Template/Pro forma for Submission

NMHS-Himalayan Institutional Fellowship Grant

FINAL TECHNICAL REPORT (FTR)

NMHS Reference No.:	GBPNI/NMHS-2017-18/HSF10/604 & 28/03/2018

Date of Submission:	1	7	0	8	2	0	2	2
	d	**d**	**m**	**m**	**y**	**y**	**y**	**y**

FELLOWSHIP TITLE (IN CAPITAL)

GLACIAL LAKES AND GLACIAL LAKE OUTBURST FLOODS (GLOFS) IN WESTERN HIMALAYA, INDIA USING REMOTE SENSING AND GIS

Sanctioned Fellowship Duration: *from* (**28.03.2018**) *to* (**28.03.2021**).

Extended Fellowship Duration (if applicable): *from* (29.03.2021) *to* (30.11.2021).

Submitted to:

Er. Kireet Kumar
Scientist 'G' and Nodal Officer, NMHS-PMU
National Mission on Himalayan Studies, GBP NIHE HQs
Ministry of Environment, Forest & Climate Change (MoEF&CC), New Delhi
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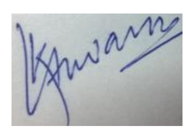

Submitted by:
[*Dr. K C Tiwari, Professor, PI*]
[*Multidisciplinary Centre for Geoinformatics, Department of Civil Engineering, Delhi Technological University, Bawana Road, Delhi-110042*]
[*Contact No.:9971862304*]
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GENERAL INSTRUCTIONS:

1. The Final Technical Report (FTR) has to be commenced from the date of start of the Institutional Fellowship (as per the Sanction Order issued at the start of the Fellowship) till its completion. Each detail has to comply with the NMHS Sanction Order.
2. The FTR should be neatly typed (in Arial with font size 11 with 1.5 spacing between the lines) with all details as per the enclosed format for direct reproduction by photo-offset process. Colored Photographs (4-5 good action photographs), tables and graphs should be accommodated within the report or should be annexed with captions. Sketches and diagrammatic illustrations may also be given giving step-by-step details about the methodology followed in technology development/modulation, transfer and training. Any correction or rewriting should be avoided. Please give information under each head in serial order.
3. Training/ Capacity Building Manuals (with detailed contents of training programme, technical details and techniques involved) or any such display material related to fellowship activities along with slides, charts, photographs should be sent at the NMHS-PMU, GBP NIHE HQs, Kosi-Katarmal, Almora 263643, Uttarakhand. In all Knowledge Products, the Grant/ Fund support of the NMHS should be duly acknowledged.
4. The FTR Format is in sync with many other essential requirements and norms desired by the Govt. of India time-to-time, so each section of the NMHS-FTR needs to duly filled by the Fellowship Coordinator/ PI and verified by the Head of the Implementing Institution/ University.
5. Five (5) bound hard copies of the NMHS-Institutional Fellowship Final Technical Report (FTR) and a soft copy should be submitted to the **Nodal Officer, NMHS-PMU, GBP NIHE HQs, Kosi-Katarmal, Almora, Uttarakhand** *via* e-mail nmhspmu2016@gmail.com.

The FTR is to be submitted into following two parts:

Part A – Cumulative Fellowship Summary Report

Part B – Comprehensive Report

Following Financial and other necessary documents/certificates need to be submitted duly signed and verified along with Final Technical Report (FTR):

Annexure I	Consolidated and Audited Utilization Certificate (UC) & Statement of Expenditure (SE), including interest earned for the last Fiscal year including the duly filled GFR-19A (with year-wise break-up)
Annexure II	Consolidated Interest Earned Certificate
Annexure III	Consolidated Manpower Certificate and Direct Benefit Transfer (DBT) Details showing the education background, i.e. NET/GATE etc. qualified or not, Date of joining and leaving, Salary paid per month and per annum (with break up as per the Sanction Order and year-wise).
Annexure IV	Details and Declaration of Refund of Any Unspent Balance as Real-Time Gross System (RTGS) in favor of NMHS GIA General
Annexure V	Details of Technology Transfer and Intellectual Property Rights developed.

DSL: *Date of Sanction Letter*

2	8	0	3	**2**	**0**	**1**	**8**
d	d	m	m	y	y	y	y

DFC: *Date of Fellowship Completion*

3	0	1	1	**2**	**0**	**2**	**1**
d	d	m	m	y	y	y	y

Part A: CUMULATIVE SUMMARY REPORT

(to be submitted by the Coordinating Institute/Coordinator)

1. Details Associateship/Fellowships

1.1 Contact Details of Institution/University

NMHS Fellowship Grant ID/ Ref. No.:	GBPNI/NMHS-2017-18/HSF10/604 & 28/03/2018
Name of the Institution/ University:	Delhi Technological University
Name of the Coordinating PI:	Dr. K C Tiwari
Point of Contacts (Contact Details, Ph. No., E-mail):	Contact No.:9971862304, E-mail:kcchtphd@gmail.com

1.2 Research Title and Area Details

i.	Institutional Fellowship Title:	Glacial Lakes and Glacial Lake Outburst Floods (GLOFs) Study In Western Himalaya, India Using Remote Sensing and GIS					
ii.	IHR State(s) in which Fellowship was implemented:	1. Himachal Pradesh 2. Uttarakhand					
iii.	Scale of Fellowship Operation	Local:		Regional:	✓	Pan-Himalayan:	

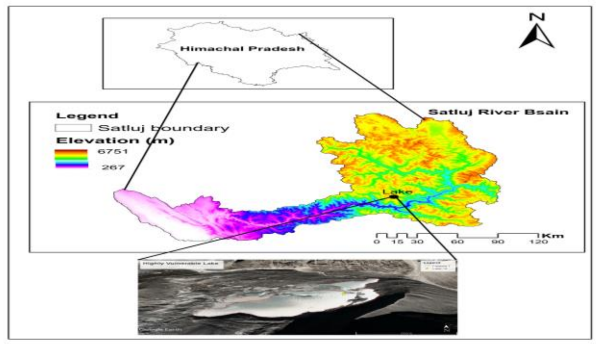
<table>
<tr>
<td>iv.</td>
<td>Study Sites covered (site/location maps to be attached)</td>
<td>
1.Himachal Pradesh
The Satluj River is one of the important tributaries of the Indus river system as well. The river's total length is 1448 km, and total drainage area up to Bhakra reservoir is about 56,500 km^2. The basin area falls in Lahaul & Spiti, Kinnaur, Shimla, Kullu, Mandi, Solan, and Bilaspur districts of Himachal Pradesh. However, for the present study, the Indian part of the Satluj River basin (30º 22' – 32º42' N and 75º57' –78º51' E) up to Bhakra reservoir has been selected (Figure 1).


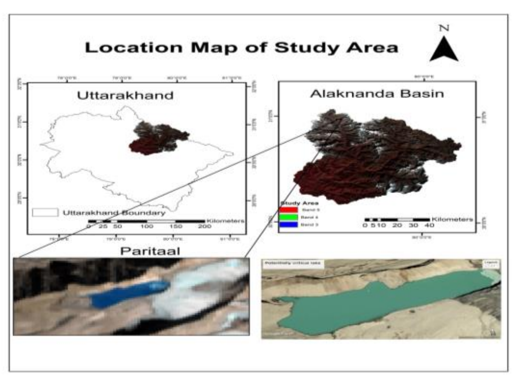
Figure 1. Location of the potentially dangerous glacial lake in the Satluj basin
2. Uttarakhand
The Alaknanda Basin extends between 30° 0' N to 31° 0' N and 78° 45' E to80° 0' E, covering an area about 10882 Km^2. It represents the eastern part of the Garhwal Himalaya. Out of the total area of the basin, 433 km^2 is under glacier landscape and rest of 288 km^2 is under fluvial landscape.


Figure 2. The location map of Alaknanda river basin.
</td>
</tr>
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v.	Total Budget Outlay (Crore) :	INR 35,43,408/-

1.3 Details Himalayan Research /Project Associates/Fellows inducted

Type of Fellowship	Nos.	Work Duration	
		From	To
Jr. Research Fellows	2		
	Gopinadh Rongali	28/11/2018	19/11/2021
	Aayushi Pandey	29/11/2018	11/02/2020
	Ashish Mishra	18/09/2020	25/06/2021
	Poonam Vishwas	28/07/2021	30/11/2021

3. Research Outcomes

2.1. Abstract (not more than 1000 words) (it should include background of the study, aim, objectives, methodology, approach, results, conclusion and recommendations based on the institutional fellowship proposal sanctioned under the NMHS).

Glacial lake outburst floods (GLOFs) are a serious and potentially increasing threat to livelihoods and infrastructure in most high-mountain regions of the world. Sudden release of water from a glacial lake is referred to as GLOF. This is capable of threatening human lives and triggering environmental damage and utilities. Climate change will lead to the retreat of glaciers and to creation of new lakes for glaciers. GLOFs are among the most common hazards caused by climate change across the Western Himalayan states of Himachal Pradesh and Uttarakhand, India. In the present study, GLOFs mapping has been carried out using remote sensing (RS) and geographic information system (GIS). Landsat-7 and 8 data for the year 2005, 2010, 2015 and 2019 have been used for glacial lake mapping. Landsat images have been used for classification and change detection using normalized difference water index (NDWI) for identification of the temporal variation of glacial lakes. A 30 m digital elevation model (DEM) was created by the data providers by the shuttle radar topography mission (SRTM) 1 arc sec global used for calculating certain parameters i.e maximum, minimum, mean elevation, slope and aspect. The lake volume and depth have been calculated using Huggel empirical formulae and other parameters such as area, slope, aspect and drainage network have been prepared using ArcGIS 10.8. The NDSI and Band ratio method could not differentiate the extent of debris covered glacier ice due to spectral interference from the surrounding debris. NDSI (GREEN/SWIR) and Band ratio (VIS/NIR) misclassified proglacier lakes in threshold glacier areas, whereas Band ratio NIR/SWIR classified clean glacier ice with partly glacier ponds, therefore Band ratio NIR/SWIR is a more appropriate method for clean glacier ice than NDSI (GREEN/SWIR) in addition, Band ratio NIR/SWIR performs better than NDSI (GREEN/SWIR) in the case of shadow areas. For the present study, slope map has been utilized along with the NDSI approach to delineate glaciers manually. For glacier lake mapping, NDWI, NDSI and unsupervised classification and its overlay on Google earth has been used for identification of glacier lakes. It is followed by manual editing afterwards using Google Earth images.

Inventory of glacial lakes for Alaknanda basin has been compiled containing information of 463 glacial lakes (Figure in Part-B). Analysis of these lakes has been carried out for identification of potentially dangerous lakes. On the basis of these parameters (area, distance from the outlet, growth of the lake and slope), in total, 4 lakes (Lakes 196,194, 195, 462- Figure 3.22 in Part-B) have been identified as potentially dangerous glacial lakes. Out of these 4 lakes, further analysis has been carried out for the identification of the most vulnerable lake. Lake 196 (Lat 30°54'1.67"N/Long 79°45'22.00"E) comes out to be the most vulnerable for a GLOF event. The volume (508.31 Cu. Meter) and area (0.23 Sq.Km) have been computed, and other parameters such as cross-sections from the lake to outlet have been prepared in ArcGIS 10.1. As a result, the area of the potentially dangerous lake 196 is 0.23 Square Km and the volume of this lake is 508.31 cubic meters and the distance of this lake from the outlet of the basin is 1.38 Km.

The maps for land use and land cover (LULC) produced by using the supervised classification technique by considering maximum likelihood classification (MLC) algorithm. The lake size has increased from 0.54 to 0.92 km^2 for Geepang Gath glacial lake (Figure in Part-B) and 0.84 to 1.23 km^2 for Samudra Tapu glacial lake (Figure in Part-B) during the time period of 2005 – 2019. These results will assist in the development of risk management plans, spatial planning and better preparedness for future potential hazards of GLOFs. The study has been focused on finding the potential glacial lakes in Satluj River basin that may be vulnerable to GLOF. Though extensive research is required to predict GLOFs, it is recommending that an early warning system, comprising of deployment of real time sensors network at vulnerable lakes, coupled with GLOF simulation models, be installed for the study area. Glacial hazards relate to hazards associated with glaciers and glacial lakes in high mountain areas and their impacts downstream. In the present study, identification of glacial lakes has been carried out using Landsat time series data. Also, criteria for identification of potentially dangerous lake have been discussed. One of the possible highest dangerous glacial lake of Satluj basin in the western Himalaya has been considered with a view to estimate the GLOF. The Glacial lake (Latitude 31°39′40.81″ N and Longitude 78°10′7.32″ E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.20 sq.km acquired on 16 September 2018 of Landsat 8 satellite image data. The Glacial lake in Alaknanda basin (Latitude 30°58'33.55" N and Longitude 79°27'34.66" E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.21 sq.km acquired on 16 September 2018 of Landsat 8. The area, volume and depth of the lakes have been calculated using the Huggel's formulae. The Volume and Depth of the Potentially identified glacial Lake in Alaknanda basin at 30°58'35.81"N, 79°27'39.91"E are 37547822.09 m^3 and 17.87 m respectively. The Volume and Depth of the identified Potentially Critical Glacial lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E are 4527981.19 m^3 and 18.89 m respectively.

2.2. Objective-wise Major Achievements

S. No.	Cumulative Objectives	Major achievements (in bullets points)

1	Generation and analysis of the data of the selected region of Western Himalaya to identify the potentially and vulnerable glacial lakes. Susceptible to outburst and predict the consequences of the GLOF.	Satluj River Basin (HP) • The study has been focused on finding the glacial lakes and potential glacial lakes in Satluj basin, Himachal Pradesh, India that maybe vulnerable to GLOF. • Glacier and glacial lakes mapping has been carried out by manual digitization on the basis of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI) and slope information. Inventory of glacial lakes including the increased number of glacial lakes with the area greater than 0.01 sq km from 1972 to 2018 of Landsat data sets has been done in Satluj basin. The data has been downloaded by using the USGS Earth Explorer website https://earthexplorer.usgs.gov/.
		Alaknanda River Basin (UK) • With the help of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI), Band Ratio analysis, slope, Aspect information a total of 73 Lakes have been mapped in Alaknanda Basin in 1994. • Area and volume estimation has been done for the mapped glacial lakes. 26 lakes out of 73 lakes were having the area greater than 0.01 km2. Detailed study using number of indicators for hazardous lake has been carried out on these lakes. The two lakes (79°45'20.301"E 30°54'0.964"N) and (30o58'33.26'' N 79o27'33.52"E) have been identified as potentially hazardous by at least three indicators.

2	To define conditions of glacial lakes, moraine dams associated with mother glacier attributing those with topographic features around lake/ moraine dams.	Satluj River Basin (HP) • Area and volume estimation has been done for the mapped glacial lakes. • The Glacial lake in Satluj basin (Latitude 31o39′40.81″ N and Longitude 78o10′7.32″ E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.2396 sq.km acquired on 16 September 2018 of Landsat 8. • Glacial lakes have been classified in three ways first one is 1-5 hect. is Less vulnerable, second one is 5-10 hect Medium vulnerable and third one is >10 hect is High vulnerable. There has been 15 critical glacial lake has been identified in Satluj river basin.
		Alaknanda River Basin (UK) • The Glacial lake in Alaknanda basin (Latitude 30°58'33.55" N and Longitude 79°27'34.66" E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.21 sq.km acquired on 16 September 2018 of Landsat 8. The area, volume and depth of the Lake has been calculated using the Huggel's formulae. The Volume and Depth of the Potentially identified glacial Lake in Alaknanda basin at 30°58'35.81"N, 79°27'39.91"E are 37547822.09 m^3 and 17.87 m respectively.
3	To Define geometrical parameters (spread area, depth and volume of the water) of the vulnerable lakes and their further examination and analysis to estimate the scale and size of the GLOF hazard.	Satluj River Basin (HP) • Glacial lake area and volume has been calculated using Huggel's formulae. The lake volume V = 0.104 A1.42, The lake depth D = 0.104 A0.42 where D is the depth of lake in m and A is the lake area in m^2. The Volume and Depth of the identified Potentially critical Glacial lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E are 4527981.19 m^3 and 18.8980 m respectively.

		Alaknanda River Basin (UK) • 26 lakes out of 73 lakes were having the area greater than 0.01 km2. Detailed study using number of indicators for hazardous lake has been carried out on these lakes. • For selecting potentially dangerous lakes, following parameters has been used. Lakes of area larger than 0.03 km2 has been considered as harmful owing to the less volume of water contained by it (area and volume are empirically related by Huggel's formulae).
4	To apply dam reach model on dangerous lake and study the effect of GLOF at downstream.	Satluj River Basin (HP) • HecGeoRAS software is used for creation of river cross-section and setting up analysis environment for HEC-GeoRAS, create stream centre line,bank line, creating river centerline and topology, length and elevation profile process has been carried out for dam breach model on dangerous lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E and study the affect of GLOF at downstream. • Flood inundation work has been done. Plot of Longitudinal and cross-sectional profile of the Watershed has been carried out. Analysis of 1-D Steady flow data has been carried out. Cross-Section of 1-D Steady flow data and Analysis of 1-D Unsteady flow data has been carried out.

		Alaknanda River Basin (UK) • The lake 30o58'33.26'' N 79o27'33.52''E) have been identified as potentially hazardous by at least three indicators. HecGeoRAS software is used for creation of river cross-section and setting up analysis environment for HEC-GeoRAS, create stream centre line,bank line, creating river centerline and topology, length and elevation profile process has been carried out for dam breach model on dangerous lake in Alaknanda Basin for study the effect of GLOF at downstream. • Categorization of lakes from lowest to highly vulnerable category has been done. Field visit on highly vulnerable glacial lake in Alaknanda basin has been done. Manuscript is being prepared from the information gathered through the remote sensing data along with the field measurement of the study area in Alaknanda basin. GLOF mitigation, prevention, warning and rescue has been done.
5	To identify the vulnerable locations downstream where GLOF can crate disaster and prepare the roadmap for prevention, warning, and mitigation rescue.	Satluj River Basin (HP) • GLOF mitigation, prevention, warning and rescue have been prepared in the Sutlej River basin, Himachal Pradesh.
		Alaknanda River Basin (UK) • GLOF mitigation, prevention, warning and rescue have been prepared in the Alaknanda River basin, Uttarakhand.

2.3. Outputs in terms of Quantifiable Deliverables*

S. No.	Quantifiable Deliverables*	Monitoring Indicators*	Quantified Output/ Outcome achieved	Deviations made, if any, and Reason thereof:
1	A detailed analytical report on selected region of Western Himalaya (based on data available) with details of probable potentially dangerous and	Inventory of glacial lakes, Find out the most vulnerable glacial lakes	NDWI (GREEN – NIR) / (GREEN + NIR) along with the band ratio of Green and NIR with suitable	No deviation

	vulnerable glacial lakes susceptible to outburst and predict the consequences of the GLOF. The report will also highlight the conditions of glacier lakes, moraine dams associated with mother glaciers, geometrical parameters and their analysis to estimate the scale and size of the GLOF hazard. Dam breach model analysis on dangerous lake and the likely affect of certain selected GLOF downstream.	and GLOF modelling at the downstream.	thresholding has been used in ArcGIS and ERDAS to map the glacial Lakes. Google Earth has also been used for the verification of lakes in case of shadows. The selection of these wavelengths was done to: maximize the typical reflectance of water features by using green light wavelengths, minimize the low reflectance of NIR by water features; and take advantage of the high reflectance of NIR by terrestrial vegetation and soil features.	
2	An inventory of glaciers and glacial lakes.	Glacial lake area, volume and depth	After the mapping of lakes the area and volume calculation for each lake has been done using ArcGIS. Indicators that are considered for hazardous lake identification is lake type, distance from mother glacier, periphery in contact with glacier, area expansion over the years, Mean slope of lake front area ,Mean slope of glacier end	No deviation
3	Flood maps due to outburst.	River Cross-Section, HecGeoRAS and Dam breach model	Flood inundation work has been done. Plot of Longitudinal and cross-sectional profile of the Watershed has	No deviation

			been carried out. Analysis of 1-D Steady flow data has been carried out. Cross-Section of 1-D Steady flow data and Analysis of 1-D Unsteady flow data has been carried out. HecGeoRAS software is used for creation of river cross-section and setting up analysis environment for HEC-GeoRAS, create stream centre line,bank line, creating river centerline and topology, length and elevation profile process has been carried out for dam breach model on dangerous lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E and study the affect of GLOF at downstream.	
4	To identify the vulnerable locations downstream where GLOF can create disaster and assess the scale of disaster and prepare the road map for prevention, warning, mitigation, rescue	GLOF, prevention, warning, mitigation, rescue	GLOF mitigation, prevention, warning and rescue have been prepared. Flood modelling, estimation, forecasting and alarms: Controlled breaching can be carried out by blasting, excavation, or even by dropping bombs from an aircraft. For more permanent and precise control of lake outflows, rigid structures made out of stone, concrete, or steel	No deviation

			can be used. Tunneling through moraines or debris barriers, although risky and difficult because of the type of material blocking the lake, has been carried out in several countries. Real-time monitoring, early warning systems and preparedness education are the most beneficial ways to minimize risk. Preparedness hazard mapping, improving communication, education to create awareness.	

(*) As stated in the Sanction Letter issued by the NMHS-PMU.

2.4. Strategic Steps with respect to Outcomes (in bullets)

S. No.	Particulars	Number/ Brief Details	Remarks/ Enclosures
1.	New Methodology developed:	Landsat images have been used to detection of glacial lakes using Normalized Difference Water Index (NDWI). In the present study, for mapping of snow-covered glacier, band ratio and NDSI approach has been used.	Normalized Difference Snow Index (NDSI) is used to mask the glaciated region. NDSI = $\frac{Green - SWIR}{Green + SWIR}$ Where, SWIR = Short Wave Infra-Red The NDWI has been calculated as NDWI = $\frac{GREEN - NIR}{GREEN + NIR}$

S. No.	Particulars	Number/ Brief Details	Remarks/ Enclosures
2.	New Models/ Process/ Strategy developed:	GLOF simulation parameters and HecRAS dam break modelling.	Following parameters has been required as the input for dam break simulation. Cross-sections: ArcGIS software has been used to delineate cross-section area along the stream.
3.	New Species identified:	NA	NA
4.	New Database established:	Inventory of glacial lakes including the increased number of glacial lakes with the area greater than 0.01 sq km from 1972 to 2018 of Landsat data sets has been done. Glacial Lakes has been identified for the study area. Lake situation and area changes has been studied from Landsat of 1994-2017.	Landsat TM, ETM+ and Landsat-8 data for GL mapping and LU/LC mapping SRTM DEM (30 m) for river cross-section and drainage network.
5.	New Patent, if any:		
	I. Filed (Indian/ International)	Field visit on highly vulnerable glacial lake in Alaknanda basin has been done. Field visit on highly vulnerable glacial lake in Satluj basin has been done.	The two lakes (79°45'20.301"E 30°54'0.964"N) and (30o58'33.26" N 79o27'33.52"E) have been identified as potentially hazardous and field visit has been conducted respectively.
	II. Granted (Indian/ International)	---	----
	III. Technology Transfer (if any)	---	---
6.	Others, if any:	No	No

3. Technological Intervention

S. No.	Type of Intervention	Brief Narration on the interventions	Unit Details (No. of villagers benefited / Area Developed)
1.	Development and deployment of indigenous technology	RS and GIS technology has been applied on the inventory of glacial lakes in the Satluj river basin and Alaknanda River basin of Western Himalaya.	Two study areas are covered in this study. 1) Satluj River basin, Himachal Pradesh 2) Alaknada River basin, Uttarakhand
2.	Diffusion of High-end Technology in the region	NA	NA
3.	Induction of New Technology in the region	NA	NA
4.	Publication of Technological / Process Manuals		
	Others (if any)	NIL	NIL

4. New Data Generated over the Baseline Data

S. No.	New Data Details	Existing Baseline	Additionality and Utilisation of New data (*attach supplementary documents*)
1.			
2.		**NIL**	**NIL**
3.			
4.			

5. Linkages with Regional & National Priorities (SDGs, INDC, etc.)/ Collaborations

S. No.	Linkages /collaborations	Details	No. of Publications/ Events Held	Beneficiaries
1.	Sustainable Development Goals (SDGs)			
2.	Climate Change/INDC targets	NIL	NIL	NIL
3.	International Commitments			
4.	National Policies			
5.	Others collaborations			

6. Financial Summary (Cumulative)*

*Please attach the **consolidated and audited Utilization Certificate (UC) and Consolidated and *<u>Year-wise</u>* Statement of Expenditure (SE)** separately, *ref*. **Annexure I.**

UC and SE has been attached separately at Annexure I

7. Quantification of Overall Research Progress

S. No.	Parameters	Total (Numeric)	Attachments* with remarks
1.	IHR State(s) Covered:	*2*	*1. Himachal Pradesh* *2. Uttarakhand*
2.	Fellowship Site/ LTEM Plots developed:	*2*	*1.Satluj River basin* *2.Alaknanda River basin*
3.	New Methods/ Model Developed:	*3*	*1 Glacial lakes mapping and* *2. Highly vulnerable glacial lake identification* *3.GLOF dam break model developed using HecRAS*
4.	New Database generated:	*2*	*1. Landsat MMS TM ETM+ and OLI/TIRS data from 1985-2018 for HP state* *2. Landsat MMS TM ETM+ and OLI/TIRS data from 1985-2018 for UK state*
5.	Types of Database generated:	*2*	*1. Remote Sensing data sets* *2. GIS data sets*
6.	No. of Species Collected:	*NA*	*NA*
7.	New Species identified:	*NA*	*NA*
8.	Scientific Manpower Developed (PhDs awarded/ JRFs/ SRFs/ RAs):	*4*	*1. Gopinadh Rongali(SRF) and PhD awarded from IIT Delhi* *2. Aayushi Pandey (JRF)* *3. Ashish Mishra (JRF)* *4. Poonam Vishwas (JRF) and PhD thesis submitted from JNU, Delhi*
9.	No. of SC Himalayan Researchers benefited:	*NIL*	*NIL*
10.	No. of ST Himalayan Researchers benefited:	*NIL*	*NIL*
11.	No. of Women Himalayan Researchers empowered:	*2*	*1. Aayushi Pandey (JRF)* *2. 4. Poonam Vishwas (JRF)*
12.	No. of Knowledge Products developed:	*NIL*	*NIL*
13.	No. of Workshops participated:	*3*	*1.Aayushi pandey, Attended Two Days National Workshop On Modern Geomatics Techniques at IIT Ropar August 6-7, 2019.* *2. Gopinadh Rongali*

			attended, National Seminar-Cum-M&E Workshop on 4-7 February 2019 at GBPNIHESD, Almora, Uttarakhand. Presented poster on entitled ‘’Inventory of Glacier and Glacial Lake Outburst Flood (GLOF) Study in the Western Himalaya’. *3. 4th Himalayan Consortium 2019 attended by Gopinadh Rongali and Aayushi pandey*
14.	No. of Trainings participated:	*3*	*1. Gopinadh Rongali attended Webnar Training at HecRAS Modeling on 13th Feb, 2021 organized by TGIS.* *2. Ashish Mishra attended Training course on Advanced tools and techniques for hydrological investigations from Feb 22-26, 2021 organized by NIH Roorkee.* *3.* Aayushi Pandey, *Attended "Cryospheric Applications using Space Based Observations "Training program at SAC, Bopal campus from 14-18 October, 2019*
15.	Technical/ Training Manuals prepared:	*NIL*	*NIL*
	Others (if any):	*NIL*	*NIL*

***** Please attach the soft copies of supporting documents word files and data files in excel.

8. Knowledge Products and Publications*

S. No.	Publication/ Knowledge Products	*Number*		*Total Impact Factor*	*Remarks/ Enclosures***
		National	International		
1.	Journal Research Articles/ Special Issue (Peer-reviewed/ Google Scholar)		3		1. K. C. Tiwari, Gopinadh Rongali Poonam Vishwas. (2022). Assessment of Potentially Dangerous Glacier

S. No.	Publication/ Knowledge Products	Number		Total Impact Factor	Remarks/ Enclosures**
		National	International		
					Lakes Risk in Alaknanda River Basin Using Remote Sensing and GIS Techniques. (*Under Review*) 2. Gopinadh Rongali, Poonam Vishwas, K. C. Tiwari,(2022). Glacial Lake Outburst Flood hazard assessment in Kinnaur district, Himachal Pradesh. (*Under Review*) 3. Poonam Vishwas, , Gopinadh Rongali, K. C. Tiwari, (2022). Mapping of glacial lakes and glacial lake outburst flood in Lahul and Spiti district using remote sensing and GIS. (*Under Review*)
2.	Book Chapter(s)/ Books:		1		1. Rongali, G., Tiwari, K. C., &

S. No.	Publication/ Knowledge Products	*Number*		*Total Impact Factor*	*Remarks/* Enclosures**
		National	International		
					Vishwas, P. (2022). Potentially Dangerous Glacial Lake Risk Mapping and Assessment in Satluj River Basin, Himachal Pradesh Using Remote Sensing and GIS. In Recent Trends in River Corridor Management (pp. 245-260). Springer, Singapore.
3.	Technical Reports/ Popular Articles	NIL	NIL	NIL	NIL
4.	Training Manual (Skill Development/ Capacity Building)	NIL	NIL	NIL	NIL
5.	Papers presented in Conferences/ Seminars		4		1. Gopinadh Rongali and K C Tiwari. (2019)."Glacial Lakes and Glacial Lakes Outburst Floods in Himachal Pradesh, India using Remote Sensing and GIS. C2E2 Himalaya 2019" International Workshop on Climate Change and Extreme Events in the Himalayan

S. No.	Publication/ Knowledge Products	*Number*		*Total Impact Factor*	*Remarks/* Enclosures**
		National	International		
					Region, IIT Mandi, H.P., India, April 18-20. 2.Pandey A., Tiwari K.C .(2020) The potential of UAV Based Remote Sensing for monitoring Hindu Kush Himalayan Glaciers .Proceedings of UASG 2019.1st International Conference on Unmanned Aerial System in Geomatics - IIT Roorkee Noida Campus. 3. Gopinadh Rongali and K C Tiwari. (2019).”Glacial Lakes and Glacial Lakes Outburst Floods in Himachal Pradesh, India using Remote Sensing and GIS. C2E2 Himalaya 2019" International Workshop on Climate Change and Extreme Events in the Himalayan

S. No.	Publication/ Knowledge Products	*Number*		*Total Impact Factor*	*Remarks/* Enclosures**
		National	International		
					Region, IIT Mandi, H.P., India, April 18-20. 4. Gopinadh Rongali attended, 1st International Conference on River Corridor Research and Management, 25th to 27th February 2021, conducted by Dept. of Civil Engineering, Indian Institute of Technology Jammu, J&K, India
6.	Policy Drafts (if any)	NIL	NIL	NIL	NIL
7.	Others (specify)	NIL	NIL	NIL	NIL

*Please append the list of KPs/ publications (with impact factor and URL link details) with due Acknowledgement to NMHS.

**Please provide supporting copies of the published documents.

9. Recommendation on Utility of Research Findings, Replicability and Exit Strategy

9.1 Utility of the Fellowship Findings

S. No.	*Research Questions Addressed*	*Succinct Answers (within 150–200 words)*
1.	How many lakes are present in the study area?	• The Glacial lake in Satluj basin (Latitude 31o39′40.81″ N and Longitude 78o10′7.32″ E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.2396 sq.km acquired on 16 September 2018 of Landsat 8. Glacial lakes has been classified in three ways first one is 1-5 hect. is Less vulnerable, second one is 5-10 hect Medium vulnerable and third one is >10 hect is High vulnerable. There has been 15 critical glacial lake has been identified in Satluj river basin. For selecting potentially dangerous lakes, following parameters has been used. Lakes of area larger than 0.03 km2 has been considered as harmful owing to the less volume of water contained by it (area and volume are empirically related by Huggel's formulae). • Comparison based on the number of lakes present in the time series data yielded the result that the number of glacial lakes has been continuously increasing from 1994 to 2019. a total of 73 lakes have been mapped in 1994 in alaknanda basin , out of which 26 lakes are of area greater than 0.01 and the number of lakes are rapidly increasing in the years 2001, 2013 and in 2019.
2.	Is the area of identified lakes expanding over the period of time?	• The area of the lake in Satluj basin is rapidly increasing. The lake that have been identified as highly critical glacial lakes have increased in area from 0.158 km2 in 1994 to 0.23 km2 in 2019 (79°45'20.301"E 30°54'0.964"N) • The area of the lake in Alaknanda basin is rapidly increasing. The lake that have been identified as highly critical glacial lakes have increased in area from 0.09 km2 in 1994 to 0.21km2 in 2019(30o58'33.26" N 79o27'33.52"E).
3.	Are the identified lakes highly vulnerable?	• Number of indicators has been applied to the glacial lakes to identify potentially critical lakes such as the lake type, distance from mother glacier, periphery in contact with glacier, area expansion over

		the years, Mean slope of lake front area ,Mean slope of glacier end etc. these two lakes have been identified as potentially hazardous by at least three indicators. • The glacial lakes to identify potentially critical lakes such as the lake type, distance from mother glacier, periphery in contact with glacier, area expansion over the years, Mean slope of lake front area ,Mean slope of glacier end are the indicators to identified lakes highly vulnerable are not.
4.	What risk may be posed by glacial lake outburst floods (GLOFs) in the study area?	• At the time of second field visit depth estimation and other field data required for the dam breach modeling are to be collected for downstream hazard assessment if lake outburst in HP. • At the time of second field visit depth estimation and other field data required for the dam breach modeling are to be collected for downstream hazard assessment if lake outburst in UK.

9.2 Recommendations on Replicability and Exit Strategy:

Particulars	Recommendations
Replicability of Fellowship, if any	Though continuously and extensive research is required to predict GLOFs, it is recommending that an early warning system be installed for the study areas. The early warning system should be capable of providing alerts to the Government authorities in case there is a threat of GLOF. Deployment of real time sensors network at vulnerable lakes, capable of measuring rise and discharge of water, will enable the authorities to set up an early warning system. The early warning system coupled with GLOF simulation models capable of predicting the time of arrival of the flash flood and showing the flooded areas downstream will enable the local authorities to take precautionary measures in the event of a GLOF.

Exit Strategy:	Using the NMHS project Fellowship, Himalayan Research Fellows are devoted full time effort to the proposed plan of study. Continued funding from the Delhi Technological University, including continued infrastructure and lab facilities, is encouraged. Home and fellowship institutions are encouraged to the researchers to do the innovative work. The intent of this Fellowship is to provide support to advance the career of the Fellow, by allowing them to pursue a fellowship project/plan of study, which would not be otherwise possible based on existing resources. The NMHS Project methodology steps for GLOFs study has been well defined and implemented successfully to complete the deliverables set earlier. The project methodologies or techniques have been approached using a defined structure and process activities. Innovative research concept and study design has been developed to fulfil the objectives. The developed and optimized methodologies has been implemented to study the solutions on GLOFs. The innovative research has been focused on identifying the causes due to GLOFs. All the deliverables have been completed as per the timeline as proposed at the begin of the project. Firstly we have done glacial lakes inventory on the respective study areas and there after find the highly vulnerable glacial lakes. Thirdly the GLOF modeling has been carried out for identified glacial lakes. Finally, the roadmap has been prepared for GLOF at downstream locations to minimize the risk.

(**NMHS FELLOWSHIP COORDINATOR**)

(Signed and Stamped)

(**HEAD OF THE INSTITUTION**)

(Signed and Stamped)

Place: ………………..
Date: …../……/……..

PART B: COMPREHENSIVE REPORT (including all sanctioned positions of Researchers)

Based on the Fellowship Proposal submitted/approved at the time of sanction, the co-ordinating Principal Investigator shall submit a comprehensive report including report of all individual researchers.

The comprehensive report shall include an **Executive Summary** and it should have separate chapters on (1) **Introduction** (2) **Methodologies, Strategy and Approach** (3) **Key Findings and Results** (4) **Overall Achievements** (5) **Impacts of Fellowship in IHR** (6) **Exit Strategy and Sustainability** (7) **References/ Bibliography** and (8) **Acknowledgements** (It should have a mention of financial grant from the NMHS, MoEF&CC).

Further, description of Technical Activities, List of Trainings/ Workshops/ Seminars with details of trained resources, list of New Products developed under the fellowship, Manual of Standard Operating Procedures (SOPs) developed, Technology developed/Transferred etc should be enclosed as Appendix.

Report (hard copy) should be submitted to:

Er. Kireet Kumar
Scientist 'G' and Nodal Officer, NMHS-PMU
National Mission on Himalayan Studies (NMHS)
G.B. Pant National Institute of Himalayan Environment (GBP NIHE)
Kosi-Katarmal, Almora 263643, Uttarakhand

Report (soft copy) should be submitted at:

E-mail: nmhspmu2016@gmail.com; kireet@gbpihed.nic.in; gupta.dharmendra@gov.in

PART B: COMPREHENSIVE REPORT

Executive Summary

The study has been focused on finding the glacial lakes and potential glacial lakes in Satluj basin, Himachal Pradesh and Alaknanda basin, Uttarakhand, India that may be vulnerable to GLOF. Glacier and glacial lakes mapping has been carried out by manual digitization on the basis of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI) and slope information. Inventory of glacial lakes including the increased number of glacial lakes with the area greater than 0.01 sq km from 1972 to 2018 of Landsat data sets has been done in Satluj basin and Alaknanda basin. The Glacial lake L1 in Satluj basin (Latitude 31o39′40.81″ N and Longitude 78o10′7.32″ E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.2396 sq.km acquired on 16 September 2018 of Landsat 8. The Glacial lake L2 in Alaknanda basin (Latitude 30°58'33.55" N and Longitude 79°27'34.66" E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.21 sq.km acquired on 16 September 2018 of Landsat 8. The area, volume and depth of the L1 and L2 have been calculated using the Huggel's formulae. The Volume and Depth of the Potentially identified glacial Lake in Alaknanda basin (L2) at 30°58'35.81"N, 79°27'39.91"E are 37547822.09 m3 and 17.8799 m respectively. The Volume and Depth of the identified Potentially critical Glacial lake in Satluj Basin (L1) at 31°39'40.81"N, 78°10'7.32"E are 4527981.19 m3 and 18.8980m respectively.

With the help of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI), Band Ratio analysis, slope, Aspect information a total of 73 Lakes have been mapped in Alaknanda Basin in 1994. Area and volume estimation has been done for the mapped glacial lakes. 26 lakes out of 73 lakes were having the area greater than 0.01 km2. Detailed study using number of indicators for hazardous lake has been carried out on these lakes. The two lakes (79°45'20.301"E 30°54'0.964"N) and (30o58'33.26" N 79o27'33.52"E) have been identified as potentially hazardous by at least three indicators. Categorization of lakes from lowest to highly vulnerable category has been done. Field visit on highly vulnerable glacial lake in Alaknanda and Satluj basin has been done. Digital elevation model and slope and aspect of the Alaknanda study area have been done. And stream Oder has been identified. Glacial Lakes has been identified for the study area. Lake situation and area changes has been studied from 1994-2017. Flood inundation work has been done. Plot of Longitudinal and cross-sectional profile of the Watershed has been carried out. Analysis of 1-D Steady flow data has been carried out. Cross-Section of 1-D Steady flow data and Analysis of 1-D Unsteady flow data has been carried out.

Glacial lakes has been classified in three ways first one is 1-5 hect. is Less vulnerable, second one is 5-10 hect Medium vulnerable and third one is >10 hect is High vulnerable. There has been 15 critical glacial lake has been identified in Satluj river basin. For selecting potentially dangerous lakes,

following parameters has been used. Lakes of area larger than 0.03 km2 has been considered as harmful owing to the less volume of water contained by it (area and volume are empirically related by Huggel's formulae). Glacial lake area and volume has been calculated using Huggel's formulae. The lake volume V = 0.104 A1.42 ,The lake depth D = 0.104 A0.42 where D is the depth of lake in m and A is the lake area in m2. The Volume and Depth of the identified Potentially critical Glacial lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E are 4527981.19 m3 and 18.8980m respectively. HecGeoRAS software is used for creation of river cross-section and setting up analysis environment for HEC-GeoRAS, create stream centre line,bank line, creating river centerline and topology, length and elevation profile process has been carried out for dam breach model on dangerous lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E and study the affect of GLOF at downstream. GLOF mitigation, prevention, warning and rescue have been prepared.

In the Satluj basin, a GLOF modelling study was conducted for a potentially deadly lake. Because the lake's maximum size is 263,240 m^2, it was selected to build up the model for the GLOF investigation. The Lake is 4267 metres above sea level. The Satluj River has been represented in the model via a series of cross-sections at 1 km intervals, produced using DEM, from the glacial lake position down to the catchment outflow (a total length of 106 km). The complete length of the journey from Satluj Lake to the outflow. All cross-sections were taken at various intervals. Given the boulder beds and mountainous terrain of Himalayan Rivers comparable to those found in Bhutan's surrounding regime, the manning coefficient 'n' was set at 0.06. (Sharma, 2009). The lake may collapse due to overtopping flow incising and damaging the dam as the lake's water level rises. The HEC-RAS model was created for the Satluj Lake outburst research. In the Alaknanda basin, a GLOF modelling study was conducted for a potentially deadly lake. Because the lake's maximum size is 182,000 m^2, it was selected to build up the model for the GLOF investigation. The Alaknanda River has been represented in the model via a series of cross-sections at 5 km intervals, produced using DEM, from the glacial lake position down to the mouth (total length 50 km). The distance between Alaknanda Lake and the outflow. All of the cross-sections were taken at various intervals.

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Fellowship Report No.:

n of N *(n = Sequential number; N= Total no. of fellowships granted to the Institute/ University)*

Researchers Details

Type of Fellowship (HRA/HJRF/HJPF)	Name of Himalayan Researcher	Date of Joining	Date of Resignation**	Research Title	Name of the PI & Designation
HJRF	1.Gopinadh Rongali	28/11/2018	19/11/2021	Glacial Lakes and Glacial Lake	Dr. K C Tiwari Professor

				Outburst Floods (GLOFs) in Satluj River basin, Himachal Pradesh, India using Remote Sensing and GIS	
(*in case of continuation of fellowship*)	2. Aayushi Pandey	29/11/2018	11/02/2020	Glacial Lakes and Glacial Lake Outburst Floods (GLOFs) in Alaknanda River basin, Uttrakhand, India using Remote Sensing and GIS	Dr. K C Tiwari Professor
	3.Ashish Mishra	18/09/2020	25/06/2021	Glacial Lakes and Glacial Lake Outburst Floods (GLOFs) in Alaknanda River basin, Uttrakhand, India using Remote Sensing and GIS	Dr. K C Tiwari Professor
	4.Poonam Vishwas	28/07/2021	30/11/2021	Glacial Lakes and Glacial Lake Outburst Floods (GLOFs) in Alaknanda River basin, Uttrakhand, India using	Dr. K C Tiwari Professor

				Remote Sensing and GIS	

*If the appointed researcher resigned in the mid of the fellowship duration, then also mention the name of the Himalayan researcher who carried forward the fellowship.

1 INTRODUCTION

1.1 Background/ Summary of the Associateship / Fellowship Study undertaken (max. 500 words)

Global climate is changing due to various natural processes and human activities. High mountain glacial environment and ecosystems with snow, glaciers and permafrost are very sensitive to such climatic changes, thus quickly affected as evidenced by the ongoing worldwide accelerated glacier retreat over the past few decades (Zemp et al. 2008). Climate change-induced glacier recession have triggered the dynamic evolution of glacial lakes in high-mountain areas worldwide, leading to the formation, growth and disappearance of different types of glacial lakes (Frey et al. 2010; Mergili et al. 2013; Wang et al. 2013; Emmer et al. 2015; Wang et al. 2016). Some of these lakes are hazardous and pose a threat to downstream communities and infrastructure because of their potential to outburst and drain suddenly to cause rapid and highly devastating glacial lake outburst floods (GLOFs) (Richardson and Reynolds 2000).

GLOFs have emerged as a serious hazard in the mountain region in recent decades due to increased human settlements, anthropogenic and other developmental activities into areas which were inhabited and were not developed previously (Khanal et al. 2015; Nie et al. 2017). With continued global warming and glacier recession, the frequency and damage potential of GLOFs is anticipated to increase significantly in future (Richardson and Reynolds 2000; Wang et al. 2013). GLOFs evolve as a consequence of series of different processes, for example, mass movement into lakes, glacier/ ice front calving into lake, progressive enlargement of lake, rising lake levels leading to overflow, mechanical rupture/failure of dam, hydrostatic failure, degradation of dam or melting of ice cores in dam, earthquakes, a flood wave from lake located upstream and intensive rainfall or snowmelt (Costa and Schuster 1988; Clague and Evans 2000; Richardson and Reynolds 2000; Emmer and Cochachin 2013; Clague and O’Connor 2015).

GLOFs pose a serious hazard in many high mountain regions around the world and have sought growing attention in recent years due to the associated catastrophic damages and fatalities (Mool et al., 2001; Nie et al., 2013; Westoby et al., 2014). Recent expansion of glacial lakes in the Himalaya has mainly been studied in north Bhutan (Fujita et al., 2008; Komori, 2008) and in the Everest region (Yamada and Sharma, 1993; Sakai et al., 2000; Benn et al., 2001; Wessels et al., 2002). Gardelle et al. (2011) selected seven study sites along the east-west widespread mountain range from the Bhutan to the Hindu Kush and mapped glacial lakes between 1990 and 2010. They found that glacial lake in the eastern part were bigger and more numerous than in the west, and have continuously grown, while glacial lakes have shrunk during that period in the Hindu Kush and in the Karakoram.

Understanding of climate change impact and induced glacial lake changes is crucial for the evaluation of water resources (Fang et al. 2016), assessment of associated hazard potential (Huggel et al. 2002) and prediction of future spatio-temporal evolution of glacial lakes (Frey et al. 2010). Many scientists and researchers have prepared inventory of glacial lakes in Indian Himalayan region using remote sensing techniques (Govindha Raj 2010; Govindha Raj, Kumar, et al. 2013; Worni et al. 2013; Chander Prakash & Nagarajan 2017). There are few researches on the regional spatio-temporal evolution, differences and heterogeneity of glacial lakes; hence, we still lack an understanding about impact of climate change and glacier recession on glacier lake dynamics in Indian Himalayan region. Thus, there is a need to analyse the spatio-temporal glacial lake changes in the Indian Himalaya to understand the impact of climate change on glaciers and glacier lakes for future water resource management and potential hazard assessment and risk management.

1.2 Baseline and Scope of the Associateship / Fellowship (max. 1000 words)

The aim of the present study is to use remote sensing data and apply geomatics-based approach to up-to-date the knowledge on glacial lakes and analyse their distribution and temporal evolution/ development in Satluj and Alaknanda River basin located in western Indian Himalaya. A further aim is to identify potentially dangerous glacial lake (PDGL) and prioritize the same for detailed field investigation. A multi-temporal glacial lake inventory is prepared using remotely sensed satellite data i.e. Lansat with attribute information about location, characteristics, development pattern and surrounding conditions of the glacial lake. The information/result shall serve as a baseline for GLOF hazard assessment in Satluj and Alaknanda basin. GLOF study has been carried out for the biggest lake using HecRAS software.

1.3 Overview of the Major Issues to be addressed (max. 1000 words)

The objectives of the study are based on the glacial lakes & glacial lakes outburst floods in the Himachal Pradesh region using satellite data.

1. Generation and Analysis of the data of selected region of Western Himalaya to identify the potentially dangerous and vulnerable glacial lakes susceptible to outburst and predict the consequences of the GLOF

2. To define conditions of glacial lakes, moraine dams associated with mother glaciers attributing those with topographic features around lakes/moraine dams.

3. To define geometrical parameters (Spread area, depth and volume of water) of the vulnerable lakes and their further examination and analysis to estimate the scale and size of the GLOF hazard.

4. To apply dam breach model on dangerous lake and study the affect of GLOF at downstream.

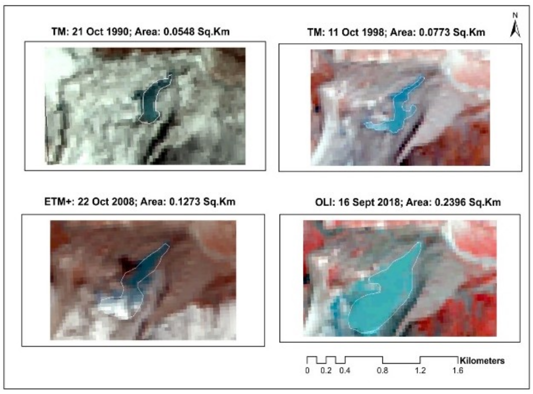
5. To identify the vulnerable locations downstream where GLOF can create disaster and assess the scale of disaster and prepare the road map for prevention, warning, mitigation, rescue.

1.4 Brief summary of the activities under taken by the researcher (max. 1000 words)

[Providing full details of Field study, experimental set up, methods adopted, data collected supported by necessary table, charts, diagrams & photographs (**Data, table and figures should be attached as separate source file (.docx, .xls, jpg, .jpeg, .png, .shp, etc.)].**

1.4.1 Field Work/ Himachal Pradesh - Satluj River Basin

The study under the project is focused on finding the potential glacial lakes in Satluj River basin, Himachal Pradesh that may be vulnerable due to GLOF. Identification of glacial lakes have been done using Landsat time series data and is known as inventorisation of lakes. Identification of potentially dangerous lakes have been also simultaneously done. Recently, while making the inventory of vulnerable lakes, we have identified one of the possible highest dangerous glacial lake of Satluj basin, Hiachal Pradesh in the Western Himalaya which may also be a potential vulnerable lake for GLOF. This Glacial lake is situated at an altitude of 4276 m (Lat/ Long: $31^{o}39'40.81''$ N, $78^{o}10'7.32''$ E) and is possibly one of the highest potentially dangerous lake at this altitude. The maximum surface area of the lake as assessed from the satellite image, acquired on 16 September 2018, is approximately 0.2396 sq.km. In order to validate the findings and also to ascertain various other physical parameters of the lake, a massive field work was carried out from 17^{th} October to 26^{th} October, 2021 ahead of Recong Peo in general area Pangi and Kashag Gramang, Himachal Pradesh. Mr. Gopinadh Rongali along with PhD Research Scholar Mr. Abhay Raj of MCG, DTU took part in the field work. The mission was accomplished successfully, the field data has been collected in the form of lake photographs, videos and discharge data. The identified lake is known as Mukim-Chikkim by the locals. The water coming from the lake and flowing through a stream is used by the Himachal Pradesh Power Corporation Limited (HPPCL) for hydro-electricity power generation. The intake for the HPPCL is situated 17 kms downstream from the lake. For the reaching the lake there is a motorable road up to the HPPCL intake, after which the difficult terrain starts. The data is being analysed and the flood modelling has been carried out.



Lake as appears on satellite Image

Way to lake

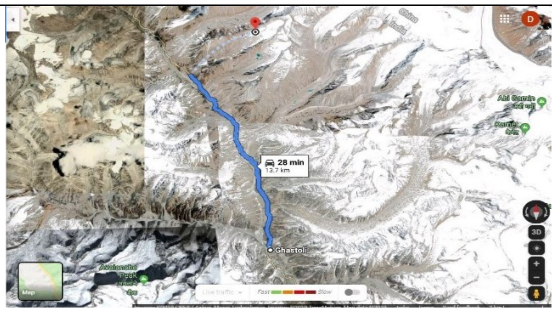
	
Actual lake	The extent of water in Lake at 4276 m
	
GPS Survey at HPPCL intake	Team members near the glacial lake

Figure 1. Field photographs of the highly vulnerable glacial lake at Kashang Gramang, Himachal Pradesh.

1.4.2 Field Work/Uttarakhand- Alaknanda River Basin

Identification of glacial lakes has been done using Landsat time series data and is known as inventorisation of lakes. Identification of potentially dangerous lakes have been also simultaneously done. While making the inventory of vulnerable lakes, we have identified one of the possible highest dangerous glacial lake of Alaknanda basin, Uttrakhand in the western Himalaya which may also be a potential vulnerable lake for GLOF. This Glacial lake has situated at an altitude of 5584 m (Lat/ Long: 30°58'33.26'' N, 79°27'33.52'' E) and is possibly one of the highest potentially dangerous lake at this altitude particularly because of Army and ITBP staying nearby. The maximum surface area of the lake as assessed from the satellite image, acquired on 16 September 2018, is approximately 0.21 sq.km. In order to validate the findings and also to ascertain various other physical parameters of the lake, a massive field work was carried out from 29 September, 2019 to 11 October, 2019 ahead of Joshimath in general area Ghastoli and Raktakona, Uttrakhand. The mission was accomplished successfully, the field data has been collected in the form of lake photographs, videos and soil samples. The data has been analysed and the flood modelling has been carried out.

Lake as appears on satellite Image



Way to lake

Actual lake

The extent of water in Lake at 5584 m

DGPS Survey

Team members near one of the lakes

Figure 2. Field photographs of the highly vulnerable glacial lake at Raktakona, Uttarakhand.

2 METHODOLOGIES, STARTEGY AND APPROACH

2.1 Methodologies used for the study (max. 1000 words)

2.1.1 Normalized difference water index (NDWI- for Lahul Spiti District, H.P)

The study of temporal variation in the lake region has been carried out using the satellite images. Landsat images have been used classification and change detection using Normalized Difference Water Index (NDWI). The NDWI (McFeeters, 1996) has been calculated as

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad (1)$$

When applying the NDWI to the spectral bands, the following equation results is obtained,

For Landsat 7,

$$NDWI = \frac{BAND\ 2 - BAND\ 4}{BAND\ 2 + BAND\ 4} \quad (2)$$

For Landsat 8,

$$NDWI = \frac{BAND\ 3 - BAND\ 5}{BAND\ 3 + BAND\ 5} \quad (3)$$

The highest reflectance is used by NDWI, green with the NIR bands for the extracting bodies of water. The resulting images has been visually examined and associated with google earth imagery. The NDWI values differ from −1 to +1. Much of the characteristics of water are found near the value of +1. McFeeters (1996) defined zero as for water bodies, the threshold value. Values towards −1 indicate the characteristics of vegetation and bare soil or ground.

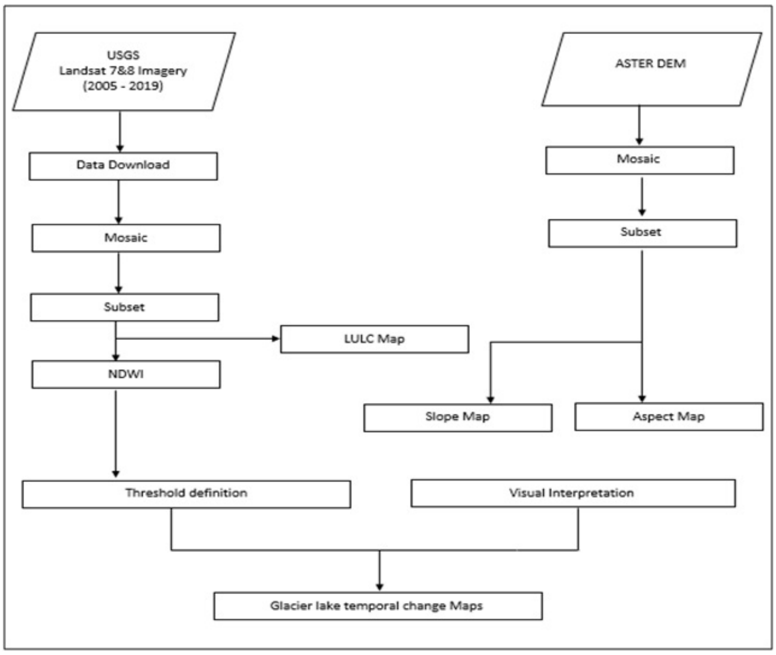


Figure 3. Methodology flow chart

2.1.2 Identification of potentially dangerous lakes

For selecting potentially dangerous lakes, following parameters has been used. Lakes of area larger than 0.03 km^2 has been considered as harmful owing to the less volume of water contained by it (area and volume are empirically related by Huggel's formulae). Lakes which are still attached to or are near to the parent glaciers or at the snout of the glaciers has been considered as more dangerous as they are capable of expanding. In general, lakes which are isolated are stagnant, do not expand and pipe their volume of water in most of the cases rather than bursting. For this purpose, overlay analysis has been carried out to check the position of the lakes with respect to glaciers. Glacial lakes has been checked for the presence of supraglacial lakes around them, or for the lakes which fall in their downstream area. These lakes are interconnected in the sense that bursting of one lake causes bursting of another. Lakes will also be checked for the steep slopes around them (which can cause influx into them). Conditions of the moraine (thick or thin) has been estimated from the visual inspection and distance calculations using satellite imagery on Google Earth.

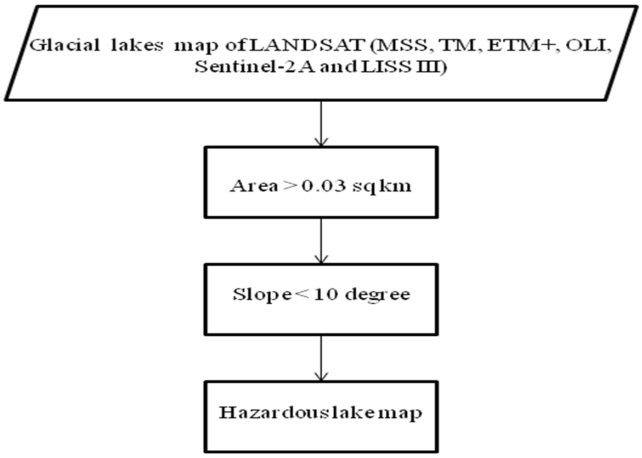


Figure 4. Methodology for the hazardous lake map

In this study, we have identifed 2 lakes as potentially dangerous using the frequently applied parameters, such as lake area, lake connected to feeding glacier snout, lake expansion and lakes dammed by moraines. By applying the first parameter i. e., lake area greater than 0.1 km^2 , only two lakes, located at 31.6613 N–78.1687 E and 30.9759 N–79.4597 E coordinates, were found to be potentially dangerous and subsequently taken for further analysis. As per the assessment, these two glacial lakes have a relatively higher potential for the occurrence of GLOF in the Satluj River Basin, H.P. and Alaknanda River Basin, U.K. respectively. The details of the parameters used for the further evaluation of potentially dangerous glacial lakes are given below:

1. **Lake area**: Lakes having an area greater than 0.1 km^2 are considered as potentially dangerous because such lakes possess sufficient volume of water to cause a flash food in the downstream valley (Aggarwal et al. 2016; Washakh et al. 2019; Ahmed et al. 2022). In the present study, the area of both the potentially dangerous glacial lakes was estimated to be greater than 0.1 km^2.

2. **Lake connected to the snout of feeding glacier**: Lakes that are located near or at the snout of the feeding glacier are also considered as potentially dangerous because they are affected due to calving and floating of ice (Bajracharya and Shrestha 2011; Ahmed et al. 2022). Both the lakes identified as potentially dangerous are located at the snout of the glaciers having direct contact with the glacier ice and are therefore subjected to be affected by the calving activity of the glacier.

3. **Lake expansion**: It is generalized fact that glacial lakes across the globe are expanding at faster rates due to the continuous glacier recession. In the present study, glacial lakes have also shown a considerable increase in area from 1990 to 2018, which can be attributed to the glacier melting in the region. Lakes that are expanding at faster rates are more hazardous because the potential for ice avalanches or area movements increases, and dams may be subjected to larger hydrostatic pressures. In our case, both the lakes are increasing significantly in terms of the area from 1990 to 2018 which may increase the GLOF susceptibility in the region.

4. **Moraine dammed lakes**: MDLs are considered potentially most dangerous to cause outburst foods (GLOFs), thereby posing a serious threat to the downstream communities and other infrastructure. As the glaciers retreat, more and more meltwater accumulates in front of the calving snout and consequently, such lakes burst and result in high-intensity GLOF events. Lakes with weak moraine structures are more likely to breach than the lakes dammed by consolidated moraines. It is because in the former case, an increase in the volume of water generates huge hydrostatic pressure in the lake, which eventually leads to dam failure. Both the lakes are dammed by an unconsolidated moraine.

2.1.3 GLOF simulation parameters and HecRAS dam break modeling

In the study, HecRAS dam break model has been used for GLOF modeling. MIKE-11 is a professional engineering software package for the simulation of one-dimensional (1D) flow in estuaries, rivers, irrigation systems, channels and other water bodies. It is a dynamic, user-friendly 1D modeling tool for the detailed design, management and operation of both simple and complex river and channel systems. The HD module contains an implicit, finite difference computation of unsteady flows in river and estuaries. The formulation can be applied to branched and looped networks and flood plains.

GLOFs increase to peak flow than gradually or abruptly decrease to normal levels once the water source is exhausted. Outburst flood peak flow is directly related to lake volume, dam height and width, dam material composition, failure mechanism, downstream topography and sediment availability. In order to get the maximum GLOF peak at any location, the breaching of moraine dams of above glacial lakes has been considered along with channel routing. Thus, estimation of GLOF is akin to dam break study of the moraine dams, which assesses the flood hydrograph of discharge from the dam breach and water level/discharge time series at different locations of the river downstream of the dam due to propagation of flood waves. Following parameters has been required as the input for dam break simulation.

(1) **Cross-sections:** ArcGIS software has been used to delineate cross-section area along the stream. For this purpose the vector layer of the stream and the buffer lines along the stream on the both side of stream at the distance of 1 km has been created. The stream has been divided at the distance of 1 km from lake side and the cross-section layer has been created.

(2) **Lake volume and depth:** There is no estimate available for volume of glacial lakes in the Himalayas from their water spread areas. However, some estimates are available for glacial lakes in Swiss Alps, as given by Huggel et al. (2002). In the absence of information on the volume of potentially dangerous glacial lakes, it is considered appropriate to use the same relationships developed for the lakes in Swiss Alps for estimating the water volume for the lakes in this area. The empirical relations as available in the study by Huggel et al. (2002) are the following.

(3) **Breach invert level:** Breach invert level is the final breach level, i.e. the breaching starts at top of the dam and continues up to the breach invert level. As the glacial lakes may generally outburst due to overtopping and/or by piping, the breach invert level should be taken as two-thirds to three-fourths of the height of the dam below its top level.

(4) **Average breach width and time of failure:** The breach parameter's average breach width (B) and time of failure (tf) have been estimated using the empirical equations available for earth and rock fill dams, as similar estimates for supraglacial dam are not available.

The dam break model setup consists of a single or several channels, reservoirs, dam break structures and other auxiliary dam structures such as spillways, sluices. The river is represented in a model by cross-sections at regular intervals. However, due to highly unsteady nature of dam break flood propagation, it is advisable that the river course is described as accurately as possible through the use of a dense grid of cross-sections, particularly where the cross-section is changing rapidly. Further, the cross-sections shall extend as far as the highest modeled water level, which normally has been in excess of highest recorded flood level. In the study, the lake has been represented as dam break structures having certain crest level and crest length. The dam breach parameters has been specified as a time series and assigned to corresponding lake. The glacial lake has been represented as reservoir in the model by its elevation–surface area relation, at chainage ‘‘0’’ km of the reservoir branch.

In any dam break study, prediction of the dam breach parameters and timing of the breach are very important factors. But prediction of these parameters is extremely difficult. The important aspects to deal when considering the failure of dam are, time of failure, extent of overtopping before failure, size, shape and time of the breach formation. Estimation of the dam break flood depends on these parameters. Important breach characteristics that are needed as input to the existing dam break models are (1) initial and final breach width and level; (2) shape of the breach; (3) time duration of breach development; and (4) reservoir level at time of start of breach.

Arc-GIS and ERDAS Imagine software has been used to delineate cross-sections of the stream. For this purpose the vector layer of the stream and the buffer lines along the stream on the both side of stream at the distance of 1 km has been created. The stream has been divided at the distance of 5 km from lake side, and the cross-section layer has been created. ERDAS Imagine Software has been used to overlay DEM of basin and vector layer of cross-section. The Spatial Profile Viewer in ERDAS allows to visualize the reflectance spectrum of a polyline of data file values in a single band of data (one-dimensional mode) or in many bands (perspective three-dimensional mode). This is being used to create a height cross-section profile along a route. This helps in interpreting changes in elevation along a planned route and in identifying the sections of the route which are particularly steep or flat. Inquire cursor of ERDAS Imagine has been used to extract the elevation values at each pixel.

There was no estimate available for volume of glacial lakes in Gharwal Himalaya from their water spread areas. However, some estimates were available for glacial lakes in Swiss Alps, as given by Huggel et al. (2002). In the absence of information on the volume of glacial lakes, it will considered appropriate to use the same relationships developed for the lakes in Swiss Alps for estimating the water volume for the lakes in this area. The empirical relations as available in the study by Huggel et al. (2002) are:

The lake volume $V = 0.104A^{1.42}$ (4)

where V is the lake volume in m3 and A is the lake area in m^2.

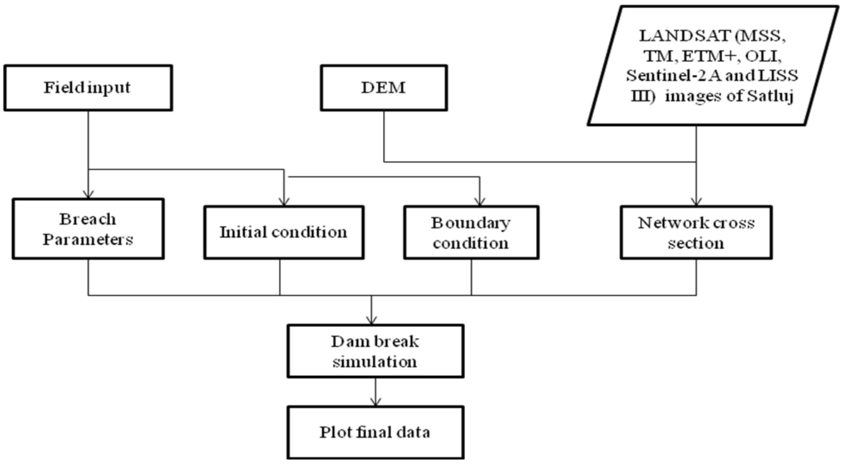


Figure 5. Methodology for GLOF simulation using MIKE-11 dam breaks modeling

2.2 Details of Scientific data collected and Equipments Used (max 500 words)

The remote sensing datasets used for this study is high resolution satellite imagery and digital elevation model. To carry out the analysis of glacial lakes from 2005 to 2019, Landsat-7 and Landsat-8 data has been used in the research. By comparing all available dataset for this study, images with maximum 10% cloud cover and least snow cover from the month of October to November has been selected for this study. A total of 12 Landsat images have been downloaded from USGS Website (https://earthexplorer.usgs.gov). The months for which Landsat images have been used are October (11 scenes) and November (1 Scene). The following are the datasets details along with their specifications.

2.2.1 Datasets specification and details

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

Table 1. Details of datasets

Sl. No	Data	Sensor	Swath (km)	Spectral Resolution (µm)	Spatial Resolution (m)	Temporal Resolution (days)	Radiometric Resolution
1	Landsat 7	EMT+	185	Blue:0.450 – 0.515	30 × 30		8 bit
				Green:0.525 – 0.605	30 × 30	16	
				Red:0.630 – 0.690	30 × 30		
				NIR:0.750 – 0.900	30 × 30		
				NIR:1.55 – 1.75	30 × 30		
				Thermal:10.40 – 12.50	60 × 60		
				MIR:2.08 – 2.35	30 × 30		
				PAN:0.52 – 0.90	15 × 15		
2	Landsat 8		185	Visible:0.433 – 0.453	30 × 30		
		OLI		Blue:0.450 – 0.515	30 × 30	16	12 bit
				Green:0.525 – 0.600	30 × 30		
				Red:0.630 – 0.680	30 × 30		
				NIR:0.845 – 0.885	30 × 30		
				SWIR 1: 1.56 – 1.66	30 × 30		
				SWIR 2: 2.1 – 2.3	30 × 30		
				PAN:0.52 – 0.90	15 × 15		
				Cirrus1.36 - 1.39	30 × 30		
		TIRS		TIRS 1: 0.3 – 11.3	100 × 100		
				TIRS 2: 11.5 – 12.5	100 × 100		

2.2.2 For 2005 (Landsat-7)

Table summarizes the details of Landsat-7 data

Table 2. Landsat-7 data

Data	Path	Row	Date of acquisition
Landsat 7	147	37	2005-10-29
Landsat 7	147	38	2005-10-29
Landsat 7	146	38	2005-10-22

2.2.3 For 2010 (Landsat-7)

Table summarizes the details of Landsat-7 data

Table 3 . Landsat-7 data

Data	Path	Row	Date of acquisition
Landsat-7	147	38	2010-10-11
Landsat-7	147	37	2010-10-11
Landsat-7	146	38	2010-11-05

2.2.4 For 2015 (Landsat-8)

Table summarizes the details of Landsat-8 data

Table 4. Landsat- 8 data

Data	Path	Row	Date of acquisition
Landsat 8	147	38	2015-10-17
Landsat 8	147	37	2015-10-17
Landsat 8	146	38	2015-10-10

2.2.5 For 2019 (Landsat-8)

Table summarizes the details of Landsat-8 data

Table 5. Landsat- 8 data

Data	Path	Row	Date of acquisition
Landsat 8	147	38	2019-10-28
Landsat 8	147	37	2019-10-12
Landsat 8	146	38	2019-10-21

2.2.6 Digital elevation model

DEM is useful for calculating the parameters such as maximum, minimum, mean elevation, slope and aspect. The 30 m DEM was created by the data providers by the shuttle radar topography mission (SRTM) 1arc Sec Global download from USGS website. (https://earthexplorer.usgs.gov) the data has been acquired September 23, 2014. These data projected to latitude and longitude coordinate system, WGS84 horizontal datum and UTM 43 vertical datum. In this study, we used Satellite Radar Topography Mission (SRTM) DEM with a spatial resolution of 30 m downloaded from the web portal www.earthexplorer.usgs.gov. The DEM was used to extract the catchment/watershed of the glacial lake and its feeding glacier. It was also used to generate a cross-section at 1 km intervals for Satluj and 5 km intervals for Alaknanda as well as elevation data. The cross-sections were created downstream from the lake to the final selected location. The cross-sections from the DEM were generated because the field-measured cross sections were not available for this area due to the rugged terrain and harsh weather conditions. Besides that, high resolution Google Earth imagery was used for the crosschecking and validation of the lake extents. Chow, 1959, has suggested a Manning coefcient range between 0.03 to 0.07 for the hilly terrain with a steep slope and no vegetation, gravel, cobbles, boulders, and bushes on the banks. Considering this, we have used a Manning coefficient range of 0.04 to 0.06 as an input parameter for the GLOF routing of the selected lake of Satluj basin and Alaknanda basin in HEC-RAS software.

For topographic information, Digital Elevation Model (DEM) has been utilized. DEM's can be used as source elevation data for digital ortho-photos, and, as layers in geographic information systems, for earth science analysis. DEM's can also serve as tools for volumetric analysis, for site location of towers, or for drainage basin delineation. One degree DEM's have rows and columns which are based on the geographic coordinate system. The use of this system results in a rectangular DEM which shares a common edge and therefore duplicate points with other adjacent 1-degree DEM's. The accuracy of a DEM is dependent upon the level of detail of the source and the grid spacing used to sample that source. The geographic horizontal coordinate Latitude Resolution 0.0001 and Longitude Resolution 0.0001. Its spatial reference information like Horizontal Datum Name: North American Datum of 1983, Ellipsoid Name: Geodetic Reference System 80, Semi-major Axis: 6,378,137 and Denominator of Flattening Ratio: 298.257. The DEM data is used for mapping slope and aspect. Google Earth images were also used for carrying out manual checking and analysis. The specification of the data used is given in table.

Table 6 . Data used

Sensor/Source	Product	Date	Resolution
IRD / LISS III	Satellite image	---	23.5 m
LANDSAT 8	Satellite image	04, May 2013 & 11, November 2013	30 m
DEM SRTM	Open dem	---	30 m

2.3 Primary Data Collected (max 500 words)

The LANDSAT time series data has been downloaded from 1972 to 2018 for Satluj River basin, Himachal Pradesh, Alaknanda River basin, Uttrakhand. The data has been downloaded by using the USGS Earth Explorer website https://earthexplorer.usgs.gov/.

2.3.1 Database Generation

In the first step, preprocessing of satellite data has been carried out, Landsat and Indian Remote Sensing (IRS) images were geometrically corrected; however, atmospheric correction was applied owing to clear weather during those days. For atmospheric correction, the Noise reduction and Haze reduction method is used. IRS image has been re-sampled to 30 m using nearest neighborhood method in order to match the spatial resolution of Landsat image, and both the images from Landsat and IRS were calibrated to convert digital values to true reflectance. Slope, elevation and drainage maps were prepared which were required for analysis in later stages.

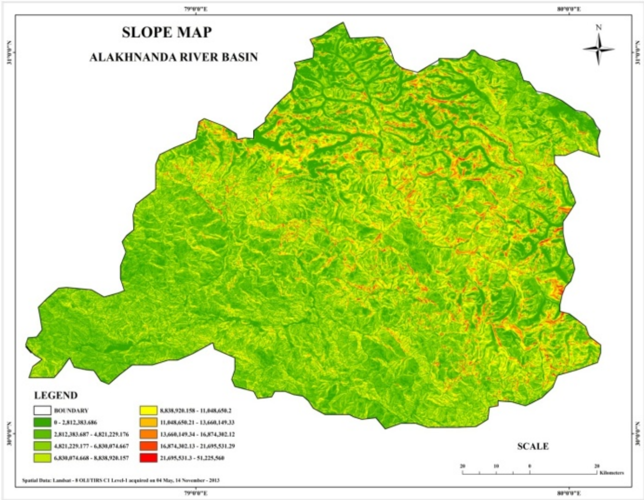


Figure 6. Slope at Satopanth glacier region, Uttarakhand, Indian Himalayas

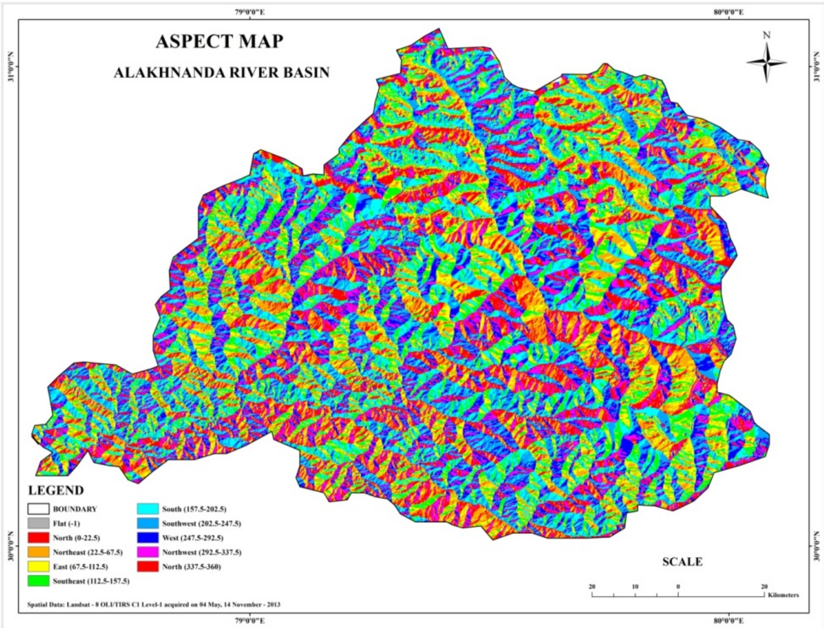


Figure 7. Slope direction of aspect map

2.4 Details of Field Survey arranged (max 500 words)

2.4.1 Himachal Pradesh

Recently, while making the inventory of vulnerable lakes, the two research fellows identified one of the possible highest dangerous glacial lake of Satluj basin, Hiachal Pradesh in the Western Himalaya which may also be a potential vulnerable lake for GLOF. This Glacial lake is situated at an altitude of 4276 m (Lat/ Long: 31o39′40.81″ N, 78o10′7.32″ E) and is possibly one of the highest potentially dangerous lake at this altitude. The maximum surface area of the lake as assessed from the satellite image, acquired on

16 September 2018, is approximately 0.2396 sq.km2. In order to validate the findings and also to ascertain various other physical parameters of the lake, a massive field work was carried out from 17th October to 26th October, 2021 ahead of Recong Peo in general area Pangi and Kashag Gramang, Himachal Pradesh. Mr. Gopinadh Rongali along with PhD Research Scholar Mr. Abhay Raj of MCG, DTU took part in the field work. The mission was accomplished successfully, the field data has been collected in the form of lake photographs, videos and discharge data. The identified lake is known as Mukim-Chikkim by the locals. The water coming from the lake and flowing through a stream is used by the Himachal Pradesh Power Corporation Limited (HPPCL) for hydro-electricity power generation. The intake for the HPPCL is situated 17 kms downstream from the lake. For the reaching the lake there is a motorable road up to the HPPCL intake, after which the difficult terrain starts. The data is being analysed and the flood modelling has been carried out.

2.4.2 Uttrakhand

The two research fellows Mr Gopinadh Rongali and Ms Aayushi Pandey identified one of the possible highest dangerous glacial lake of Alaknanda basin, Uttrakhand in the western Himalaya which may also be a potential vulnerable lake for GLOF. This Glacial lake is situated at an altitude of 5584 m (Lat/ Long: 30°58'33.26'' N, 79°27'33.52'' E) and is possibly one of the highest potentially dangerous lake at this altitude particularly because of Army and ITBP staying nearby. The maximum surface area of the lake as assessed from the satellite image, acquired on 16 September 2018, is approximately 0.21 sq.km2. In order to validate the findings and also to ascertain various other physical parameters of the lake, a massive field work was carried out from 29 September, 2019 to 11 October, 2019 ahead of Joshimath in general area Ghastoli and Raktakona, Uttrakhand. Both the JRFs along with two students of M.Tech Geoinformatics (Mr Vishal and Mr Vivek) took part in the field work. Since the area fell along the Indo-China border, the mobilization not only required Inner Line Permit from the SDM Joshimath but also successive stages of acclimatization and support and permission of both the Indian Army and ITBP (Mana,,Ghastoli and Raktakona). The mission was accomplished successfully, the field data has been collected in the form of lake photographs, videos and soil samples. The data is being analysed and the flood modelling has been carried out.

2.5 Strategic Planning for each Activities (max. 1000 words)

Activities	**Strategic Planning**

Activity1: Generation and Analysis of the data of selected region of Western Himalaya to identify the potentially dangerous and vulnerable glacial lakes susceptible to outburst and predict the consequences of the GLOF.	A detailed analytical report has been made on selected regions of Satluj River basin, Himachal Pradesh and Alaknanda River basin, Uttarakhand of Western Himalaya (based on data available) with details of probable potentially dangerous and vulnerable glacial lakes susceptible to outburst and prediction has been done for the consequences of the GLOF.
Activity 2: To define conditions of glacial lakes, moraine dams associated with mother glaciers attributing those with topographic features around lakes/moraine dams.	The report has been highlighted the conditions of glacier lakes, moraine dams associated with mother glaciers, geometrical parameters and the analysis has been estimated the scale and size of the GLOF hazard. Dam breach model analysis on dangerous lake and the likely affect of certain selected GLOF downstream has been done.
Activity 3: To define geometrical parameters (Spread area, depth and volume of water) of the vulnerable lakes and their further examination and analysis to estimate the scale and size of the GLOF hazard.	An inventory of glaciers and glacial lakes has been prepared for the Western Himalayas using Remote Sensing and GIS data.

Activity 4: To apply dam breach model on dangerous lake and study the affect of GLOF at downstream.	Flood maps has been prepared for the two lakes identified in Satluj and Alaknanda River basin due to outburst.
Activity 5: To identify the vulnerable locations downstream where GLOF can create disaster and assess the scale of disaster and prepare the road map for prevention, warning, mitigation, rescue.	Early warning system with a road map for prevention, early warning, mitigation, rescue has been prepared

2.6 Activity-wise Timeframe followed using Gantt/ PERT Chart (max. 1000 words)

S.No.	Activity	1st Year (2018-2019)		2nd Year (2019-2020)		3rd Year (2020-2021)	
		0- 6 months	7- 12 months	13-18 months	19-24 months	25-30 months	31-36 months
1.	Literature Review						
2.	Collecting Data						
3.	Objective 1 and Field Work						
4.	Objective 2 and Communicating Paper						
5.	Objective 3						
6.	Objective 4 and Field Work and Paper						
7.	Objective 5 and Writing Report						

Figure 8. Timeline Activity for the NMHS Project Work

3 KEY FINDINGS AND RESULTS

3.1 Major Research Findings (max. 1000 words)

With the help of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI), Band Ratio analysis, slope, Aspect information a total of 73 Lakes have been mapped in alaknanda Basin in 1994.

Area and volume estimation has been done for the mapped glacial lakes. 26 lakes out of 73 lakes were having the area greater than 0.01 km2. Detailed study using number of indicators for hazardous lake has been carried out on these lakes. The two lakes (79°45'20.301"E 30°54'0.964"N) and (30o58'33.26" N 79o27'33.52"E) have been identified as potentially hazardous by at least three indicators. Categorization of lakes from lowest to highly vulnerable category has been done. field visit on highly vulnerable glacial lake in alaknanda basin has been done. The study has been focused on finding the glacial lakes and potential glacial lakes in Satluj basin, Himachal Pradesh, India that maybe vulnerable to GLOF. Glacier and glacial lakes mapping has been carried out by manual digitization on the basis of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI) and slope information. Inventory of glacial lakes including the increased number of glacial lakes with the area greater than 0.01 sq km from 1972 to 2018 of Landsat data sets has been done in Satluj basin. The data has been downloaded by using the USGS Earth Explorer website https://earthexplorer.usgs.gov/. The Glacial lake in Satluj basin (Latitude 31o39′40.81″ N and Longitude 78o10′7.32″ E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.2396 sq.km acquired on 16 September 2018 of Landsat 8. Glacial lakes has been classified in three ways first one is 1-5 hect. is Less vulnerable, second one is 5-10 hect Medium vulnerable and third one is >10 hect is High vulnerable. There has been 15 critical glacial lake has been identified in Satluj river basin. For selecting potentially dangerous lakes, following parameters has been used. Lakes of area larger than 0.03 km2 has been considered as harmful owing to the less volume of water contained by it (area and volume are empirically related by Huggel's formulae). Glacial lake area and volume has been calculated using Huggel's formulae. The lake volume V = 0.104 A1.42 ,The lake depth D = 0.104 A0.42 where D is the depth of lake in m and A is the lake area in m2. The Volume and Depth of the identified Potentially critical Glacial lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E are 4527981.19 m3 and 18.8980m respectively. HecGeoRAS software is used for creation of river cross-section and setting up analysis environment for HEC-GeoRAS, create stream centre line,bank line, creating river centerline and topology, length and elevation profile process has been carried out for dam breach model on dangerous lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E and study the affect of GLOF at downstream. GLOF mitigation, prevention, warning and rescue have been prepared.

3.1.1 Case Study-1: Lahul-Spiti District, Himachal Pradesh

The study area taken for this study is the Lahul & Spiti District, located in the north- western Indian Himalayan state of Himachal Pradesh (Figure 9). The District occupies location from 31°44´57´´N to 32°59´57´´N latitude and 76°46´29´´ E to 78°41´34´´E longitude with a geographical area of 13,835 km^2. Area wise, it is the largest district of Himachal Pradesh state compare to others district.

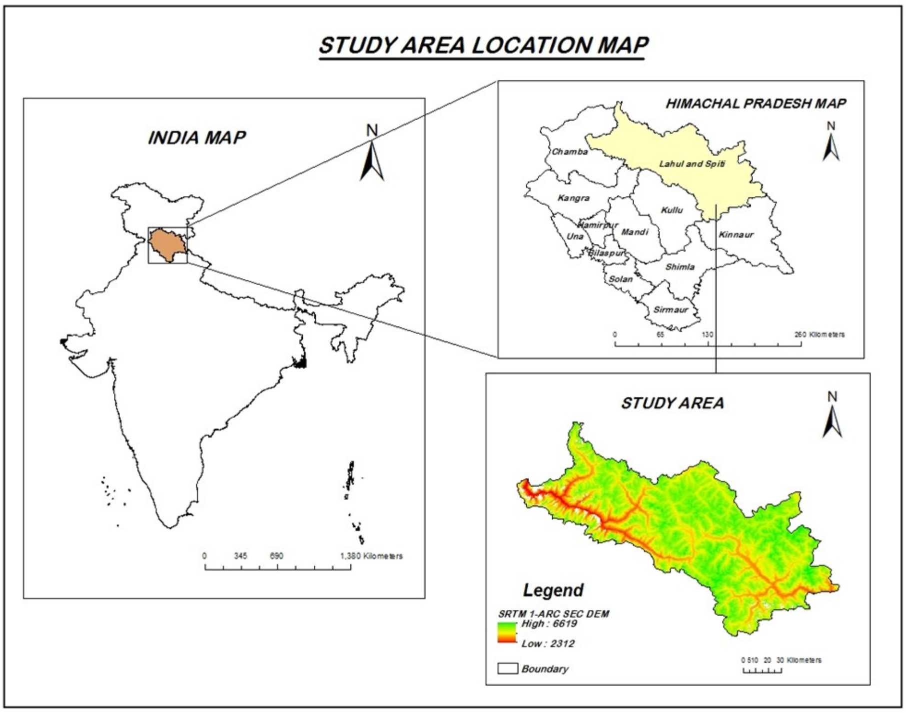


Figure 9. Study area of Lahul-Spiti District, H.P.

3.1.2 Slope and Aspect maps

One of the essential physiographic elements affecting the slope is usage of an area's agricultural property. The impact of slopes on farming can be both direct and indirect. The most noticeable direct slope effect is in the form of restrictions on cultivation and availability. The indirect effect of slope manifests itself in pedological and climatic shifts, including the location of the water table, soil growth, air drainage and the relative freedom from frost.

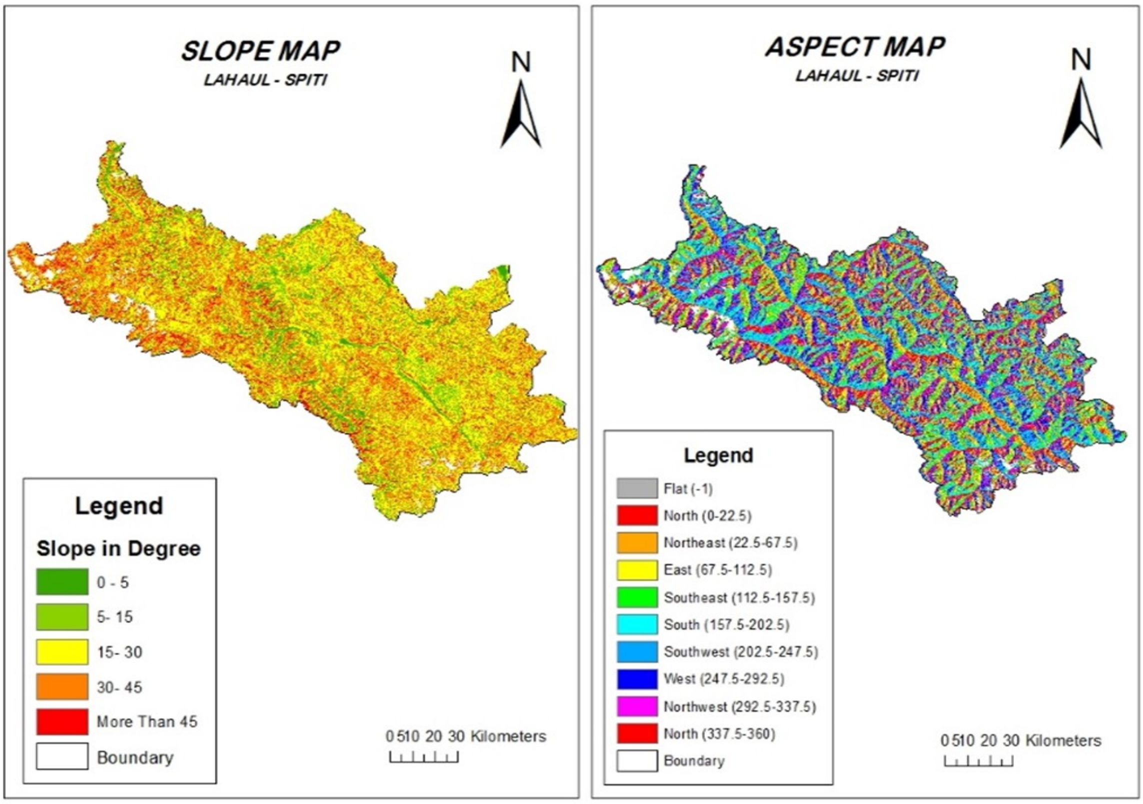


Figure 10. Slope and aspect map

Table 7. Percentage of area under slopes

Slope (in degree)	Area (km^2)	Area (in hectares)	Percentage of total area
0 - 5	1743	174263	13
5 – 15	3996	399596	29
15 – 30	3478	347800	25
30 – 45	2275	227459	16
More than 45	2344	234381	17
Total area	13835	1383500	100

3.1.3 Drainage Network

The study of drainage network provides an idea about the topography, climate, geology, and hydrological fe atures of the region (Figure 11). Much of the runoff is in sculpturing landforms, a major natural agent. It is also linked to settlement patterns in this high altitude arid region. Lahaul & Spiti Higher Himalayan and trans Himalayan regions are inhabited, where there are mainly settlements along the river valleys.

There are three main rivers in Lahaul & Spiti: Chandra, Bhaga and Spiti and their many tributaries as well. Chandra and Bhaga river after their Chandra-Bhaga, also known as Chenab, is the confluence at Tandi. These are the main drainage basins of the entire region.

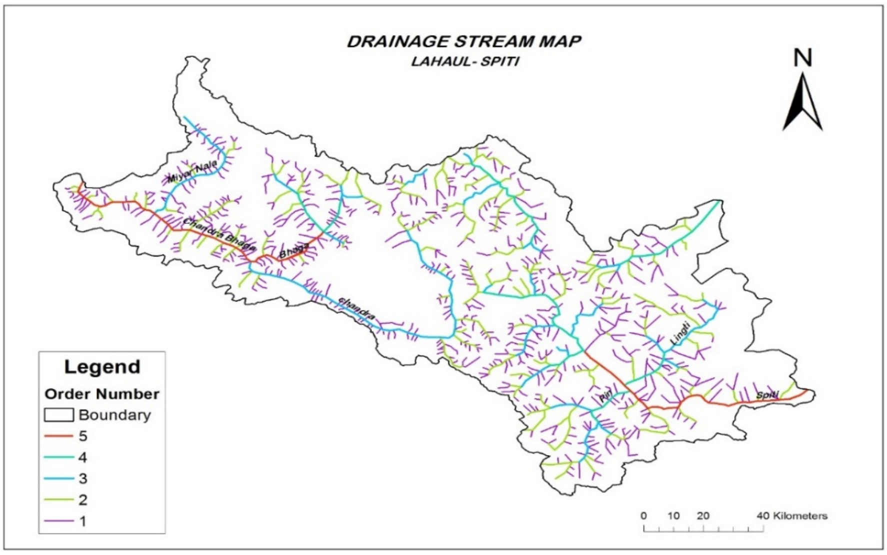


Figure 11. Drainage stream map

3.1.4 Land Use and Land Cover (LU/LC)

The maps for LU/LC of Lahul – Spiti District has been produced using supervised classification techniques on landsat satellite imagery for 2005, 2010, 2015 and 2019 (Figure 12). The classification process started with identification of training sets representing different land use classes. These training sets has been used for supervised classification using maximum likelihood classification (MLC) algorithm. The maximum likelihood classification is the most accurate and reliable classifier (Richards and Jia, 1999; Foody et al., 1992; Saha et al. 2005) the pixels in the unknown class are assigned to a specific land use class of which it has the greatest likelihood of membership. In this analysis, five major classes of LU/LC are identified: snow/glacier, barren/rocky surface, forest, agriculture/grass, and water. The area of each class can be estimated using the field calculator tool in ArcGIS.

Table 8. Land use/ Land cover change (2005 - 2019)

	Land use/Land cover Class	Area (Percent)				Percent Change (2005 - 2019)
		2005	2010	2015	2019	
1.	Snow/Glacier	27.313	45.491	37.145	39.155	43.357
2.	Barren/Rocky Surface	55.219	47.188	53.762	52.286	-5.312
3.	Forest	4.343	2.528	1.137	1.587	-63.458
4.	Water	0.061	0.062	0.057	0.047	-22.951
5.	Agriculture/Grass	13.064	4.731	7.899	6.925	-46.992
		100.00	100.00	100.00	100.00	

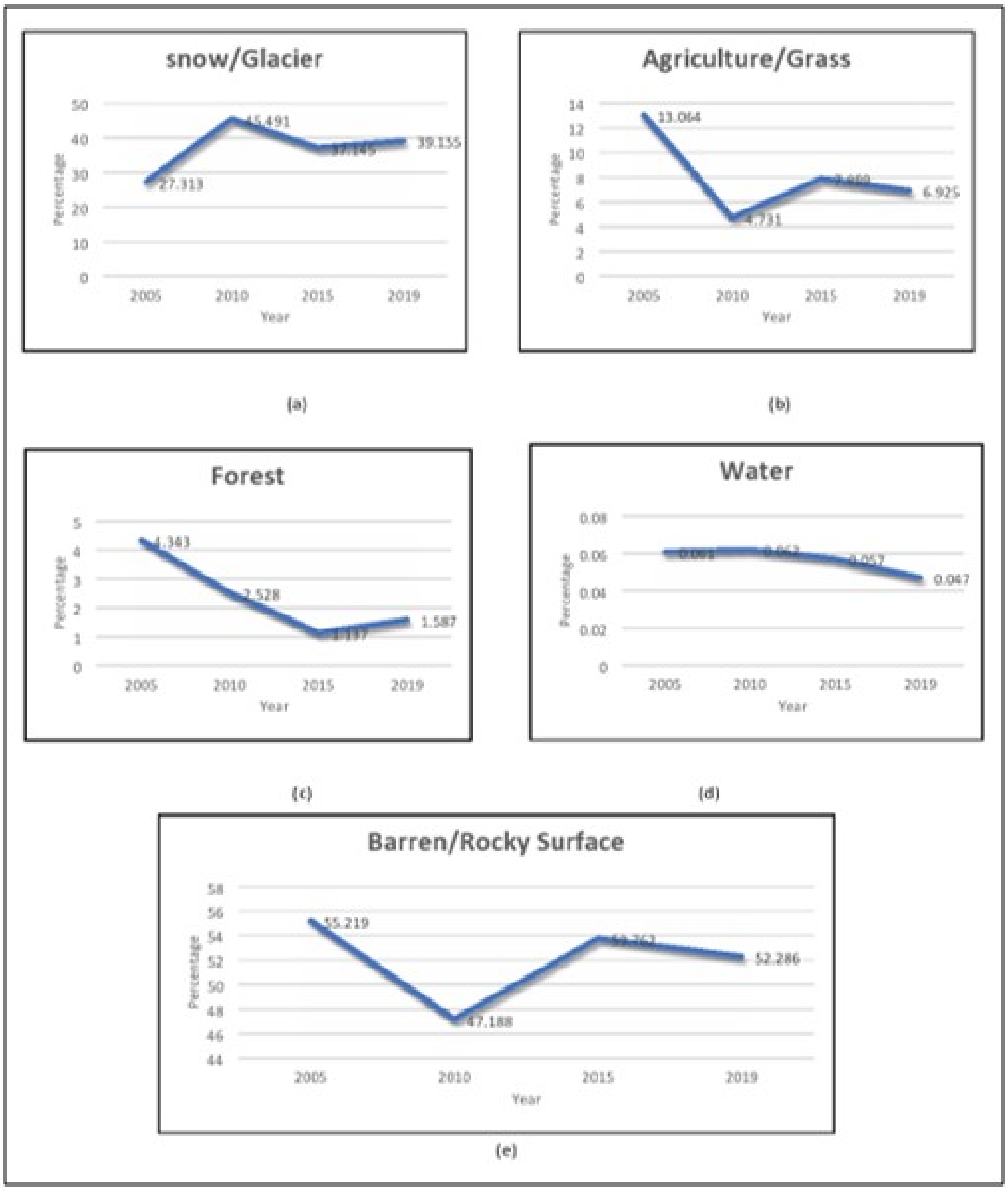


Figure 12. Graph (a) snow/glacier, (b) agriculture/grass, (c)forest, (d) barren/rocky surface and (e)water showing percentage change in Land use/ Land cover (LULC)

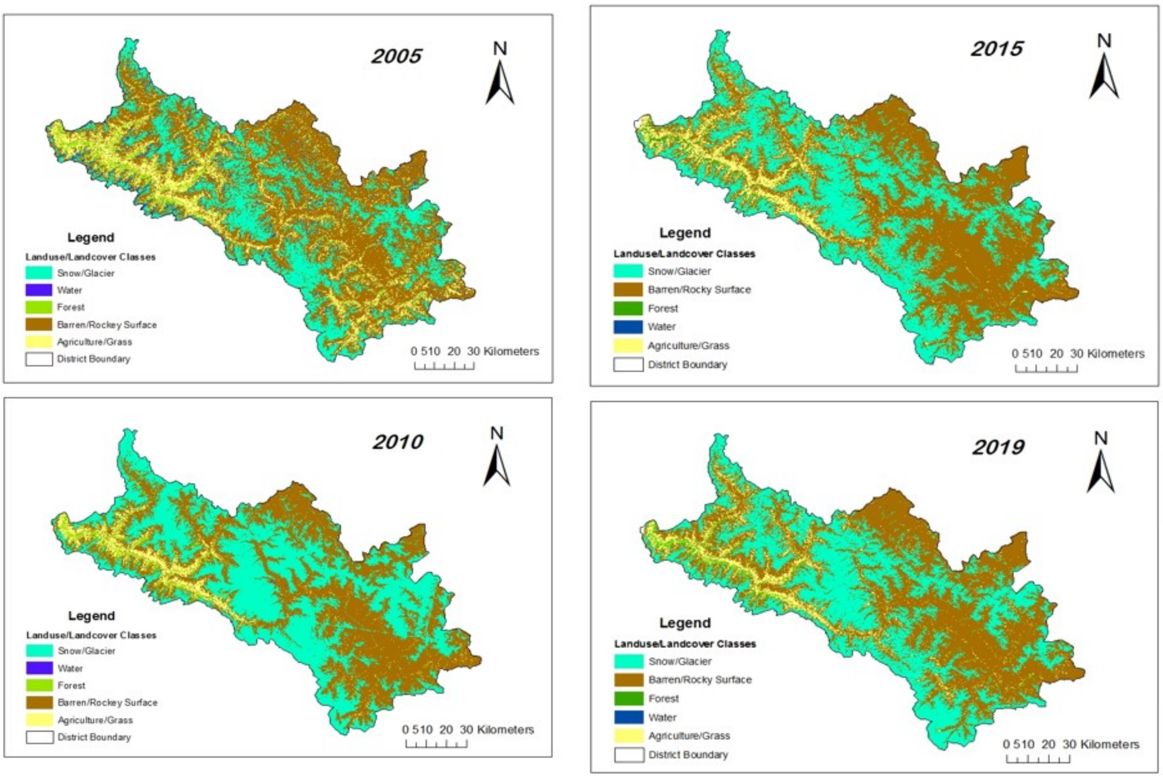


Figure 13. Land use/ Land cover Map (2005, 2010, 2015 & 2019)

3.1.5. Mapping of Glacier Lake

Samudratapu glacial lake and Geepang Gath glacial lakes are two main glacial lakes in Lahul & Spiti District. As both show an increase in their area, the area of interest has been described as coverage. Coverage separately, the inventory of these two lakes has been performed using Landsat 7 and 8 satellite images from 2005,2010,2011 and 2019.

3.1.5.1 Geepang gath glacial lake

Geepang gath glacier is situated in Chandra basin of Lahaul & Spiti District of Himachal Pradesh. It is located at a longitude of 77 ° 13 '11.937 "E and 32 ° 31' 38.143" N latitude. The current glacial lake extent measurement analysis is based on a satellite image 30 m spatial resolution Landsat 7 and 8. The temporal discrepancies have been satellite data assessments for the years 2005,2010,2011 and 2019 (Figure 14). After using the Normalised Difference Water Index (NDWI), digitalization of the result can be extracted. The present result suggests that from the year 2005 to 2019, the lake area is continuously increasing (as shown in Table 9).

Table 9. Temporal variations in the area extent of Geepang gath glacial lake

Year	Area (in ha)	Area (in sq km)	Increase in Per cent
2005	54.2106	0.542106	-
2010	68.1484	0.681484	25.709
2015	78.1553	0.781553	14.684
2019	92.9685	0.929685	18.954

3.1.5.2 Samudra tapu Glacial Lake

Samudra tapu glacial is situated in Chandra basin of Lahaul & Spiti district of Himachal Pradesh. It is located at a longitude of 77°32'49.18''E and 32°29'54.13''N latitude. satellite data Landsat 7 and 8 were used to map the lake extensions. Temporal variations in the area extent of Samudra tapu glacier lake are shown in Table 8. With the help of NDWI, digitalization of the result can be extracted (Figure 14).

Table 10. Temporal variations in the area extent of Samudra tapu glacier lake

Year	Area (in ha)	Area (in sq km)	Increase in Per cent
2005	84.923	0.84923	-
2010	117.752	1.17752	38.657
2015	121.085	1.21085	2.830
2019	123.964	1.23964	2.379

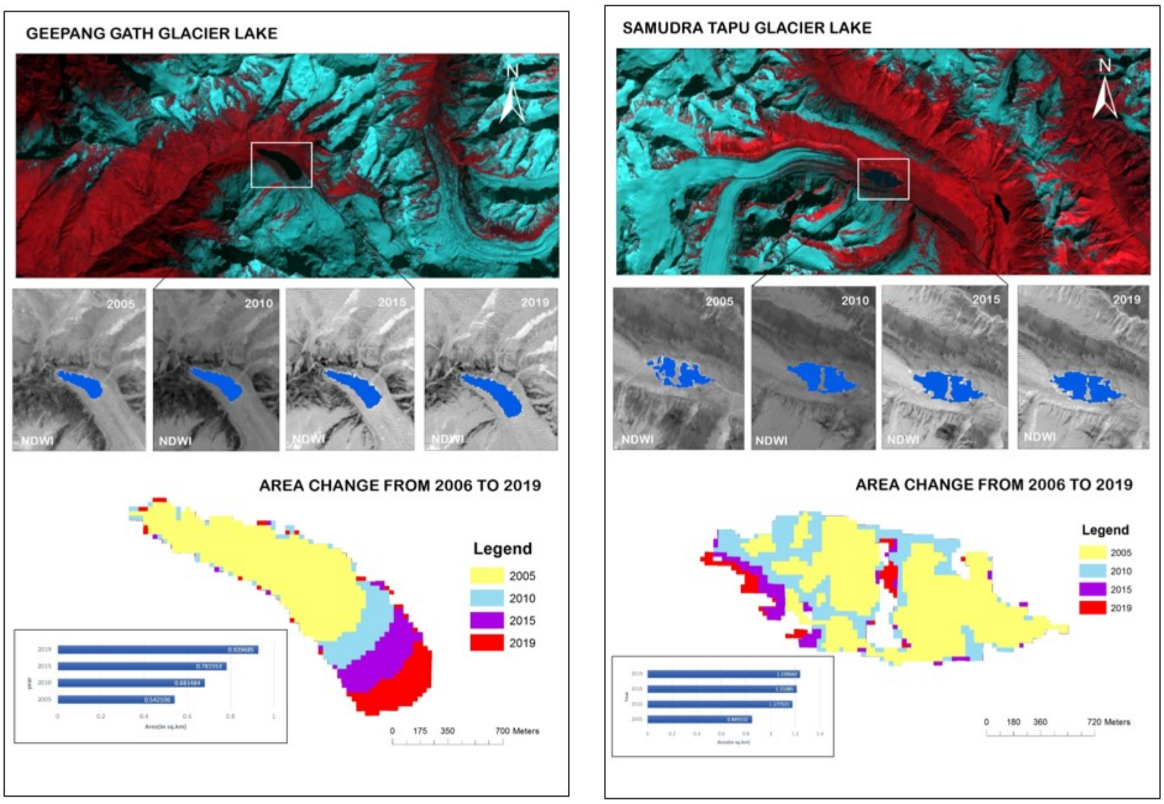


Figure 14. Geepang Gath (Left) and Samudra Tapu (Right) Glacial Lake Map

3.1.6 Case Study-2: Kinnaur District, Himachal Pradesh

Kinnaur, is about 235 km from the state capital, Shimla, located in the northeast corner of Himachal Pradesh bordering Tibet to the east. It has three high mountains ranges, namely, Zanskar and Himalayas that enclose valleys of Sutlej, Spiti, Baspa and their tributaries. The slopes are covered with thick wood, orchards, fields and hamlets. At the peak of Kinnaur Kailash mountain is a natural rock Shivling (Shiva lingam). The district was opened to outsiders in 1989. The old Hindustan-Tibet Road passes through the Kinnaur valley along the bank of river Sutlej and finally enters Tibet at Shipki La pass. Kinnaur is the second richest district in terms of per capita income after Solan in Himachal Pradesh.

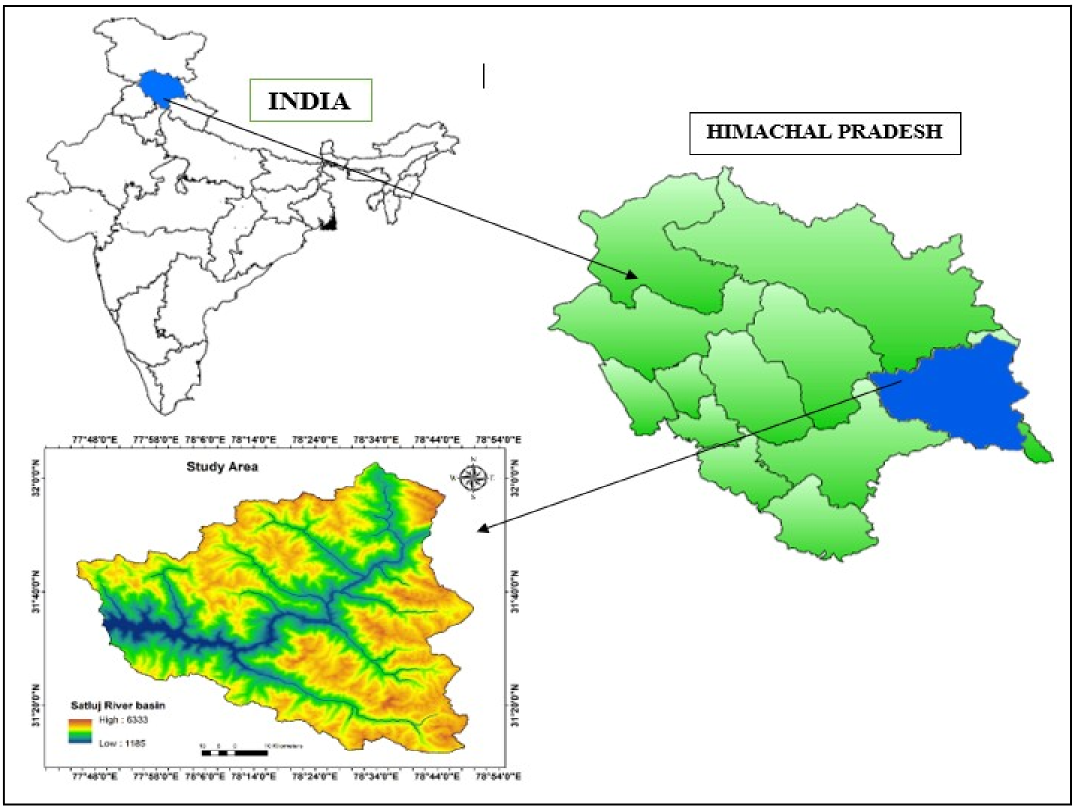


Figure 15. Study area of Kinnuar District, H.P.

3.1.7 Results

In this present study, the four land use and land cover map was prepared since 1989, 1998, 2008 and 2018 respectively. The purpose of land use and land cover was for analyzing the changes and findings glacier lake. For this maximum likelihood supervised technique was used in ERDAS Imagine software. Further these were classified into six categories i.e. Glacier, forest, Scrubland, wasteland, waterbody and agriculture respectively. Most of the area was covered from glaciers in all maps of year1989, 1998, 2008 and 2018. As seen these figures, we found that snow coverage was less in in the year 1989 than 1998 and also less in area of waste land but the after 10 year and snow coverage decreased continuously and waste land also increased. The river path was also wide in the map of 2018.

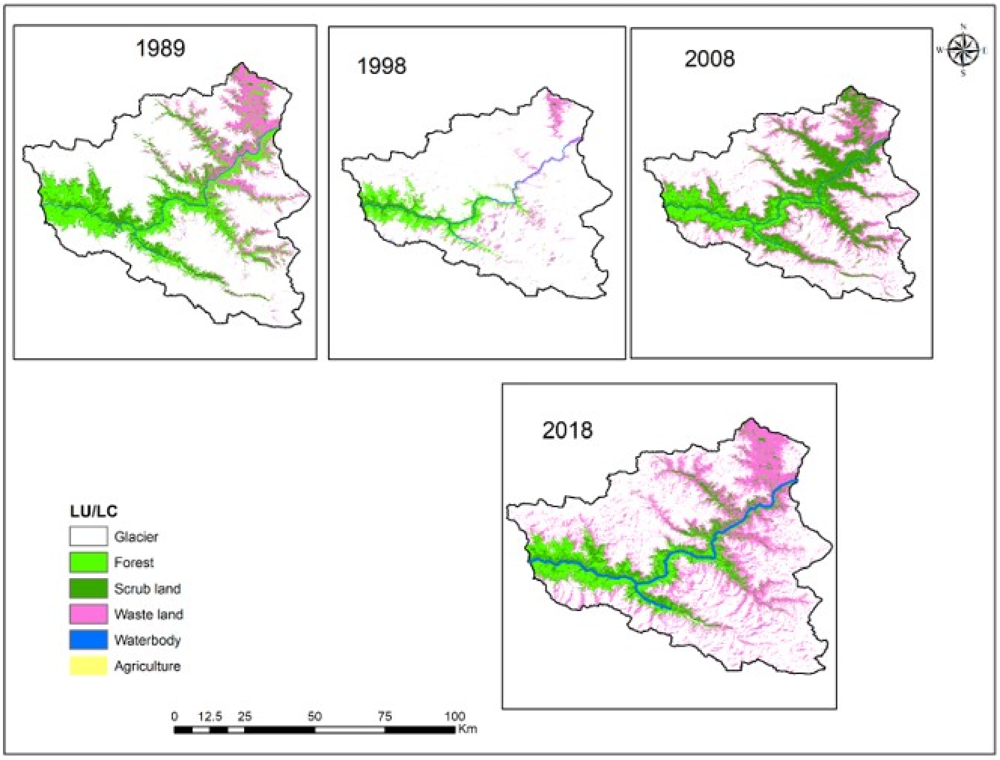


Figure 16. LU/LC of Kinnuar District, H.P from 1989 to 2018

3.1.7.1 NDSI mapping of Kinnuar

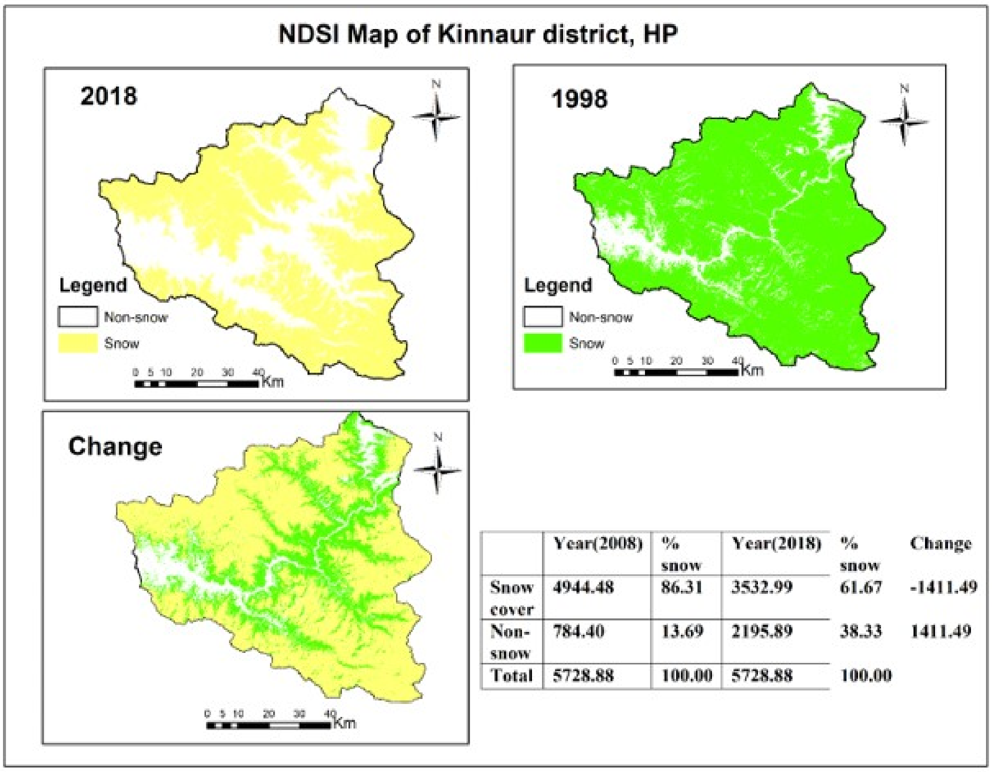
Mapping of glaciers is an important part of the glacial lake hazard assessment as their position with respect to lakes, their slope and surface area play an important part in assessing glacial lake hazard. Remote sensing is, in general, the only possible method for mapping and monitoring these glaciers. The thresholding of normalized difference snow index (NDSI) image and time-intensive manual delineation is generally known to be most accurate (Paul 2000). NDSI is generally used for snow cover mapping using satellite data (Hall et al. 1995; Kulkarni et al. 2001; Kulkarni & Bahuguna 2009). NDSI uses high and low reflectance of snow in visible (green) and short-wave infrared region, respectively, and it can also delineate and map snow in mountain shadows (Kulkarni et al. 2001).

Normalized Difference Snow Index (NDSI) is used to mask the glaciated region.

$$NDSI = \frac{Green - SWIR}{Green + SWIR} \quad (5)$$

Where, SWIR = Short Wave Infra-Red

Clean ice glaciers can be mapped using NDSI but many glaciers in the Himalayas are characteristically debris covered. Manual delineation is, in general, still possible because the glacier boundary exhibits differences in illumination caused by its shape. A threshold of 0.4 was used here to map the glacier. All the values laid above this threshold came into Glacier and below came under non-snow cover. Here the figure shows the snow coverage was lager in the year 1998 and lesser in the year of 2018.



	Year(2008)	% snow	Year(2018)	% snow	Change
Snow cover	4944.48	86.31	3532.99	61.67	-1411.49
Non-snow	784.40	13.69	2195.89	38.33	1411.49
Total	5728.88	100.00	5728.88	100.00	

Figure 17. NDSI of Kinnuar District, H.P from 1998 to 2018

3.1.7.2 NDWI and NDPI mapping of Kinnuar

As far as glacial lakes are concerned Normalized Difference Water index (NDWI= (NIR -Blue) / (NIR+ Blue) and Normalised Difference Pond Index (NDPI) was applied to identify and to see the change in the nature of these lakes. The combination of digital satellite data and the Digital Elevation Model (DEM) of the area was also used for better and more accurate results for the inventory of glaciers and glacial lakes. Ground truthing were done to rectify the errors while identifying the exact location of glaciers and glacial lakes through google earth.

The Samples of lake pixels were taken from the known glacial lakes and water body. From the NDWI and NDPI images of range between -1 to +1. From the collected samples mean value were calculated for water body. The calculated mean value were taken as threshold to demarcate glacial lake features from the other features. The gray scale threshold was used to segment an input into two classes – one for those pixels having values below an analyst defined gray level and one for those above this value. The calculated threshold value for NDWI and NDPI combine indices is -0.69. On screen digitisation were performed on reclassified image to extract the areal extent of each and every glacial lake lying in district of Kinnaur district. A total of 39 glacial lakes were identified in this district lying 1200 - 6,300 m in altitude. The total area of the lakes in the district is around 4.02 sq km.

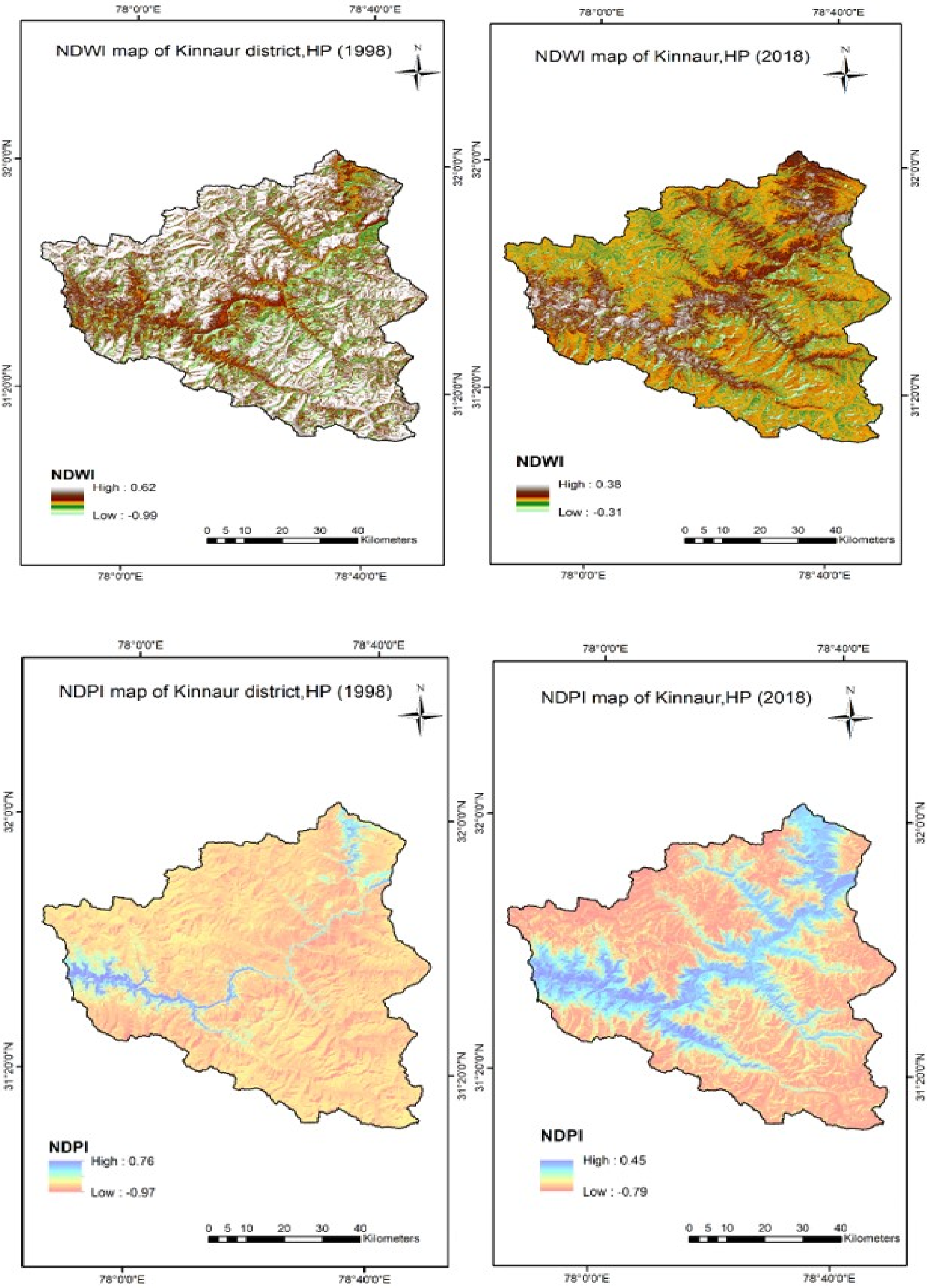


Figure 18. NDWI and NDPI of Kinnuar District, H.P from 1998 to 2018

3.1.7.3 Identification of potentially dangerous lakes

For selecting potentially dangerous lakes, following parameters have been used.

(1) Lakes of area smaller than 0.1 km^2 have been considered as harmless owing to the less volume of water contained by it (area and volume are empirically related by Huggel's formulae).

The lake volume; $V = 0.104\ A^{1.42}$ (6)

(2) Lakes which are still attached to or are near to the parent glaciers or at the snout of the glaciers are considered as more dangerous as they are capable of expanding. In general, lakes which are isolated are stagnant, do not expand and pipe their volume of water in most of the cases rather than bursting. For this purpose, overlay analysis has been carried out to check the position of the lakes with respect to glaciers.

(3) Lakes were also checked for the steep slopes around them (which can cause influx into them). Conditions of the thick or thin were estimated from the visual interpretation and distance calculations using high-resolution satellite imagery on Google Earth.

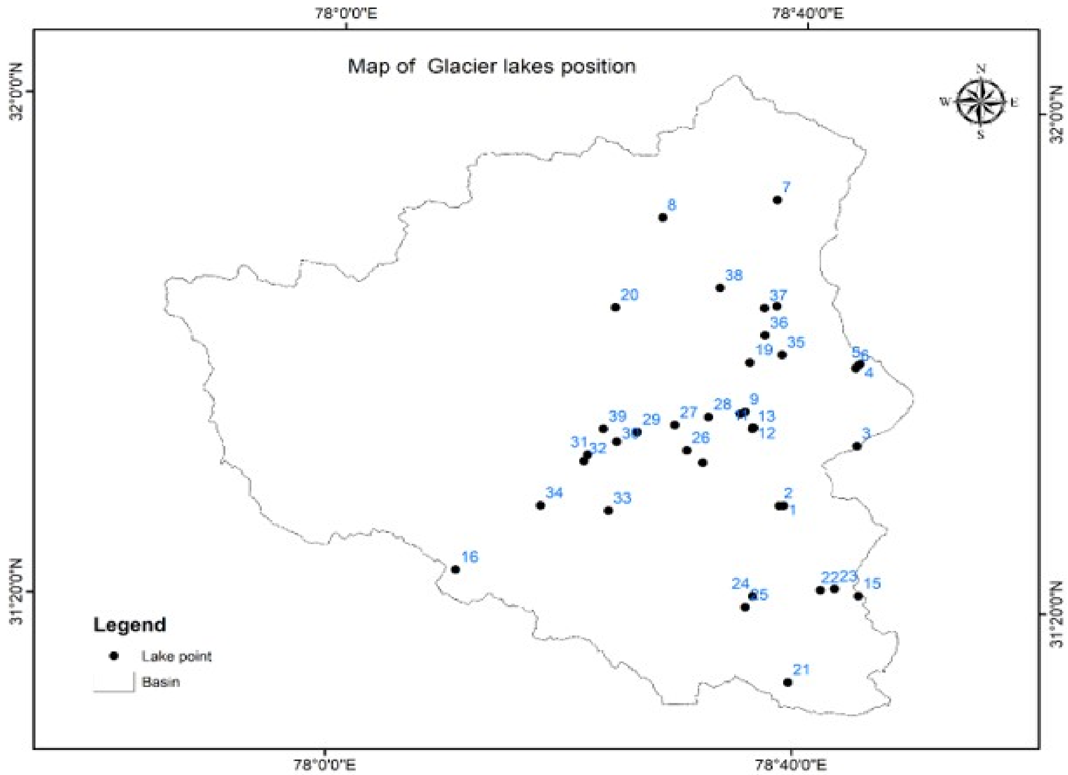


Figure 19. Identification of the most vulnerable lakes

Now, for the final GLOF modelling, the most dangerous lake was to be selected. For the selection of the most dangerous lake, volume is generally considered as the single most important factor, and the largest lake is generally selected. Here, in this study, four main factors have been considered for selecting the most dangerous lake: (1) area of the lake; (2) distance from the outlet of the basin; (3) Altitude at which the lake was positioned.

Table 11. The most dangerous lakes

Lake no.	Area	Volume	Distance from Outlet
9	0.76	0.07	65.23
17	0.20	0.01	60.32
21	0.11	0.0045	78.21
24	0.13	0.0057	39.91
26	0.21	0.113	87.25
34	0.10	0.0039	73.32
31	0.11	0.0045	34.74
33	0.10	0.0039	46.32
36	0.33	0.0215	76.67
37	0.29	0.017	53.67

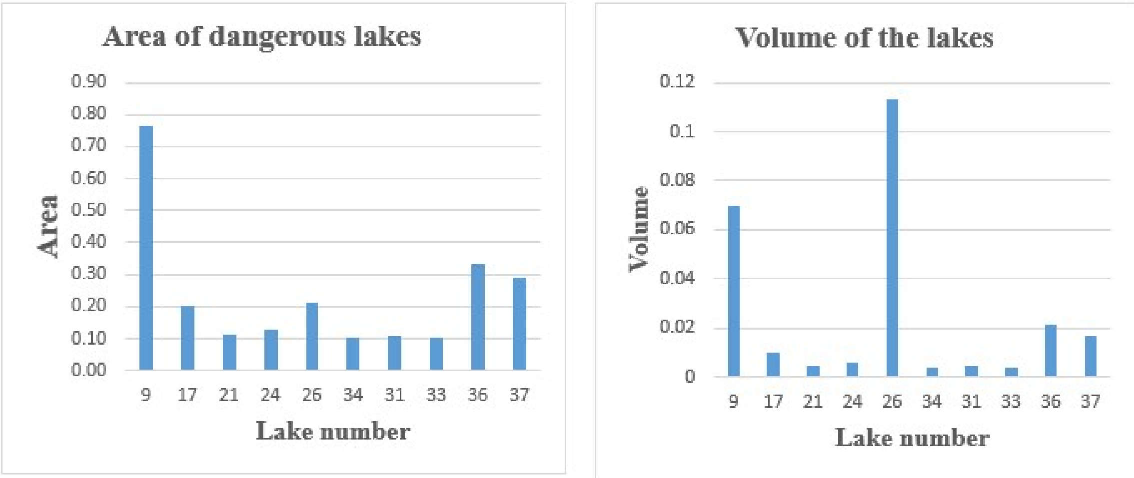


Figure 20. Area calculation of the most vulnerable lakes

3.1.7.4 Validation

Validation of Glacier lake were done through high resolution google earth images. In total of 39 glacial lakes, 10 lakes were found dangerous lakes having area >0.1 Km2 were shown in the table in Kinnaur district of HP. The formation and expansion of glacial lakes were in concert with the climatic change (increase in temperature and decrease in precipitation) induced glacier retreat in Kinnaur district. The rate of growth of glacial lakes varied inversely with the proximity to the parent glacier, closer the glacial lake to mother glacier higher was its growth rate. Hence, glacier meltwater flowing into the lakes is the main source of water to the areal expansion of lakes in the region. As a consequence of the continuous expansion of lakes and glacier retreat, GLOF is an emerging threat in Kinnaur district.

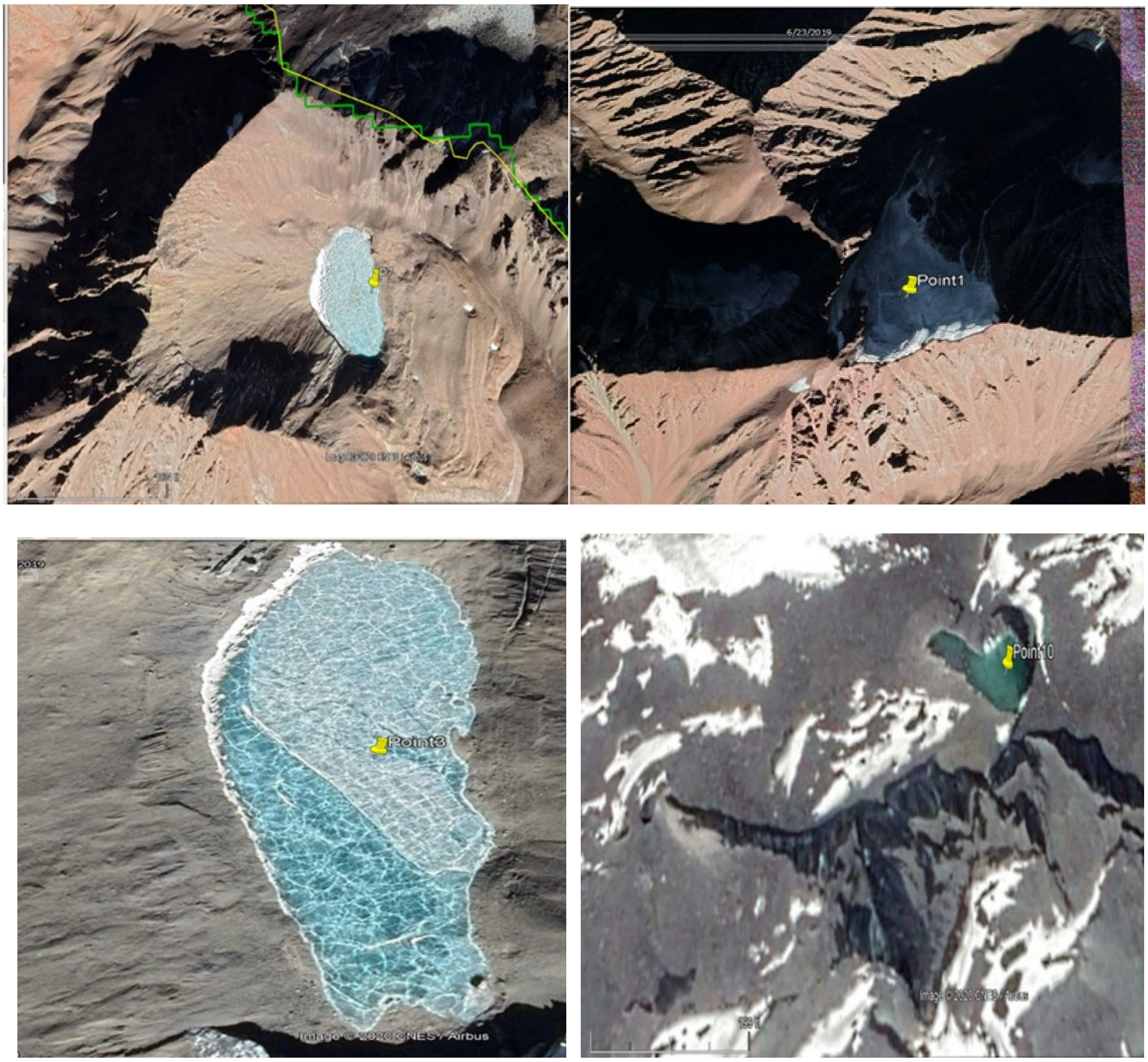


Figure 21. Validation of Glacier lake through high resolution google earth images

3.1.8 Case Study-3: Highly Vulnerable Glacial Lake near Kasang Gramang, Himachal Pradesh

3.1.8.1. Study Area

The Satluj River is one of the key tributaries of the Indus river system. The river's overall length is 1448 km, and the entire drainage area up to Bhakra reservoir is around 56,500 km^2. The basin area is located in the Himachal Pradesh and expands over the area of Lahaul and Spiti, Kinnaur, Shimla, Solan, Mandi, Kullu, and Bilaspur. However, in this study, the Indian part of the Satluj River basin (30^o 22' – 32^{o}42' N and 75^{o}57' –78^{o}51' E) up to Bhakra reservoir has been selected (Figure 22).

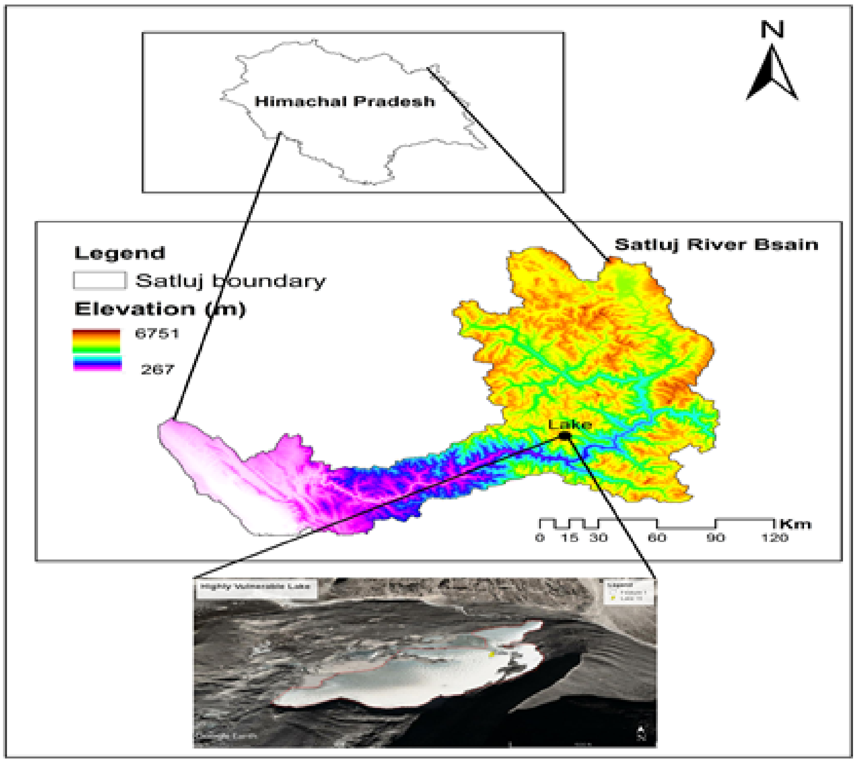


Figure 22. Location of the potentially dangerous glacial lake in the Satluj basin.

3.1.8.2 Glacial lakes inventory

A total of 15 potentially significant glacial lakes have been located and catalogued in the Satluj basin using Landsat imagery. Glacial lakes have been classified in three ways; the first one is 1-5 ha (less vulnerable), second one is 5-10 ha (medium vulnerable), and third one is >10 ha (very vulnerable) (highly vulnerable). In total, 15 key glacial lakes have now been identified in the Satluj river basin (Figure 23), and their position, area, and elevation have been presented in Table 12. It has been noticed that large-sized lakes are fewer in number. As the contemporary glaciers are at higher elevations and lakes are forming and expanding in the fore fields of glaciers that have evacuated owing to glacier retreat, these observations of lakes in relation to elevation and distance from glaciers reflect the basin's continual glacier retreat.

Table 12. Potentially critical glacial lakes identified in Satluj basin

Lake	Latitude	Longitude	Elevation(m)	Area(km^2)
L1	32°19'50.58"N	78°43'16.92"E	3867	1.121
L2	31°59'34.31"N	78°80'44.34"E	5780	0.210
L3	32°5'24.39"N	78°56'49.42"E	5297	0.001
L4	32°6'26.33"N	78°56'31.68"E	4893	0.161
L5	32°6'24.88"N	78°55'57.66"E	5624	0.133
L6	32°7'11.03"N	78°57'2.74"E	4438	0.002
L7	32°7'20.95"N	78°56'51.69"E	5394	0.001
L8	32°7'45.14"N	78°58'12.57"E	4595	0.005
L9	32°54'49.80"N	78°50'24.15"E	5583	0.184
L10	32°8'42.24"N	78°19'46.80"E	5721	0.081
L11	31°39'46.40"N	78°10'1.14"E	4193	0.096
L12	32°1'45.33"N	78°50'39.63"E	5628	0.161
L13	31°55'5.75"N	78°47'6.24"E	5376	0.143
L14	32°3'32.23"N	78°48'26.17"E	5572	0.122
L15	31°39'40.81"N	78°10'7.32"E	4261	0.239

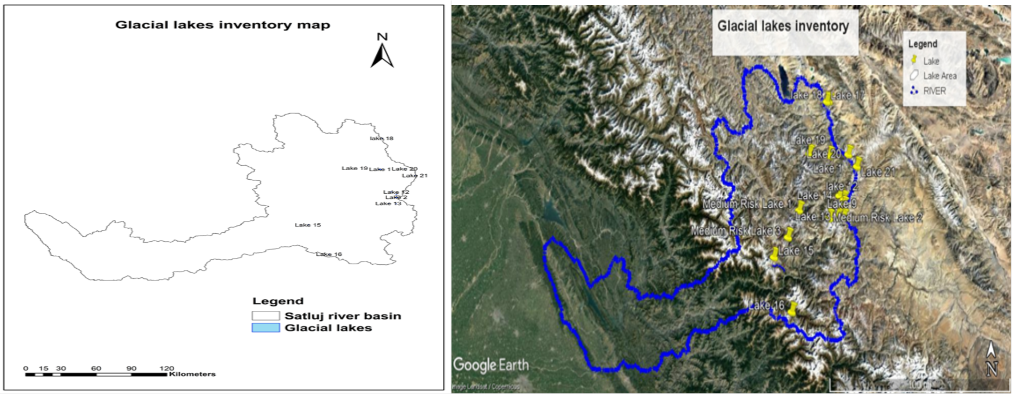


Figure 23. Glacial lake inventory map in the Satluj river basin using NDWI technique (left) and Google earth (right).

3.1.8.3 Glacial lake changes 1990–2018 and analysis for the identification of most vulnerable lake in the basin

From 1990 to 2018, the evolution and modifications of glacial lakes in the Satluj basin have been exceedingly complicated, with recently developing lakes, as well as the growth and disappearance of preexisting glacial lakes. Between 1990 and 2018, the density and extent of glacier lakes in the Satluj basin expanded considerably (Figure 24). Newly emerging lakes (recently formed lakes), rising lakes (substantial increase in area), and steady lakes (no significant changes in the expansion area) are the three groups based on their evolution conditions and trends from 1990 to 2018. Between 1990 and 2018, certain ice-dammed lakes and bedrock-dammed lakes also developed.

Growth and advancement of glacier lakes in Satluj basin have been highly complex, encompassing rapidly evolving lakes, enlargement, and elimination of preexisting glacial lakes from 1990 to 2018. The frequency and extent of glacier lakes rose considerably from 1990 to 2018 in the Satluj basin (Figure 3.16). Lakes are categorized into three groups based on their evolutionary conditions and trends from 1990 to 2018: emerging lakes (recently formed lakes), rising lakes (major growth in the size), and constant lakes (no significant changes in the area).

Some ice-dammed lakes and bedrock-dammed lakes emerged from 1990-2018. Most of the emerging lakes close to the parent glacier are progressing along the course of the glacier in the vacuum generated by glacier retreat. Beyond 500 m from the glacier, bedrock-dammed lakes and moraine-dammed lakes are constant lakes as their area does not change substantially. As a consequence, lakes with a closer hydrological link to glaciers expand faster than lakes with a distant or no hydrological relationship.

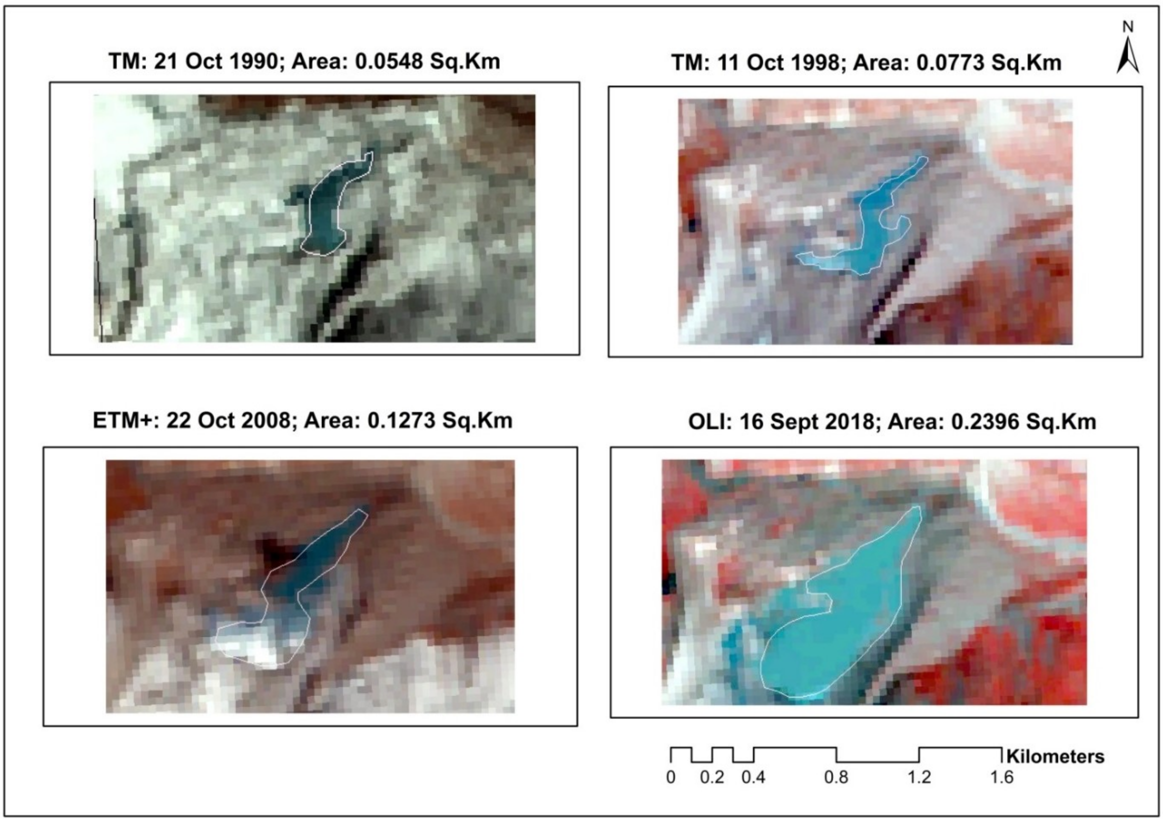
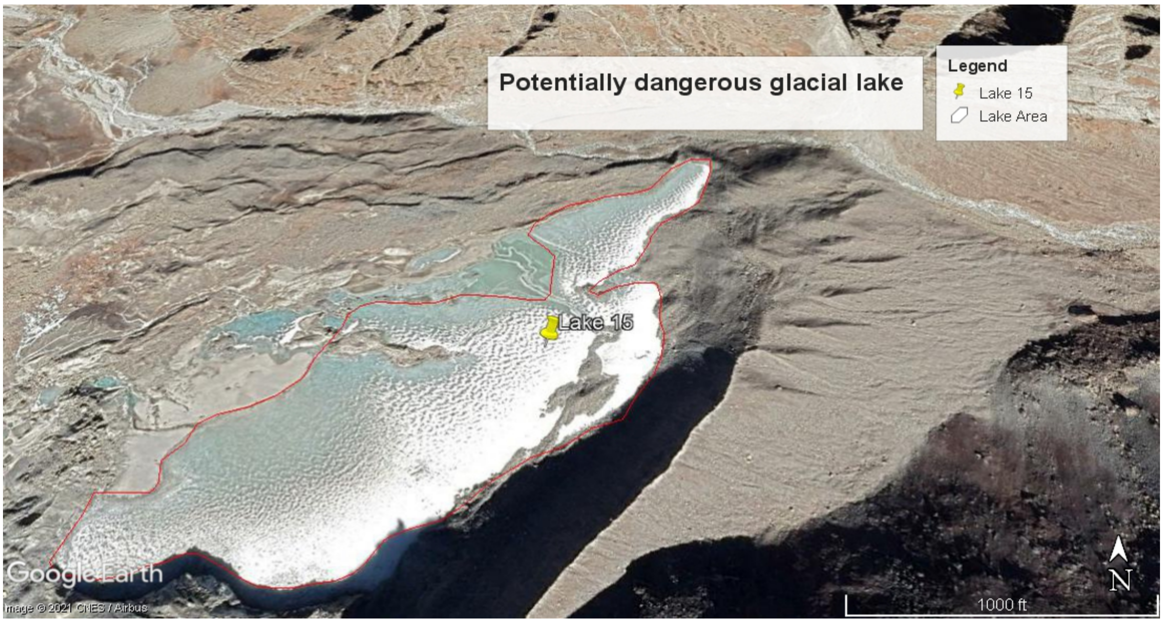


Figure 24. Potentially critical lake expansion from 1990 to 2018 in Satluj basin using Landsat data

3.1.8.4 Potentially dangerous glacial lake

Based on a precursory evaluation, lake 15 in the Satluj basin, with a total size of 0.239 km^2, was categorized as PDGL. Table 3.6 offers data on the lake and its environs that can be utilized to construct a qualitative assessment of the possibility of an eruption. Between 2004 and 2014, two lakes grew by 64% and 39%, respectively; two lakes grew by just 23% and 16%, respectively, while three lakes grew insignificantly (decadal). Of all three lakes were in direct contact with the potential glacier as it emerged. Two lakes have a high outburst possibility, one has a medium outburst probability, and four have a low outburst probability, according to the eruption probability and priority scheme presented. The temporal history of lakes with a high likelihood of outburst is depicted in Figure 25.



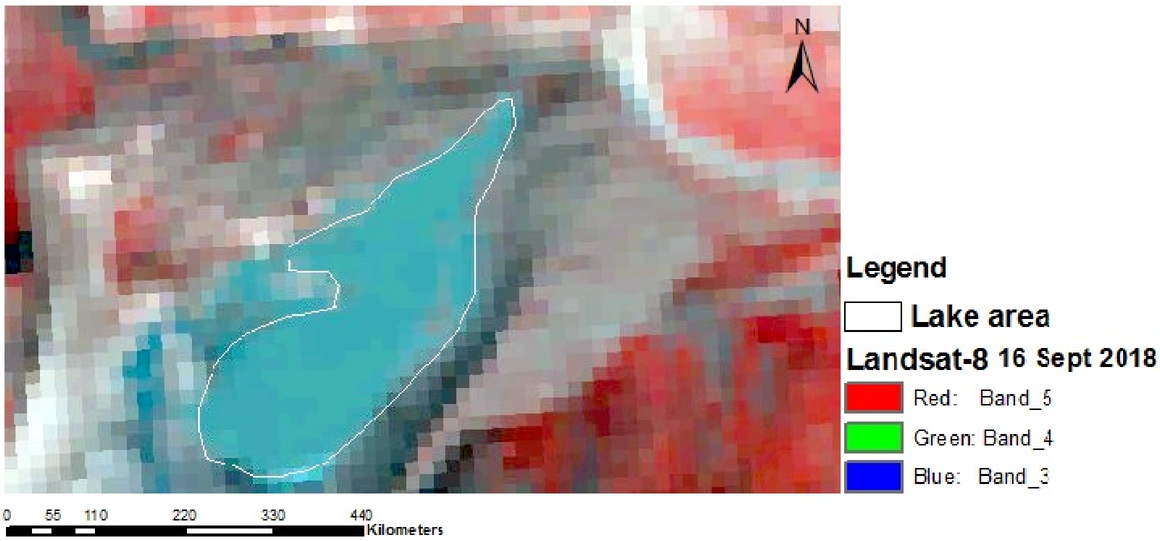


Figure 25. The highly susceptible potentially dangerous glacial lake in Satluj basin of Landsat-8 16 September 2018 (right) and Google earth (left)

3.1.9. Case Study 4: Study Area and Data Used

The study area taken in this study is the Alaknanda basin (Figure 26). The Alaknanda is a Himalayan river in the Indian state of Uttarakhand and one of the two headstreams of the Ganges, the major river of Northern India and the holy river of Hinduism. The Alaknanda basin located 30.1333˚ N latitude and 78.6029˚ E longitude which can be mapped to the closest address of Alaknanda river. It is considered to rise at the confluence and foot of the Satopanth and Bhagirath Kharak glaciers in Uttarakhand and meet the Sarasvati River tributary at Mana, India, 21 km from Tibet. Three km below Mana the Alaknanda flows past the Hindu pilgrimage centre of Badrinath.

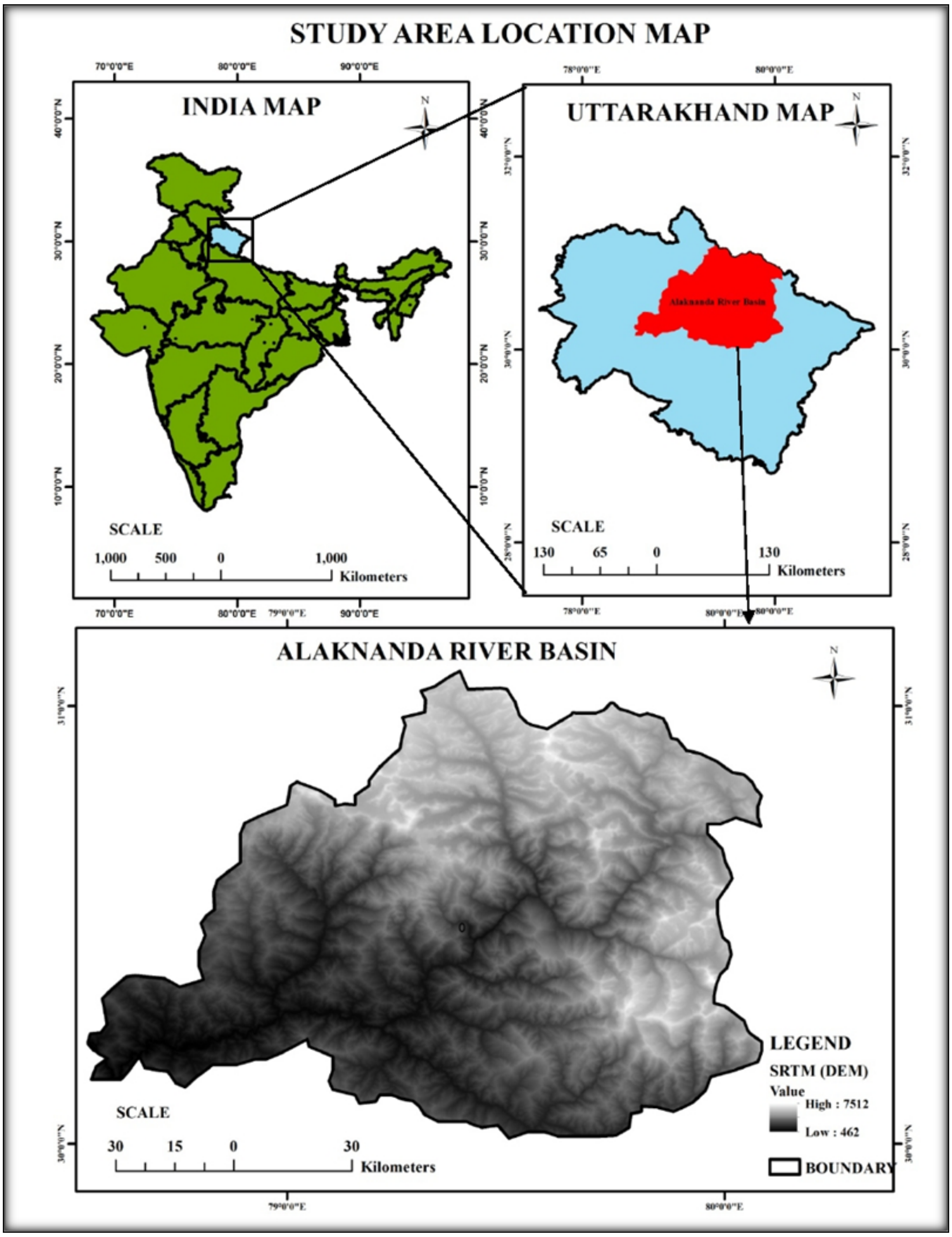


Figure 26. Study Area of Alaknanda River basin, U.K.

3.1.9.1 Glacier Mapping

In the present study, for mapping of snow-covered glacier, band ratio and NDSI approach has been used. As given by Paul et al. (2004), use of slope can be used for debris-covered glacier mapping. From Figure 27, it can be seen how slope map can be used as a tool for finding actual extent of the debris-covered glacier. Glaciers without lateral moraine are also difficult to delineate; for solving this problem, a Slope threshold of 16,874,302.12 and 51, 225,560 in percentage rise can be used to delineate smoother part of the glaciers is generally used. Using NDSI (Figure 28) and band ratio image and slope map (Figure 29), glaciers have been manually delineated.

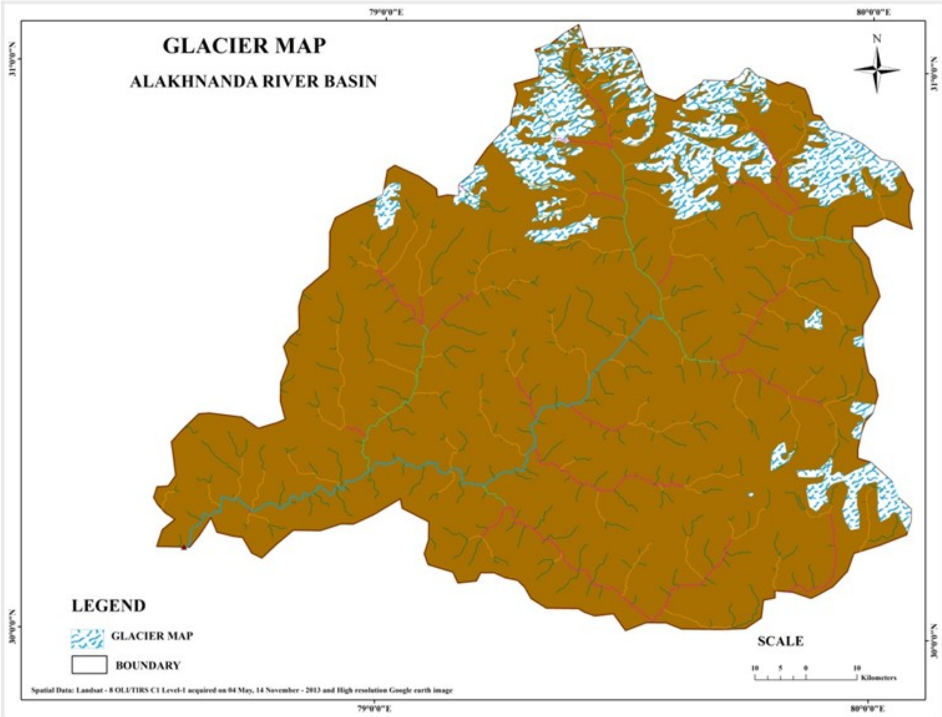


Figure 27. Glacier map of Alaknanda river basin

3.1.9.2 Glacier Lake Mapping

Glacier lakes and their possible outbursts which can occur in the form of glacier floods are one of the major hazards in high mountain areas. It can effect down slope physical and cultural environments like hydropower plant, road and canal network, forest and settlements.

In the present study, various supervised and unsupervised classification methods along with NDWI and NDSI have been used to delineate the glacial lakes. All methods led to shadow misclassification and hence lake exaggeration. NDWI value for typical lake surfaces ranges from 0.60 to 0.85 (Huggel et al. 2002). The index value from -0.08 to 1 has been found good for glacial lake mapping in the present study area. The main challenges of using NDWI approach were as follows.

(1) Shadows were classified as lakes due to Rayleigh scattering in blue band.

(2) Every water surface (melt water on glaciers) and even water-rich soil was mapped as lakes.

After applying the 0.1 km^2 area threshold, rest of the lakes to be further analyzed. Lakes have been superimposed on glacier map to check for their spatial relation with respect to the glacier. As discussed in the methodology, lakes which are at the snout or are still attached to the mother glacier have been identified as shown in the Figure 27. A pairs of lakes, i.e. Lakes 463 and 453 lying in the downstream of the other lake as shown in Figure 28. After making this analysis along with others as mentioned in the methodology, in total, 4 lakes have been found to have potential to cause GLOF; all these lakes have been recorded with their location, area, distance from the outlet of the basin, classification and reason for their vulnerability.

Extensive manual editing and delineation were carried out using Google Earth software for mapping the final lakes. The compiled images of NDSI, NDWI and unsupervised classification and overlay on the Google Earth for lineate the glacial lakes. Some lakes which were ice covered or were not visible are not reported in the inventory. For nomenclature purpose, the glacial lakes were numbered in a "binary tree format" depending on the position of the lakes with respect to the streams. The outlet of the basin has been taken as the starting node of the tree and "left then root then right" rule has been used to number the lakes. In total, The Satopanth and Bhagirathi Kharak glaciers are located at the head of Alaknanda Valley in Chamoli district of Uttarakhand. Both Satopanth glacier (13 m) and Bhagirath Kharak glacier (18.5 m) have an average width of 750-850 meters. These glaciers sprawl over an area of 21.17 and 31.17 square km respectively. These glaciers were mapped. The glacier map of the basin is given in Figure 3.20. The mapping of glacier is crucial in finding the vulnerability of the lakes, their position with respect to glacier. Slope of the glaciers which are attached to lakes is also an important factor, so glacier mapping has been very useful in assessing potentially dangerous lakes. In total, 463 glacial lakes have been mapped in the basin (Figure 30).

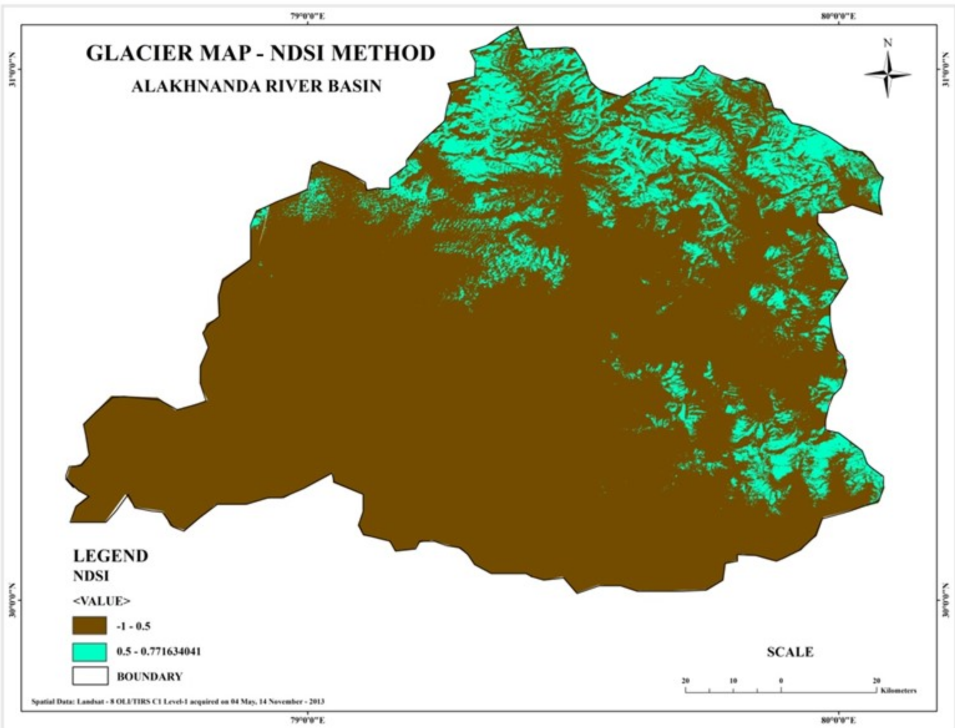


Figure 28. Glacier Map using NDSI Method

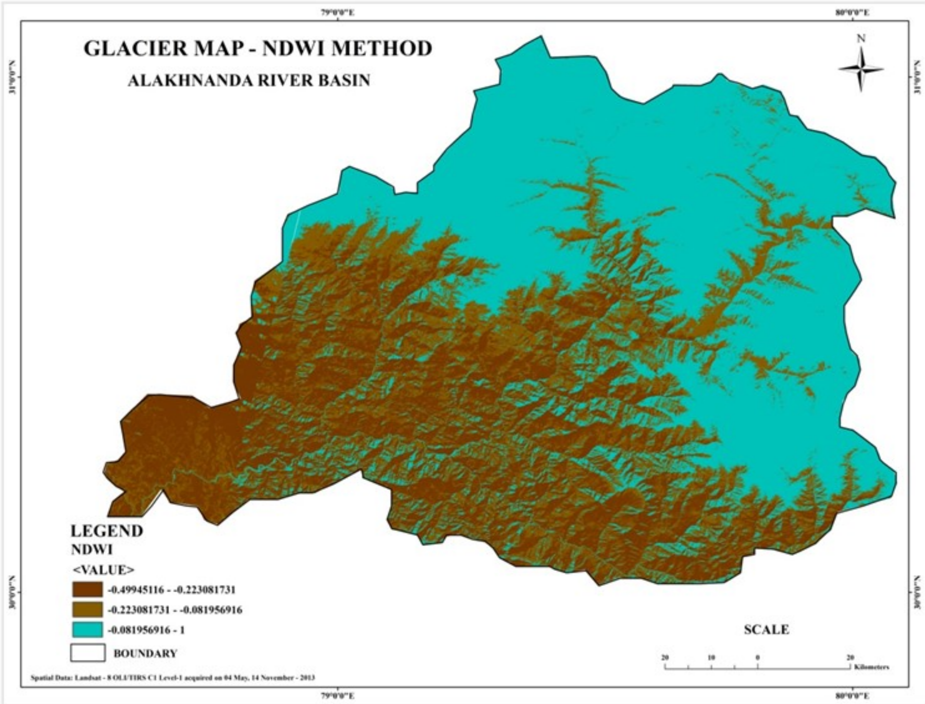


Figure 29. Glacier Map using NDWI

3.1.9.3 Analysis for the Most Vulnerable Lake in the Basin

As discussed in the methodology, area, distance from the outlet, growth of the lake and slope have been taken into account. The graph (Figure 31) shows areas of the total glacial lakes identified. Although areas of all the lakes are above 0.1 km^2, there is a significant variation in the area of the lakes. It can be observed that 0.6 km^2 is the threshold dividing lakes into lakes of significant area and lakes having comparatively less area; hence Lakes 196,194, 195, 462 are considered as output of this stage with Lake 196 as the most important one.

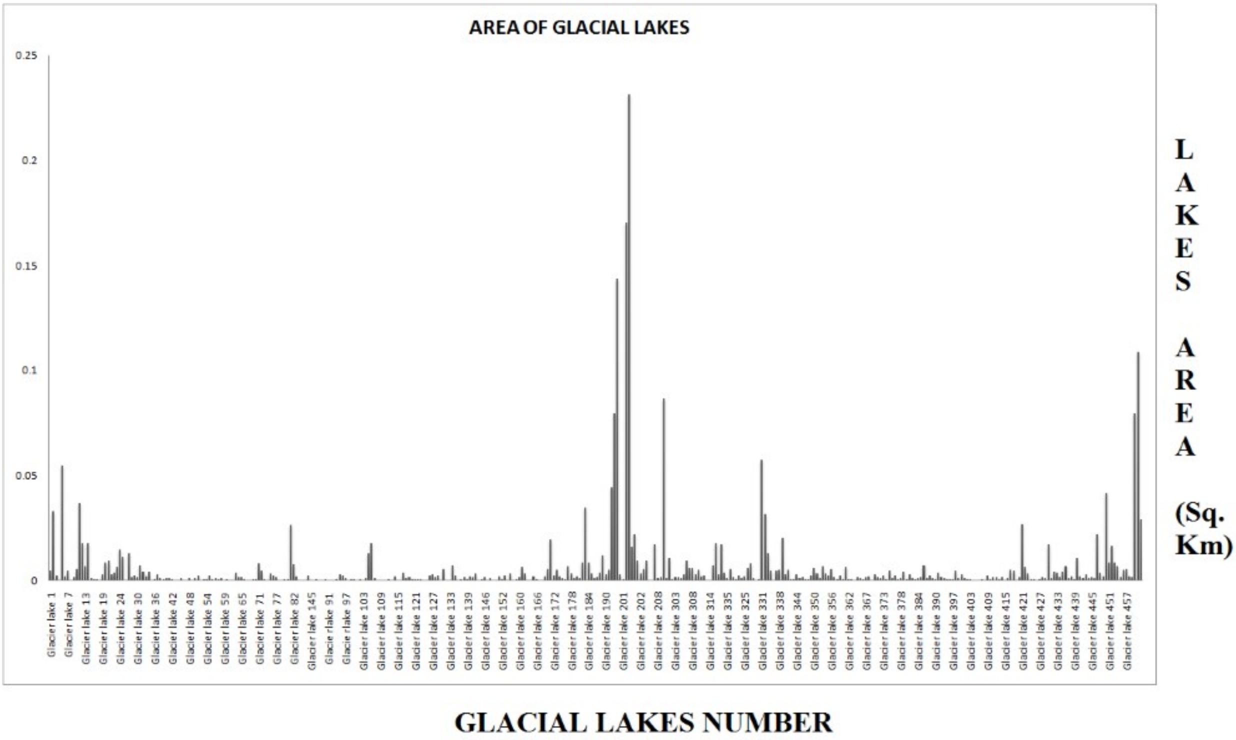


Figure 30. Area of Glacial Lakes

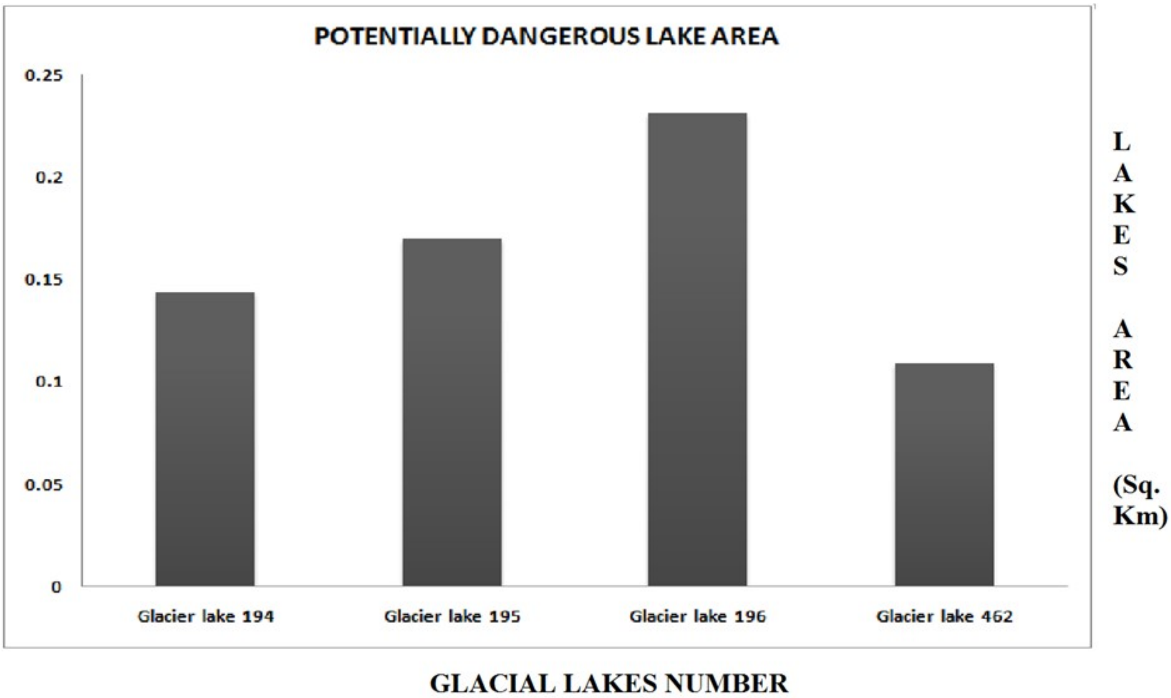


Figure 31. Area of Potential Glacial Lakes

3.1.9.4. Distance from The Outlet of the Basin

As shown in the Figure 32, it can be observed that distance does not play an important role here because the variation in the distance is not much prominent except for Lakes 462 and 194. Their area is less in comparison to other lakes, i.e. 0.1088 and 0.1435 km^2 , so no significance can be given. Both the above images of Google Earth shows the growth of lakes from 2009 to 2013. From this seen, the potentially dangerous lake is Basudhara Tal, Uttarakhand state of India.

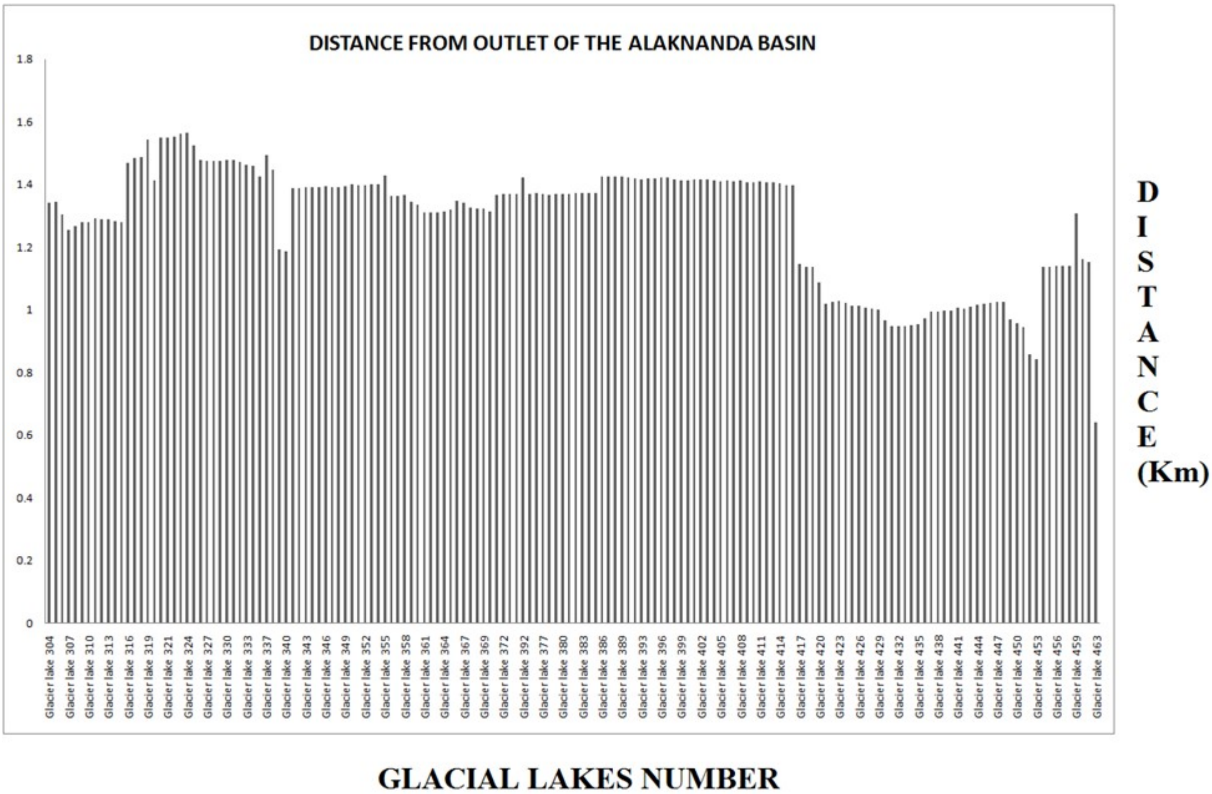


Figure 32. Distance from the outlet of the Alaknanda basin

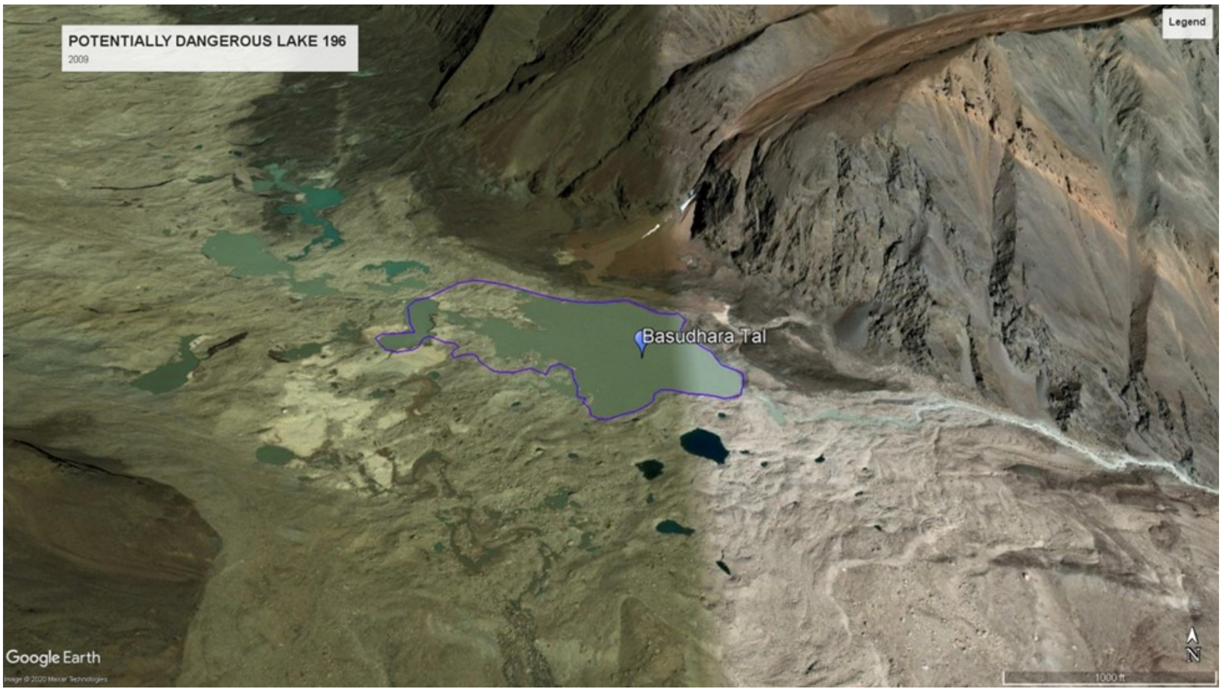


Figure 33. The Basudhara lake since 2009

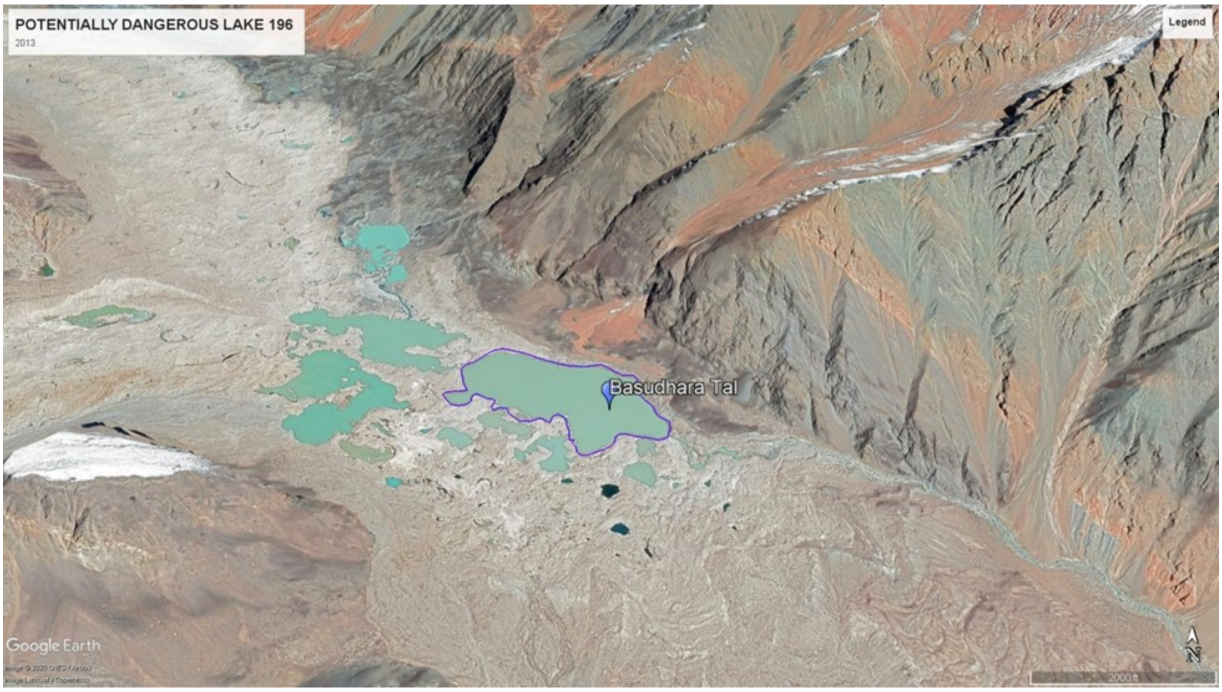


Figure 34. Potentially Dangerous lake, 2013, Basudhara Tal

In the year 2013, there were, in total, 463 lakes, out of which 3 lakes were having areas greater than 0.1 km^2 while more lakes were having areas less than 0.1 km2 . Most of the lakes are situated above 4500 m. The area of the biggest lake, i.e. Lake 196, is increasing (Figure 34) over the past years. The lake is also expanding laterally and longitudinally; therefore, this lake has been considered as a potentially dangerous lake from GLOF point of view (Table 13).

Table 13. Lake 196 Parameters

LAKE AREA (Sq. Km)	LAKE DISTANCE FROM THE OUTLET (Km)	LAKE VOLUME (Cu.Meter)	LAKE ALTITUDE (Feet)
0.23138	**1.37214881**	**508.315287**	**4680.0243071**

3.1.10 GLOFs modeling using HecRAS

3.1.10.1 Satluj River Bsain, H.P.

In the Satluj basin, a GLOF modelling study was conducted for a potentially deadly lake. Because the lake's maximum size is 263,240 m^2, it was selected to build up the model for the GLOF investigation. The Lake is 4267 metres above sea level. The Satluj River has been represented in the model via a series of cross-sections at 1 km intervals, produced using DEM, from the glacial lake position down to the catchment outflow (a total length of 106 km). Figure 35 shows the complete distance from Satluj Lake to the outflow. Figure 36 shows all of the cross-sections collected at various intervals. Given the boulder beds and mountainous terrain of Himalayan Rivers comparable to those found in Bhutan's surrounding regime, the manning coefficient 'n' was set at 0.06. (Sharma, 2009). The lake may collapse due to overtopping flow incising and damaging the dam as the lake's water level rises. Figure 37 shows the HEC-RAS model that was used for the Satluj Lake outburst research.

Geometry data (river cross-sections, center lines, bank lines, flow lines, and elevation data) was derived from the satellite imagery in a plugin of HEC-Geo-RAS in ArcGIS environment. Subsequently, the geometric data was imported into HEC-RAS software for the unsteady flow simulation. The flow data requires upstream and downstream boundary conditions. The dam breach outflow hydrograph is commonly used for upstream and downstream boundary conditions as normal depth, which is calculated using the channel bed slope. The present study considered a glacial lake as a dam failure structure with a specific crest level and crest length. Various parameters such as simulation time series, elevation above the invert level and its breach dimensions were specified to the corresponding lake.

An inline structure that characterizes the lateral-frontal moraine is entered at the lower elevation of the lake, and the failure catastrophe is modeled and evaluated by breaching the inline structure before performing a dam break analysis. For an upper boundary condition, glacial lake acts as a storage area by its elevation storage relationship. The total volume and maximum depth acquired from the empirical equations and DEM were used to generate the elevation-storage volume. DEM was also used to get the Triangular Irregular Network (TIN) terrain to set up the 1-D (hydrodynamic) modeling and subsequently minimum elevation of the lake was derived from the TIN network. The storage capacity at the minimum elevation of the lake (last elected location) is zero, whereas it was obtained for the maximum elevation (topmost elevation of lake). On the basis of these two parameters, elevation storage capacity for the lake was generated. Such parameters are required as an input to the empirical equations that estimate the potential peak discharge and the failure time of a GLOF event (moraine dam breach event). For a dam break analysis, the Froehlich model uses fewer input parameters to estimate peak breach out flow hydrograph. At the fnal stage, unsteady fow analysis was computed to derive important results like maximum food depth, maximum food velocity, peak food hydrographs, and water surface elevation at different cross sections in the downstream region.

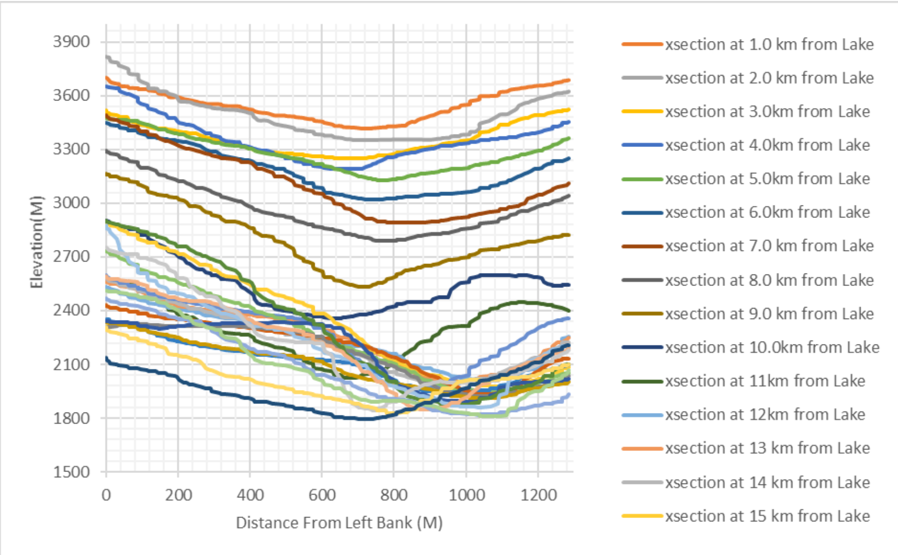


Figure 35. Cross sections at 1 km interval downstream lake

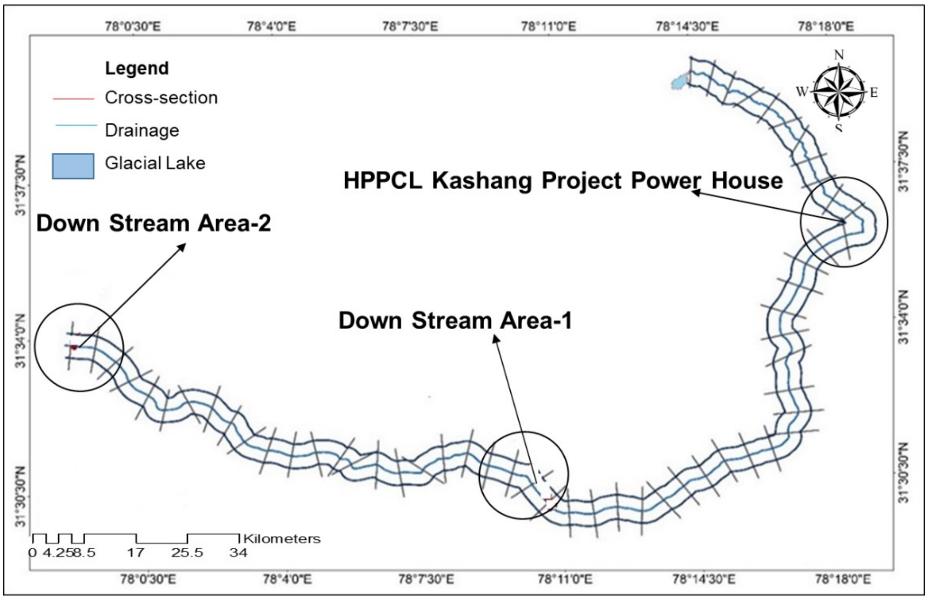
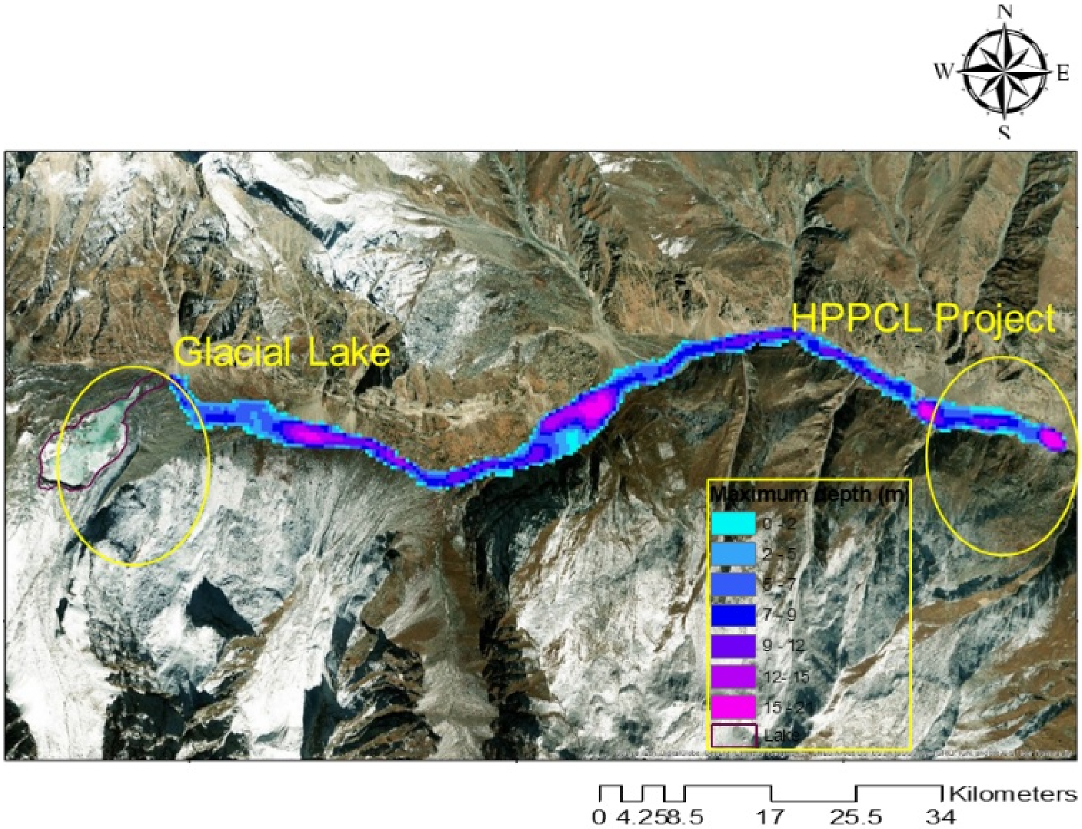


Figure 36. River Cross-section model for GLOF study from Lake to Downstream site



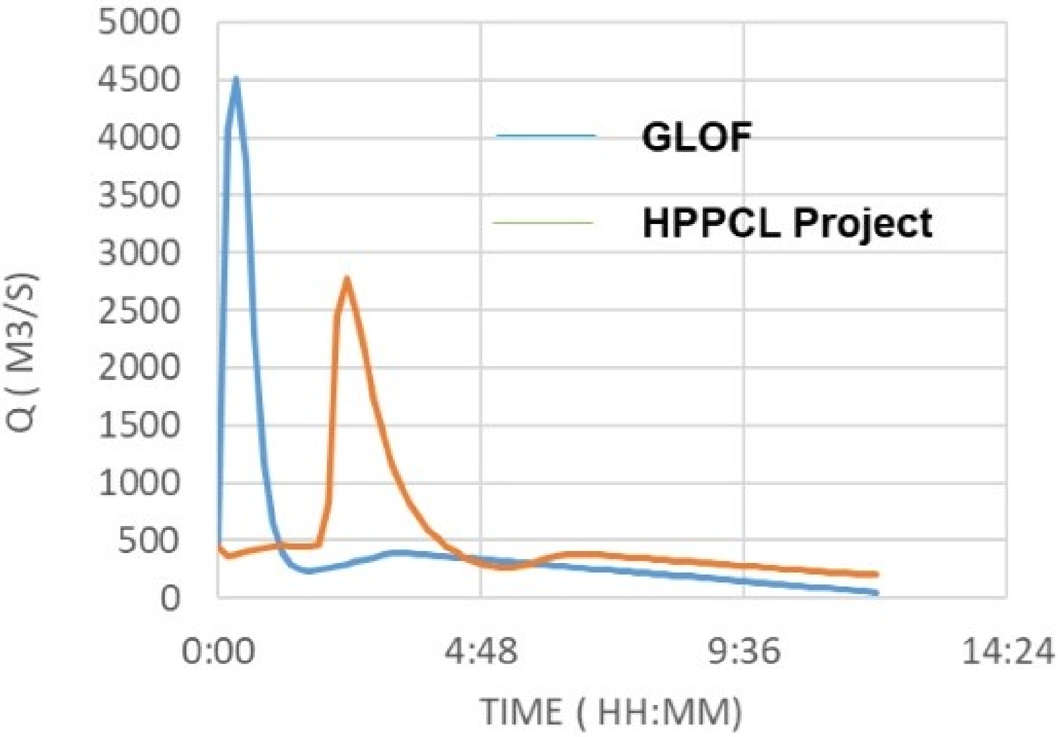


Figure 37. Maximum depth flood inundation from Lake and Flow hydrograph

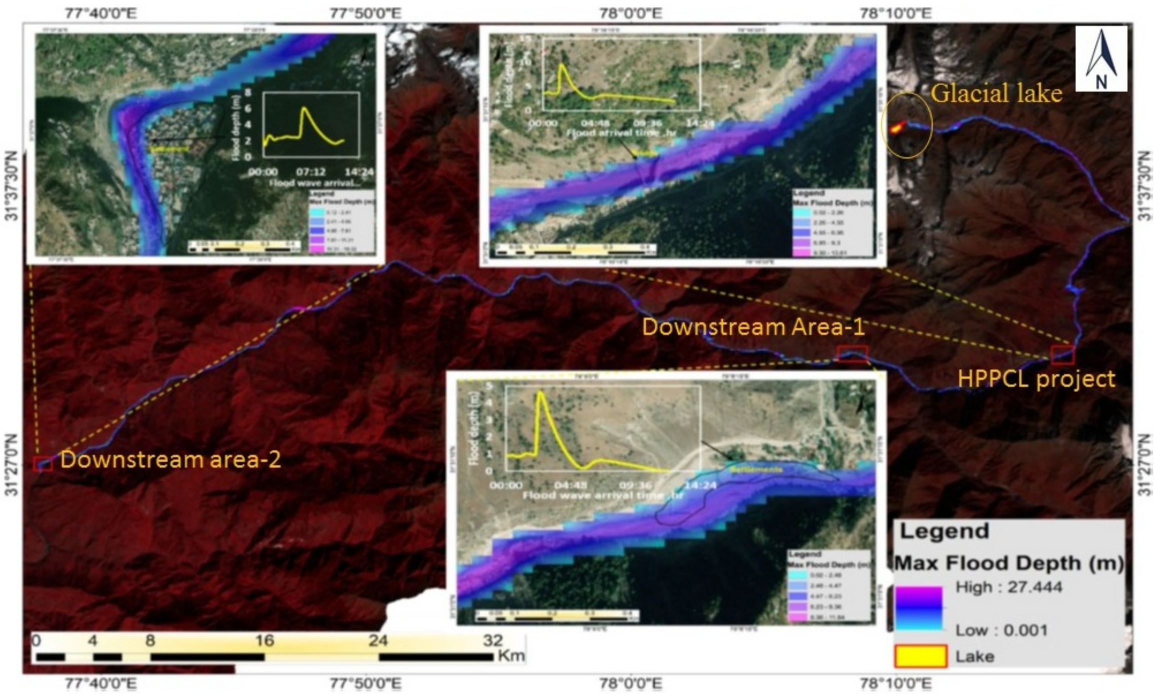


Figure 38. Spatial distribution of Maximum Flood inundation

3.1.10.2 Alaknanda River Basin, U.K.

In the Alaknanda basin, a GLOF modelling study was conducted for a potentially deadly lake. Because the lake's maximum size is 182,000 m^2, it was selected to build up the model for the GLOF investigation. The Alaknanda River has been represented in the model via a series of cross-sections at 5 km intervals, produced using DEM, from the glacial lake position down to the mouth (total length 50 km). Figure 39 depicts the whole reach from Alaknanda Lake to the outflow. Figure 40 shows all of the cross-sections collected at various intervals. The HEC-RAS model that was used for the Lake Outburst investigations for Alaknanda Lake.

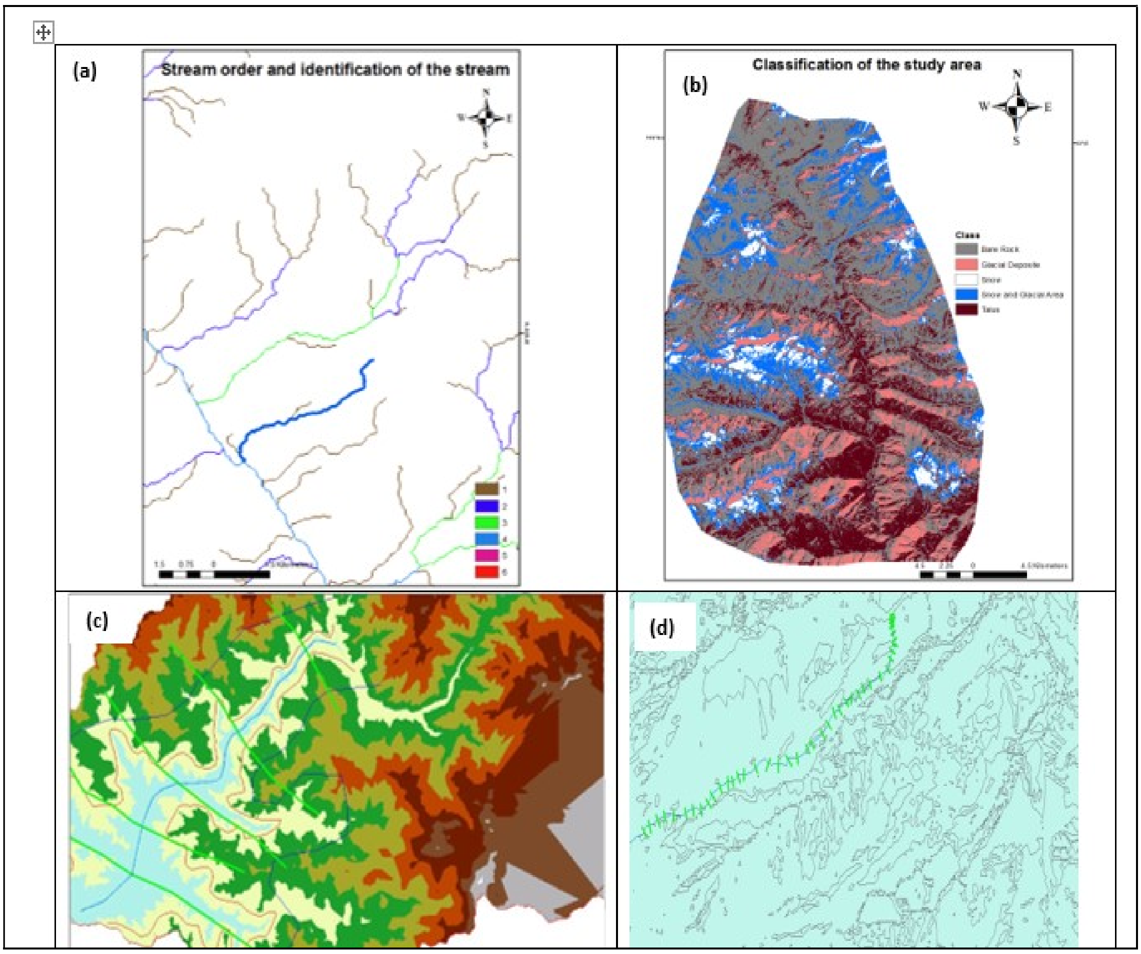
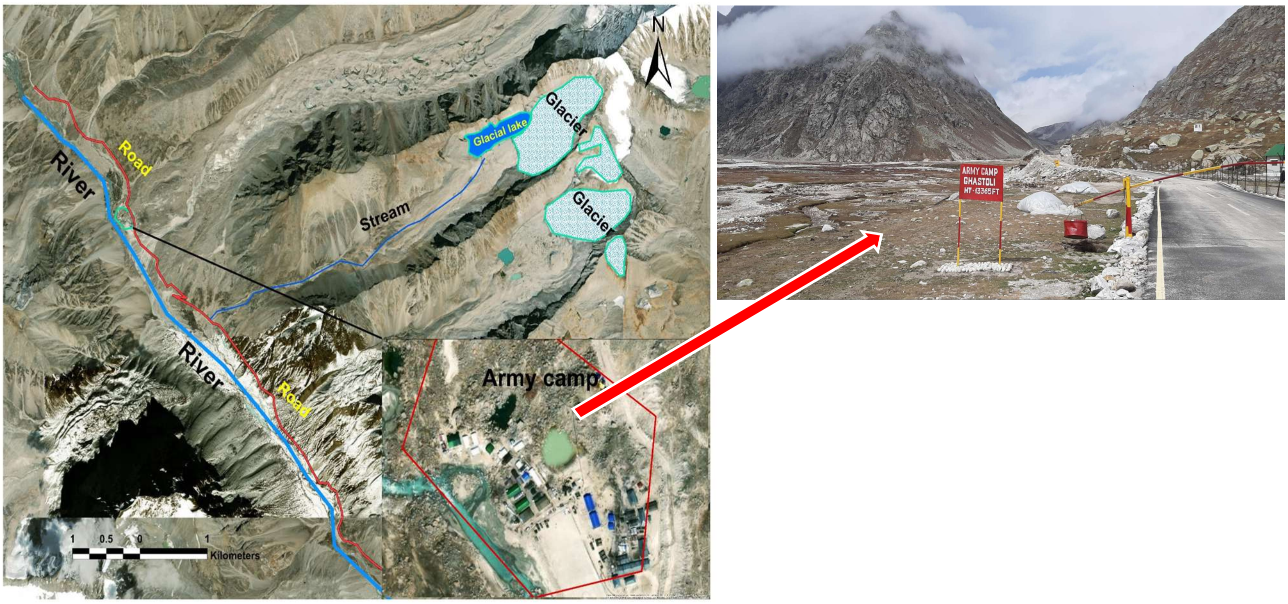
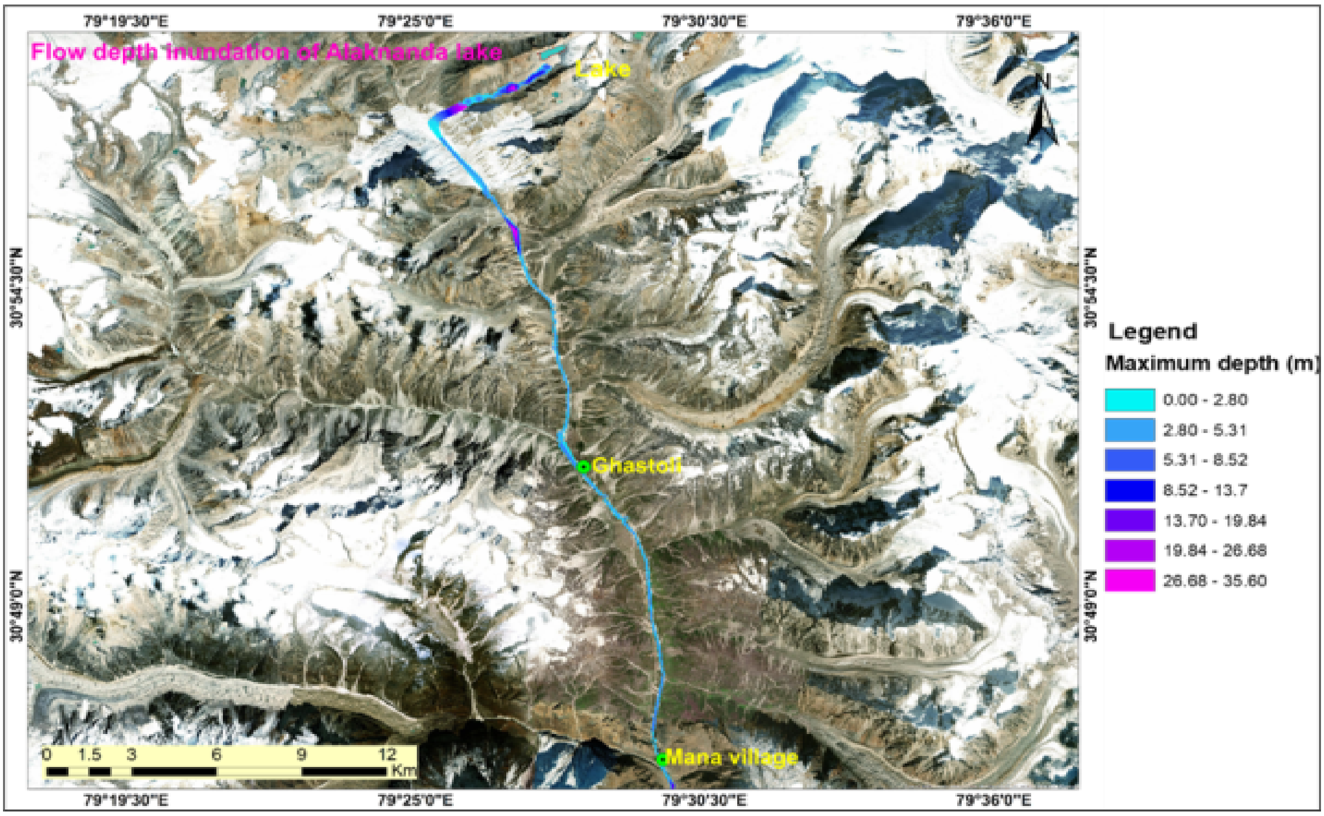


Figure 39. (a) Stream order and Identification of Stream, (b) Classification of the Study Area, (c) River cross-sections map using DEM and (d) Flood inundation modeling induced by GLOF using HEC-RAS for Alaknanda River basin, U.K.


N
Glacial lake
Glacier
Glacier
Road
River
Stream
River
Road
Army camp
1 0.5 0 1
Kilometers
ARMY CAMP
GHASTOLI


79°19'30"E
79°25'0"E
79°30'30"E
79°36'0"E
Flow depth inundation of Alaknanda lake
Lake
N
30°54'30"N
30°49'0"N
Ghastoli
Mana village
0 1.5 3 6 9 12
Km
Legend
Maximum depth (m)
0.00 - 2.80
2.80 - 5.31
5.31 - 8.52
8.52 - 13.7
13.70 - 19.84
19.84 - 26.68
26.68 - 35.60

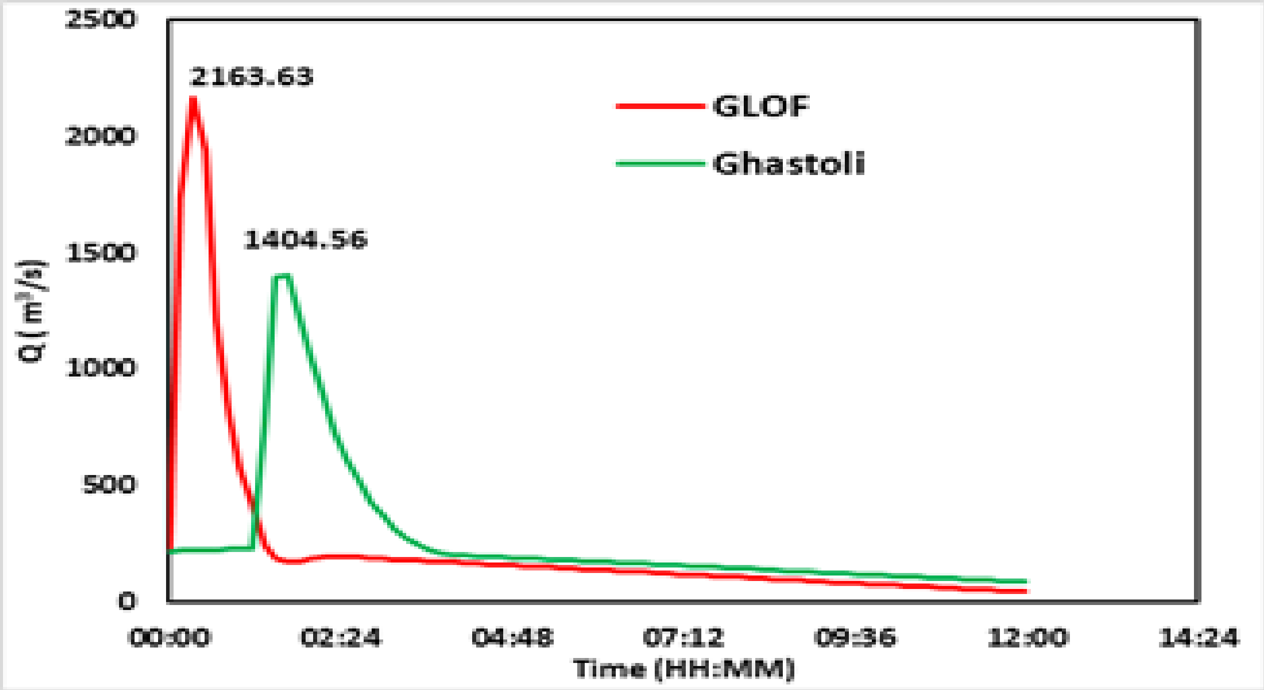


Figure 40. (a) Army/ITBP Camps at Ghastoli, Uttarkhand near the Glacial Lake, (b) Maximum depth inundation from Alaknanda lake, (c) Flood Hydrograph Ghstoli and (d) Maximum velocity flood inundation from Alaknanda lake for U.K.

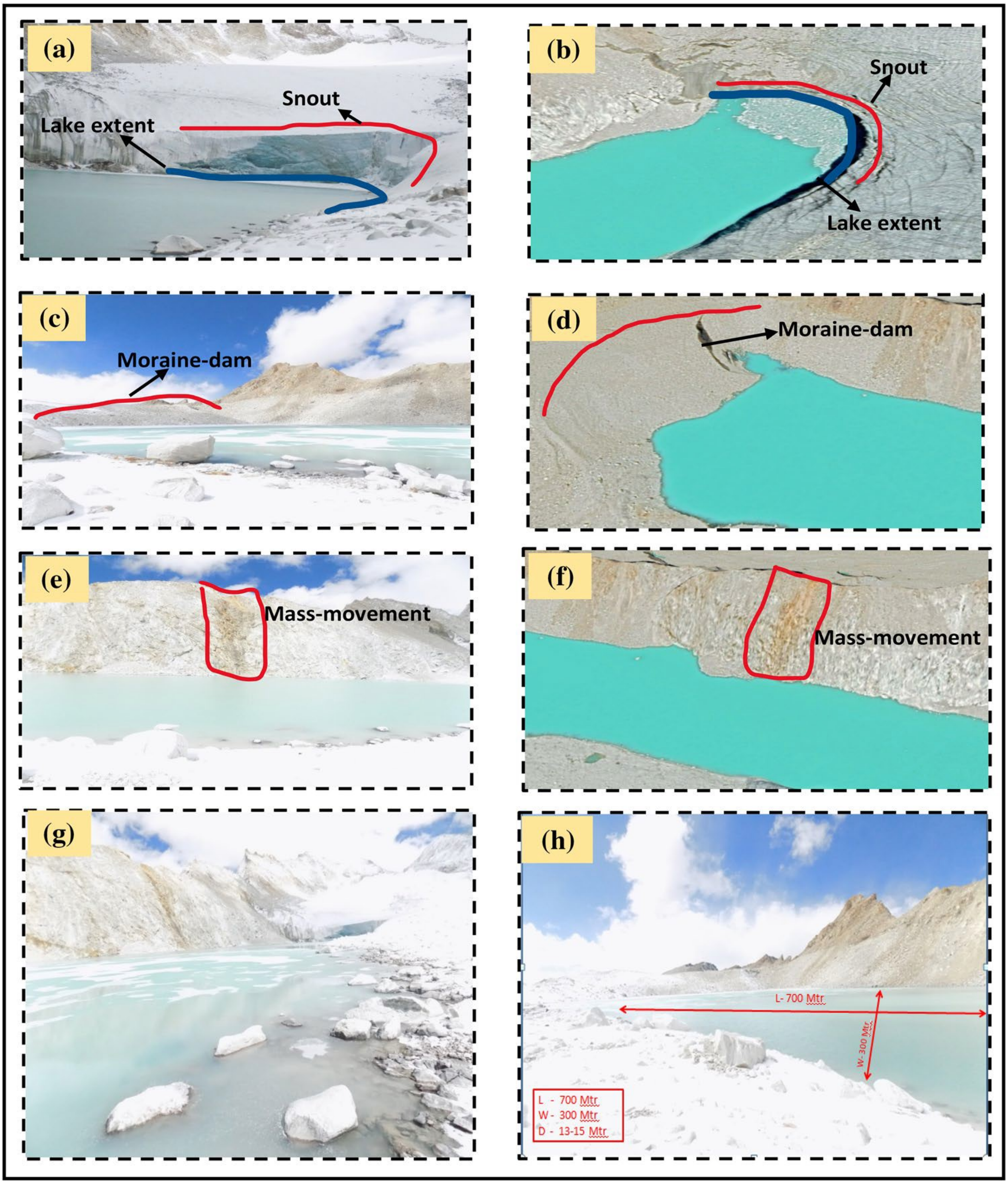


Figure 41. a, c, e, g and h showing field photographs of snout, lateral-moraine dam, mass movement, floating ice and lake parameters respectively. b, d and f showing snout, lateral moraine dam and mass movement on Google Earth imagery.

3.2 Key Results (max. 1000 words in bullets covering all activities)

- Methodology for inventorisation of Glacial Lake Identification: Normalized Difference Water Index (NDWI) = (GREEN – NIR) / (GREEN + NIR) .GREEN is a band that encompasses reflected green light and NIR represents reflected near infrared radiation.
- The selection of these wavelengths was done to: maximize the typical reflectance of water features by using green light wavelengths, minimize the low reflectance of NIR by water features; and take advantage of the high reflectance of NIR by terrestrial vegetation and soil features. Potentially vulnerable Lake mapping: Rise in lake water level, Activity of supraglacial lakes , Position of Lakes ,Dam Conditions, Condition of Associated Mother Glacier and Physical Conditions of Surroundings.
- LAKE DEPTH: The empirical relations as available by Huggel et al. (2002) is: The lake volume D = 0.104 A0.42 where D is the depth of lake in m and A is the lake area in m2. LAKE VOLUME :The empirical relations as available by Huggel et al. (2002) is: The lake volume V = 0.104 A1.42 where V is the lake volume in m3 and A is the lake area in m2.
- GLOF SIMULATION: Inputs required for HecGeoRAS software for Glacier and Glacier lake mapping, Drainage network and Length of stream d/s lake, DEM of the basin, Cross Section at regular interval downstream of lake, Area and Volume of the lake, Breach width and Depth and 100 year return flood if available Flood modelling, estimation, forecasting and alarms: Controlled breaching can be carried out by blasting, excavation, or even by dropping bombs from an aircraft. For more permanent and precise control of lake outflows, rigid structures made out of stone, concrete, or steel can be used.
- Tunneling through moraines or debris barriers, although risky and difficult because of the type of material blocking the lake, has been carried out in several countries. Real-time monitoring, early warning systems and preparedness education are the most beneficial ways to minimize risk. Preparedness hazard mapping, improving communication, education to create awareness.
- NDWI (GREEN – NIR) / (GREEN + NIR) along with the band ratio of Green and NIR with suitable thresholding has been used in ArCGis and Erdas to map the glacial Lakes. Google Earth has also been used for the verification of lakes in case of shadows. After the mapping of lakes the area and volume calculation for each lake has been done using ArcGis.
- Indicators that are considered for hazardous lake identification is lake type, distance from mother glacier, periphery in contact with glacier, area expansion over the years, Mean slope of lake front area ,Mean slope of glacier end. Results has been observed in 1994 Area <0.01 sq. km no of lakes 26 and Area <0.01 sq. km. In the year 2017 Area <0.01 sq. km 45 to 12 lakes

3.3 Conclusion of the study undertaken (maximum 500 words in bullets)

- In the year 2013, there were, in total, 463 lakes, out of which 3 lakes were having areas greater than 0.1 km2 while more lakes were having areas less than 0.1 km2 . Most of the lakes are situated above 4500 m. The area of the biggest lake, i.e. Lake 196, is increasing (Figure 30) over the past years. The lake is also expanding laterally and longitudinally; therefore, this lake has been considered as a potentially dangerous lake from GLOF point of view.

- In total of 39 glacial lakes, 10 lakes were found dangerous lakes having area >0.1 Km2 were shown in the table in Kinnaur district of HP. The formation and expansion of glacial lakes were in concert with the climatic change (increase in temperature and decrease in precipitation) induced glacier retreat in Kinnaur district.

- The rate of growth of glacial lakes varied inversely with the proximity to the parent glacier, closer the glacial lake to mother glacier higher was its growth rate. Hence, glacier meltwater flowing into the lakes is the main source of water to the areal expansion of lakes in the region. As a consequence of the continuous expansion of lakes and glacier retreat, GLOF is an emerging threat in Kinnaur district.

- The use of GIS and Remote sensing technology has allowed lakes developed at higher altitudes to be mapped, which would not have been possible through field investigations. Information provided by systematic study of satellite images give an idea about the formation of these lakes. In order to understand the change in their location, the monitoring of two glacial lakes, Geepang gath and Samudratapu, was carried out in depth.
- Over the years, the monitoring showed a gradual increase in their size, which is further justified by primary survey results. It is therefore important to research such lakes in detail using high resolution satellite data in order to evaluate the hazards of such lakes.
- This will assist in evaluating potential hazards and also in mapping some other new lakes that are being developed in the area.

4 OVERALL ACHIEVEMENTS

4.1 Achievements on Objectives [Defining contribution of deliverables in overall Mission (max. 1000 words)]

Research Objectives	Achievements
1) Generation and Analysis of the data of selected region of Western Himalaya to identify the potentially dangerous and vulnerable glacial lakes susceptible to outburst and predict the consequences of the GLOF. 2) To define conditions of glacial lakes, moraine dams associated with mother glaciers attributing those with topographic features around lakes/moraine dams.	1) The study has been focused on finding the glacial lakes and potential glacial lakes in Satluj basin, Himachal Pradesh, India that maybe vulnerable to GLOF. Glacier and glacial lakes mapping has been carried out by manual digitization on the basis of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI) and slope information. Inventory of glacial lakes including the increased number of glacial lakes with the area greater than 0.01 sq km from 1972 to 2018 of Landsat data sets has been done in Satluj basin. The data has been downloaded by using the USGS Earth Explorer website https://earthexplorer.usgs.gov/. With the help of visual interpretation along with normalized difference snow index (NDSI), normalized difference water index (NDWI), Band Ratio analysis, slope, Aspect

3) To define geometrical parameters (Spread area, depth and volume of water etc) of the vulnerable lakes and their further examination and analysis to estimate the scale and size of the GLOF hazard. 4) To apply dam breach model on dangerous lake and study the affect of GLOF at downstream. 5) To identify the vulnerable locations downstream where GLOF can create disaster and assess the scale of disaster and prepare the road map for prevention, warning, mitigation, rescue.	information a total of 73 Lakes have been mapped in Alaknanda Basin in 1994. 2) The Glacial lake in Satluj basin (Latitude 31o39′40.81″ N and Longitude 78o10′7.32″ E) is one of the possible highest potentially dangerous lake, whose maximum surface area is approximately 0.2396 sq.km acquired on 16 September 2018 of Landsat 8. Glacial lakes has been classified in three ways first one is 1-5 hect. is Less vulnerable, second one is 5-10 hect Medium vulnerable and third one is >10 hect is High vulnerable. There has been 15 critical glacial lake has been identified in Satluj river basin. Area and volume estimation has been done for the mapped glacial lakes. 3) For selecting potentially dangerous lakes, following parameters has been used. Lakes of area larger than 0.03 km2 has been considered as harmful owing to the less volume of water contained by it (area and volume are empirically related by Huggel's formulae). Glacial lake area and volume has been calculated using Huggel's formulae. The lake volume V = 0.104 A1.42 ,The lake depth D = 0.104 A0.42 where D is the depth of lake in m and A is the lake area in m2. The Volume and Depth of the identified Potentially critical Glacial lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E are 4527981.19 m3 and 18.8980m respectively. 26 lakes out of 73 lakes were having the area greater than 0.01 km2. Detailed study using number of indicators for hazardous lake has been carried out on these lakes. 4.) The two lakes (79°45'20.301"E 30°54'0.964"N) and (30o58'33.26" N 79o27'33.52"E) have been identified as potentially hazardous by at least three indicators. HecGeoRAS software is used for creation of river cross-section and setting up analysis environment for HEC-GeoRAS, create stream centre line,bank line, creating river centerline and topology, length and elevation profile process has been carried out for dam breach model on dangerous lake in Satluj Basin at 31°39'40.81"N, 78°10'7.32"E and study the affect of GLOF at downstream. 5.) Categorization of lakes from lowest to highly vulnerable category has been done. Field visit on highly vulnerable glacial lake in Alaknanda basin has been done. Manuscript is being prepared from the information gathered through the remote sensing data along with the field measurement of the study area in Alaknanda basin. GLOF mitigation, prevention, warning and rescue has

	been done.

4.2 Establishing New Database/Appending new data over the Baseline Data (max. 1500 words, in bullet points)

Because of its free availability, 30 m resolution, and vast area coverage, Landsat data has been widely used for delineation and mapping glacial lakes. The current investigation employed 30 m resolution Landsat images and the Advanced Spaceborne Thermal Emission & Refection Radiometer—Digital Elevation Model (ASTER DEM, 30 m) acquired from the web portal. The Global Land Survey (GLS) data system of the United States Geological Survey (USGS) held Landsat images, which were downloaded and utilised for the present investigation. With little cloud and snow cover in the post-monsoon season, glacial lakes display modest changes. The research employed Landsat sceneries from the post-monsoon season, which had low cloud coverage (less than 10%) or were cloud-free. Glacial lake inventories were prepared using Landsat photos from 1990 to 2018 for area change analysis. The Survey of India (SOI) toposheet 1979, Scale 1: 50,000, was used to validate glacial lake borders for 1990. Because the SOI toposheets are less dependable for change identification, the Landsat TM (1990) scene was utilised as a foundation picture for glacial lake area change. Because of the comparably low quality of Google Earth photos, it was utilised to confirm the glacial lake contours. Landsat data at a coarser resolution. A time series of meteorological data (temperature and precipitation, for example) from Climate data was analyzed from 1980 to 2018 in order to better understand climate as a potential limiting factor for development.

4.3 Generating Model Predictions for different variables (if any) (max 1000 words in bullets)

4.3.1 HEC-RAS Model and Parameters

HEC-RAS is a two-dimensional hydraulic model with several flood prediction and reconstruction applications. In flood modelling, parameters including lake volume, peak discharge, and outburst duration were collected by field study or empirical estimate. They'd be used to calculate the dam-breach hydrograph, which is important for the model's accuracy. A high-resolution DEM and a proper land surface roughness value may also help the model provide better results.

4.3.2. Estimating Lake Volume, Peak Discharge, and Breaching Time

The largest quantity of water that may be involved in a GLOF is the lake volume. In this work, Cook and Quincey (2015) employed the volume–area connection for moraine-dammed lakes (with an R2 value of 0.94, Equation given by Cook and Quincey (2015). To run the model for Cirenmaco, we utilised a lake volume of 18 106 m3 based on an in-situ bathymetric study. Empirical formulae were used to calculate the peak discharge (Qp) and breaching time (Tp). Most models that predict peak discharge overestimate, whereas those that forecast breaching time underestimate. However, following verification, the Froehlich equations exhibit the lowest error when compared to observed data.

4.3.3. Dam-Breach Hydrograph

The GLOF process line may be deduced indirectly in the absence of observed or simulated data. We assume that the flood discharge will rise and fall in a linear fashion. The outburst volume is then utilised to create the GLOF process line as a control. This hypothetical procedure has been used in a number of GLOF experiments, and the findings are consistent with reality.

4.3.4. Hazard Index

In earlier GLOFs, complete draining in big or medium-sized lakes was uncommon. As a result, we classified the lake drainage percentage into four categories: 25%, 50%, 75 percent, and 100 percent. We computed the frequency of distinct lake drainage scenarios based on an inventory of GLOF incidents from nine moraine-dammed lakes in the Himalayas. Only one glacial lake drained more than 75 percent of its water volume, four lakes drained 50–75 percent, two lakes drained 25–50 percent, and two lakes drained less than 25 percent, according to the findings.

4.4 Technological Intervention (max. 1000 words)
4.5 On-field Demonstration and Value-addition of Products (max. 1000 words, in bullet points)
4.6 Developing Green Skills in IHR
4.7 Addressing Cross-cutting Issues (max. 500 words, in bullet points)

5 IMPACTS OF FELLOWSHIP IN IHR

5.1 Socio-Economic Development (max. 500 words, in bullet points)
5.2 Scientific Management of Natural Resources In IHR (max. 500 words, in bullet points)
5.3 Conservation of Biodiversity in IHR (max. 500 words, in bullet points)
5.4 Protection of Environment (max. 500 words, in bullet points)
5.5 Developing Mountain Infrastructures (max. 500 words, in bullet points)
5.6 Strengthening Networking in IHR (max. 700 words, in bullet points)

6 EXIT STRATEGY AND SUSTAINABILITY

6.1 How effectively the fellowship findings could be utilized for the sustainable development of IHR (max. 1000 words)
6.2 Efficient ways to replicate the outcomes of the fellowship in other parts of IHR (max. 1000 words)
6.3 Identify other important areas not covered under this study, but needs further attention (max. 1000 words)

Though extensive research is required to predict GLOFs, it is recommending that an early warning system be installed for the study areas. The early warning system should be capable of providing alerts to the Government authorities in case there is a threat of GLOF. Deployment of real time sensors network at vulnerable lakes, capable of measuring rise and discharge of water, will enable the authorities to set up an early warning system. The early warning system coupled with GLOF simulation models capable of predicting the time of arrival of the flash flood and showing the flooded areas downstream will enable the local authorities to take precautionary measures in the event of a GLOF.

6.4 Major recommendations for sustaining the outcomes of the fellowship in future (500 words in bullets)

7. EWS with a road map

Vulnerable downstream locations in the respective glacial lakes were identified in the two study areas namely Alakanda river basin, Uttarakhand and Satluj river basin, Himachal Pradesh. The road maps have been prepared for GLOF mitigation, warming, prevention and rescue mechanism.

Figure 42. Vulnerable downstream locations in the Satluj river basin, Himachal Pradesh

Figure 43. Vulnerable downstream locations in the Alaknanda river basin, Uttarakhand

8 Publications - Journal

Rongali, G., Tiwari, K.C., Vishwas, P. (2022). Potentially Dangerous Glacial Lake Risk Mapping and Assessment in Satluj River Basin, Himachal Pradesh Using Remote Sensing and GIS. In: Chembolu, V., Dutta, S. (eds) Recent Trends in River Corridor Management. Lecture Notes in Civil Engineering, vol 229. Springer, Singapore. https://doi.org/10.1007/978-981-16-9933-7_16

Rawat, M., Ahmed, R., Jain, S. K., Lohani, A. K., Rongali, G., & Tiwari, K. C. (2022). Glacier–glacial lake changes and modeling glacial lake outburst flood in Upper Ganga Basin, India. Modeling Earth Systems and Environment, 1-20. DOI https://doi.org/10.1007/s40808-022-01512-5

Conferences and Seminars

Rongali, G., Tiwari, K.C. (2022). Potentially dangerous glacial lake risk mapping and assessment in Satluj river basin, Himachal Pradesh using remote sensing and GIS 1st International Conference on River Corridor Research and Management. 25/02/2021 – 27/02/2021 – IIT Jammu.

Rongali, G., Pandey, A., and Tiwari, K.C. (2019). Glacial Lakes and Glacial Lakes Outburst Floods in Himachal Pradesh, India using Remote Sensing and GIS 4th Himalayan Researchers Consortium (HRC) 2019. 26/09/2019 – 27/09/2019 – WII, Dehradun.

Rongali, G., Pandey, A., and Tiwari, K.C. (2019). Inventory of Glacier and Glacial Lake Outburst Flood (GLOF) Study in the Western Himalaya National Seminar-Cum-M&E Workshop. 04/02/2019 – 07/02/2019 – GBPNIHESD, Almora, Uttarakhand.

Rongali, G., Pandey, A., and Tiwari, K.C. (2019). Glacial Lakes and Glacial Lakes Outburst Floods in Himachal Pradesh, India using Remote Sensing and GIS International Workshop on Climate Change and Extreme Events in the Himalayan Region. 18/04/2019 – 20/04/2019 – IIT Mandi, H.P

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APPENDICES

Appendix 1 – Details of Technical Activities
Appendix 2 – Copies of Publications duly Acknowledging the Grant/ Fund Support of NMHS
Appendix 3 – List of Trainings/ Workshops/ Seminars with details of trained resources and dissemination material and Proceedings
Appendix 4 – List of New Products (utilizing the local produce like NTFPs, wild edibles, bamboo, etc.)
Appendix 5 – Copies of the Manual of Standard Operating Procedures (SOPs) developed
Appendix 6 – Details of Technology Developed/ Patents filed
Appendix 7 – Any other (specify)

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(Signature of HRA/HJRF/HPF)

(**NMHS FELLOWSHIP COORDINATOR**)

(Signed and Stamped)

(**HEAD OF THE INSTITUTION**)

(Signed and Stamped)

Place: ………………..
Date: ……../……/……