Glacial lake outburst flow analysis Using Hydrodynamic modelling

A DISSERTATION

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By

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MAY 2019

CERTIFICATE

I, **BHAWANI SINGH MEENA,** hereby solemnly declare that the work presented in the project, entitled "**Glacial lake outburst flow analysis using hydrodynamic modelling"** is submitted by me for the partial fulfillment of requirements for award of the degree of Integrated Master of Technology to the Department of Earth sciences , Indian Institute of technology Roorkee, is an authentic record of my work carried out during the period of May 2018 to May 2019 under the supervision of **Dr. Ajanta Goswami,** Assistant professor, Department of Earth Sciences, Indian Institute of Technology Roorkee.

The matter embodied in this project has not been submitted by me for award of any other degree of Indian Institute of Technology, Roorkee or any other institute.

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Declaration

I, **Bhawani Singh Meena**, hereby declare that this written submission represents my own ideas and words. Wherever I have used the ideas or words of others, I have duly cited and referenced the original sources. I also declare that I adhered to all the principles of academic honesty and veracity, and have not misinterpreted and fictitious or falsified any information in my thesis and I realize that doing so will not result in disciplinary action from the institute or the sources which have not been properly cited or from whom passable permission has not been taken.

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ABSTRACT

The Indian Himalayas stretches out for almost 2400 kms and has a breadth of around 400 kms. The stretch has approx. 10,000 glaciers in Indian Himalayan boundary which dynasties few thousands glacial lakes which are growing in terms of area and volume. The glaciers in high mountain region are unstable because of varying climatic conditions. Due to melting of glaciers new glacial lake of varying size take place, some of which are very willing to outburst flooding.

The lakes are dammed by ice or moraines makes them unstable. The glacial lakes which are prone to outburst can damage nearby settlements cause loss of lives, infrastructure in downstream valleys.

The recent Kedarnath tragedy in Uttarakhand Himalayas in the year 2013 which led to massive loss to life and livelihood in surrounding areas is an alarm to the ever-increasing threat from those store house of water. The study proposes an agenda for a first stage hazard assessment of glacial lakes using GIS techniques and a digital elevation model. It introduces a new dynamic flow runoff model in a glacial lake threat context.

Table of contents

1. Introduction ……………………………………………………...10

1.1 Background …………………………………………………………………………. 12

1.2 Glacial lake outburst flood events history ………………………………………….. 13

1.3 Importance of Glof Study ……………………………………………..……….…... 16

1.4 Importance of Remote Sensing……………………………………………………... 17

2. Literature review ……………………………………………. 18

2.1 Background ………………………………………………………………………… 18

2.2 Causes of flood and characteristics ………………………………………….……. 20

2.3 Hazard assessment ……………………………………………………………….…….21

2.4 Glof modelling ……………………………………………………………………………. 21

2.5 Saint Venant Equation ………………………………………………………………….23

3. Study area …………………………………………………….25

4. Data used ………………………………………………………29

4.1 Satellite data ……………………………………………………………………….…... 29

4.2 Software Used ………………………………………………………………………….30

5. Methodology ………………………………………………….31

5.1 Model parameters………………………………………………………………………….31

5.2 Breach parameters calculations ………………………………………………………. 45

5.3 Manning roughness coefficient ……………………………………………………….47

6. Results and Discussion ………………………………………..48

7. Conclusion………………………………………………………. 54

List of figures

Fig 1: Map showing the glacial lakes formed in study area and the presence of 400 MW hydroelectric plant and the newly proposed 140 MW hydroelectric plant ………………10

Fig.2: Map showing the glacial lakes and the hydroelectric plant without satellite image.11

Fig 3 and 4: Before and after images of chorabari lake (Kedarnath tragedy). Source Dr. Ajanta Goswami……………………………………………………………………………14,15

Fig 5 and 6: helicopter image of before and after image of Kedarnath temple. Source-: google images ……………………………………………………………………………………16

Fig. 7: Different types of moraines in glaciers. Source: -Google images…………………18

Fig. 8: Terminal moraine at the foot of a small glacier. Source: Stebinger, E.C., U.S. Geological survey ………………………………………………………………………………..19

Fig. 9: Types of glacial lakes (Source: ICIMOD) ………………………………………..…..20

Fig.10: Uttarakhand, source: Amit Anand …………………………………………………25

Fig.11: Glacial lakes mapped by ICIMOD, source – ICIMOD……………………………..26

Fig-12: Study area (Google Earth)…………………………………………………………27

Fig.13: Satopanth tal source: Ramesh c Sharma and Rahul Kumar …………………..28

Fig.14 ASTER GDEM of the study area ……………………………………………………....29

Fig.15: Methodology ………………………………………………………………………..32

Fig.16: Dem with bank lines and centerline ………………………………………………33

Fig.17: Water shed of study area…………………………………………………………….34

Fig.18: LULC of study area ………………………………………………………………..35

Fig.19: Map showing terrain in meter ……………………………………………………….37

Fig.20: Map of study area showing slope in degree ………………………………………39

Fig.21: mesh area for 2D unsteady flood over on satellite images ………………………40

Fig.22: 3D river plot …………………………………………………………………………40

Fig.23: Elevation with main channel distance ……………………………………………41

Fig.24: Map showing mesh along with banks, flow path and centerline…………………42

Fig.25: Lake location georeferenced with satellite image …………………………….....44

Fig.26: HEC-RAS Map showing mesh along with boundary conditions and inflow and outflow ……………………………………………………………………………………….45

Fig.27: Map showing the Flood Inundation depth water along the valley over DEM…..48

Fig.28: Flood Inundation depth water along the valley over Satellite Images…………..49

Fig.29: Map showing the Flood Inundation map – Maximum Depth over DEM ……….50

Fig.30: Map showing cross sections ………………………………………………………53

List of Tables

Table 1: Satopanth tal location …………………………………………….....26

Table 2: Data used in the present study ……………………………………. 30

Table 3: Description of given values in LULC study area………………… 36

Chapter 1- INTRODUCTION

High mountain regions have experienced decreased glacier steadiness due to varying climate conditions (Casassa et al. 2014). As glaciers melt, they are being replaced by glacial lakes of different sizes, some of which are prone to outburst flooding, and have caused catastrophic mutilation to downstream clearings and structure (Rounce et al. 2016). Carrying water and sediment, floods from moraine dammed lakes can travel more than 100 kilometers at high velocities (Worni et al. 2014). Moraine dams formed during the Little Ice Age (conventionally 16th–mid 19th century period of glacial advance), are glacial landforms serene of loose sediments, coarse materials left behind by advancing glacial ice (Section 2.1). Released floodwaters are mixed with rock, mud, glacial sediments and can erode the banks along the flood path (Iturrizaga 2011).

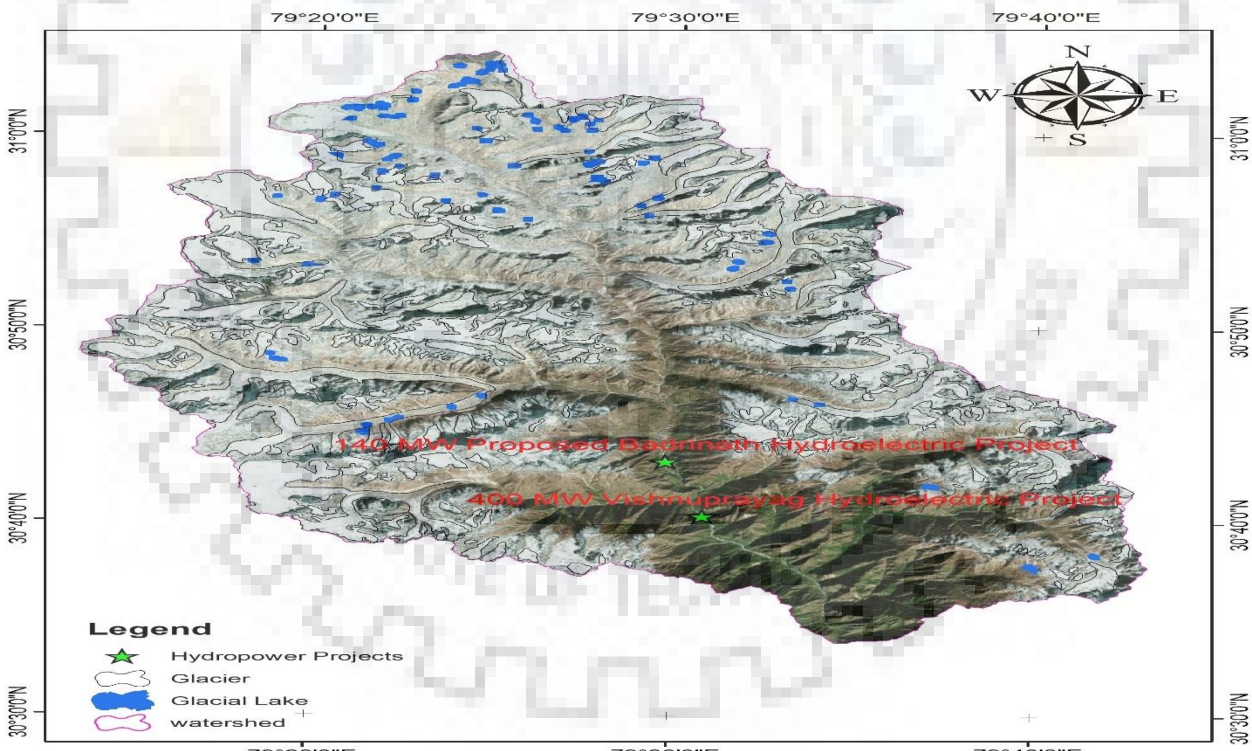


Fig 1: Map showing the glacial lakes formed in study area and the presence of 400 MW hydroelectric plant and the newly proposed 140 MW hydroelectric plant

There are more than 80 glacial lakes in the study area which are dammed by moraines which consists of loose particles and formed by retreating of glaciers. Some of these lakes are very prone to outburst and can causes severe damage in downstream areas. We have two hydroelectric plant one is 400 MW present in Vishnuprayag and the second one is of 140 MW which is newly proposed in Badrinath area. The study area is very important in order to understand the GLOF events because it has more than 80 glacial lakes and two hydropower plants in river path and at high elevation, If the lakes outburst in any instance they will increase the amount of water in river which can cause severe damage to hydroelectric plant and several area at an low elevation which are present at the bank of river like pipalkoti, batula, haat, jainsal, tartoli, birahi khainuri, chinka, mathmalana and so on.

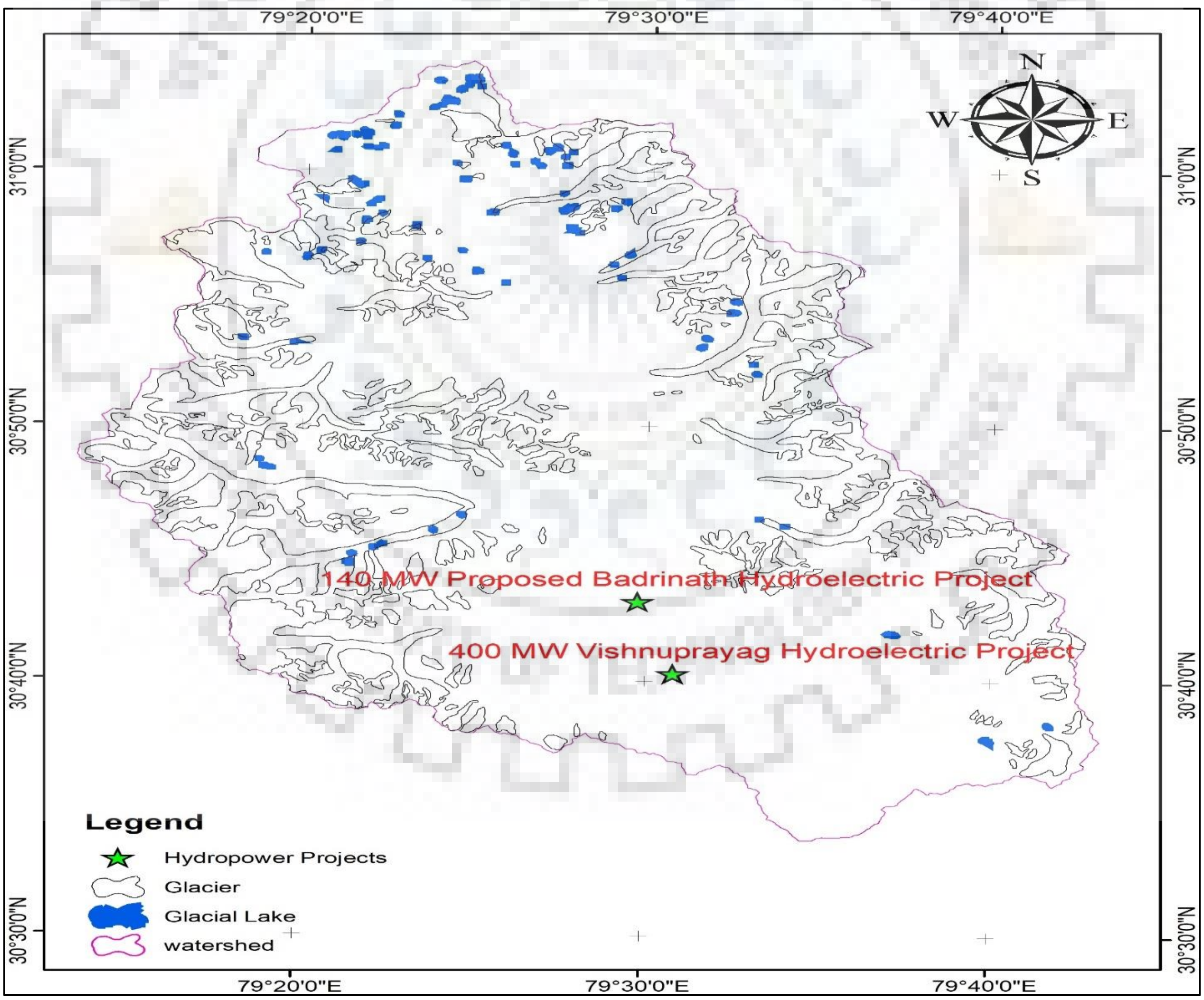


Fig.2: Map showing the glacial lakes and the hydroelectric plant without satellite image

Objective and Scope

- To identify the flood prone area
- To give sufficient warning to the downstream side inhabitants
- To give an idea about the time and flood level at which the flood strikes a particular area

1.1 Background

Earlier events of lake flooding have been recorded in high mountain shires of the world including the Peruvian Andes, Himalayas, Hindu Kush and Karakoram mountain ranges. In 1941, the Laguna Palcacocha lake surge resulted in six thousand people losing their lives in the city of Huaraz, Peru (Huggel et al. 2002). Peru has experienced more than 21 glacial lake floods in the last 65 years (Wang et al. 2015). This comprises the Lake Safuna Alta flood in 2002 set off by a rock avalanche (Hubbard et al. 2005) and the 2010 glacial lake outburst flood in Chucchún valley, Cordillera Blanca, when a glacial block packed up into the lake (Vilímek et al. 2015).

The average increase in earth temperature is called global warming. This has been increasing rapidly and extremely dangerous over the last few centuries. In the high-altitude regions of earth where the mountains are all covered with snow the effect is more prominent by global warming.

We have seen the melting of ice in Arctic and Antarctic as a result of global warming which are reported frequently, despite larger number of people affected in Himalayas regions but there is no report on that.

The Himalayas contribute 9.05% glacier cover and an additional area of 40% covered with snow out of 10% of world snow blanket.

The duration of snowfall is depended by the strength of ice crystals as shorter periods of snowfall proscribes formation of solid ice crystals from snow which results in quick melting of glaciers. If there is precipitation instead of snowfall than there is greater chance to change in climatic which increases the melting process of glaciers thus the glaciers melt rapidly because there is no snow for forming glaciers and the precipitation causes increase in temperature and hence the snow melts.

Because of this change in climatic conditions Indian scenario has been affected. Indian glaciers cover expands to 37579 km square with over 5243 glaciers. Gangotri glacier, Millain glacier and Dukrian are the bulging glaciers of India which are decreasing at the rate of 20-23 miles per year, 30m/year and 15-20m/year respectively.

The reason behind these melting or decreasing of glaciers is global warming. The last few years have seen a dramatic rise in the rate of melting of Gangotri glacier around 6m/yr to the current value. Glacial lake outburst flood i.e. GLOF is the catastrophic effect of glacial retrieval.

The rate of receding is very high in Himalayan glaciers in compare to any other part of glaciers all over world, if this kind of rate continues than Himalayan glaciers will be disappeared by 2035 or may be earlier than this if the average temperature increased this way. The Himalayas will be left 1.9% of it by 2035

1.2 Glacial lake outburst flood events history

Kedarnath is the recent flood tragedy that is very notable in recent past in India which causes loss of many lives, infrastructure, properties. There are two events which had happened in consecutive days on 16th June 2013 and 17th June 2013.

On 16th June there is heavy rainfall which cause erosion and accumulation of sediments in mandakani river and its surrounding river channels. As a result, a large amount of debris in mandakani river and its surrounding rivers moves towards the upper part of Kedarnath and washed away it fully. The second event happened on 17th June around 6am- 7am overflow of water in chorabari lake which broke the moraine dam on it, results in releasing larger amount of water which results in flash flood in Kedarnath town. Around 15th to 17th June 2013, because of substantial rainfall and soppy glacier lateral basin which covered more than seven feet thick ice near the upper part of the lake accumulated a huge quantity of water in lake of chorabari thus the shear asset of weir is decreased, ultimately the glacial deposit dam is broken causing heavy damage in low lying areas.

Fig 3 and 4: Before and after images of chorabari lake (Kedarnath tragedy). Source Dr. Ajanta Goswami

According to reports 236 people injured,197 killed, 4031 went missing in flash flood. It affects more than 5 districts of Uttarakhand. Around 2200 house are brutally damaged 3000 are badly damaged and 11000 are partially damaged.

Fig.5 and 6: helicopter image of before and after image of Kedarnath temple. Source-:google images

1.3 Importance of GLOF study

Suitable planning and precautions are few steps that may be taken to minimize the damages. A GLOF incident result in dam failures causes destruction in low lying areas.

The aim of this study is to minimize the effect causes by dam failures by estimating the amount of discharge at dam sites so that necessary measurement can be taken to divert or accommodate the water.

1.4 Importance of remote sensing

The elevation of Himalayan glaciers snowline is at 3800m from mean sea level (msl) Collection of data for investigation on high altitude areas are very difficult as compare to plane areas because most of the area are inaccessible. Remote sensing is used to overcome this problem for collecting data in inaccessible areas. The important information like topography, geomorphology and physical conditions are find out by remote sensing softwares like Arc GIS, HEC RAS QGIS etc. Time series analysis can be carried out to study the changes in region for a given time period.

Chapter 2- LITERATURE REVIEW

2.1 Background

Moraines and Glacial lakes

Landform in glacial environment is called moraines, which consists of till or loose sediments which are deposited whenever there is movement in glacier. It consists almost of all type of sediment size like boulder, cobble, pebble, sand, silt, clay. Moraines can be of different types depends on their positions and the process by which they formed. Often, they are ten to fifteen meters of high and the ration of their width to height oi vary from 0.1 to 0.2 . Terminal, Lateral, Parallel, Medial, Recessional are some type of moraines.

Recessional moraines are younger in comparison to other moraines and it is parallel to terminal moraine. Whereas the lateral moraines are formed on either side of the glacier. Medial moraine presents in between the two lateral moraines.

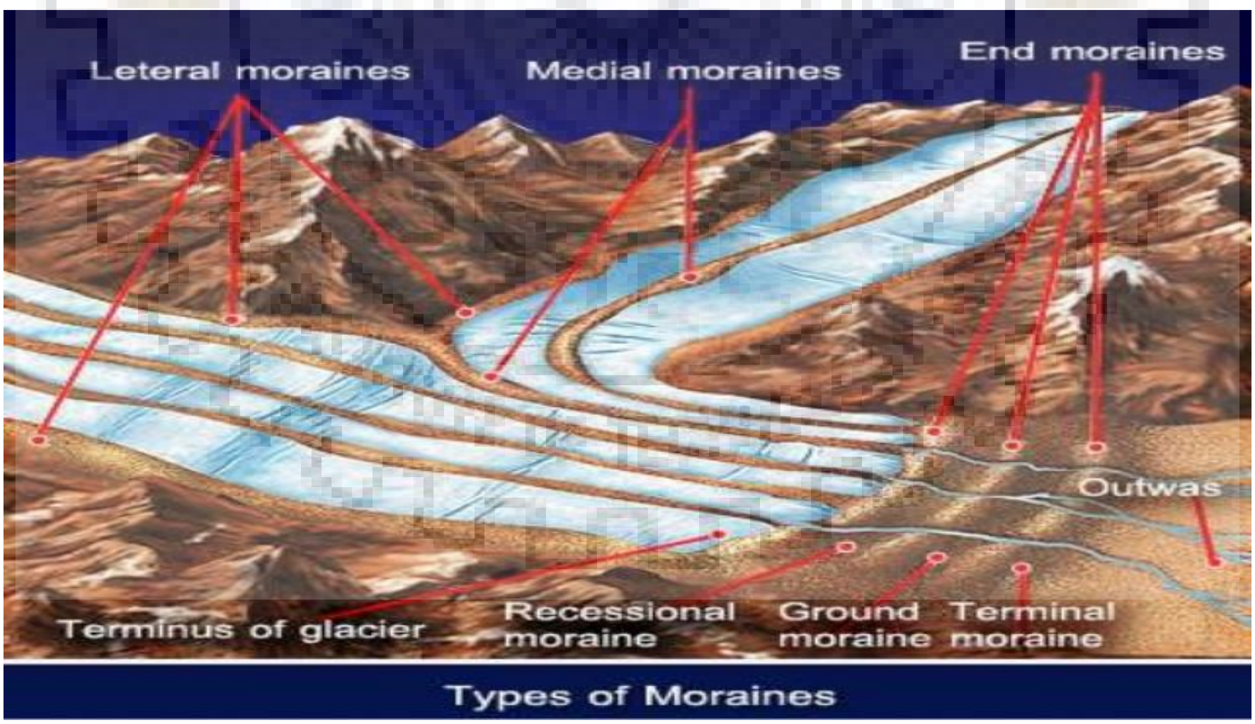


Fig.7: Different types of moraines in glaciers. Source:-Google images

Fig.8 Terminal moraine at the foot of a small glacier. Source: Stebinger, E.C., U.S. Geological Survey

At a height above 3500m because of retreating of glaciers, the lakes are evolved are called glacial lakes. The earth crust got depressed by huge weight of ice sheets or glaciers, so when these glaciers move in forward direction, they erode the land surface resulting in huge depressions. As these glaciers retreats, they leave a large amount of ice in it. Whenever the ice melts these depressions got filled by large amount of water which we called glacier lakes

The name of glaciers is defined by their positions and how they enclosed in present area. The lakes which are formed on the surface of glaciers is supraglacial lake and the one which found under the surface subglacial lake. When the glaciers melt, sometimes the melted water get trapped inside them glaciers channel they are termed as englacial lakes.

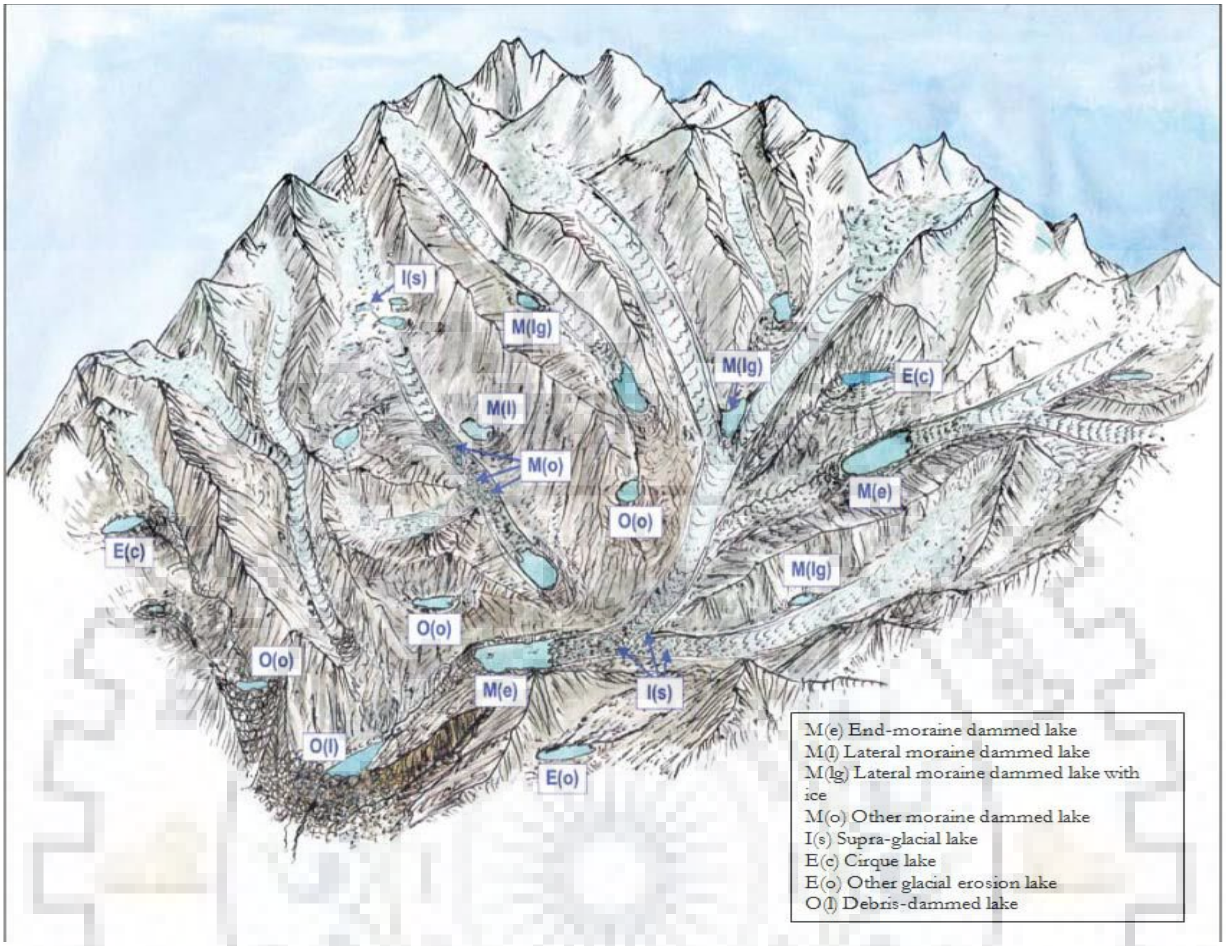


Fig.9: Types of glacial lakes (Source: ICIMOD)

When glacier drainage is stopped by retreating glacier as a result dammed glacial lake formed. So, in this study we focused on moraine dammed lakes or proglacial lakes as they are prone to outburst flood because of sediment accumulation and the amount of melt water entering increase the size of lake hence the lake expands quickly. Usually, they form near glaciers enclosed with rock trashes and sediments because enclosed glacier ends have a tendency to depreciate and create depressions

2.2 Causes of flood and characteristics

Glacial lake floods from moraine dammed lakes are costs of a chain of events leading to moraine dam disaster or dam overflow. Formed on slopes downward under glaciers and rock faces, the lake relaxes on loose sediments. Lake outbursts may be set off by external triggers causing displacement waves which erode the moraine. Triggers could be rock or ice avalanches, glacier calving into the lake, seismic activity or atmospheric activity (Westoby et al. 2014a). The most common trigger leading to dam breaching is due to glacier calving or avalanches setting off impact waves (Jain et al. 2015).

Conditioning factors which contribute to moraine weakness could be piping or ground water flow, the moraine dam geometry such as low width-to-height ratio and low freeboard, permafrost or buried ice core presence in the moraine (Westoby et al. 2014a).

2.3 Hazard assessment

Several studies have applied techniques based on remote sensing and geographic information systems (GIS) for a first order hazard assessment, which are exclusively useful in difficult to access and data scarce regions (Quincey et al. 2007; Huggel et al. 2004; Rounce et al. 2016; Wang et al. 2011). Because of the little possibility of studying each lake in the field, a 1st stage assessment is carried out through isolated sources and selected indicators to slight down potentially hazardous lake sites. A more detailed assessment after this is assumed and requires site precise knowledge. So far, multiple approaches to such an assessment have been proposed, though the indicators significant for consideration are frequently used in different studies

2.4 Glof modelling

Model is the mathematical illustration of actual world phenomena. Modeling is always related with set of mathematical equations which are not enough to signify the total complexity of real spectacles rather than the approximation. Various Hydrological models are used worldwide depending upon the application. For GLOF simulation, Dam break models are used (Huggel et al. 2002).

Flood inundation model

Guessing frequencies of floods from storms is usually done with the help of past streamflow records. For glacial lake floods, different methods are applied as the discharges are much higher and originate from a single slource, capable of changing the characteristics of the drainage basin itself (Post & Mayo, 1971).

Physically based numerical models for flood inundation, after the moraine breach, mostly include one-dimensional (1-D) or two-dimensional (2-D) models, which assume different versions of the Navier Stokes equation for fluid flow. HEC-RAS, Mike 11, NWS-FLDWAV, BOSS DAMBRK, FLO-2D, RAMMS, SOBEK are model examples (Westoby et al. 2014a).

For instance, RAMMS simulation software uses a second order numerical solution of shallow water equations and the specification of a hydrograph to model debris flow (Frey et al. 2016). The HEC-RAS model uses energy and momentum flow equations for unsteady or steady flow through a channel.

Flood modelling

The glacial lake flood phenomenon is regularly described as an intricate manacle reaction. In terms of modelling, Westoby and colleagues (2014a) note that processes are divided into the following components:

1. Triggers such as mass movement into the lake;
2. breaching of moraine dam;
3. Propagation of flood,

Rare studies have attempted to model the entire process chain of the lake flood incident. It is more mutual that processes are modelled distinctly, with the output from one being used as an early condition in the further.

Dam breach model

The models of dam breach may be empirical or deterministic. Calculation of flood peak discharge at the dam breakdown location and time to peak. Empirical models have been often used, though they do not consider basic hydraulic principles associated with breach expansion but rely on regression from historical cases (Westoby et al. 2014a). Deterministic models use numerical sediment-transport relationships to represent erosion processes which cause the dam to break and the dam breach width expansion (Rivas et al. 2015). Inputs to numerical models such as HR-BREACH may require detailed dam geometry characteristics (Westoby et al. 2014b).

2.5 Saint Venant Equation

The Saint Venant Equations were expressed in the 19th century by two mathematicians, de Saint Venant and Bousinnesque.

$$\frac{(\partial Q/\partial X) + \partial\,(A + A_0)}{\partial t - q} = 0\ldots\ldots$$

Equation1:Continuity Equation

$$(\partial Q/\,\partial t)\ +\ \{\partial\,(Q2/A)/\,\partial X\}\ +\ g\,A\,((\partial h/\,\partial X)\ +\ Sf\ +\ Sc)\ =\ 0$$

Equation 2:Momentum equation

Where,

Q = discharge

A0 = inactive storage area

q= lateral flow

A = active flow area

h = water surface elevation

x = distance along waterway;

t = time S_f = friction slope

S_c = expansion contraction slope and g = gravitational acceleration.

Chapter 3- STUDY AREA

Location

Satopanth is one of the biggest and important glacier lakes of Alkapuri glacial of Garhwal Himalaya of Uttarakhand state is chosen for the GLOF study. The distance between Satopanth and Badrinath is 22 km the world most eminent temple. It is situated at an altitude of 16000 feet from mean sea level. The lake has it`s religious significance foe the local people, they throw the ashes in Satopanth lake.

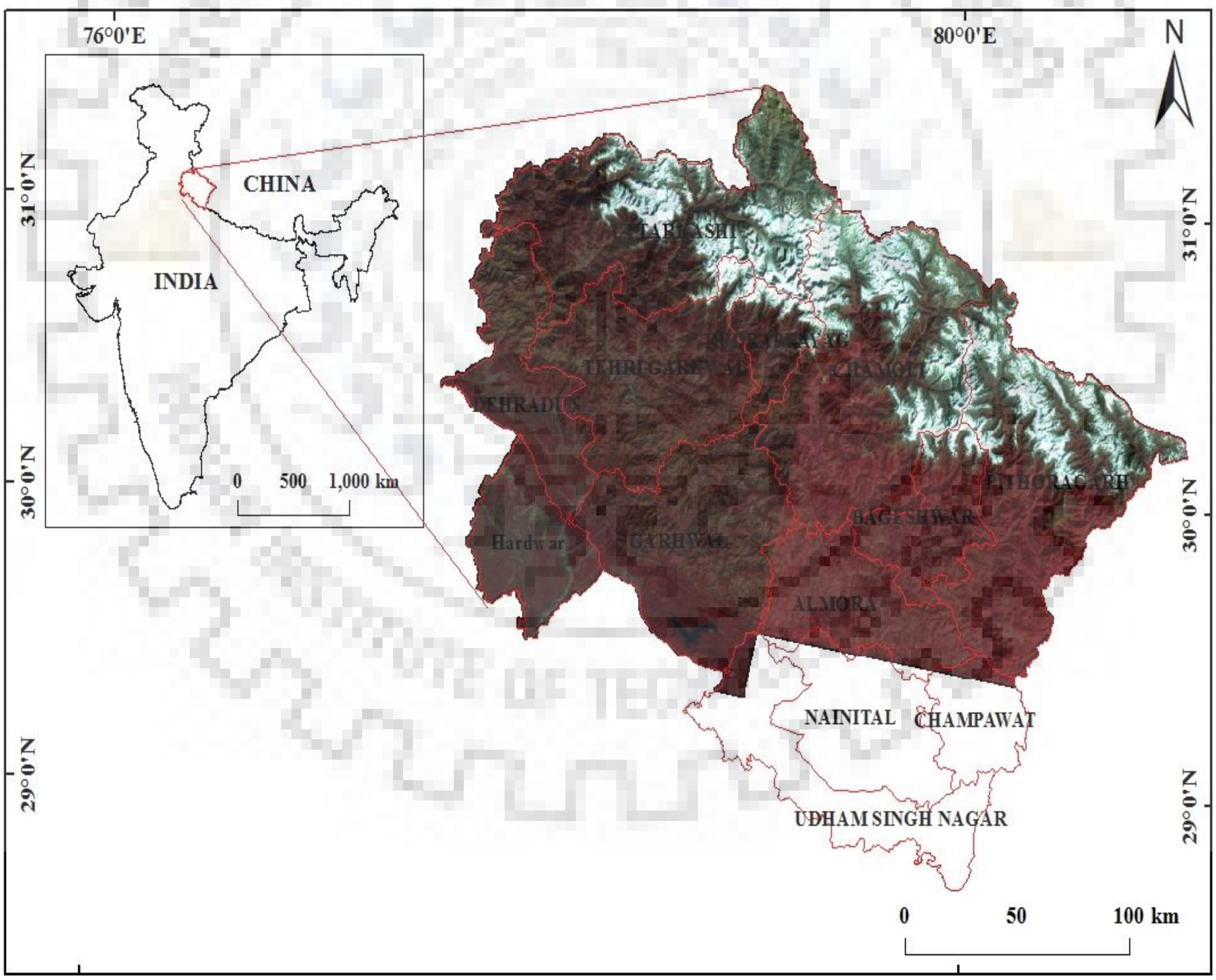


Fig.10: Uttarakhand, source: Amit Anand

Elevation	4602 m
Latitude	30º44`682` N
Longitude	79º21`468` E
Location	North West Himalayas

Table -1 : Satopanth Tal Location

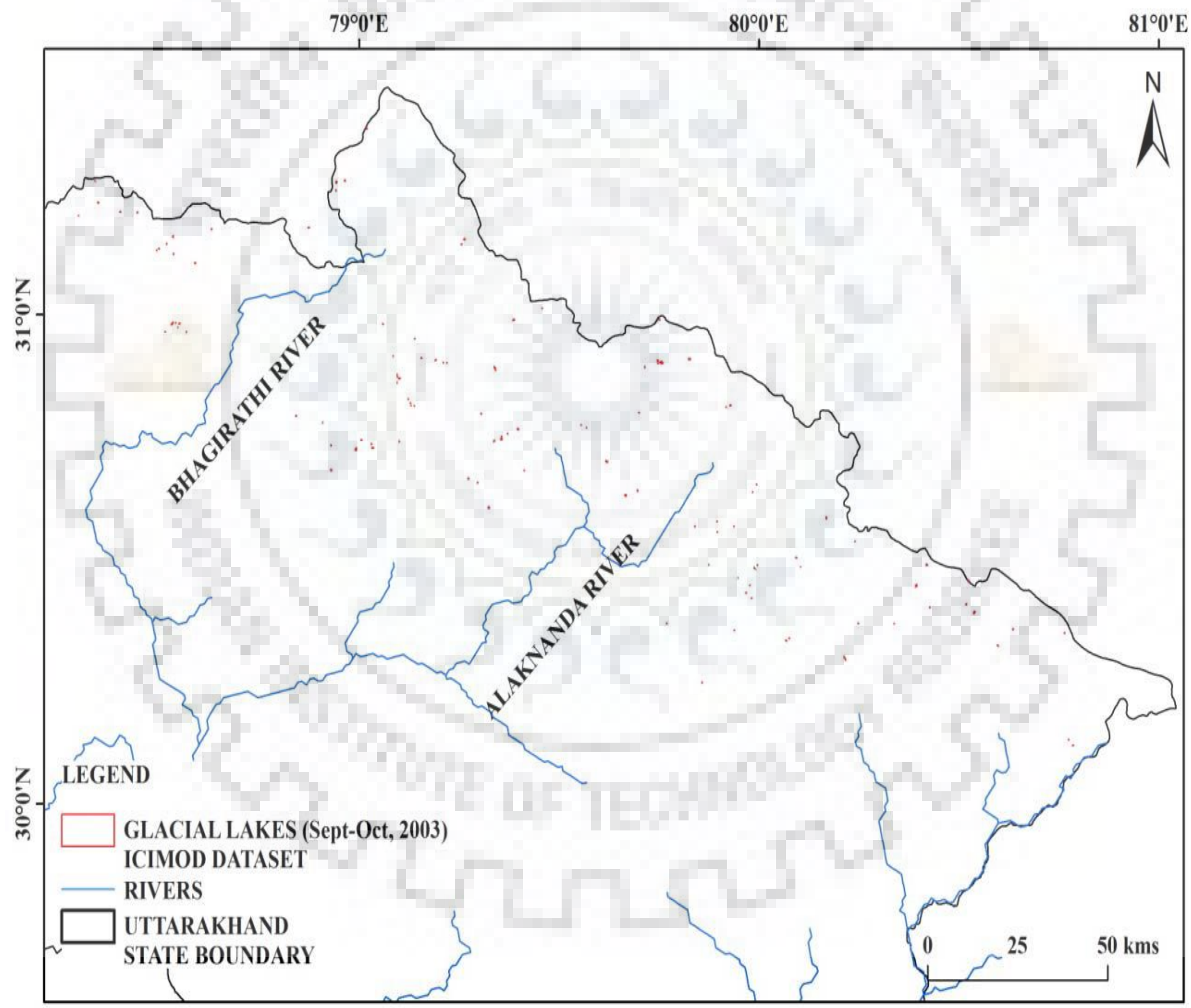


Fig.11 Glacial lakes mapped by ICIMOD, source – ICIMOD

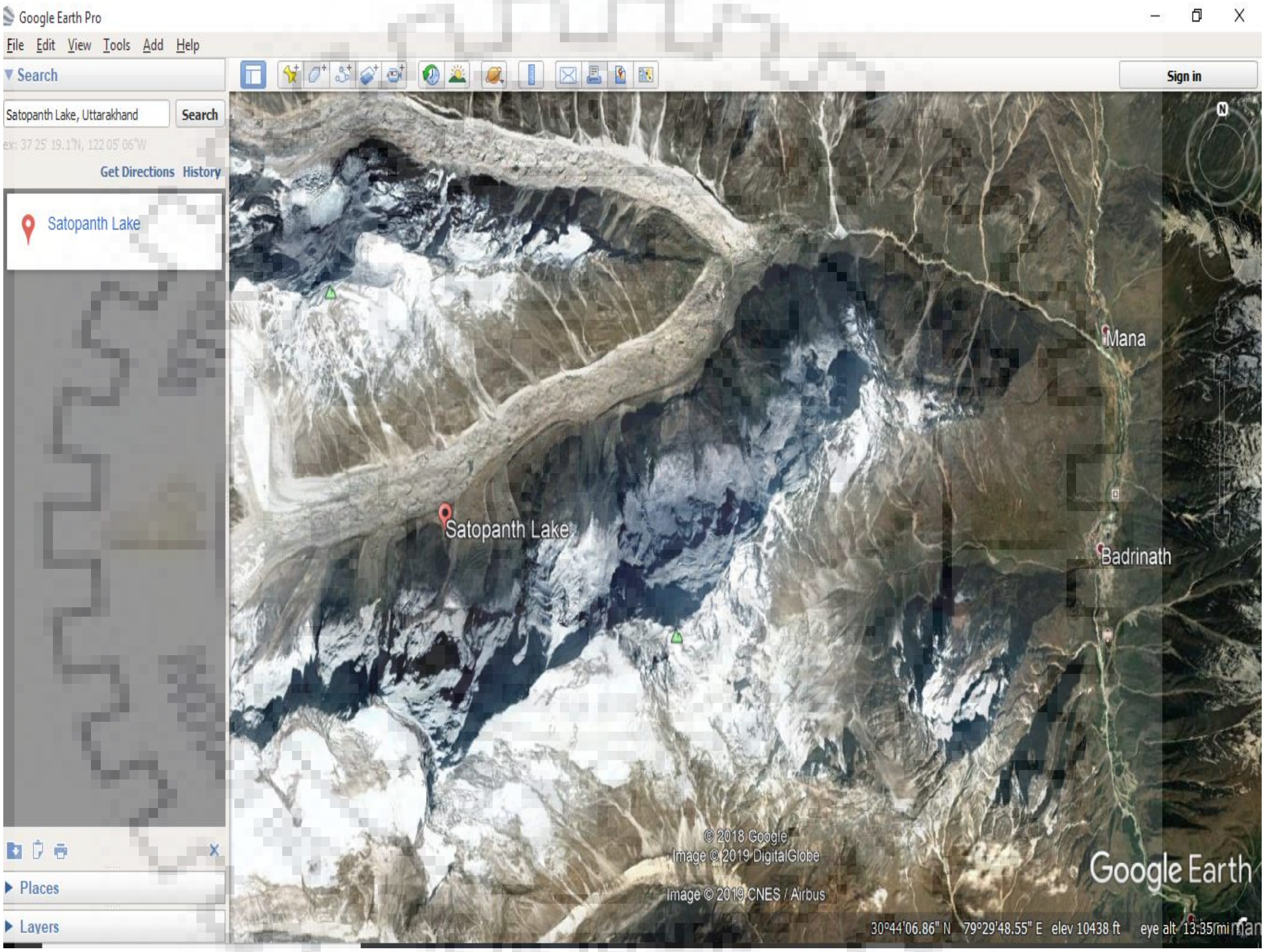


Fig-12: Study area (Google Earth)

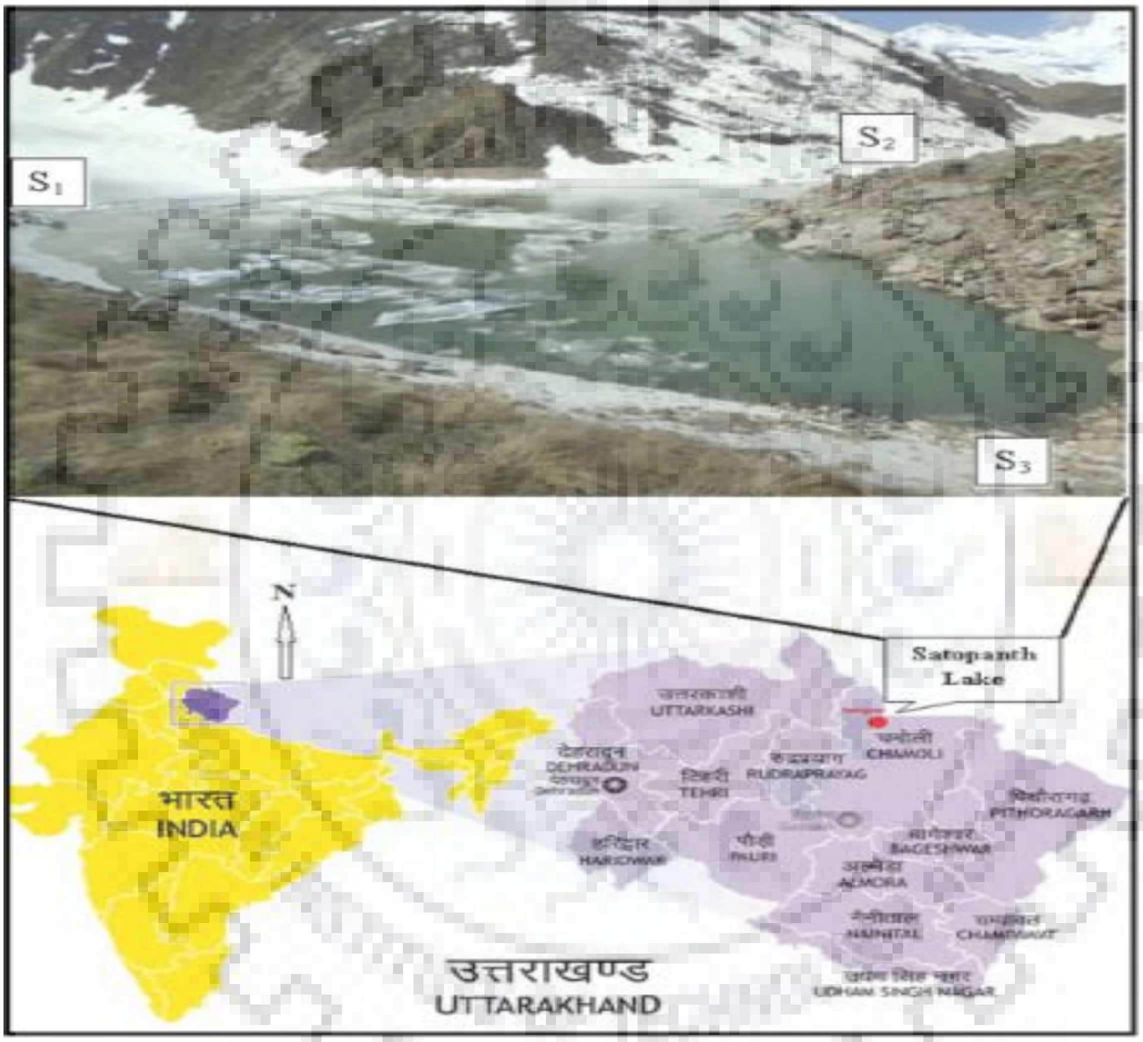


Fig.13: Satopanth tal   source: Ramesh c Sharma and Rahul Kumar

Chapter 4-DATA USED

4.1 Satellite data

The remote sensing datasets used for the study are rough to high resolution satellite imagery and Digital Elevation Model (DEM).

The DEM and Landsat data are downloaded from the site USGS earth explorer. On comparing the availability of the for-study area 2 LANDSAT data are downloaded and 2 DEM also downloaded from united state geological survey area (USGS) earth explorer

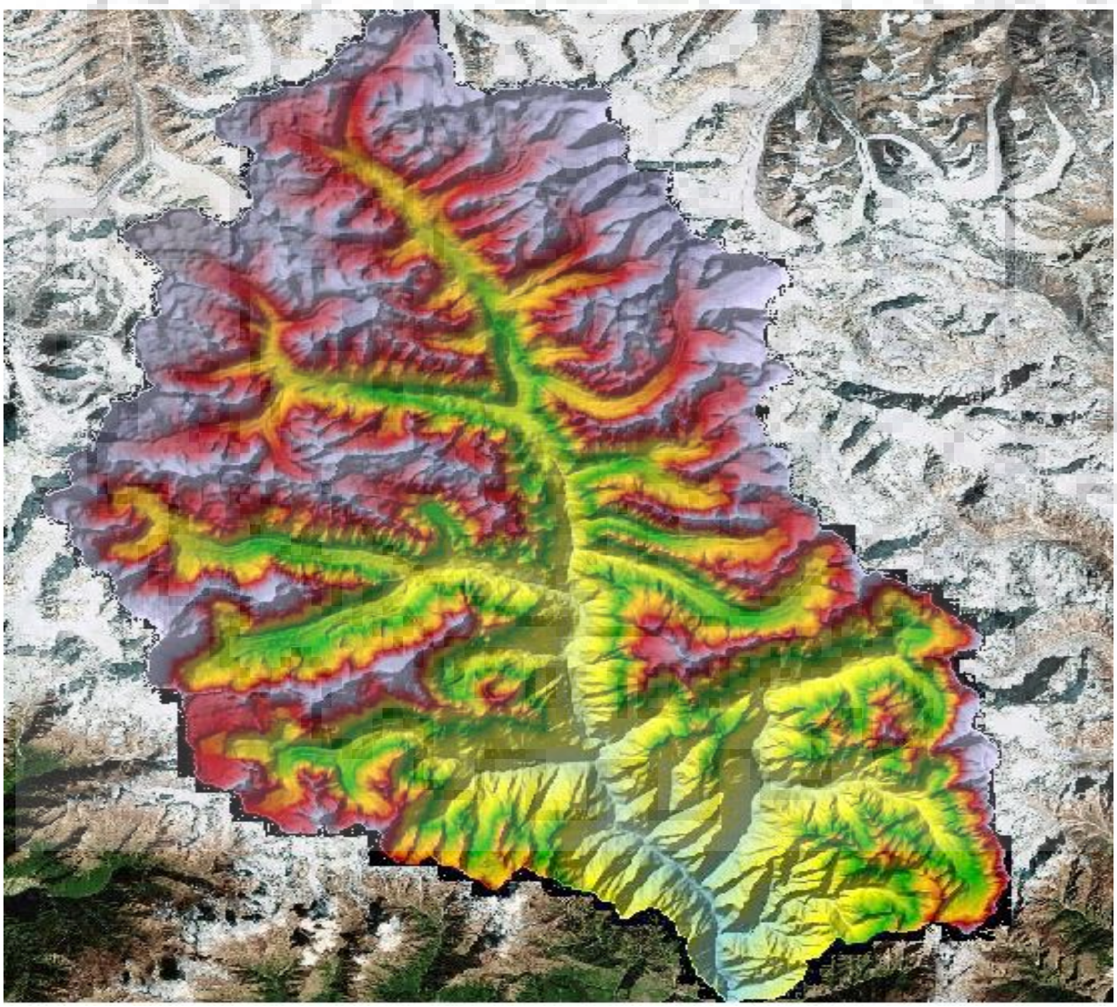


Fig.14: ASTER GDEM of the study area

4.2 software used

- Arc GIS
- HEC-RAS
- QGIS
- GOOGLE EARTH PRO

DATA	USE	RESOLUTION
ASTER GDEM	- Stream cross-section - Simulation in HEC-RAS - Watershed delineation	Spatial resolution-30m Horizontal accuracy- ±30m (95%confidence) Vertical accuracy- ±20m (95%confidence)
Field Data	- Experimental Modelling - Validation of results	
ICIMOD lake Inventory	- Selection of potentially dangerous lakes	
LANDSAT TM	LULC	Spatial Resolution - 30m

Table 2- Data used in the present study

Chapter 5- METHODLOGY

5.1 Model Parameters

The Landsat data is used to visually classify the map to establish the area and its type. The most common classes that is used are rivers, boulders, vegetation etc. The value of manning plays a vital role in when we are computing the unsteady flow analysis in HEC-RAS.

For marking the centerline which is the river and the bank lines and flow path HEC-GEORAS is used. Bank lines and Flow paths are unremitting lines which run sideways the main channel and are drawn in upward direction on calm sides of the river.

The lines are drawn from upstream direction to downstream direction. If one can stand in the direction of flow path, then the right is marked as right flow path and the left is marked as left flow path.

The XS lines which are cross section and are perpendicular to all these lines must cut all these lines in perpendicular way. The table of attributes of cross sections which includes right bank, left bank, station, Left length Right length and channel too.

GeoRAS gives the tool which automatically populates these fields The R length and L length verified the values. The river in which the cross sections are marked are routing for 100 years.

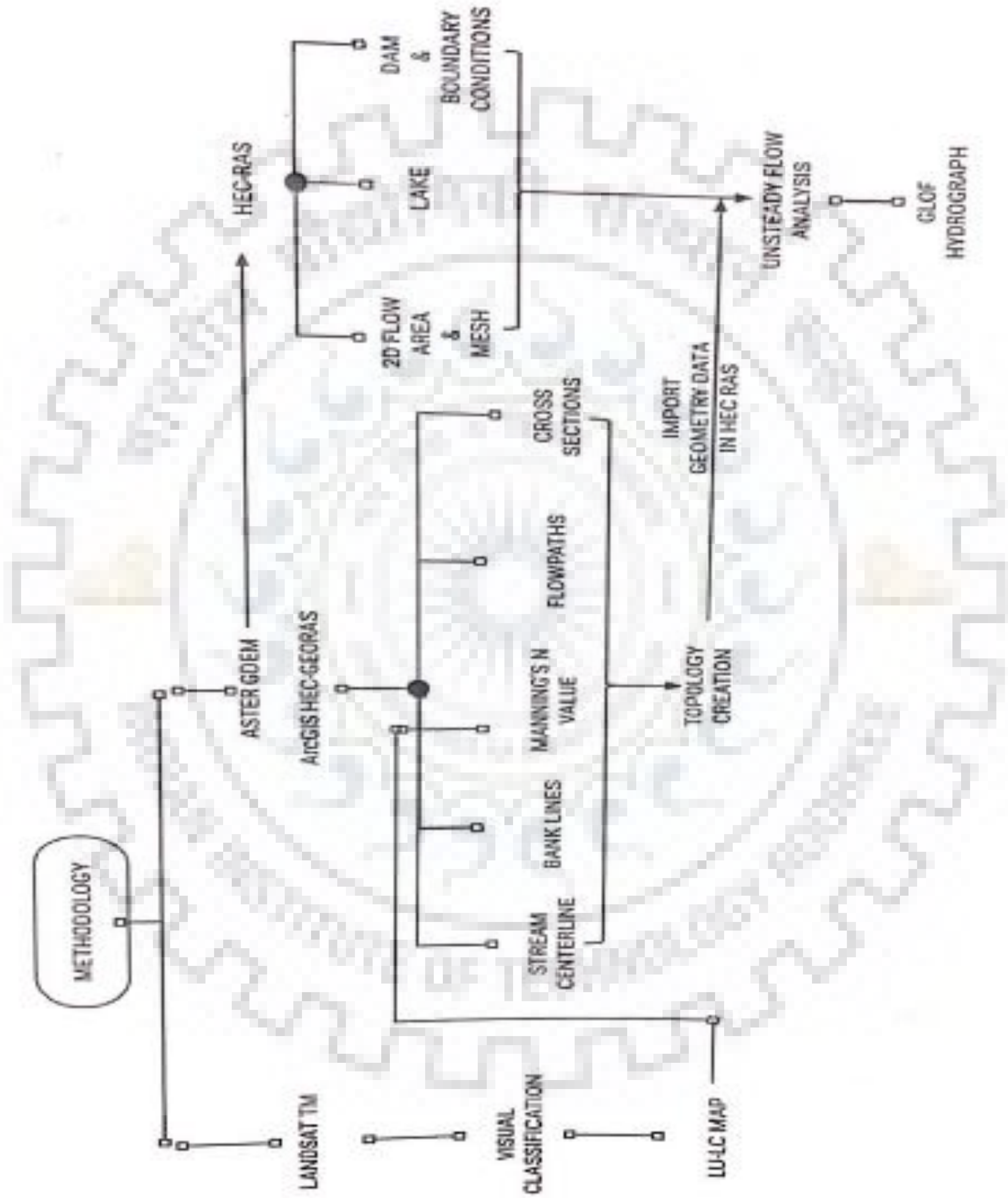


Fig.15: Methodology

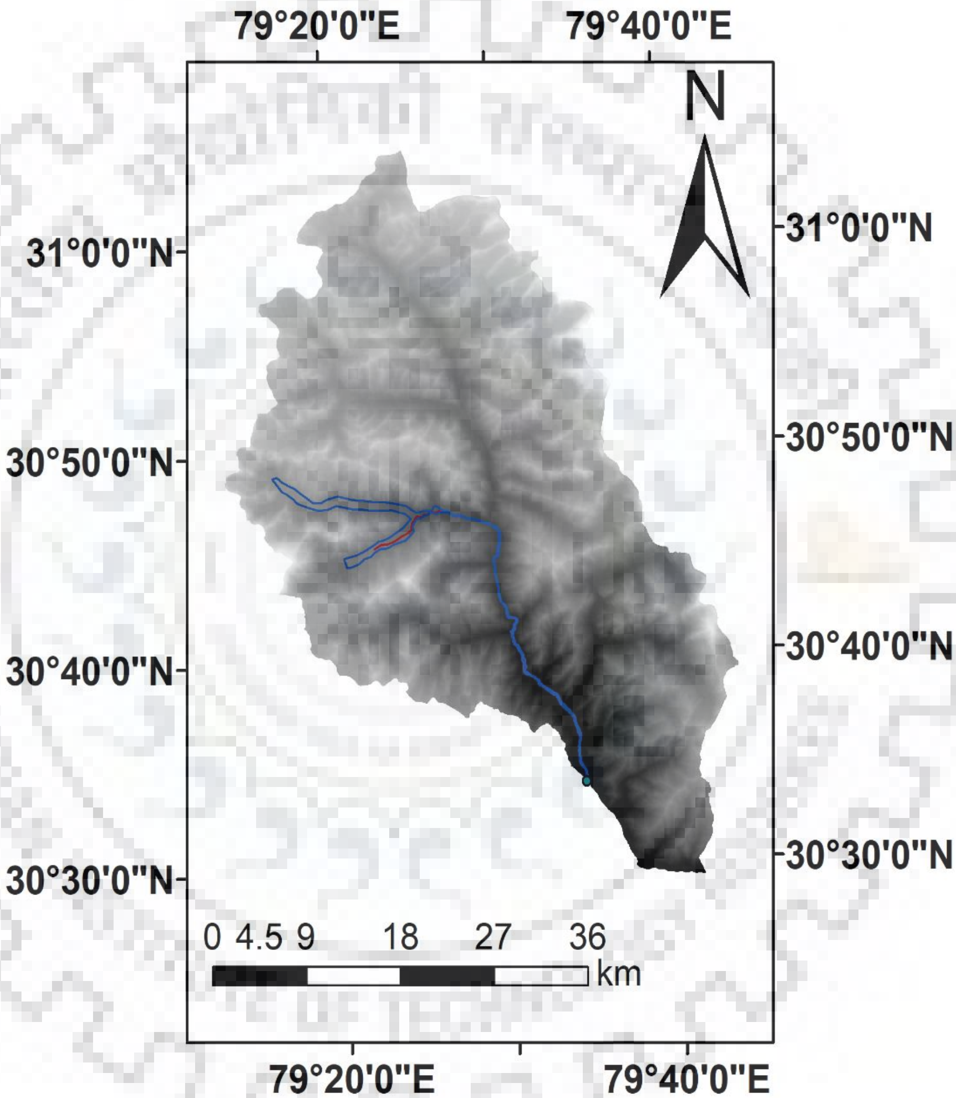


Fig. 16 Dem with bank lines and ceter line

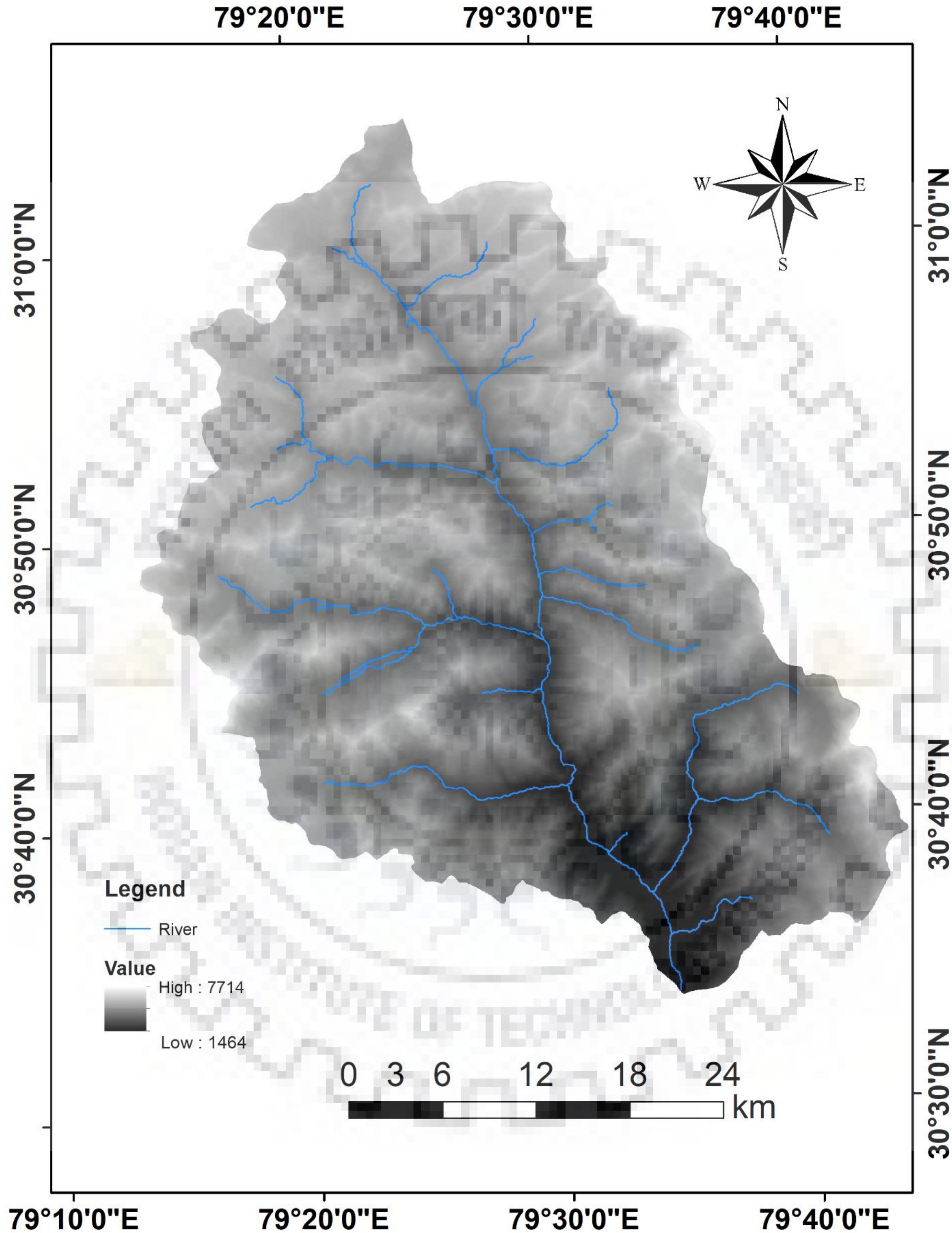


Fig.17: Water shed of study area

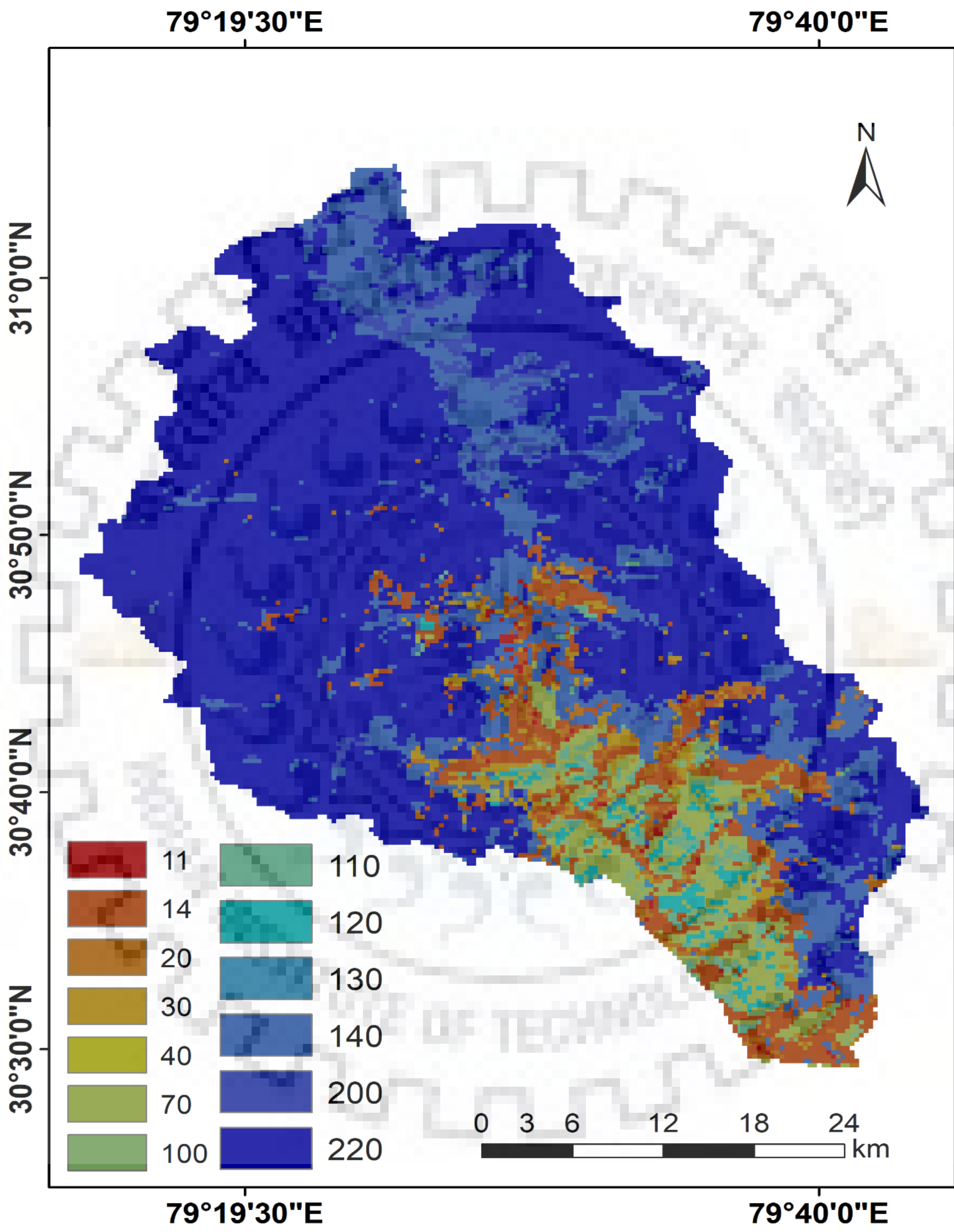


Fig. 18: LULC map of the study area

Legend (value)	Description	Area
11	Post flooding or irrigated croplands (or aquatic)	6.48 km square
14	Rainfed Croplands	124.02 km square
20	Mosaic cropland (50-70%) /vegetation (grassland/shrubland/forest) (20-50%)	37.17 km square
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	37.35 km square
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	0.36 km square
70	Closed (>40%) needle leaved evergreen forest (>5m)	81.27 km square
100	Closed to open (>15%) mixed broadleaved and needle leaved forest (>5m)	22.86 km square
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)	22.32 km square
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)	22.77 km square
130	Closed to open (>15%) (broadleaved or needle leaved, evergreen or deciduous) shrubland (<5m)	1.08 km square
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	296.55 km square
200	Bare areas	47.25 km square
220	Permanent snow and ice	1097.64 km square

Table. 3: Description of given values in LULC study area

This topology created in ArcGIS can be exported as a layer in GIs format which is accepted in HEC-RAS software.

ASTER-GDEM can be loaded in HEC-RAS after a few steps of processing

1. Assigning dummy persistent value to all the elevation values that initially were NILL. This can be done in ArcGIS using raster project and adapting the dem into tiff file.
2. While working on HEC-RAS and Arc-GIS the projection for the terrain must be remain constant

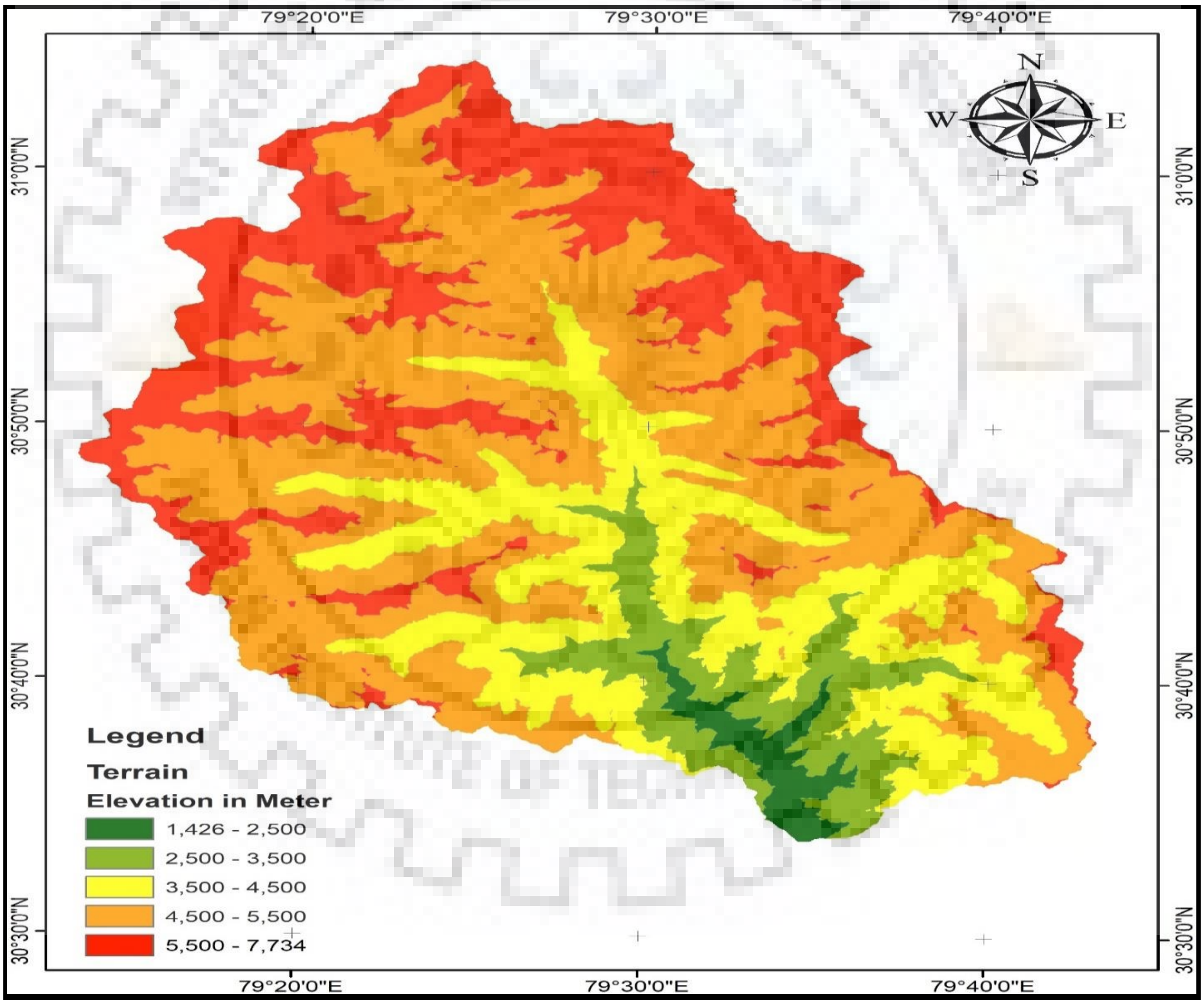


Fig.19: Map showing terrain elevation in meter

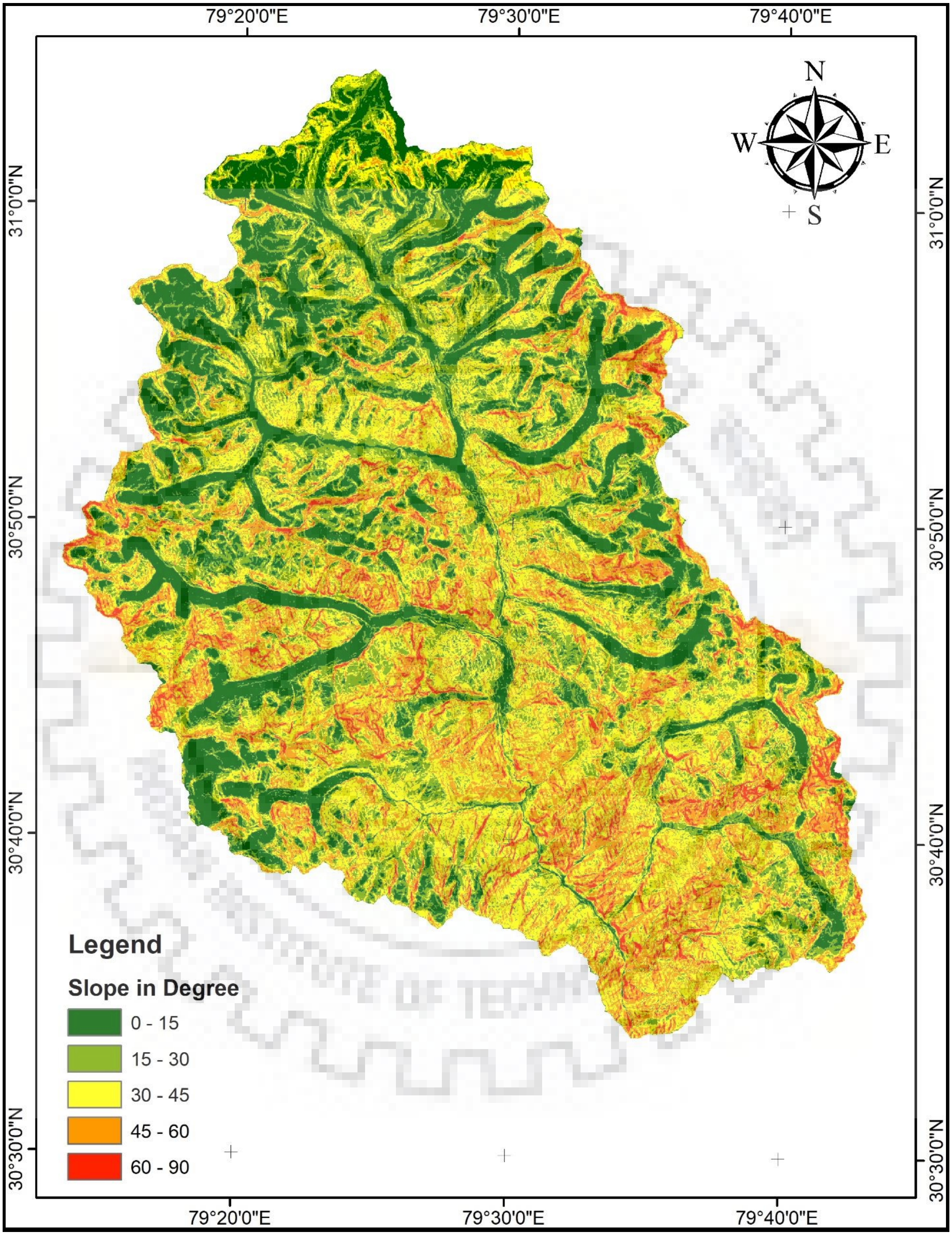


Fig.20: Map of study area showing slope in degree

After creating the loading the terrain in RAS-Mapper the geometry file was edited.

Following things were done-:

1. 2-D flow area creation- Stream area is polygon that contains the river area laterally with its banks. 2-D flow area is where the water is probable to flow.

2. Mesh creating- The two D flow area is covered with a mesh of cell size 30 is to 30. The mesh contains 143000 cells. The size of cell rests on the degree of calculation that needs to be performed.

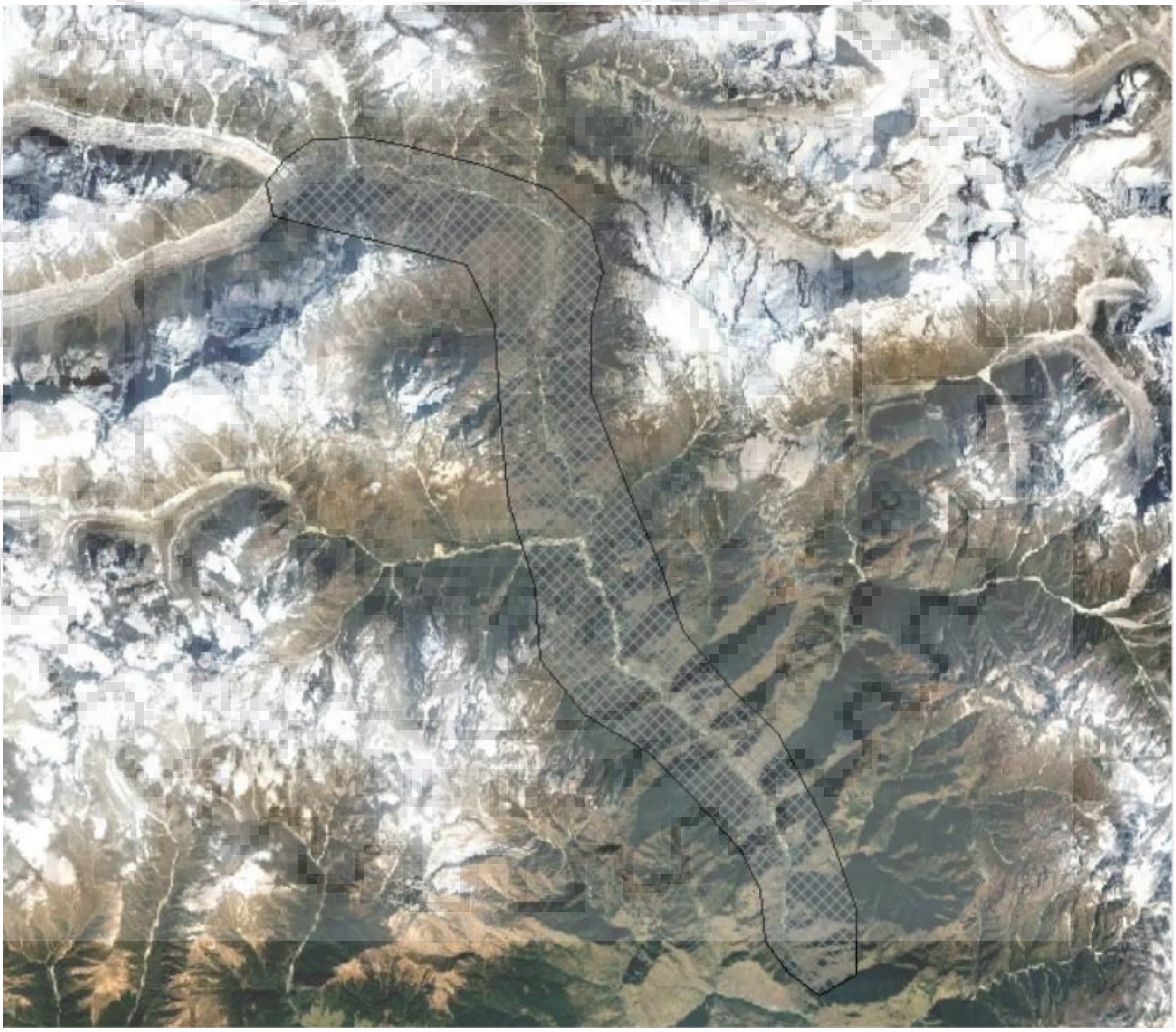


Fig.21: Mesh area for 2D unsteady Flood over on satellite images

3. Exporting the geometry data systematized in ArcGIS(HEC-GeoRAS). Again, the unit's system that is tracked is to be maintained. Georeferenced cross sections may be seen all laterally the river contour. A 3D plot of the river outline can be gained after accurate georeferencing.

Fig.22: 3D river plot

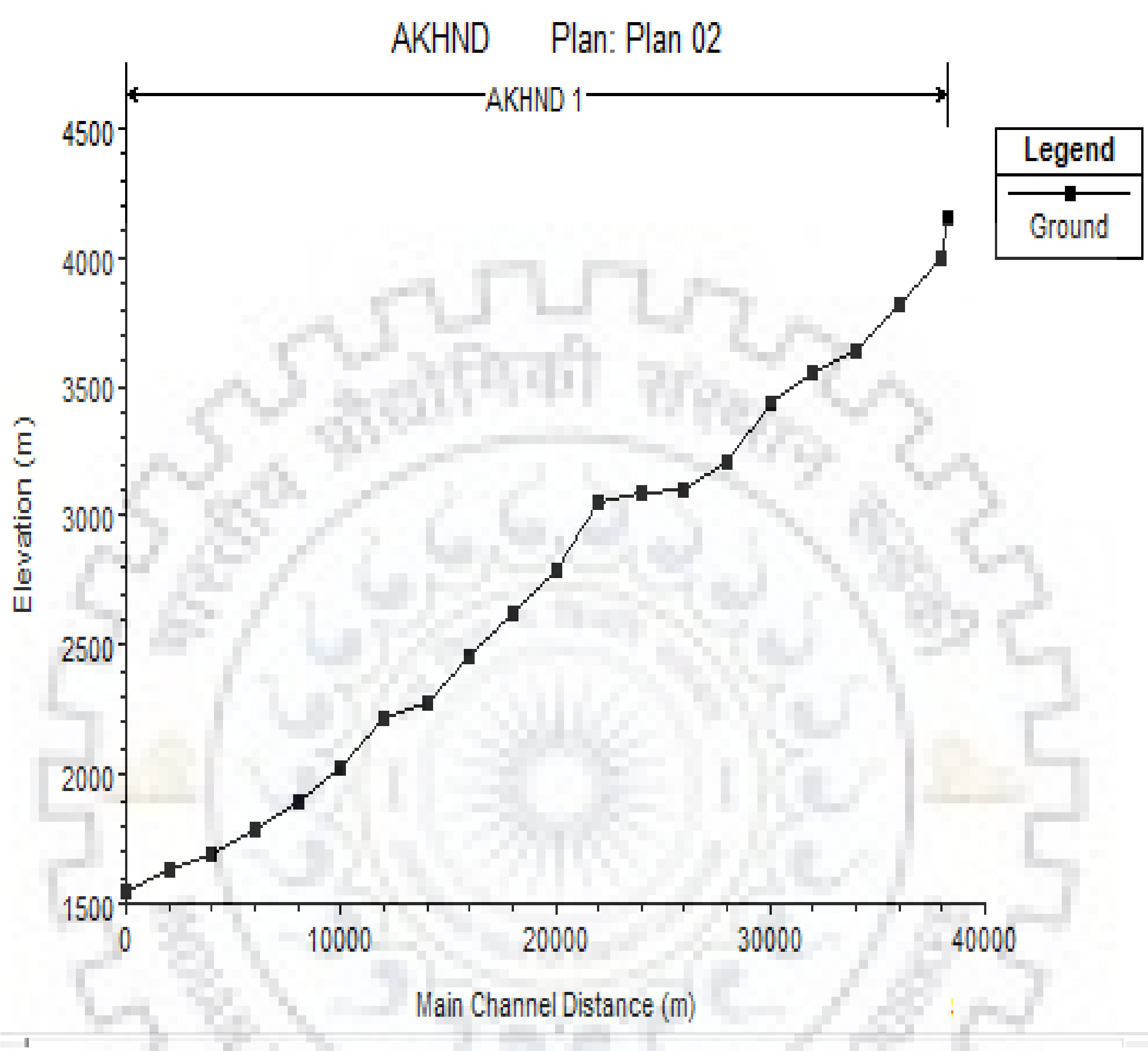


Fig. 23: Elevation vs Main channel distance Graph

4. Marking the borderline conditions- These includes the downstream BC line and the dam. The downstream BC is a SA/2D area boundary condition line.

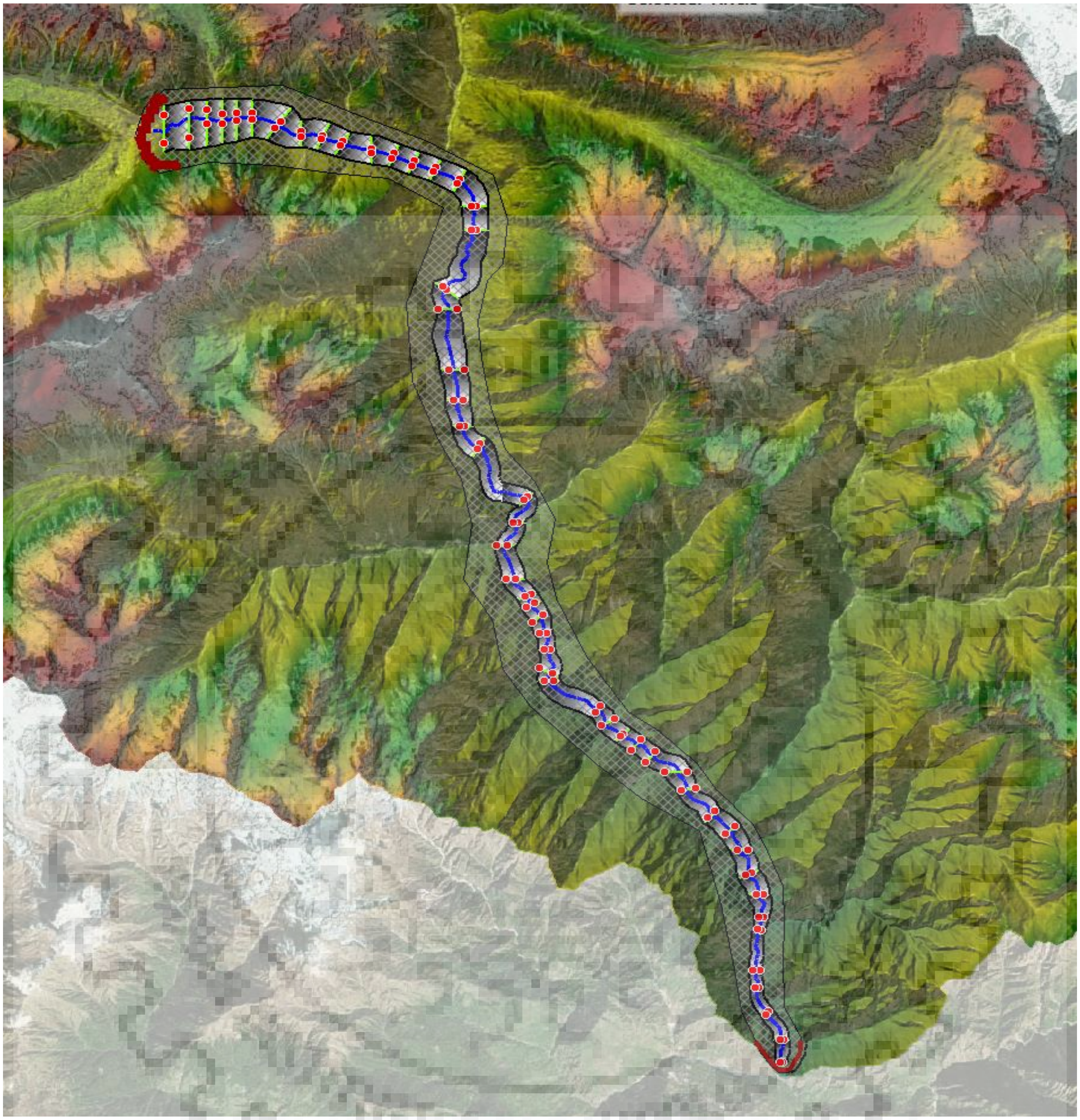


Fig.24: Map showing mesh along with banks, flow paths and centerline

5. Storage Area-The lake that is the Satopanth tal is delineated as a 2D stowing Area. huggel`s formulae are used for calculating the lake volume

$$\text{The lake volume, } V = 0.104\,A^{1.42}$$

Where V is volume of lake and the A is area of lake area.

6. Weir creation- A weir is defined as “a low dam built across river to raise the level of river upstream or normalize its flow.” The Weir is built in orientation to its location in satellite data. Its acts as a SA/2D Area Connection between the lake and the flow area. Both the lakes as well as flow area laterally with river should meet at the weir line.

7. Dam break Parameters- The dam break parameters include the following-:
    - Weir width
    - Weir coefficient
    - Weir crest shape
    - Embankment station and Elevation table
    - Midpoint station
    - Ending lowest width
    - Final Bottom Elevation
    - Left side gradient
    - Right side gradient
    - Failure Mode
    - Breach establishment time

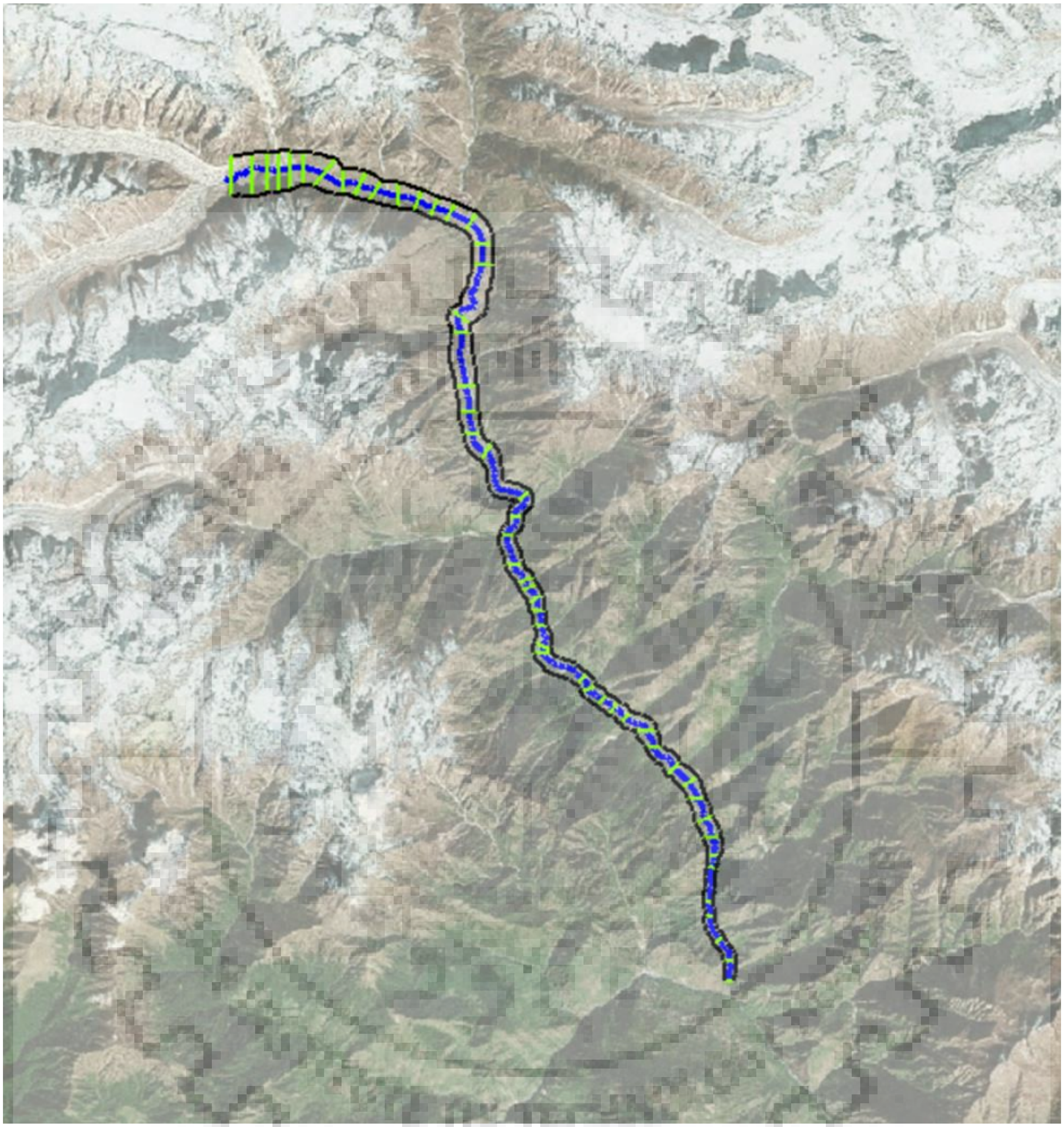


Fig.25: Lake location georeferenced with satellite image

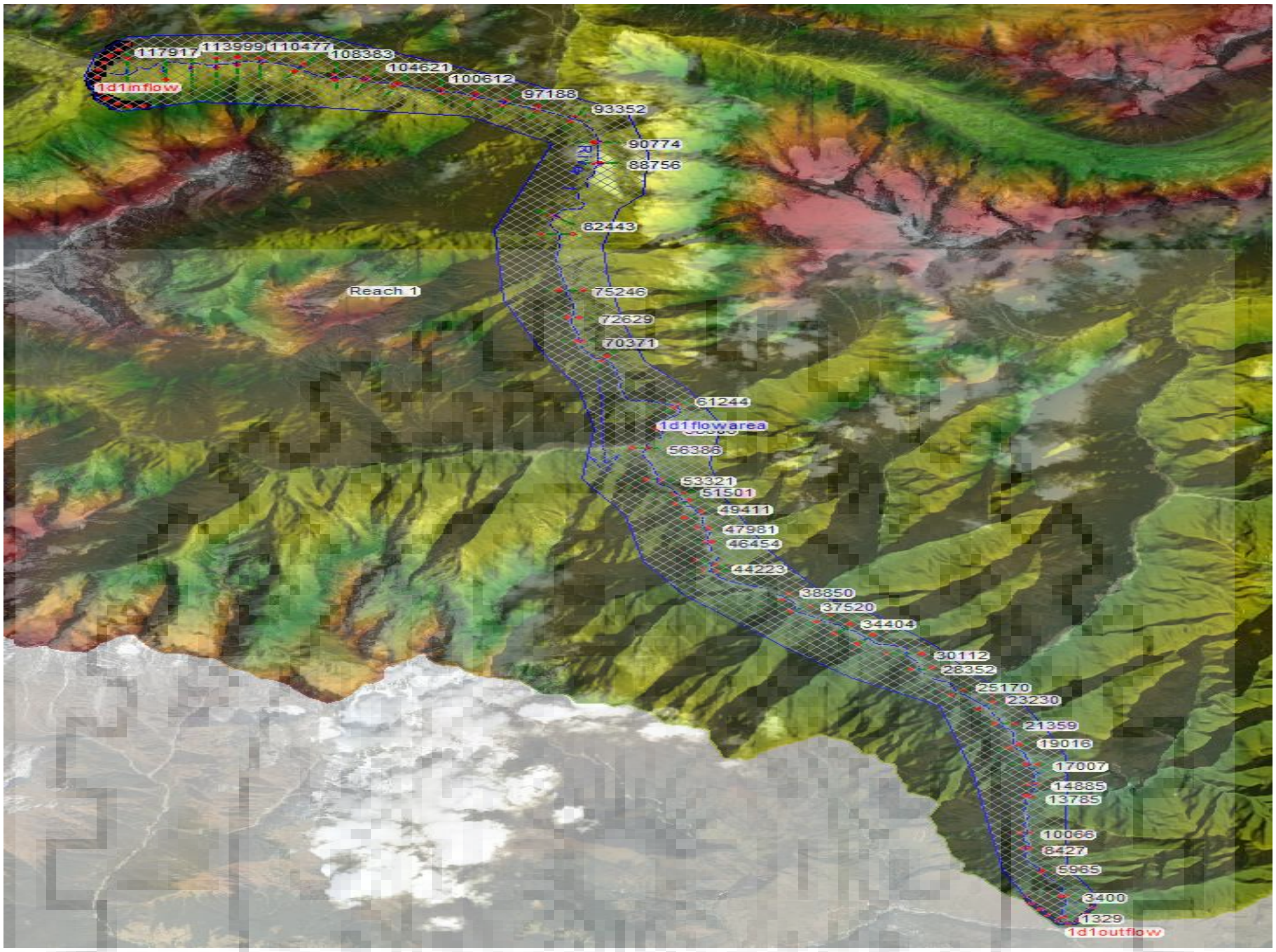


Fig.26: HEC-RAS Map showing mesh along with boundary conditions and inflow and outflow

5.2 Breach parameters calculations

Several empirical relations have been deduced in order to calculate the breach parameters. Almost all these relations use hw that is the height of water above the breach expect for Froelich`s which uses hb that is height of break.

The reason being, hw is a tough constraint to calculate without adequate knowledge of dam break event. While the dam break height can be assessed by taking into deliberation the height of dam.

Weir Width

The width of the dam that is built over the river. That was estimated in orientation to previous work done and or field work done by the research group. The weir width was taken as 150m.

Breach width

The width of the breach that will led to overflow of water is called breach width. It can be computed using a very popular empirical relation by Froehlich for sand dams.

Average breach width is given by

$$(B_w)\ in\ \ m = 0.1803K_o(V_w)^{0.32}(h_b)^{0.19}$$

where as V_w is the volume of lake, lake hb is the height of breach and K_o is a constant that is diverges with the method of disaster.

K_o = 1.4 in case of overtopping

K_o = 1 in case of piping

Failure Time

At what time after the start of the computation will the dam fall is known as failure time.

This parameter is directly proportional to the volume of lake and height of breach. Failure time is alternative parameter that is calculate from another such empirical relation.

Which is give by-

$$(T_f)\ in\ \ h = 0.00254K_o(V_w)^{0.53}(h_b)^{-0.9}$$

The side slope for dam cbreach has been taken as 0.8 h:1V

5.3 Mannng`s roughness coefficient

The manning`s coefficient for roughness for mountainous stream with no vegatation, banks, usually steeps, tree and bushes on the submerged banks, having gravel, cobbles and boulders at bottom, ranges from 0.03 to 0.07 (chow, 1959 as cited in HEC-RAS Manual HEC, 2010)."

It is a known fact that himalayan rivers generally tend to have a mountainous terrain in upstram reaches. The sediment load includes cobbles, pebbles, gravel, sand and large boulders settled at the river bed. Also, debris flow in the form of landslies is a common pehnomena during GLOF events which adds to the residue load. Along with this the river tends to flow at a very high speed and erodes most its banks during its course, all this collectively results in high manning`s roughness coefficient which has been taken as 0.05 for most of the regions around the river. To check for the sensitivity of the model, the model was run for different values of n and breach width.

Chapter 6- RESULTS AND DISCUSSION

For Satopanth lake GLOF modelling is performed which may outburst in future. Flood inundation and 1-d modelling has been run on HEC-RAS. The results for the models can be seen in below pictures.

Flood inundation model

A flood map provides information on depth of flooding, extent of inundation, and most importantly the direction of flow paths as the flood water travels. The flood map can be overlaid with other varieties of maps and aerial photographs so that anyone can easily read and understand the map. This allows the residents to find out whether their farm/ property/ community is likely to be flooded in a specific situation.

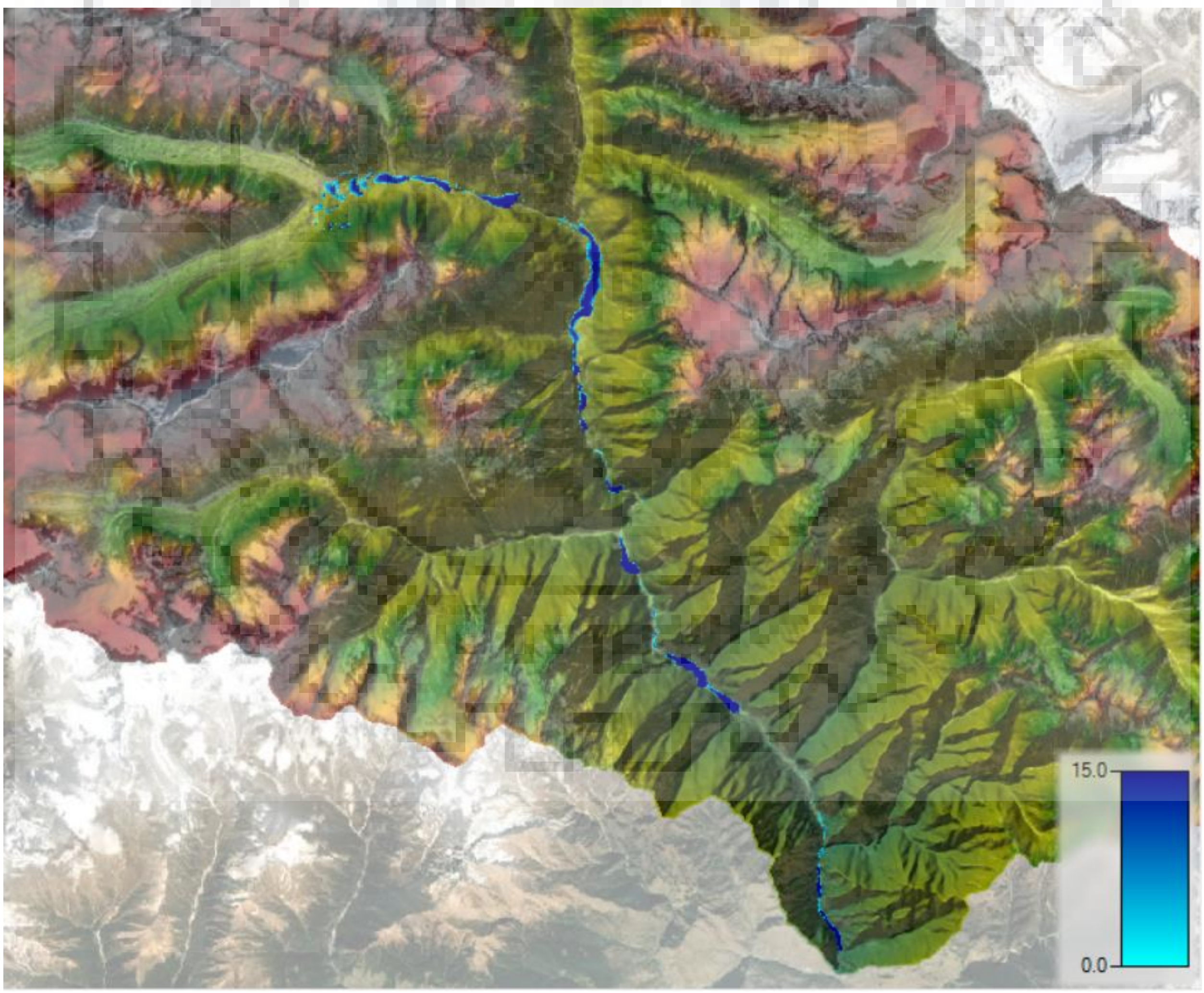


Fig.27: Map showing the Flood Inundation depth water along the valley over DEM

Figure.28: show the distribution of the water depth along the main flow channel. The dam break simulation was carried out from the mouth of the glacier to Visnunuprayag which is located at a distance of 29 km from the lake.

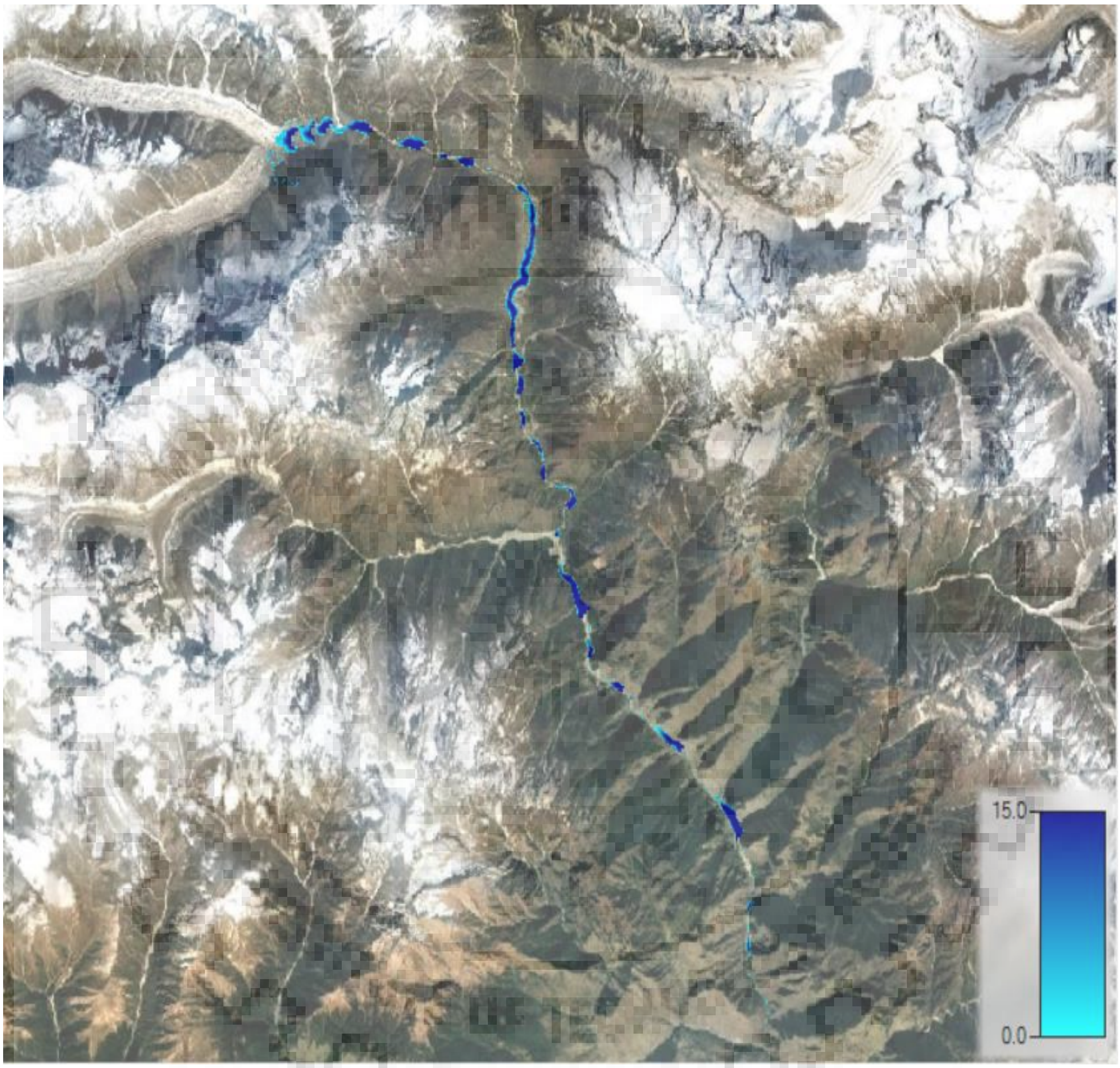


Fig.28: Flood Inundation depth water along the valley over Satellite Images

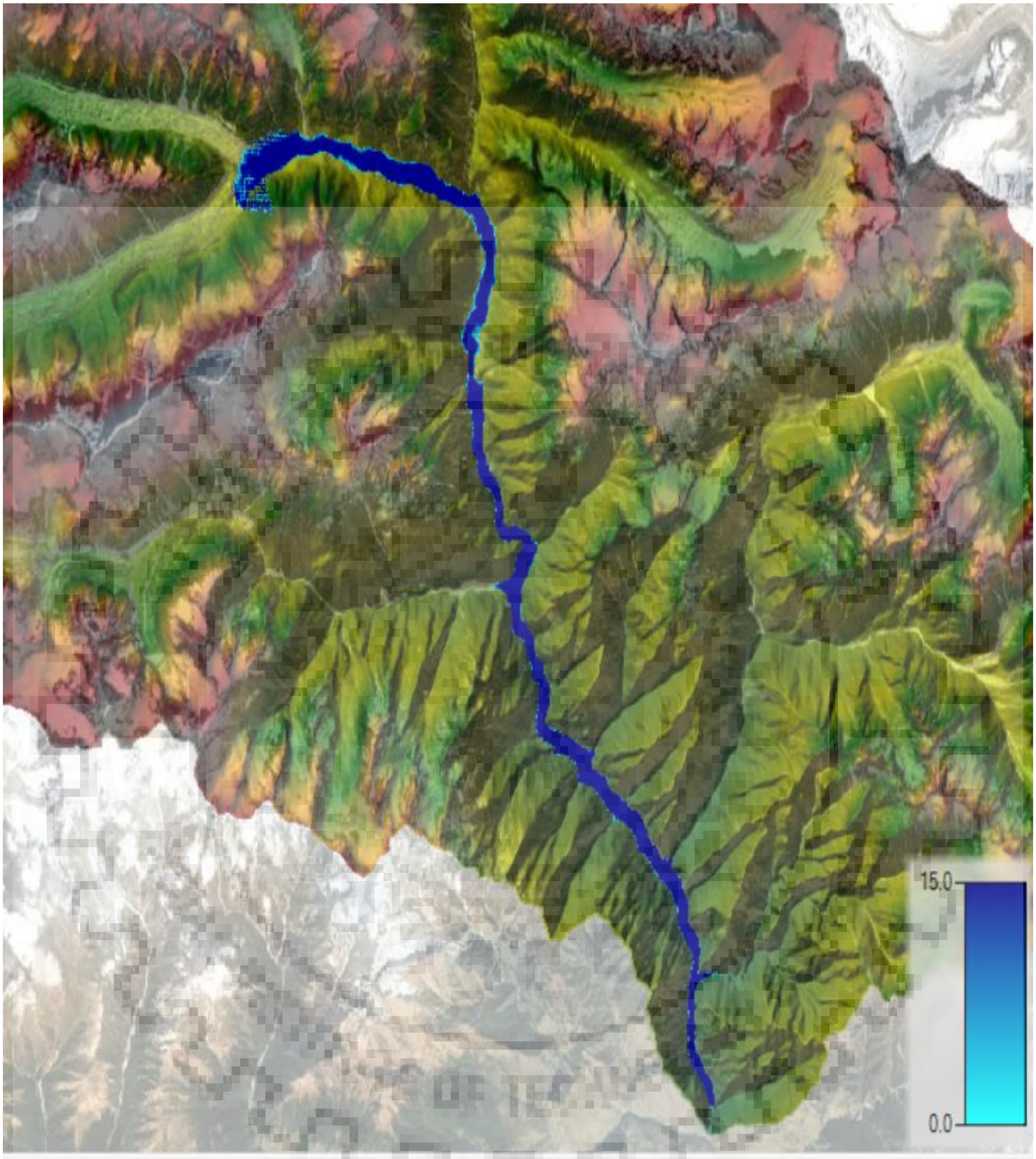
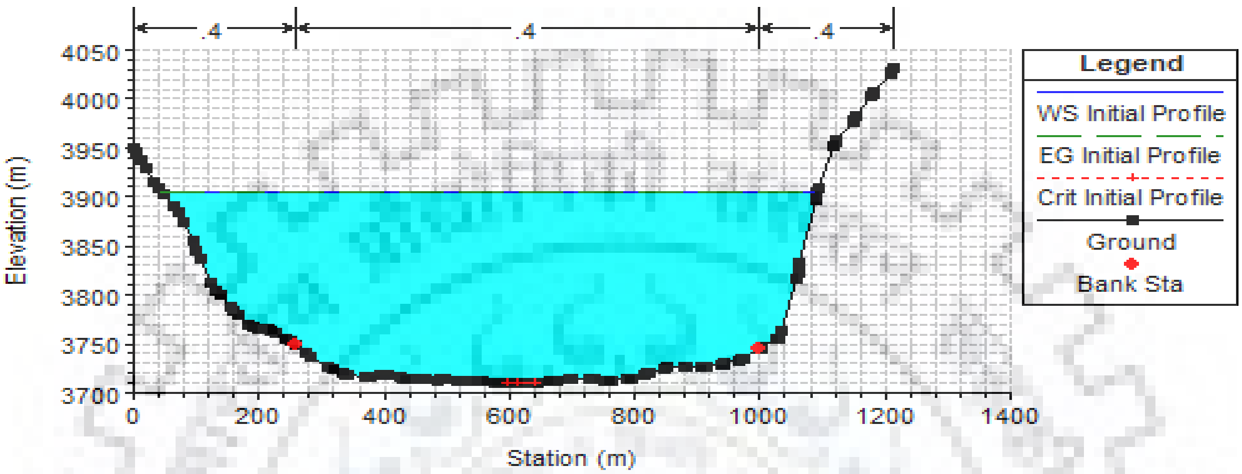
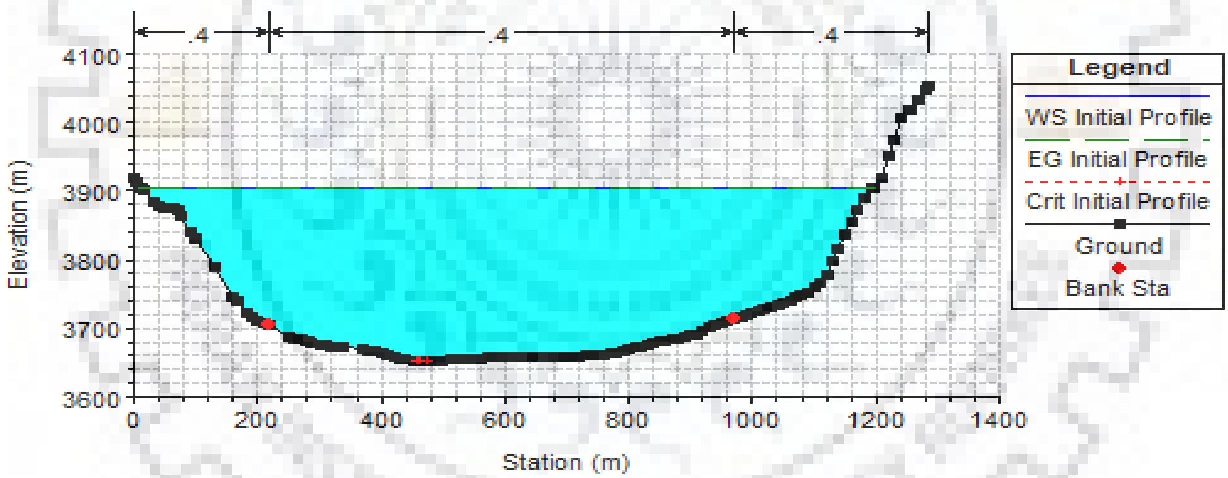


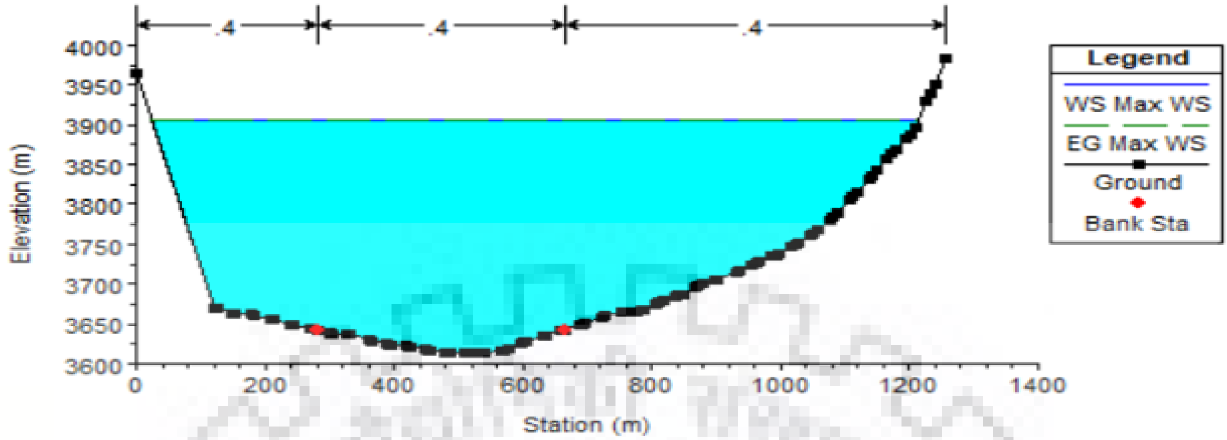
Fig.29: Map showing the Flood Inundation map – Maximum Depth over DEM

Here the legend showing the value of depth in meters. If the water flow is obstructed by any obstructions which can be modeled over the main flow channel, the water depth increases as the with time.

Cross sections for HEC-RAS 1-D Modelling






.4
.4
.4
4000
3950
3900
3850
3800
3750
3700
3650
3600
Elevation (m)
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Station (m)
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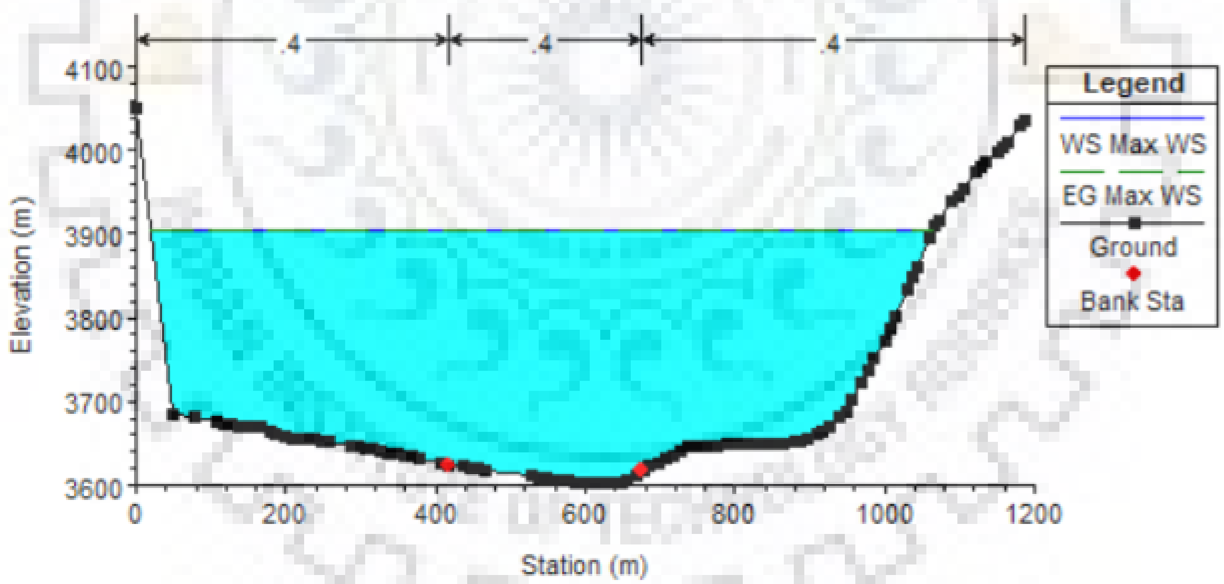
.4
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4100
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3700
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Elevation (m)
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Station (m)
Legend
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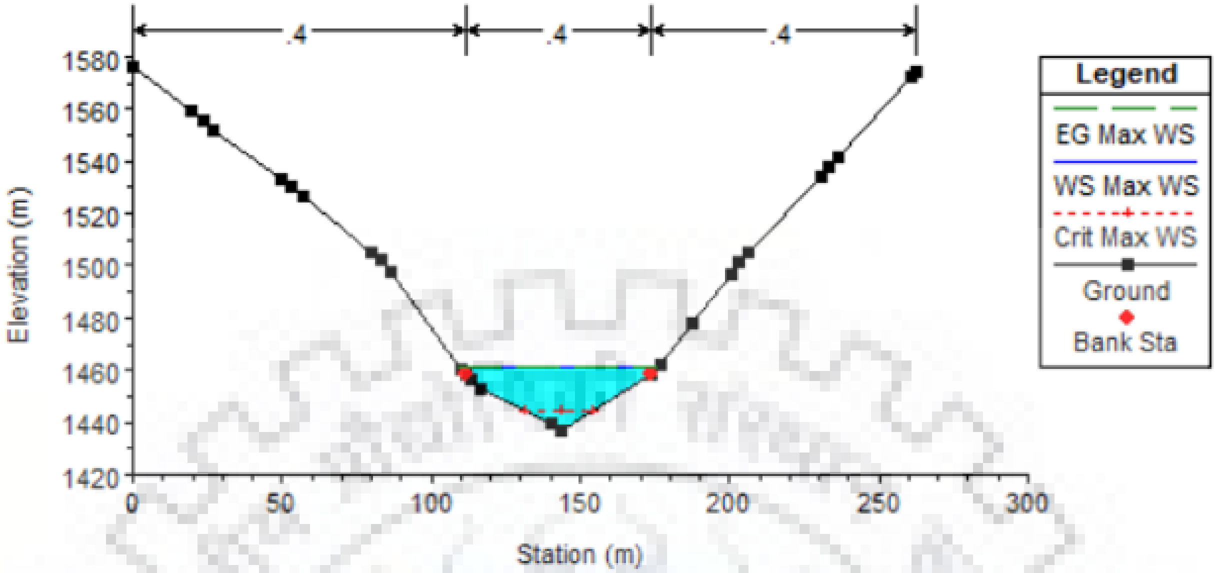

Fig.30: Map showing cross sections

The above figures show the valley cross sections ay different along the flow channel. the cross sections are derived from DEM. Arc hydo tools are used to construct the topological connection.

The hazard potential of the lake is analysed by complex hydrodynamic modelling. Both one dimensional and 2 dimensional hydrodynamic has been employed

It is conclusive that the hydrodynamic simulations may facilitate hazard potential of existing glacial lake. In this study we have simulate a dam break analysis of a lake in the Himalayas.

Chapter-7 CONCLUSION

In present day the glacial lakes in Himalayan region of Uttarakhand are increasing drastically due to melting of glaciers. The rise in global temperature is the reason behind the melting of glaciers as a result most the glacial lakes are at verge of outburst. Most of the lakes in Uttarakhand are not mapped yet and it is essential to map all the glacial lakes and monitor their growth regularly. It is very important to find the lakes which are prone to outburst and simulate their breaching to know the impact they can have in downstream areas.

The lakes which are increasing at drastic rates can pose a threat to the people which are living in the downstream area, can cause loss of lives in large number and damage infrastructures, properties, the hydropower plants which are situated in the way of river path.

So, the present study is conducted on the Satopanth lake in Alaknanda basin. The flood inundation model and 1-D modelling simulation on HEC-RAS software. The 1-D model is governed by the saint Venant`s equation of conservation of mass and momentum. The one-dimensional model is chosen over two-dimensional model because it runs very quickly and have many iterations of geometric and boundary conditions.

The results that obtained after the successful modelling are validated using the well-established empirical relations. Here we came to know that GLOF model can similate both normal and worst-case scenarios, so we can know about the conditions which may even worse when GLOF events happened.

The high-resolution map of the study area must be prepared and the proper monitoring of glacial lakes must be maintained so the information of lakes which are dangerous are well known so the proper techniques can be taken to tackle the worst situations if this kind of events happened in future.

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