.09
0.25	0.75	6.4	0.28	1.87
0.25	0.8	6.82	0.28	1.87
0.25	0.85	7.23	0.28	1.87
0.25	0.9	7.67	0.28	1.87
0.25	0.95	8.1	0.28	1.87
0.2	0.75	7.65	0.23	1.64
0.2	0.8	8.16	0.23	1.64
0.2	0.85	8.67	0.23	1.64
0.2	0.9	9.18	0.23	1.64
0.2	0.95	9.68	0.23	1.64
0.15	0.75	9.51	0.19	1.42
0.15	0.8	10.14	0.19	1.42
0.15	0.85	10.78	0.19	1.42
0.15	0.9	11.41	0.19	1.42
0.15	0.95	12.04	0.19	1.42

2.3.3 Results

Unit Hydrographs characteristics for different values of coefficients have been checked for compliance with basic requirements of unit hydrograph theory (Fig. 2.5). Unit hydrograph obtained using SCS method and Snyder's method (C_t=0.25, C_p=.85) have almost equal peak and also have same volume of runoff. Rational formula gives small peak as compare to other methods as well as estimated by Renoj et al. (2012).

Therefore, it is recommended that flood hydrograph obtained by Snyder's method with C_t = 0.25; and C_p= 0.85 (Fig. 2.6). However, one can also use the SCS method (Fig. 2.7) as it is less data intensive with reasonable level of accuracy.

The results of Snyder's (C_t =0.25, C_p=.85) and SCS methods are compared with Renoj et al (Table 2.4) and found to hold good considering the uncertainties involved in estimation (Flaxman 1974,Jarret 1986).

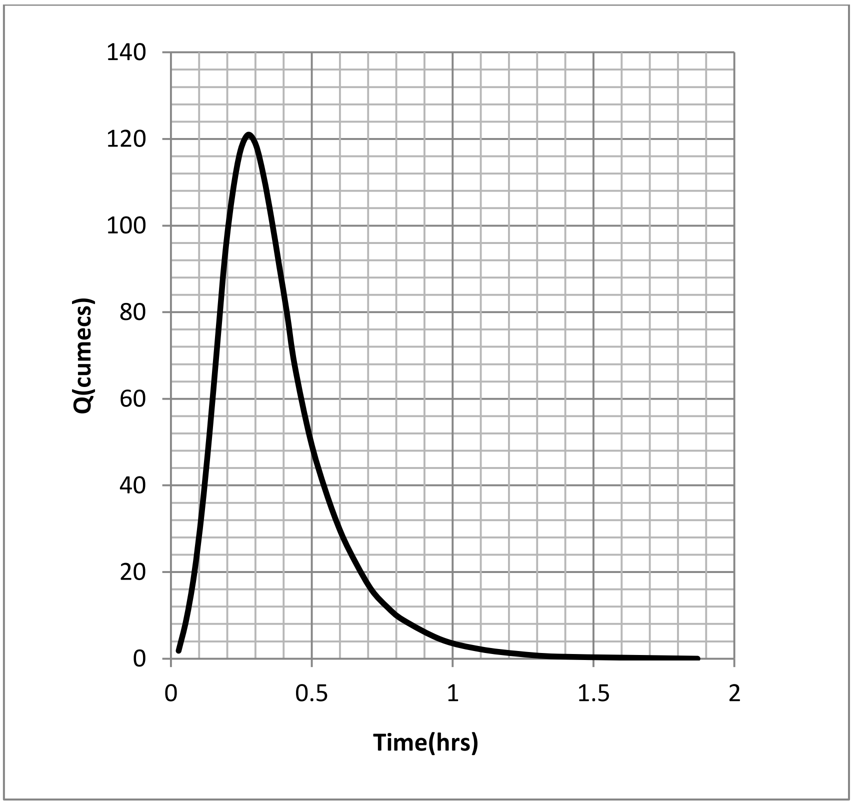

Figure 2.5: Unit hydrographs by different methods

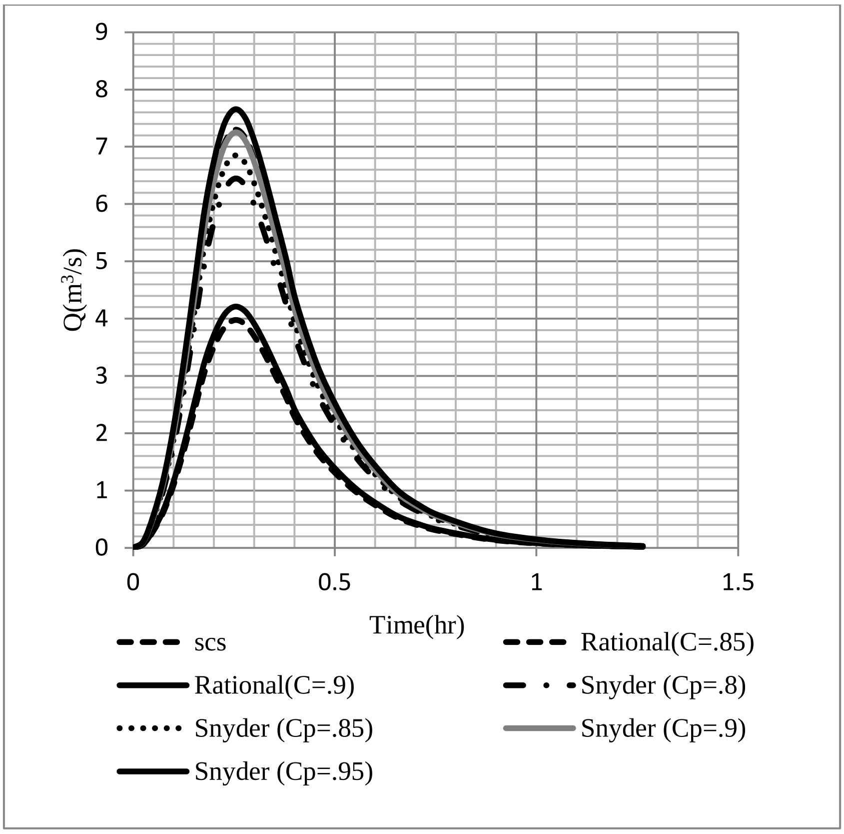

Figure 2.6: Flood Hydrograph using Snyder's method

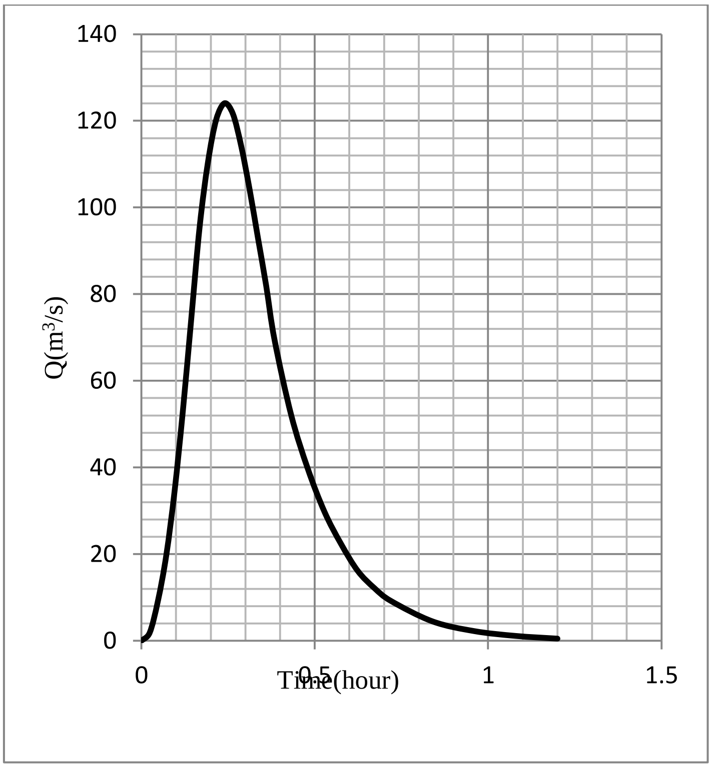

Figure 2.7: Flood Hydrograph using SCS method

Table 2.4: Comparison of flood hydrograph characteristics for Leh catchment estimated using different methods.

Method	Dicken's	Snyder	SCS	SCS*
t_p(hours)	-	0.258	0.236	-
t_b(hours)	-	1.87	1.28	0.92
Q_p(m^3/s)	168.8	120.9	124.06	107

SCS*: Rennoj, et al., (2012)

Based on the identified parameters of the Snyder's and SCS approach, unit hydrograph characteristics for different size catchments have been assessed for 15 and 30 minutes storm durations as shown in Table 2.5.

Table 2.5: SUH characteristics by Snyder and SCS methods.

Method	Duration	Snyder		SCS	
Area	t_R	t_p'	Q_p	t_p	Q_p
km²	hours	hours	m^3/s	hours	m^3/s
1	0.5	0.34	6.82	0.23	8.96
1	0.25	0.28	8.32	0.23	8.96
5	0.5	0.49	23.67	0.39	26.52
5	0.25	0.43	27.05	0.39	26.52
10	0.5	0.65	36.25	0.55	37.69
10	0.25	0.58	40.1	0.55	37.69

2.4 Conclusion

It is concluded that cloud burst contributes significantly in flood disasters particularly in hilly areas. Rational formula gives the underestimated values of peak flood whereas Dicken's method overestimates the same and both these methods provide peak flood value only. On the other hand flood estimation using techniques of unit-hydrograph for an ungauged catchment can help in estimating the temporal variation of cloud burst induced flood in hilly isolated areas. Further, results show that both SCS Triangular Unit Hydrograph method and Snyder's SUH method (for C_t= 0.25 and C_p=0.85) can be used for peak flood estimation for cloudburst event in ungauged Himalayan catchments. However since Snyder's method takes into account more number of parameters and hence give more reliable results. So Snyder's method is suggested for estimation of flood hydrograph characteristics using corrected values of coefficients (C_t= 0.25 and C_p=0.85). SCS method may be used for rough estimations as it is easy and needs no adjustments. Further, there is need for comprehensive data base of such events over the entire Himalayan range for research work and hence effective disaster management in the region.

CHAPTER 3
FLOOD RISK ANALYSIS AND MAPPING

3.1 Introduction

Flood risk analysis is a very complicated process as it includes a very large number of factors and uncertainties associated with them. It requires knowledge of different elements to be considered for analysis and various risk analysis methodologies. Sediment transport is also an important factor to be considered in flood risk analysis. So it requires the knowledge of assumptions, empirical and theoretical background and working of modeling software to be used for flood inundation mapping and sediment transport analysis. So the study has been carried out to study the various factors and methodologies to be considered for flood risk analysis. Also, literature studies for the software i.e. Arc GIS and HEC RAS have been carried out with special context to sediment transport analysis. As the results of sediment transport analysis significantly vary with selection of transport function, sorting method and fall velocity method, all the functions available in HEC RAS have been studied to select the best suited combination of these. Cloudburst induced flash floods also contribute to the flood in Himalayan regions. So various methods reported in literature for estimation of flood hydrograph characteristics have been studied and correction and modifications have been suggested for their use in case of cloudburst. Also Choosing by Advantage (CBA) technique has been studied for its application in identification of hotspots.

3.2 Flood Risk Analysis

Frequent flooding events with severe damages in upper Himalayan region in recent past have shown the importance of flood risk analysis and management. One of the cornerstones of flood risk analysis is the information of people and property at risk. An adequate response to the threat can only be expected if the stakeholders i.e. people and decision makers are aware of the flood risk and are able to evaluate it. Risk analysis considering various aspects of the flood risk, e.g. economic, social, hydraulic, hydrological, and ecological aspects forms the basis of effective and efficient risk reduction measures. The spatial description of the flood risk plays an important role in communicating the results to decision makers and people at risk. The flood risk analysis may be done at different scales, ranging from the local to the global scale.

Most of the flood risk mapping approaches work on the local scale. Such types of maps help in analyzing the flood situation for smaller areas and objects like buildings and infrastructure and hence form the basis for local flood defence policies and measures. Flood risk maps contain information about the intensity and frequency or exceedance probability of flood events. Combination of intensity and exceedance probability quantifies the hazard that is expressed as hazard levels. By means of these hazards levels areas are defined as zones of land-use bans, guidance and restrictions etc. that are used as the basis for land-use planning. Generally the information about flood losses is limited to economic damages in most of flood mapping approaches. Other loss types, e.g. social, ecological losses are rarely mapped. Overview (Marco, 1994,Watt, 2000), (Environment Agency, 2004), (TAW, 2004), (Menendez, 2000), (BUWAL, 1998), (BWW-BRP-BUWAL, 1997), (Jonkman, 2003)shows that most of the flood mapping approaches are limited up to identifying the inundated areas for few specific flood scenarios, mainly the 100-year flood. In some cases additional information regarding the intensity of hazard, e.g. the depth of water is given but possible consequences of flooding or any other information that helps in mitigation of flood damages has rarely been reported.

3.2.1 Flood Risk – Definitions and Indicators

Risk is defined as the probability of suffering loss, and risk analysis is evaluation of the probability of the adverse effects of a process (natural, technology, industrial etc.) or an agent (chemical, physical, etc.). In the context of natural disasters, risk can be described as the probability that natural events of a given magnitude will occur and cause certain amount of loss. Therefore, risk comprises of two major aspects i.e. hazard and vulnerability (Kaplan & Garrick, 1981, Mileti, 1999).

Flood hazard is defined as the exceedance probability of an inundation situation in a particular area within a specified period of time that can cause a potential damage. Flood hazard statements do not provide any information about the social, ecological or economic effects of such flood events. But as these effects depend, among others, on the intensity of the flood, the intensity of the flood beyond flood frequency curve should be quantified in flood hazard statements. Inundation depth is the most important indicator of the intensity of a flood. Inundation depth has been reported as the most important flood characteristic to have influence on flood damage (Penning-Rowsell et al., 1994, Wind et al., 1999). Flow velocity is another important indicator of flood intensity. Especially high velocity floods in mountainous areas (e.g. Kedarnath floods of 2013) can lead to severe damages to buildings, infrastructure etc. Damage to humans, cattle and wild animals also increases with velocity: Flow velocities above 0.5 m/s may lead to sweeping away of people(Marco, 1994). However, a product of flow velocity ‘v’ and inundation depth ‘h’ can give better indication of human instability during flood. Experiments made by (Abt et al., 1989) found that the critical product ranges from 0.7 to 2.0 m^2/s depending on the weight of body and type of surfaces in contact. Because of the cumbersome calculations of the spatial distribution of velocities flood hazard maps do not generally contain information about flow velocity. Duration of flood, rate of rise of inundation depth, concentration and size of sediment and other transported materials are other important indicators of flood intensity. Different type of systems can bear inundation for different time period without much damage. The rate of rise of inundation depth directly affects the time available for flood defense measures such as flood warning and evacuation.

3.2.2 Flood Vulnerability

Along with the hazard, flood risk analysis also involves the characteristics of the elements at risk which includes all elements of the social, anthropogenic the natural environment in a given area that are at risk of flooding. These elements face adversities like deaths, injuries, stress (psychological and physical), loss of infrastructure, inventory and working hours, interruption of traffic, pollution, erosion of soils etc. Flood damage depends not only on the characteristics of the flood but also on the vulnerability of the flooded area. Different areas based on the vulnerability may experience different flood damage for the flood of same intensity and exceedance probability.

Different concepts of vulnerability have been reported in literature but there is no agreed understanding of this term (Blaikie, 1994; Comfort, 1999; Mileti, 1999; Smith, 2001). Vulnerability can simply be explained to be comprising of two elements i.e. exposure and susceptibility. Exposure analysis covers the elements that will be affected and can be quantified in terms of the value or number of elements at risk. Susceptibility analysis covers the extent and type of damage that will be experienced by the elements that are at risk. Susceptibility is usually described by relative damage functions that give the degree of damage experienced by the flooded elements. Most of the damage models estimate the direct monetary damage based on the use of element and depth of inundation (Wind et al., 1999; NRC, 2000). Such depth-damage functions forms the essential components for the assessment of flood damage are widely accepted as the standard approach for the assessment of urban flood damage (Smith, 1994).The analysis becomes further more complex when intangible flood damage (deaths, psychological stress, ecological losses etc.) are analyzed. Therefore, a number of flood damage assessments are limited to direct economic losses only. Flood risk considering both direct economic and intangible losses may be evaluated as more severe than the one considering direct economic losses only.

3.2.3 Flood Risk

Flood risk is defined as the probability that floods of a given intensity will occur in a certain area within a specified time period and cause a given damage. Risk can be expressed as the interaction of hazard and vulnerability. Flood risk can be expressed in terms of the following relationship:-

Flood Risk = Probability of Flooding x Consequences of Flooding

Flood risk assessments require identification and assessment of following three components:

1. The probability and magnitude of the source(s).
2. The performance and response of pathways and barriers to pathways.
3. The consequences to receptors.

However, technical risk analyses is often criticized by social scientists for it do not considers the multidimensionality and variety of views on risk (e.g. Pidgeon et al., 1992, Blackie et al., 1994, Slovic, 1998).

3.2.4 Flood Mapping

A flood hazard map shows the intensity of flood and exceedance probability associated with it. Generally, flood hazard maps represent synthetic events with a certain return period in which flood intensity is illustrated by the spatial distribution of the inundation depth. Additional information such as the distribution of flow velocity is also giver some times in flood hazard maps. Maps without the information of vulnerability are known as flood danger maps. Flood danger maps needs to be combined with vulnerability information to illustrate the effects floods on elements at risk. Flood damage risk maps illustrate the spatial distribution of flood risk. Generally flood damage risk maps are based on synthetic events of different return periods or exceedance probability. The damage risk can be qualitatively expressed in different classes ranging from very low to very high. The damage risk varies even within a certain land-use zone because the hazard may vary within the land-use zones.

3.2.5 Developing and Updating Flood Maps

Different methods are available for quantifying flood hazard, vulnerability and risk according to which the effort for generating flood maps may vary significantly. Estimation of flood hazard requires the calculation of inundation scenario and exceedance probability associated with it. Most commonly used and simplest method is the flood frequency analysis combined with simple hydraulic modeling. Observed discharge time series data is used to derive a flood frequency curve that is extrapolated to different return periods. Simulation for floods different return periods are then done to calculate the water surface elevations at different cross sections. Inundation areas are obtained by overlaying the water levels with the DEM of the area. The horizontal water surface is assumed to be perpendicular to the direction of flow. This approach being based on several assumptions may lead to unsatisfactory results. Better results may be obtained by using rainfall-runoff models for modeling the processes in the catchment and 1- or 2-dimensional hydrodynamic models for modeling he processes in the rivers and floodplains (Todini, 1999, Werner, 2001). But this approach is very complex, data-demanding and costly. Information required for the development of flood damage risk map is more than that for flood danger map. The danger maps only show the inundated area for an observed flood event while a flood damage risk map shows the information about the exposure and susceptibility linked to the estimation of hydrological and hydraulic calculations for flood hazard. Flood damage risk mapping is a complex and costly process as the data which are required for the quantification of vulnerability are often not available and that too with the needed reliability.

Flood maps needs to be updated to take account of the developments that can significantly affect the flooding. The time interval for updating these developments depends on the rate of change of the developments such as change in the retention capacity of the basin, land use change and climate change. Unless there is some significant development in form of large civil engineering works or some natural disaster, the rate of change in flood hazard is generally expected to be small. The vulnerability of an area can change at higher rates due to various factors such as increased flood risk awareness or oppositely the accumulation of high value assets in flood-prone areas. Therefore risk maps being based on both, hazard and vulnerability need to be updated very frequently. Frequent updating of flood hazard risk maps is necessary for the areas with high damage potential such as densely populated and industrial areas.

3.2.6 Reliability of Flood Maps and Risk Analysis

Flood maps mainly represent imaginary situation are which are outside everyday life experiences and have not been observed before. Therefore it is usually very difficult to validate such maps. Such maps are expected to be uncertain as they are based on the modeling of complex natural processes.   Potential sources for uncertainties are data quality, data processing algorithms and methodologies, assumptions associated with modeling and extrapolation of results to rare events without enough data for validation of model results. Assumption of stationarity and homogeneity associated with flood frequency analysis is increasingly questionable due to both climate change and land use change in catchment (Klemés, 1993, Jain & Lall, 2002, Milly et al., 2002).Vulnerability of elements at risk is another potential source of uncertainties. Field of flood damage modeling has not been given much attention and is based on theoretically and empirically weak models (Wind, 1999; Merz, 2004). Uncertainty associated with the vulnerability estimation is generally expected to be high as the objectspecific statements with sufficient reliability are difficult to be made and so the risk statements are often aggregated to areas of the land-use plan.

The quality and reliability of maps is largely affected by the quality, resolution and completeness of the data and algorithms or techniques used to process this data to derive the maps. The expected range of errors should be documented and it should be ensured that the methods are so explicit that the user can assess their suitability. As the validation is difficult and sources uncertainties are very large, consistent and scientific methods should be used to prepare flood maps. So the possible errors should be indicated along with flood maps to provide a realistic idea of accuracy to the users.

3.2.7 Use of Flood Maps

Flood mapping is necessary and increasingly important step in flood management. Flood maps can provide crucial information to be used for a number of purposes such as disaster preparedness, raising awareness among people at risk, land use planning, investment planning, assessment of feasibility of flood control measures and base for deriving flood insurance premiums. Flood maps are more effective than any other form of risk communication (diagrams, descriptions or verbal) because they have direct and stronger impression of the spatial distribution of flood risk. But it is important to consider the end user and information to be communicated as the wrong interpretation of maps may lead to misunderstanding (Bartels & Beurden, 1998).

3.2.8 Challenges in Flood Risk Analysis

Ideally, the flood maps should include the information about all type of consequences of floods i.e. social, economic and ecological. Mostly the scope of flood maps is limited only to the hazard aspects and vulnerability aspects are only considered as the land use information. Most of the existing approaches focus on direct economic damages and largely ignore intangible and indirect economic losses. Flood vulnerability needs comprehensive studies. Flood maps are often considered static but actually, the situations represented by the maps are based on certain conditions and assumptions. Small scale seasonal changes in vulnerability cannot be addressed by static flood maps and hence maps including dynamic behavior are needed. Recent shift of paradigm calls for the participation of all the stakeholders in risk based decision making. Also the communication of the knowledge from research community to users and reverse feedback needs to be facilitated.

3.3 Software Overview

Flood inundation maps are obtained by hydraulic modeling of river in HEC-RAS. HEC-RAS model is build using HEC-GeoRAS using a digital terrain model (DTM). Elevation data is extracted from DTM for features such as cross-sections and streamlines. Optional data layers can also be generated and included in the model if required. The GIS data is then extracted by HEC-GeoRAS to a format that is recognized by HEC-RAS. Then parameters such as discharge and boundary conditions can be specified in HEC-RAS. After successful run of the steady-flow analysis, the water-surface elevations data is exported from HEC-RAS and imported into HEC-GeoRAS and attributed to a cross-section spatial layer. This spatial layer is then overlapped with the terrain surface in GIS to develop floodplain boundaries and other representations required as model outputs.

3.3.1 ArcGIS

ArcGIS has grown out of number of technologies including cartography, information management, computer science, photogrammetry and remote sensing .this technology, therefore consist of computer software and hardware designed to recognize the spatial data for analysis, assessment, and cartographic depiction. It provides a mechanism by which information on a feature location, spatial interaction and geographic relation can be viewed in moments and can be analyzed easily. It provides an opportunity to efficiently view and access geographic data to improve the decision making process.

Nowadays, GIS technologies have been applied to diverse fields to assist experts and professionals in analyzing various types of geospatial data and dealing with complex situations. GIS systems are used in cartography, remote sensing, land surveying, public utility management, natural resource management, photogrammetry, geography, urban planning, emergency management, navigation, aerial video, localized search engines, archaeology, environmental impact study, infrastructure assessment and development, for a thematic and/or time based purpose, marketing, logistics, population and demographic studies, prospectively mapping, location attributes applied statistical analysis, warfare assessments, and other purposes.

3.3.2 HEC-GeoRAS

HEC-GeoRAS is an extension to ArcGIS that is used for preprocessing and post processing of HEC-RAS data. It is used to extract the geometry directly from DEM. These elevations can be mapped in ArcGIS to form a flood inundation map. In this exercise, you will run a HEC-RAS model for a particular location on Brushy Creek and use ArcGIS to create the corresponding floodplain map. HEC GeoRAS significantly speeds up HEC-RAS model creation and review, producing better and more accurate results. It works as interface between HEC RAS and Arc GIS both pre and post modeling.

3.3.3 HEC-RAS

HEC-RAS is an integrated software system that can be used interactively in multitasking environment. HEC-RAS system comprises of four one dimensional (1-D) river analysis components that are as follow:-

1. Steady flow water surface computations.
2. Unsteady flow computations.
3. Movable boundary sediment transport computations.
4. Water quality analysis.

In addition to this it contain several features of hydraulic design which can be invoked after the basic water profiles have been computed. It supports steady, unsteady flow water profile computations, sediment transport computations and water quality analysis.

3.4 Methodology for Flood Risk Analysis and Mapping

Flood plain mapping and risk analysis for Mandakini river has been completed in two stages that are as follow:-

1. Hydraulic modeling of river reach and flood plain mapping.
2. Geospatial analysis of the simulation results.

3.4.1 Hydraulic Modeling

Flood inundation maps have been obtained from hydraulic modeling of the river reach (Fig 3.1). Catchment area for the study area has been delineated in Arc GIS. River bed profile and cross section have been extracted from DEM and exported to HEC-RAS for modeling using HEC-GeoRAS. Water surface elevations, velocities, shear and power for different flood events have been simulated using HEC-RAS and using HEC-GeoRAS, these results have been imported back into Arc-GIS for post processing analysis. Simulation result layers have been overlaid on base map (LULC) of area for generating flood inundation maps and flood risk analysis. Based on this flood risk analysis for the study area has been estimated. Potential sites for hotspot identification have also been selected by applying fuzzy rule based on visual inspection of flood plain maps.

SRTM DEM of 30m resolution has been delineated for the study area and then converted to 'tin' format in Arc Map (Fig 3.2). Flow accumulation layer has been generated for the DEM and River centerline, Bank lines, Flow path lines and cross sections for Mandakini River and its main tributaries are then created with reference to flow accumulation layer using HEC GeoRAS (an extension to Arc Map) (Fig 3.3). Preprocessing analysis is then done on the model created using HEC-GeoRAS. River reach lengths, bank points, cross section and elevation data is extracted from TIN file.

Geometry data for the river model i.e. reach length, topology, elevations, stationing, bank stations and cross section data is created from "tin" layer of study area and then a geometry file compatible with HEC RAS is created and exported to be used in HEC RAS for hydraulic modeling.

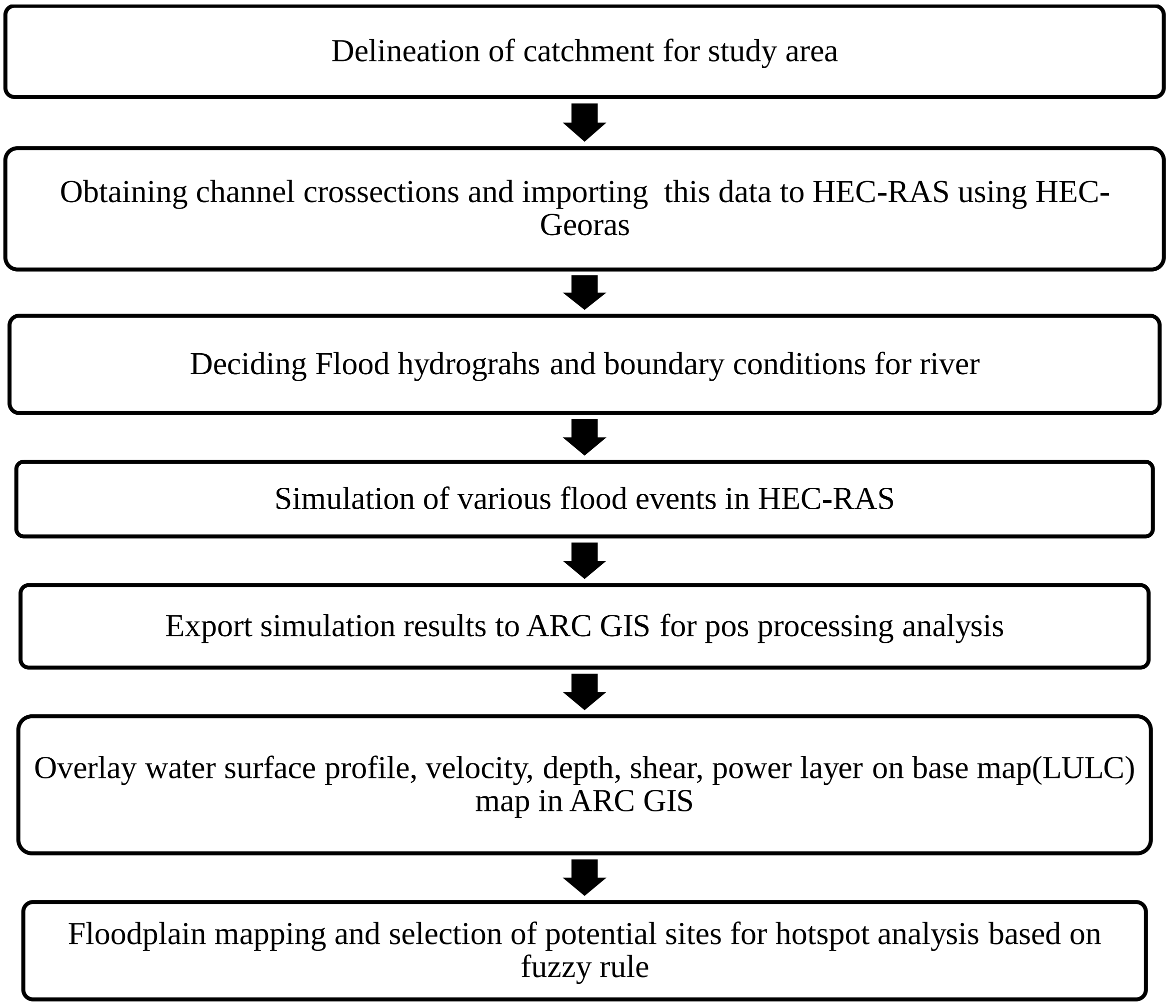

Figure 3.1: Flow chart for hydraulic modeling of river

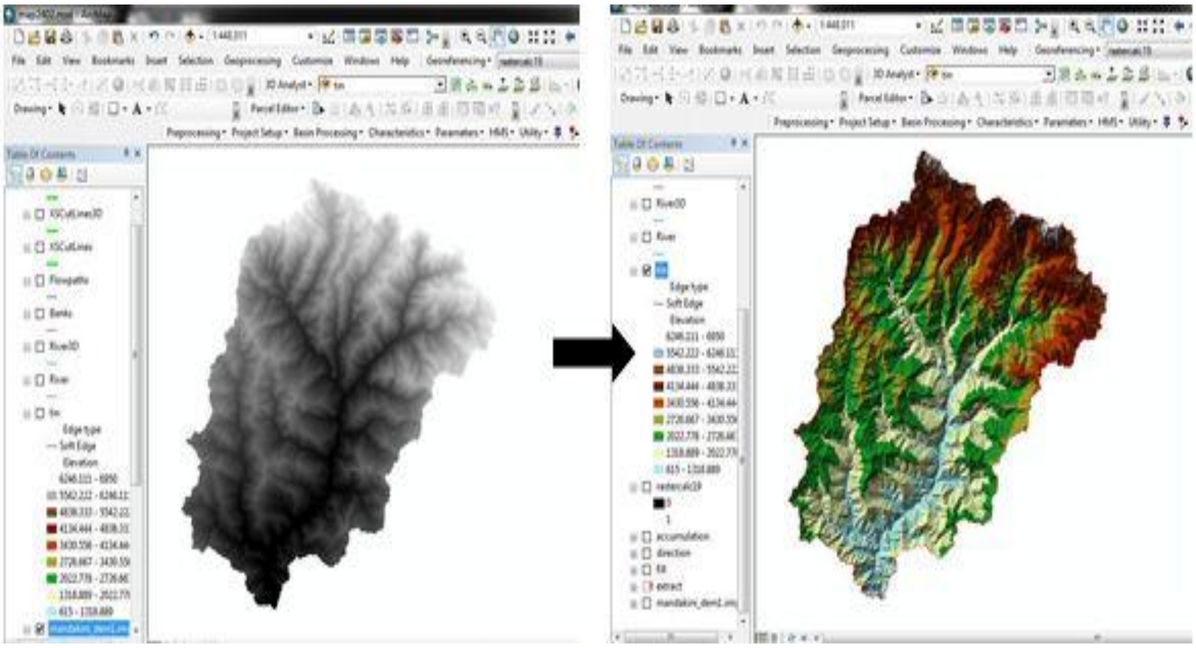

Figure 3.2: DEM and TIN file for the Mandakini basin

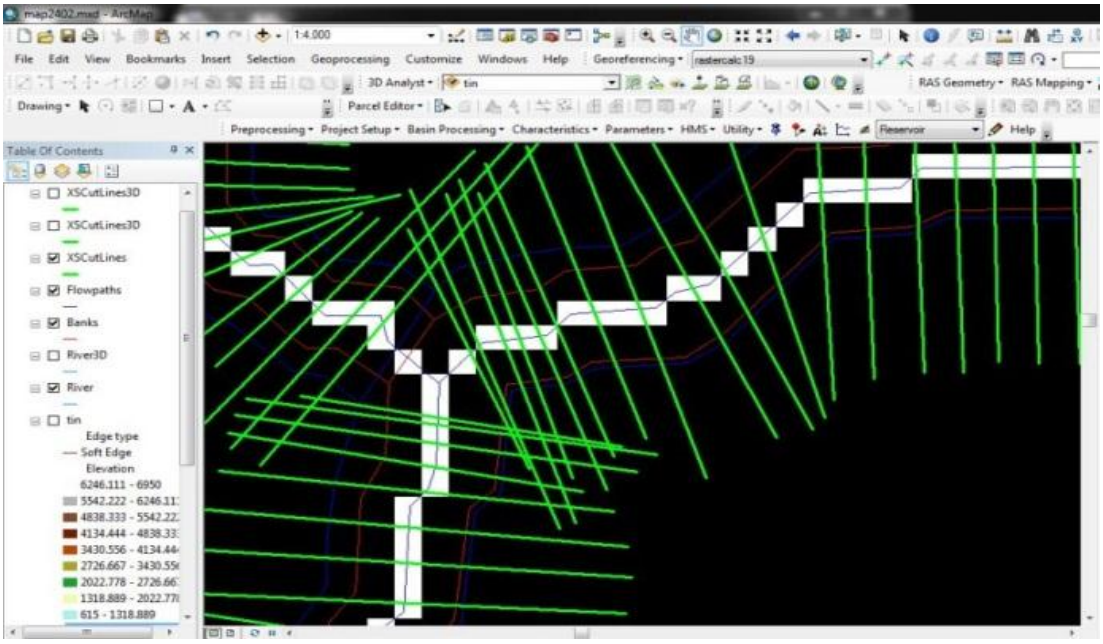

Figure 3.3: Creation of river geometry data using flow accumulation layer

Geometry file created using HEC GeoRAS has been imported into an HEC RAS project and then initial boundary conditions i.e. Bed gradation templates, Sediment rating curves and transport functions have been set for the simulation. Then different quasi static flow series have been entered and simulations (Fig. 3.4) are done for the same and flood plain inundation has been done using RAS mapper (Fig. 3.5). Method of overlaying geospatial data with ArcGIS has been used to analyse the impacts of flooding. Exposure of social, economic and environmental hazards is located within the floodplains corresponding to 1500, 2000, 2500 and 3000 cumecs flood discharge.

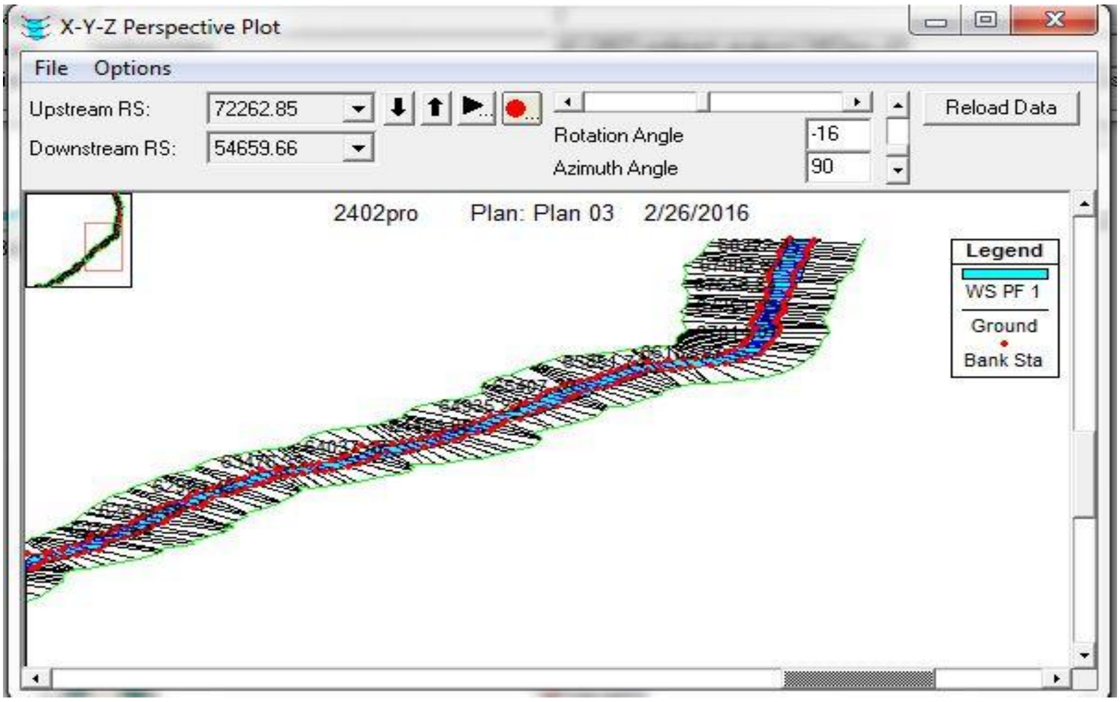

Figure 3.4: Simulation results obtained in HEC RAS

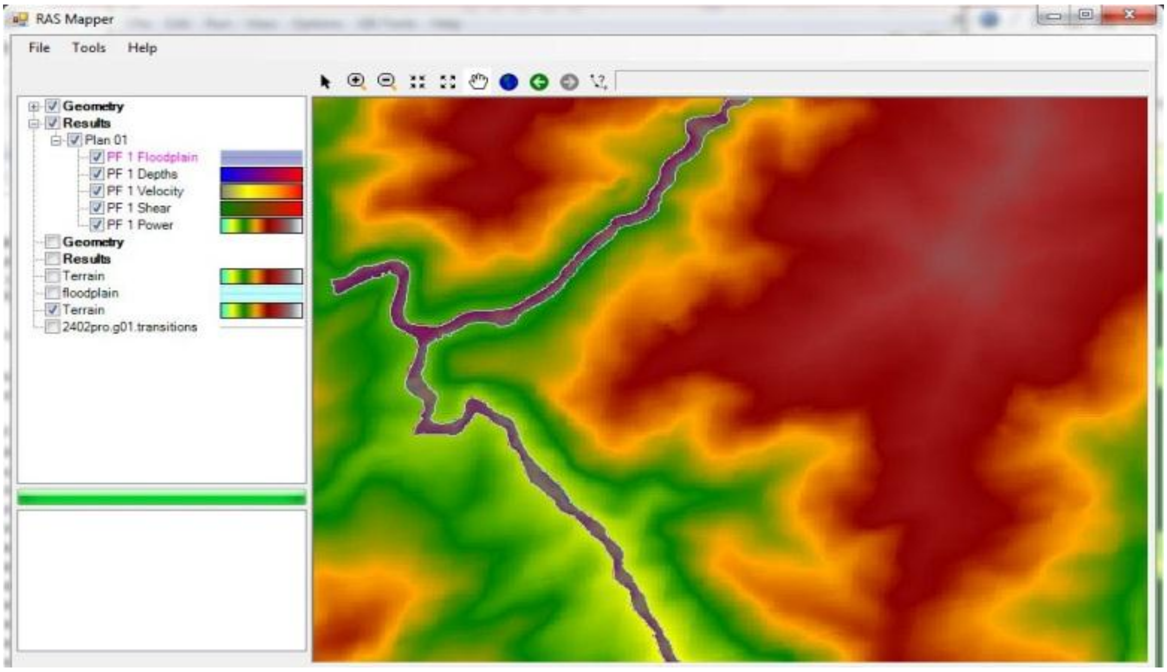

Figure 3.5: Flood plain mapping using RAS Mapper

3.4.2 Geospatial Analysis

The results of simulation are then imported back into Arc Map using HEC GeoRAS. The flood plain inundation has been performed in Arc Map using simulation results. To generate the Land Use Land Cover (LULC) layer (Fig. 3.6) for the area LANDSAT-8 imagery has been buffered to an extent of 3 km and then unsupervised classification has been done using Erdas Imagine.

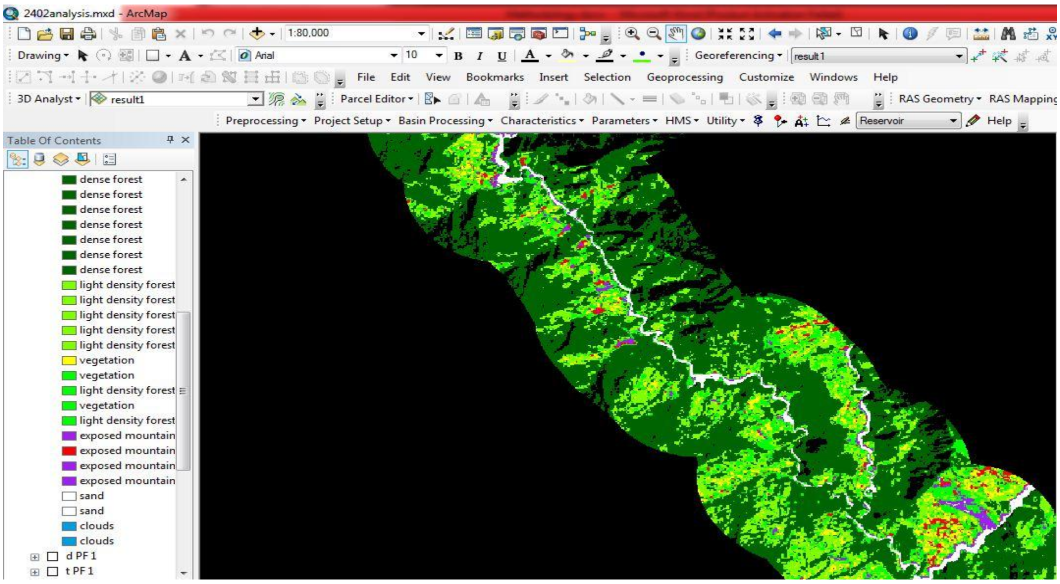

Figure 3.6: LULC file for area buffered to an extent of 3 km from river

The results for inundation extent, depth, velocities, shear and stream power have been overlaid on LULC map (Fig. 3.7) for flood risk analysis. Also the results from RAS mapper are imported into Arc Map and overlaid on base map. Results from RAS mapper are in form of continuous/ stretched terrain files while results generated in HEC GeoRAS are in form of discrete/point data and hence both have been used in combination for better results.

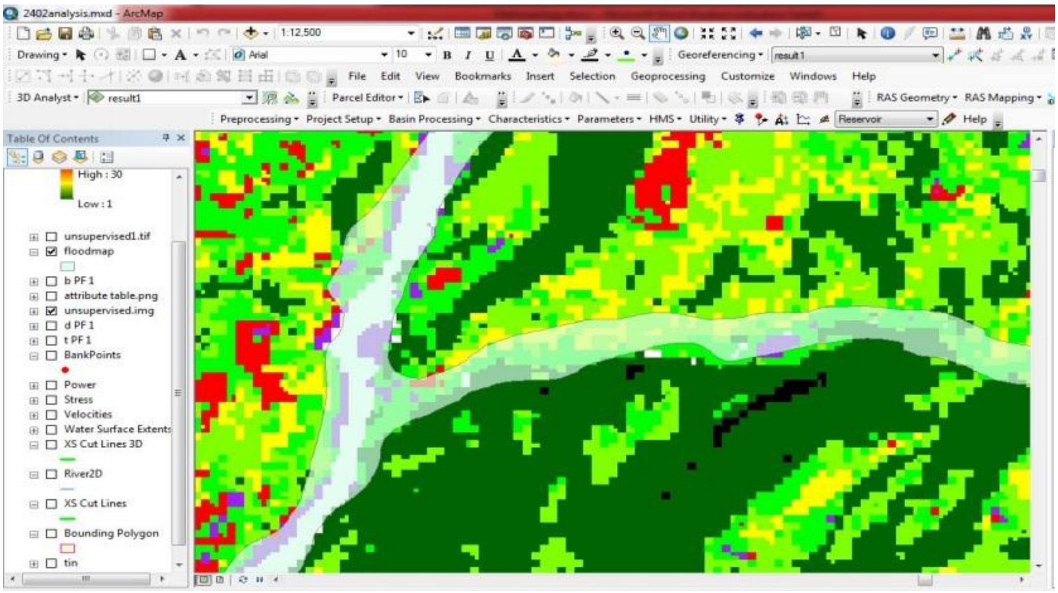

Figure 3.7: Flood map overlayed on LULC map

Area under different categories of land use in flood inundation extent has been calculated as shown in representative example (Table 3.1) and severity of risk for the area has been estimated from combined analysis of depth, stress, and velocity and stream power.

Table 3.1 : Representative example of submerged area for different land use categories

Land Use	Pixel count	Area Submerged(km^2)
Residential/urban	2427	0.546075
Agricultural Land	15792	3.5532
Dense forest	9318	2.09655
Light density forest	6114	1.37565
Barren Land	21614	4.86315

Severity indices based on the depth of inundation and velocity have been decided independent of each other (Table 3.2).

Table 3.2: Severity indices based on depth and velocity of flow

Severity	Inundation Depth (m)	Velocity (m/s)
Very Low	<0.25	>0.5
Low	0.25-0.5	0.5-1.0
Moderate	0.5- 0.75	1.0-1.5
High	0.75-1.0	1.5-2.5
Very High	>1.0	>2.5

3.5 Results

Flow simulation for one dimensional model of the river has been done for different flood scenarios i.e. 1500 cumecs (Table 3.3), 2000cumecs (Table 3.4), 2500 cumecs (Table 3.5), 3000 cumecs (Table 3.6) and cloudburst scenario (Table 3.7) using HEC-RAS and flow parameters such as flow velocity, water surface elevation, energy grade elevation, energy grade slope and top width has been calculated at different cross section.

Table 3.3: Hydraulic modeling results for 1500 cumecs flood.

River	Reach	River Station	Q Total	Min Ch. El	W.S. Elev.	E.G. Elev.	E.G. Slope	Vel. (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Basti Dammar	Main	1204	211	245.7	247.9	248.6	0.022	3.81	38.3
	Main	1048	211	240.9	243.3	244.1	0.022	3.98	33.3
	Main	955.1	211	236.9	239.5	240.3	0.021	4.02	32.1
	Main	764	211	232.7	235.2	235.9	0.021	3.88	35.9
	Main	572	211	228.4	230.4	231.1	0.02	3.82	40.9
	Main	419.2	211	223.3	225.3	225.9	0.021	3.6	46.7
	Main	247.4	211	219.5	221.7	222.4	0.021	3.89	39.2
	Main	37.47	211	215.5	217.1	218.4	0.023	2.48	17

River	Reach	River Station	Q Total	Min Ch. El	W.S. Elev.	E.G. Elev.	E.G. Slope	Vel. (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Dangi Khad	Main	829.4	85.8	293.2	294.4	294.8	0.026	2.88	35.3
	Main	613.6	85.8	282	283.7	284.2	0.025	3.27	24.7
	Main	292.5	85.8	267.3	268.9	269.4	0.025	3.12	27.8
	Main	127.3	85.8	266	268	268.6	0.024	3.44	20.7
	Main	34.1	85.8	256.6	258	258.4	0.026	2.92	34.1
Mandani	Main	749.2	149	319.7	321.7	322.4	0.023	3.63	30.7
	Main	573.5	149	305.9	307.8	308.5	0.023	3.64	30.6
	Main	369.4	149	290.7	293	293.8	0.023	3.84	26.4
	Main	196.7	149	284.7	286.9	287.6	0.022	3.77	27.5
	Main	17.05	149	274.6	276.1	276.6	0.024	3.08	44.5
Madhyamaheshwar	Main	488	360	348	350.4	351.2	0.016	4.28	56.1
	Main	368	360	343.2	346.4	347.6	0.016	4.87	36.8
	Main	227.7	360	340.9	344.8	345.7	0.009	4.28	34.4
	Main	134.2	360	336	339.1	340.1	0.015	4.66	45.3
	Main	22.94	360	331.5	334.7	335.9	0.017	4.78	37.2
Kaliganga	Main	359.3	120	370.8	372.7	373.4	0.022	3.55	27.5
	Main	221.5	120	367.3	369.4	370.1	0.021	3.69	25.4
	Main	154.5	120	359.7	361.6	362.3	0.023	3.53	27.5
	Main	15.05	120	357.2	359.3	360	0.023	3.69	23.5
Sonprayag	Main	520.3	120	554.3	556.1	556.6	0.018	3.18	38.8
	Main	358.7	120	542.7	545	545.7	0.023	3.73	23
	Main	161.4	120	528.8	530.5	531.1	0.021	3.47	28.6
	Main	29.01	120	522.1	524.2	524.9	0.023	3.58	26.9
Mandakini	R1	22005	84	1217	1219	1220	0.025	3.34	22.6
	R1	19228	84	800.9	803.4	804.1	0.024	3.61	17.9
	R2	15858	27	479.3	480.3	480.7	0.028	2.6	15.2
	R2	12502	27	364.9	366.2	366.6	0.029	2.61	15.2
	R2	11939	27	355.2	355.8	356.1	0.025	1.13	18.4
	R3	11894	18	352.3	353	353.2	0.032	2.09	20.5
	R3	11257	18	331.3	332.1	332.3	0.032	2.12	19
	R4	11127	101	328.7	330.4	330.9	0.025	3.15	32
	R4	8269	101	269.2	270.7	271.2	0.025	3.03	38.5
	R5	8146	52.4	271.6	272.9	273.3	0.027	2.78	24.3
	R5	7042	52.4	260	261.2	261.6	0.028	2.67	27.5
	R6	6790	98.4	257.9	259.7	260.3	0.023	3.37	25.5
	R6	5760	98.4	244.6	246.1	246.5	0.025	3.06	33.7
	R6	2558	98.4	212	213.9	214.5	0.024	3.02	23.9
	R7	2479	73.2	218.9	220.2	220.5	0.013	2.21	39.4
	R7	1592	73.2	217.4	219	219.5	0.025	3.18	22.6
	R7	1378	73.2	202.8	204.5	205	0.021	2.97	23.7

River	Reach	River Station	Q Total	Min Ch. El	W.S. Elev.	E.G. Elev.	E.G. Slope	Vel. (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
	R7	970.1	73.2	202.2	204	204.4	0.014	2.59	24.1
	R7	938.5	73.2	201.6	203.2	203.8	0.025	3.25	21
	R7	638.6	73.2	199.3	200.6	201	0.024	2.85	34
	R7	340.4	73.2	193.2	194.9	195.4	0.025	3.17	22.6
	R7	17.68	73.2	191.6	193.4	193.9	0.023	3.19	24

Table 3.4: Hydraulic modeling results for 2000 cumecs flood

River	Reach	River Station	Q Total	Min Ch. El	W.S. Elev	E.G. Elev.	E.G. Slope	Vel. (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Basti Dammar	Main	1204	281	245.7	248.2	249.1	0.02	4.1	41.3
	Main	955.1	281	236.9	239.8	240.8	0.021	4.34	34.2
	Main	744.5	281	230.6	233.4	234.3	0.021	4.18	38.2
	Main	508.3	281	223.8	226.7	227.7	0.02	4.31	36.2
	Main	213.9	281	218.2	219.7	220.4	0.015	2.17	48.6
	Main	37.47	281	215.5	217.7	219.2	0.022	3.04	19.2
Dangi Khad	Main	829.4	114	293.2	294.5	295	0.025	3.1	37.7
	Main	539.6	114	279.5	281.2	281.7	0.024	3.35	30.4
	Main	292.5	114	267.3	269.1	269.7	0.024	3.36	29.7
	Main	34.1	114	256.6	258.2	258.7	0.025	3.15	36.5
Mandani	Main	749.2	199	319.7	322	322.8	0.022	3.93	32.2
	Main	490.3	199	302.6	305.2	306	0.022	3.96	31.6
	Main	251	199	288.8	291.9	292.7	0.021	4.16	27.4
	Main	17.05	199	274.6	276.3	276.9	0.023	3.45	46.2
Madhyam-aheshwar	Main	488	480	348	350.8	351.7	0.015	4.66	59.5
	Main	274.3	480	342.6	345.9	347	0.015	5.1	49.8
	Main	22.94	480	331.5	335.3	336.5	0.015	5.17	40.7
Kaliganga	Main	359.3	160	370.8	373	373.8	0.021	3.84	29.8
	Main	171.5	160	361.4	363.5	364.2	0.02	3.8	31.4
	Main	154.5	160	359.7	361.9	362.7	0.021	3.86	29.6
	Main	15.05	160	357.2	359.6	360.4	0.022	3.95	25.6
Vasukiganga	Main	520.3	160	554.3	556.4	556.9	0.016	3.33	41.7
	Main	246.1	160	536.5	538.9	539.6	0.02	3.91	27.6
	Main	29.01	160	522.1	524.5	525.3	0.021	3.82	29.3

River	Reach	River Station	Q Total	Min Ch. El	W.S. Elev	E.G. Elev.	E.G. Slope	Vel. (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Mandakini	R7	2471	112	218.7	220.2	220.7	0.024	3.13	39.5
	R7	1592	112	217.4	219.3	220	0.023	3.54	25
	R7	1449	112	204.8	206.9	207.6	0.023	3.61	23.7
	R7	938.5	112	201.6	203.6	204.3	0.023	3.56	24.5
	R7	638.6	112	199.3	200.9	201.4	0.021	3.19	37.8
	R7	360	112	194.5	196.5	197.1	0.023	3.52	25.5
	R7	340.4	112	193.2	195.2	195.9	0.023	3.54	24.9
	R7	17.68	112	191.6	193.7	194.4	0.02	3.52	27.5
	R6	6777	36	257.8	258.8	259.1	0.029	2.52	22.7
	R6	6549	36	256.4	257.3	257.5	0.016	1.9	42.4
	R6	6391	36	253.5	254.4	254.6	0.033	2.23	35
	R6	6067	36	247.8	248.9	249.1	0.017	2.1	23.5
	R6	5783	36	246.3	247.3	247.5	0.03	2.39	26.5
	R6	5312	36	241.2	242.3	242.7	0.029	2.62	20.1
	R6	4854	36	237.5	238.3	238.5	0.02	2.04	36.1
	R6	3695	36	225.9	227	227.3	0.029	2.63	19.8
	R6	2861	36	215.8	215.5	215.8	0.03	2.62	25.1
	R6	2558	36	212	213.2	213.6	0.029	2.54	20.8
	R5	8137	24	270.9	271.8	272	0.031	2.35	18.6
	R5	7817	24	268.6	269.3	269.5	0.021	1.73	29.8
	R5	7042	24	260	260.9	261.1	0.032	2.22	22
	R4	11127	134	328.7	330.6	331.2	0.023	3.38	34.9
	R4	10694	134	321.8	324	324.6	0.023	3.54	30.4
	R4	9756	134	299.3	301.5	302.2	0.023	3.81	24.1
	R4	9096	134	288.8	290.2	290.7	0.019	2.1	46.1
	R4	8269	134	269.2	270.9	271.4	0.024	3.25	40
	R3	11894	69.9	352.3	353.6	354.1	0.024	3.03	27.5
	R3	11531	69.9	337.3	339.1	339.6	0.025	3.2	21.2
	R3	11257	69.9	331.3	332.8	333.2	0.023	3.05	26.7
	R2	16597	131	522.4	524.5	525.1	0.023	3.64	26.8
	R2	16050	131	489.1	491.1	491.8	0.023	3.54	29.2
	R2	15551	131	470.7	472.7	473.3	0.022	3.55	29.8
	R2	15243	131	457.3	459.4	460.1	0.023	3.59	27.9
	R2	14836	131	440.7	442.6	443.3	0.023	3.54	29.1
	R2	14131	131	416.6	418.9	419.6	0.023	3.77	24.3
	R2	13283	131	388.8	391	391.7	0.023	3.61	27.6

River	Reach	River Station	Q Total	Min Ch. El	W.S. Elev	E.G. Elev.	E.G. Slope	Vel. (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
	R2	12216	131	359	360.7	361.3	0.024	3.31	35.5
	R2	11939	131	355.3	356.7	357.3	0.02	2.59	34.8
	R1	22005	97.7	1217	1219	1220	0.024	3.47	23.5
	R1	20766	97.7	1054	1055	1055	0.025	3.09	32.7
	R1	20685	97.7	1048	1049	1050	0.022	3.17	32.7
	R1	20261	97.7	988.9	990.5	991.1	0.025	3.21	29.1
	R1	19720	97.7	888.9	890.4	890.9	0.025	3.24	28.6
	R1	19040	97.7	763.7	765.6	766.2	0.021	3.55	22.9
	R1	17889	97.7	618.3	620	620.6	0.024	3.36	25.4
	R1	17505	97.7	587.1	588.8	589.4	0.024	3.37	25.1
	R1	17259	97.7	570.8	572.6	573.3	0.023	3.48	22.7
	R1	16826	97.7	538.4	540.3	541	0.024	3.48	23
	R1	16646	97.7	523.6	525.4	526	0.024	3.38	24.9
	R1	16638	97.7	522.4	524.1	524.7	0.023	3.36	26
	R1	16634	97.7	522	523.7	524.2	0.023	3.35	27.5

Table 3.5: Hydraulic modeling results for 2500 cumecs flood

River	Reach	River Station	Q Total	Min Ch. Elev.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Basti Dammar	Main	1204	351.8	245.7	248.5	249.5	0.019	4.35	43.4
	Main	1048	351.8	240.9	244	245.1	0.02	4.57	37
	Main	955.2	351.8	236.9	240.2	241.3	0.02	4.59	36.2
	Main	744.5	351.8	230.6	233.7	234.7	0.02	4.4	40.9
	Main	572	351.8	228.4	231.1	232	0.018	4.35	47.3
	Main	419.2	351.8	223.3	225.9	226.7	0.018	4.05	63.8
	Main	247.3	351.8	219.5	222.3	223.3	0.019	4.44	44.4
	Main	37.47	351.8	215.5	218.3	219.8	0.021	3.46	21.1
Dangi Khad	Main	829.3	143	293.2	294.7	295.3	0.024	3.29	39.7
	Main	613.7	143	282	284.1	284.8	0.023	3.7	28.1
	Main	390.9	143	274	276.6	277.5	0.022	3.99	22.3
	Main	292.5	143	267.3	269.3	270	0.023	3.56	31.1
	Main	127.3	143	266	268.5	269.3	0.022	3.93	23.2
	Main	34.09	143	256.6	258.3	258.9	0.024	3.34	38.5

River	Reach	River Station	Q Total	Min Ch. Elev.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Mandani	Main	749.1	248.9	319.8	322.3	323.2	0.021	4.17	33.7
	Main	573.5	248.9	305.8	308.2	309.1	0.021	4.16	34.1
	Main	471	248.9	301.4	304.2	304.9	0.019	3.96	43.2
	Main	369.5	248.9	290.7	293.7	294.7	0.021	4.36	29.7
	Main	235.3	248.9	287.9	291.5	292.6	0.02	4.66	24.3
	Main	114.8	248.9	277.5	279.6	280.4	0.022	3.88	42.4
	Main	17.05	248.9	274.6	276.5	277.2	0.022	3.76	47.9
Madhyamaheshwar	Main	488.1	600	347.9	351.2	352.1	0.015	4.99	62.4
	Main	382.3	600	344.5	348.5	349.7	0.014	5.38	53.5
	Main	283	600	343	346.6	347.6	0.012	5	57.5
	Main	209.3	600	339.9	344.8	346.3	0.014	5.91	35.1
	Main	134.2	600	336	339.9	341.2	0.014	5.4	52
	Main	56.07	600	332.6	337.2	338.4	0.01	4.83	48.1
	Main	22.94	600	331.4	335.7	337.2	0.014	5.46	43.9
Kaliganga	Main	359.5	200	370.7	373.2	374.1	0.019	4.03	31.9
	Main	303.2	200	368.3	371	372	0.02	4.18	28.1
	Main	221.5	200	367.4	370.1	370.7	0.018	4.19	29.3
	Main	154.5	200	359.8	362.2	363.1	0.019	4.07	31.6
	Main	24.3	200	357.6	360.4	361.6	0.021	4.38	23.7
	Main	15.05	200	357.3	359.8	360.7	0.021	4.2	27.1
Vasukiganga	Main	520.4	200	554.3	556.7	557.3	0.015	3.54	44
	Main	445.7	200	550.6	552.7	553.7	0.021	3.94	36.4
	Main	358.8	200	542.7	545.4	546.6	0.02	4.3	25.9
	Main	265.9	200	537.2	539.6	540.2	0.02	4.04	32
	Main	181.9	200	530.5	532.9	533.8	0.021	4.11	29.5
	Main	69.97	200	527.1	529.9	530.8	0.019	4.28	27
	Main	29.02	200	522.3	524.7	525.6	0.02	4.07	30.9
Mandakini	R7	2471	140	218.7	220.4	220.9	0.02	3.24	44.4
	R7	2396	140	213.4	220.6	220.7	0.022	0.49	53.2
	R7	2316	140	213.8	220.6	220.6	0.021	0.5	71.6
	R7	2198	140	213	220.6	220.6	0.022	0.11	143
	R7	2112	140	207.7	220.6	220.6	0.022	0.15	120
	R7	1975	140	215.5	220.5	220.6	0.022	1.22	36.8
	R7	1871	140	205.2	220.5	220.5	0.021	0.24	66
	R7	1758	140	200.9	220.5	220.5	0.022	0.2	72.8
	R7	1645	140	214.2	220.4	220.5	0.022	0.57	69.1
	R7	1592	140	217.4	219.6	220.3	0.022	3.74	26.5
	R7	1538	140	207.3	209.4	210.1	0.021	3.77	29
	R7	1449	140	204.8	207.2	207.9	0.022	3.76	25.8

River	Reach	River Station	Q Total	Min Ch. Elev.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
	R7	1434	140	203.7	206	206.7	0.022	3.77	25.8
	R7	1338	140	201.3	205.5	205.6	0.022	1.17	44.6
	R7	1227	140	198.8	205.4	205.5	0.021	0.77	43.5
	R7	1145	140	198.8	205.4	205.4	0.022	0.52	59.3
	R7	1027	140	200.3	205.3	205.3	0.022	0.85	50.6
	R7	970.1	140	202.2	204.7	205.2	0.021	3.13	28.2
	R7	938.4	140	201.6	203.9	204.6	0.022	3.74	26.4
	R7	638.7	140	199.3	201.1	201.6	0.022	3.4	38.9
	R7	340.2	140	193.2	195.6	196.2	0.017	3.36	27.3
	R7	17.68	140	191.6	194	194.6	0.02	3.72	29.4
	R6	6777	45.01	257.8	258.9	259.2	0.028	2.67	23.5
	R6	6755	45.01	257	258.1	258.4	0.028	2.64	24.4
	R6	6570	45.01	257.3	258	258.1	0.023	1.95	59.5
	R6	6378	45.01	252.7	253.4	253.5	0.035	1.9	64.3
	R6	5760	45.01	244.6	245.6	245.9	0.029	2.54	27.2
	R6	5226	45.01	238	239	239.3	0.025	2.44	29.9
	R6	4371	45.01	233.4	234.4	234.7	0.029	2.49	29.4
	R6	4006	45.01	230.9	232.1	232.5	0.027	2.79	20.7
	R6	3695	45.01	225.9	227.1	227.5	0.028	2.78	21
	R6	3023	45.01	224.5	225.6	226	0.028	2.69	22.8
	R6	2558	45.01	212	213.4	213.7	0.028	2.63	21.3
	R5	8113	30.01	269.8	270.4	270.6	0.027	1.93	34.6
	R5	7806	30.01	268.4	269.1	269.3	0.032	2.17	29.4
	R5	7042	30.01	260.1	260.9	261.2	0.031	2.34	23.4
	R4	11127	167.9	328.7	330.8	331.4	0.022	3.6	37.4
	R4	10495	167.9	313.4	315.5	316.2	0.021	3.68	37.7
	R4	9812	167.9	310.4	313.1	313.7	0.022	3.95	27.2
	R4	9559	167.9	295.8	298	298.7	0.022	3.85	29.3
	R4	9096	167.9	288.8	290.4	290.9	0.019	2.24	51.1
	R4	8341	167.9	270.4	272.2	272.8	0.021	3.6	41.4
	R4	8269	167.9	269.2	271.1	271.7	0.024	3.43	41.4
	R3	11894	87.41	352.1	353.7	354.3	0.023	3.2	29.9
	R3	11697	87.41	343.9	345.7	346.3	0.024	3.44	21.1
	R3	11531	87.41	337.2	339.3	339.9	0.025	3.37	22.9
	R3	11257	87.41	331.4	332.9	333.5	0.022	3.21	28.5
	R2	16597	163.9	522.3	524.7	525.3	0.022	3.86	28.7
	R2	16361	163.9	512.5	514.6	515.5	0.022	3.71	31.5
	R2	15551	163.9	470.7	472.9	473.5	0.021	3.78	31.1
	R2	15061	163.9	448.8	451.2	451.8	0.022	3.98	26

River	Reach	River Station	Q Total	Min Ch. Elev.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
	R2	14401	163.9	425.6	427.4	427.7	0.02	3.4	47.7
	R2	13849	163.9	409.5	412.2	413.1	0.022	4.31	20.5
	R2	12320	163.9	362.2	364.6	365.5	0.022	3.85	28.3
	R2	12055	163.9	357.9	360.4	361	0.022	3.75	30.6
	R2	11939	163.9	355.2	357	357.6	0.02	2.9	36.1
	R1	22005	122.1	1217	1220	1220	0.023	3.67	24.6
	R1	21380	122.1	1116	1118	1119	0.024	3.7	32
	R1	20598	122.1	1037	1039	1039	0.023	3.48	29
	R1	20397	122.1	1008	1010	1011	0.024	3.5	28.4
	R1	19742	122.1	894.2	896	896.6	0.024	3.4	30.7
	R1	19040	122.1	763.7	765.9	766.5	0.02	3.76	24.5
	R1	18579	122.1	720.4	723.5	724.4	0.022	4.21	16.1
	R1	17784	122.1	614.6	616.5	617.4	0.023	3.59	25.9
	R1	17366	122.1	571	574.1	575	0.019	3.95	17
	R1	17141	122.1	561.9	564.6	565.5	0.022	4.17	16.6
	R1	16814	122.1	537.8	539.9	540.5	0.023	3.66	24.5
	R1	16634	122.1	522	523.8	524.4	0.022	3.54	29.3

Table 3.6: Hydraulic modeling results for 3000 cumecs flood

River	Reach	River Station	Q Total	Min Ch. El.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl.)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Basti Dammar	Main	1203.9	422.1	245.7	248.8	249.8	0.019	4.57	45.3
	Main	1048.4	422.1	240.9	244.3	245.5	0.019	4.82	38.6
	Main	955.09	422.1	236.9	240.5	241.7	0.019	4.8	38
	Main	812.5	422.1	235.2	238.5	239.5	0.02	4.56	44.2
	Main	744.45	422.1	230.6	234	235.1	0.02	4.59	43.2
	Main	572.04	422.1	228.4	231.3	232.3	0.017	4.56	49.6
	Main	419.24	422.1	223.3	226.2	227	0.014	4	66.6
	Main	247.35	422.1	219.5	222.6	223.6	0.018	4.72	45.9
	Main	37.466	422.1	215.5	218.7	220.4	0.021	3.8	22.9
Dangi Khad	Main	829.39	171.6	293.2	294.9	295.5	0.023	3.45	41.1
	Main	613.63	171.6	282	284.4	285.1	0.022	3.88	29.1
	Main	520.52	171.6	277.2	279.3	280	0.022	3.69	33.7
	Main	390.73	171.6	274	276.9	277.8	0.022	4.19	23.2
	Main	292.52	171.6	267.3	269.5	270.2	0.022	3.73	32.4
	Main	127.35	171.6	266	268.7	269.6	0.021	4.11	24.3

River	Reach	River Station	Q Total	Min Ch. El.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl.)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Mandani	Main	749.21	298.6	319.8	322.6	323.5	0.02	4.38	35
	Main	621.89	298.6	309.8	312.8	313.7	0.02	4.43	33.9
	Main	507.13	298.6	303.8	306.7	307.6	0.02	4.33	36.2
	Main	369.39	298.6	290.7	294	295	0.02	4.55	31.1
	Main	268.34	298.6	289.8	293	293.9	0.02	4.26	36.8
	Main	114.78	298.6	277.5	279.8	280.7	0.021	4.06	44.4
	Main	17.05	298.6	274.6	276.7	277.5	0.021	4	51.6
Madhyamaheshwar	Main	488.05	720	347.9	351.5	352.7	0.014	5.27	65.1
	Main	382.44	720	344.5	348.8	350.3	0.014	5.66	56.3
	Main	227.74	720	340.9	346.6	347.9	0.007	5.02	41.3
	Main	161.97	720	336.9	341.2	342.7	0.013	5.76	53.5
	Main	56.07	720	332.6	337.5	338.7	0.01	5.16	50.2
	Main	22.94	720	331.4	336.3	337.8	0.013	5.76	45.9
Kaliganga	Main	359.33	240	370.7	373.5	374.4	0.019	4.23	33.5
	Main	303.24	240	368.3	371.3	372.3	0.019	4.38	29.4
	Main	221.49	240	367.4	370.1	371	0.018	4.41	30.6
	Main	154.5	240	359.8	362.5	363.4	0.018	4.31	33
	Main	15.049	240	357.3	360.1	361.3	0.02	4.42	28.4
Vasukiganga	Main	520.3	240	554.3	556.7	557.3	0.014	3.68	46.3
	Main	408.41	240	547.3	550	550.9	0.015	4.09	41.8
	Main	326.62	240	538.1	541.5	542.4	0.02	4.45	27.7
	Main	206.76	240	533.5	536.6	537.5	0.019	4.52	27.5
	Main	69.97	240	527.1	530.2	531.1	0.018	4.49	28.4
	Main	29.014	240	522.3	525	525.9	0.019	4.25	32.3
Mandakini	R7	2487.2	168	218.9	221	221.4	0.01	2.69	45.6
	R7	2425.3	168	214.7	220.9	221	0.019	0.63	68
	R7	2348.2	168	212.9	220.9	220.9	0.018	0.52	76.6
	R7	2274.3	168	214.2	220.9	220.9	0.019	0.3	83
	R7	2170.7	168	212	220.9	220.9	0.019	0.12	147
	R7	2086.3	168	206.8	220.9	220.9	0.019	0.21	105
	R7	1961.2	168	216.8	220.6	220.9	0.018	2.06	34.7
	R7	1839.6	168	204.7	220.7	220.7	0.019	0.27	69.5
	R7	1757.7	168	200.9	220.7	220.7	0.019	0.23	73.6
	R7	1592.5	168	217.4	219.8	220.5	0.022	3.92	27.8
	R7	1434.1	168	203.7	206.2	207	0.022	3.95	26.8
	R7	1234.8	168	198.8	205.7	205.7	0.019	0.98	40.6
	R7	1124.1	168	200	205.7	205.7	0.018	0.8	56.1
	R7	938.48	168	201.6	204.1	204.8	0.019	3.92	27.6
	R7	814.27	168	188.7	202.1	202.1	0.019	0.31	67

River	Reach	River Station	Q Total	Min Ch. El.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl.)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
	R7	719.36	168	193.7	202	202.1	0.018	0.5	53.5
	R7	603.54	168	196.6	198.5	199.2	0.019	3.64	38.8
	R7	509.54	168	193.9	197.9	198	0.019	1.12	52.7
	R7	360	168	194.5	196.9	197.7	0.022	3.89	28.1
	R7	200.35	168	187.8	196.3	196.3	0.019	0.53	58.5
	R7	29.18	168	192.4	195.1	195.9	0.018	4.2	26.1
	R7	17.679	168	191.6	194.2	194.9	0.019	3.89	31.3
	R6	6776.8	54	257.8	259	259.4	0.027	2.81	24.3
	R6	6570.1	54	257.3	258	258.2	0.021	2	60.3
	R6	6378.4	54	252.7	253.4	253.6	0.034	2.02	64.7
	R6	6049.4	54	247.6	248.7	249.1	0.025	2.81	25.2
	R6	5311.9	54	241.2	242.6	243	0.027	2.88	22.8
	R6	4845.1	54	237.3	238.3	238.5	0.023	2.37	50
	R6	4361.6	54	232.7	233.9	234.3	0.028	2.69	27.7
	R6	4006.1	54	230.9	232.2	232.6	0.027	2.91	21.8
	R6	3033.6	54	224.7	226	226.4	0.027	2.86	22.9
	R6	2900.1	54	218.5	219.5	219.8	0.028	2.28	34.5
	R6	2708.3	54	212.8	214.3	214.5	0.009	1.94	33
	R6	2557.9	54	212	213.4	213.9	0.027	2.73	21.7
	R5	8146	36	271.6	272.7	273	0.029	2.55	21.9
	R5	7805.8	36	268.4	269.1	269.4	0.031	2.27	30.7
	R5	7488.1	36	263.9	264.7	265	0.029	2.31	30
	R5	7041.8	36	260.1	261	261.3	0.03	2.45	24.6
	R4	11127	201.6	328.7	331.1	331.7	0.021	3.74	39.9
	R4	10743	201.6	325.3	328	328.7	0.015	3.5	33.8
	R4	10495	201.6	313.4	315.9	316.5	0.02	3.9	38.8
	R4	9559.5	201.6	295.8	298.1	299	0.021	4.09	30.1
	R4	9149.4	201.6	292.4	293.8	294.3	0.025	2.98	69.5
	R4	8268.9	201.6	269.2	271.3	271.9	0.023	3.57	42.6
	R3	11894	104.9	352.1	354	354.6	0.021	3.32	32.3
	R3	11531	104.9	337.2	339.3	339.9	0.024	3.51	24.3
	R3	11292	104.9	337.5	339	339.3	0.025	2.97	40.2
	R3	11257	104.9	331.4	333.2	333.5	0.022	3.36	30
	R2	16597	196.7	522.3	525	525.6	0.021	4.05	30.3
	R2	16284	196.7	498.2	500	500.6	0.02	3.6	45.7
	R2	16249	196.7	496.3	499.1	499.4	0.011	3.19	39.5
	R2	16213	196.7	495.4	498.8	499.1	0.004	2.26	43.7
	R2	16200	196.7	495.1	499.1	499.1	0.002	1.86	45.6
	R2	16171	196.7	495.7	498.2	498.8	0.02	4.03	31.9

River	Reach	River Station	Q Total	Min Ch. El.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl.)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
	R2	16157	196.7	495.1	497.6	498.5	0.02	3.99	32
	R2	16134	196.7	494.2	496	496.6	0.021	3.61	45.5
	R2	16103	196.7	491.2	493	493.6	0.023	3.41	45.3
	R2	16076	196.7	489.9	492.4	492.7	0.014	3.07	45.6
	R2	16050	196.7	489	491.5	492.4	0.022	3.95	31.4
	R2	16031	196.7	487.5	491.8	492.1	0.003	2.16	36.1
	R2	16012	196.7	487.2	491.8	491.8	0.002	1.75	36.9
	R2	15995	196.7	487.2	491.8	491.8	0.002	1.88	36.4
	R2	15976	196.7	488.4	490.9	491.8	0.021	3.92	32.8
	R2	15959	196.7	487.8	490.2	491.2	0.022	3.96	31.3
	R2	15944	196.7	486.6	488.7	489.6	0.021	3.93	33.9
	R2	15928	196.7	485.1	487.2	488.1	0.021	4	31.5
	R2	15913	196.7	482.9	486	486.3	0.005	2.43	35.9
	R2	15894	196.7	482.3	485.4	486.3	0.021	4.08	29.3
	R2	15876	196.7	481.7	484.5	485.4	0.021	4.37	23.5
	R2	15590	196.7	478.4	480.8	481.7	0.021	4.13	27.8
	R2	14718	196.7	438.1	440.2	441.2	0.019	3.95	34.9
	R2	14131	196.7	416.5	419.2	420.1	0.021	4.18	26.5
	R2	13666	196.7	402.1	404.9	405.8	0.02	4.24	26.4
	R2	13283	196.7	388.7	391.5	392.4	0.022	4.01	30.4
	R2	12216	196.7	359.1	361.3	361.9	0.017	3.36	39.8
	R2	11939	196.7	355.2	357	357.9	0.02	3.16	37.2
	R1	22005	146.5	1217	1220	1221	0.022	3.84	25.7
	R1	21680	146.5	1178	1180	1181	0.022	3.8	26.3
	R1	20491	146.5	1021	1024	1025	0.022	3.94	23.7
	R1	19921	146.5	932.9	934.5	935.1	0.023	3.52	33.4
	R1	19485	146.5	839	841.5	842.1	0.021	3.85	26.4
	R1	18829	146.5	745.1	748.8	749.7	0.023	4.35	17.8
	R1	18579	146.5	720.4	723.8	724.7	0.022	4.41	16.9
	R1	18251	146.5	680.8	682.9	683.5	0.021	3.6	39.8
	R1	17902	146.5	620.7	622.9	623.5	0.02	3.64	32.3
	R1	16814	146.5	537.8	540.2	540.9	0.023	3.86	25.6
	R1	16634	146.5	522	524.1	524.7	0.021	3.7	31

Table 3.7: Hydraulic modeling results for 2500 cumecs flood along with cloudburst

River	Reach	River Station	Q Total	Min Ch Elev.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Basti Dammar	Main	1203.9	351.8	245.7	248.5	249.5	0.019	4.35	43.4
	Main	1048.4	351.8	240.9	244	245.1	0.02	4.57	37
	Main	836.04	351.8	236	238.9	239.9	0.02	4.39	40.9
	Main	744.45	351.8	230.6	233.7	234.7	0.02	4.4	40.9
	Main	572.04	351.8	228.4	231.1	232	0.018	4.35	47.3
	Main	419.24	351.8	223.3	225.9	226.7	0.018	4.05	63.8
	Main	287.58	351.8	220.1	223	224.1	0.018	4.6	37.7
	Main	37.466	351.8	215.5	218.3	219.8	0.021	3.46	21.1
Dangi Khad	Main	829.39	143	293.2	294.7	295.3	0.024	3.29	39.7
	Main	613.63	143	282	284.1	284.8	0.023	3.7	28.1
	Main	520.52	143	277.2	279.1	279.8	0.023	3.5	32.7
	Main	390.73	143	274	276.6	277.5	0.022	3.99	22.3
	Main	292.52	143	267.3	269.3	270	0.023	3.56	31.1
	Main	127.35	143	266	268.5	269.3	0.022	3.93	23.2
	Main	34.098	143	256.6	258.3	258.9	0.024	3.34	38.4
Mandini	Main	749.21	248.9	319.8	322.3	323.2	0.021	4.17	33.7
	Main	636.8	248.9	311	313.7	314.6	0.021	4.24	32.1
	Main	490.3	248.9	302.6	305.5	306.4	0.021	4.17	33.8
	Main	369.39	248.9	290.7	293.7	294.7	0.021	4.36	29.7
	Main	268.34	248.9	289.8	292.7	293.6	0.021	4.11	35.5
	Main	17.05	248.9	274.6	276.5	277.2	0.022	3.76	47.9
Madhyamaheshwar	Main	488.05	600	347.9	351.2	352.1	0.015	4.99	62.4
	Main	382.44	600	344.5	348.5	349.7	0.014	5.38	53.5
	Main	274.32	600	342.7	346.6	347.6	0.01	4.87	54.5
	Main	209.27	600	339.9	344.8	346.3	0.014	5.91	35.2
	Main	110.49	600	334.1	338.1	339.3	0.014	5.54	46.1
	Main	22.94	600	331.4	335.7	337.2	0.014	5.46	43.9
Kaliganga	Main	359.33	200	370.7	373.2	374.1	0.019	4.03	31.9
	Main	303.24	200	368.3	371	372	0.02	4.18	28.1
	Main	221.49	200	367.4	370.1	370.7	0.018	4.19	29.3
	Main	154.5	200	359.8	362.2	363.1	0.019	4.07	31.6
	Main	15.049	200	357.3	360.1	360.7	0.021	4.2	27.1
Vasukiganga	Main	520.3	543.9	554.3	558.2	559.1	0.009	4.24	60.8
	Main	418.41	543.9	548.2	551.8	553	0.016	5.25	47
	Main	326.62	543.9	538.1	543	544.5	0.016	5.69	35
	Main	216.92	543.9	534.1	539	540.5	0.016	5.62	33.6
	Main	161.45	543.9	528.7	532.9	534.1	0.01	4.87	42.7

River	Reach	River Station	Q Total	Min Ch Elev.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
Mandakini	R1	21835	122.1	1208	1210	1211	0.023	3.77	22.7
	R1	21529	122.1	1168	1170	1170	0.022	3.31	36.4
	R1	21228	122.1	1086	1088	1088	0.023	3.3	34.5
	R1	20975	122.1	1067	1069	1070	0.024	3.27	36.2
	R1	20666	122.1	1047	1048	1049	0.023	3.23	37.7
	R1	20322	122.1	995.4	997.3	997.9	0.019	3.12	32.9
	R1	19941	122.1	937.2	939	939.6	0.024	3.38	31.4
	R1	19544	122.1	850	851.5	852.1	0.022	3.46	30.5
	R1	18409	122.1	711	713.7	714.3	0.023	3.8	22.2
	R1	17649	122.1	603	605.2	606.1	0.023	3.68	24.2
	R1	17393	122.1	574.7	577.4	578	0.023	3.63	25.2
	R1	17059	122.1	553.7	556.1	556.7	0.023	3.74	22.9
	R1	16634	122.1	522	523.8	524.4	0.022	3.55	29.3
	R2	16284	163.9	498.2	500	500.6	0.021	3.45	43.4
	R2	15577	163.9	476.5	479	479.6	0.023	3.77	30.5
	R2	15061	163.9	448.8	451.2	451.8	0.022	3.98	26
	R2	14565	163.9	436.6	438.7	439.3	0.022	3.72	31.4
	R2	14223	163.9	420.7	424.1	425	0.022	4.11	23.5
	R2	13893	163.9	413.1	415.9	416.8	0.022	4.23	21.5
	R2	13666	163.9	402.1	404.6	405.5	0.021	4.08	25
	R2	13332	163.9	396	398.8	399.7	0.022	3.98	25.7
	R2	12837	163.9	381.1	383.2	383.8	0.023	3.64	33.4
	R2	12502	163.9	364.9	367.7	368.3	0.022	3.92	27
	R2	12055	163.9	357.9	360.4	361	0.022	3.75	30.6
	R3	11843	87.4	350.3	352.1	352.7	0.024	3.37	22.5
	R3	11581	87.4	341.5	343.3	343.6	0.024	3.27	24.8
	R4	10525	168	321.6	323.5	324.4	0.023	3.56	36.6
	R4	9819.2	168	311.3	313.7	314.6	0.022	3.88	28.8
	R4	9595.7	168	298.4	300.5	301.2	0.022	3.73	33
	R4	9215.9	168	294.8	296.6	297.2	0.024	3.34	44.2
	R4	9096.3	168	288.8	290.4	290.9	0.019	2.24	51.1
	R4	8608.5	168	280.9	283.4	284.2	0.022	3.79	30.6
	R4	8354	168	271.5	273.3	273.9	0.023	3.49	41.2
	R5	8146	30	271.6	272.6	272.9	0.03	2.43	20.9
	R5	7805.8	30	268.4	269.1	269.3	0.032	2.17	29.4
	R5	7502.4	30	264.2	265	265.2	0.015	1.68	34.2
	R5	7043.3	30	260.1	261.1	261.3	0.014	1.77	25.9
	R6	6755.5	45	257	258.1	258.4	0.028	2.64	24.4
	R6	6442.1	45	255.8	257	257.3	0.02	2.46	25.2

River	Reach	River Station	Q Total	Min Ch Elev.	W.S. Elev.	E.G. Elev.	E.G. Slope	Velocity (Chnl)	Top Width
		(m)	(cumecs)	(m)	(m)	(m)	(m/m)	(m/s)	(m)
	R6	6299.1	45	249.8	250.7	250.9	0.025	2.34	40.9
	R6	5782.6	45	246.3	247.3	247.7	0.029	2.52	28.4
	R6	5322.3	45	242.3	243.2	243.6	0.026	2.65	25.7
	R6	4808.5	45	234.4	235.3	235.6	0.03	2.39	34.1
	R6	3869.8	45	229.8	230.8	231.1	0.03	2.46	30.3
	R6	3033.6	45	224.7	225.9	226.3	0.027	2.73	22
	R6	2860.6	45	215.8	215.6	215.9	0.029	2.71	27.2
	R6	2700.7	45	212.8	213.8	214.2	0.026	2.67	27.1
	R6	2557.9	45	212	213.4	213.7	0.028	2.63	21.3
	R7	360	140	194.5	196.7	197.4	0.023	3.72	26.9
	R7	29.18	140	192.4	194.9	195.6	0.02	3.99	24.6
	R7	17.679	140	191.6	194	194.6	0.02	3.72	29.4

Plots showing values of different parameters at different resections have also been generated for different river reaches. Figure 3.8 shows the various water surface profiles i.e. energy grade line, hydraulic grade line and critical water surface for Reach R1 (Kedarnath to Sonprayag) of Mandakini river. Figures 3.9, 3.10 and 3.11 the plot of velocity, shear and stream power respectively against channel distance for the reach R1 of Mandakini River.

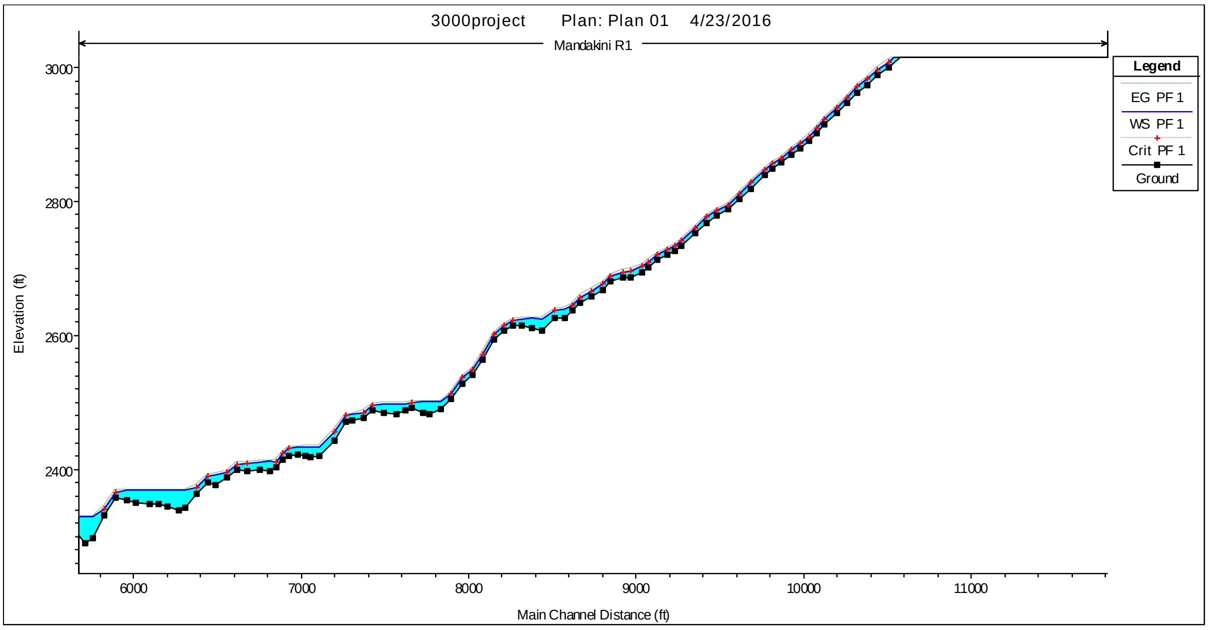

Figure 3.8: Water surface profiles for R1 reach of Mandakini River

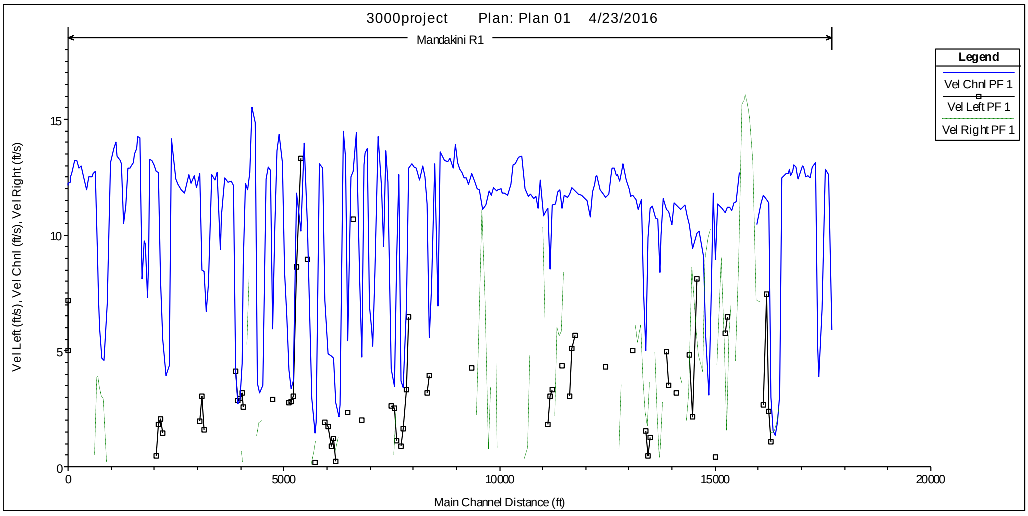

Figure 3.9: Velocity profiles for R1 reach of Mandakini River

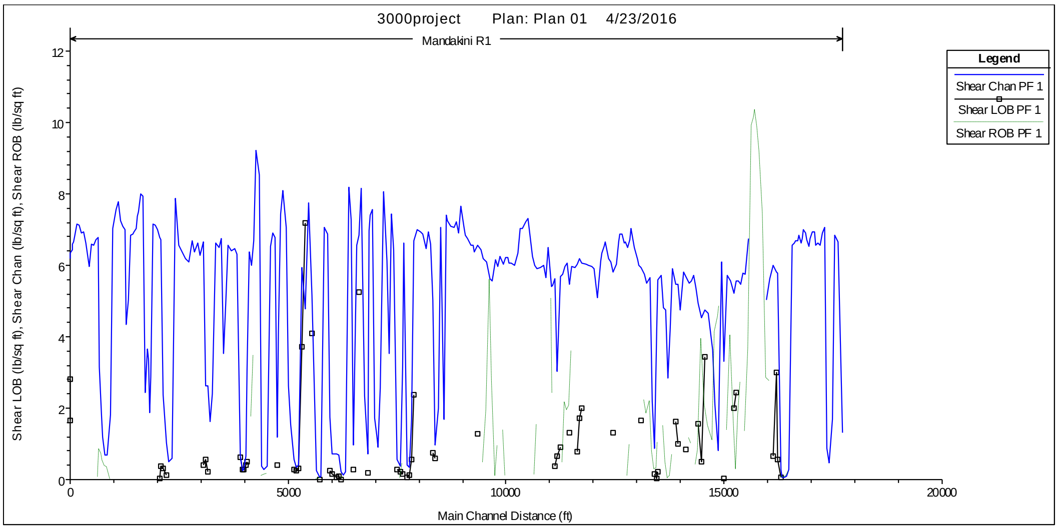

Figure 3.10: Shear profile for R1 reach of Mandakini River

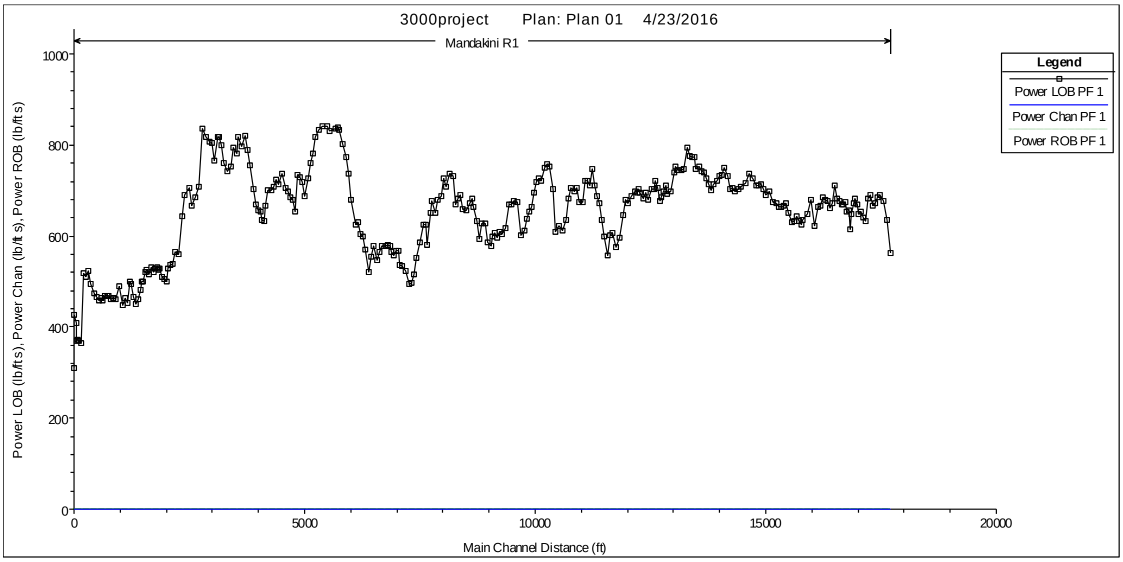

Figure 3.11: Stream power profile for R1 reach of Mandakini River

Intersection of LULC raster with flood inundation maps of different floods has characterized the corresponding flood prone areas. The flood inundation corresponding to 3000 cumecs flood at Sonprayag has been shown in Figure 3.12. Figure 3.13 shows the combinations of inundated land use corresponding to floods of different magnitudes. Inundation varies from 9.67 sq. km for 1500 cumecs flood to 11.74 sq. km for 3000 cumecs flood. A major portion of the inundated area is classified as barren land. Change in both extent and composition of inundated land cover can be clearly seen from the comparison (Table 3.8).

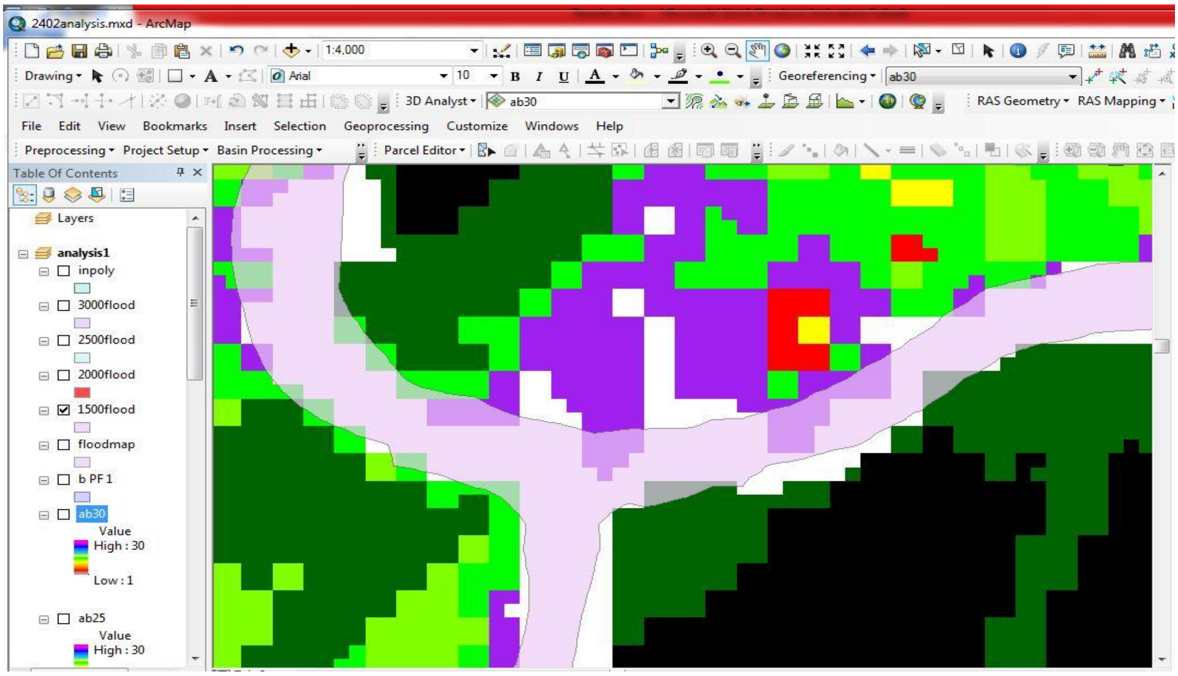

Figure 3.12: Flood inundation at Sonprayag corresponding to a flood of 3000 cumecs.

Table 3.8: Extent and composition of inundated land cover for different flood magnitudes

Flood Magnitude (cumecs)	1500	2000	2500	3000
Land Use	Area Inundated (km2)	Area Inundated (km2)	Area Inundated (km2)	Area Inundated (km2)
Residential/urban	1.334	1.456	1.540	1.599
Agricultural Land	2.060	2.216	2.305	2.394
Dense forest	1.207	1.482	1.586	1.675
Light density forest	0.708	0.756	1.0348	1.087
Barren Land	4.357	4.797	4.913	4.982
Total	9.666	10.707	11.378	11.736

Floodplain for 2000 cumecs flood is 10.8% larger than that corresponding to 1500 cumecs. However floodplain for 2500 cumecs flood is 6.3% larger than that corresponding to 2000 cumecs. Incremental changes for the floodplain are more rapid for floods of lower magnitude. Figure 3.13 shows inundation extent of different flood events at Sonprayag. As the magnitude of flood keep on increasing, the valley widens ups and hence per unit incremental inundation keeps on decreasing

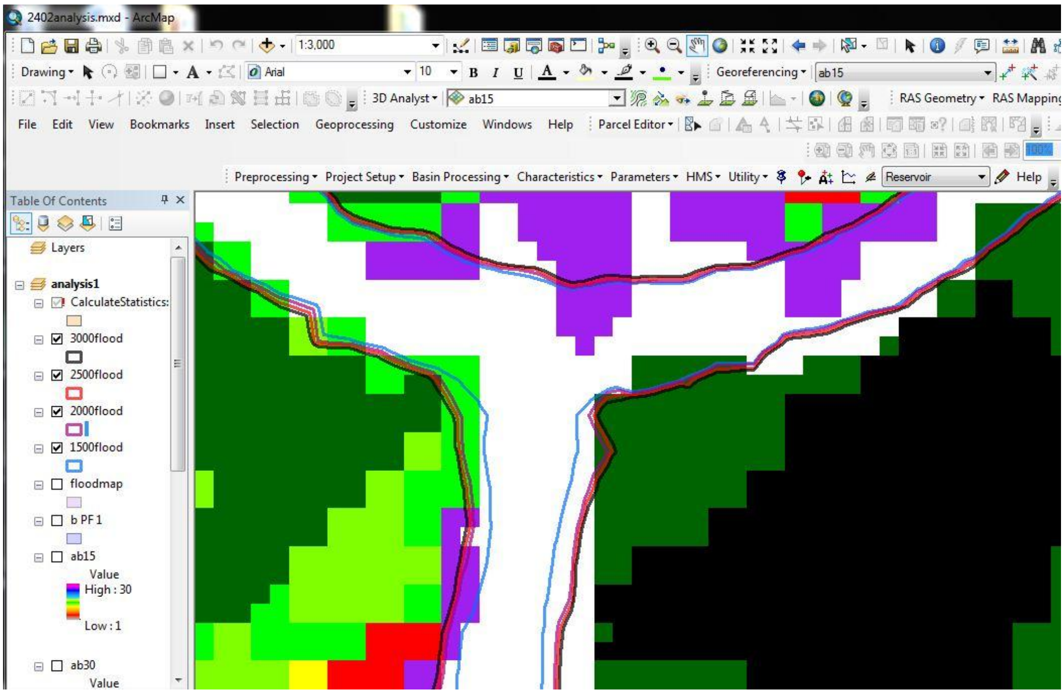

Fig. 3.13: Inundation extent of different flood events at Sonprayag

3.6 Conclusion

Flood risk analysis and mapping is a very complex process and need the knowledge of a number of factors. Quality of the results depends on the reliability of the data and methods used for flood risk analysis such as resolution of geospatial data, suitability of the software used, quality of demographic, socio-economic and hydrometeorological data. SRTM DENM of 30 m resolution has been used in the study. However use of higher resolution data if available can give better and more reliable results in such studies. It is observed that the major part of area under inundation is barren land. Area of inundation increases with increase in magnitude of flood but the incremental increase in the inundated area keeps on decreasing with increase in flood magnitude. The decrease in incremental inundation of area may be attributed to the widening of valleys upwards that reduces the depth per unit volume of flow.

CHAPTER 4

HOTSPOT IDENTIFICATION AND PRIORITIZATION

4.1 Introduction

Flood risk is not spread uniformly over space and time. Flood maps generated by geospatial analysis often indicate few localized sites of considerably high flood risk. A number of tools are available that allow the users to identify and interpret these sites of higher flood risk. Among these tools "hot spot" analysis is widely accepted and increasingly used to identify areas where flood risk is most prominent and where appropriate resources and policies should be deployed to minimize the damage. Hot spot analysis is used to guide decisions about the allocation of limited resources for management of any undesirable activity. When available resources are insufficient to manage the problem entirely, decision makers can use hotspot analysis to identify the areas where problem or its risk is more pronounced and accordingly allocate resources to selected areas. This can help the decision makers to use the available resources in most effective and efficient way considering spatial, temporal and quantity constraints.

- Hot Spot Identification**:** In geospatial software ArcGIS, the standard set of available hot spot analysis tools fall into three categories.
- Thematic Mapping: Concentrations of events are color-coded in discrete geographic area.
- Kernel Density Interpolation: A smooth surface is overlayed on a map reflecting the concentration of actual events, and spaces between events are assigned interpolated value based on the amount of nearby events.

After the potential sites for flood risk have been selected as hotspots, the decision makers may face the problem of resource quantity constraints against the requirement for these. Therefore it is required to further prioritize these hotspots that are candidate for the allocation of resources. Prioritization of hotspots should be aimed at achieving the optimum allocation of resources considering various spatial, quantity, temporal, technical and financial constraints. Prioritization approach should also consider the mobility of resources and their simultaneous requirement. Decision outcomes are largely influenced by decision-making methods. According to Suhr (1999), outcomes are results of actions triggered by people's decisions and these decisions are influenced by decision-making methods. So the selection of decision making method is as important as the outcomes are. TOPSIS and CBA are two methodologies that are widely used in prioritization of hotspots.

4.1.1 Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)

TOPSIS was proposed by Hwang and Yoon. It is known as an ideal point Multi-Criteria Decision Analysis method. In this method, a total number of m alternatives are evaluated by n attributes. The technique is based on the concept that the chosen alternative should have the shortest distance from the positive ideal solution (the best possible state) and the maximum distance from the negative ideal solution (the worst case). The positive and negative ideal solutions are artificial alternatives which are hypothesized by the decision maker, based on the ideal solution for all criteria and the worst solution which possesses the most inferior decision variables. Assuming every criterion has an increasing or decreasing scale, TOPSIS calculates the results by comparing Euclidean distances (direct "as the bird flies" distance) between the actual alternatives and the hypothesized ones. Since all the criteria may or may not be equally important, we need to assign weightage (in terms of percentage) to each criterion for final decision making process.

This method includes six steps as described below:

1. Formation of decision matrix: TOPSIS evaluates those decision matrices with m alternatives and n attributes**.**
2. Normalization of the decision matrix (Eq. 1)

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} a_{ij}^2}} \qquad (1)$$

   The normalized matrix is called N_D

3. calculation of weighted N_D (Eq. 2)

$$V = N_D * W_{n*n} \qquad (2)$$

   Where, V is the weighted N_D and W is a diagonal matrix of the weighted attributes.

4. Calculation of the positive ideal and negative ideal alternatives.

$$A^+ = \{(\max_i V_{ij} | j \in j_1), (\min V_{ij} | j \in j_2) | i = 1,2,...,n\} \qquad (3)$$

$$A^- = \{(\min_i V_{ij} | j \in j_1), (\max V_{ij} | j \in j_2) | i = 1,2,...,m\} \qquad (4)$$

5. Deviation from the ideal positive and negative alternatives.

$$d_i^+ = \left\{ \sum_{j=1}^{n} (V_{ij} - V_j^+)^2 \right\}^{\frac{1}{2}} \qquad (i=1, 2, 3\ldots, m) \qquad (5)$$

$$d_i^- = \left\{ \sum_{j=1}^{n} (V_{ij} - V_j^-)^2 \right\}^{\frac{1}{2}} \qquad (i=1, 2, 3\ldots, m) \qquad (6)$$

6. Calculation of C_i indicating the closeness to the positive ideal and distance from the negative ideal (Eq.7):

$$C_i = \frac{d_i^-}{\left(d_i^- + d_i^+\right)} \qquad (i=1, 2, 3\ldots, n) \qquad (7)$$

Ultimately, the alternatives are ranked on descending order of C_i. The available alternatives can be ranked based on the highest importance.

4.1.2 Choosing By Advantages (CBA)

CBA is a decision-making system that compares advantages of alternatives for decision-making process. This method was developed by Suhr while working in the U.S. Forest Service. This system makes use of well-defined vocabulary in the decision-making process to ensure clarity and transparency. CBA definitions given by Suhr (1999) are as follow:

- Alternatives: Two or more options from which one or a combination of them is to be chosen.
- Factor: An element, part, or component of a decision.
- Criterion: A guideline or rule for making decision.
- Attribute: A characteristic, quality, or consequence of one alternative.
- Advantage: Favorable difference between the attributes of two alternatives.

This system gives importance to identify the factors that will highlight significant differences among different alternatives instead of the factors that will be important in the decision. This method helps in making decisions based on relevant facts and hence minimizing the conflict. In contrast, the stakeholders may have problems in resolving conflicts when using value-based methods, as these methods need to weight the factors and therefore may not focus on the significance of the advantages between attributes of different alternatives to the same extent as that of CBA. Methods that weight factors are more likely to produce wrong decisions as the decisions taken are not based on the relevant facts. Addition of any factor on later stages of analysis in CBA can be done easily because it will be independent of previous factors whereas in methods that weight factors, weightage assigned to every factor need to be changed if a new factor is added to the analysis.

CBA includes methods for almost all types of decisions ranging from very simple to very complex decisions CBA method helps the decision makers to differentiate alternatives and to understand the importance of those differences. Decisions in this method are based only on the advantages of alternatives (which are positive differences) instead of both advantages and disadvantages to avoid double counting.

CBA analysis can be done using simple steps as given in example:

1. Identifies alternatives likely to have significant advantages over other alternatives.
2. Define factors that will reveal significant differences among alternatives.
3. Decide the criteria to evaluate attributes of alternatives.
4. Summarize the attributes of each alternative.
5. Identify the least preferred attribute for each factor, and then relative to that least-preferred attribute decide on the advantage of attributes of other alternatives.
6. Decide on the importance of advantages. First, select the paramount advantage, which is the most important advantage among all.
7. Finally, evaluate the alternatives to rank them in order of preference.

The decision as a whole can also be reconsidered, incorporating other factors, or new alternatives. In such case decision can easily be update using the CBA tabular method. Hence this method is used for prioritization of hotspots.

4.2 Methodology for Identification and Prioritization of Hotspots

Five potential sites for the hotspot analysis have been identified on the banks of the river for 3000 cumecs flood. Hotspots have been selected based on the visual interpretation of geospatial data. Flood map, velocity profile, and depth profiles generated from modeling for 300 cumecs floods have been overlayed on the LULC file of the area and visually inspected. Criteria for the selection of hotspots are as follow:

1. Populated areas exposed to moderate, high and very high severity index for both of the parameters i.e. velocity or depth.
2. Populated area exposed to very high severity index for any of the parameter.
3. Populated area exposed to high severity index for one parameter and low severity index posed for other.
4. Agricultural land exposed to very high severity index for any of the parameter.
5. Agricultural land exposed to high severity index for both the parameters.
6. Land use areas other than residential and agricultural land exposed to severity index for both of the parameters.
7. Any religious, historic or cultural monument exposed to moderate or higher severity index for any of the parameters.

Based on the above criteria five hotspots (Fig. 4.1) have been selected and evaluated for prioritization. Evaluation of different locations has then been done and hotspots have been prioritized based on the total scores using following steps:

1. Identifies alternatives likely to have significant advantages over other alternatives.
2. Define factors that will reveal significant differences among alternatives.
3. Decide the criteria to evaluate attributes of alternatives.

4. Summarize the attributes of each alternative.
5. Identify the least preferred attribute for each factor, and then relative to that least-preferred attribute decide on the advantage of attributes of other alternatives.
6. Decide on the scores for advantages. First, select the paramount advantage, which is the most important advantage among all.
7. Finally, evaluate the alternatives to rank them in increasing order of scores.

Fig. 4.1: Potential hotspots for Flood risk

.

Severity of the flood corresponding to depth (S1) and velocity (S2) are assigned scores as per severity index. Vulnerability (V1) of different attributes for different locations is assigned as per Table 4.1.

$$\text{Multiplying Factor (F)} = (S1+S2)*V$$

Score to attributes for different locations are assigned as multiplication of multiplying factor (F) and maximum score (Table 4.2)

$$\text{Score (S)} = \text{Maximum score (MS)}*\text{Multiplying Factor (F)}$$

Hotspots are ranked in decreasing order of the scores (Table 4.3). Fig 4.2 shows the potential land slide site (Site -1) exposed to very high severity index for velocity.

Table 4.1: Scores corresponding to severity and vulnerability indices

Severity /Vulnerability Index	Score for Depth severity (S1)	Score for velocity severity (S2)	Score for vulnerability (V)
Very Low	0.1	0.1	0.00
Low	0.2	0.2	0.25
Moderate	0.3	0.3	0.50
High	0.4	0.4	0.75
Very High	0.5	0.5	1.00

Table 4.2: Maximum scores for different attributes

Attributes		Maximum Scores (MS)
Social Impacts	Human causalities and Injuries	2000
	Health Impacts due to water born disease	1600
	Public Inconvenience	800
	Water logging and backups	500
	Psychological effects	600
	Loss of shelter and livelihood	1000
	Effects on religious, cultural and tourists monuments	1000
	Effects on educational & administrational working	800
Environmental Impacts	Water Pollution (Point & Non Point)	600
	Erosion	500
	Ecosystem Degradation (Terrestrial &Aquatic)	800
	Habitat Losses	800
	Impact on Endangered Species	800
	Sedimentation in lower areas	600
	Sewer outflows (CSO/SSO)	400
Economic Impacts	Productivity Loss (working hours)	800
	Agricultural Productivity (short & long term)	800
	Industrial & commercial Impacts	1000
	Property losses (movable & immovable)	1500
	Expenditure on evacuation & rehabilitation	1500

In present study qualitative analysis has been done due to lack of data But for detailed study statistical data such as population density, population breakup (male, female, children, and senior citizens), Crop pattern, detailed data for flora and fauna, Inventory of critical infrastructure, can be used for better results.

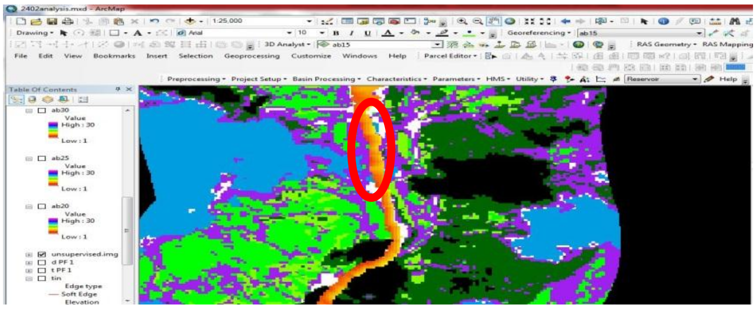

Fig. 4.2: Site -1 exposed to very high severity index for velocity

Table 4.3: CBA analysis for Hotspot Prioritization.

Attributes		Max. score (MS)	Kedarnath		Sonprayag		Kalimath		Rudraprayag		Site-1	
			S1= 0.5	S2= 0.5	S1= 0.4	S2=0 .4	S1= 0.3	S2= 0.4	S1= 0.4	S2= 0.3	S1= 0.5	S2= 0.4
			V	S	V	S	V	S	V	S	V	S
Social Impacts	Human causalities and Injuries	2000	1	2000	0.5	800	0.5	700	0.75	1050	0	0
	Public Inconvenien ce	800	0.74	592	0.75	480	0.75	420	0.75	420	0.5	360
	Health Impacts due to water born disease	1000	0.75	750	0.5	400	0.5	350	0.5	350	0	0
	Psychologic al effects	500	0.75	375	0.5	200	0.5	175	0.5	175	0.25	112. 5
	Loss of shelter and livelihood	600	0.75	450	0.5	240	0.5	210	0.5	210	0	0
	Effects on religious, cultural and tourists monuments	1000	1	1000	0.5	400	0.75	525	0.5	350	0	0
	Effects on educational & administrati onal working	1000	0.25	250	0.5	400	0.5	350	0.5	350	0.25	225

Attributes		Max. score (MS)	Kedarnath		Sonprayag		Kalimath		Rudraprayag		Site-1	
			S1= 0.5	S2= 0.5	S1= 0.4	S2=0 .4	S1= 0.3	S2= 0.4	S1= 0.4	S2= 0.3	S1= 0.5	S2= 0.4
			V	S	V	S	V	S	V	S	V	S
Environmental Impacts	Water Pollution (Point & Non Point)	800	0.5	400	0.25	160	0.25	140	0.75	420	0.25	180
	Erosion	600	0.75	450	0.5	240	0.5	210	0.5	210	1	540
	Ecosystem Degradation (Terrestrial &Aquatic)	500	0.25	125	0.25	100	0.5	175	0.5	175	0.5	225
	Habitat Losses	800	0	0	0.25	160	0.5	280	0.5	280	0.5	360
	Impact on Endangered Species	800	0.25	200	0.25	160	0.25	140	0.25	140	0.5	360
	Sedimentati on in lower areas	800	0.25	200	0.25	160	0.5	280	0.5	280	0.5	360
	Sewer outflows (CSO/SSO)	600	0	0	0.25	120	0.25	105	0.25	105	0	0
Economic Impacts	Productivity Loss (working hours)	400	0.25	100	0.5	160	0.5	140	0.75	210	0.25	90
	Agricultural Productivity (short & long term)	800	0	0	0.25	160	0.25	140	0.25	140	0	0
	Industrial & commercial Impacts	800	0	0	0.25	160	0.25	140	0.5	280	0	0

Attributes		Max. score (MS)	Kedarnath		Sonprayag		Kalimath		Rudraprayag		Site-1	
			S1= 0.5	S2= 0.5	S1= 0.4	S2=0 .4	S1= 0.3	S2= 0.4	S1= 0.4	S2= 0.3	S1= 0.5	S2= 0.4
			V	S	V	S	V	S	V	S	V	S
	Property losses (movable & immovable)	1000	0.5	500	0.75	600	0.75	525	0.75	525	0	0
	Expenditure on evacuation & rehabilitatio n	1500	0.5	750	0.75	900	0.75	787.5	0.75	787.5	0.25	337. 5
	Total Importance			8142		6000		5792		6457		3150
	Rank			1		3		4		2		5

4.3 Results

Five hotspots have been identified that are Rudraprayag, Sonprayag, Klamath, Kedarnath and Site-1 (A landslide prone reach near Gaurikund). After the CBA analysis Kedarnath has been ranked one for the flood risk and it is followed by, Rudraprayag, Sonprayag, Kalimath and Site-1 respectively.

4.4 Conclusion

Kedarnath has been ranked one for flood risk. This is because of unique combination of various parameters at this place. It is a religious place where a large number of pilgrimages visit every year. Since it open for only few months of the year, most of the shelters there are temporary. Further being at very high elevation it is most cloudburst prone area and also exposed to very high velocities of flood because of steep slopes.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Flood Risk Analysis and Mapping

Inundation varies from 9.67 sq. km for 1500 cumecs flood to 11.74 sq. km for 3000 cumecs flood. A major portion of the inundated area is classified as barren land. Figure 5.1 shows the combinations of inundated land use corresponding to floods of different magnitudes.

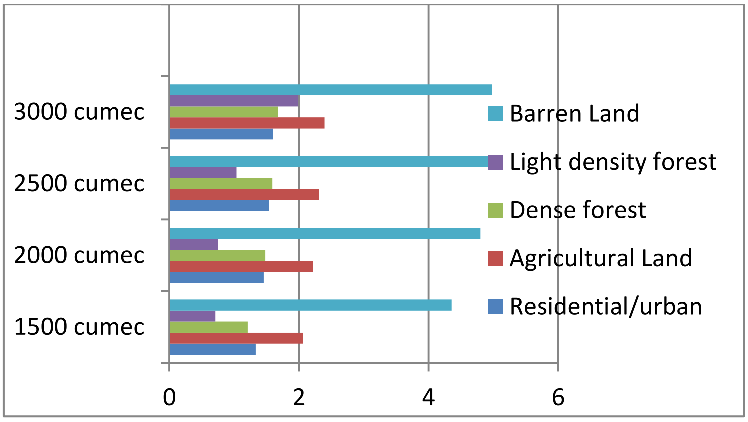

Fig. 5.1: Inundated area corresponding to different flood events

Floodplain for 2000 cumecs flood is 10.8% larger than that corresponding to 1500 cumecs. However floodplain for 2500 cumecs flood is 6.3% larger than that corresponding to 2000 cumecs. Incremental changes for the floodplain are more rapid for floods of lower magnitude. Figure 5.2 shows the breakdown for different categories of land use and their percentage corresponding to given four flood magnitudes.

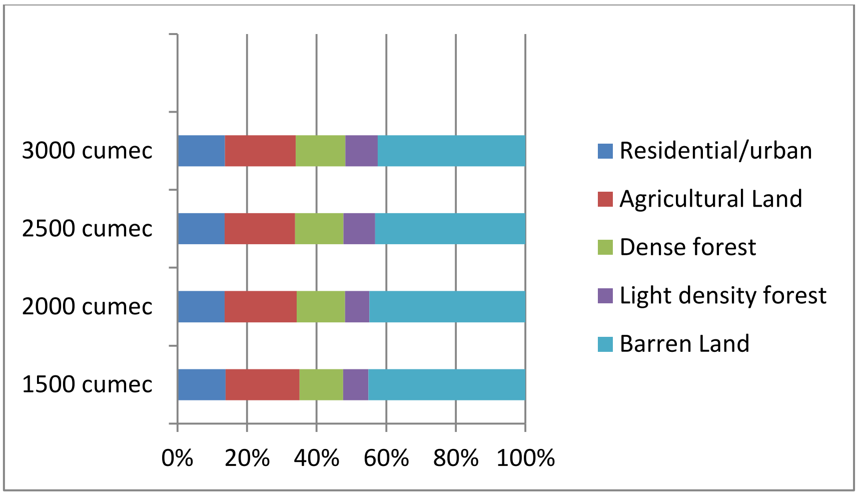

Fig. 5.2: Percentage inundation of different Land Use categories for different flood events

5.2 Hotspot Identification and Prioritization

Five hotspots have been identified that are Rudraprayag, Sonprayag, Klamath, Kedarnath and Site-1 (A landslide prone reach near Gaurikund). Based on the CBA analysis Kedarnath has been ranked first for the flood risk and it is followed by Rudraprayag, Sonprayag, Kalimath and Site-1 respectively. Based on the priority these sites may be considered for resource allocation, and policy planning for flood risk management.

CHAPTER 6
CONCLUSION

The basic idea of flood risk analysis and mapping as undertaken in this study is to provide basic information for planning and management of flood risk. In the light of above discussion, Flood risk mapping, being a non-structural tool can be effectively used in flood management in the areas frequented by flood. Integration of hydraulic modelling with geospatial analysis is a very good approach provided the data used are accurate and standardized. This study confirmed that the proposed methodology was capable of integrating the factors and the components of flood risk through hydraulic modelling as well in a GIS. In this fashion, flood inundation maps were generated to assess the flood risk for Mandakini basin hotspot for prioritization of resources and policies have been identified using CBA. Therefore, it has been shown that this method has the potential to provide information for decision making in disaster studies. Also the proposed methodology for estimation of flash floods induced by cloudburst can be used by practitioners, as the commonly used empirical equations do not apply to the cloudburst.

Flooding being a natural phenomenon cannot be stopped completely but we can minimize the losses by better planning and management. Flood management and consequently flood mapping is a key focus for Himalayan states. To support this important target this study was focused on developing an efficient and easy method aiming at a reliable flood-risk analysis and mapping. Also this study points towards the lack of availability of reliable data that ultimately leads to inaccurate results. A strong need is felt for record or inventory of historic disaster events and other meteorological and socioeconomic data along with an easy access to it. On the other hand, flood hazard and risk assessment is still associated with large uncertainties, even in areas where reliable data and good model base is available.

Furthermore, as hazard and vulnerability are constantly varying factors, corresponding analyses and maps must be updated from time to time. This work can be further extended as pilot studies where more detailed and quantitative socio economic and meteorological and geospatial data of better resolution and reliability can be used for better results. The detail of such uncertainty and risk analysis can be defined for the individual cases, such as planned protection measures and specific area of interest. The study can be incorporated into other, science-based methodologies related to current policies for disaster risk management. The capacities of modelling integrated with GIS and remote sensing must be explored and essentially used as an element in community based disaster management projects.

REFERENCES

1. Abt SR, Wittler RJ, Taylor A, Love DJ (1989) Human stability in a high hazard flood zone. Water Resources Bulletin 25(4):881–890
2. Bartels CJ, van Beurden AUCJ (1998) Using geographic and cartographic principles for environmental assessment and risk mapping. J Hazard Mate 61:115–124
3. Blaikie P, Cannon T, Davis I, Wisner B (1994) At risk. Natural hazards, people's vulnerability, and disasters. Routledge, London, New York
4. BUWAL (Bundesamt für Umwelt, Wald und Landschaft) (1998) Methoden zur Analyse und Bewertung von Naturgefahren. Umwelt-Materialien Nr. 85, Bern, p 229
5. Comfort L, Wisner B, Cutter S, Pulwarty R, Hewitt K, Oliver-Smith A, Wiener J, Fordham M, Peacock W, Krimgold F (1999) Reframing disaster policy: the global evolution of vulnerable communities. Environmental Hazards 1:39–44
6. Central Water Commission, 1972, Estimation of Design Flood- Recommended Procedures, New Delhi.
7. Central Water Commission, 1994, Flood Estimation report for Western Himalayas-Zone 7, India,.
8. Das S, Ashrit R, 2006, Moncrieff MW Simulation of a Himalayan cloudburst event. J Earth SystSci115(3):299 313.
9. Dhar ON, Nandargi S, 1998, Rainfall magnitudes that have not been exceeded in India. Weather 53(5):145–150.
10. District Profile, LADHC Leh, Leh District Administration, web, 19th October 2015, http://www.leh.nic.in
11. Dooge J. C. I., 1959, A general theory of the unit hydrograph.'' J. Geophys. Res., 64~2!, 241–256,
12. Flaxman E.M., 1974, Potential errors in peak discharge estimates obtained by indirect methods: Portland, Oregon, U.S. Soil Conservation Service, West Technical Service Centre, Engineering technical note no. 5, 15 pp.
13. Gourley JJ, Erlingis JM, Smith TM, Ortega KL, Hong Y, 2010, Remote collection and analysis of witness reports on flash floods. J Hydrol 394:53–62.
14. Jain S, Lall U (2002) Floods in a changing climate: Does the past represent the future? Water Resources Research 37(12):3193–3205
15. Jarret R.D., 1986, Evaluation of slope-area method for computing peak discharge. In: Selected papers of the hydrological sciences. U.S. Geological Survey Water Supply Paper 2310, pp 13–24.

16. Jonkman SN, van Gelder PHAJM, Vrijling JK (2003) An overview of quantitative risk measures for loss of life and economic damage. J Hazardous Material A99:1–30
17. Kaplan S, Garrick BJ (1981) On the quantitative definition of risk. Risk Analysis 1(1):11–27
18. Klemés V (1993) Probability of extreme hydrometeorological events – a different approach. In:Kundzewicz ZW, Rosbjerg D, Simonovic SP, Takeuchi K (eds) Extreme hydrological events: precipitation, floods and droughts, IAHS-Publication, No. 213:167–176
19. Kumar MS, Shekhar MS, Rama Krishna SSVS, Bhutiyani MR, Ganju A, 2012, Numerical simulation of cloud burst event on August 05, 2010, over Leh using WRF mesoscale model. Nat Hazards 62(3):1261–1271.
20. Linsley, R.K., 1958, Hydrology for Engineers, McGraw-Hill, New York, USA.
21. Marco JB (1994) Flood risk mapping. In: Rossi G, Harmancioglu N, Yevjevich V (eds) Coping with floods, Kluwer Academic Publishers, Dordrecht, 353–373
22. Menendez M (2000) Design discharge calculations and flood plain management. European Commission (Directorate General XII): FLOOD aware Final report, Cemagref, pp53–82
23. Mileti DE (1999) Disasters by design. A reassessment of natural hazards in the United States, Joseph Henry Press, Washington, DC
24. Milly PCD, Wetherald RT, Dunne KA, Delworth TL (2002) Increasing risk of great floods in a changing climate. Nature 415:514–517
25. Owen L.A., Caffee M.W., Bovard KR, Finkel R.C., Sharma M.C., 2006, Terrestrial cosmogenic nuclide surface exposure dating of the oldest glacial successions in the Himalayan orogeny: Ladakh Range, northernIndia. GSA Bull 118(3/4):383–392
26. Penning-Rowsell E, Fordham M, Correia FN, Gardiner J, Green C, Hubert G, Ketteridge A-M, Klaus J, Parker D, Peerbolte B, Pflügner W, Reitano B, Rocha J, Sanchez-Arcilla A, Saraiva MdG, Schmidtke R, Torterotot J-P, Van der Veen A, Wierstra E, Wind H (1994) Flood hazard assessment, modelling and management: results from the EUROflood project. In: Penning-Rowsell E, Fordham M (eds) Floods across Europe: flood hazard assessment, modelling and management, Middlesex University Press, London, pp37–72
27. Petrow T, Thieken AH, Kreibich H, Merz B, Bahlburg CH (2006) Improvements on flood alleviation in Germany – Lessons learned from the Elbe floods in August 2002. Environmental Management, 38(5):717–732

28. Pidgeon N, Hood C, Jones D, Turner B, Gibson R (1992) Risk perception. The royal society, Risk: analysis, perception and management, London, pp89–134
29. Renoj J. Thayyan, A.P.Dimri, Pradeep Kumar, G. Agnihotri, 2012, Study of cloudburst and flash floods around Leh, India during August 4–6, 2010, Springer Science+Business Media Dordrecht.
30. Singh, V. P., 1988, Hydrologic systems: Rainfall-runoff modeling, Vol.1, Prentice-Hall, Englewood Cliffs, N.J.Sokolov.
31. Slovic P (1998) The risk game. Reliab Eng and Syst Saf 59:73–77
32. Smith DI (1994) Flood damage estimation – a review of urban stage-damage curves and loss functions. Water SA 20(3):231–238
33. Smith K (2001) Environmental hazards. Assessing risk and reducing disaster, Routledge, 3rd edn. London, New York
34. Suhr, J. (1999). The Choosing By Advantages Decision making System. Quorum, Westport, CT, 293 pp
35. TAW (Technical Advisory Committee on Flood Defence) (2004) Floris: flood risks and safety in the Netherlands
 www.tawinfo.nl/engels/downloads/FloodRisksandSafety.pdf)
36. Tideman, 2007, WATERSHED ANAGEMENT, Guidelines for Indian Conditions, Omega Scientific Publishers, New Delhi, India
37. Todini E (1999) An operational decision support system for flood risk mapping, forecasting and management. Urban Water 1:131–143
38. Watt WE (2000) Twenty years of flood risk mapping under the Canadian national flood damage reduction program. In: Marsalek J et al (eds) Flood issues in contemporary water management, Kluwer Academic Publishers, pp155–165
39. Werner MGF (2001) Impact of grid size in GIS based flood extent mapping using a 1D flow model. Phys. Chem. Earth (B) 26(7–8):517–522
40. Wind HG, Nierop TM, de Blois CJ, de Kok JL (1999) Analysis of flood damages from the 1993 and 1995 Meuse flood. Water Resources Research 35(11):3459–3465