GLACIAL LAKE OUTBURST FLOOD HAZARD ASSESSMENT IN A PART OF UTTARAKHAND, INDIA

AMIT ANAND
March, 2014

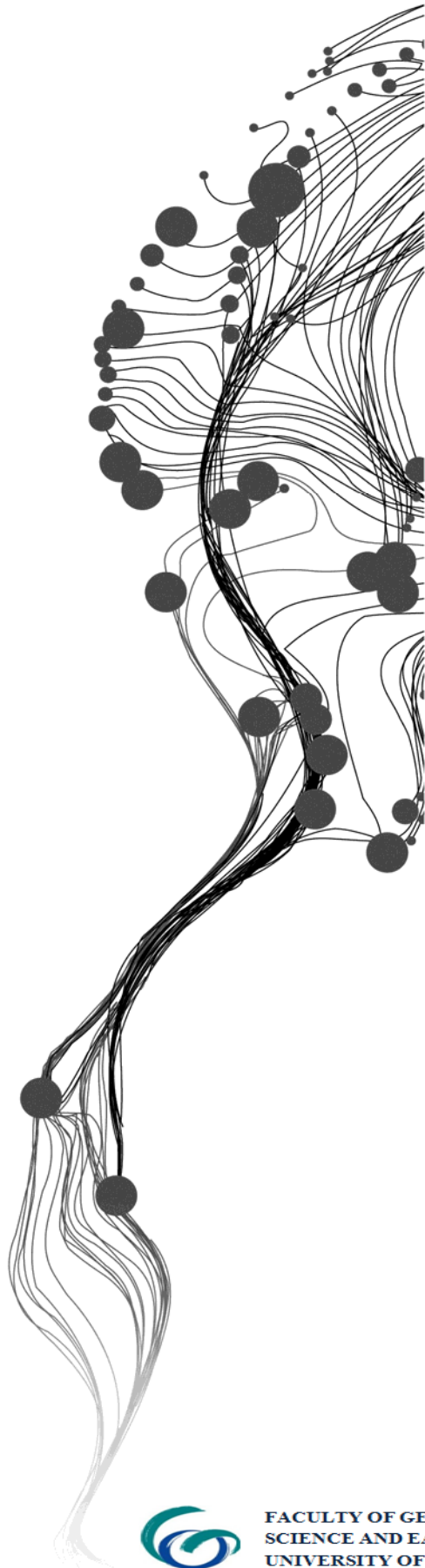**IIRS SUPERVISOR**
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Enschede, The Netherlands [March, 2014]

Thesis submitted to the Faculty of Geo-information Science and Earth Observation (ITC) of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: [Natural Hazards and Disaster Risk Management]

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Dedicated to supervisors, parents & friends. . .

ABSTRACT

Recent scientific studies have reported that no glacial lakes in Uttarakhand are potentially dangerous. But 17th June 2013, Kedarnath GLOF event has created a need to update the analysis of glacial lakes study. In the present research Glacial Lake Outburst Flood (GLOF) hazard assessment, using remote sensing has been carried out in a part of Uttarakhand state of India. The study includes mapping of glacial lakes using time series LANDSAT and LISS 4 satellite data ranging from 1972 to 2012 at 1:50,000 scale. Lakes' mapping has been carried out by manual digitization on the basis of visual interpretation along with NDVI, NDWI and slope information. Inventory of glacial lakes was prepared showing presence of 24 lakes in 1976 that increased to 93 lakes in 2011 with area greater than 0.01 sq km. Lakes were also assessed on the basis of growth rate at various altitude ranges. Altitude range 3500- 4000 m was found maximum sensitive for lake growth in last 40 years. Hazard assessment was carried out for the lakes which had area more than 0.03 sq.km and slope less than 10°. According to these criteria 7 lakes were found hazardous in the state at present.

MIKE-11 software was used to simulate the recent Chorabari lake breach of Kedarnath area. Various input like cross section from lake to outlet, dam breach parameters etc were collected during field visit. Using these field input and remote sensing data, simulation was carried out and final results were obtained. Simulated result was compared with field readings. It was found that the discharge between cross section was 1080 m³ / sec and the flood height near Kedarnath temple cross section was around 2.5 m which was nearly equal to the field reading. The result of the study can help in carrying out downstream risk assessment, spatial planning and better preparedness for future GLOF hazards.

Keywords
Glacial lakes, Glacial lake Outburst flood, Remote Sensing, MIKE 11

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1. Background

Glacial lake outburst impacts around the globe have scientific records available from Little Ice Age (1550 AD –1850 AD**.** The average surface temperature of the Earth has been increasing since the end of the Little Ice Age and has increased between 0.3°C to 0.6°C over the past hundred years (ICIMOD 2007)**.** Continuous change in temperature causes faster melting of glacial ice, resulting in formation of large number of glacial lakes. Glacial lake is defined as water mass existing in a sufficient amount and extending with a free surface in, under, beside, and/or in front of a glacier and originating from glacier activities and/or retreating processes of a glacier (Banerjee 2013). Outside the polar region, the Himalayas have the largest concentration of glaciers. Most of the Himalayan glaciers have retreated in recent past, leaving behind large number of glacial lakes. A study carried out jointly by ICIMOD, UNEP, and APN between 1999 and 2003 documented about 15,000 glaciers and 9000 glacial lakes in Bhutan, Nepal, Pakistan and selected basins of China and India (ICIMOD 2007). IPCC in 2007 reported that there will be an increase in temperature in Himalayan region between 1 to 6°C by 2100 (Banerjee 2013). As a result of this more glacial ice will melt and snow cover would decrease between 43 to 81 percent leaving behind many more glacial lakes in future. Burst or sudden discharge of large volume of water along with debris from these lakes causes glacial lake outburst flood (GLOF) in valley downstream causing massive damage to infrastructure, natural resources and human life (Banerjee 2013). The degree for loss of life and damage to infrastructure due to GLOF varies depending on various factors such as the size and depth of the lake, the nature of the outburst, the geomorphology of the river valley and elements exposed to the flash flood. To minimize the risk of glacial lake outburst flood and to reduce the vulnerability of nearby communities, it is important to carry out the systematic inventory of these lakes, their growth analysis and simulation of lake breach with better accuracy to understand the flash flood extent more precisely**.**

1.2. Historical overview of GLOF events

Scientific investigations have declared that GLOF occurred along the Seti Khola in Nepal about 450 years ago. In 1941, 4,500 people lost their lives in an outburst flood in the city of Huaraz in Peru (ICIMOD 2010). 1964 GLOF event of China damaged several kilometres of highway and washed away 12 timber trucks. A number of GLOFs has been recorded in the Hindu Kush-Himalayas in recent past**.** The most notable GLOF event after detailed GLOF study started, occurred in 1985 in Dig Tsho lake at Bhote Kosi in Nepal. On 10th June 2000, the outburst flood from the landslide dam extended upto 500 km downstream in Arunachal Pradesh, North-Eastern part of India, resulting heavy damages. June 2005, outburst of landslide dam lake on Parechu river (China) caused a transboundary flood in Himachal Pradesh(India) (ICIMOD 1993
). Recent flash flood in Kedarnath, is the most notable event in Indian history till date. The collected field information and scientific correspondence suggest that two events on consecutive days caused heavy devastation in the Kedarnath area of Mandakini River basin. On 16th June 2013, heavy rain followed by active erosion resulted excessive water and sediment accumulation in Mandakini river and surrounding channels. As a result, voluminous water laden with debris from the surrounding regions and glacial moraines moved towards Kedarnath town, washing off upper part of the town. The second event occurred on 17th June 2013 at around 6 a.m., after overflow and collapse of the moraine dammed Chorabari Lake (represented in Figure 1and2) which released large volume of water that caused flash flood in the Kedarnath town and downstream area. Between 15 to 17 June 2013, due to heavy rainfall and rapid melting of lateral basin of glacier, which was thickly covered by snow (more than 7 feet) near the upper part of lake resulted large amount of water accumulation in the Chorabari lake and reduced the shear strength of the dam. Ultimately the loose-moraine dam breached causing severe damage downstream (Dobhal et al. 2013).

Figure 1: Chorabari lake before disaster (Source: Vadakayil A, 2013)

Figure 2: Chorabari lake after disaster (Field photograph)

1.3. Role of remote sensing and GIS in present study

The snow line in Himalayan glaciers exists at 3800 meters form m.s.l. (mean sea level). Due to inaccessible location of glacial lakes, their studies, field investigations, inventory preparation and monitoring requires extensive time and resources. Remote sensing serves as the best practical tool for mapping, monitoring and analysing these high altitude glacial lakes with reasonable accuracy. Products like DEM (Digital elevation model) along with satellite imagery can be used together effectively for finding critical information like various surface features, geometry and physical conditions like, slope, elevation etc. Time

series analysis can also be carried out using remote sensing datasets under various climatic conditions. Hence remote sensing offers strong advantages in terms of qualitative as well as quantitative hazard assessment of glacial lakes. With GIS, large amount of geographical information can be stored and retrieved in database that can be used for further analysis and simulation purposes (Aggarwal 2012).

1.4.   Rationale of the study

ICIMOD prepared an inventory (represented in Figure 3) for glacial lakes of Uttarakhand in 2005 using remote sensing dataset of 2003 and identified 127 glacial lakes in Uttarakhand. SAC Ahmadabad in 2011 also prepared the inventory for Uttarakhand glacial lakes using single year dataset and reported existence of 118 glacial lakes in the state. Other studies are also limited with either limited period dataset or complete Uttarakhand inventory preparation. The present study was carried out to make the inventory of glacial lakes of complete Uttarakhand region using 4 decade remote sensing datasets from 1972 to 2012 to understand more accurate numbers & areal extent at different altitude range and changes in the lakes in last 40 years. GLOF hazard assessment studies are still very limited for complete Uttarakhand region (represented in Figure 4)
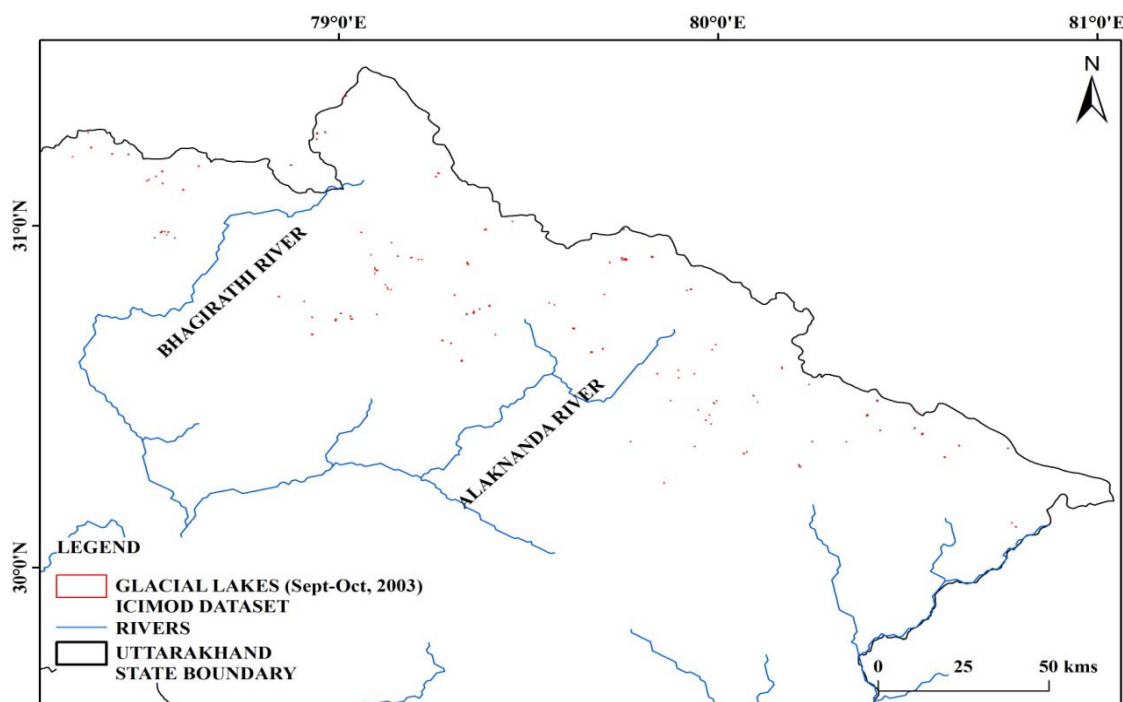
Figure 3: Mapped glacial lakes (Source: ICIMOD)
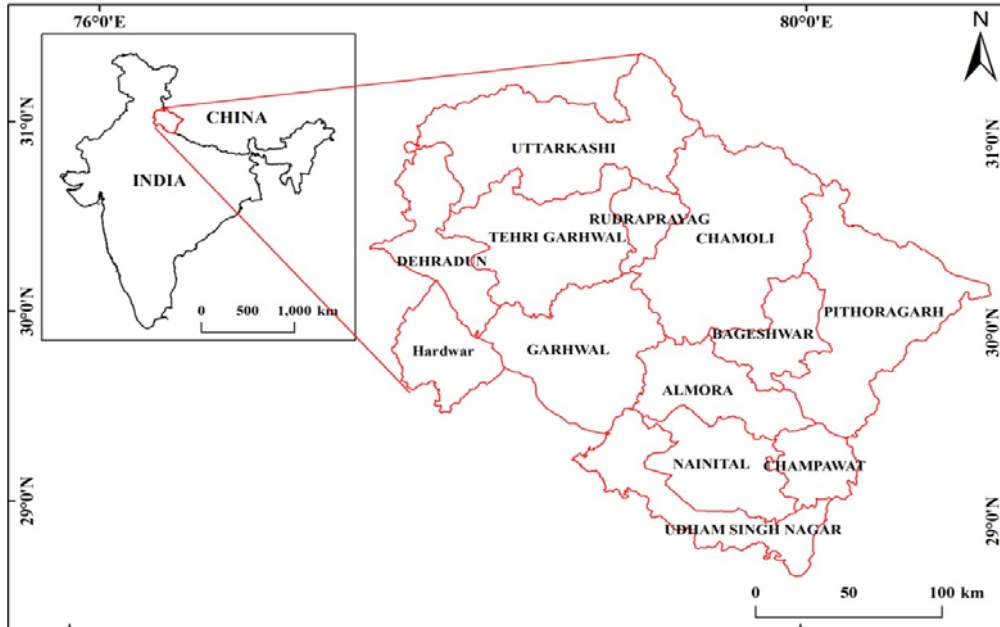
Figure 4: District boundary map, Uttarakhand

According to Sah et al. 2005, ICIMOD reported no glacial lakes in Uttarakhand are potentially dangerous. Recent Kedarnath GLOF event creates a need to update the analysis of glacial lakes hazard assessment for understanding the future GLOF hazards. Lake volume calculation using the power law of K. Fujita et. al., 2013, for Himalaya was verified on Chorabari lake and was used to calculate the volume of glacial lakes of Uttarakhand. Simulation of Chorabari lake breach that occurred on 17th June, 2013 in Kedarnath using MIKE 11 and field data was carried out to understand the mechanism of lake breaching and outburst flood effects (flood level and discharge). The result of the study can help in carrying out risk assessment, downstream spatial planning and better preparedness for future GLOF hazards.

1.5.   Research Objectives

i.   To map the Glacial lakes using time series (1972-2012) remote sensing data (LANDSAT/LISS 4) of complete Uttarakhand state.

ii.   To carry out the hazard assessment and sensitivity analysis of mapped glacier lakes.

iii.   To assess the accuracy of the collected data by remote sensing and field work for GLOF modelling using MIKE 11 software.

1.6.   Research Questions

1.6.1.   Question pertaining to 1st objective

- How many lakes have appeared/disappeared or grown in last 40 years in the study area?

1.6.2.   Questions pertaining to 2nd objective

- What is the total change in area and volume of lakes in last 40 years?
- What is the growth rate in terms of area and numbers at various altitude range?
- Which zone is maximum sensitive for lake change?

- What is the average slope of glacier lake beds in recent dataset?

1.6.3. Questions pertaining to 3rd objective

- What is the damming material, breach width, breach height and shape of the breached wall of Chorabari lake?
- What is the difference in maximum flood peak and extent at critical locations under different breach scenario using satellite data and field data inputs?

1.7. Layout of Chapters

- The research work carried out in this thesis has been organized into seven chapters.

Chapter 1 briefly summarizes **Introduction** i.e. about historical background related to glacial lakes, its various types, GLOF phenomena and an overview of its impact around the globe. Role of RS & GIS, importance of current study and objectives of research has also been included in this chapter.

Chapter 2 emphasizes on the studies carried out so far i.e. **Literature review** related to the background of work, data used, identification and mapping of glacier lakes, hazards assessment and simulation of lake breach.

Chapter 3 intensely explores the importance of chosen **Study area** mentioning its geographical extent, geology, river basin, climate, vegetation and tourism. The entire Uttarakhand Himalaya has been discussed in detail.

Chapter 4 describes the details of **Materials and datasets** used in the study such as LANDSAT imageries from 1972 to 2012, LISS-4 and Cartosat-1 DEM etc. Major highlights of collected field data has also been presented in this chapter.

Chapter 5 dedicated to the **Methodology** employed in the research work in detail. It starts with the pre-processing of datasets followed by inventory preparation of glacial lakes, their sensitivity analysis and hazard assessment. Input parameters and boundary conditions for simulating Chorabari lake breach using MIKE 11 has been explained in great detail.

Chapter 6 presents the **Results and Discussion** obtained for glacial lake mapping, sensitivity analysis, hazard assessment and Chorabari lake breach simulation.

Chapter 7 highlights **Conclusions and recommendations** on the implications of research. It also highlights the limitation and future scope of the project.

2. LITERATURE REVIEW

2.1. Background

2.1.1. Glacier lakes

The lakes present above 3500 m are considered to be evolved due to retreat of glaciers and are classified as Glacial Lakes (WWF 2005). These glacial lakes have been classified broadly into moraine-dammed, ice-dammed, erosion and other lakes (represented in Figure 5) (ICIMOD 2011).

- **Moraine-dammed lakes:** Due to thinning and retreat of glacier tongue, melt water gets accumulated in the depression between the glacier terminus and its end moraine and such lakes are termed as moraine-dammed lakes. Some lakes also accumulate between the lateral moraine and the valley side along the glacier margins These lakes have high tendency of bursting as dams are physically weak and unstable and undergo various changes due to slope failures, slumping etc.

- **Ice-dammed lakes:** lakes dammed by glacier ice are termed as Ice dammed lakes. Further these lakes are classified as;

  I. **Supra-glacial lakes:** Supra-glacial lakes generally exist on glacier surface that is entirely covered by a thick layer of debris. As supra-glacial lakes grow, the left glacier ice below them melts and thus moraine-dammed lakes are evolved. These lakes often merge with moraine-dammed lakes, or sometimes may develop into composite forms.

  II. **Glacier ice dammed lakes:** Lakes dammed by glacier ice without lateral moraine is termed as glacier ice dammed lakes.

- **Erosion lakes:** Erosion lakes are glacial lakes that form due to past glacial erosion process and exist in depression of glacier retreat region. They exist as cirque glaciers or as glacial trough valley lakes. They exist for from hundreds or thousands of years.

- **Other glacial lakes:** Glacier valley floors receive masses from rock falls, debris flows or landslides, damming local streams of glaciers. Such lakes are called as other glacial lakes.
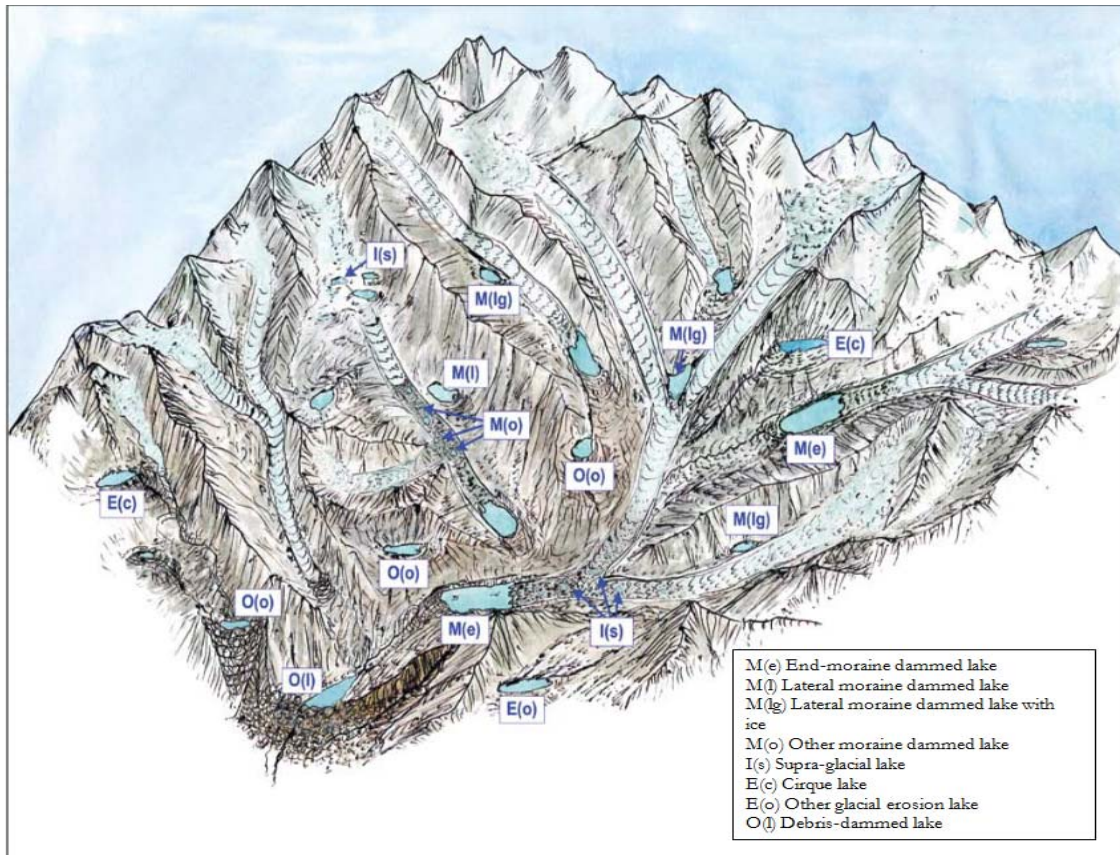
Figure 5: Types of glacial lakes (Source: ICIMOD)

2.1.2. Glacier Lake Outburst Flood (GLOF)

GLOF is characterized by instant outpour of huge amount of sediment laden water from glacial lake that comes down along the river channel in downstream region in the form of flood waves. Lake breach occurs when the damming material of the lake strength is exceeded by driving factor such as the weight of the captured water, leakage forces and shear stress due to overtopping flow. Heavy precipitation or a sudden inflow of water from upstream sources causes overtopping flows, whereas mass movements e.g. snow and ice avalanches, rock falls, etc entering the lake triggers displacement waves. Once the lake overflows, dam erosion will start, forming an initial breach ultimately leading to higher outflow that cause progressive breach expansion. Flowing water exerts critical shear forces on the dam material and the eroded sediments reaches downstream as bed load (Worni et al. 2012). Several thousand cubic meters per second is the discharge rate of these sediment laden flood water. Flood severity is a function of the amount of released water, debris load and basin characteristics of the watershed. GLOF is believed as one of the major hydro metrological hazard having potential to cause large socio-economic losses. During the early phase of scientific study of GLOF, Swedish and Icelandic scientists attempted to relate glacier lake outburst events to atmospheric temperature and sea-level increase and this gave rise to the Icelandic term **'jökulhlaup'** means glacier outburst flood. The word entered in scientific literature from that time.

2.2.   Highlights of related studies in Himalaya

Mapping of Glacial lakes have been done for different regions of the Himalaya. Between 1999 and 2005, ICIMOD in collaboration with partners in different countries has prepared an inventory of glacial lakes for various parts of Himalayan region. Bolch et al. (2008) attempted automatic detection method of glacial lake using a Normalized Difference Water Index (NDWI) on Imja Glacial Lake. Microwave data was used by Lichtenegger et al. (2008) to monitor the variations of Imja Lake of Nepal. NDSI method was applied by Racoviteanu et al. (2008b) for mapping glacier terrain of Sikkim Himalaya. TERRA-ASTER image was used by Molnia (2009) to identify glacial lakes of Afghanistan. Differential GPS survey was employed by Thompson et al. (2010) for mapping the perimeter of major lakes. Zanskar basin, J&K, India study was carried out by Raj (2010) to estimate peak discharge from the lake using empirical formula. Glacial lake inventory of Bhutan was prepared by Ukita et al. (2011), using Advanced Land Observing Satellite (ALOS) data. Gardelle et al. (2011) carried out the transboundary assessment of glacial lake distribution (Jain et al. 2012). SAC, Ahmedabad has generated the inventory for 5 Indian Himalayan states at 1:50000 scale. (Fujita et al. 2013) developed the empirical formula for potential flood volume of Himalayan glacial lakes. Banerjee et al. (2013) has reported the change in number of glacial lakes of Teesta basin, Sikkim comparing the multi temporal LANDSAT dataset of last 40 years. Some studies have also focused on Glacier lake outburst flood. Watanabe et al. (1994) assessed the potentials of glacial lake outburst in Khumbu Himalaya based upon comparisons with the change in volume of lake water.

2.3.   Identification and Mapping of Glacial lakes

Literature review suggests that numerous methods have been attempted for delineating glacial lakes. Supervised and unsupervised classification for lake identification has been carried out with limited accuracy. Wessels et al.(2002), attempted the automatic classification of glacial lakes using ASTER data, but the algorithm was not robust enough to be applied to other images except ASTER images. Using LANDSAT images, Huggel et al. (2002) suggested the NDWI (Normalized Difference Water Index), similar to Normalized Difference Vegetation Index, NDVI (Hardy and Burgan 1999), to classify glacial lakes, taking advantage of the low water reflectance in the NIR band and high reflectance in blue band. However, it was observed that glacial lakes get misclassified as shadow area using this method. Other problems in identifying the lakes are frozen, semi frozen lakes and misclassification due to cloud shadow. RADAR data can be used to avoid this problem as it penetrates cloud. RISAT 1 cloud free radar data products are available from April 2012 for complete Indian subcontinent. Using RADAR image of melt condition, cloud shadow and frozen lakes problem gets easily eliminated. Other studies mentioned manual delineation of the glacial lakes using DEM on the basis of image interpretation technique such as tone, texture and association to avoid misclassification.

$$NDWI = \frac{NIR-Blue}{NIR+Blue}$$…………... Equation1: NDWI

$$NDVI = \frac{NIR-Red}{NIR+Red}$$……………Equation 2: NDVI

2.4.   Hazard Assessment of glacial lakes

Various criteria are mentioned in literature to identify the hazardous lakes. The major criteria used for hazard assessment are as follows;

1. Large lake size and rapid growth in area
2. Increase in lake water level
3. Changes in supra-glacial lakes at different times
4. Position of the lakes in relation to associated glacier

5. Dam condition such as;

a) Narrow crest area
b) No drainage outflow or outlet not well defined
c) Steepness of slope of the moraine walls
d) Existence and stability of ice core and/or permafrost within moraine
e) Height of moraine
f) Mass movement, or potential mass movement, on the inner slope and/or outer slope of moraine
g) Breached and closed in the past and the lake refilled with water
h) Seepage through the moraine walls

6. Glacier condition such as;

a) Condition of associated glacier
b) Hanging glacier presence
c) Large glacier area
d) Rapid glacier retreat
e) Debris cover on the lower glacier tongue
f) Gradient of glacier tongue
g) Presence of crevasses and ponds on glacier surface
h) Toppling/collapsing of ice from the glacier front
i) Ice blocks draining to lake

7. Physical conditions of surrounding such as;

a) Potential rockfall/slide (mass movement) sites around the lake
b) Large snow avalanche sites immediately above the lake
c) Neo-tectonic and earthquake activities around or near the lake
d) Climatic conditions, especially large inter-annual variations
e) Very recent moraines of tributary glaciers that were previously part of a former glacier complex, and with multiple lakes that have developed due to glacier retreat
 f) Sudden advance of a glacier towards a lower tributary or main glacier which has a well-developed frontal lake (ICIMOD 2010).

All the above listed parameters are generally not considered in any study. In most of the cases only few of the parameters have been considered as these can be assessed only using remote sensing images, such as lake size, area, hanging glacier presence etc., other parameters such as condition of associated glacier, height of moraine, debris cover etc needs detail field investigation.

2.5. GLOF modelling

Model is the mathematical representation of real world phenomena. Modeling is always related with group of mathematical equations which are not sufficient to represent the total complexity of real phenomena 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). These model solve the basic flow equations i.e. Continuity and momentum equations and mainly produces (a) the outburst hydrograph due to dam breach (b) and maximum flood level and discharge including time of travel at defined cross sections. The model finds solution of two partial differential Saint Venant equations. The equations are;

$$\frac{(\partial Q/\partial X) + \partial (A + A_o)}{\partial t - q} = 0 \ldots \ldots$$ Equation 3: Continuity equation

$$(\partial Q/\partial t) + \{\partial (Q2/A)/\partial X\} + g A ((\partial h/\partial X) + Sf + Sc) = 0$$ Equation 4: Momentum equation

Where, Q = discharge; A = active flow area; A_0 = inactive storage area; h = water surface elevation; q= lateral flow; x = distance along waterway; t = time; S_f = friction slope; S_c = expansion contraction slope and g = gravitational acceleration.

2.5.1.   Choice of Model (MIKE 11)

MIKE 11 model was selected for the study due to its robustness. It is a six point distributed 1D model used for analysis of unsteady flow. Other open source model such as HEC RAS does not provide good results for steep slopes more than 10 percent as this model follow four point schemes. MIKE 11 hydrodynamic module works for various relief conditions. Various applications of the software package are Hydrodynamic modeling (HD), rainfall runoff modeling (RR), sediment transport modeling (ST) etc. MIKE 11 HD section has four components in the simulation file (*.sim11). Components are simulation mode, input, simulation parameters and HD result file (*.res11). Simulation mode helps in defining the unsteady condition. It needs input file to build the HD model setup (Network file, Cross section file, Boundary file and HD parameter file). The simulation duration and initial conditions are entered in the required file. The network file (*.nwk11) has database of drainage system with defined projection parameters. In addition to these, drainage at defined cross section point and width in projected coordinate are also defined. The cross section file(*.xns11) has numerous cross section defined with information such as channel name, cross section ID, drainage in the network file, location of the ends (left/right) of the cross section in projected coordinates, cross section datum, cross section with elevation and markers. The Boundary file (*.bnd11) has boundary description, type, ID, branch name, chainage in the network file. And time series file (*.dfs0) which describes the time series data (water level, discharge at observed time step in the field). Hydrodynamic parameter file (*.HD11) has initial condition of water level, discharge at defined chainage in the network file and Bed resistance. Sediment transport module requires shear stress value, grain diameter, porosity, specific gravity etc. as an input parameter (MIKE 2013). The model was used for generating the hydrograph (flood level and discharge) at various defined cross sections.

3. STUDY AREA

3.1. Location & Extent

Uttarakhand (represented in Figure 6) located in northern part of India, is one of the hilly states in Indian Himalaya. It lies between the latitudes **28°43´- 31°27´N** and longitudes **77°34´- 81°02´E**. The state has maximum extent of 310 km from East to West and 255 km from North to South**.** Total area of the state is 53,484 sq. km with elevation range from 210 to 7817 m.s.l. Uttarakhand has 92% area in hilly terrain whereas the remaining 8% lies in the plains (Sah et al. 2005). The Tons river separates the state from Himachal Pradesh in the north-west, whereas Kali river separates Uttarakhand from Nepal in the east. The greater Himalaya is the northern boundary of the state and Uttar Pradesh touches its southern boundary. The state consists of 13 districts and Dehradun is the capital of the state. The state has alone 25% hydro power potential out of country's total hydro potential (MoEF 2010).
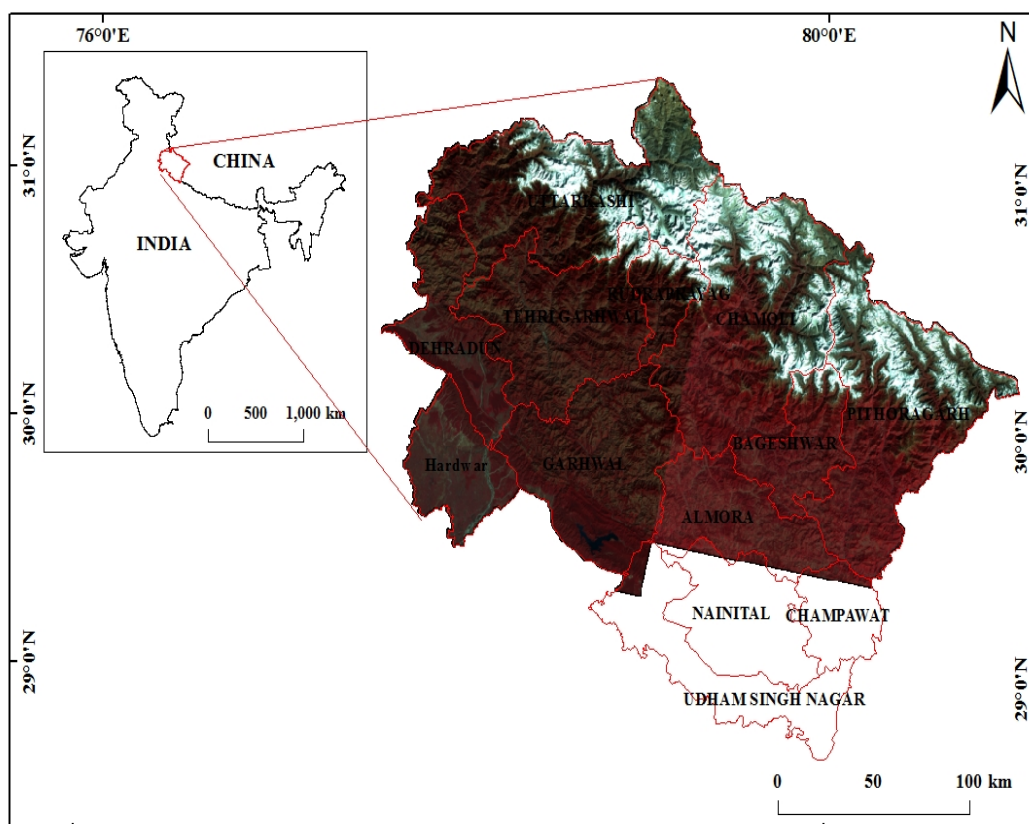
Figure 6: Study Area

3.2. Kedarnath town and Chorabari lake

Kedarnath town (represented in figure 7) (30°44´06´´N 79°04´01´´E) in Uttarakhand Himalaya is located in the Mandakini river valley which has total catchment area of approximately 67sq.km. The Kedarnath town is situated on the outwash plane of Chorabari and Companion glaciers. Mandakini river originates from Chorabari glacier and joins Saraswati river which originates from Companion glacier near Kedarnath temple. The Chorabari lake (represented in Figure 8) (30°44´50´´N 79°03´40´´E) (3855 m.s.l) also known

as Gandhi Sarovar lake is a snow melt and rain fed moraine dammed lake, located approximately 2 km upstream of Kedarnath town. Breaching of Chorabari lake on 17th June 2013 led to heavy devastation in downstream upto Sonprayag. On 16th and 17th June 2013, heavy rains together with snow melt and moraine dammed lake (Chorabari Lake) burst caused flooding in Mandakini and surrounding river channels that damaged the banks of river for 18 km between Kedarnath and Sonprayag and completely washed away Gaurikund , Rambara and Kedarnath towns (represented in Figure 9 and 10). Field visit interview and media report suggests loss of large number of human lives and heavy damage to infrastructure and livestock (Dobhal et al. 2013).

Figure 7: Overview of Kedarnath township from Chorabari Lake bank after disaster (18th Oct., 2013)

Figure 8: Breaching point of Chorabari lake (18th Oct., 2013)

Location of Rambara township before Kedarnath Disaster (Joshi Mayank, 2008)

Location of Rambara township after Kedarnath Disaster (field photograph dated:
October 19, 2013)

Figure 9: Rambara, before and after disaster

Overview of breaching part of Chaurabari lake and Kedarnath township after the disaster (Vaibhav Kaul, 2013)

Kedarnath township before the disaster (Kedarnath Pictures, 2014)

Kedarnath township after the disaster (field photos, dated October 17, 2013)

Figure 10: Kedarnath township (before and after disaster)

3.3. Geology

Half-schistose, gneissose and Precambrian are the three major rocks present in the geology of Uttarakhand. Precambrian rock is found in a major part of state and hence is a significant constituent of Uttarakhand geology. The Precambrian rock consists of schists and phyllites. The presence of schists and phyllites in the state makes its slope prone to erosion and weathering. The chances of soil erosion further increases due to heavy rainfall in the monsoon season. Thus state is always susceptible to natural disasters. Uttarakhand Himalaya is also one of the seismically active region of the world. As per the seismic zone map of India, the entire state has been assigned to seismic zone 4 and 5.

3.4. River Basin

Including high mountains, large Glaciers and passes, Uttarakhand is also the home of many holy rivers originating from the glaciers of Greater Himalayan ranges. The main rivers of Uttarakhand are Ganga, Yamuna and Kali which together with their tributary channels like Tons, Bhagirathi, Bhilangna, Mandakani, Pindar, Sarju, Gori, Dhauli and Kosi drains about 225,757 million cusecs meter water per annum. Further, these rivers are useful for irrigation purposes also. (Nandy and Dhyani 2006)

3.5. Climate

As Uttarakhand lies on the southern slope of the Himalaya, its climate varies greatly with elevation. Difference of 6 degree temperature has been observed at every 1000 m altitude variation. As the relief variation in Uttarakhand is from 200 m in south to more than 7500 m in the north, thus slope aspect also play important role in determining the climate as north facing slopes are much cooler and damp than south facing slopes due to insolation effect. Uttarakhand receives more than 70-80 % rainfall during monsoon period from June to September and remaining precipitation occur during winter due to westerly disturbances.

3.6. Flora & Fauna

Uttarakhand has a great diversity of plants and animals. It has a recorded forest area of 34651 km² which is almost 65% of the total area of the state. Uttarakhand is also home to rare species of plants and animals, many of which are protected by sanctuaries and reserve. Himalayan black bears, Indian grey mongooses, Indian pangolins and Evergreen oaks, rhododendrons, and conifers predominate in the hills.

3.7. Tourism

Uttarakhand is a land of natural beauty and place of Hindu shrines. It is also titled as *'Devbhoomi'* (the land of Gods) and attracts tourists and pilgrims from all around the world. Mussoorie, Nainital, Dhanaulti, Kausani and Ranikhet are some of the popular hill stations in the state. The state has 12 National Parks and Wildlife Sanctuaries. In addition to above, Valley of Flowers, National Park and Nanda Devi National Park, together are UNESCO World Heritage Site. The state has always been a destination for various adventurous sports such as mountaineering, hiking, and rock climbing etc. Figure 11 represents the spiritual and national importance of Kedarnath.

A) Photograph of Kedarnath temple 130 years ago (Vadakayil A, 2013); B) Photograph of Kedarnath temple in July 2013--after the floods (Vadakayil A, 2013); C) India 1975, The Kedarnath peaks in the background. The holy town Kedarnath in the foreground (India, 2014); D) India 2001, Kedarnath Mandir temple and the Kedarnath mountains in the background (India, 2014); E) Kedarnath temple and its staircase before the disaster (Kedarnath Pictures, 2014); F) Kedarnath Ice covered (Vadakayil A, 2013); G) Kedarnath Temple after the disaster

Figure 11: The spiritual importance of Kedarnath

4. MATERIAL AND DATASETS

4.1. Satellite Data

The remote sensing datasets used for the study are coarse to high resolution satellite imagery and Digital Elevation Model (DEM). Since LANDSAT data is available from 1972, therefore to carry out the time series analysis of glacial lakes from 1972 to 2012, various LANDSAT data along with Resourcesat-2, LISS 4 datasets were used in the research. By comparing all the available images for the study area, images with max 10 percent cloud cover and least snow cover from the month of September to December were selected for the study. A total of 15 LANDSAT (MSS/TM/ETM+) images were downloaded from Earth Explorer of United States Geological Survey (USGS) and 10 LISS 4 scenes were ordered to National Remote Sensing Center, Hyderabad for preparing the inventory of glacial lakes. As the area is mostly cloud covered therefore, similar seasons datasets between September to December were selected to avoid the cloud cover ensuring least snow coverage (Jain et al. 2012). The months for which LANDSAT and LISS 4 images were used are September (2 scenes), October (6 scenes), November (15 scenes), December (2 scenes). Following are the datasets details along with their specifications.

4.1.1. Datasets specification and details

The specifications and details of various dataset used in the study are summarized in Table 1

Table 1: Details of datasets

Data	No of bands	Spatial Resolution (m)	Radiometric Resolution (bit)	Swath (km)
LANDSAT 2 (MSS)	4	60	6	185
LANDSAT 5 (TM)	7	30/120(6th band)	8	185
LANDSAT 7 (ETM+)	8	30/60(6th band)/ 15(PAN,8th band)	8	185
LISS 4	3	5.8	10	70
CARTOSAT 1	1	2.5	10	9.6

4.1.2. For 1972-80 (LANDSAT MSS)

Table 2 summarizes the details of LANDSAT MSS data

Table 2: LANDSAT MSS data

Data	Path	Row	Date of acquisition
LANDSAT 2	155	39	13 Oct 1976
LANDSAT 2	156	38	19 Nov 1976
LANDSAT 2	156	39	19 Nov 1976
LANDSAT 2	157	38	02 Nov 1976
LANDSAT 2	157	39	02 Nov 1976
LANDSAT 2	158	38	03 Nov 1976

4.1.3. For 1981-90 (LANDSAT TM)

Details of LANDSAT TM data are presented in Table 3

Table 3: LANDSAT TM data

Data	Path	Row	Date of acquisition
LANDSAT 5	144	39	23 Oct 1990
LANDSAT 5	145	39	15 Nov 1990
LANDSAT 5	146	38	21 Oct 1990
LANDSAT 5	146	39	21 Oct 1990

4.1.4. For 1991-2000 (LANDSAT ETM+ SLC ON)

LANDSAT ETM + SLC ON data details are summarized in Table 4

Table 4: LANDSAT ETM+SLCON

Data	Path	Row	Date of acquisition
LANDSAT 7	144	39	09 Nov 1999
LANDSAT 7	145	38	29 Sep 1999
LANDSAT 7	145	39	15 Oct 1999
LANDSAT 7	146	38	22 Oct 1999
LANDSAT 7	146	39	25 Nov 2000

4.1.5. For 2000-2012 (Resourcesat -2, LISS -4)

Detail of Resourcesat-2 data of LISS IV are presented in Table 5

Table 5: Resourcesat-2, LISS-4 data

Data	Path	Row	Subscene	Date of acquisition
LISS 4 FMX	96	49	B	02 Dec 2011
LISS 4 FMX	97	49	A	18 Nov 2011
LISS 4 FMX	97	49	B	12 Nov 2012
LISS 4 FMX	97	49	C	18 Nov 2011
LISS 4 FMX	97	49	D	25 Sep 2012
LISS 4 FMX	98	49	C	23 Nov 2011
LISS 4 FMX	98	49	D	17 Nov 2012
LISS 4 FMX	98	50	A	23 Nov 2011
LISS 4 FMX	98	50	B	17 Dec 2011
LISS 4 FMX	99	50	A	28 Nov 2011

LISS 4 image of 18 Nov 2011 and Cartosat 1 DEM with 10 m vertical accuracy, provided by IIRS were used for Chorabari lake volume calculation and Mandakini river channel digitization. ICIMOD shape files and Google Earth were referred for glacial lakes mapping. ASTER GDEM of Uttarakhand and the NDVI image of LISS IV used for the study is represented in Figure 12.
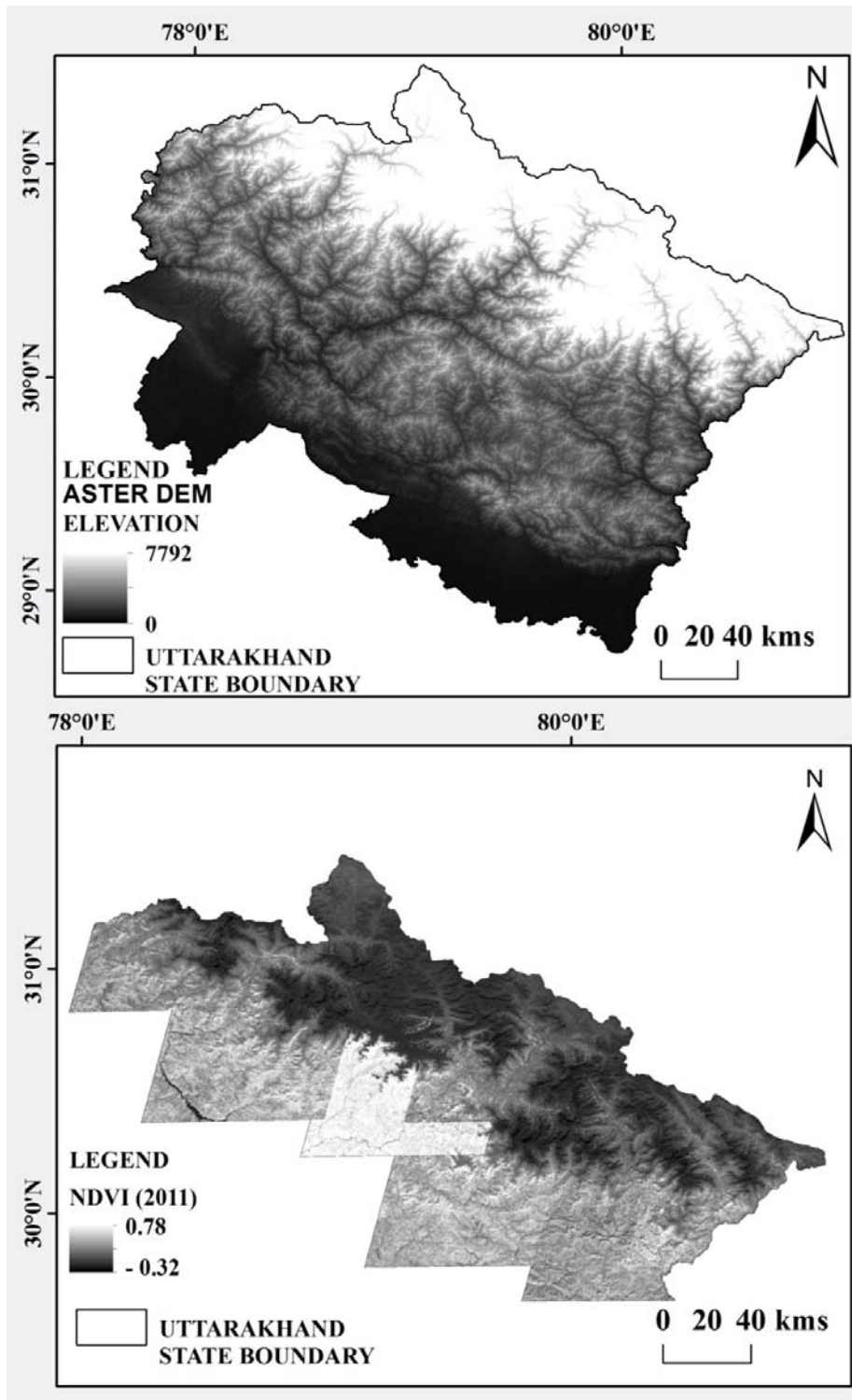
Figure 12: ASTER GDEM and NDVI Image of LISS IV of study area

4.2. DEM (Digital elevation model)

For identifying the glacial lakes, good quality DEM is required for calculating some parameters such as minimum, maximum and mean elevation, slope etc. No local or national DEM of reasonable quality were available for the study area. Generating the DEM by digitizing the contours of toposheet was not possible due to toposheet unavailability (as the study area comes under restricted zone). Cartosat-1 stereo pair generated DEM was also analysed and was not found to be of good quality because of insufficient height information of the area and unclear features. Therefore ASTER GDEM version 2 was used for the study as the best available option. The vertical accuracy of ASTER GDEM is within −0.2 m on average, with an accuracy of 17 m at the 95% confidence level (ASTER GDEM Validation Team, 2011). Figure 13 represents the DEM generated from stereo pairs of Cartosal-1 data using ERDAS LPS module.
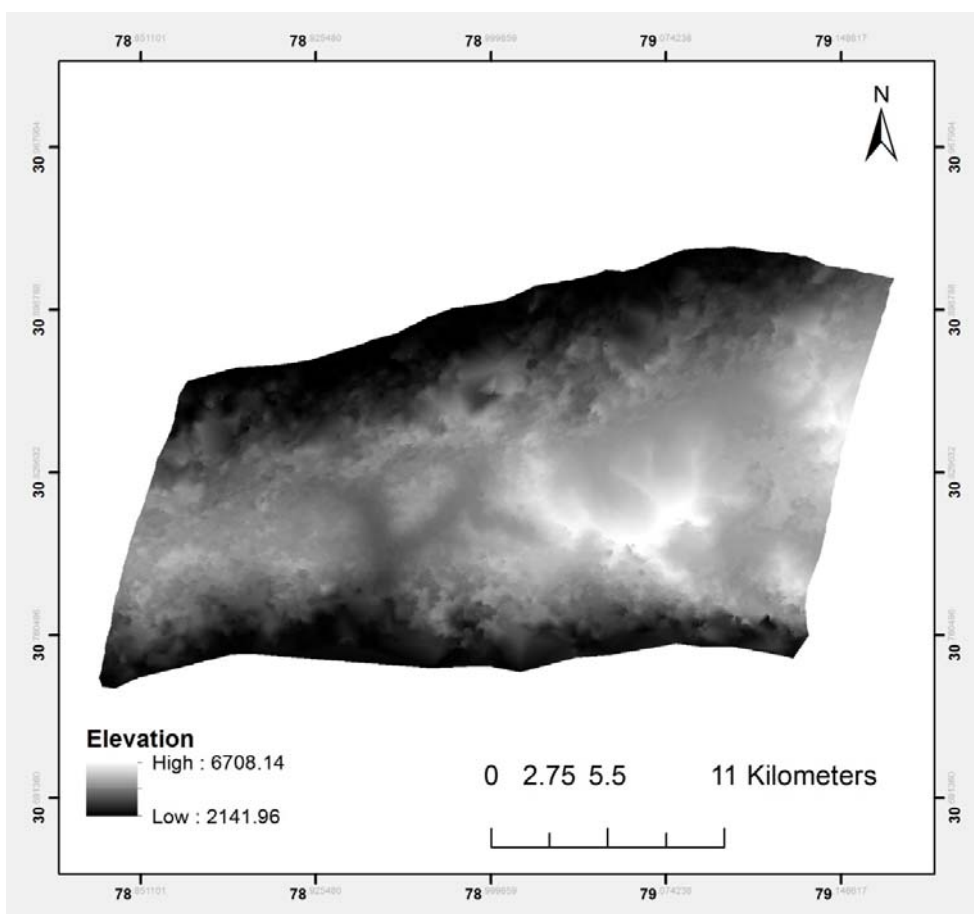
Figure 13: DEM generated from stereo pair of Cartosat-1

4.3 Field Survey

During the field survey of Kedarnath valley upto Chorabari lake in October 2013, DGPS survey was carried out from Kedarnath temple to Chorabari lake bottom at various location. River cross section profiles were also measured using Sprinter level survey device and Staff gauge. All the breach parameters required for the input of MIKE 11 were measured in the field using LASER Distance Finder. Soil sample was collected from the lake breached portion and its shear stress was measured in the IIRS lab using AIMIL soil shear test equipment.

4.4 Software used

- **ERDAS Imagine 13** :- This software was used for preprocessing and processing the satellite images such as layer stacking, mosaic , subset, image enhancement, DEM preparation, NDVI, NDWI generation etc.

- **Arc GIS 10.1**:- It was used for digitization of lakes, their analysis and various map generation.

- **MIKE 11**:- Due to exceptional flexibility and speed for handling complex flood phenomena, MIKE 11 was used. Its sediment transport module takes care of discharge and peak estimation at various points for GLOF scenario.

5. METHODOLOGY

The whole study was divided in three objectives. Various steps adopted for completing the objectives are mentioned below;

5.1. Data preparation

Important season for selecting the satellite images for glacial lake mapping is summer, when the lakes are in melt condition but Indian Himalayan region receives maximum rainfall during that time. Thus most of the area remains clouded in the region. Availability of cloud free images and image without snow cover is almost impossible for the region. Hence multi temporal LANDSAT and LISS 4 images with maximum 10 percent cloud cover and minimum snow cover between September and December were chosen for the study. The ASTER GDEM version 2 of the area was downloaded for altitude information and slope map was also generated from it. Layer stacking of different bands of image, mosaicing of images and subset of the mosaiced images were done in ERDAS Imagine software to prepare the data for further processing. NDVI and NDWI maps were also generated for all datasets.

5.2. Mapping of glacial lakes

According to available literature, several automatic and semi automatic glacial lake mapping method exists, but no methods produce good results of mapping. In this research, following spectral band combinations in Standard False Colour Composite (SFCC) were used to identify glacial lakes. Table 6 represents the different bands of various satellite imagery used in the research;

Table 6: Bands from different datasets, used in the study

S. No	Data	Bands used
1.	LANDSAT 2 (MSS)	4,5,7
2.	LANDSAT 5 (TM)	1,2,3,4,5
3.	LANDSAT 7 (ETM+)	1,2,3,4,5
4.	LISS 4	2,3,4

Lake appears from light blue to black when presented in Standard False Colour Composite (SFCC) and frozen lakes appear white. They have generally smooth texture as compared to surrounding and are usually associated with glaciers at higher altitude and with river channels at lower heights. Lake existing above 3500 m from msl were only considered for mapping, using the literature information that snow line in Himalaya exists above 3800 m from m.s.l .

ICIMOD shapefile was considered as a reference data for mapping and was overlaid on ETM+ 1999 images. Lakes which were clearly visible were manually digitized and those which were partially visible were confirmed taking the help of Google Earth imagery using spatial information. These mapped lakes were then overlaid on the NDVI and NDWI maps for threshold definition. Using defined thresholds along with visual interpretation techniques such as colour, texture, association etc rest of the lakes for the image ETM+ (1999) were manually digitized. Likewise Various NDVI and NDWI threshold range were defined manually for different satellite imagery and lakes were mapped. To generate NDVI map for LANDSAT MSS band 5 and 7, for TM, ETM+ and LISS 4 band 3 and 4 were used. Similarly to generate NDWI for LANDSAT MSS band 4 and 7, for TM, ETM+ band 1 and 4 and for LISS 4 band 2 and 4

were used. Following minimum and maximum values of NDVI and NDWI were defined after the analysis of all the satellite images, based on their DN values.

NDVI= -0.02 to -0.89
NDWI= 0.01 to 0.54

Although glacial lakes can be identified if it contains at least one pure pixel and is perfectly aligned with the raster grid, but generally they are not aligned with the raster grid. Therefore, the smallest lake that can be identified is 2X2 pixel. But 3X3 pixel is chosen to detect even the mixed pixels that contain majority of lakes (Quincey et al. 2006). The smallest glacial lake area that could be mapped in LANDSAT MSS is of area 0.03 km². In TM and ETM+ 0.01 km² area could be mapped and in LISS 4 minimum of 0.0004 km² area could be mapped. A threshold of 0.01km² was decided to map the glacial lakes of all the imagery, as lake below this threshold does not contain substantial water. In this study, error in image co-registration did not play a significant role, since comparison is not made pixel by pixel but feature to feature.

Due to spectral reflection, shadowed areas get misclassified as lakes which can be found with the help of DEM. According to literature, glacial lakes mostly exist in the areas where slope is less than 10 degree. Therefore, in order to avoid the misclassification of shadow to lakes, ASTER DEM was used in the study. Buffer of 100 m was created around the unclassified area and the mean slope of the buffer zone was calculated considering the relative vertical accuracy of GDEM which is around 20 m. The calculated slope and NDVI, NDWI threshold range were then used to verify the area. Fully frozen lakes have not been reported in the study. Figure 14 represents the glacial lake mapping from various datasets of 1976 to 2011.
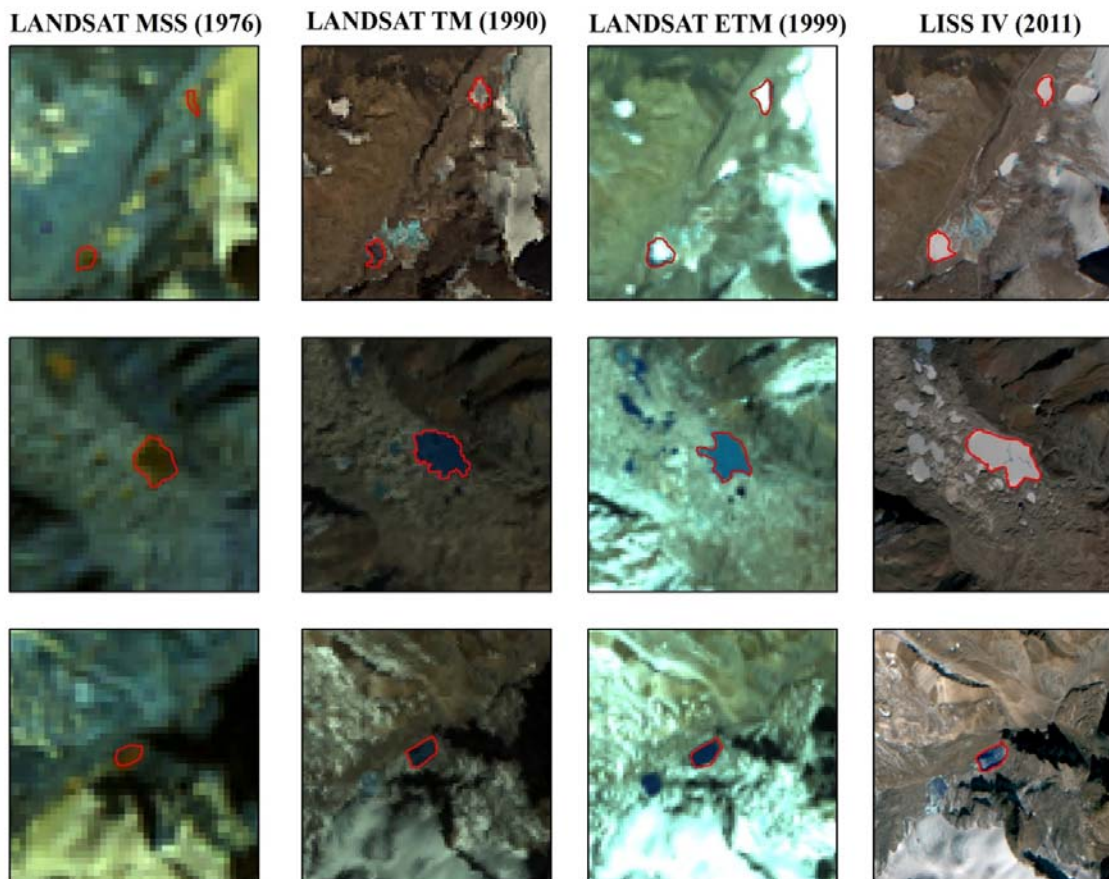

Figure 14: Glacial lake mapping (1976-2011)

After delineating the lakes boundary their area, volume, central lat-long and elevation were calculated for further analysis. Numbers, area and volume for each datasets were calculated to estimate the growth rate. The volume of the lakes was calculated using mean depth of lake value adopted from (Fujita et al. 2013) equation;

$$M = 55 \times (A)^{0.25} \ldots\ldots\ldots \text{Equation 5}$$

where, M is mean depth of lake in m
A is area of lake in sq km

The volume was then calculated by multiplying area of lake with mean depth obtained from equation 5.

Overview of methodology adopted for achieving objective 1 is represented in Figure 15
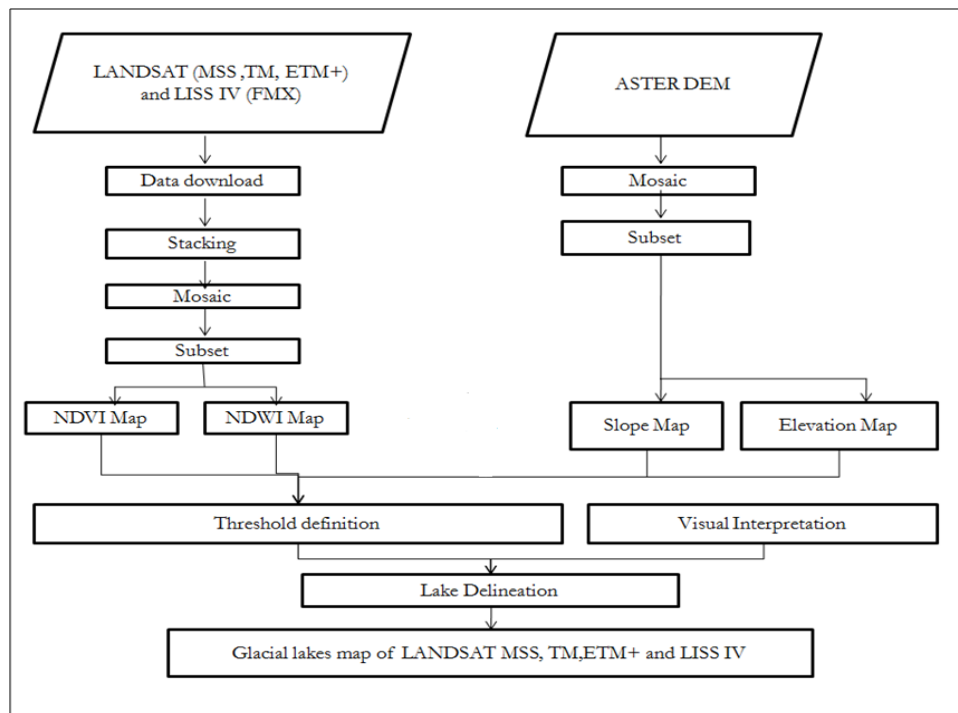
Figure 15: Methodology for objective 1

5.3. Sensitivity analysis of Glacial lakes

Using ASTER GDEM elevation was divided into various zones. The first zone was defined at elevation 3500 m. Above this elevation, upto 5000 m, at every 500 m zones were defined. The last zone was defined for 5000 m and above. Area and number for all the mapped lakes in all four datasets were then compared. The zone, where maximum change in area and number was observed was considered sensitive for lake change.

5.4. Hazard assessment

To carry out the hazard assessment, minimum lake area threshold was defined considering the area of Chorabari lake in the study. The slope of maximum 10 degree was considered as another parameter for the hazard assessment because lakes with lower slope value have more chances to grow. Following methodologies were adopted to carry out objective 2 i.e. Hazard assessment of lakes;

Figure 16: Methodology for objective 2

5.5. Chorabari lake breach simulation

To carry out the simulation of Chorabari lake breach, ground data was required to run the model. Hence the methodology was separated in two parts;

5.5.1. Field work

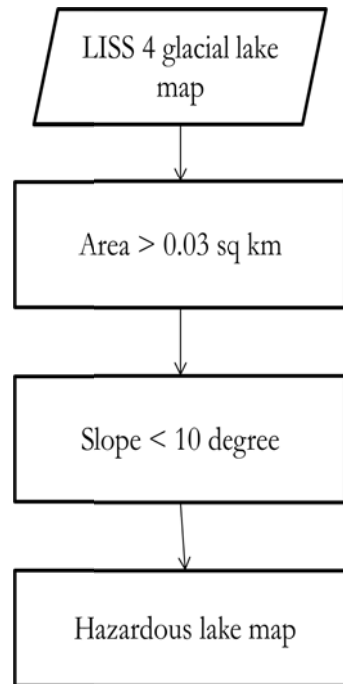Field visit of Kedarnath valley up to Chorabari lake was planned in October, 2013 to get required simulation parameters for MIKE 11 model, such as shape of breach, length, width and height of breach, lake depth, breach scenario etc. Laser Distance Finder was used to measure the length, width and height of breach and staff gauge was used to measure the lake depth. River cross section profiles were measured using Sprinter level survey device and simultaneously DGPS survey was carried out from Kedarnath temple to Chorabari lake. Soil sample was also collected from the lake breached portion and its shear stress was measured using AIMIL soil shear test equipment in IIRS lab to identify the damming material. The soil sample was tested for maximum stress and was found lying in the category of mixed clay and rock as per the criteria defined by USGS, 2008.

5.5.1.1. Post Field work

GLOF suddenly increases to peak flow and then gradually or abruptly comes down to base level once the water source is finished. Outburst flood peak flow is a function of lake volume, dam height and width, dam material, failure mechanism, downstream topography, and sediment present. MIKE 11 estimates the flood hydrograph of discharge and water level/discharge time series at different cross section downstream up to defined outlet. Its hydrodynamic (HD) module is used for dam break modelling. This module has four associated files named as Boundary file, Simulation file, Cross section file and Hydrodynamic file which requires various input data such as;

5.5.1.2. Initial Conditions

In Mike 11, before actual simulation of dam break, it is required to create a steady state "hot-start" file, which can be used for further dam break simulation. This file is created by, (a) inserting a constant lateral inflow at the first **h**-point of the reservoir branch in MIKE 11 set up and (b) specifying the dam break structure failure due to overtopping, considering dam crest level is more than reservoir level. Initial conditions (water level and discharge) were given in HD parameter file, including the lake level.

5.5.1.3. Cross section profile

Arc-GIS software was used to delineate the Mandakini river channel downstream up to the Kedarnath temple using LISS 4 image and Cartosat-1 DEM. Cross-section layer in network editor file was created at the same location where it was measured in the field. Then these lines were converted into point file. The elevation at all the points were thus calculated and the file was exported to MIKE 11.

5.5.1.4. Breach parameters

The volume of Chorabari lakes was calculated using average lake depth measured from staff gauge in field and area calculated from high resolution LISS 4 image using formula ;

$$\textbf{Volume = Area * Depth........ Equation 6}$$

In Mike 11, the lake is represented as dam break structures with certain crest level and crest length. The shape of breach was specified trapezoidal and other parameters were given as per collected data from field. Overtopping and Erosion based failure was selected as a breach mechanism. For dam break study, timing of the breach is also very important parameter but it is very difficult to predict the time. As per the interview from people during field visit, 15 min time was estimated for complete breaching of lake considering first 5-7 minutes as the maximum peak flow time.

5.5.1.5. Parametrization of Chorabari lake ;

The initial crest level (3855 m) and bottom level (3814 m) was measured using DGPS in the field and the initial crest width (56 m) and the bottom width (5 m) was measured from LASER Distance Finder (LDF). Crest length was measured 22 m during the field survey. Erosion based failure was considered and the upstream slope value of 0.76 was calculated using breach length and depth ratio. Top width of breach (46 m) was measured using LDF. The area of lake was calculated using LISS 4 high resolution Imagery and the mean depth of lake was measured using staff guage. Finally the volume was calculated using formula area* depth.

5.5.1.6. Dam break simulations

Using the required parameters, single channel simulation was carried out up to Kedarnath temple where the outlet was defined. The time was selected of the order of 15 sec. Generally, for the river with flat slope, higher value of time step can be given.

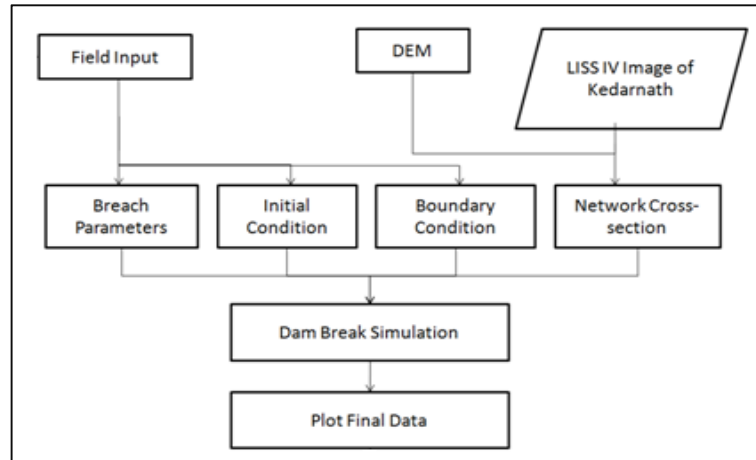Methodology adopted for achieving Objective 3 has been depicted in Figure 17

Figure 17: Methodology for objective 3

6.   RESULTS AND DISCUSSION

6.1.   Mapped glacial lakes

Figure18 represents the mapped glacial lakes from LANDSAT MSS to LISS IV. The generated database was found to be of reasonable accuracy.
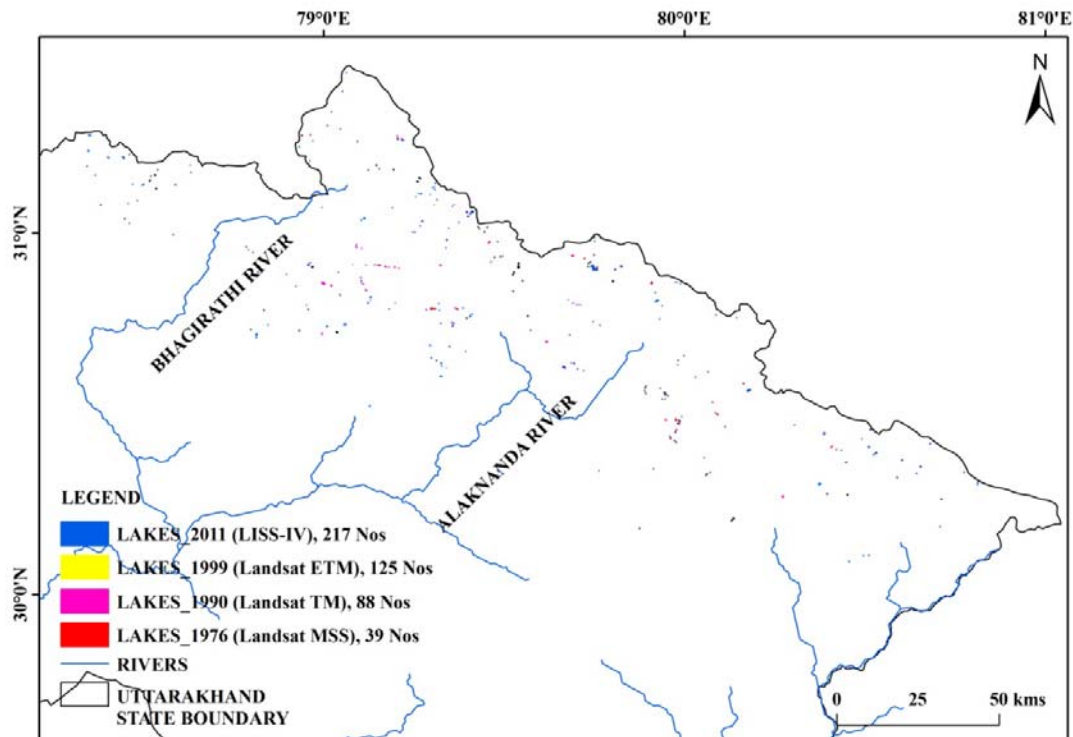
Figure 18: Mapped glacial lakes

The total area of the lakes varied from 0.85 sq km to 3.36 sq km in years 1976 to 2012. The total lake volume of 21.66 M cubic metres was calculated in the year 1976 which increased up to 90.34 M cubic metres in 2011. Comparison based on the number of lakes present in the time series yielded the following result. In the year 1976, a total of 24 lakes were present, in 1990 the number increased to 42, in 1999 total count of lakes was 67 and in 2011 total lakes were 93. All the mentioned lakes are of area greater than 0.01 km sq.

6.2.   Comparison with ICIMOD dataset

The ICIMOD dataset was compared with ETM + (1999). The number of lakes in the ICIMOD dataset greater than 0.01 sq km was 67 and was equal to the number of lakes mapped in ETM+. However, the area in ICIMOD dataset was equal to 2.17 sq km and 2.44 sq km was the area in ETM+.

6.3. Sensitivity analysis
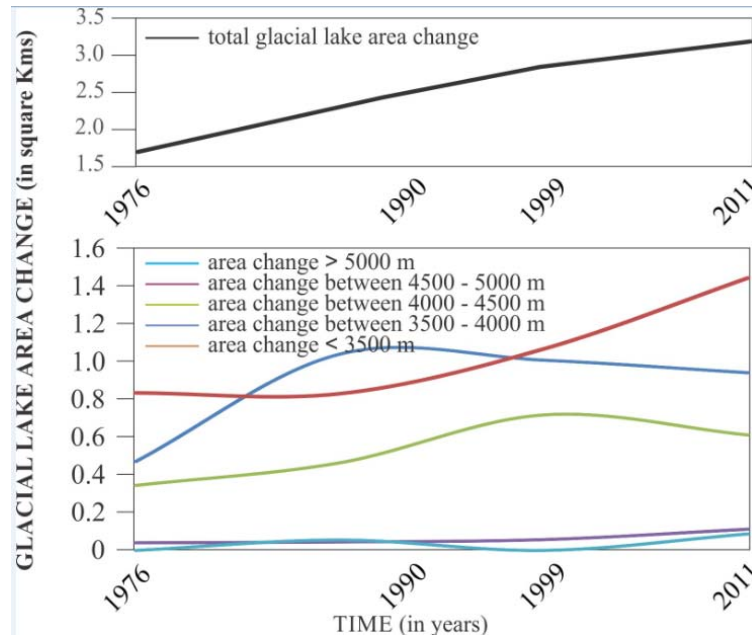
Figure 19: Change in area of lakes with elevation

The altitude variation of glacial lakes' area has been represented in Figure 19 considering the total mapped lakes and it was found that 3500-4000 m elevation zone is maximum sensitive for lake change. Number of lakes represented in Figure 20 illustrates decade wise analysis and it was found that highest number of lakes was found in the zone 3500-4000 m.
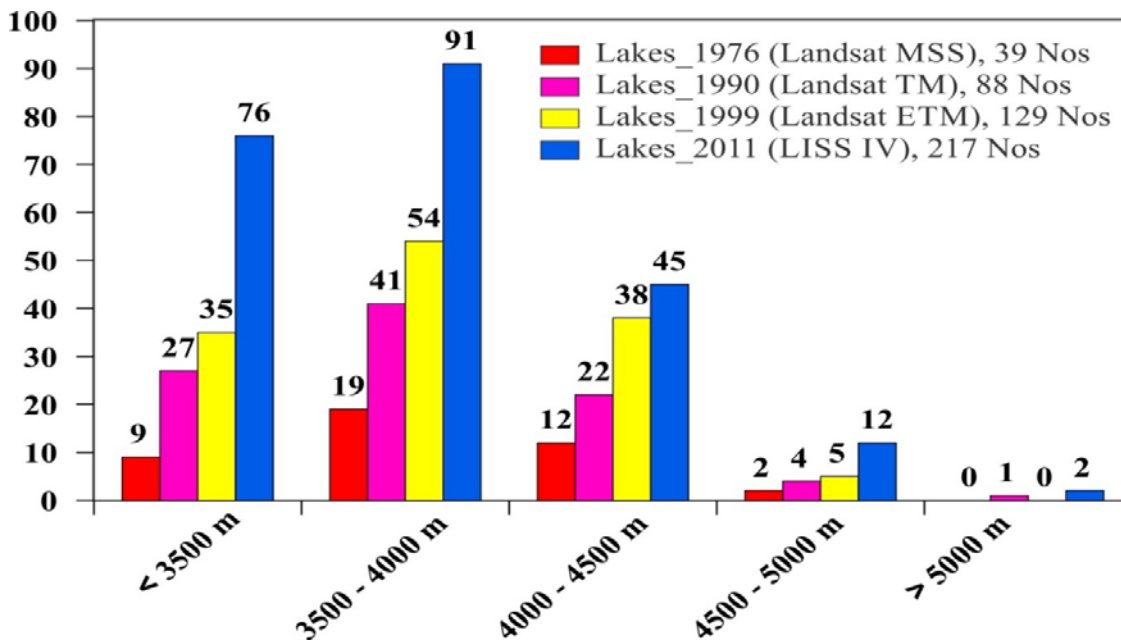
Figure 20: Distribution frequency of glacial lakes in different elevation bands

6.4. Changes in lakes from 1976 to 2011

Analysis on the appearance and disappearance and the growth of lakes was done. It was found that number of lakes increased significantly from 1976 to 2011. It was also found that some of the lakes got disappeared during the time period. The specific reason for disappearance could be concluded as there are chances that the lakes could not be mapped due the differences in snow and cloud cover conditions in different years. Figure 22 and 23 represent some examples of disappearance of lakes in different years.

Highest number of lakes appeared in LISS 4, this increase can be attributed to the high resolution of the image. It might be possible that these lakes existed and could not be mapped in other imagery due to low resolution.

Number of lakes appeared/ disappeared, grown

	1976	1990	1999	2011
Appeared	24	42	67	93
Disappeared	0	0	4	5
Grown	0	18	29	31

Figure 21: Change in number of glacial lakes (1976-2011)

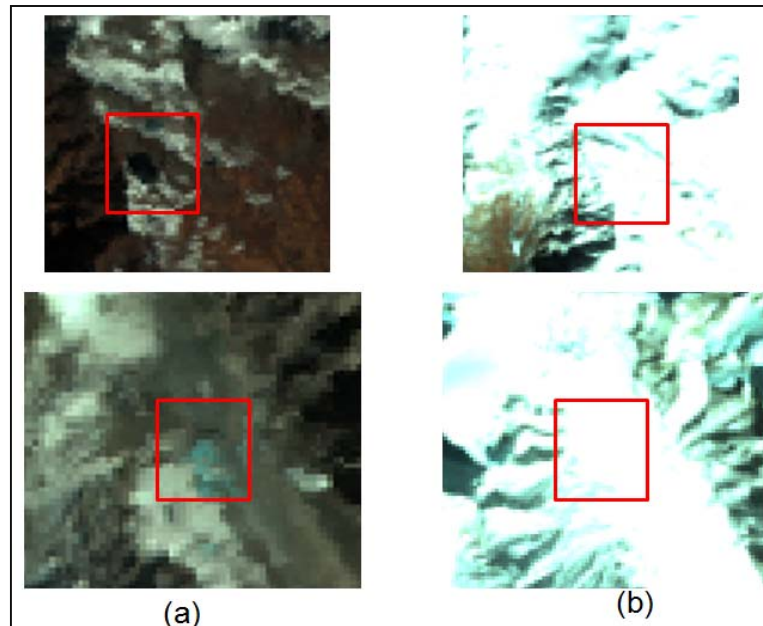Figure 22: Disappearance of lakes in LISS 4 and ETM+

Figure 23: Disappearance of lakes in TM and ETM+

6.5. Chorabari lake breach simulation

In 1894, Gohna lake breached in Uttarakhand Himalaya but the breach was forewarned as it was induced by catastrophic landslide. As per the literature, 5 people were killed in the event. No prior information about the Chorabari lake breach was available which caused the havoc in the state taking a toll of death of thousands of people.

The GLOF simulation was carried out for Chorabari lake breach. The resulting dam breach flood was routed through Mandakini River channel flowing just downstream of the lake. River channel has been represented in the model by cross-sections derived from high resolution Cartosat-1 DEM provided by IIRS with vertical accuracy of 10 m. Cross-sections interval has been taken as per the field readings. The altitude of the Chorabari lake measured in the field was 3855 m and volume of the lake was calculated using Equation 6 which comes out to be 0.65 Mm^3. Figure 24 represents the cross section of GLOF trajectory.
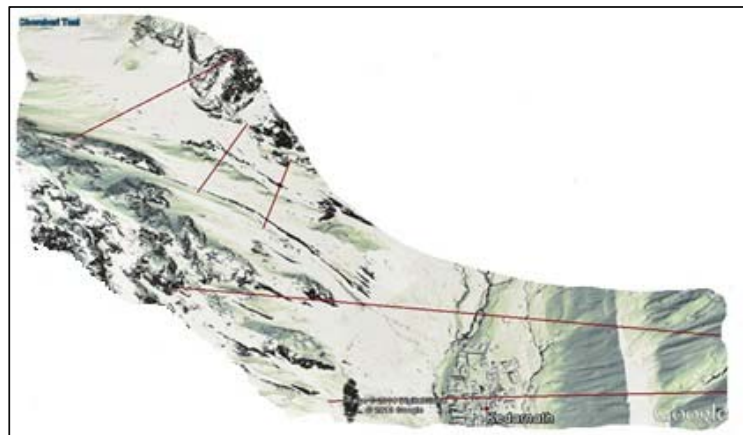

Figure 24: Cross-section representing trajectory of GLOF from Chorabari lake to Kedarnath temple (Source : Google Earth)

MIKE 11 software Hydrodynamic module and sediment transport module was run for generating the flood hydrograph.

The 1-D hydrodynamic simulation was done for the Chorabari lake. The resulted hydrograph in erosion based module shows that entire lake breached in 10-12 minutes after initial breach by overtopping (Figure 27). Figure 25 and 26 represent the cross-section locations at 1800m and 800 m downstream lake, respectively. The initial and final width of breach as measured in the field was taken as 56m and 5m respectively. The side slope was calculated as 0.76 using breach length and depth ratio.

Figure 25: Area representing cross-section point (1800m downstream of Chorabari lake)

Figure 26: Area representing cross-section point (800m downstream of Chorabari lake

The Initial and final breach failure level as observed in the field was taken as 3855 m & 3814 m respectively. The top width of lateral moraine wall which was acting as dam wall for Chorabari lake was taken as 46 m. Initially the crest length of dam was taken as 56m, but that gave a flood hydrograph of >150000 m³/s and water level increase of > 25m at Temple site (1800 m downstream of lake), which was never reported and observed during post floods field work. Therefore final dam crest length of 22 m,

along with other parameters given above was used for simulating flood discharge considering erosion based overtopping of Chorabari lake. The peak discharge of 1127 m³/s and 1080 m³/s was estimated at site 715 m and 1714.5 d/s of lake. The site at 1714.5 is near Kedarnath temple. This discharge corresponds to approximately the volume of 0.65 M m³ of water.
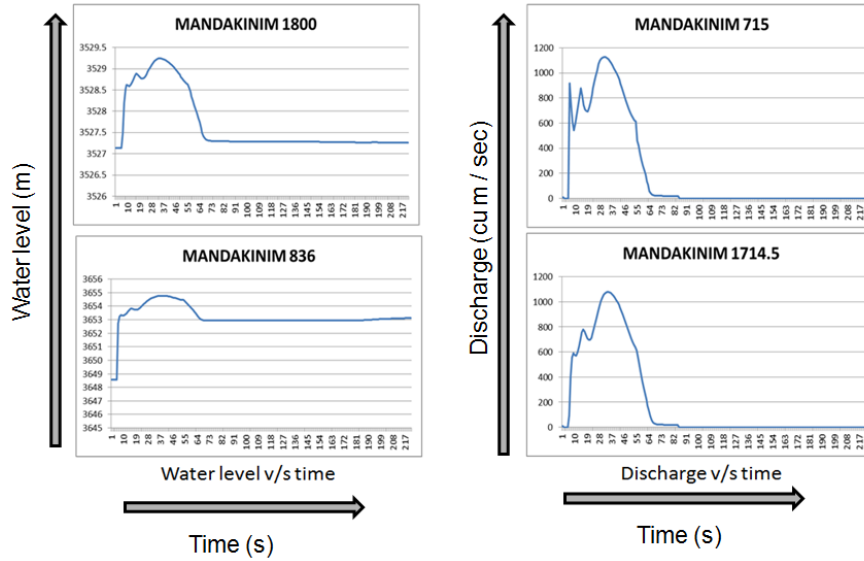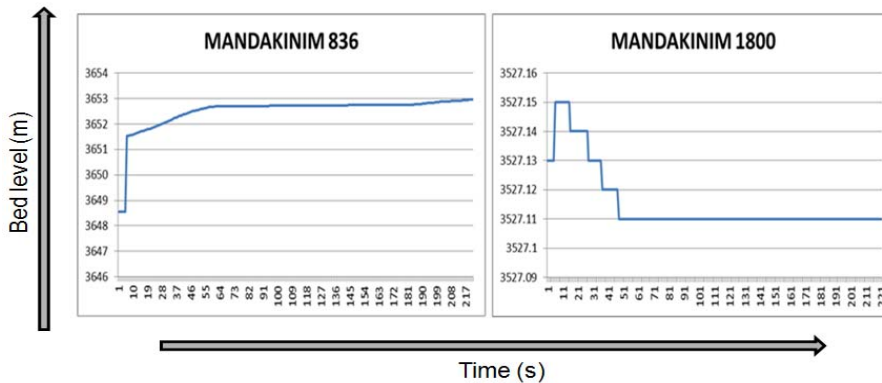

Figure 27: water and discharge v/s time

Figure 28: Bed level v/s time

The water level change at temple site (at 1800 m d/s of lake) was approximately 2.5m and at 836 m d/s of lake it is about 7m, which was similar to what was observed in post flood field survey at Kedarnath temple situated next to the Mandakini river channel.

The Smart and Jaeggi (1983) presented a sediment transport formula which calculates the transport of coarse sediments in steep channels/rivers. This method is used here in Mike 11 HD sediment transport model Figure 28. This method was use to model the sediment transport as well update the bed level of rivers due to erosion and deposition of sediments during GLOF event. The river bed level increased by 5 m at 836m and decreased by 0.05m at 1800m. This result does not match with field observations. During field survey the bed level increase of 2m and higher was seen upto and at Kedarnath temple. It was found during interview with locals in field, that there was one major flood event on 16 June 2013 evening, in which major back part of Temple area was totally washed out and lot of debris got deposited. But this event could not be simulated in present study, as river cross-sections are available for before flood event, derived from NRSC's cartosat-1 DEM of 10 m resolution.

Figure 29 represents the height and discharge at 836 and 715 m downstream the lake, respectively as MIKE 11 gives discharge and height at two different points.
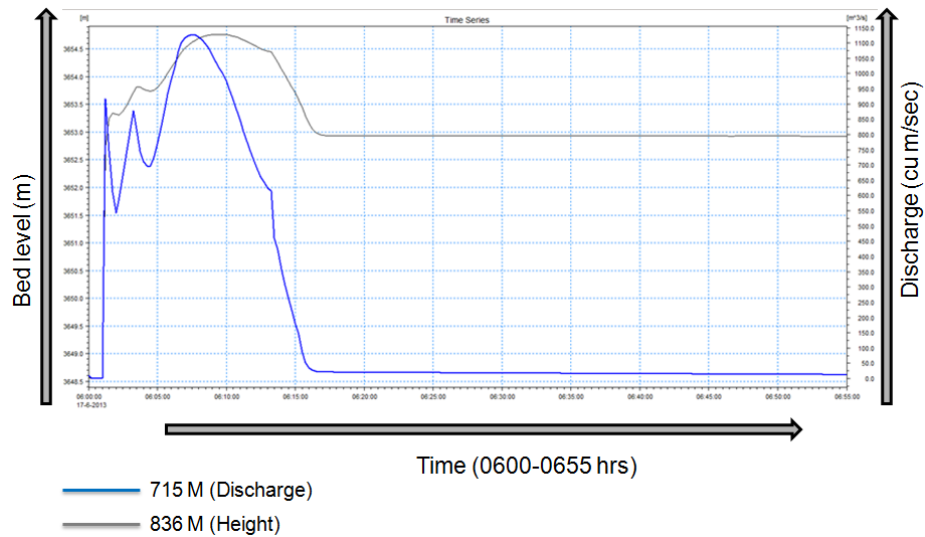

Figure 29: Bed level and discharge at 836 m and 715 m downstream of lake

Overall flood water level and discharge matched with the ground observations, but mismatch was found between the bed level changes due to sediment transport model. Therefore more field data is required on depth and size distribution of sediments of study area downstream of lake. As area surrounding Kedarnath temple was highly developed in term of number of hotels and civil infrastructure, the roughness value of this area need to be relooked along with high resolution DEM of area so that better simulation of floods as well as sediment transport can be done in future studies.

7. CONCLUSION AND RECOMMENDATION.

7.1. Conclusions

In the present study a time series glacial lake database from 1972 to 2012 was generated. The dataset was used to perform various kinds of analysis regarding glacier lakes change. The analysis answered the following research questions.

How many lakes have appeared/disappeared or grown in last 40 years in the study area?
From 1976 to 2011 there has been an increase of 69 lakes having area more than 0.01 sq km. 18 new lakes grown in 1990 where as this number increased to 29 in 1999 and 31 new lakes were found in LISS 4 imagery of 2011. Very less disappearance of lakes were observed in last 40 years of datasets.

What is the area and volume of lakes in last 40 years?
Lakes area have increased from 0.85 sq km to 3.36 in last 40 years. The volume calculated in 1976 data was 21.66 M cubic m which increased to 90.34 in 2011 indicating a significant increase in volume in last 40 years.

What is the growth rate in terms of area and number at various altitude range?
The most marked increase in the lake area and number was observed in the altidute range of 3500-4000m while very less variation was seen in the range more than 5000m.

Which zone is maximum sensitive for lake change?
The analysis involves selection of the most sensitive altitude zone for glacial lakes on the basis change in area. A strong topographic control has been found on the distribution pattern of the glacial lakes in the given region. In this regards most of the glacial lakes are found to be concentrated within an elevation band of 3500 m to 4000 m.

What is the average slope of the lakes beds in recent datasets?
The average slope of the lake bed varied from around 5 to 38 degrees in LISS 4 dataset. 7 lakes with slope of less than 10 degree were considered hazardous.

What is the damming material, breach width, breach height   and shape of the breached wall of Chorabari lake?
During the field visit the following observations were made. Lake breach was V-shaped with length of 64 m, width 46 m and height 36 m. The average depth of the lake water was measured around 20 m. the damming material of the lake was mixed rock and clay.

What is the difference in maximum flood level and flood extent at critical locations using satellite data and field data inputs?
The simulated flood level was found to be 2.5 m which was approximately equal to the field observation. The simulated extent of flood mismatched with the field readings.

Erosion-based, dynamic dam breaks model are still in the preliminary stages of development when it comes to their application in real case or incidence. Therefore, it is essential to study a proper modelling approach for moraine breaching in order to assess the potential threat of hazard from the existing glacial lakes. Many studies have been done in past on GLOFs and on lakes prone to outburst, but there is a lack of systematic analysis of GLOF events and glacial lakes for their potential of hazard. It is imperative to study the complex processes interacting in GLOF disasters.

7.2. Recommendation

Satellite images are the major input of this kind of study but associated climatic conditions makes the data limited for applications. Therefore RADAR data must be incorporated for such kind of study more and more. High resolution imagery and LIDAR DEM can give the output with maximum accuracy.

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ACRONYMS

APN: Asia- Pacific Network
ASTER: Advance Space-borne Thermal Emission and Reflection Radiometer
DEM: Digital Elevation Model
ETM+: Enhanced Thematic Mapper Plus
FCC: False Colour Composite
GIS: Geographic Information System
GLOF: Glacial Lake Outburst Flood
ICIMOD: International Centre for Integrated Mountain Development
IRS: Indian Remote Sensing
LANDSAT: Land Resources Satellite
LISS: Linear Imaging and Self Scanning
Masl: Metre above sea level
MSS: Multi spectral
NDVI: Normalized Difference Vegetation Index
NDWI: Normalized Difference Water Index
NIR: Near Infra Red
PAN: Panchromatic
SRTM: Shuttle Radar Topography Mission
TM: Thematic Mapper
UNDP: United Nations Development Programme
UTM: Universal Transverse Mercator
WIHG: Wadia Institute Of Himalayan Geology